Lake Modeling

Is your Lake Ready for the Runway?

To retain respect for water quality models, sausages and laws, one must not watch them in the making.

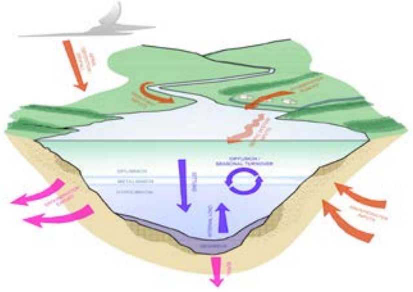
- Otto von Bismarck

Welcome to a tour of the sausage factory!

Agenda

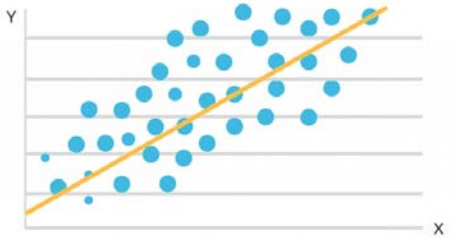
PART 1

Limnology Concepts for Modeling



PART 2

Lake Modeling Concepts / Examples



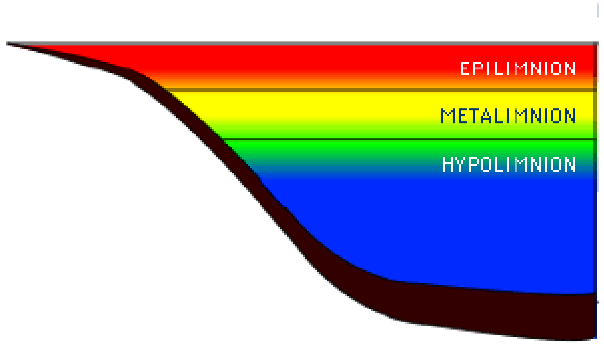
Q & A

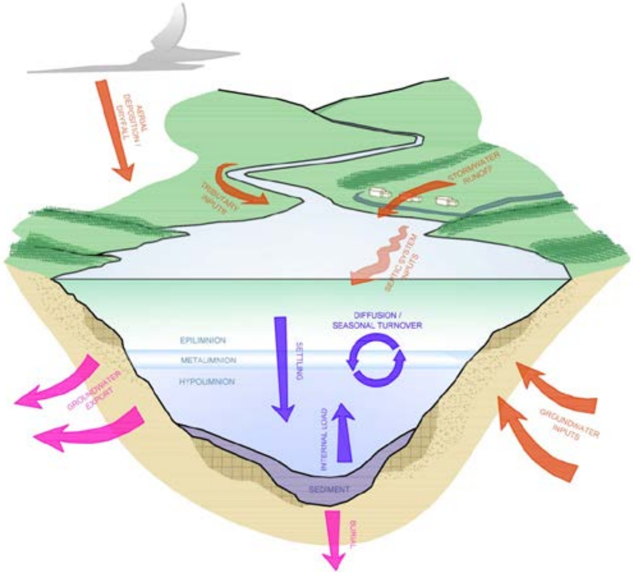
What is Lake Modeling?

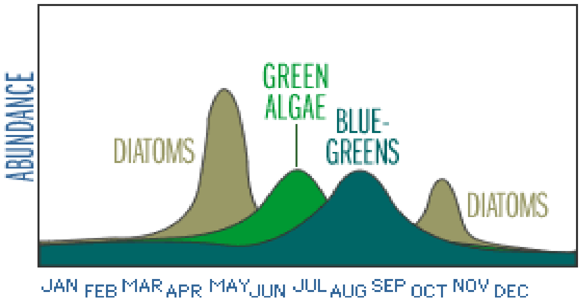
- **Lake models uses available information to explain and predict how a lake behaves.**
- **Models can inform lake management decisions and help answer questions, such as:**

  - *How much **pollutant load reduction** is needed to meet a water quality goal?*
  - *Where should **lake management funds be spent** to prevent algae blooms?*
  - *What will **lake water quality** be like in 25 years?*
  - *How much **will lake water quality improve** if a sewer system is installed?*
  - *How will a lake respond to **climate change**?*

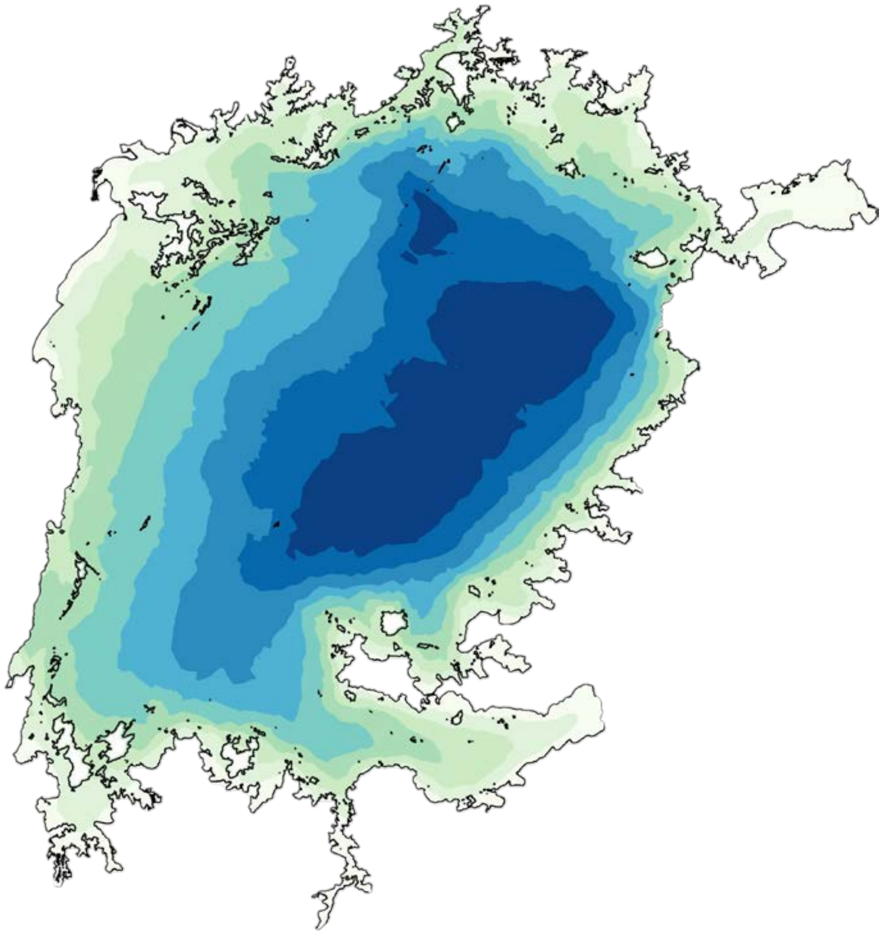
Limnology Concepts for Modeling



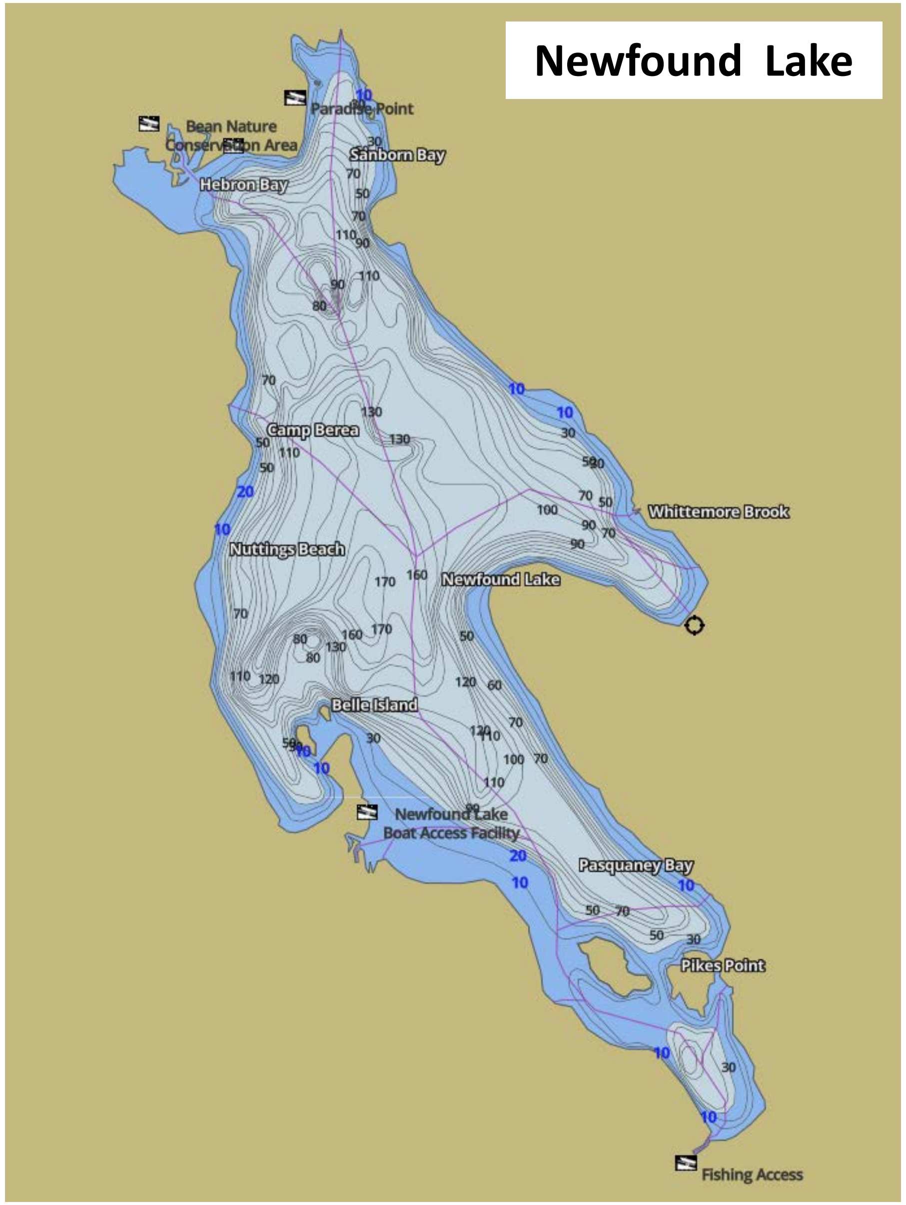


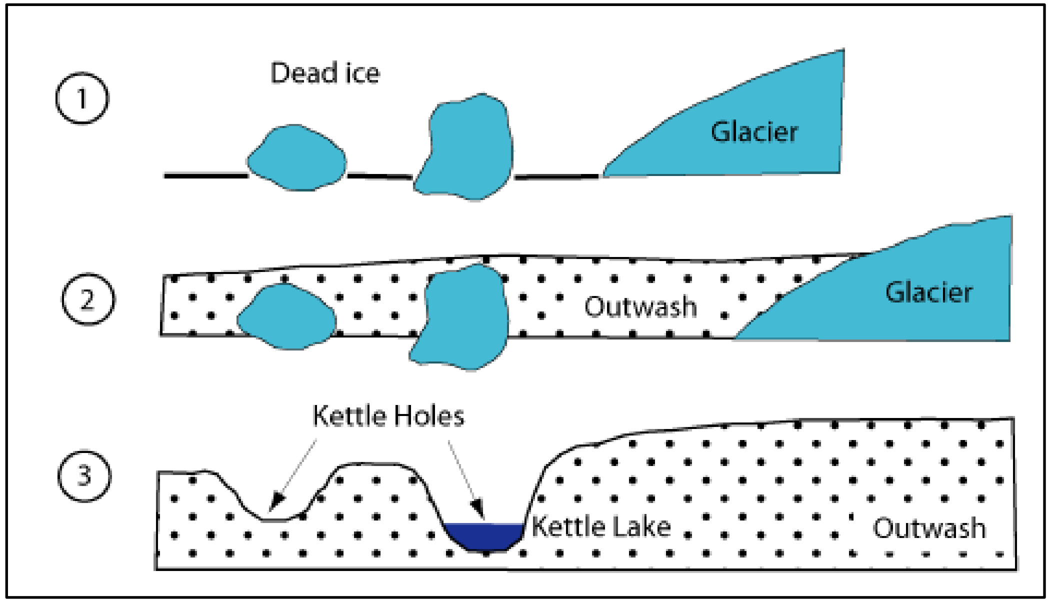


Lake Physical / Morphological Features



Lake Types: Glaciated Lakes





Lake Types – Reservoirs / Impoundments

Pontook Reservoir

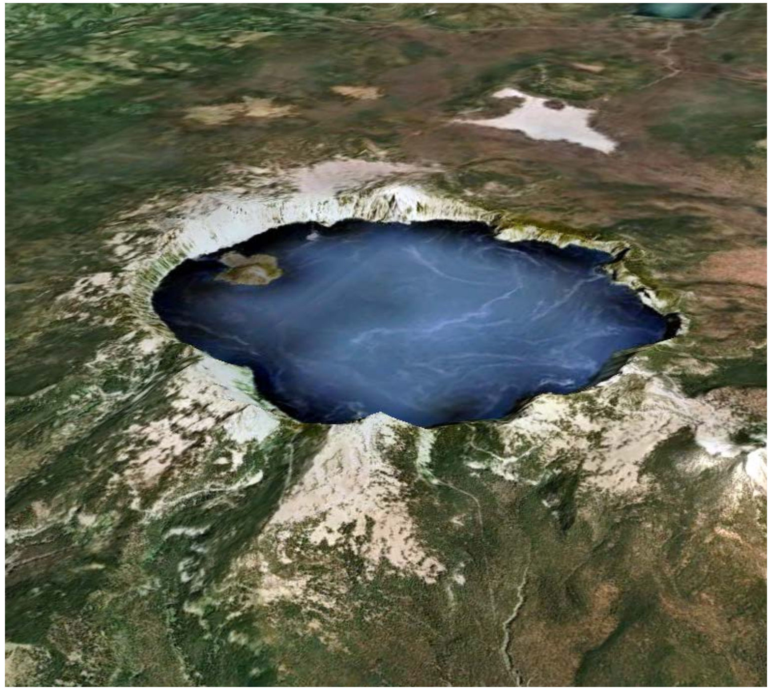
Everett Lake

beaver pond

Lake Types - Other

Oxbows
(Horseshoe Pond, Concord)

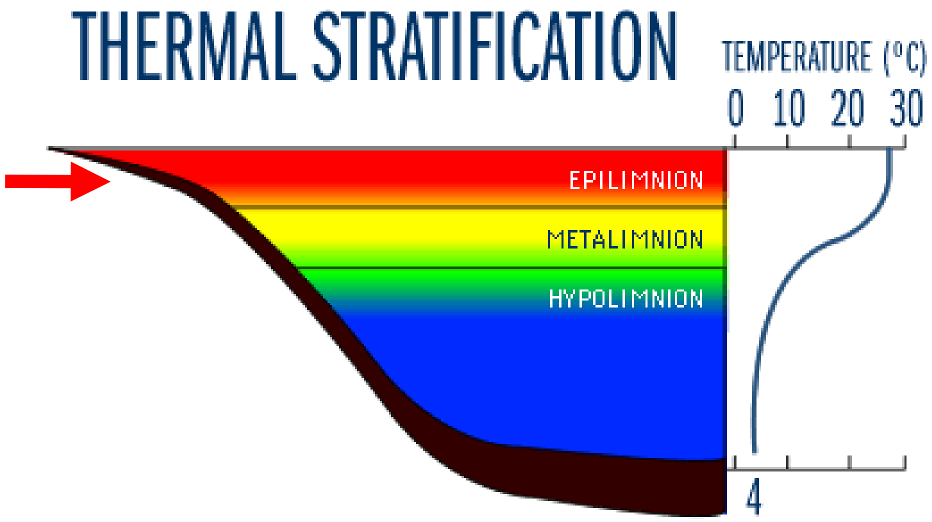
Lake Manicouagan
(impact crater from meteor with 3 mile diameter!)



Crater Lake (OR)
(volcanic crater)

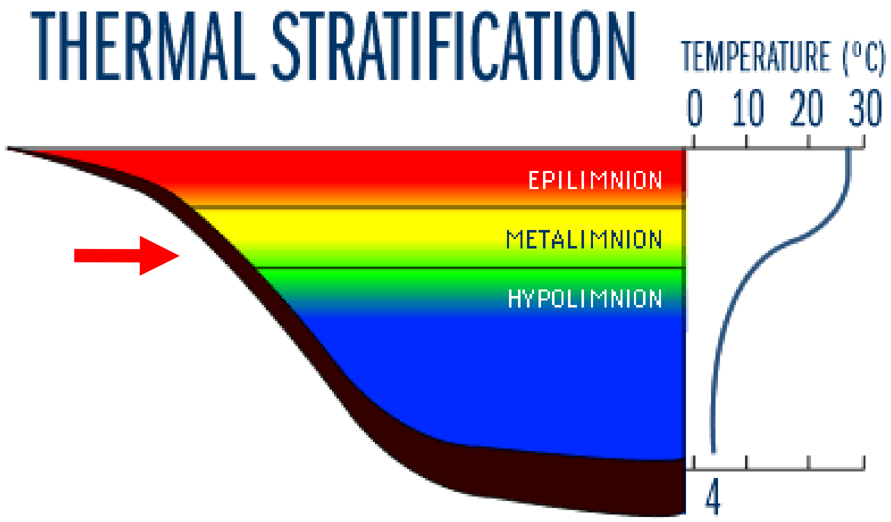
THERMAL STRATIFICATION:
EPILIMNION

- **Upper layer of the pond**
- **Well oxygenated (wind, waves, photosynthesis)**
- **Affected by the wind, motor boats, inflows, etc.**



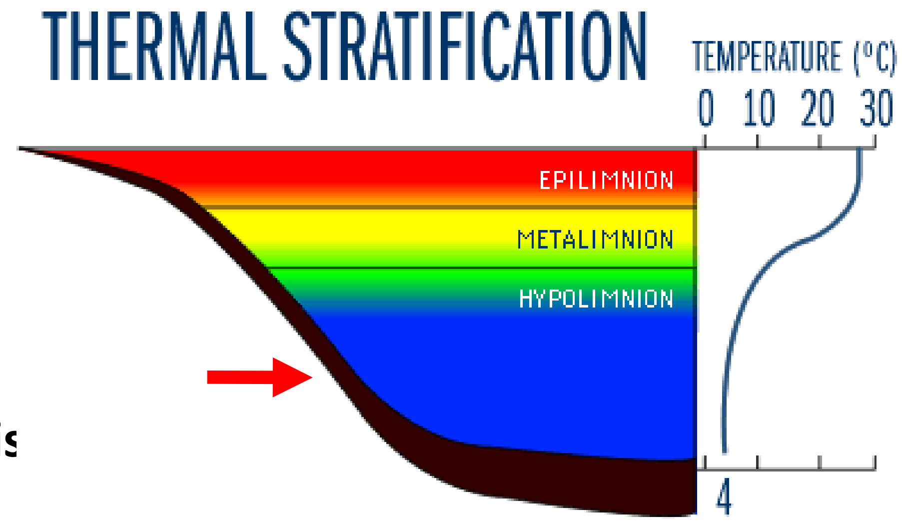
THERMAL STRATIFICATION: METALIMNION

- Middle "layer" of pond
- Greatest change in water temp., density and chemistry
- Acts as barrier between the top and bottom of the pond

