Nutrient TMDLs for Sensitive Water Supply Reservoirs

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Outline

1. Project background
2. Project area
3. SWAT watershed model
4. BATHTUB lake model
5. Sensitivity analysis
6. Monte Carlo uncertainty analysis and MOS
7. Preliminary TMDL

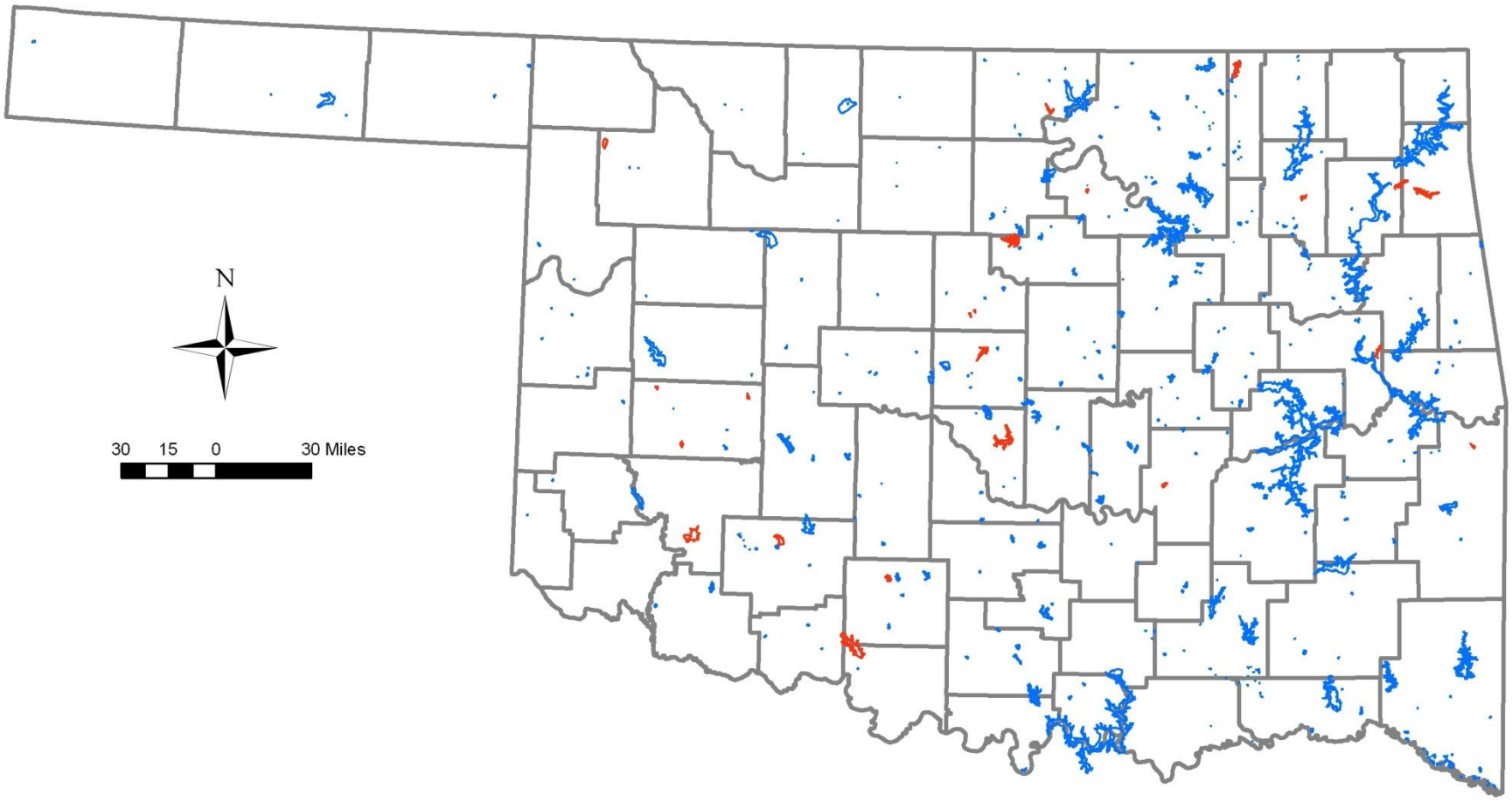
Project Background

- SWS Lakes in Oklahoma

Sensitive Water Supply Lakes

- Sources of public or private water supply
- Many of them are small municipal reservoirs with a watershed < 100 mi^2
- 81 SWS lakes in Oklahoma
- Long term average Chl-*a* standard of 10 µg/L
- 22 SWS lakes on 2008 303(d) list due to high Chl-*a*

Chl-*a* Impaired SWS Lakes



TMDLs for SWS lakes

- Limited data availability
  - In most cases, state's Beneficial Use Monitoring Program (BUMP) is the only water quality data source
  - BUMP takes 4 quarterly samples every 2-3 years

(Per site per year)	Chl-*a*	Nutrients
Rocky	1.5	1.1
Tom Steed	1.9	1.8

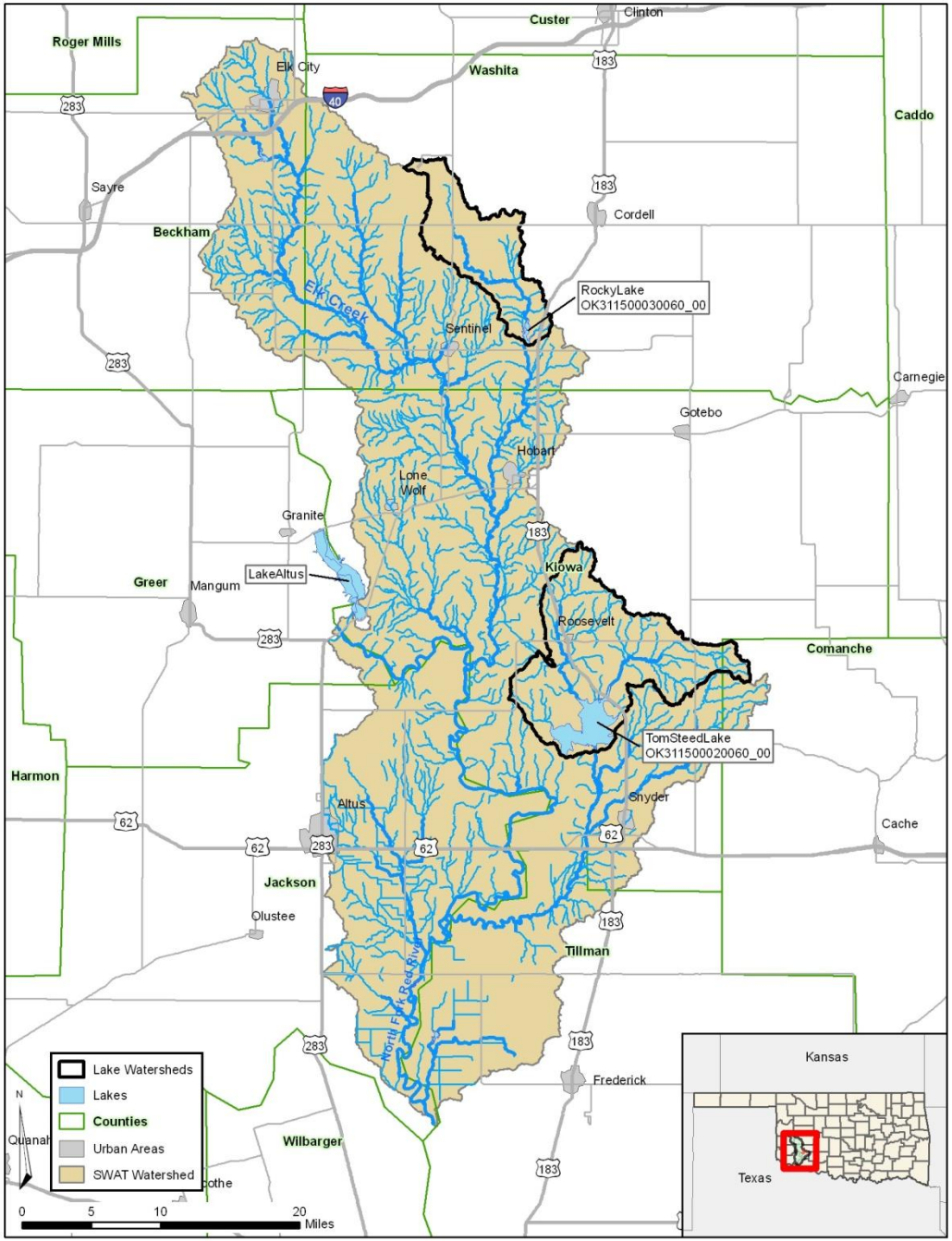
Model Selection

- We needed an acceptable method to develop Chl-*a* TMDLs for the lakes
- Data availability does not support complex hydrodynamic/water quality models such as EFDC
- Simpler models calibrated against long-term average values of monitoring data are best fit

