Nutrient TMDLs for Reservoirs with Limited Data: Assessing Uncertainty Using Monte Carlo Simulation

Andrew Fang

OKLAHOMA DEPARTMENT OF ENVIRONMENTAL QUALITY

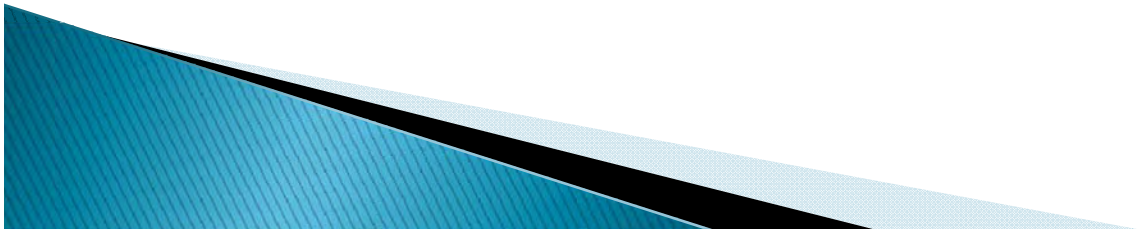
Jim Patek, Monica Suarez PARSONS

Nutrient TMDL Workshop, New Orleans, LA
February 15-17, 2011

Results are all preliminary and not to be quoted.