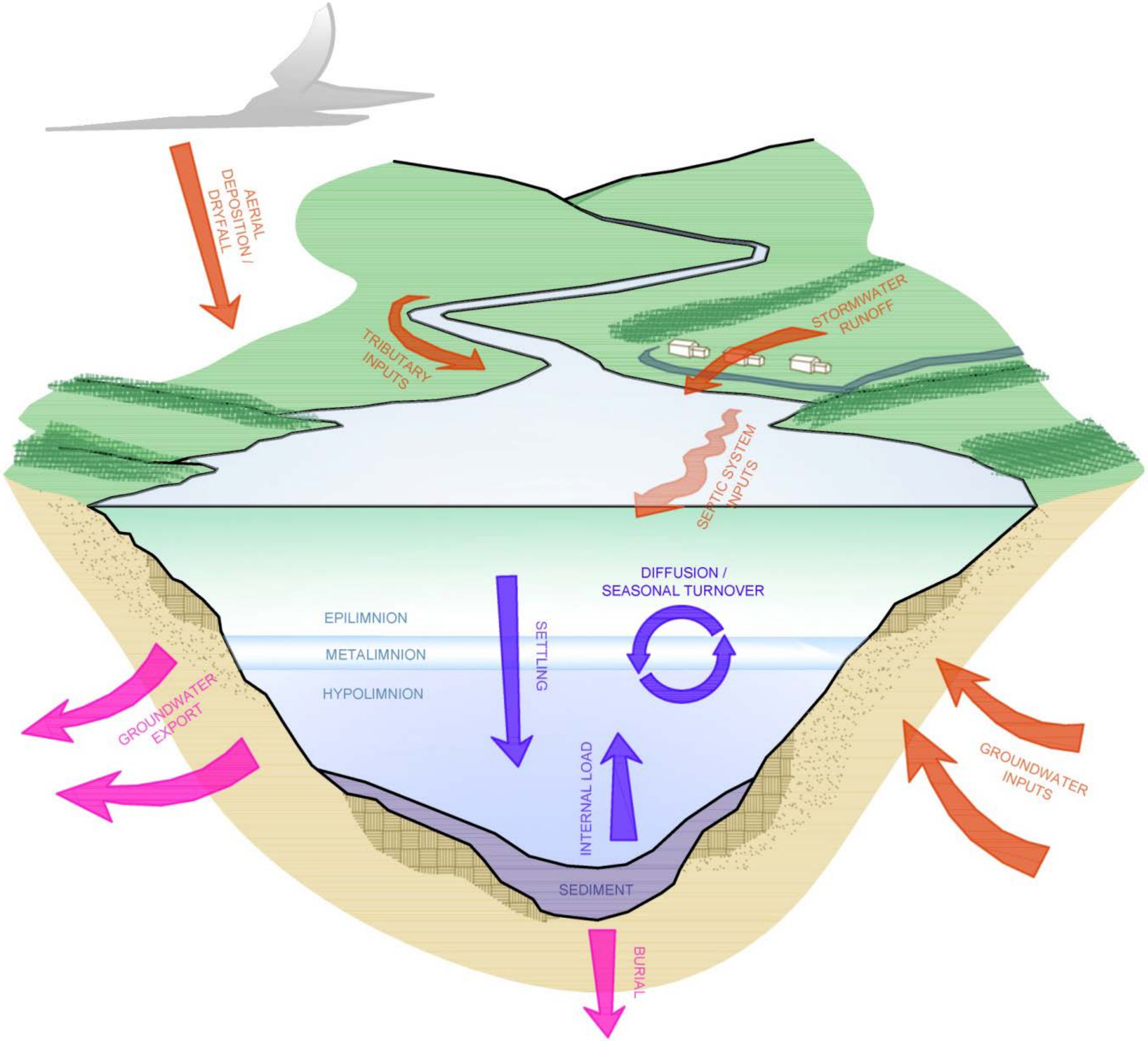


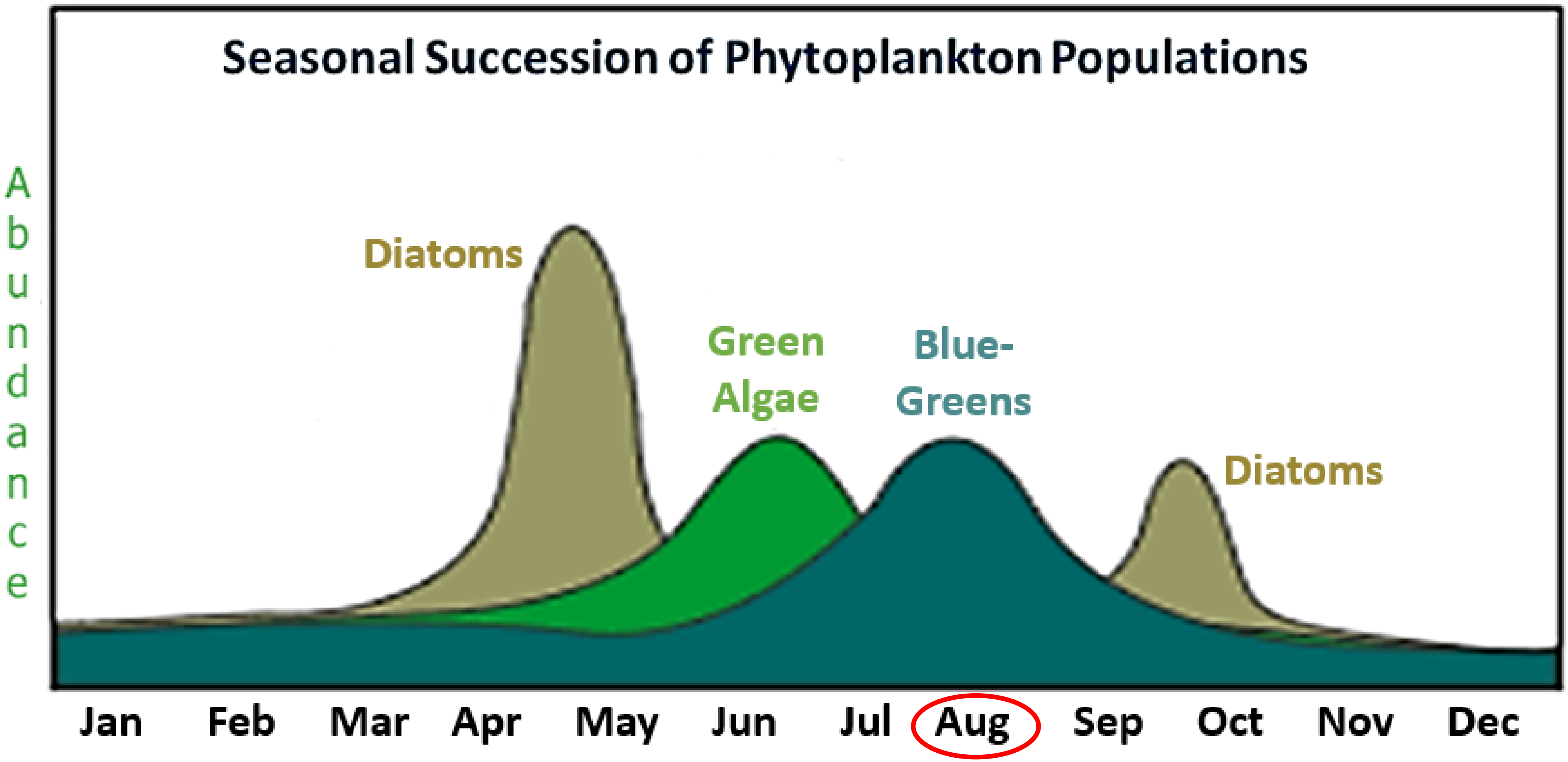
THERMAL STRATIFICATION:
HYPOLIMNION

- Bottom “layer” of pond
- Aphotic (no light)
- Anoxic
  - No internal O_2 source from photosynthesis
  - O_2 consumed by decomposition



Lake/Watershed Nutrient Dynamics





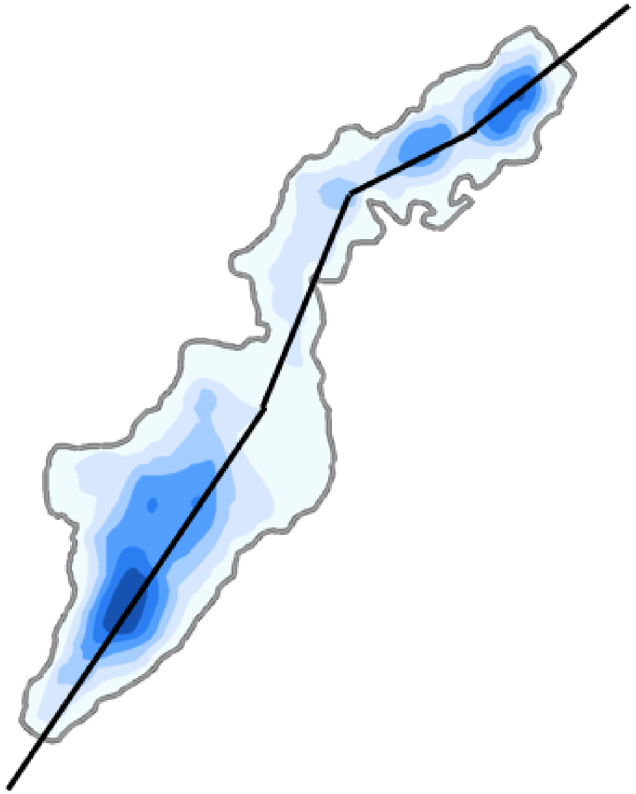
Seasonal Succession of Phytoplankton Populations
Abundance
Diatoms
Green Algae
Blue-Greens
Diatoms
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

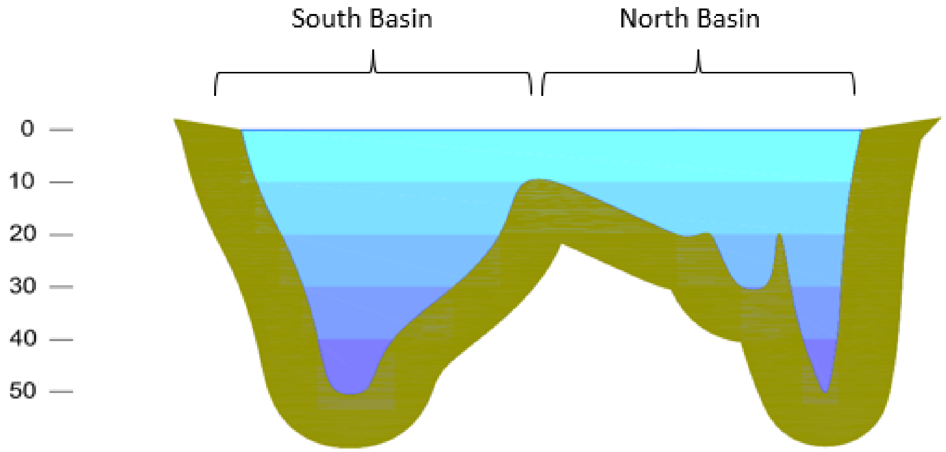
How do the lake types differ?

- Depth
- Lake: Watershed Ratio
- Residence Time
- Lifespan

Depth

Glaciated Lakes = Deep relative to area





Depth

Reservoirs = Vary, but often shallow for a given size relative to glaciated lake

Why is depth important?

Mixing…NH lakes are typically dimictic or polymictic

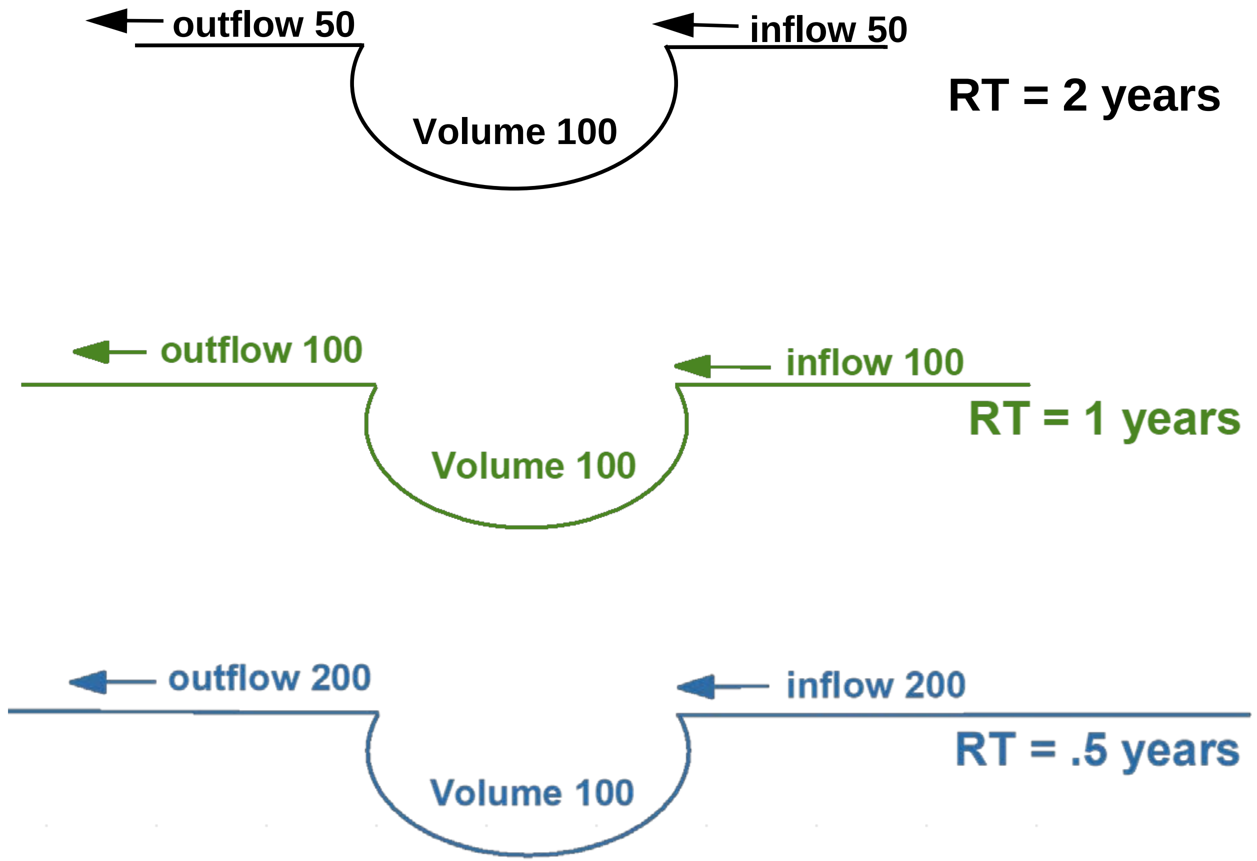
Dimictic	Polymictic
2 mixes/year (spring /fall)	Many mixes/year
Deeper lakes and ponds	Shallow lakes/ponds; mixing from wind, waves, etc.

Why is depth important?

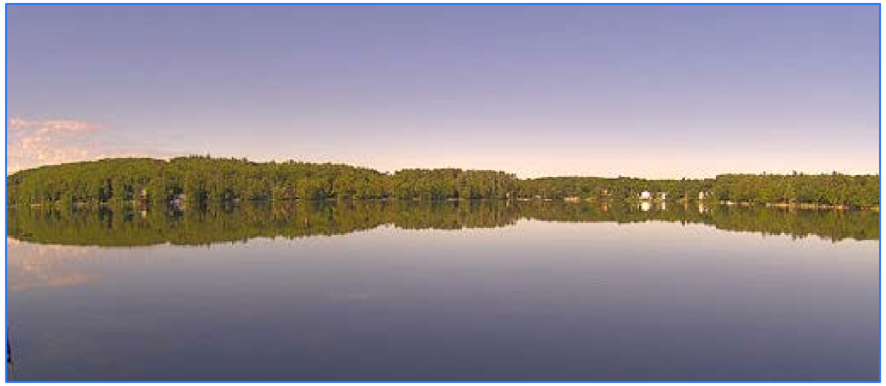
- **Deeper lakes have larger volume of water, which influences water quality factors such as residence time and settling.**

Residence Time: The time required for the full volume of lake water to be replaced. It is the reciprocal of turnover ratio (aka "flushing rate").

Volume / Inflow = Residence Time (years)



Residence Time…a few examples



Mirror Lake
Max. Depth: 43 feet
Residence Time: 1.4 years

Squam Lake
Max. Depth: 89 feet
Residence Time: 2.5 years

Lake Tanganyika (Deepest Lake in Africa)
Max. depth = 4,826 feet
Residence Time = 5,500 years

Residence time also influences how much sedimentation can occur:

Longer residence time

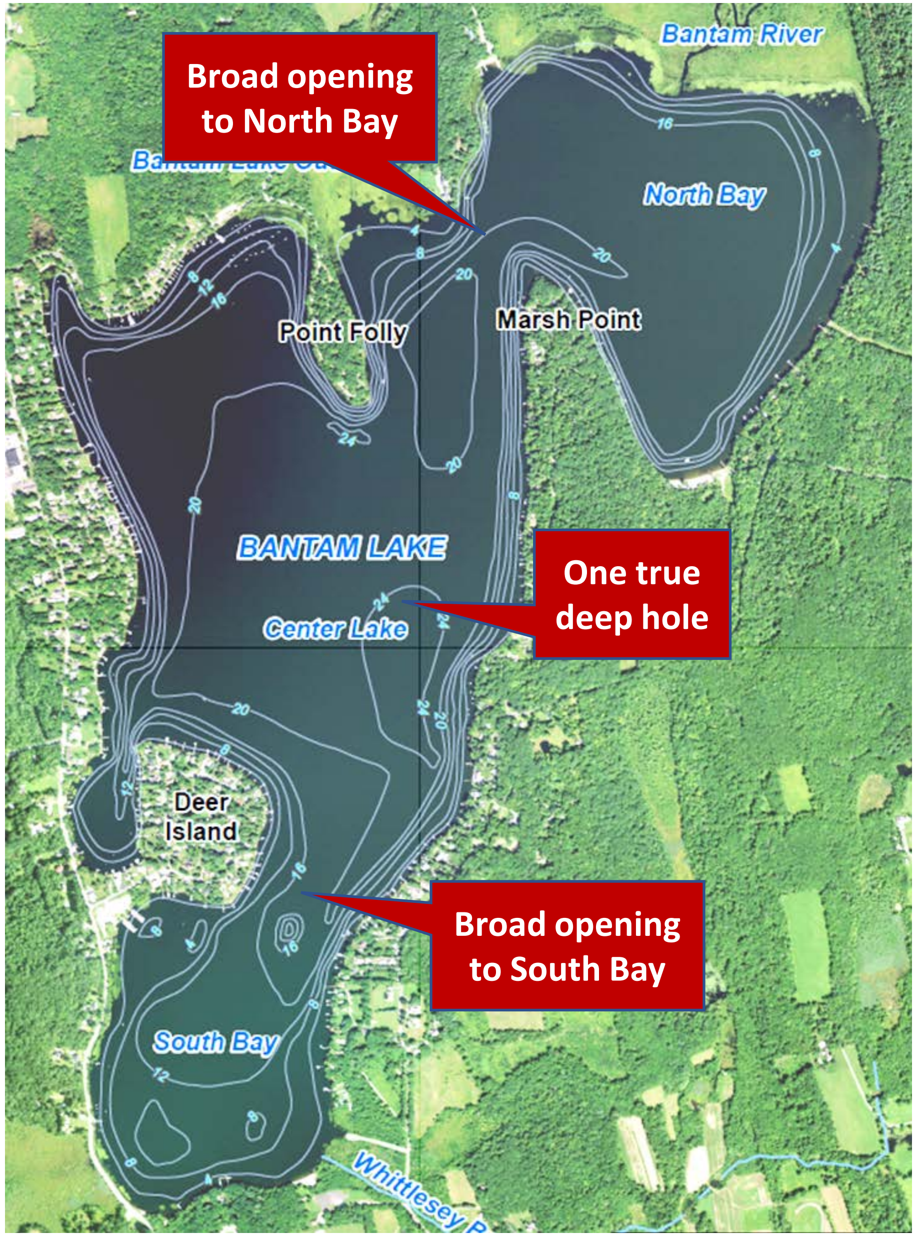
↓

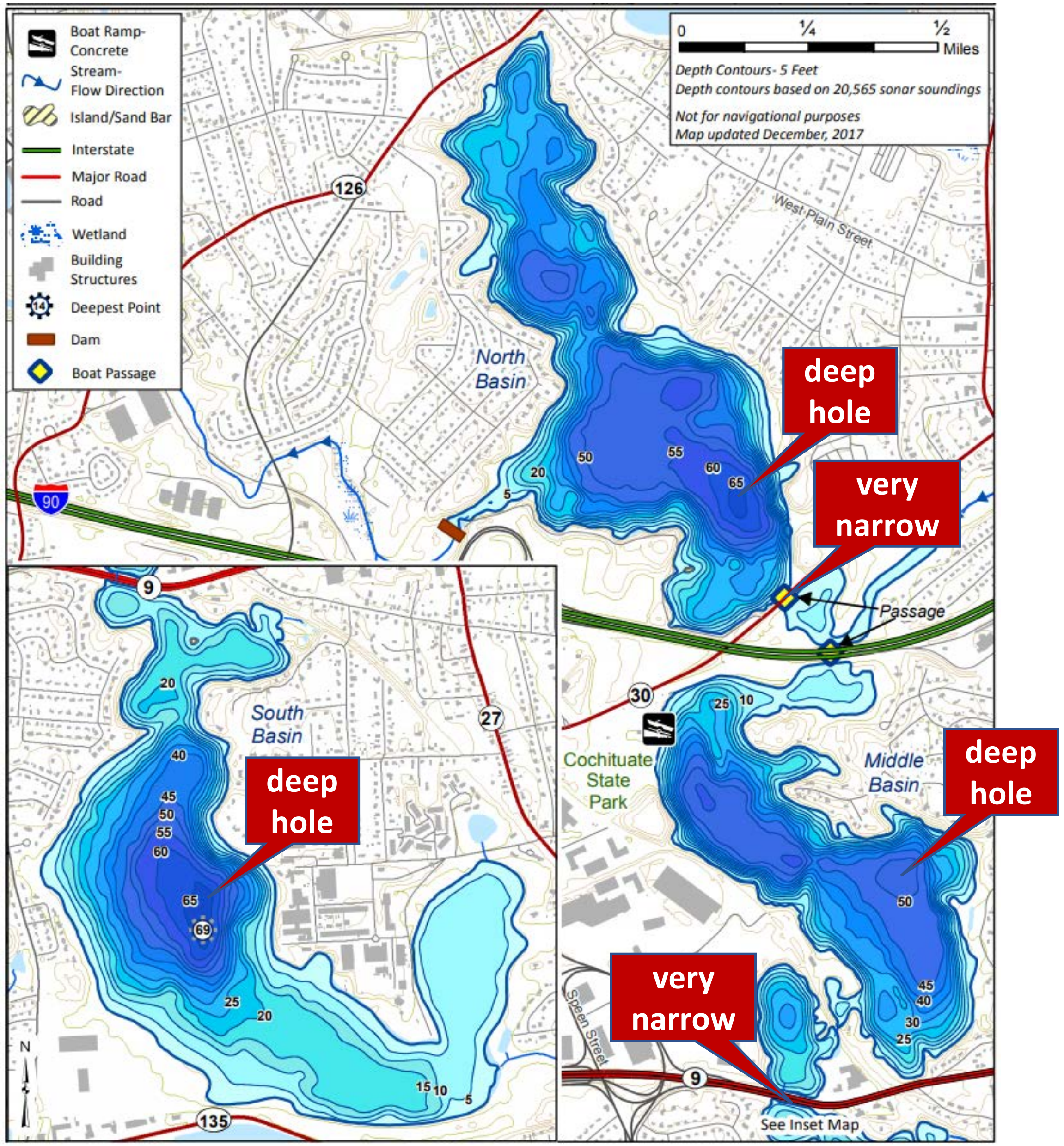
Higher settling rate

↓

More material settling at lake bottom

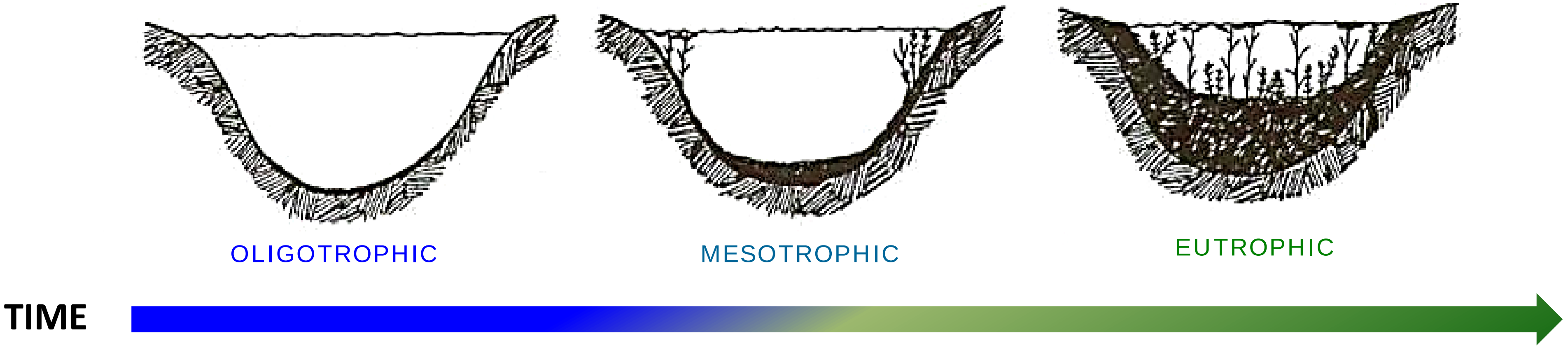
Depth and Lake Shape: *How Many Segments?*





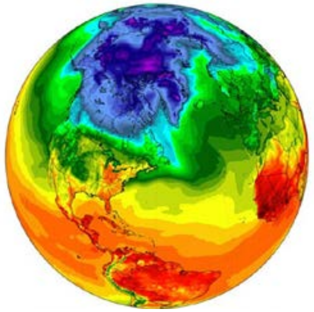
Lake Trophic Classes

EUTROPHICATION: **The natural process by which nutrients, organic matter and sediments gradually accumulate within a water body, resulting in decreased depth and increased biological productivity.**



Three Primary Factors Regulating Trophic State

1. Rate of Nutrient Supply

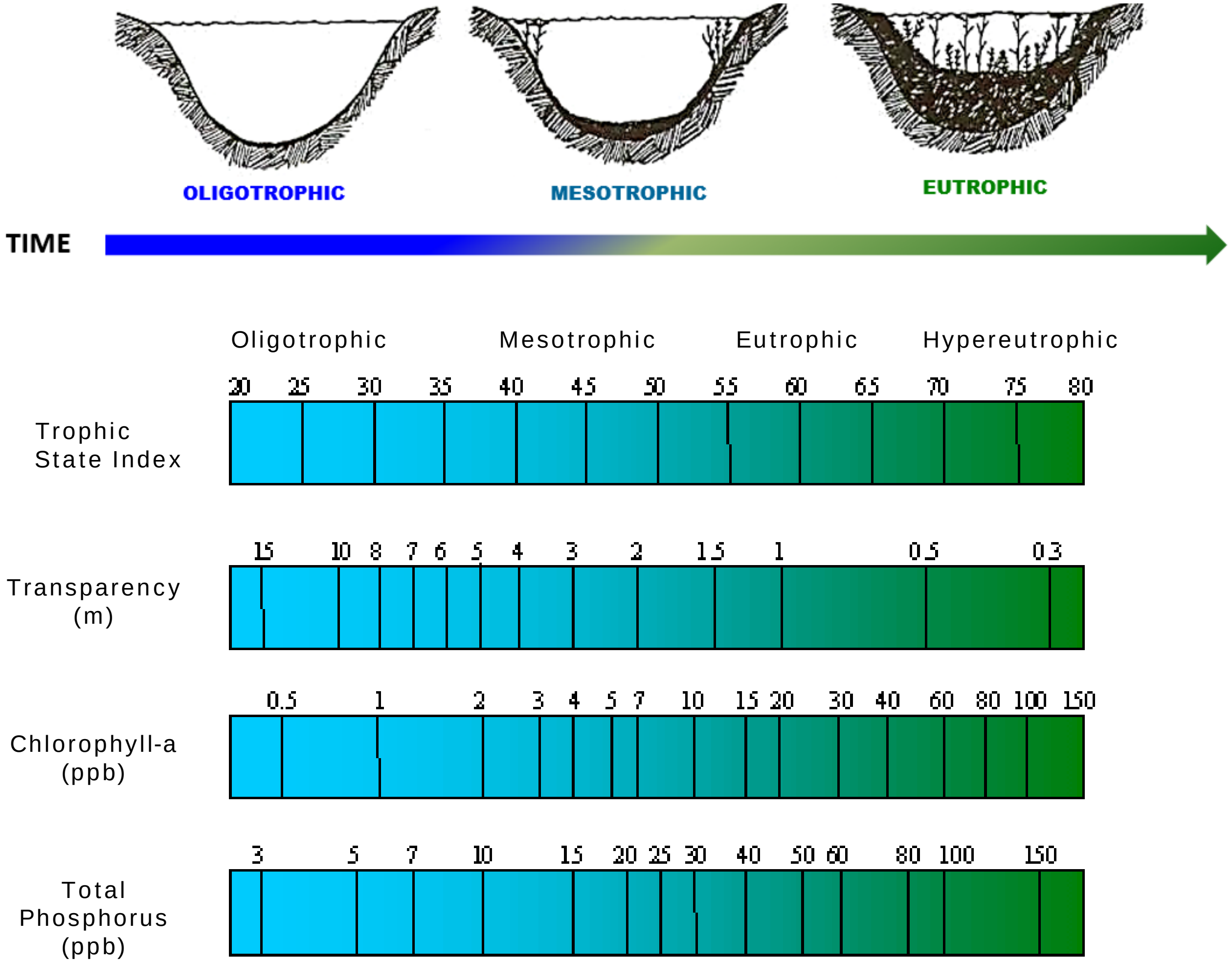


2. Climate

3. Shape of Lake Basin
   - Depth
   - Volume / Surface Area
   - Watershed to Lake Area Ratio

Carlson Trophic Status Index (TSI)

Each variable should be viewed independently…not averaged



Each 10 point TSI increase = doubling of phosphorus, 2.8 fold increase in algal biomass

NH Trophic State Categories

TP: **causal variable**

typically the "limiting nutrient" for plant/algae growth in freshwater

Chl-a: **response variable**

photosynthetic pigment in plants, algae, cyanobacteria

Secchi disk: **response variable**

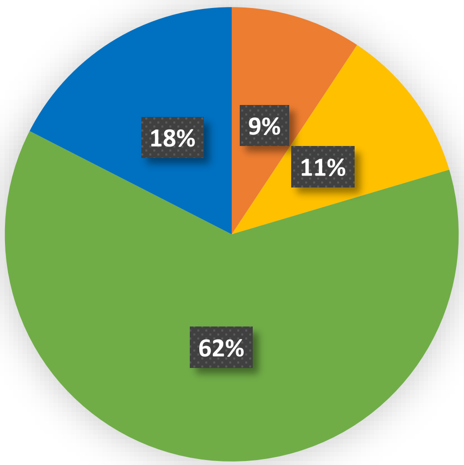
measures water clarity in response to suspended algae, sediment, water color, etc.

Trophic Class	TP (µg/L)	Chl- *a* (µg/L)	Secchi Depth (ft)
Oligotrophic	< 8	< 3.3	> 4
Mesotrophic	≤ 12	≤ 5.0	1.8 - 4
Eutrophic	≤ 28	≤ 11	< 1.8

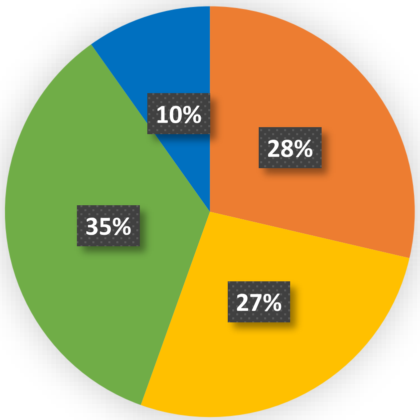
Where do the nutrients come from in a lake watershed?

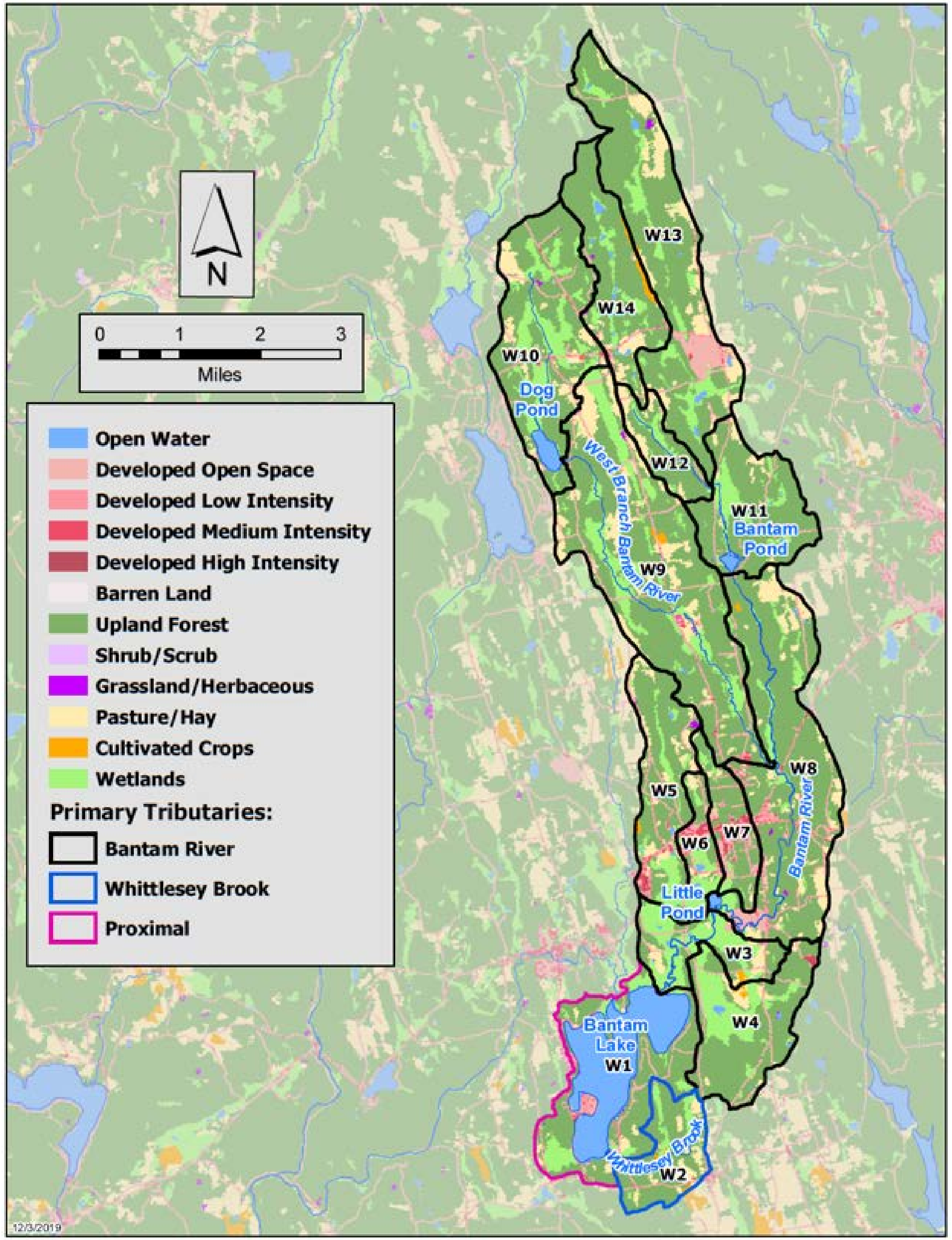
Example Lake Watershed Land Uses

Area by Land Use Category



Estimated Loads By Land Use Category





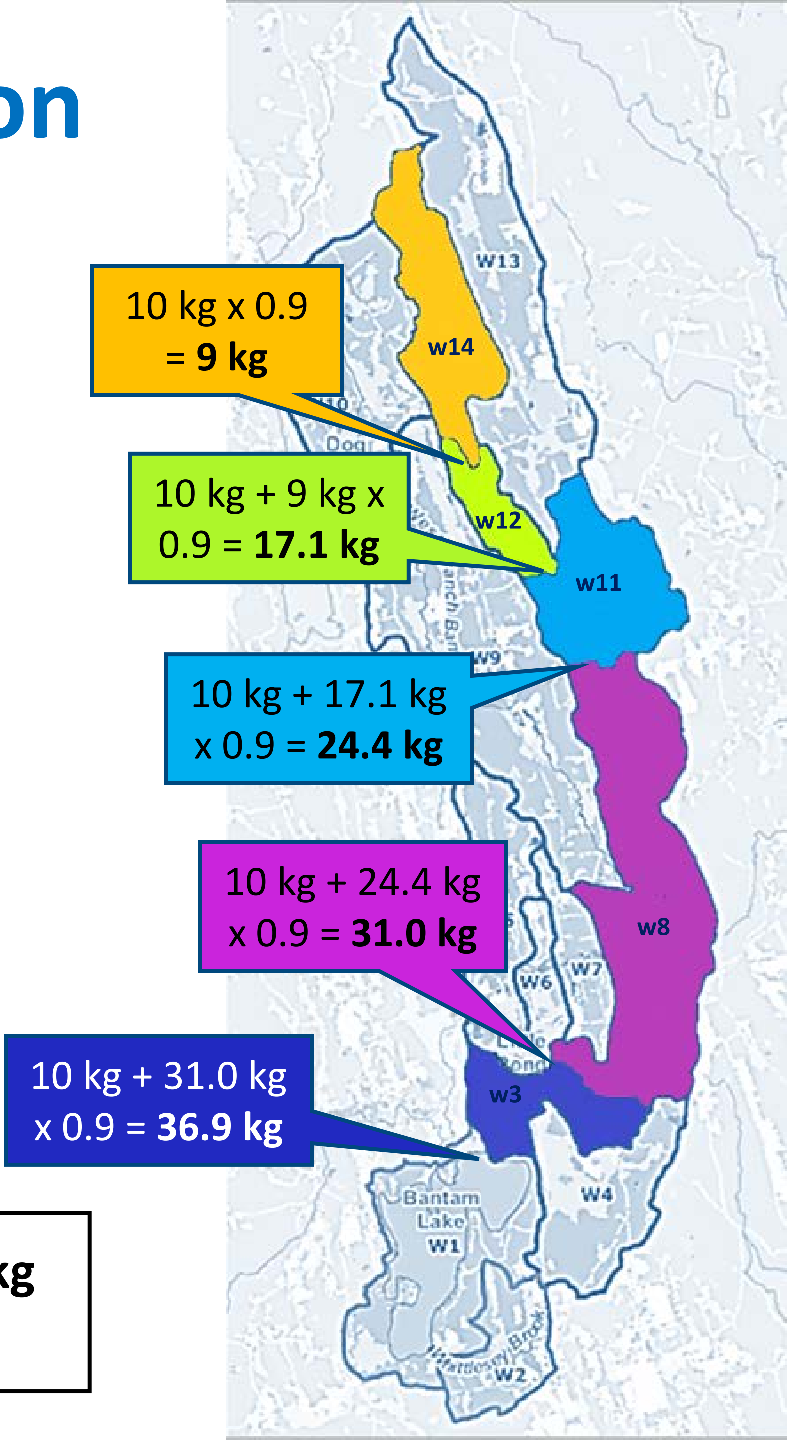
Watershed Nutrient Attenuation

Conceptual Example:

<u>Assumptions</u>

- **Equal P load from each subwatershed = 10 kg/yr**
- **Same attenuation factor for each subwatershed = 0.9 (10% removal)**

LLRM Recommended Attenuation Range:
10% to 60% removal



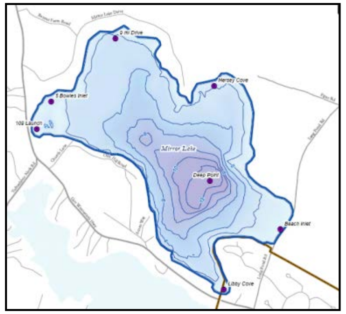
10 kg
↓
9 kg
↓
8.1 kg
↓
7.3 kg
↓
6.6 kg
↓
5.9 kg