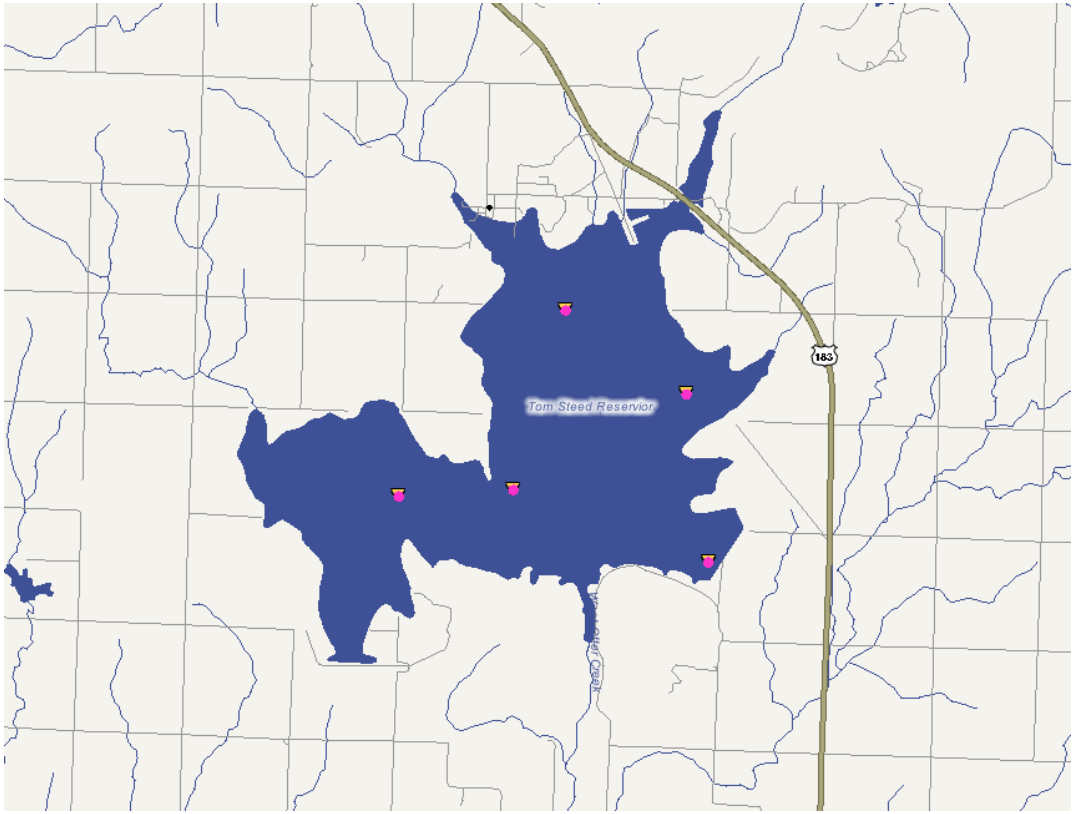
Project Lakes and Their Watersheds

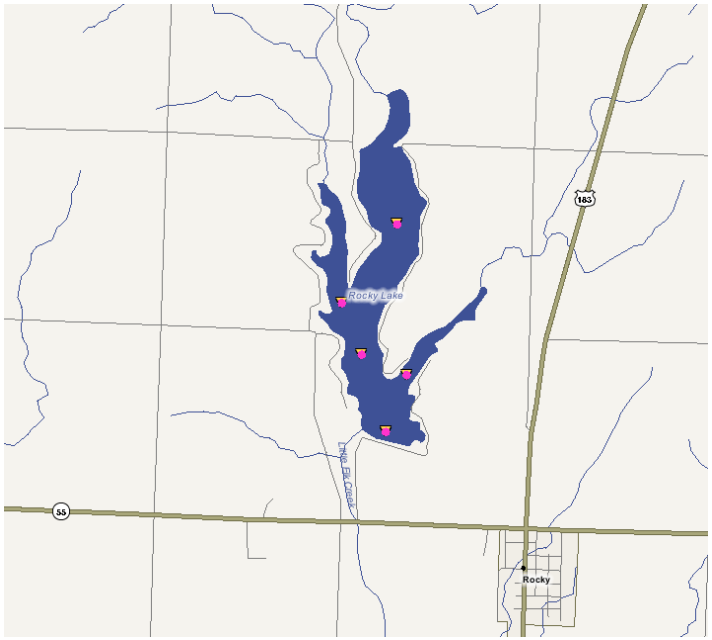
- North Fork of the Red

Annual Climatology	
Precipitation	29.7”
Temperature	60 ºF
Wind speed	11 mph
Thunderstorms	44
Tornados	1

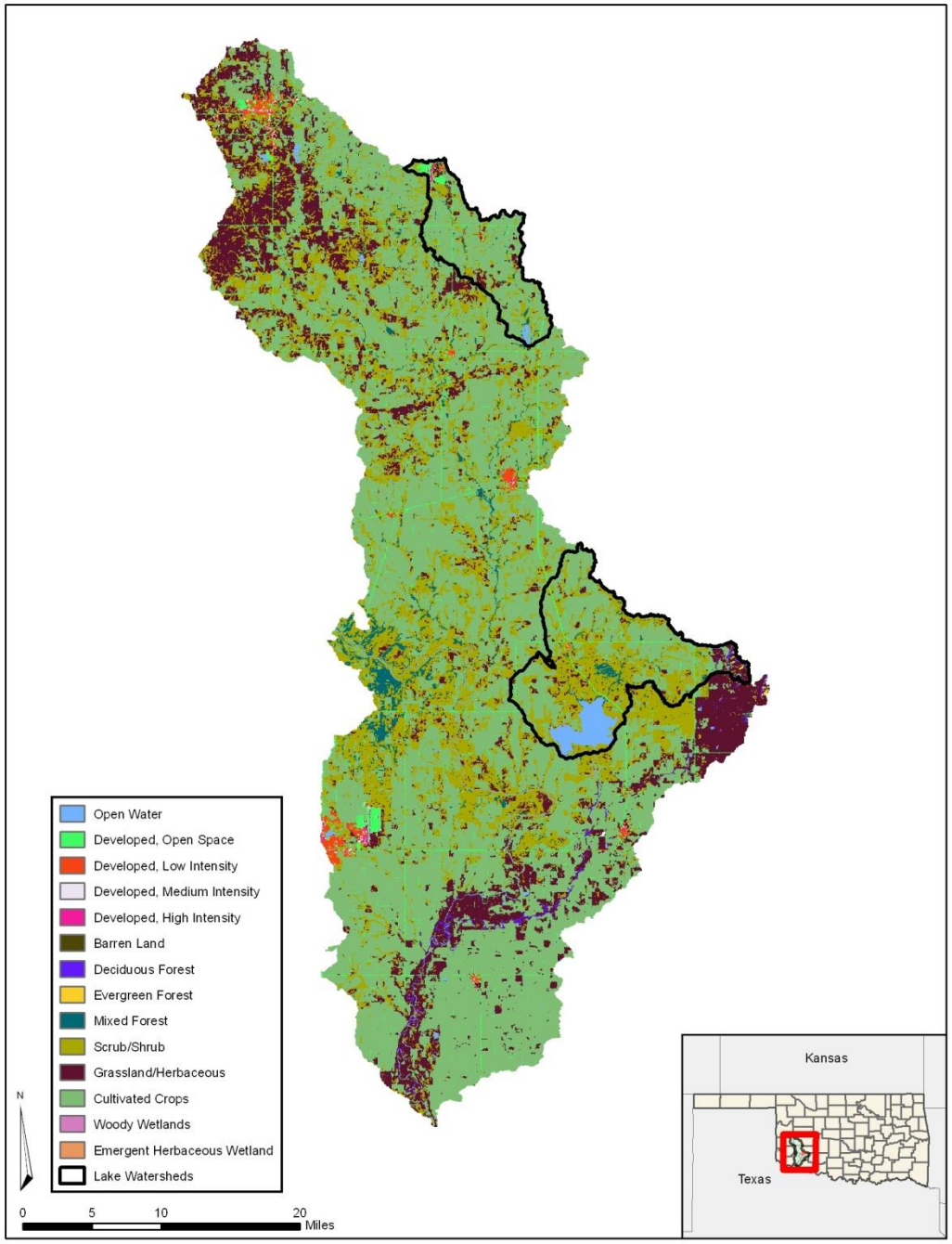


The Lakes





	Drainage (mi^2)	Volume (m^3)	Surface Area (km^2)	Mean Depth (m)
Tom Steed	119	120,176,000	25.9	4.64
Rocky	55	3,784,000	1.376	2.75