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



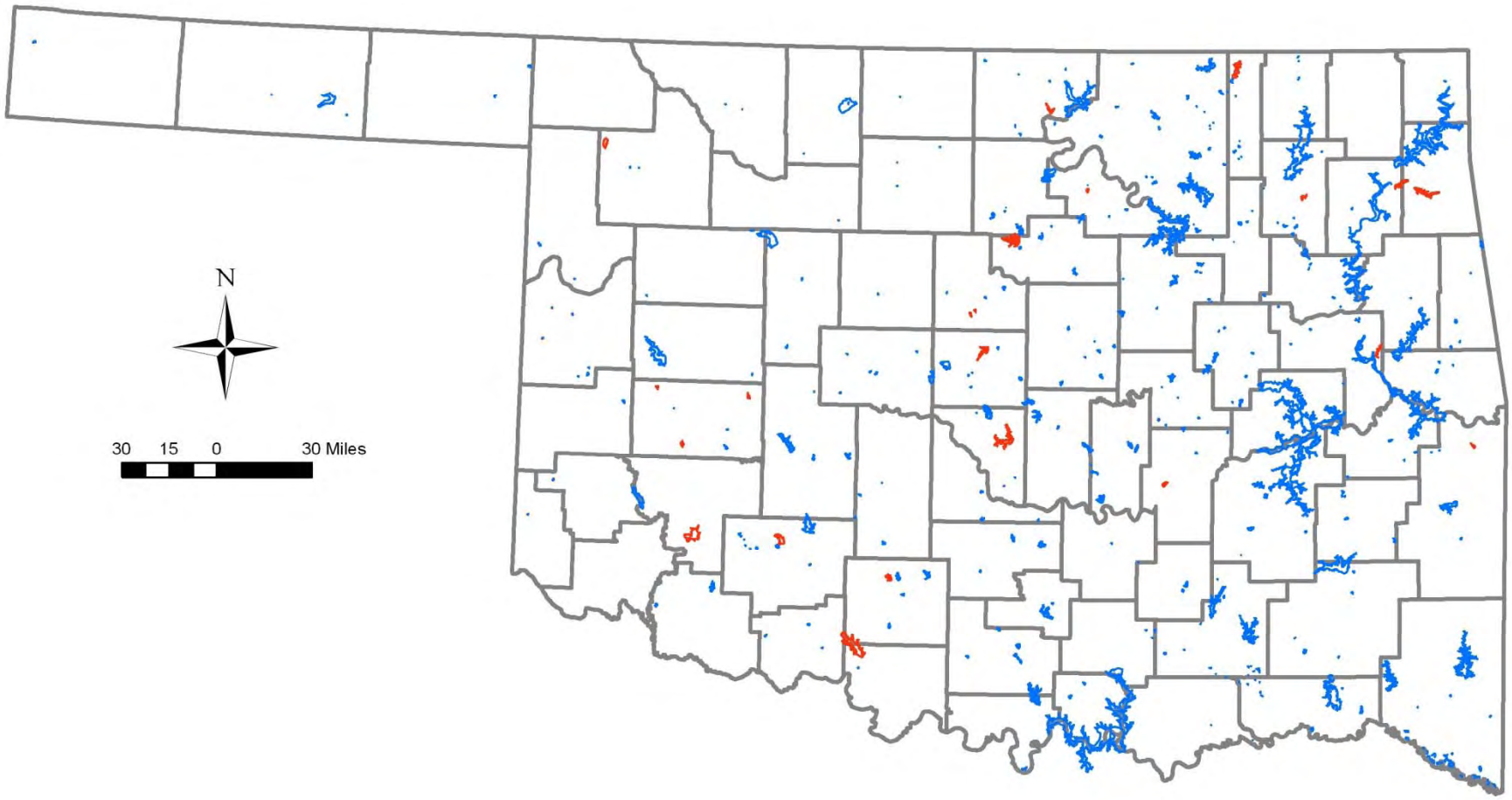
Project Background

- 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*

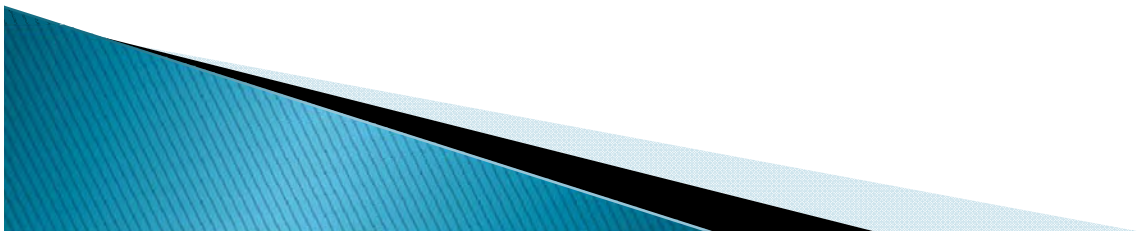
Chl-*a* Impaired SWS Lakes



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