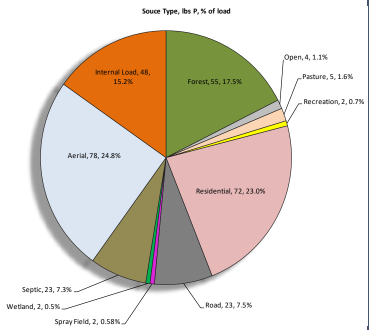
Total Load = 5 x 10kg = **50 kg**
Attenuated Load = **36.9kg**

PHOSPHORUS MODELING DATA REQUIREMENTS

PHYSICAL /CHEMICAL

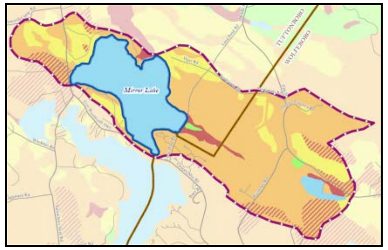
- Bathymetry
- Surface Area
- Nutrient Budget
- Monitoring Data

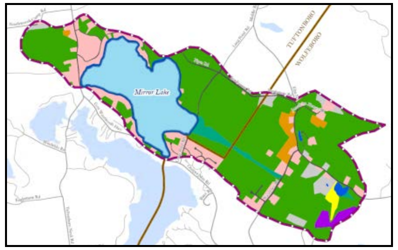




SPATIAL

- Watershed Size
- Land Use
- Population





HYDROLOGIC

- Groundwater/Surface Water Inflows
- Evaporation
- Precipitation

How many samples do you need to take at each sampling point?...*it depends*

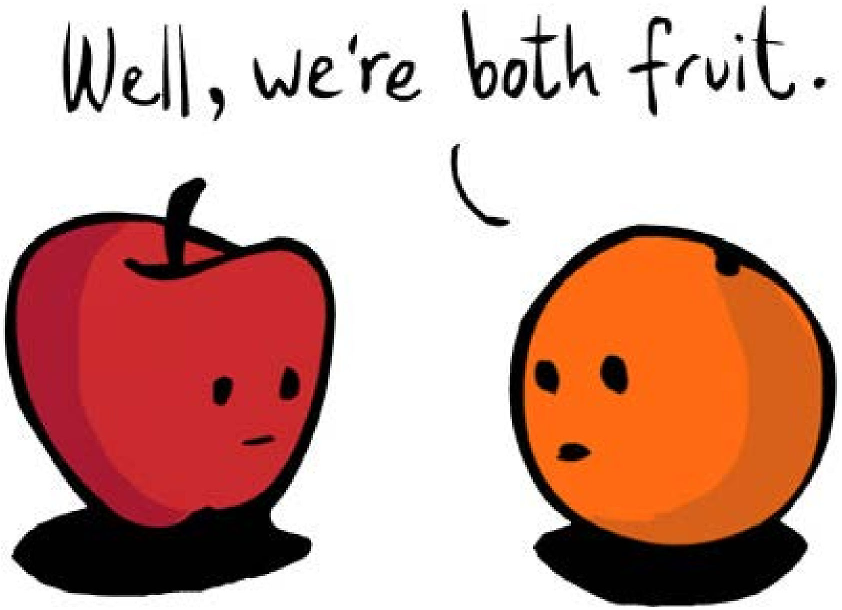
- With variations in NPS pollution or and highly variable climatic conditions (drought, very rainy period), a systematic approach is needed…**as a single sample is just a snapshot of the water chemistry and you could miss a crucial pollution peak by a day or two**.

- ***The Bottom Line*** - the more samples the better, as more samples will help catch the peaks without making them too prominent.

- From a statistics perspective, you need **at least 11 samples** before you can even start thinking about averages, but more is always better (*up to point – diminishing returns*).

Statistical Requirements

- When sampling from different points for comparison (e.g., ID “hot spots”), collect samples in **as short a timeframe as possible** for comparable conditions (discharge, weather, water temperature, etc.).
- Sampling is spread out over a long period (e.g. 2 weeks) risks **comparing apples and oranges**….lots can happen over days and weeks (heavy rainfall, farmers applying fertilizers, dramatic temp. increase, etc.)



Water Quality Goals

Setting Water Quality Targets

The Goldilocks Dilemma

1. **Too Extreme: goal not realistically attainable**
   (e.g., pre-development loading scenario)

2. **Not Protective Enough: goal is achievable but may not prevent water quality impairments**
   (e.g., algae blooms).
   - **should consider both current conditions and future buildout**

3. **Just Right: goal is both realistically attainable and will achieve WQ standards**
   - Not possible to do both in all watersheds
   - May require adaptive management approach…revise as needed based on new data, response to BMPs, etc.

Example 1: Mirror Lake (Tuftonboro, NH)

Lake Association Goal = Prevent cyanobacteria blooms

- **NH WQ Standard (Mesotrophic) = 8-12 ug/L (with 10% assimilative capacity = 10.8 ug/l)**
- **Current Lake TP median = 10 ug/l**

Reference	Recommended Total Phosphorous Limit (ug/L)	
NHDES (2009)	9	Median for unimparied NH Lakes
	11.5	80% of unimpaired NH lakes have TP below this level
NHDES (2010a)	8	or below for oligotrophic lakes
	8 - 12	for mesotrophic lakes
NHDES (2010b)	12	or below to minimize excessive cyanobacterial cell production
MEDEP (2009)	15	to prevent nuisance algal blooms in lakes
WDNR (2009)	20	to prevent nuisance algal blooms in lakes
IJC (2010)	10 - 20	to limit the growth of algae
Haney (2010)	9.5	to limit microcystin toxicity

WQ Target set at 8.5 ug/l, requiring annual load reduction of 7.4 lbs/yr

- ☑ **Conservatively Protective**
- ☑ **Realistically Achievable**
- ☑ **Consistent with State Trophic Standard**

Example 2: Lake Warner (Hadley, MA)

MassDEP TMDL:

- **Predicted TP = 120 ug/L** (*modeled, not based on in-lake data*)
- **40 ug/L cited as required to maintain 4-ft Secchi clarity**
  - **bathing beach standard…*but no beaches on Lake Warner***
  - **Other non-numeric criteria cited**

WQ Target set at 30 ug/l….requires load reduction of 1790 kg/ha/yr (44% reduction for all non-forest)

- ✗ **Conservatively Protective**
- ✗ **Realistically Achievable**
- ✗ **Consistent with State Water Quality Standards**

Example 3: Bantam Lake (CT)

- Current in-lake TP = 24.7 ug/L
- CT mesotrophic range TP: 10-30 ug/l
- “natural” trophic status for Bantam Lake defined as “upper mesotrophic” = 23-30 ug/l

WQ Target set at 23 ug/l….requiring annual load reduction of 127 kg/yr (8.6% reduction)

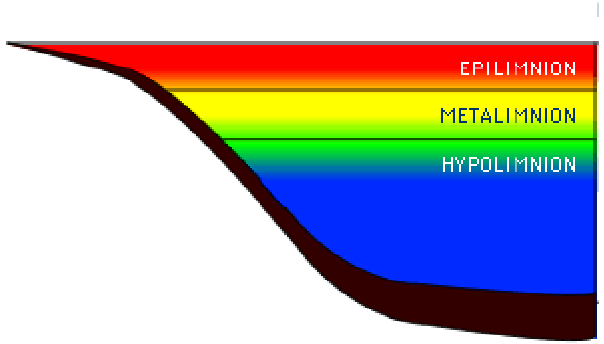
? **Conservatively Protective**

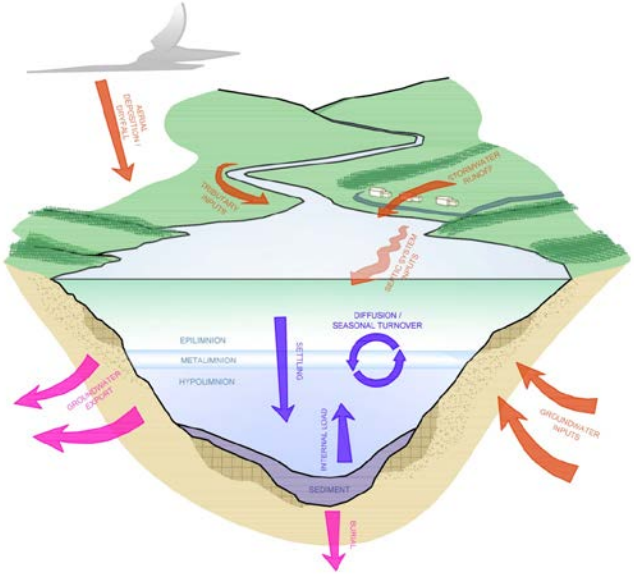
? **Realistically Achievable**

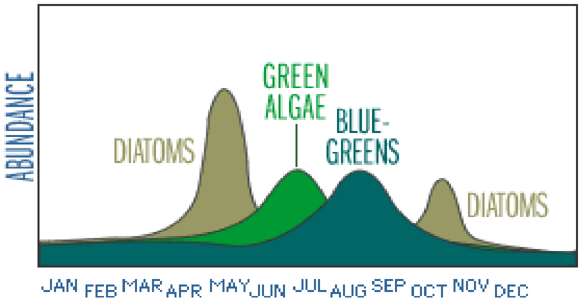
More data required to confirm these…use **adaptive management** to adjust goals as needed based on new data

☑ **Consistent with State Water Quality Standards**

Water Quality Modeling Concepts



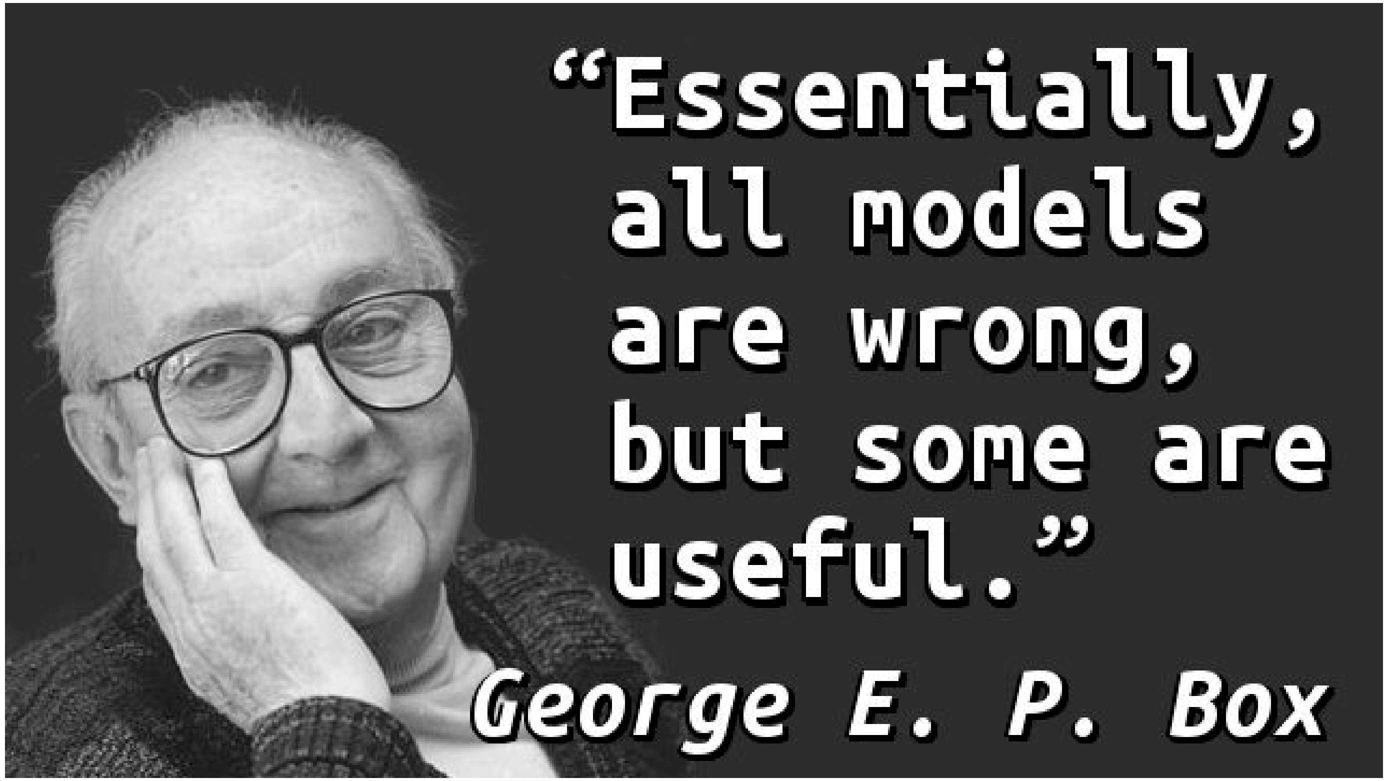




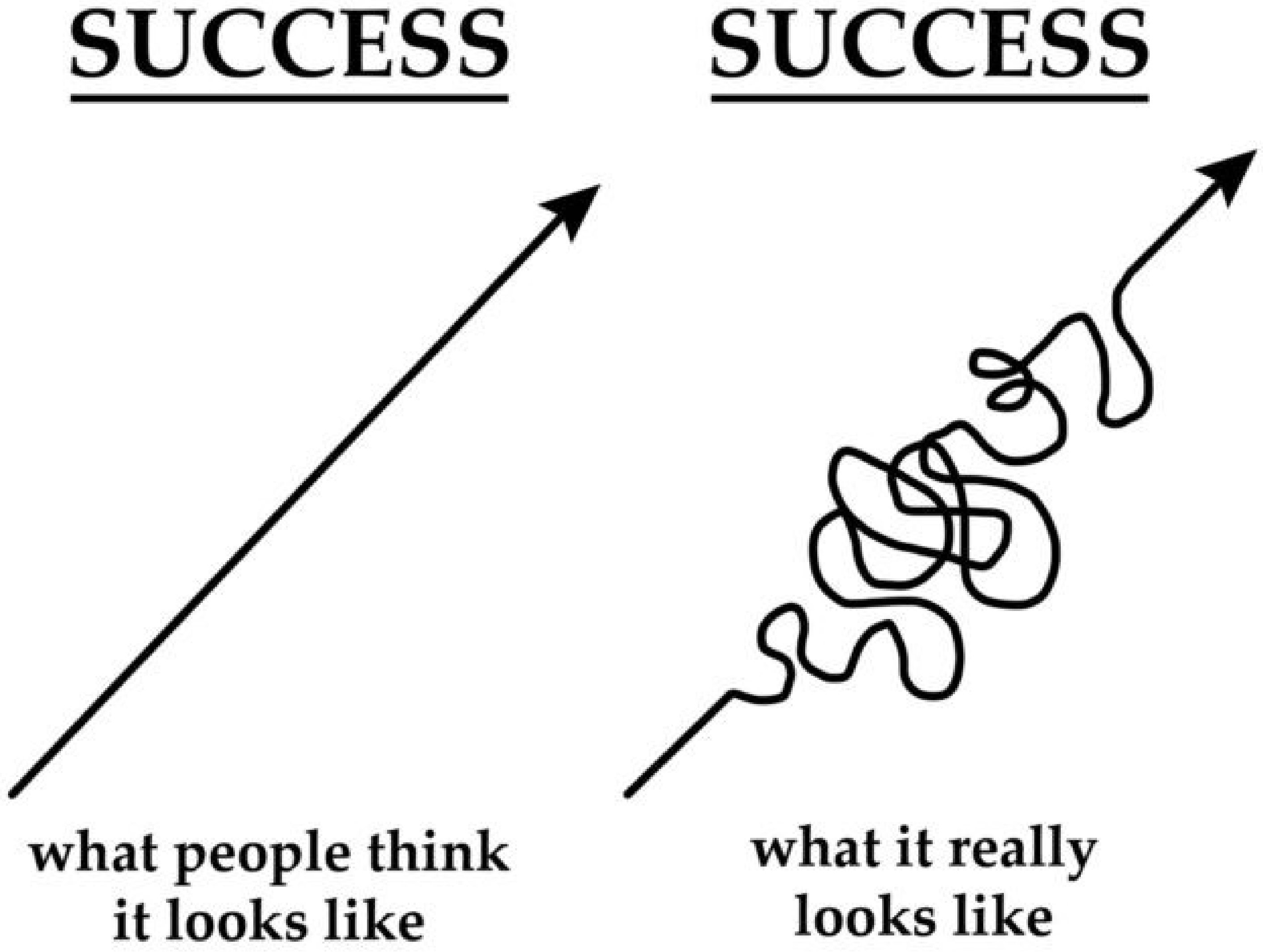
What is a Scientific Model?

The generation of a physical, conceptual, or mathematical **representation of a real phenomenon that is difficult to observe directly**.

Scientific models are used to **explain and predict the behavior of real objects or systems** and are used in a variety of scientific disciplines – *Encyclopedia Britannica*



Modeling Approach



Primary Water Quality Model Types

Receiving Water Models

- Predict what is happening in the receiving waters, e.g., rivers, lakes, estuaries
- E.g., BATHTUB, CE-QUAL-W2, Vollenweider Eq., QUAL2K

Watershed Loading Models

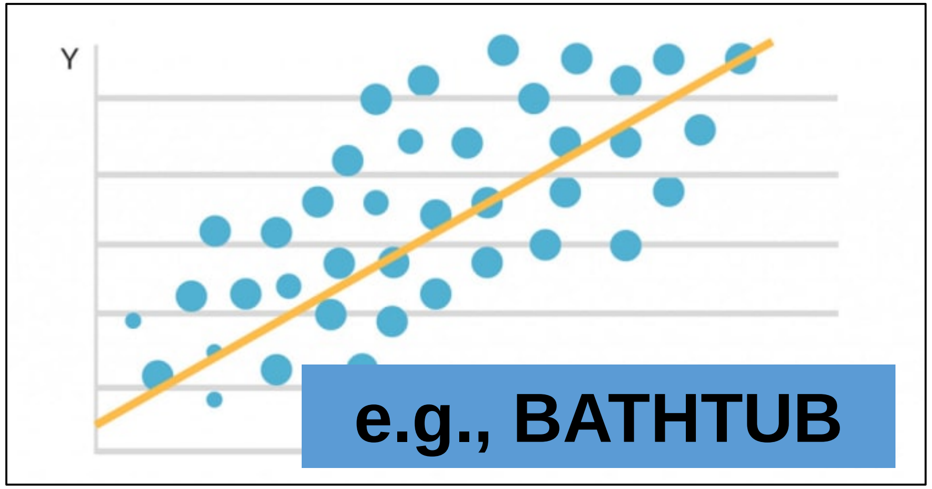
- Predict what is happening on "land" that results in an export of a pollutant to the river, lake, or estuary
- e.g., LLRM, STEPL, EUTROMOD, BASINS

Combination

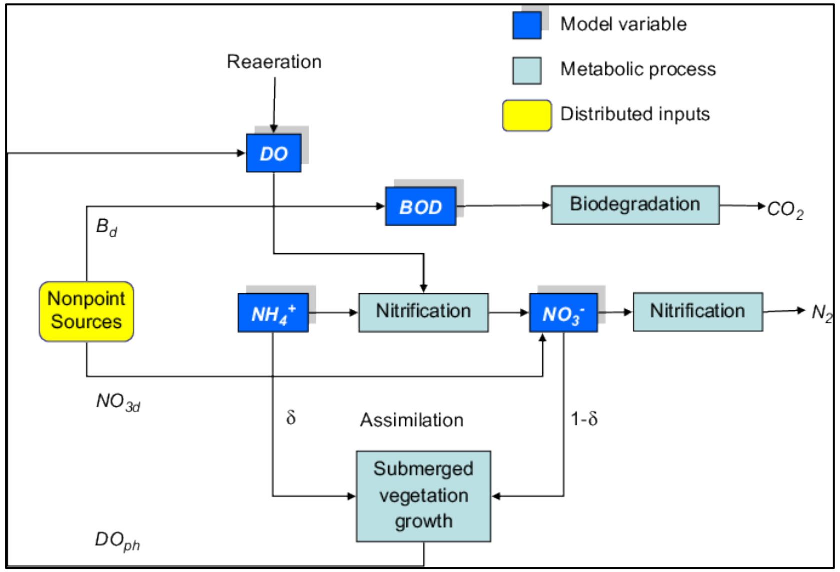
- Can simulate both processes
- e.g., HSPF, SWMM