Land Use

	Rocky	Steed
Wheat	66%	42%
Shrub	16	36
Grass	6	7
Forest	2	4

Watershed Model

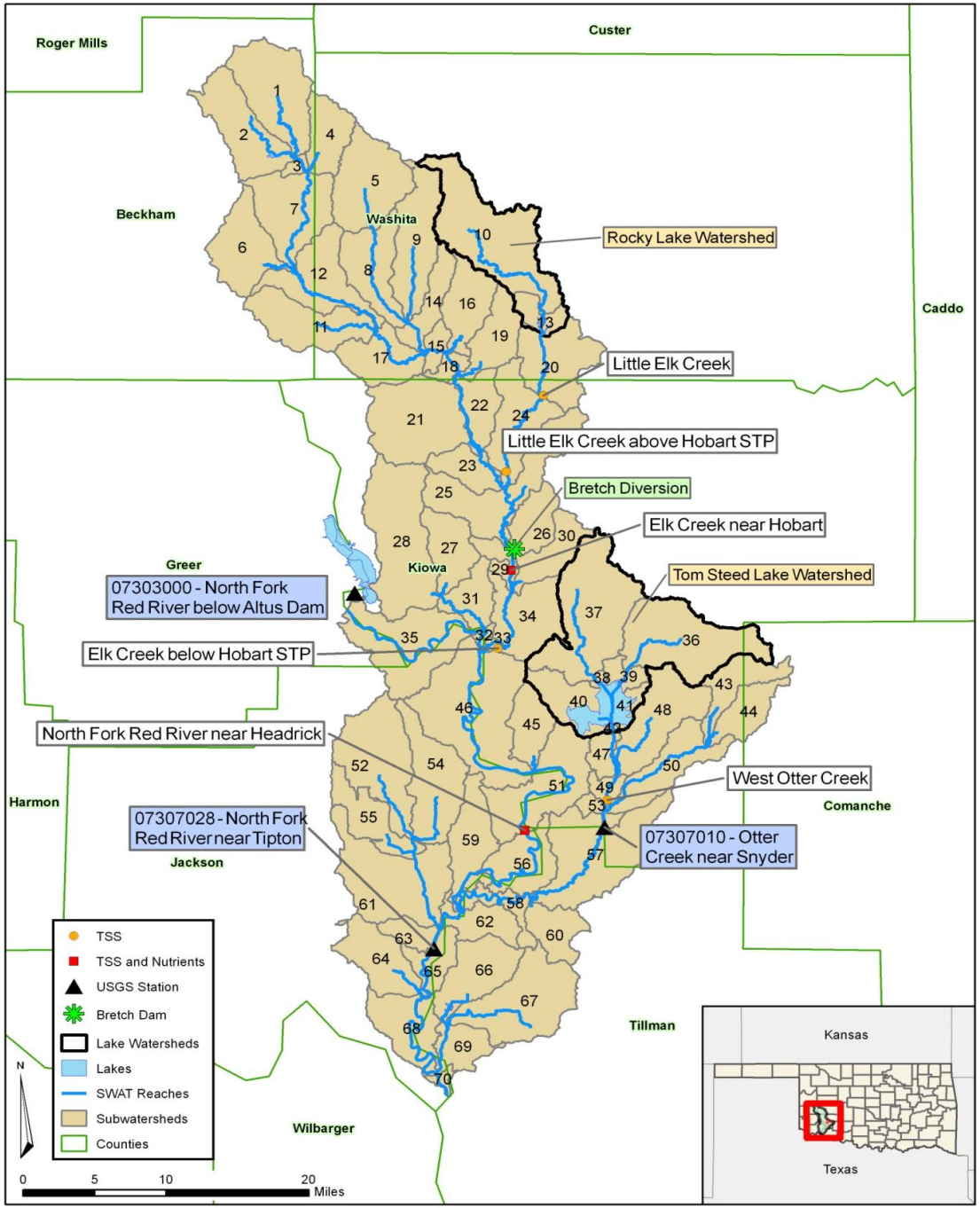
- No stream monitoring stations within either of the two lake watersheds
- Stations in the larger 8-digit HUC watershed: North Fork of the Red River
- A SWAT model was set up for the larger watershed