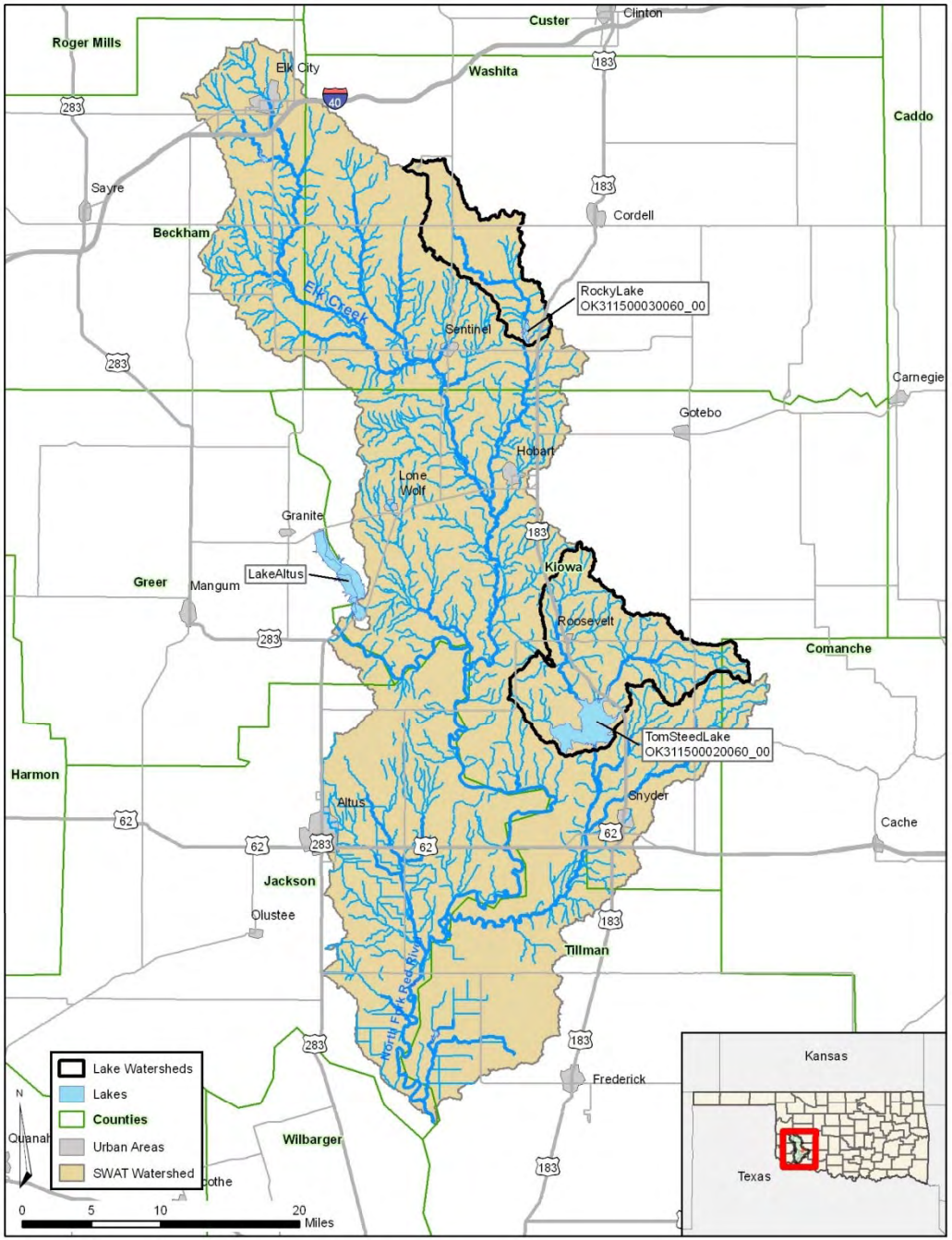
Model Selection

- 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

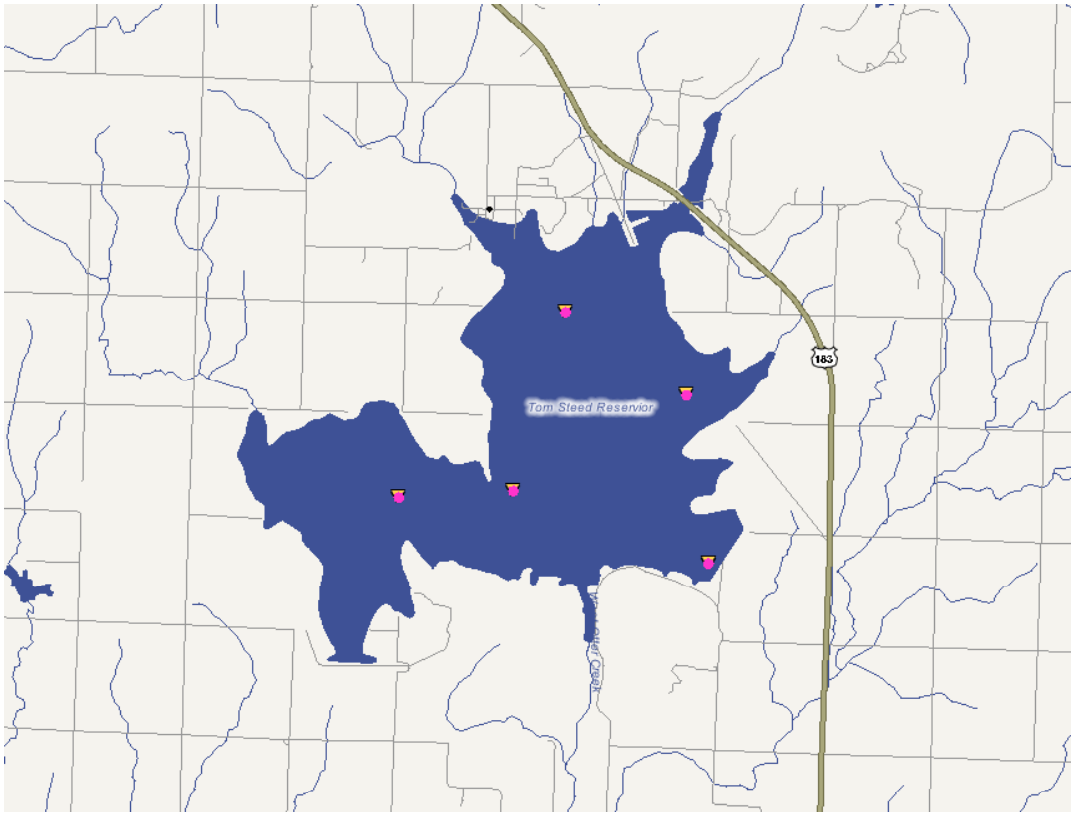
Project Lakes and Their Watersheds

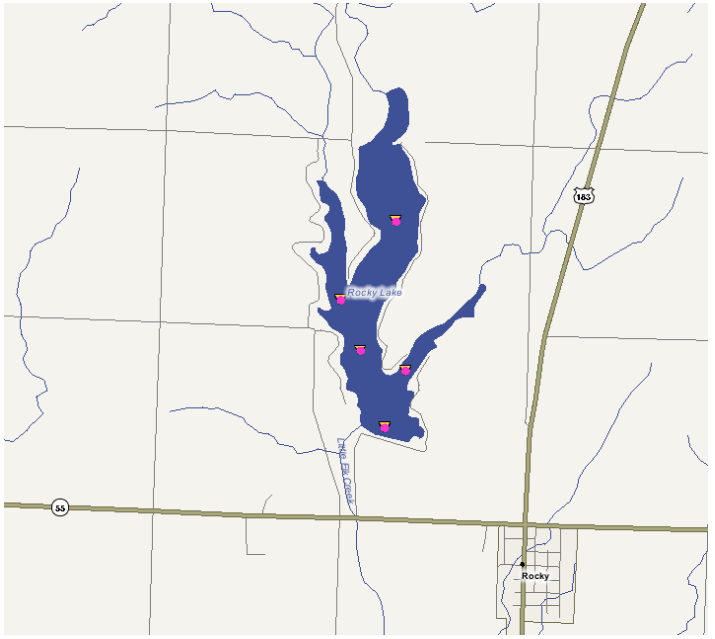
- North Fork of the Red

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

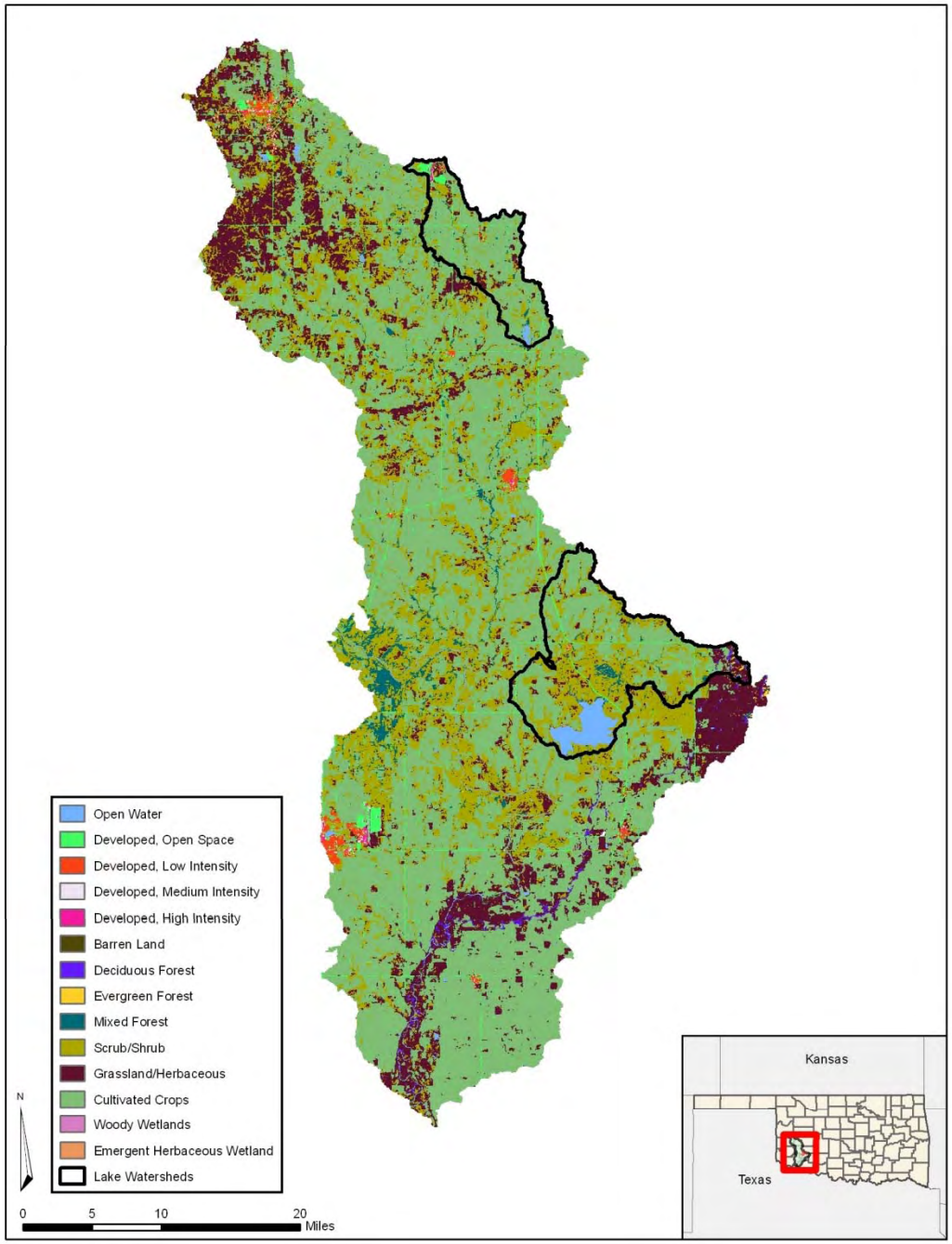