Models can be…

- **Empirical**
  - Based on statistical relationship between parameters of interest and other variables (i.e., time)



- **Deterministic and Mechanistic**
  - Developed using a combination of physics, chemistry, and statistical relationships
  - i.e., process-based or physically based models

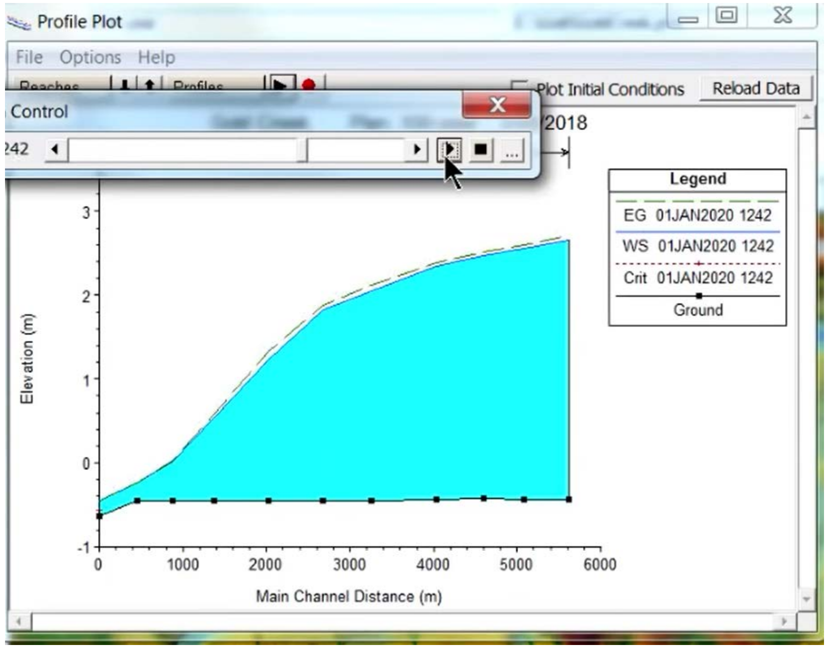


- **Combination**

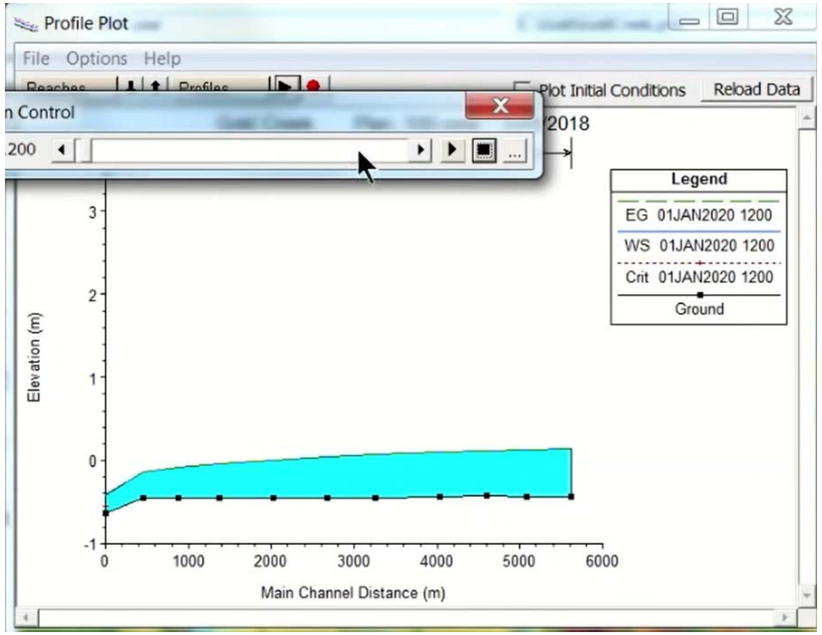
Source: *Water Quality Modeling, An Overview, NC DWQ*

Models Vary in Complexity…

- **Simple (Steady-State Models)**
  - Long-term average representation of the system
  - Returns a Single Answer



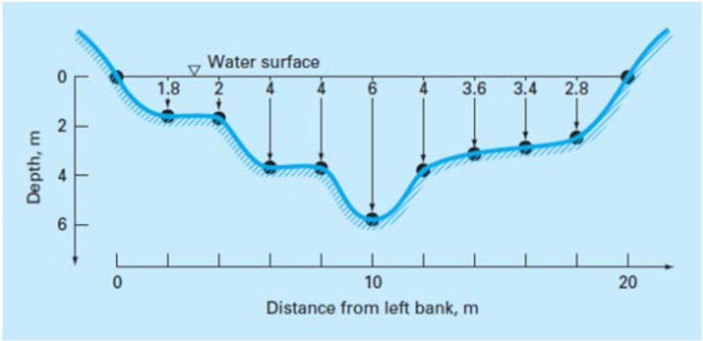
- **Complex (Dynamic)**
  - Dynamic representation of the system
  - E.g., physical behavior of waterbody over time



Models Also Vary Spatially…

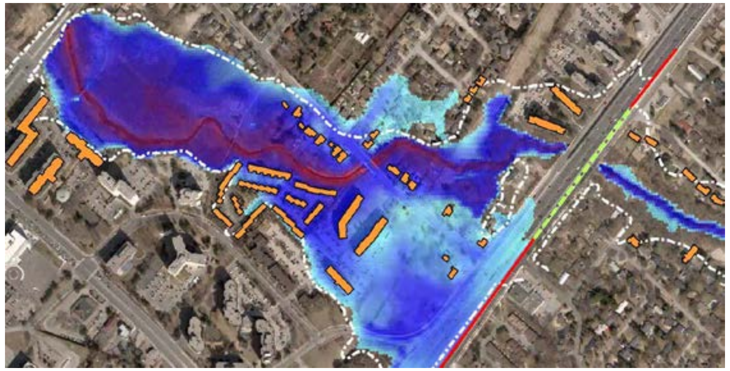
- **1D**

E.g., Channel Cross Section



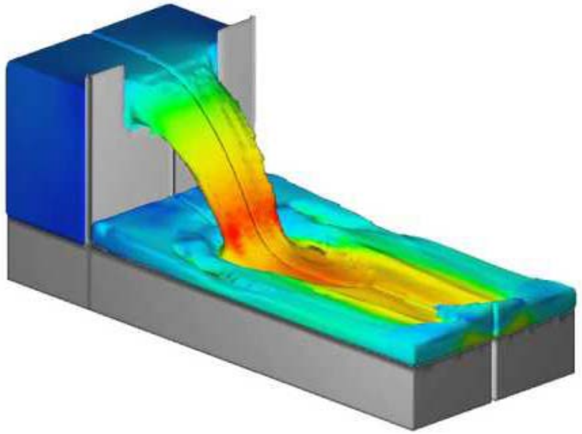
- **2D**

E.g., Flood Inundation

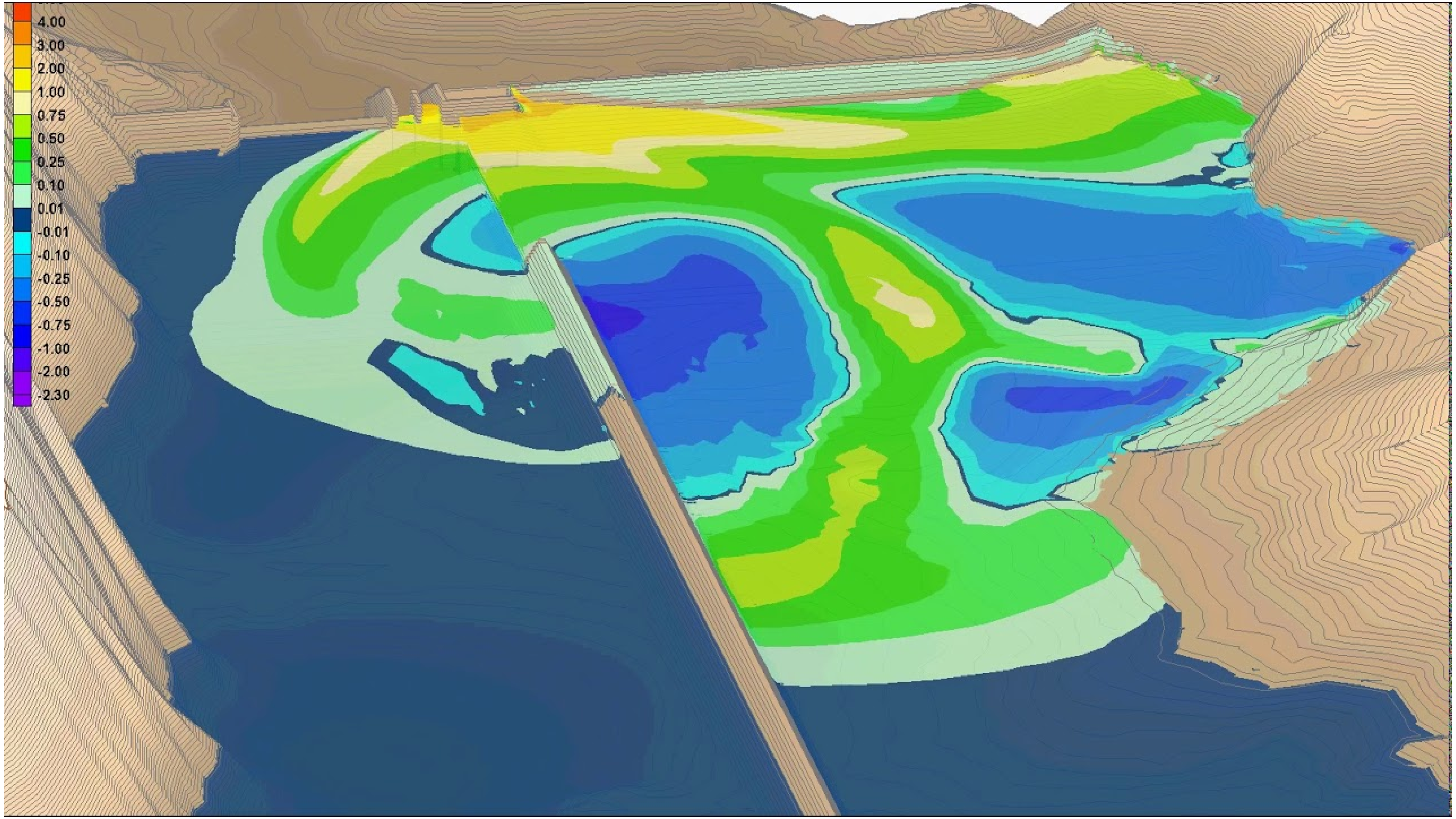


- **3D**

E.g., Sediment Scour Analysis



More Complex Models Need More Data!



Model Selection Depends on Many Factors: some examples…

Simulation Requirements

- e.g., Pollutant Types

Spatial Requirements

- **e.g., 1D vs. 2D**

Timing Requirements

- **e.g., Steady State vs. Dynamic Simulation**

Available Data vs. Data Needs

Availability of Trained Staff

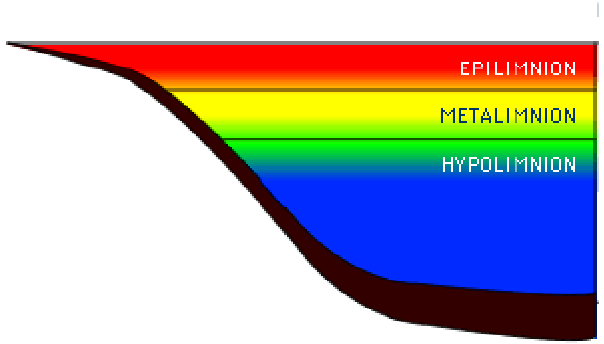
Commonly Used Nutrient Load Reduction Models

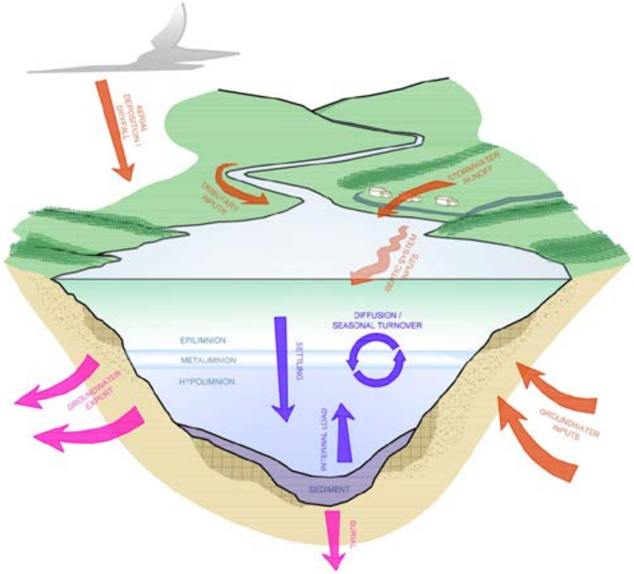
- Spatial Variability
  - Entire Lake Modeled as One Unit – EUTROMOD
  - Models different parts of lake – BATHTUB, CE-QUAL-W2, WASP, EFDC

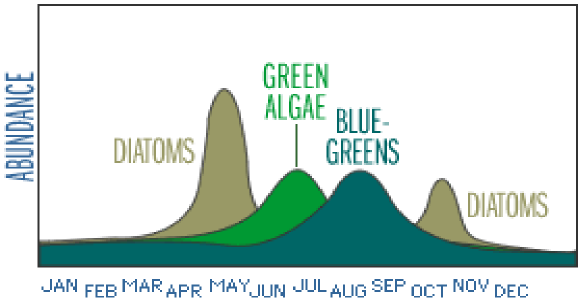
- Temporal scale of output
  - Long Term average – EUTROMOD, BATHTUB
  - Temporal output – CE-QUAL-W2, EFDC, WASP

- Hydrodynamic Simulation
  - CE-QUAL-W2, EFDC

Modeling Concepts





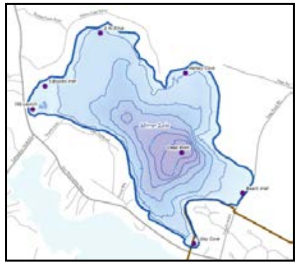


Modeling Concepts

1. Data Needs
2. Analyzing Data
3. Creating Model Geometry
4. Creating Inputs
5. Performing Simulations

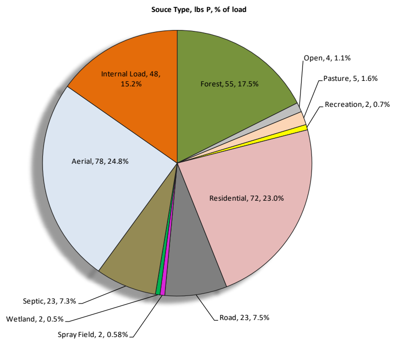
What Data is Needed?

PHYSICAL /SPATIAL	TYPICAL USES	TYPICAL SOURCES
• Hydrography	Area Calcs, Delineations	GIS (State, Federal)
• Bathymetry	Volume Calcs	GIS (State) / DF Studies
• Land Use	Pollutant Export Calcs	GIS (State, Federal - NLCD)



MONITORED VALUES	TYPICAL USES	TYPICAL SOURCES
• Precipitation	Water Quantity Calcs	Gages (NWS, USGS), Radar
• Evaporation	Water Quantity Calcs	NRCC, NOAA Climate Normals
• Water Quality	Calibration / Validation	Lake Association, State Agency
• Tributary Inflows	Calibration / Validation	Lake Association, State Agency

LITERATURE	TYPICAL USES	TYPICAL SOURCES
• Export Coefficients	Pollutant Export Calcs	LLRM, EPA MS4 Permits, Studies
• Atmospheric Deposition	Pollutant Influx Calcs	LLRM, Misc. Studies
• Septic Coefficients	Septic Loading Calcs	LLRM, Misc. Studies
• Waterfowl Coefficients	Waterfowl Loading Calcs	LLRM, Misc. Studies



How

WQ

station	depth	level	year	month	day	date	NH3	NOX	TN	TP	TDP	Fe
Bantam_River	inlet/outlet	NA	2009	4	25	4/25/2009	19	NA	NA	19	NA	NA
Bantam_River_Outlet	inlet/outlet	NA	2009	4	25	4/25/2009	23	NA	NA	15	NA	NA
Center	1	top	2009	4	25	4/25/2009	27	NA	NA	23	NA	NA
Center	4	middle	2009	4	25	4/25/2009	24	NA	NA	16	NA	NA
Center	7	bottom	2009	4	25	4/25/2009	15	NA	NA	20	NA	NA
North	1	top	2009	4	25	4/25/2009	19	NA	NA	16	NA	NA
North	3	middle	2009	4	25	4/25/2009	19	NA	NA	20	NA	NA
North	6	bottom	2009	4	25	4/25/2009	11	NA	NA	16	NA	NA
Bantam_River	inlet/outlet	NA	2009	5	26	5/26/2009	34	NA	NA	9	NA	NA
Bantam_River_Outlet	inlet/outlet	NA	2009	5	26	5/26/2009	24	NA	NA	21	NA	NA
Center	1	top	2009	5	26	5/26/2009	23	NA	NA	17	NA	NA
Center	4	middle	2009	5	26	5/26/2009	21	NA	NA	14	NA	NA
Center	7	bottom	2009	5	26	5/26/2009	18	NA	NA	17	NA	NA
North	1	top	2009	5	26	5/26/2009	21	NA	NA	16	NA	NA
North	3	middle	2009	5	26	5/26/2009	31	NA	NA	18	NA	NA
North	6	bottom	2009	5	26	5/26/2009	48	NA	NA	21	NA	NA
Beaver_Dam	inlet/outlet	NA	2009	5	26	5/26/2009	26	NA	NA	24	NA	NA
Beaver_Dam	inlet/outlet	NA	2009	6	26	6/26/2009	14	NA	NA	28	NA	NA
Bantam_River	inlet/outlet	NA	2009	6	26	6/26/2009	0	NA	NA	28	NA	NA
Center	1	top	2009	6	26	6/26/2009	0	NA	NA	22	NA	NA
Center	4	middle	2009	6	26	6/26/2009	0	NA	NA	22	NA	NA
Center	7	bottom	2009	6	26	6/26/2009	0	NA	NA	17	NA	NA
North	1	top	2009	6	26	6/26/2009	0	NA	NA	23	NA	NA
North	3	middle	2009	6	26	6/26/2009	0	NA	NA	17	NA	NA
North	6	bottom	2009	6	26	6/26/2009	19	NA	NA	26	NA	NA
Beaver_Dam	inlet/outlet	NA	2009	7	15	7/15/2009	34	NA	NA	32	NA	NA
Bantam_River	inlet/outlet	NA	2009	7	15	7/15/2009	25	NA	NA	20	NA	NA
Center	1	top	2009	7	15	7/15/2009	123	NA	NA	18	NA	NA
Center	4	middle	2009	7	15	7/15/2009	136	NA	NA	24	NA	NA
Center	7	bottom	2009	7	15	7/15/2009	118	NA	NA	32	NA	NA
North	1	top	2009	7	15	7/15/2009	113	NA	NA	20	NA	NA
North	3	middle	2009	7	15	7/15/2009	117	NA	NA	22	NA	NA
North	5.5	bottom	2009	7	15	7/15/2009	160	NA	NA	17	NA	NA
Bantam_River_Outlet	inlet/outlet	NA	2009	7	15	7/15/2009	107	NA	NA	59	NA	NA