Watershed Monitoring

2 USGS gage stations:
1998/2000-2008

6 TSS stations:
18-22 samples in 2 years

2 nutrients stations:
38 samples in 4 years

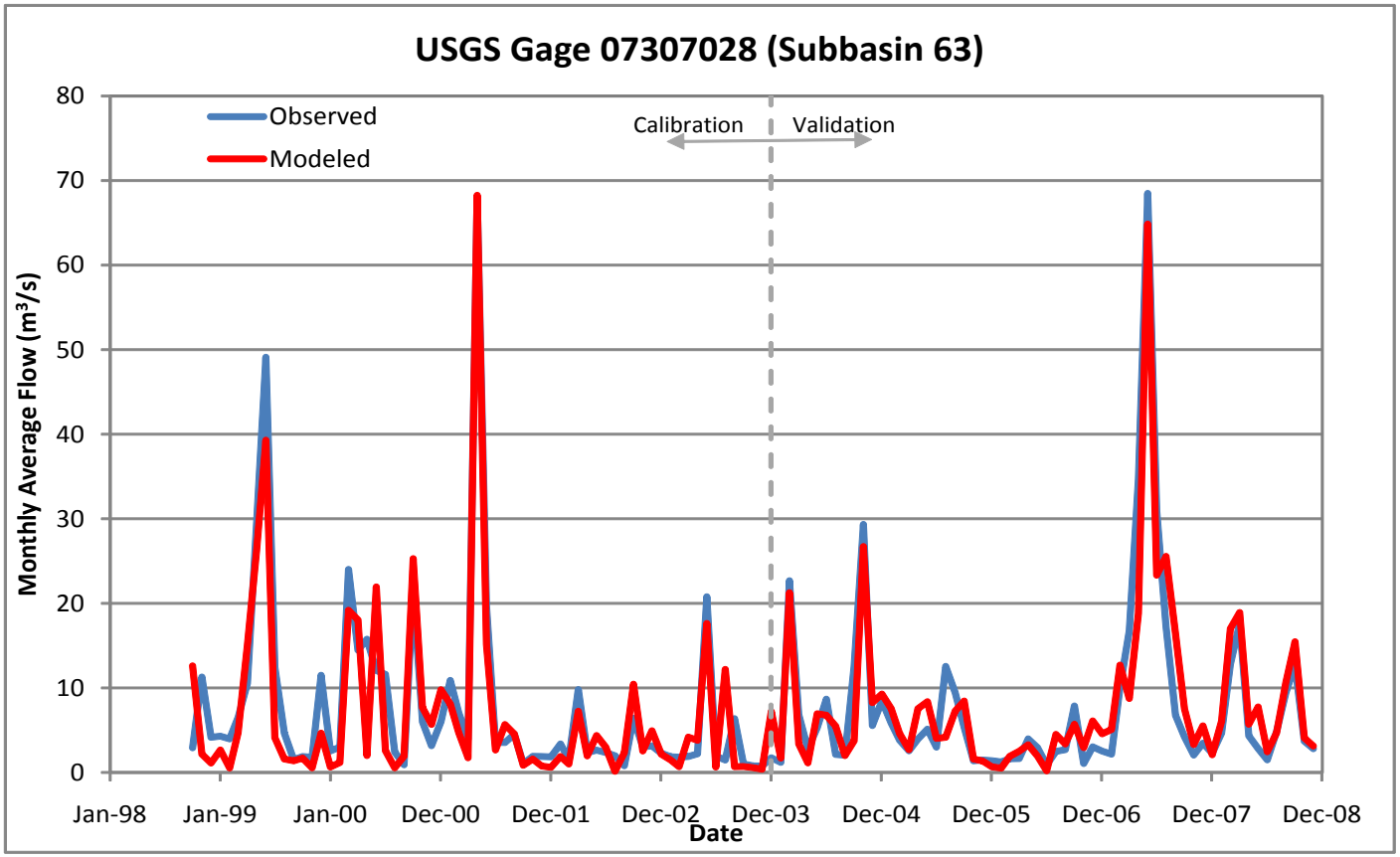


SWAT Model for the Watershed

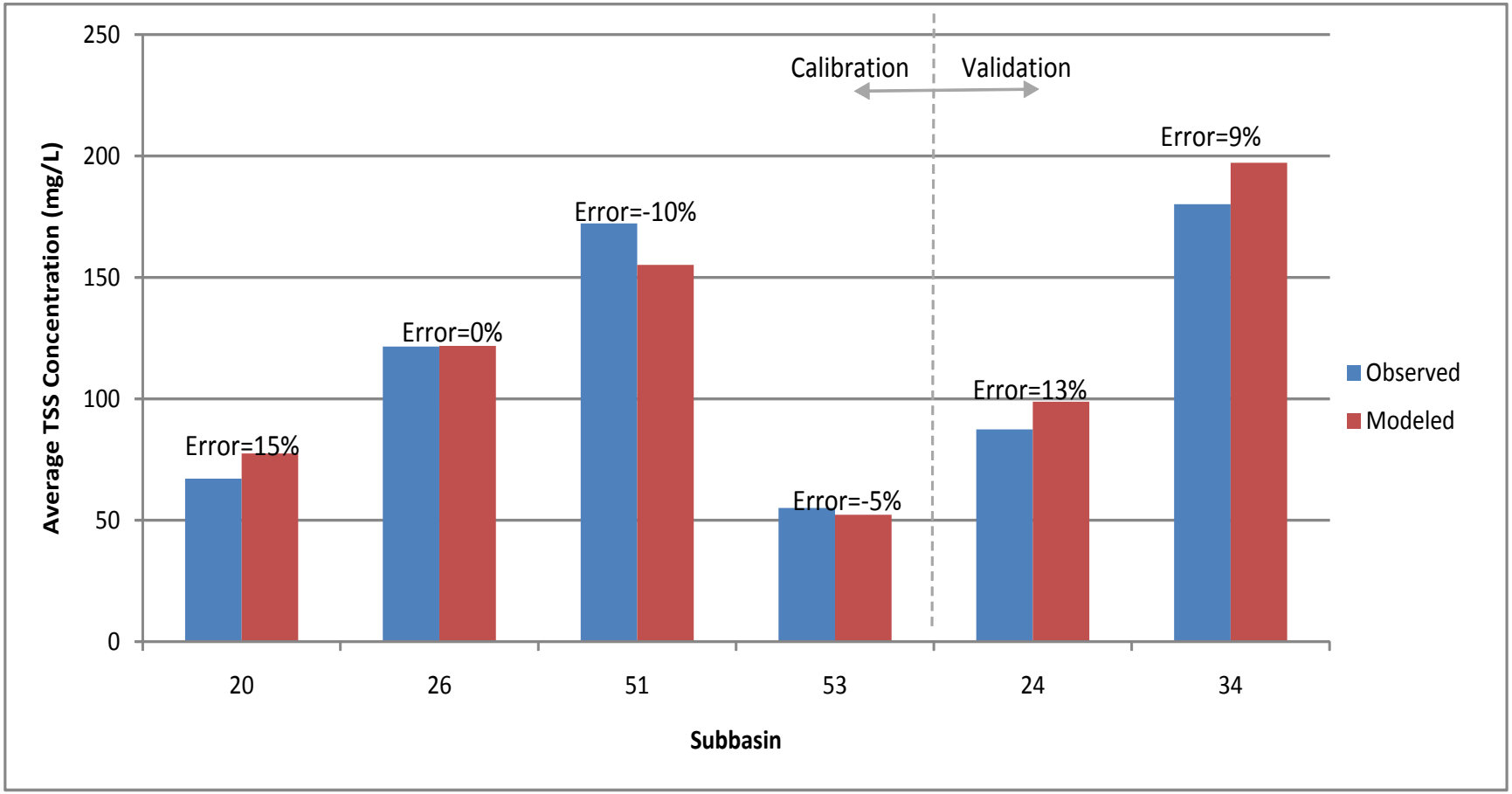
- Flows and loadings

SWAT Model

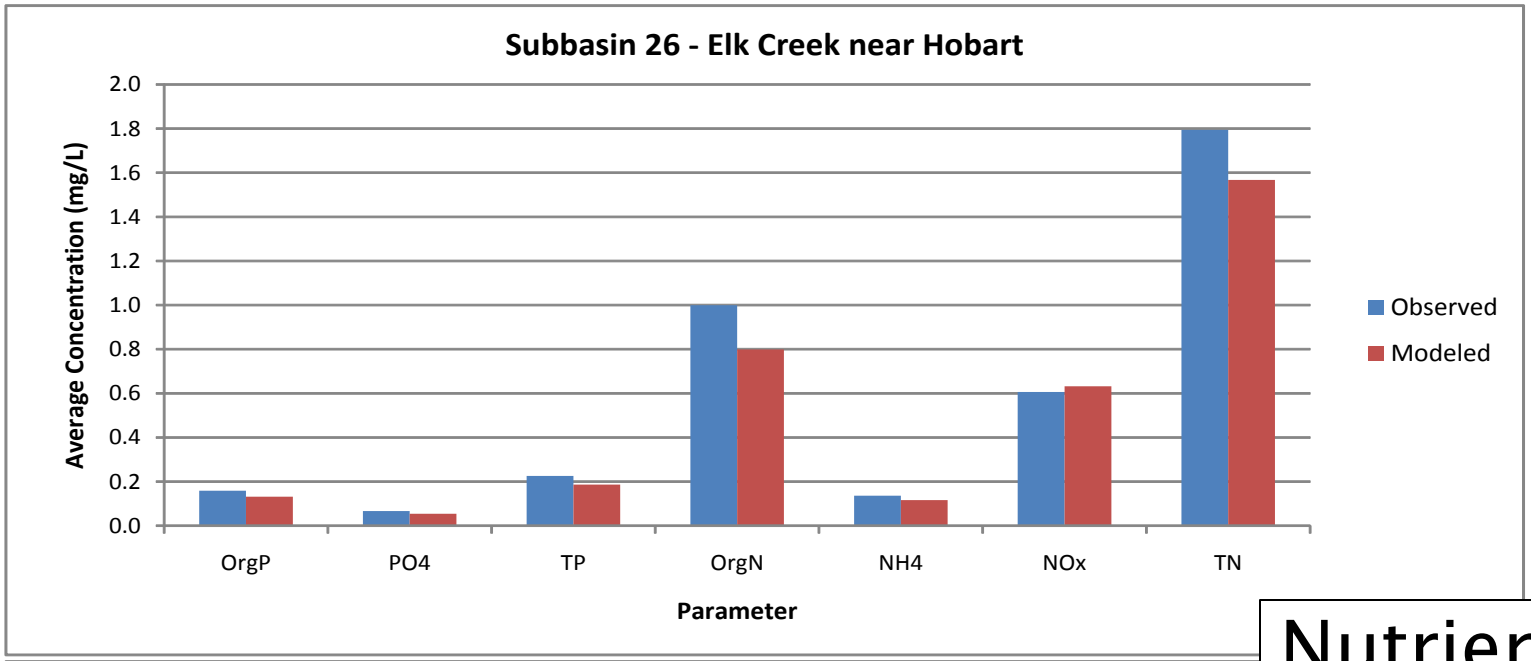
- 70 subwatersheds and 1,970 HRUs
- Local pasture, wheat, and cotton operations
- County level soil test P levels