The Lakes





	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

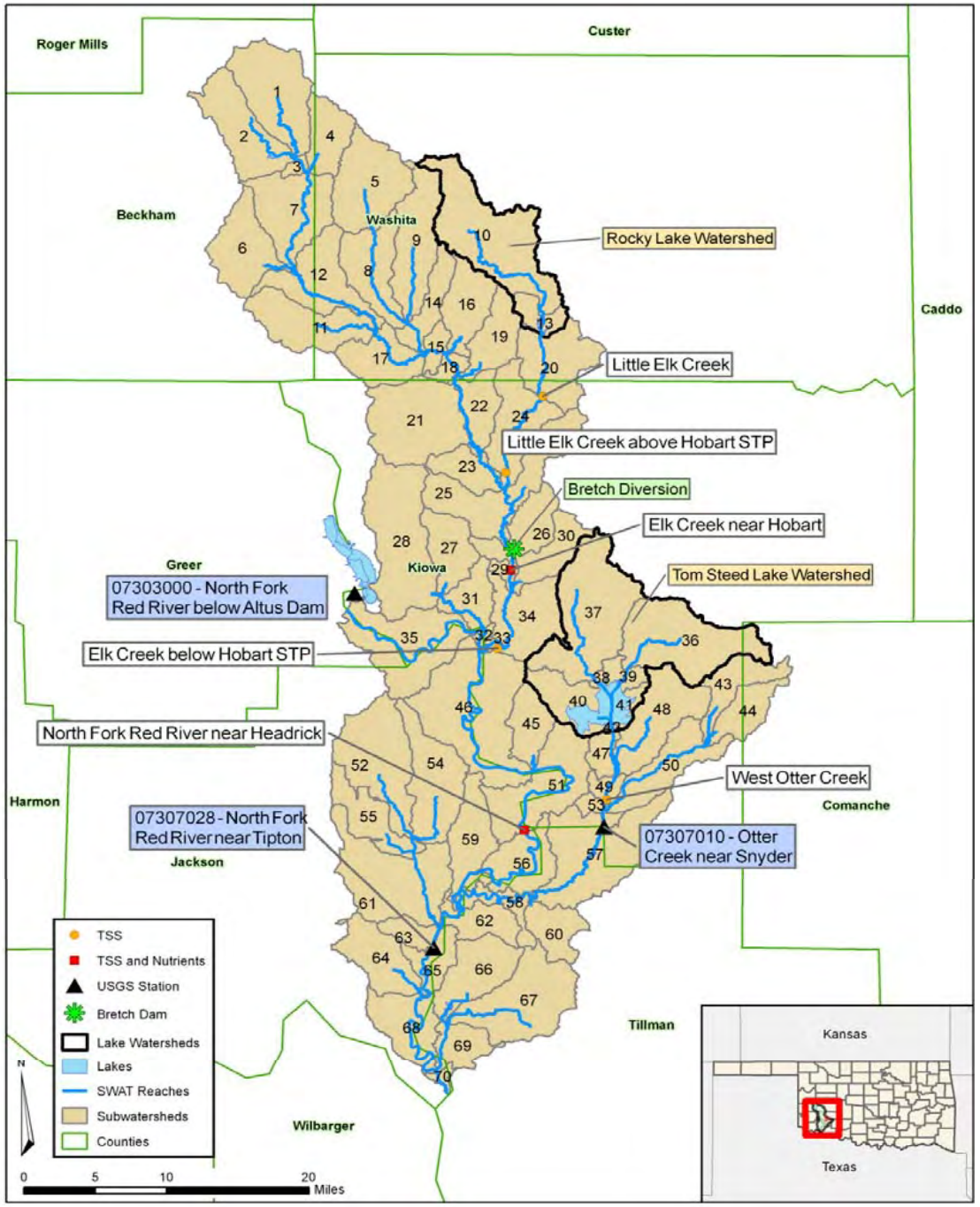
- No stream monitoring stations within either of the two lake watersheds
- Stations in the larger 8-digit HUC watershed: North Fork of the Red River
- A SWAT model was set up for the larger watershed