S

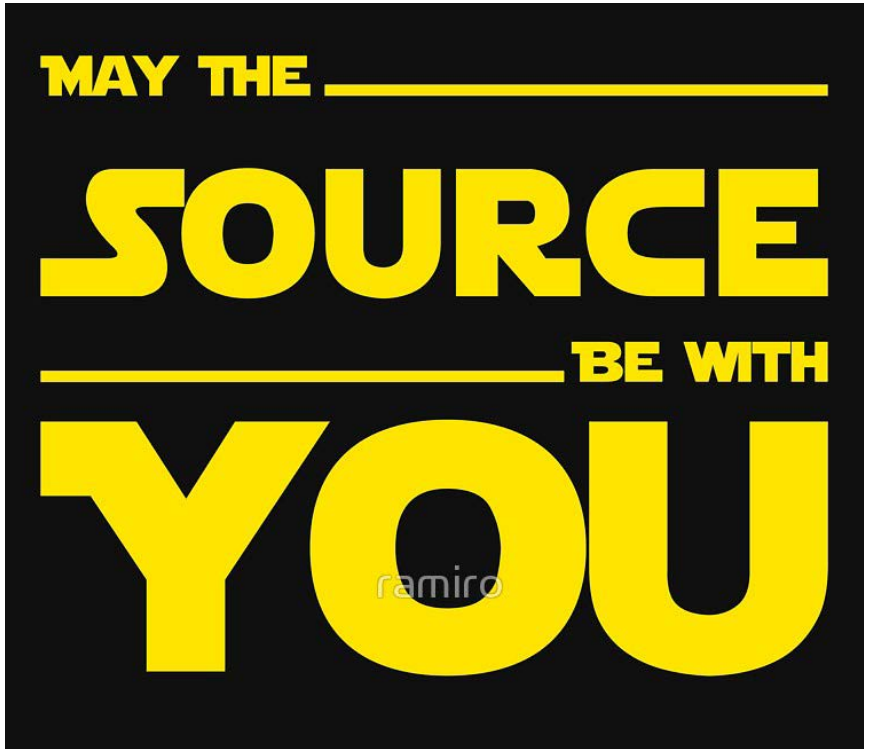
North Bay	/L)	TKN (mg/L)	TP (mg/L)
		0.29	ND
		0.25	0.004
		0.26	ND

per Profiles

There is no One Size Fits All Approach

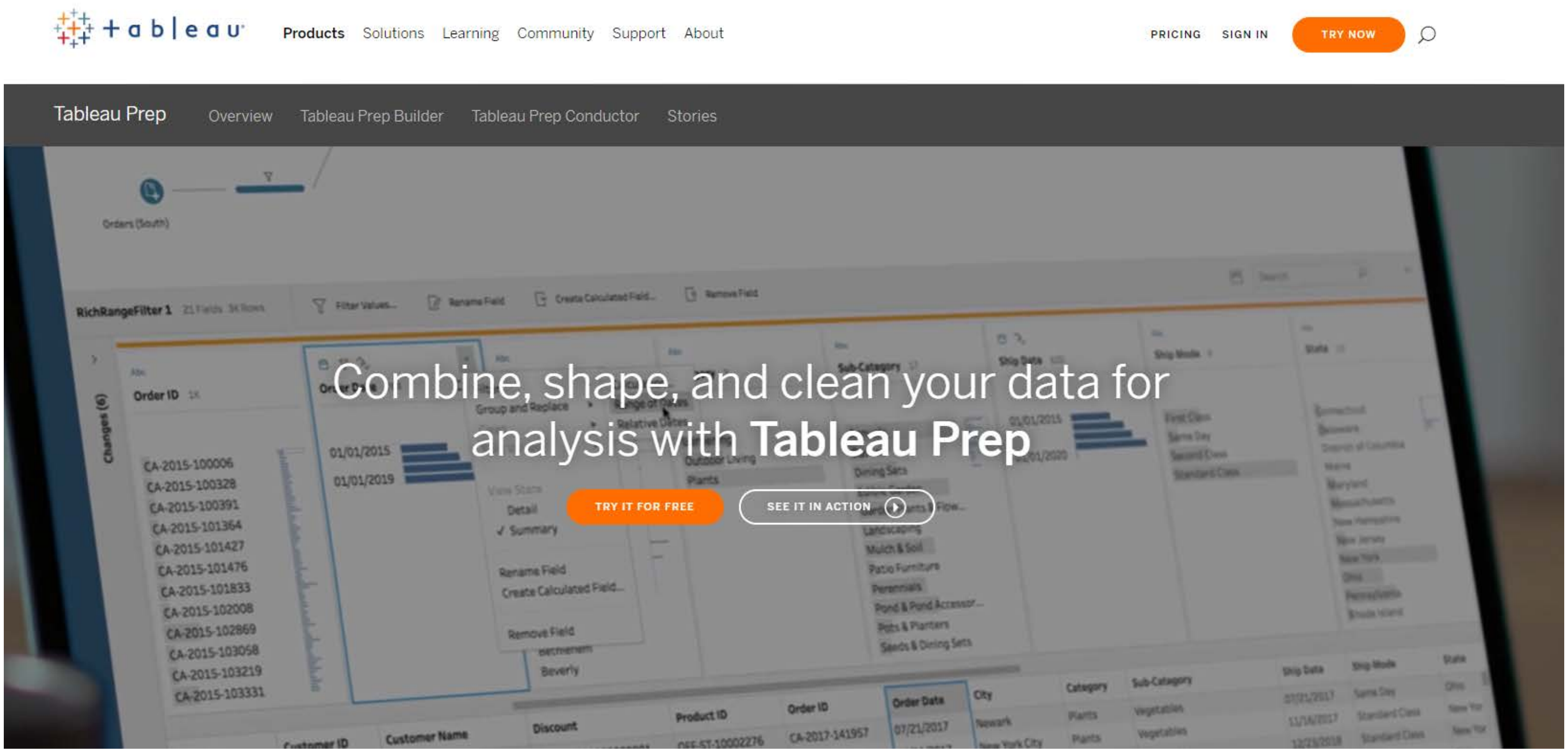
Best Practices:

- Choose a uniform format that enables easy filtering
- Simplify – Omit irrelevant fields and data
- Document all changes
- **Always be able to go back to the source!**
- Automate if possible

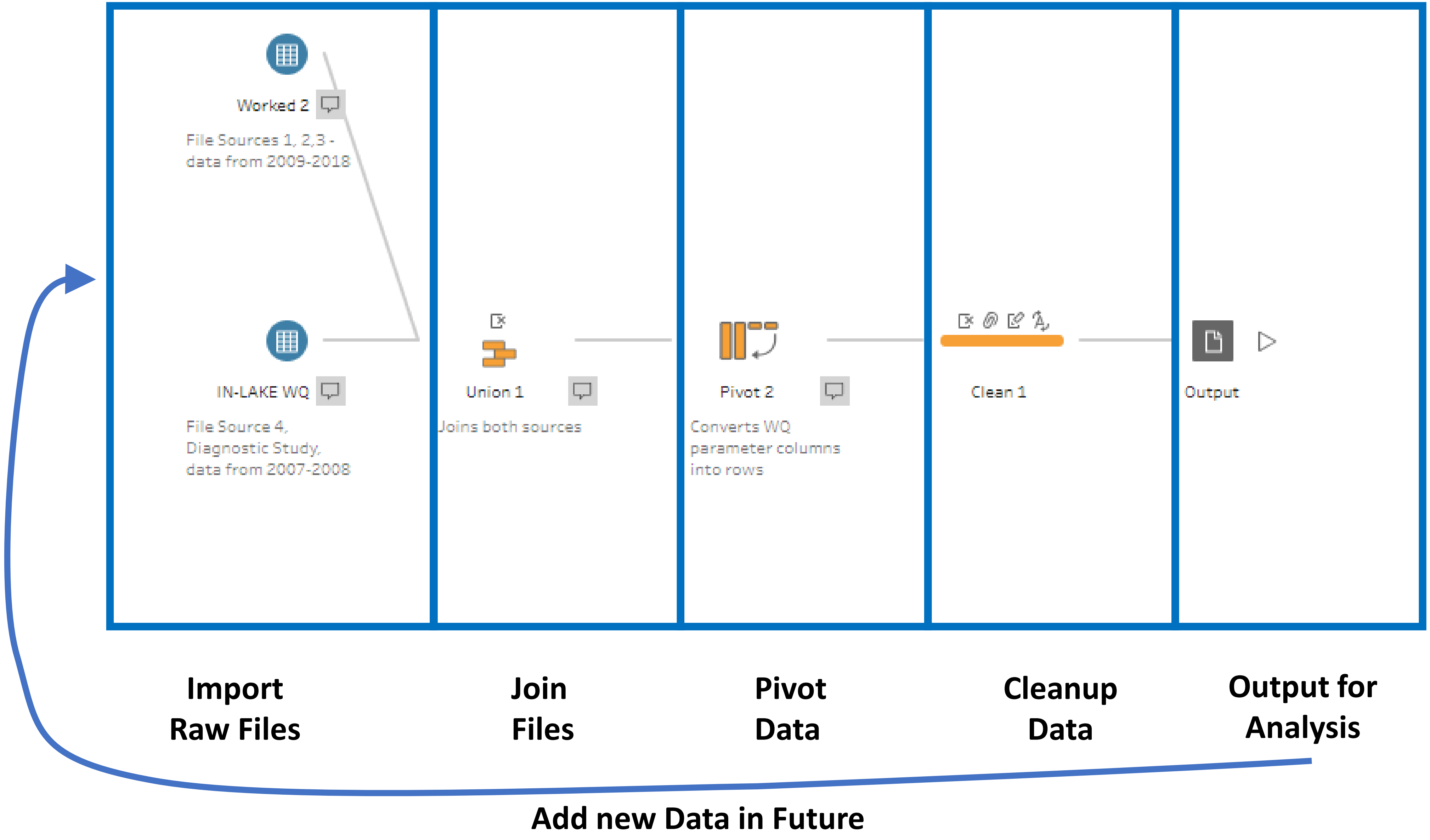


One Possible Approach:

Tableau Prep Builder



One Possible Approach:



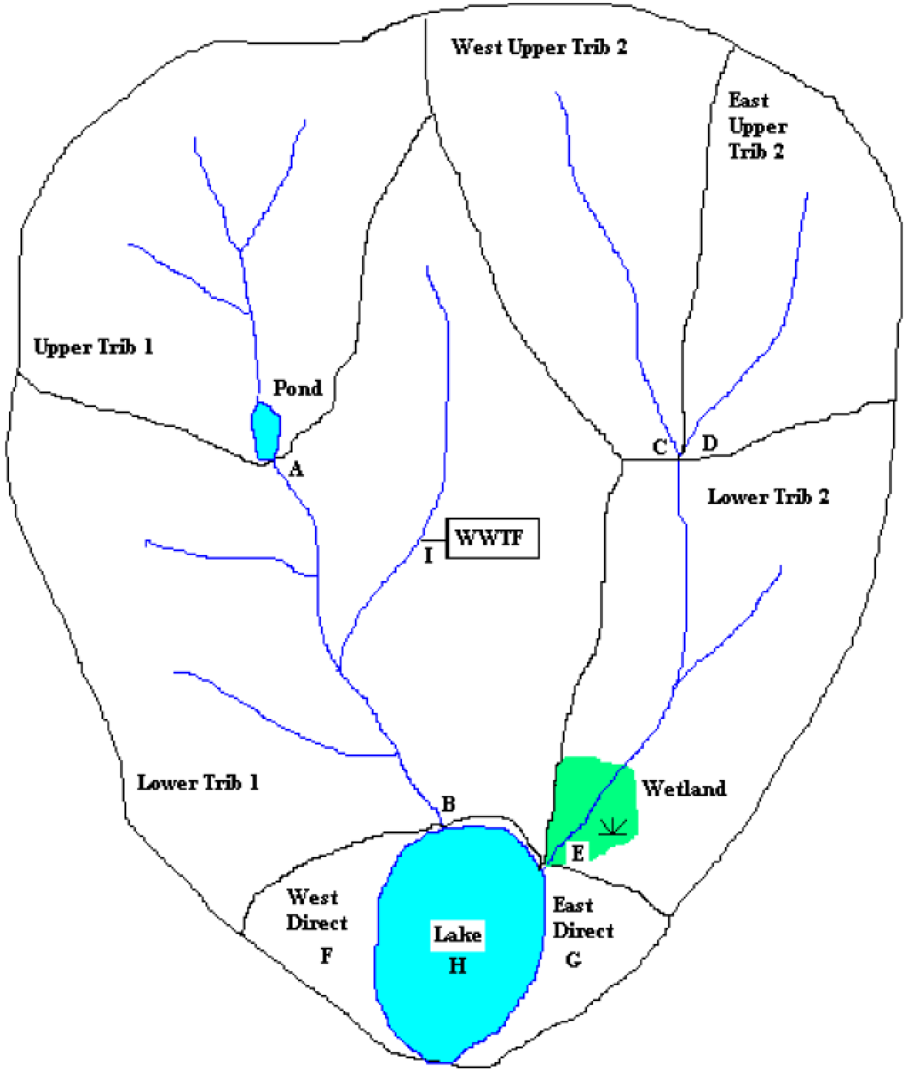
Ready for Analysis

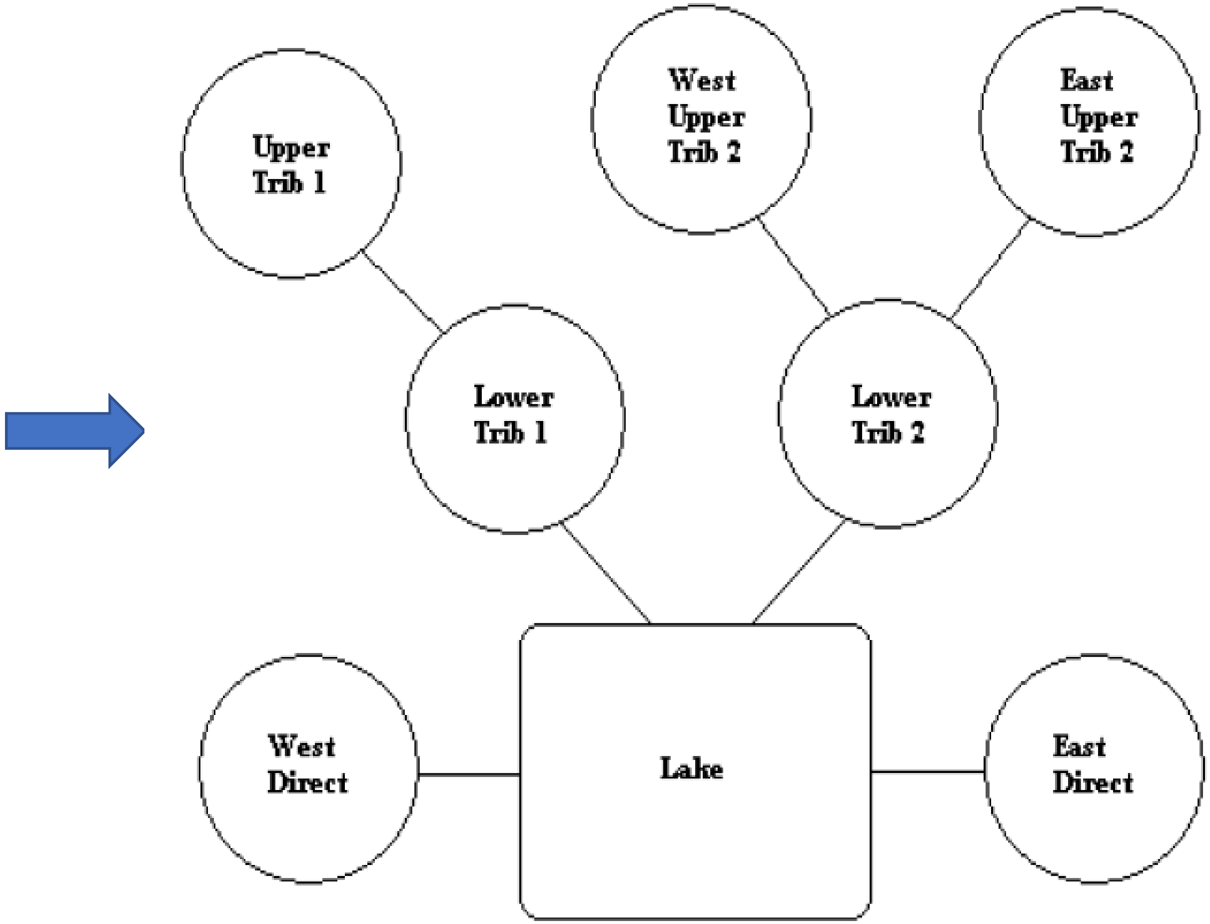
- Analyze using Excel Pivot Tables
- Or other program, such as Tableau
- Live Demo


Tableau - Book1
File
Data
Server
Help
Connect
To a File
Microsoft Excel
Text file
JSON file
Microsoft Access
PDF file
Spatial file
Statistical file
More...
To a Server
Tableau Server
Microsoft SQL Server
MySQL
Oracle
Amazon Redshift
More...
Saved Data Sources
Sample - EU Superstore
Sample - Superstore
World Indicators
Open
Open a Workbook
Analysis_WQ_Precip_Evap3
Analysis_WQ_Precip_Evap2
Analysis_WQ_Precip_Evap3_pa...
2018 expenses
Analysis_WQ_Precip_Evap_PR...
Analysis_WQ_Precip_Evap3
Analysis_WQ_Precip_Evap3_pa...
Bantam Lake Nutrient Data [pu...
DELETE
Analysis_WQ_Precip_Evap_201...
Analysis_WQ_Precip_Evap2
Analysis_WQ_Precip_Evap
Bantam_Analysis_v2
Bantam_Analysis_v1
Analysis_WQ_Precip
Precip_Analysis
Bantam_InLake_Analysis
Bantam_Analysis_v2
Sample Workbooks
More Samples
Superstore
Regional
World Indicators
Discover
Training
Getting Started
Connecting to Data
Visual Analytics
Understanding Tableau
More training videos...
Resources
Get Tableau Prep
Blog - Nominations are open for 2020 Zen Masters!
Forums
Craving some viz inspiration?
Explore stunning examples from Tableau Public with Viz of the Day ⟶
Update to 2019.4.1 Now

How to Setup Model Geometry?

Simple System



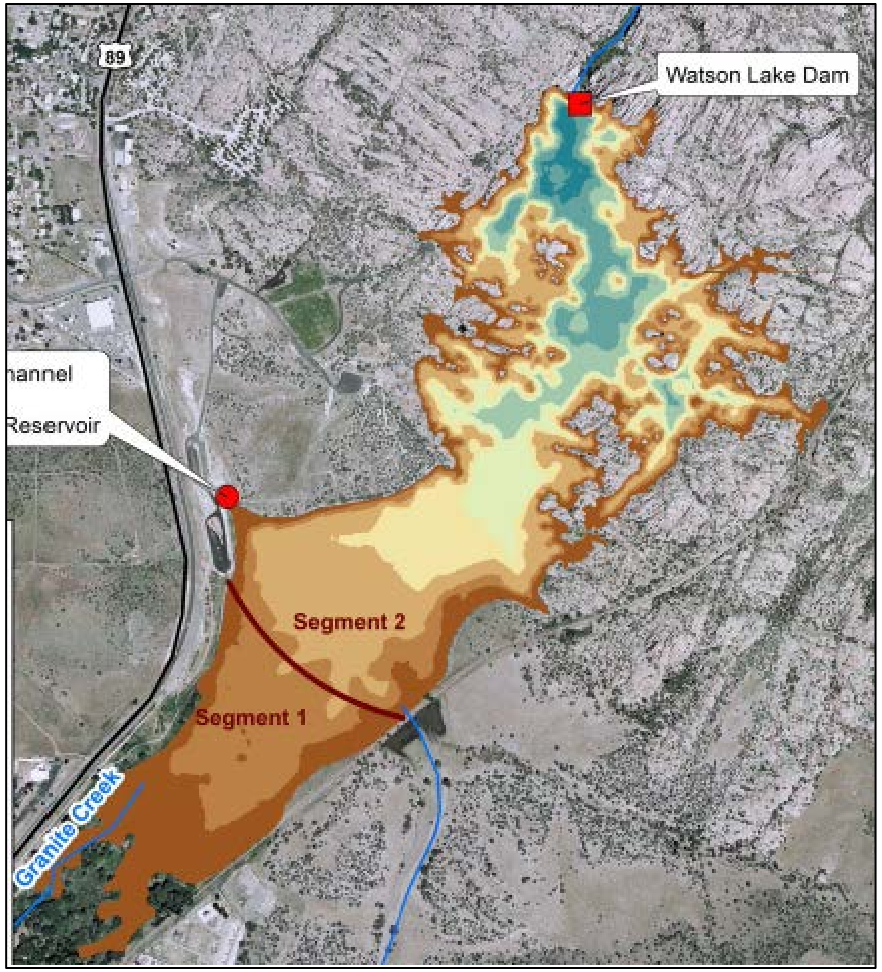


How to Setup Model Geometry?