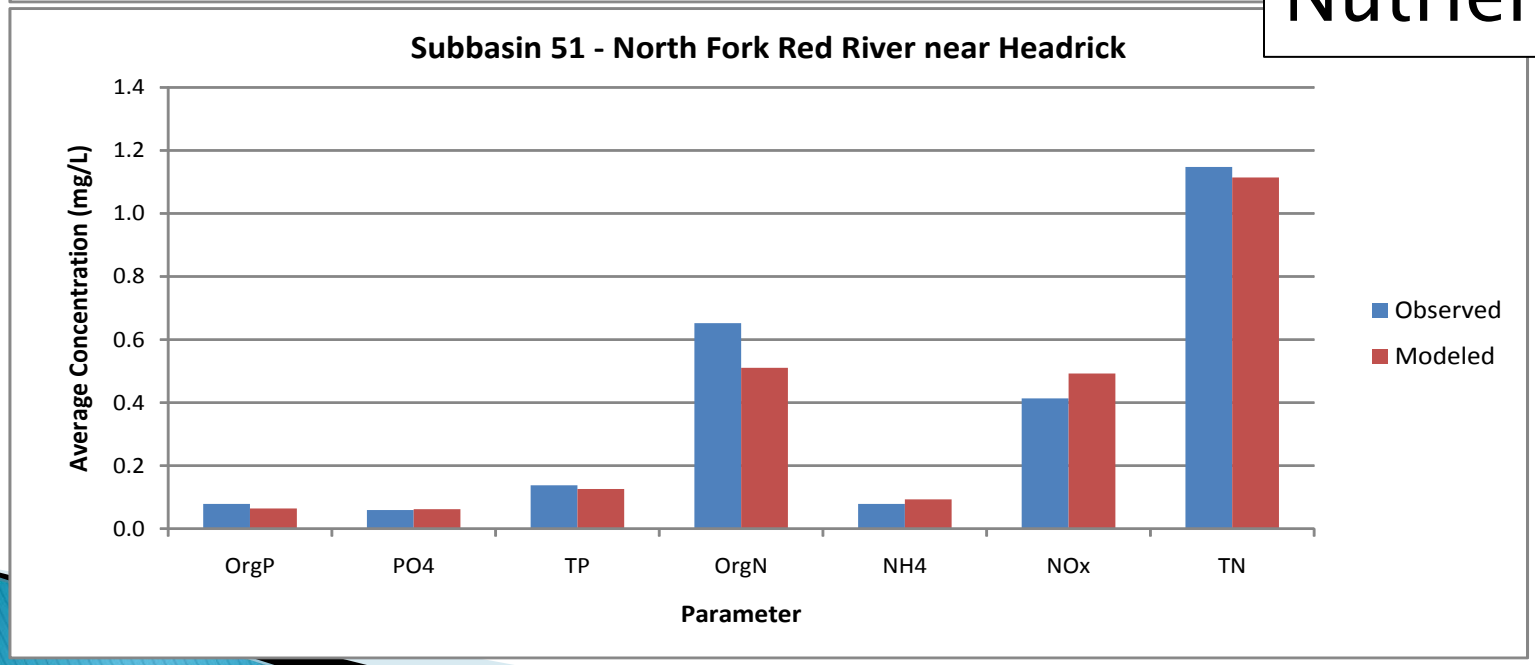
	Calibration	Validation
Model error (annual)	-12%	3%
r^2 (monthly)	0.86	0.87
NSE (monthly)	0.85	0.87



TSS average at the 6 monitoring stations


Subbasin 26 - Elk Creek near Hobart
Average Concentration (mg/L)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
OrgP
PO4
TP
OrgN
NH4
NOx
TN
Parameter
Observed
Modeled

Nutrients


Subbasin 51 - North Fork Red River near Headrick
Average Concentration (mg/L)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
OrgP
PO4
TP
OrgN
NH4
NOx
TN
Parameter
Observed
Modeled

Summary of Model Performance for Water Quality

Parameter	Subbasin	Average observed (mg/L)	Average modeled (mg/L)	Error	NSE	r^2
TSS	20	67.14	77.5	15%	0.643	0.694
	24	87.42	98.8	13%	0.778	0.985
	26	121.55	121.8	0%	0.869	0.921
	34	180.15	197.2	9%	0.861	0.895
	51	172.23	155.1	-10%	0.840	0.846
	53	55.10	52.3	-5%	0.647	0.709
Total Phosphorus	26	0.226	0.186	-17%	0.744	0.803
	51	0.138	0.126	-8%	0.661	0.665
Total Nitrogen	26	1.794	1.568	-13%	0.579	0.665
	51	1.148	1.114	-3%	0.796	0.821

Average Daily Flows and Nutrient Loads to the Lakes (SWAT model output)

Parameter	Rocky	Tom Steed
Flow (m^3/s)	0.46	1.39
Organic Phosphorus (kg/day)	40	40
Mineral Phosphorus (kg/day)	64	148
Total Phosphorus (kg/day)	**104**	**189**
Organic Nitrogen (kg/day)	67	137
NH_4 (kg/day)	28	91
NO_3 (kg/day)	73	77
NO_2 (kg/day)	2	14
Total Nitrogen (kg/day)	**170**	**319**

BATHTUB Lake Model

- Calibration

Average Morphometric Characteristics

	Volume (m^3)	Surface Area (km^2)	Mean Depth (m)
Tom Steed	120,176,000	25.9	4.64
Rocky	3,784,000	1.376	2.75

BATHTUB and Field Observations

Water Quality Parameter	Modeled Mean Concentration for Steed	Field Mean Concentrations for Steed
Total P (µg/L)	70.4	73.0
Total N (µg/L)	739.8	759
Chl-*a* (µg/L)	16.6	16.6
Secchi (meter)	0.4	0.38

Water Quality Parameter	Modeled Mean Concentration for Rocky	Field Mean Concentrations for Rocky
Total P (µg/L)	130.2	133.0
Total N (µg/L)	1452	1519
Chl-*a* (µg/L)	44.9	44.9
Secchi (meter)	0.3	0.29

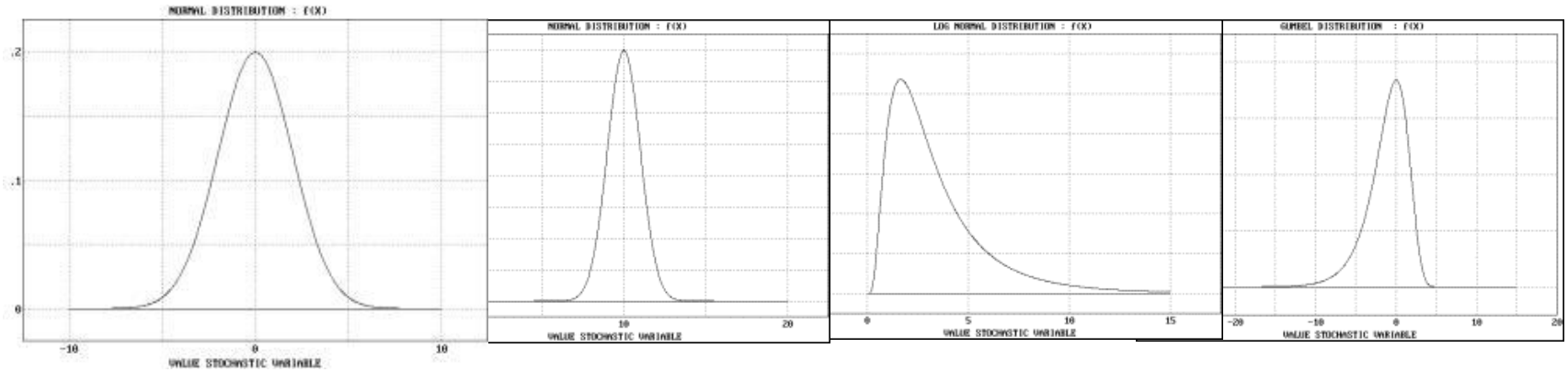
Question:

- How can we quantify the uncertainty associated with the limited water quality data and a non-mechanistic model?

- (how confident are we when we set a load reduction goal to achieve an in-lake Chl-*a* level?)

Monte Carlo Simulation

- "Random" values are selected for model parameters
  - Random, but still based on the range and frequency of possible values