Watershed Monitoring

<u>2 USGS gage stations:</u>
1998/2000-2008

<u>6 TSS stations:</u>
18-22 samples in 2 years

<u>2 nutrients stations:</u>
38 samples in 4 years

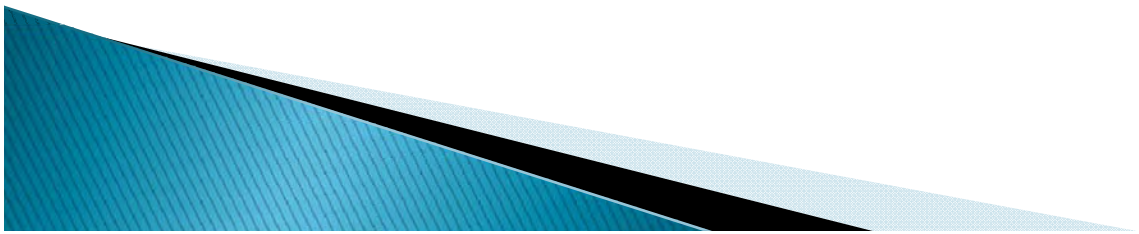


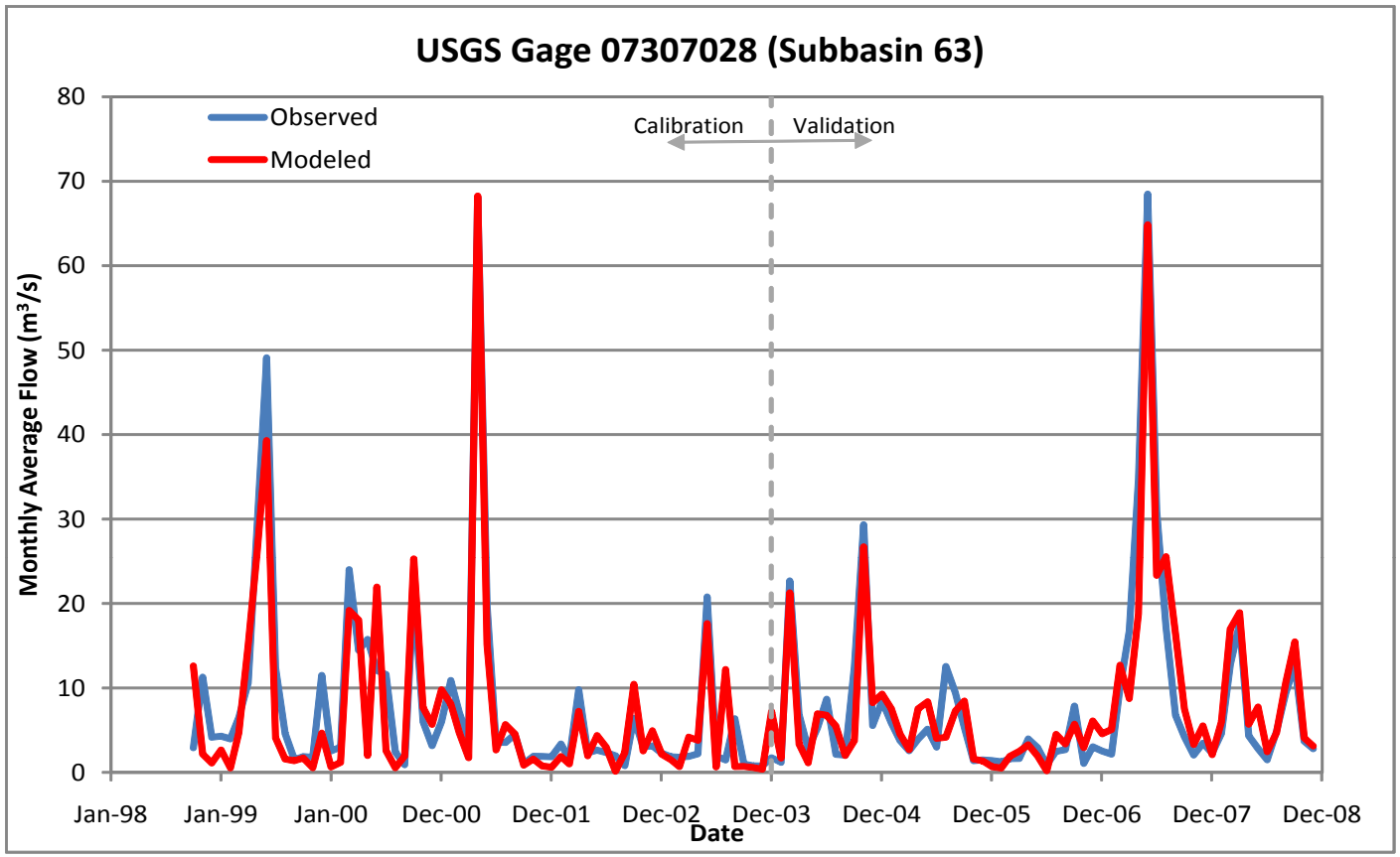
SWAT Model for the Watershed

- Flows and loadings

SWAT Model

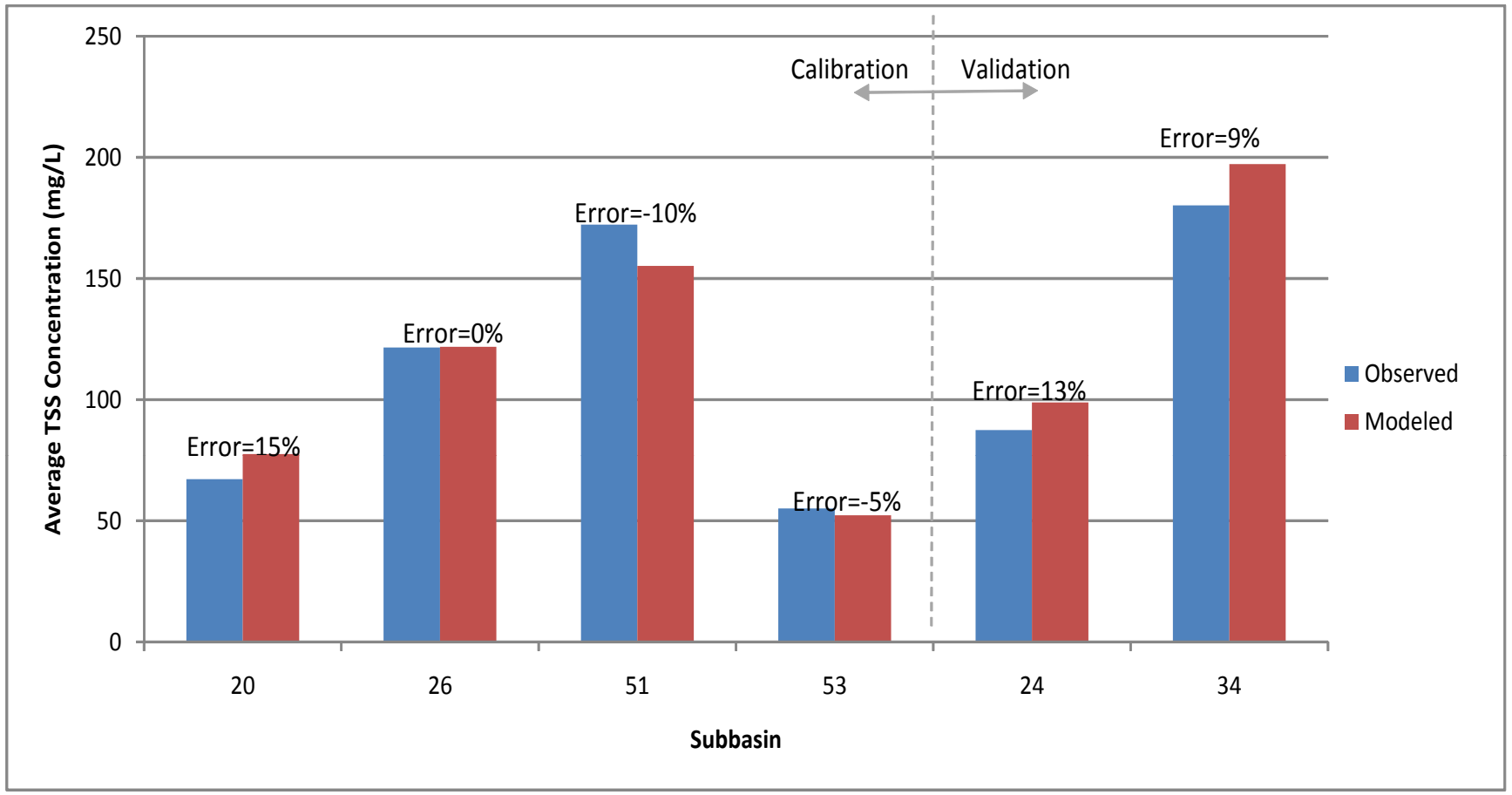
- 70 subwatersheds and 1,970 HRUs
- Local pasture, wheat, and cotton operations
- County level soil test P levels