More Complex System

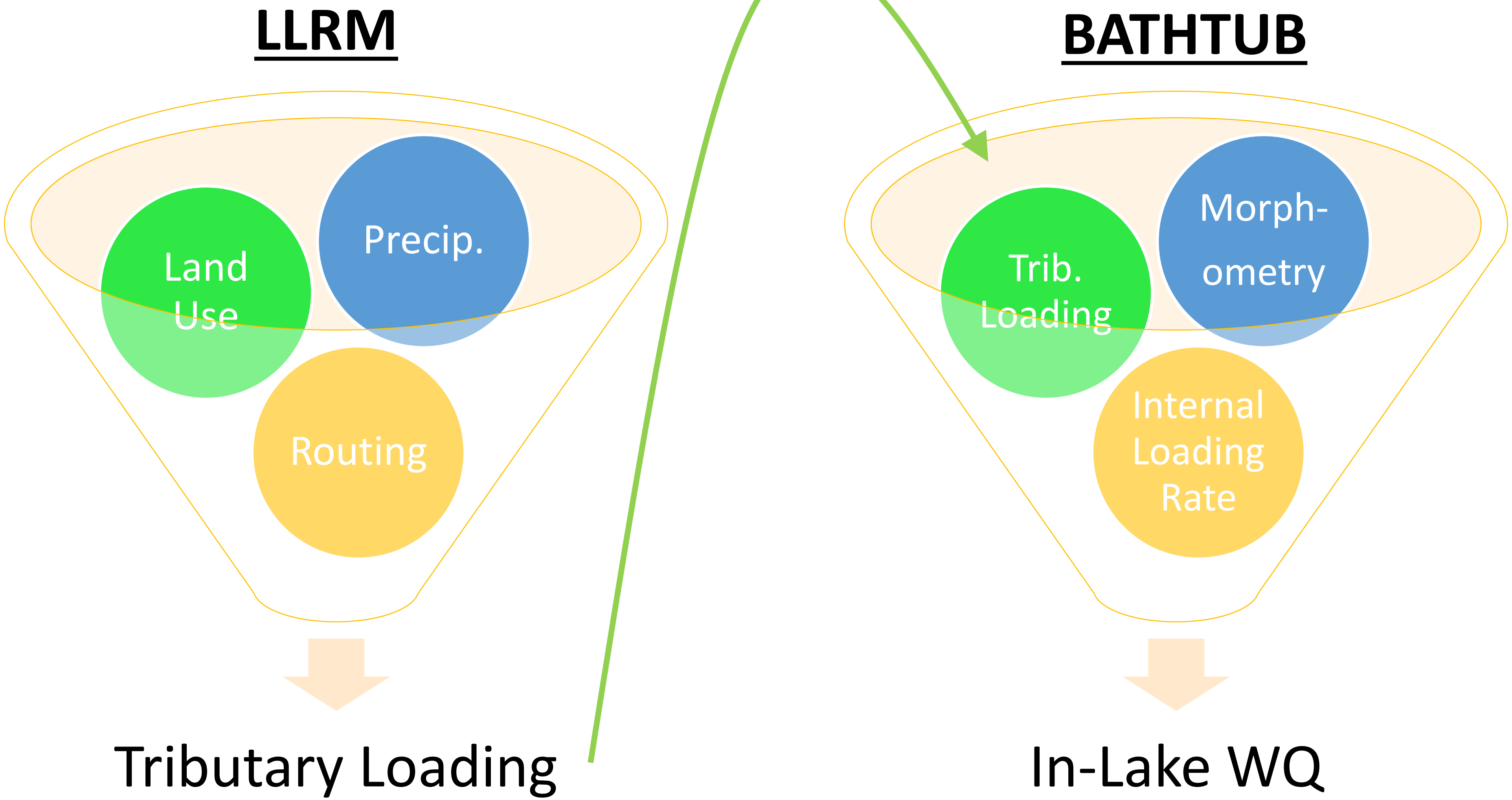
Lake with Multiple Major Tribs and spatially varied WQ

- Check Stat. Significance of WQ Data Amongst Bays / Lake Sections
- Check for Major Tributary Inputs



What are Some Key Model Inputs?

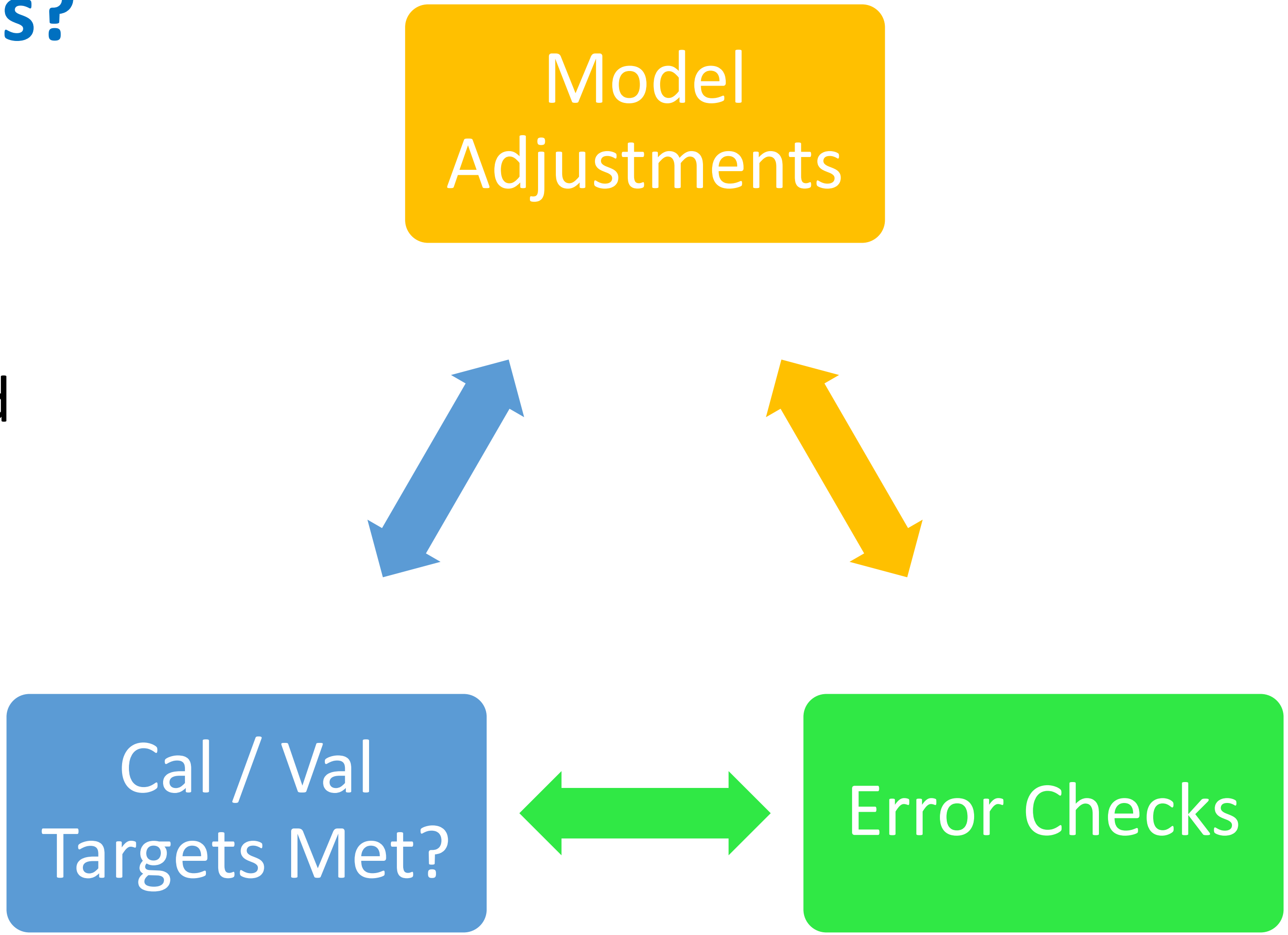
E.g., *LLRM* → *BATHTUB*



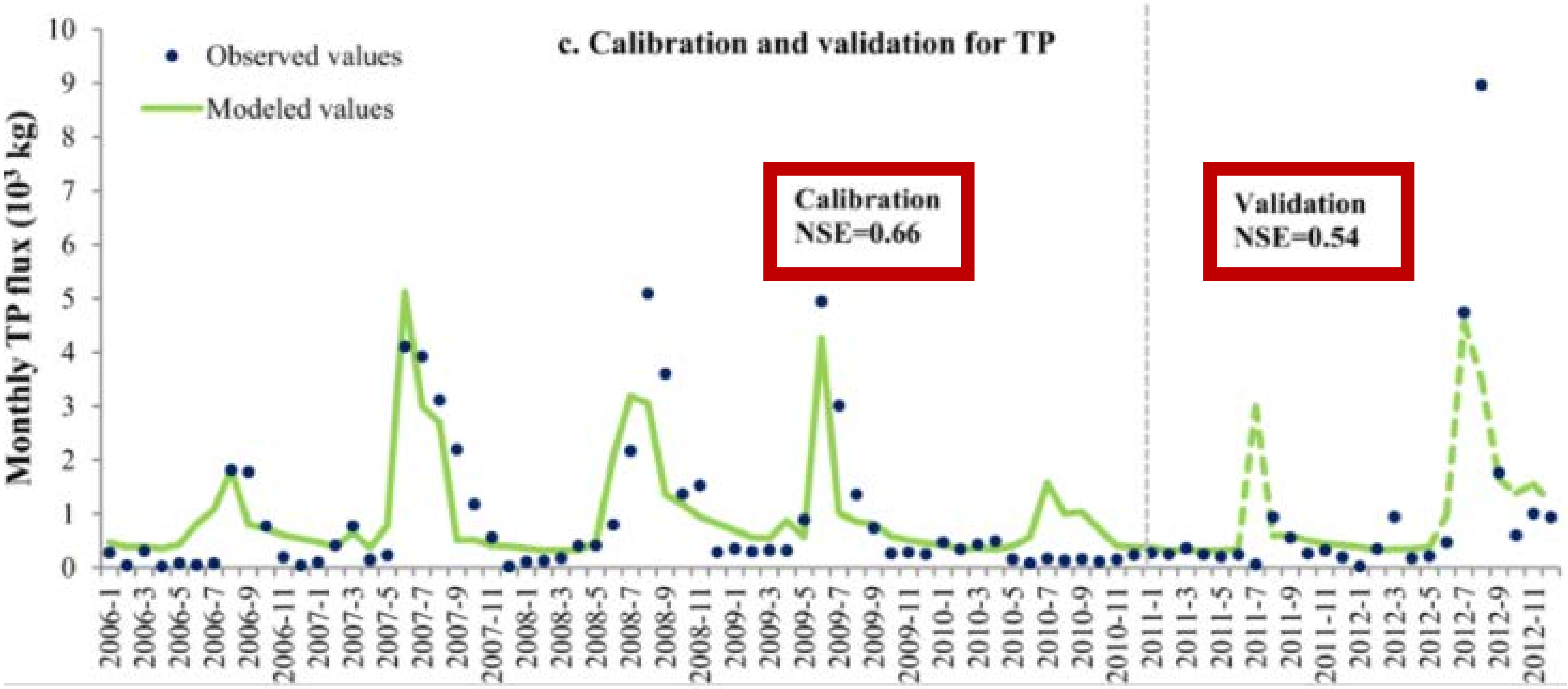
What is a Typical Calibration and Validation Process?

- Iterative Process

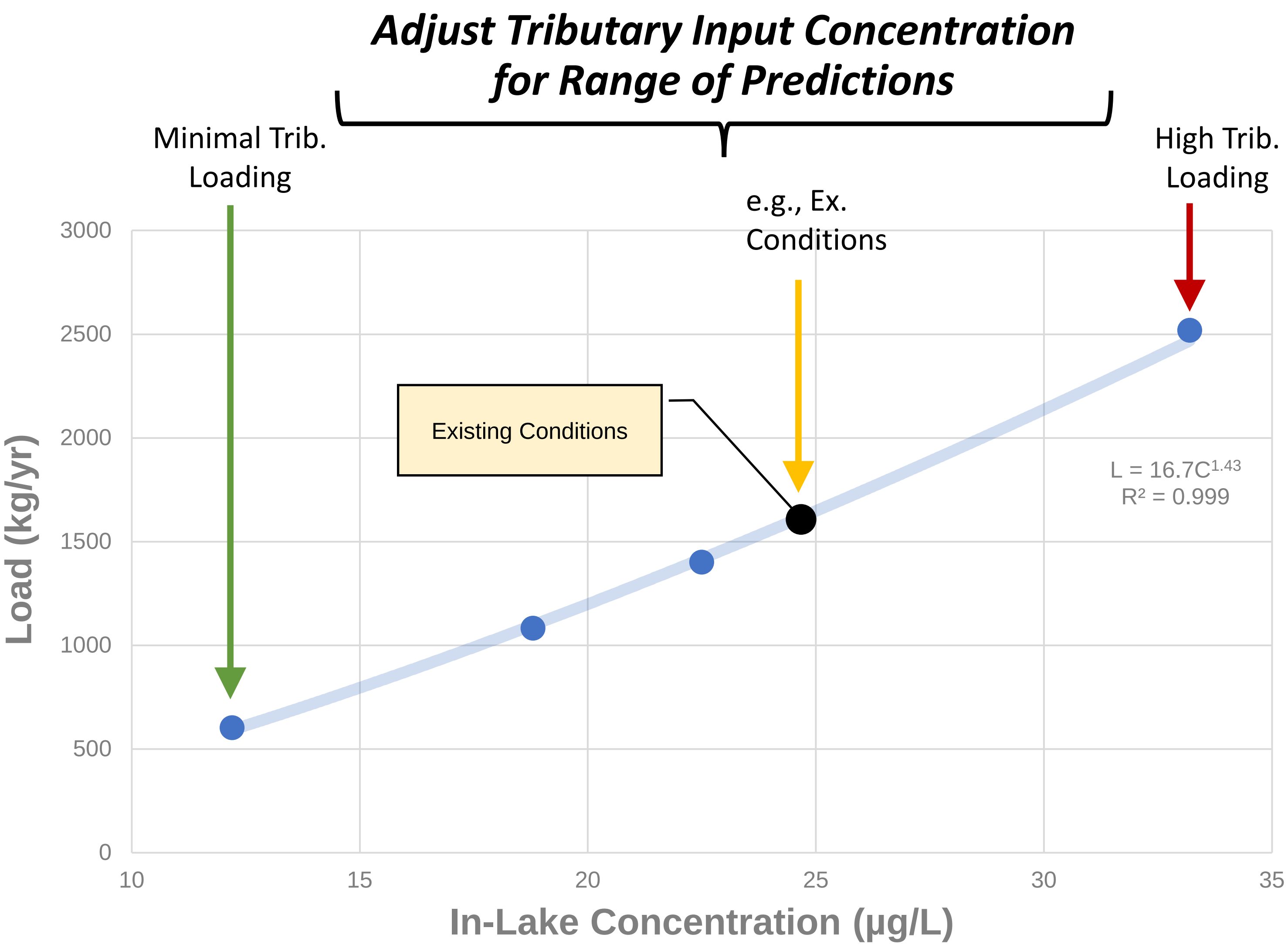
- Validation performed with <u>Independent</u> Dataset



Example Calibration and Validation Result



What is a Typical Model Outcome for a Load Reduction Analysis?



Bantam Lake Case Study

- Bantam Lake has a history of frequent cyanobacteria blooms

Keeler Cove in Bantam Lake on August 4, 2016

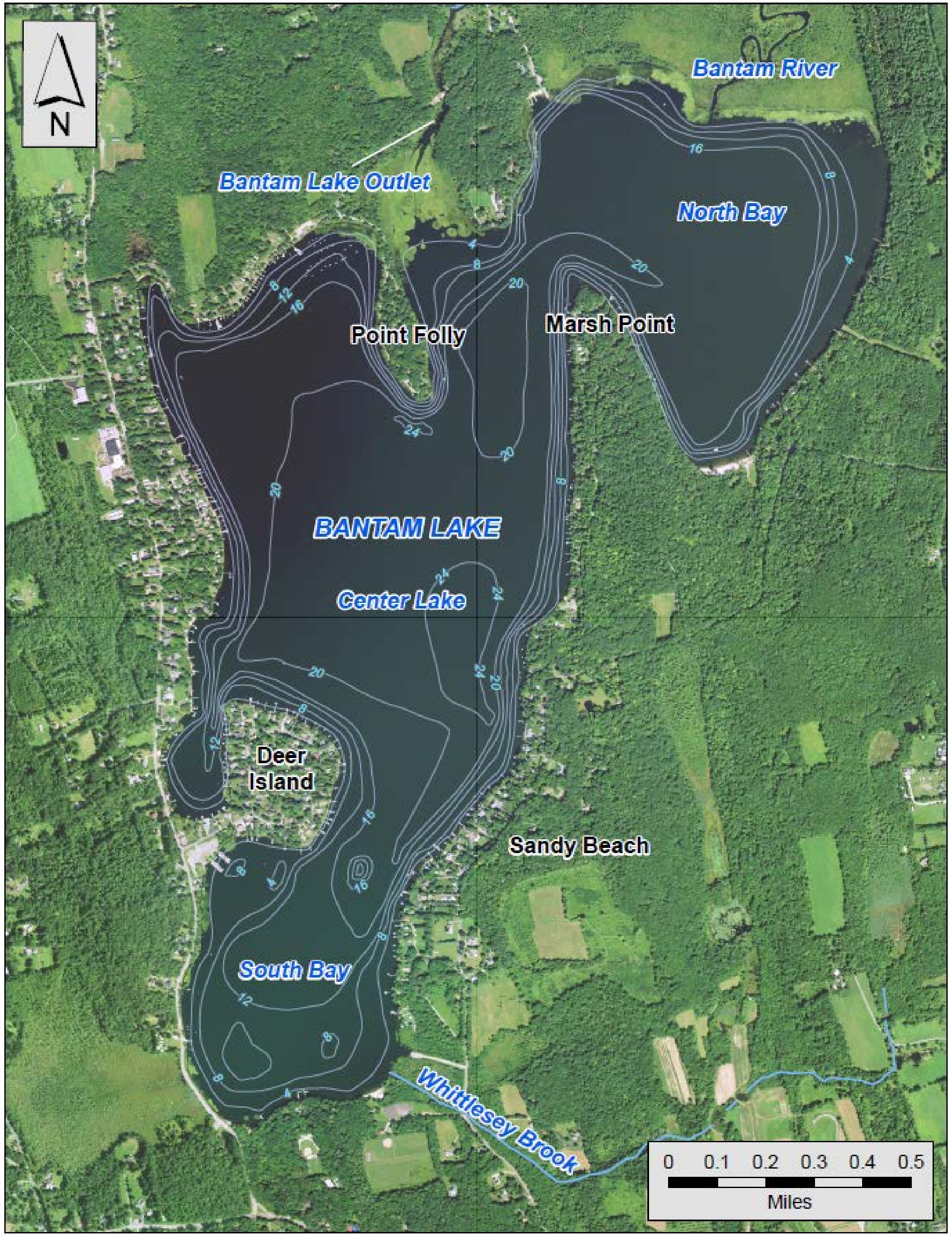
Project Goals and Objectives

Create Bantam Lake Water Quality Model

Calibrate / Validate the Model

Determine Required Load Reductions to Meet Water Quality Targets

Bantam Lake Overview



Modeling Approach

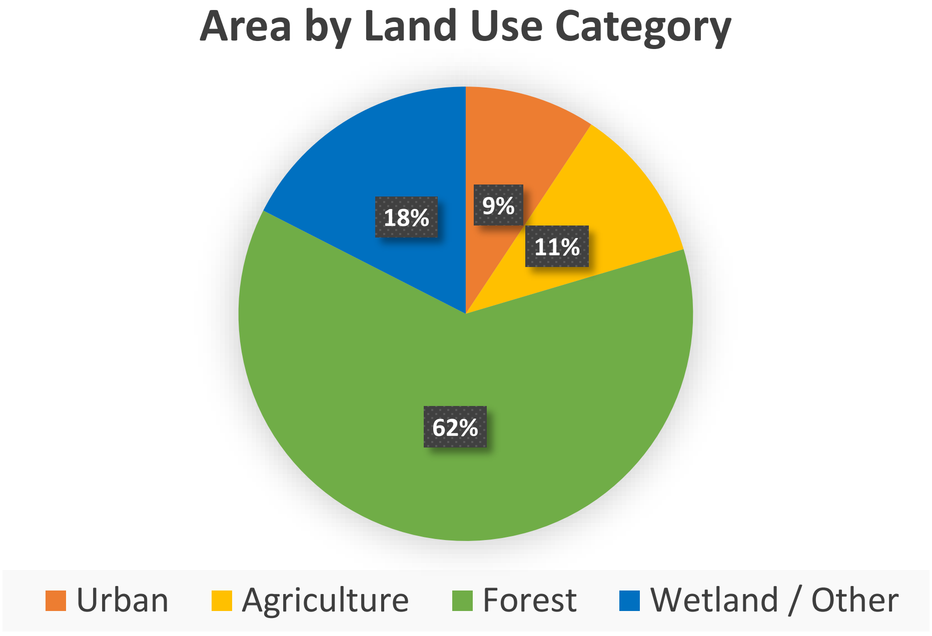
Lake Load Response Model
- Calculate Tributary Loading