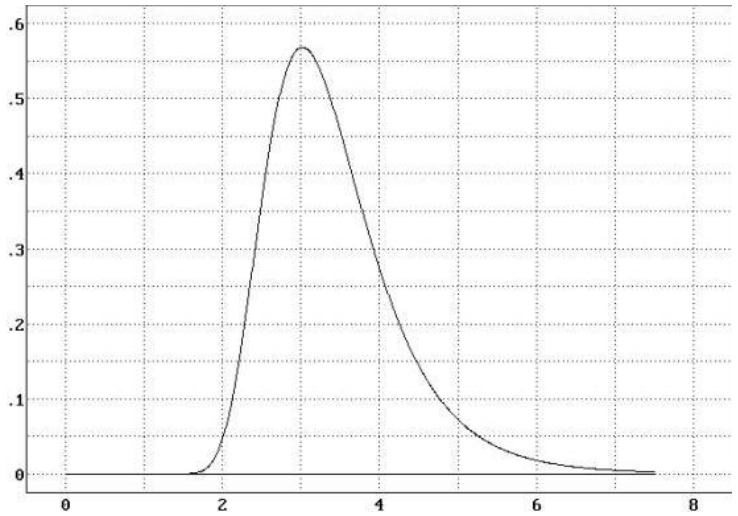


- The model is calculated using these values

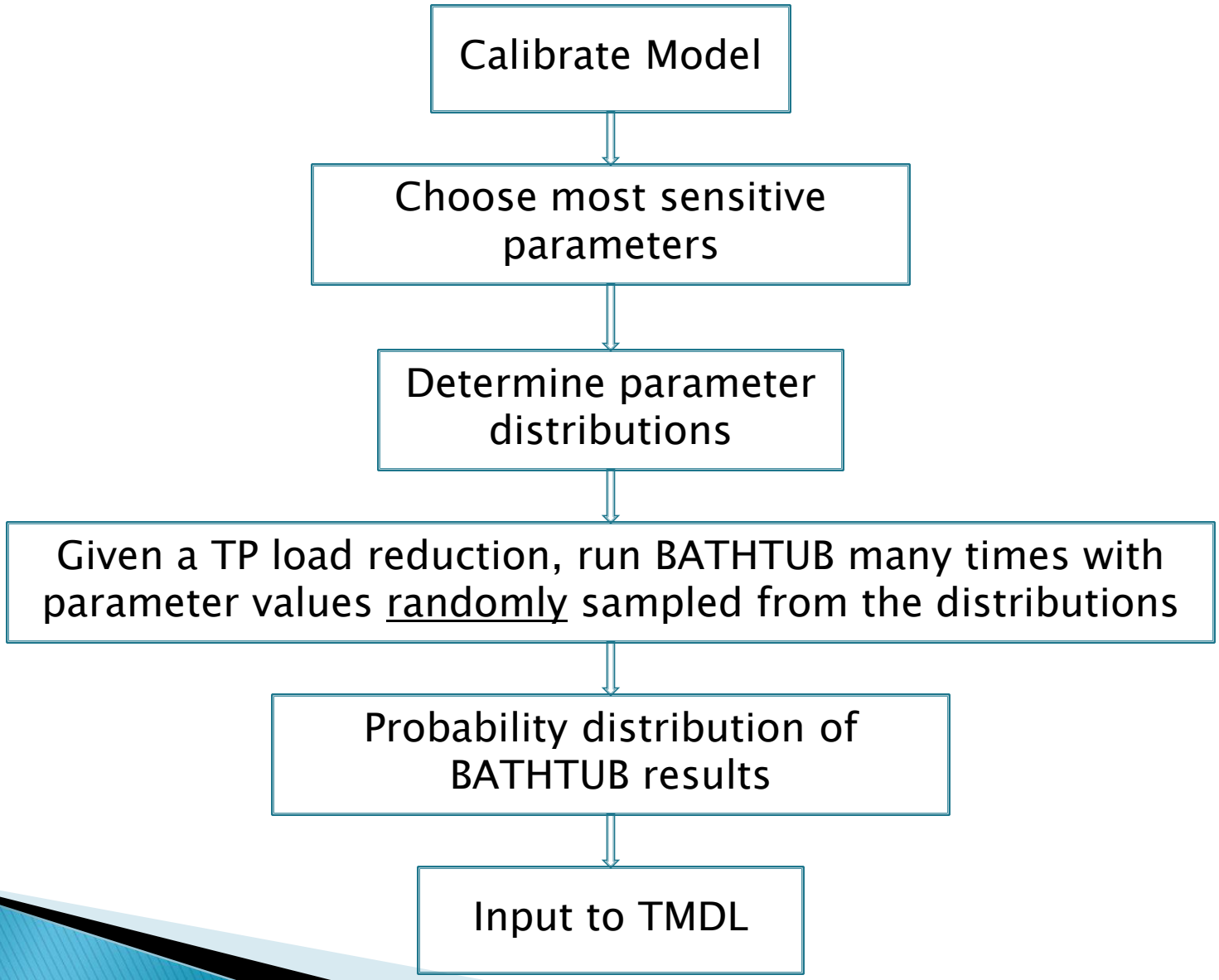
Monte Carlo Simulation

- The process is repeated hundreds or thousands of times, each time using different randomly-selected values

- Results represent the range and frequency of possible model output



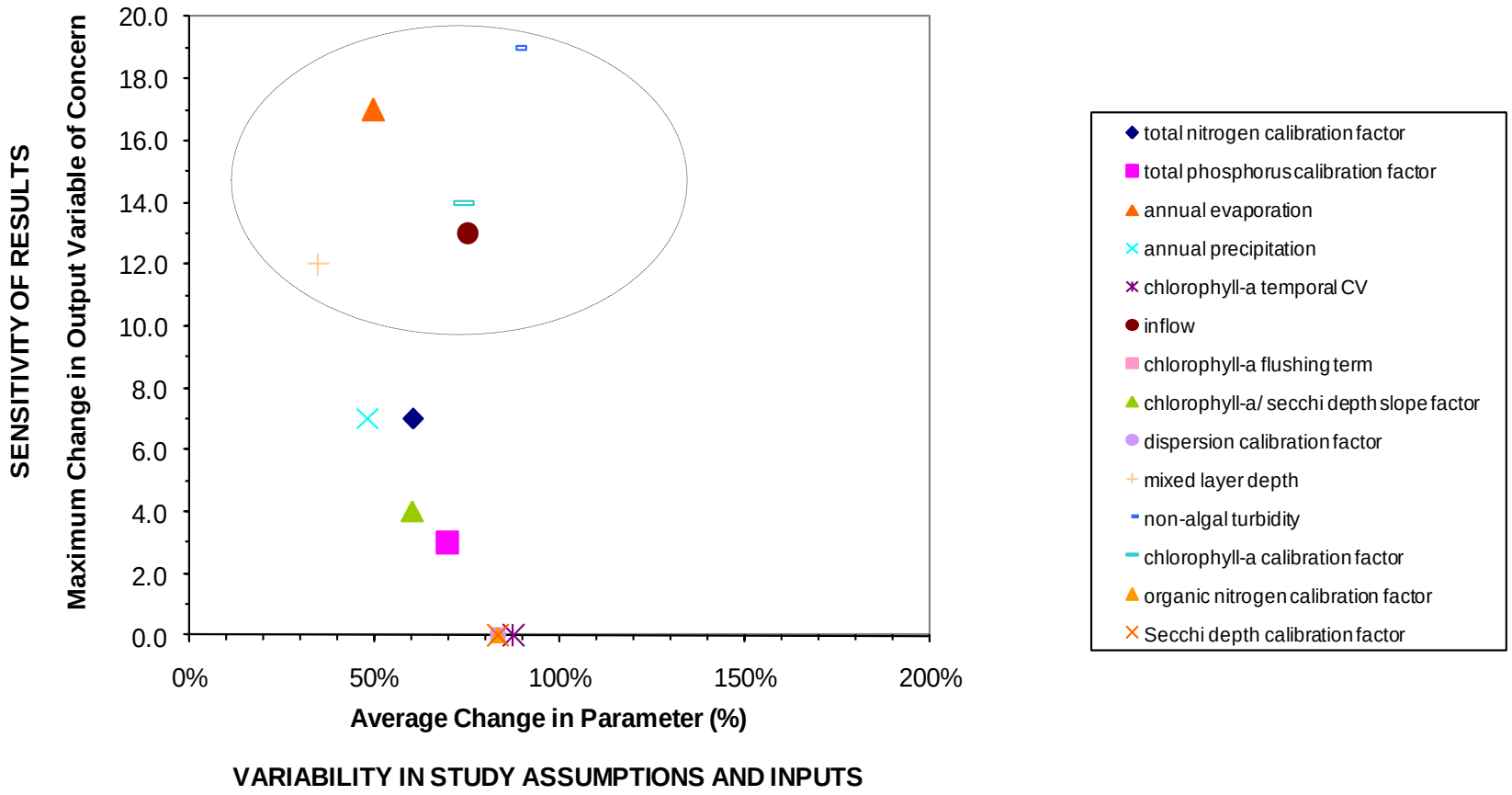
Monte Carlo Uncertainty Analysis for BATHTUB