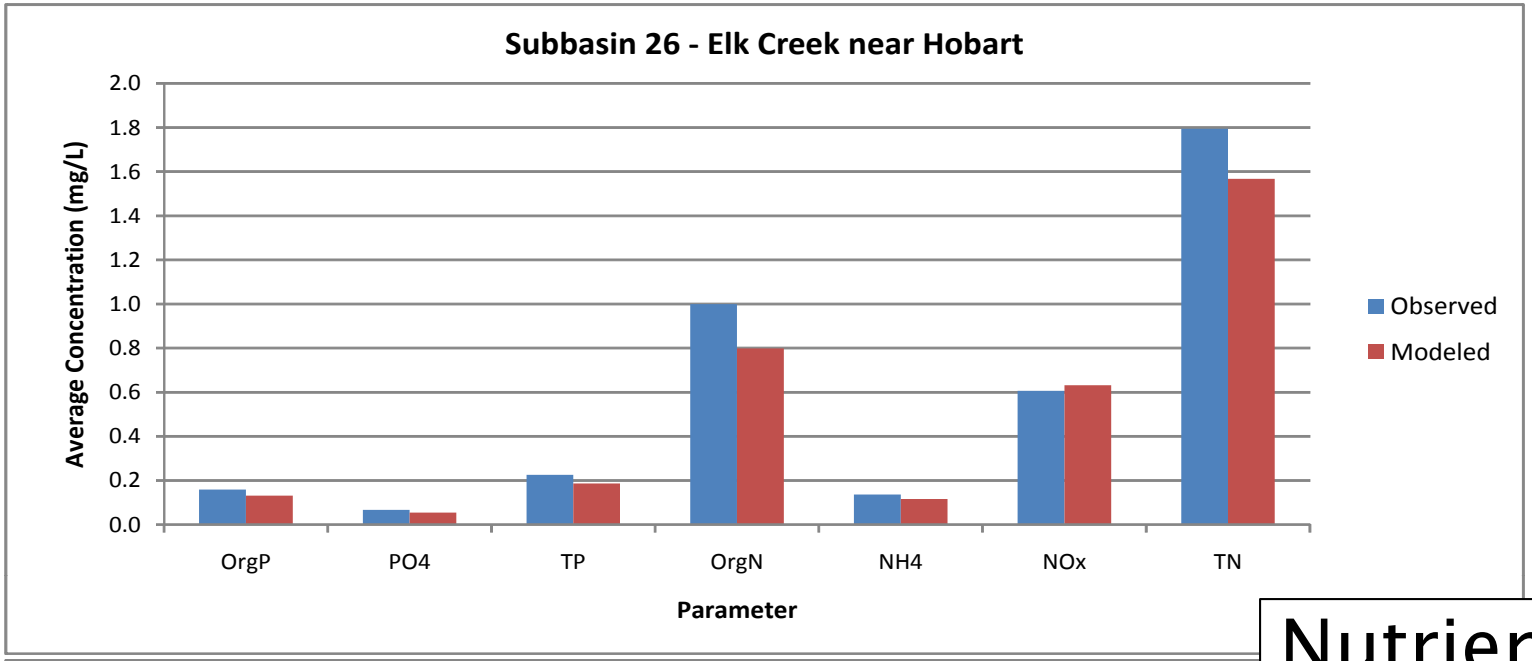
	Calibration	Validation
Model error (annual)	-12%	3%
r^2 (monthly)	0.86	0.87
NSE (monthly)	0.85	0.87

Results are all preliminary and not to be quoted.

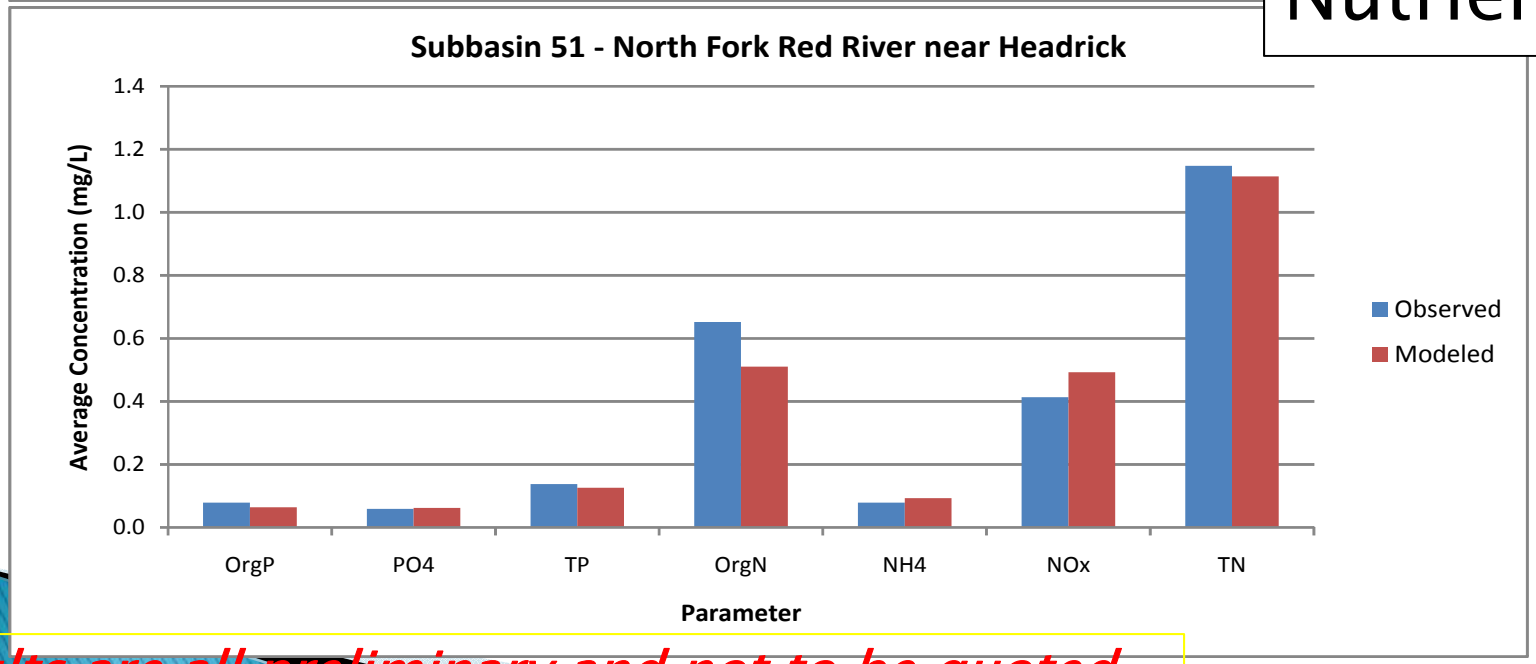


TSS average at the 6 monitoring stations

Results are all preliminary and not to be quoted.