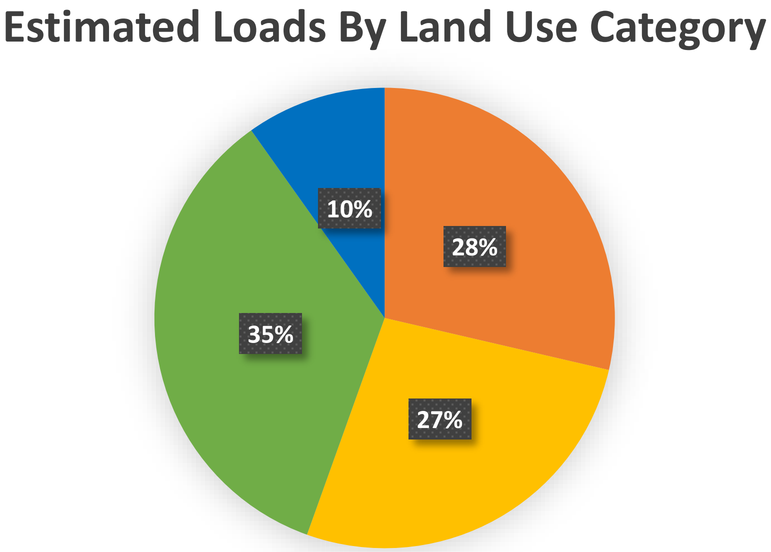
BATHTUB
- Calculate In-Lake WQ

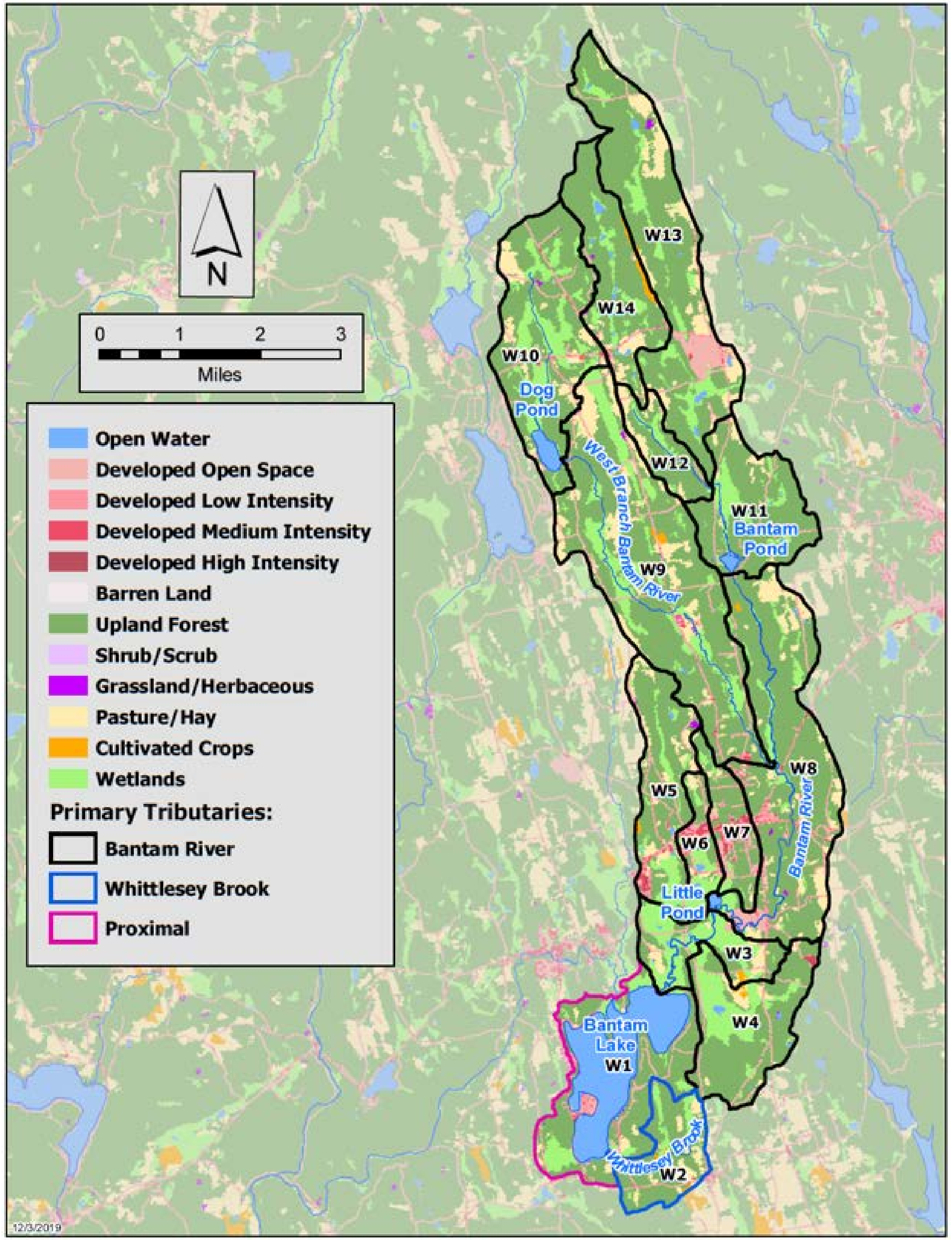
Calibrate / Validate
- Based on available data

Load Reduction Analysis
- Determine reductions to meet WQ Targets

Watershed Loading Results



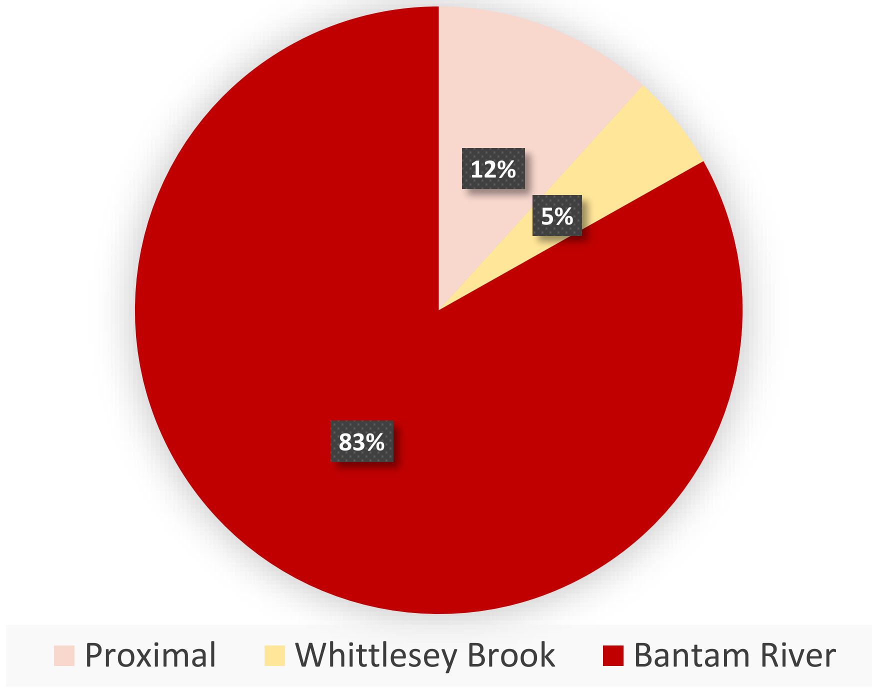


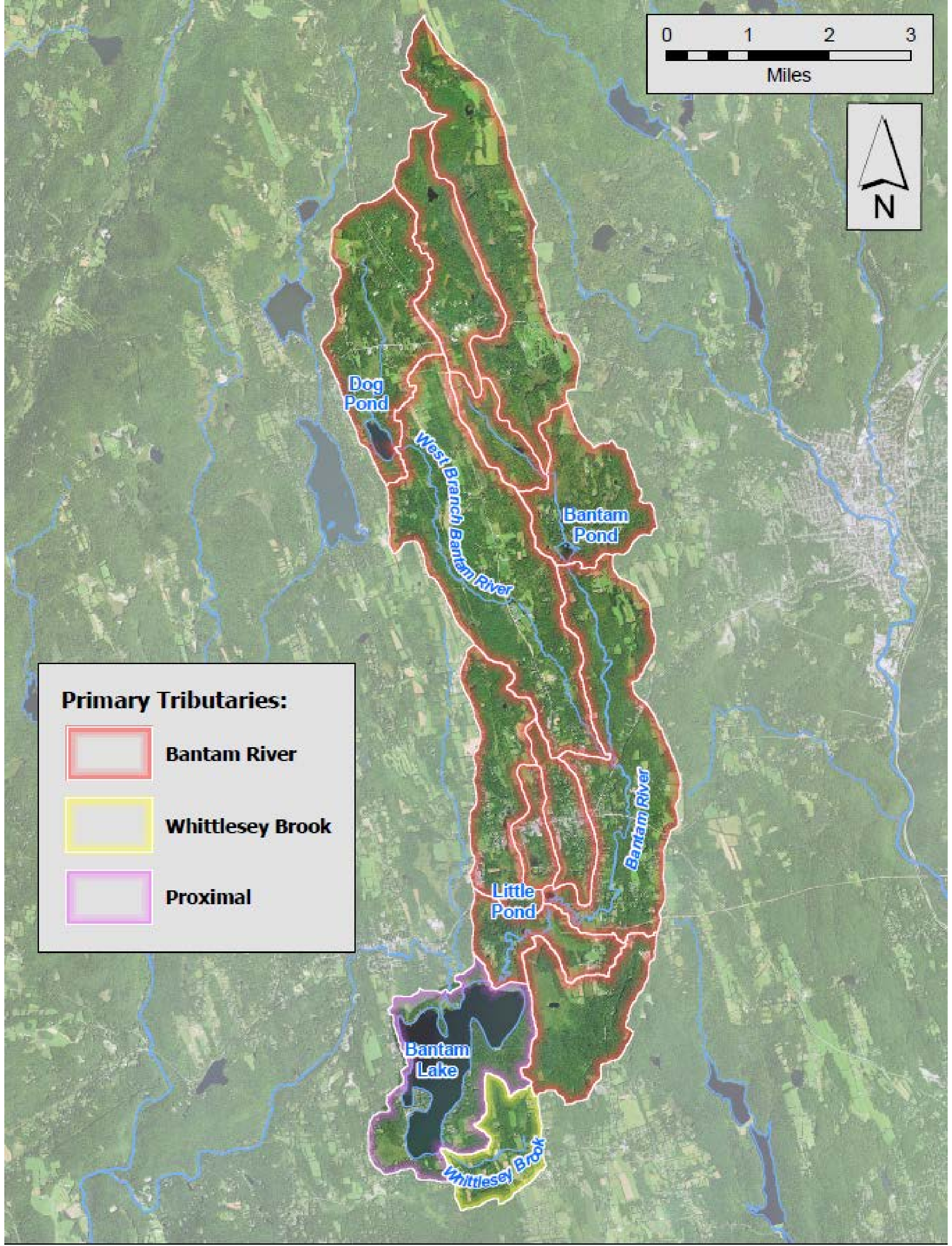


Watershed Loading Results

*Estimated Total Phosphorus Load = 1,004 kg/yr

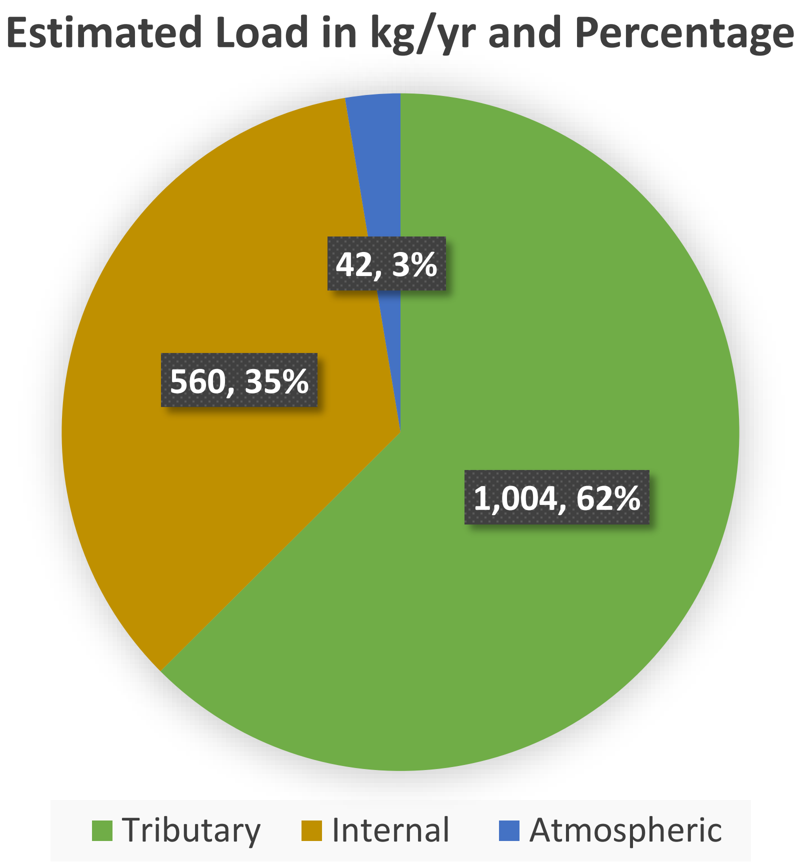
By Major Tributary





**estimate from averaging period – April through October*

Estimated Load by Source

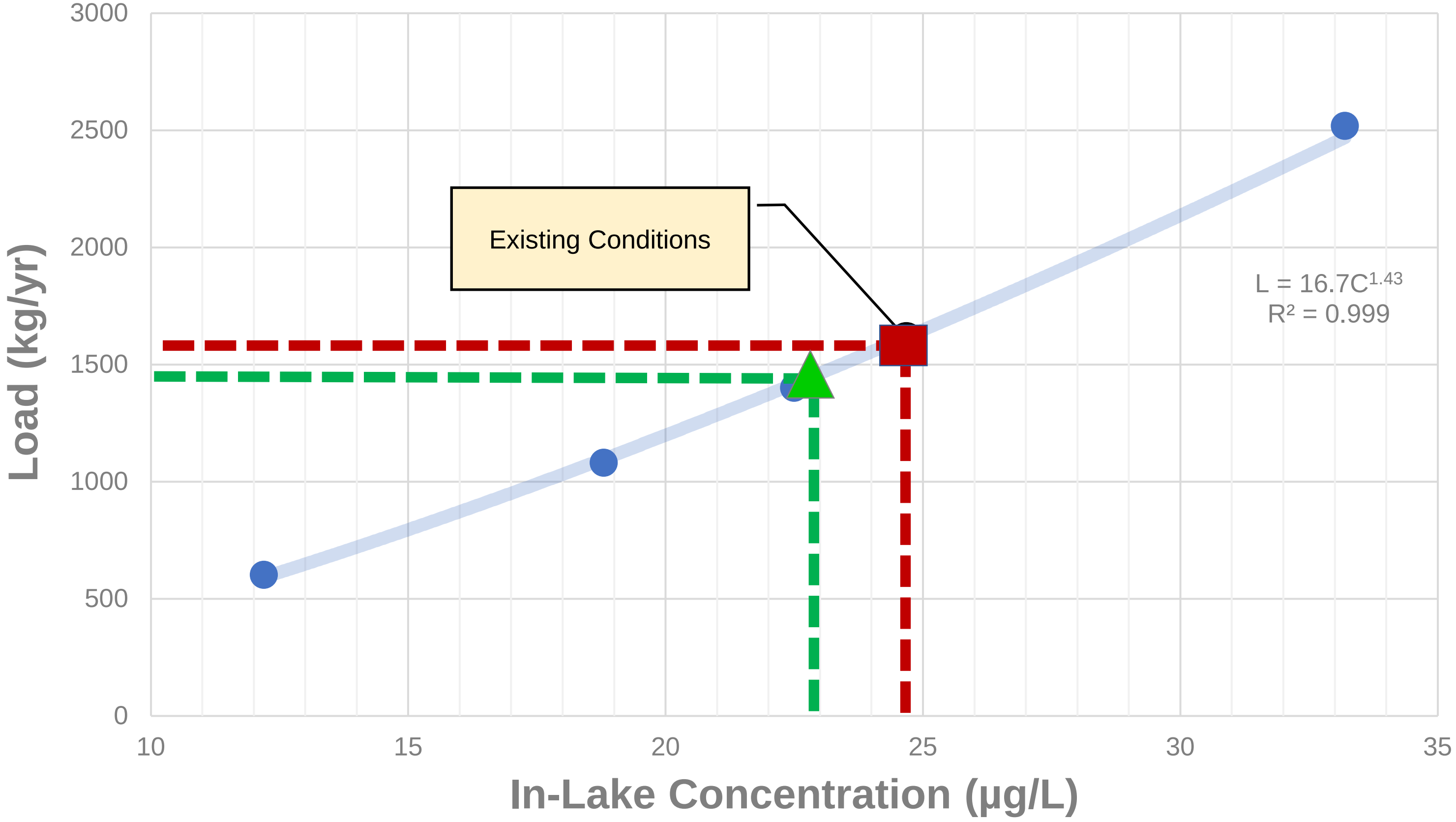


**Septic and Waterfowl Loading included in Tributary Estimate; Estimates from averaging period*

Model Results

Parameter	Units	Calibration [2007-2016]			Validation [2017-2018]		
		Observed	Predicted	% Difference	Observed	Predicted	% Difference
Total Phosphorus	µg/L	23.7	24.7	**4.2%**	24.1	22.5	**-6.6%**
Total Nitrogen	µg/L	513.8	528.6	**2.9%**	487.9	455.8	**-6.6%**
Chlorophyll-*a*	µg/L	-	12.7	**-**	-	10.6	**-**
Secchi Depth	m	2.1	1.9	**-9.5%**	2.4	2.1	**-12.5%**
Hypolimnetic Oxygen Depletion Rate	mg/m^3-day	-	427.3	**-**	-	391.2	**-**

Nutrient Load Reduction Analysis



Current Conditions

Conc = 24.7 ug/L

Load = 1,606 kg/yr

Target Conditions

Conc = 23 ug/L

Load = 1,479 kg/yr

(- 127 kg/yr of P)

8.6% Reduction in P

Thank you!
Any questions?

Lake Modeling

Is your Lake Ready for the Runway?

Bob Hartzel
rhartzel@ceiengineers.com
508-281-5201

Dave Roman
droman@ceiengineers.com
508-281-5176