Sensitivity Analysis

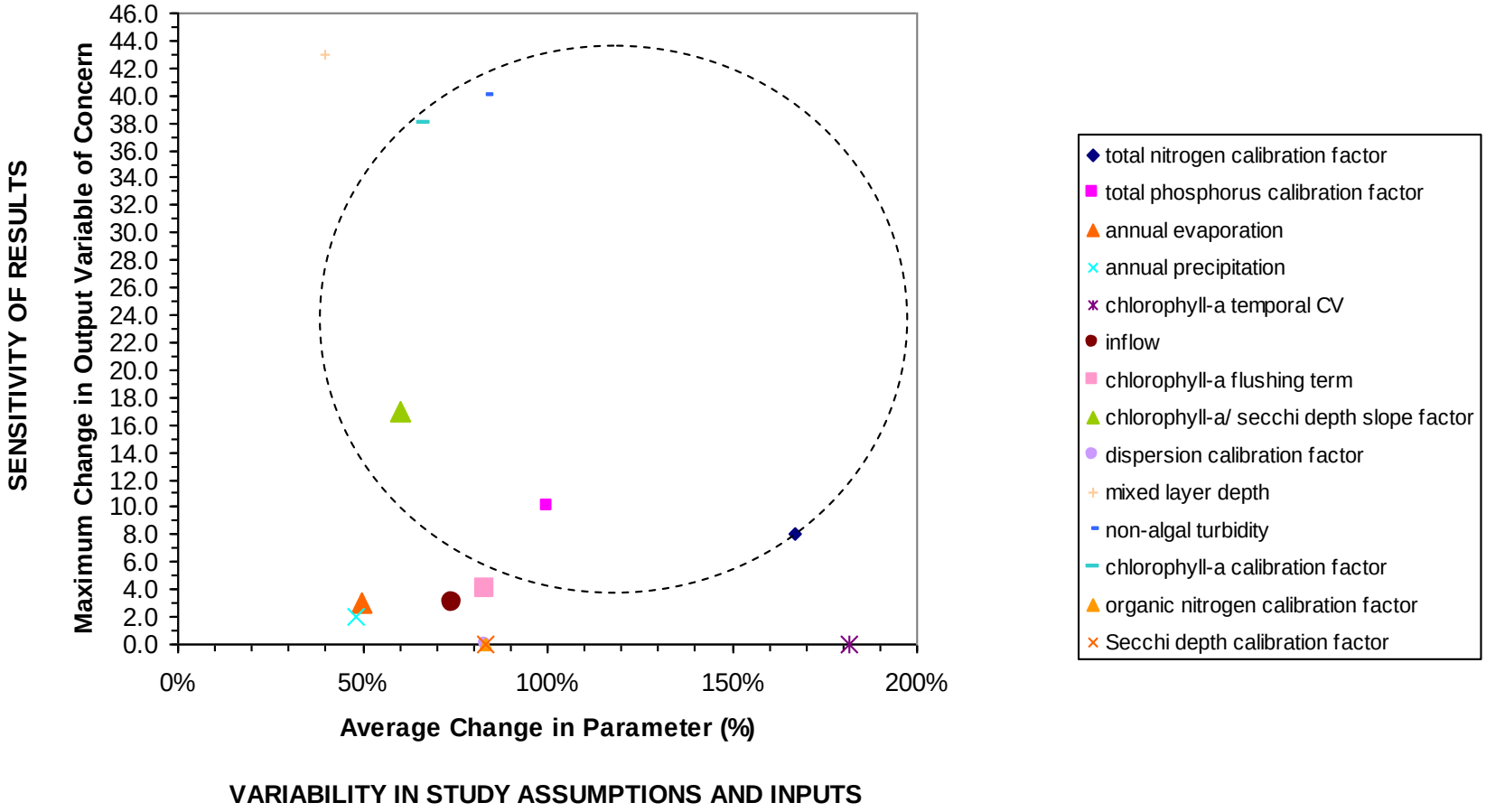
- Narrow down the parameters

Sensitivity Matrix for BATHTUB Parameters for Tom Steed



- non-algal turbidity
- annual average evaporation
- chlorophyll-*a* calibration factor
- inflow rate
- mixed layer depth

Sensitivity Matrix for BATHTUB Parameters for Rocky



- non-algal turbidity
- chlorophyll-*a* calibration factor
- chl-*a*/Secchi depth slope factor
- TP calculation factor
- TN calculation factor

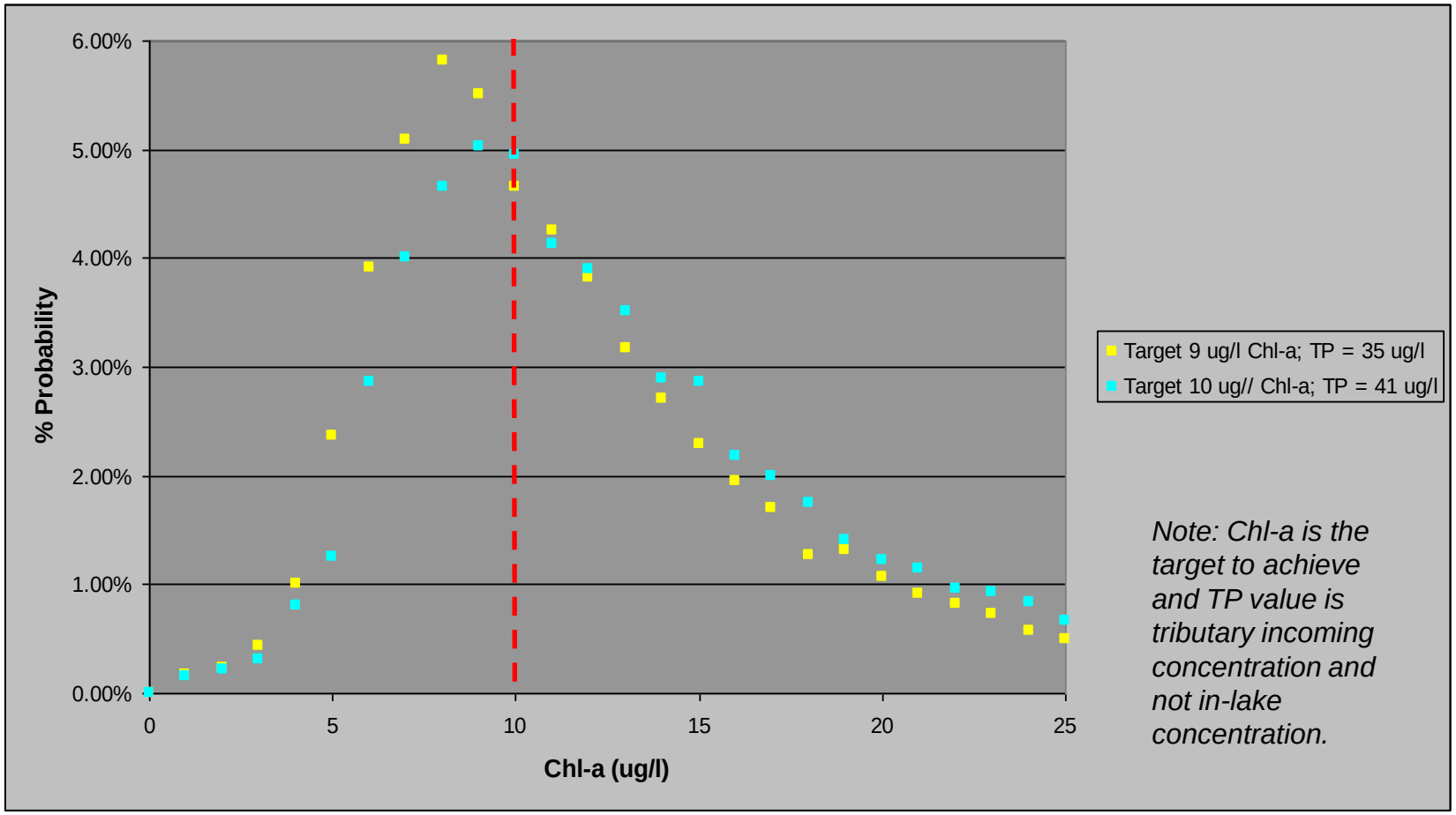
Selected Distribution of Parameters for BATHTUB Uncertainty Analysis

Parameter	Definition	Distribution
a	Non-algal turbidity (1/m)	Normal (Steed: mean = 2.21, std.dev. = 1.348; Rocky: mean = 2.33, std.dev. = 0.65)
CB	Calibration factor for chlorophyll-*a*	Normal (Steed: mean = 1.5, std.dev. = 0.25; Rocky: mean = 2.0, std.dev. = 0.25)
evp	Annual Evaporation (m/yr)	Normal (Steed: mean = 2.07, std.dev. = 0.621)
b	Chl-*a*/Secchi depth slope factor (m^2/mg)	Normal (Rocky: mean = 0.025, std.dev. = 0.015)
Q	Inflow (hm^3/yr)	Normal (Steed: mean = 45.44, std.dev. = 33.6)
zmx	Mixed Layer Depth	Normal (Steed: mean = 4.0, std.dev. = 1.5)
CP	Total P calibration factor	Normal (Rocky: mean = 0.35, std.dev. = 0.2)
CN	Total N calibration factor	Normal (Rocky: mean = 0.8, std.dev. = 0.5)