Nutrients



Results are all preliminary and not to be quoted.

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

Results are all preliminary and not to be quoted.

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**

Results are all preliminary and not to be quoted.

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

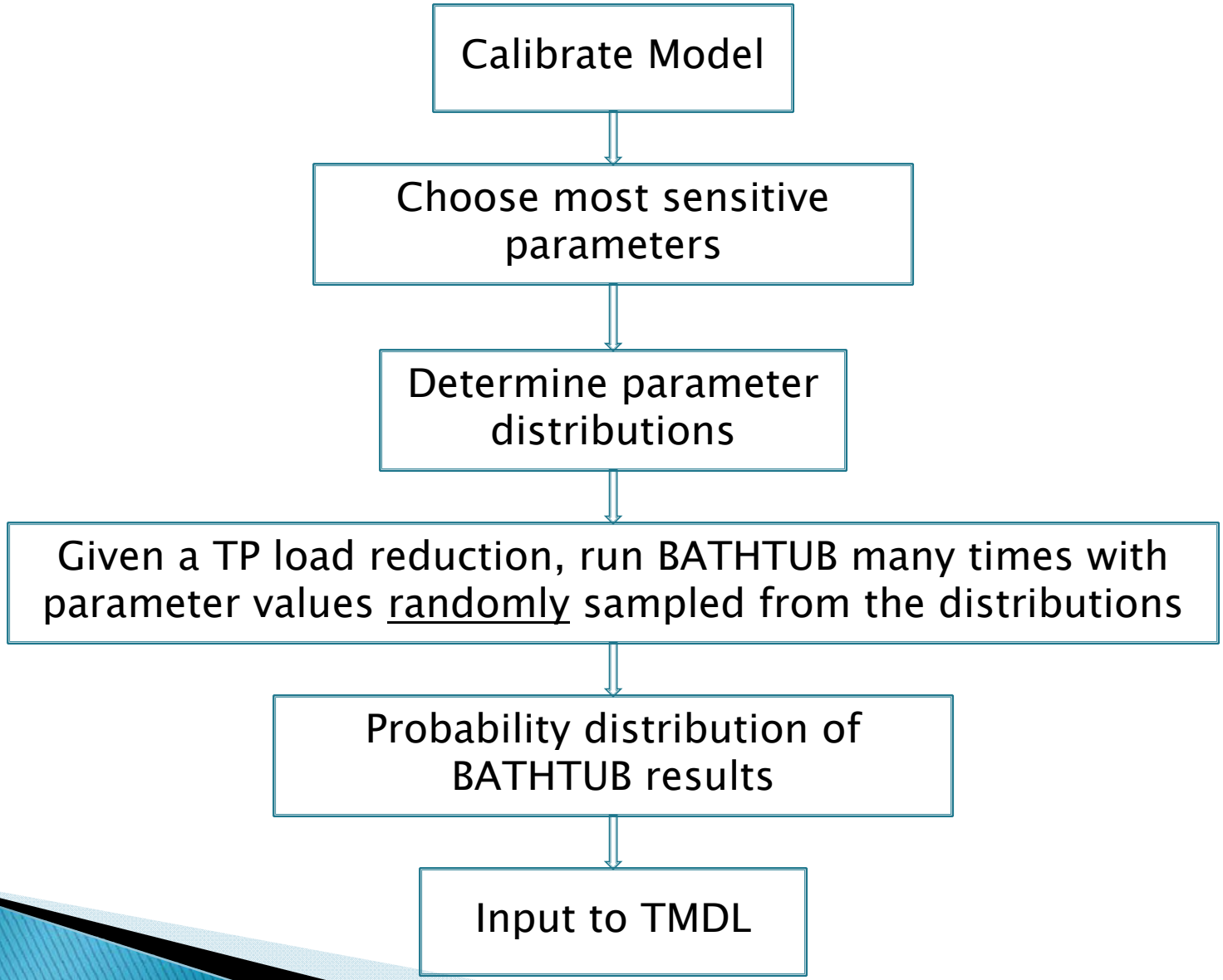
Results are all preliminary and not to be quoted.

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?)