Uncertainty Analysis and Margin of Safety

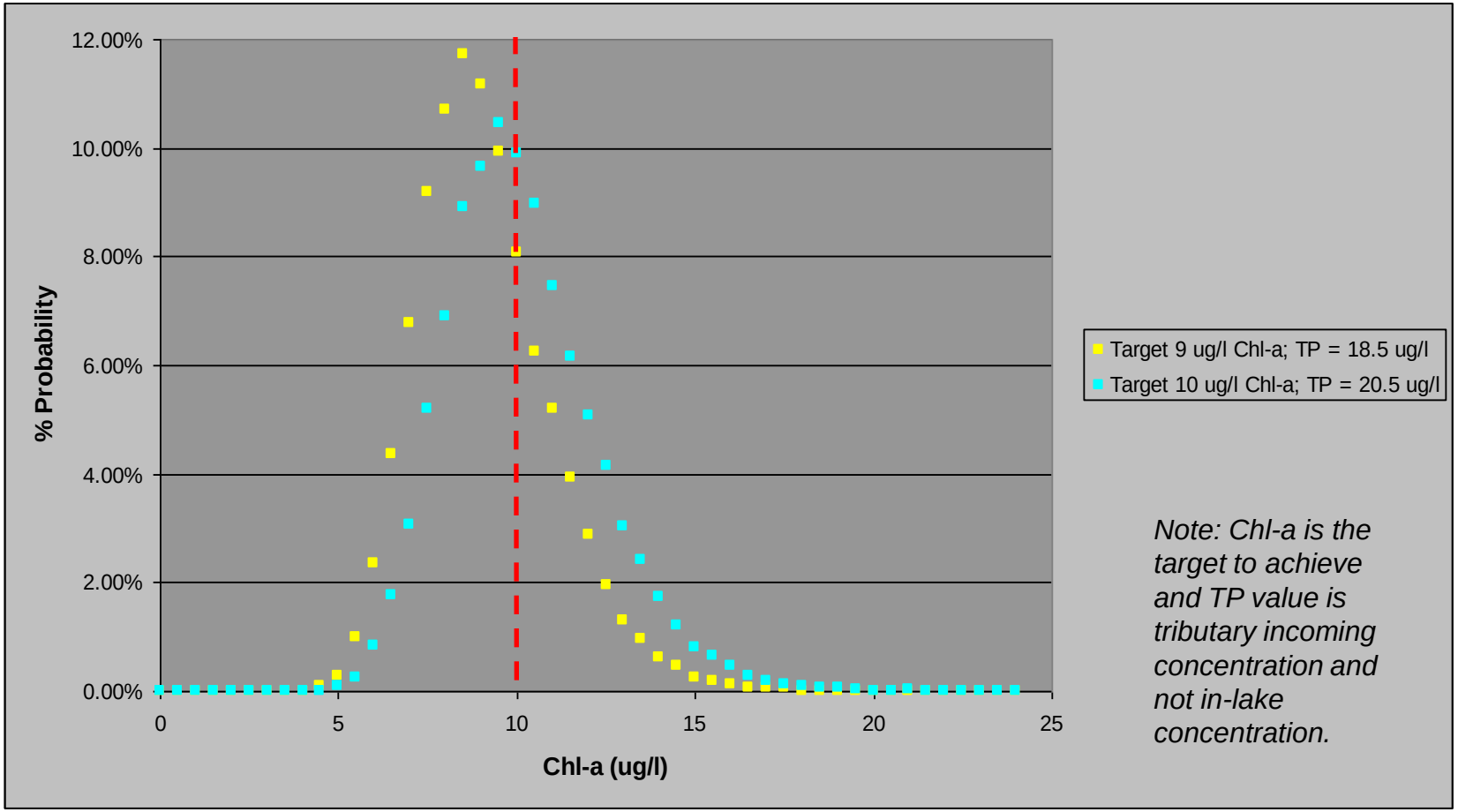
- Monte Carlo Simulations

Lake Tom Steed Probability Plot of Chlorophyll-*a* Concentrations Obtained from 20,000 MC Samples



Cumulative probability :
42% for <10 µg/L and 50%, if we target 9 µg/L

Rocky Lake Probability Plot of Chlorophyll-*a* Concentrations Obtained from 20,000 MC Samples



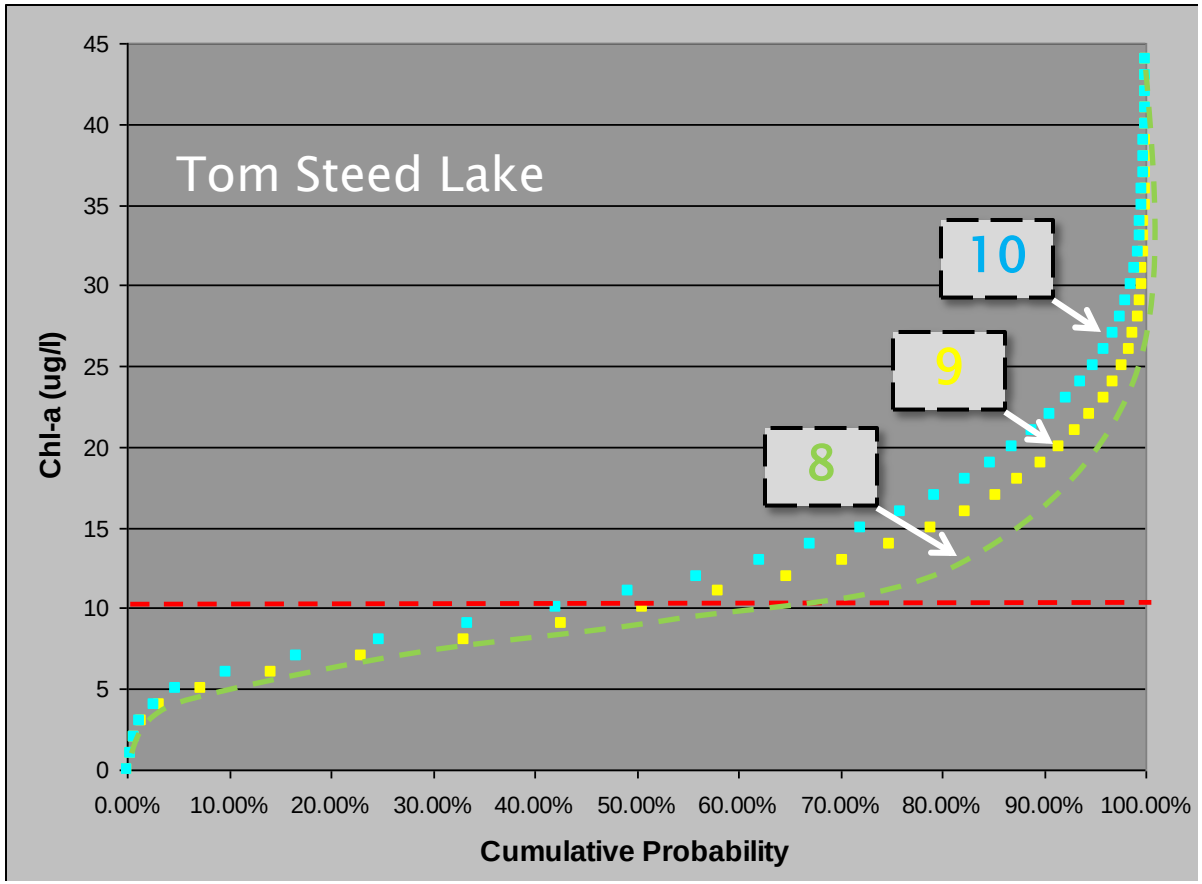
Cumulative probability :
57% for <10 µg/L and 75% if we target 9 µg/L

Margin of Safety

1. Explicit: lower target Chl-*a* level in the lake by a percentage (MOS) until achieving a certain target probability level (> 50%)

2. Implicit: reduction for both TP and TN

Explicit MOS



- **10 µg/L** (WQS)
  MOS: 0%
  Prob: 42%
- **9 µg/L**
  MOS: 10%
  Prob: 50%
- *8 µg/L*
  MOS: 20%
  Prob: 70%

Implicit MOS

Load Reduction Goals for Both Nutrients

	Rocky	Tom Steed
Maximum Allowable Load of TP (kg/year)	5,000	24,000
Maximum Allowable Load of TN (kg/year)	8,000	41,000
% Reduction	**87%**	**65%**

Anther MC Application

Probability to achieve Standard (%)	Nonpoint Sources Reduction (%)	Point Sources Reduction (%)
0	0	0
30	20	0
42	**65**	0
50	70	0
65	80	0
80	90	0
99	100	0

Preliminary TMDL

- What is the MOS?

Preliminary
Total Maximum Daily Loads

Waterbody Name	Nutrient	TMDL (kg/day)	WLA (kg/day)	LA (kg/day)	MOS (kg/day)
Rocky Lake	TP	12	0	12	Implicit
	TN	22	0	22	Implicit
Tom Steed Lake	TP	48	0	48	10%
	TN	98	0	98	10%

Translate annual loading rates to DAILY values:

$$MDL = LTA \times e^{z\sigma - 0.5\sigma^2}$$

Summary

Summary

- Model a larger watershed to include monitoring sites and multiple target lakes
- Non-mechanistic model for lakes with limited monitoring data
- Monte Carlo uncertainty analysis
- Explicit and implicit MOS

Questions?