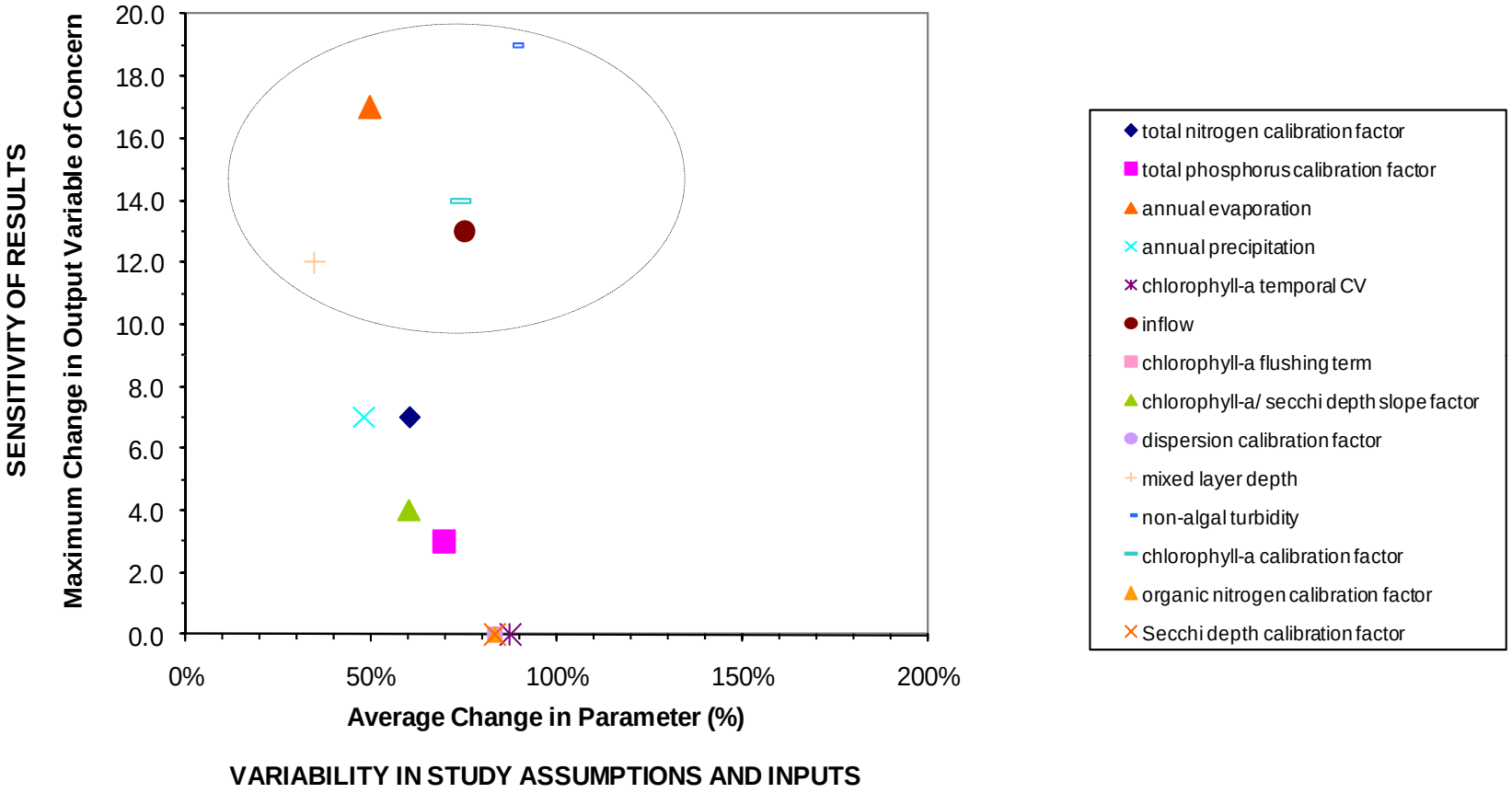
Monte Carlo Uncertainty Analysis for BATHTUB



Sensitivity Analysis

- Narrow down the parameters

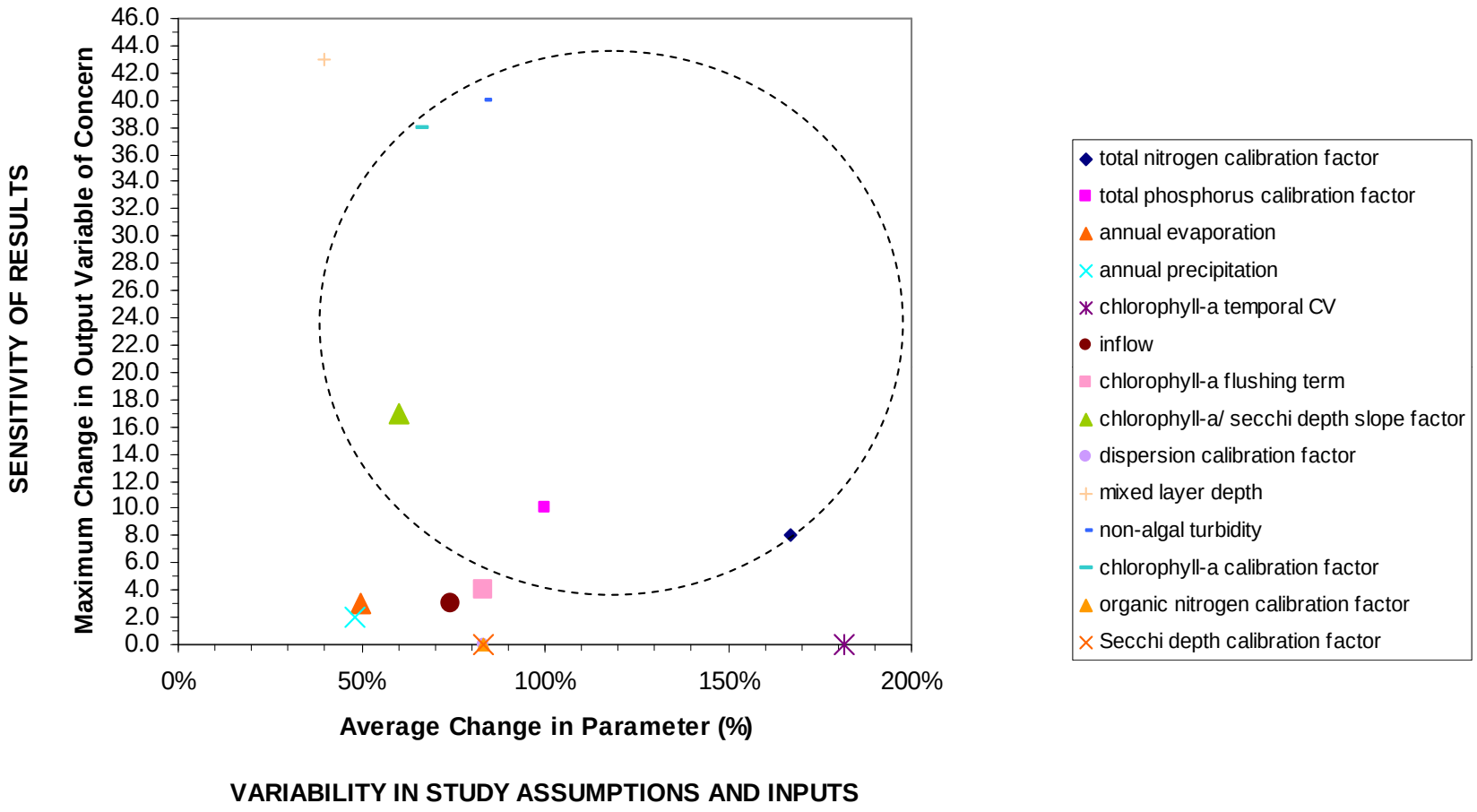
Sensitivity Matrix for BATHTUB Parameters for Tom Steed



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

Results are all preliminary and not to be quoted.

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

Results are all preliminary and not to be quoted.

Selected Distribution of Parameters for BATHTUB Uncertainty Analysis

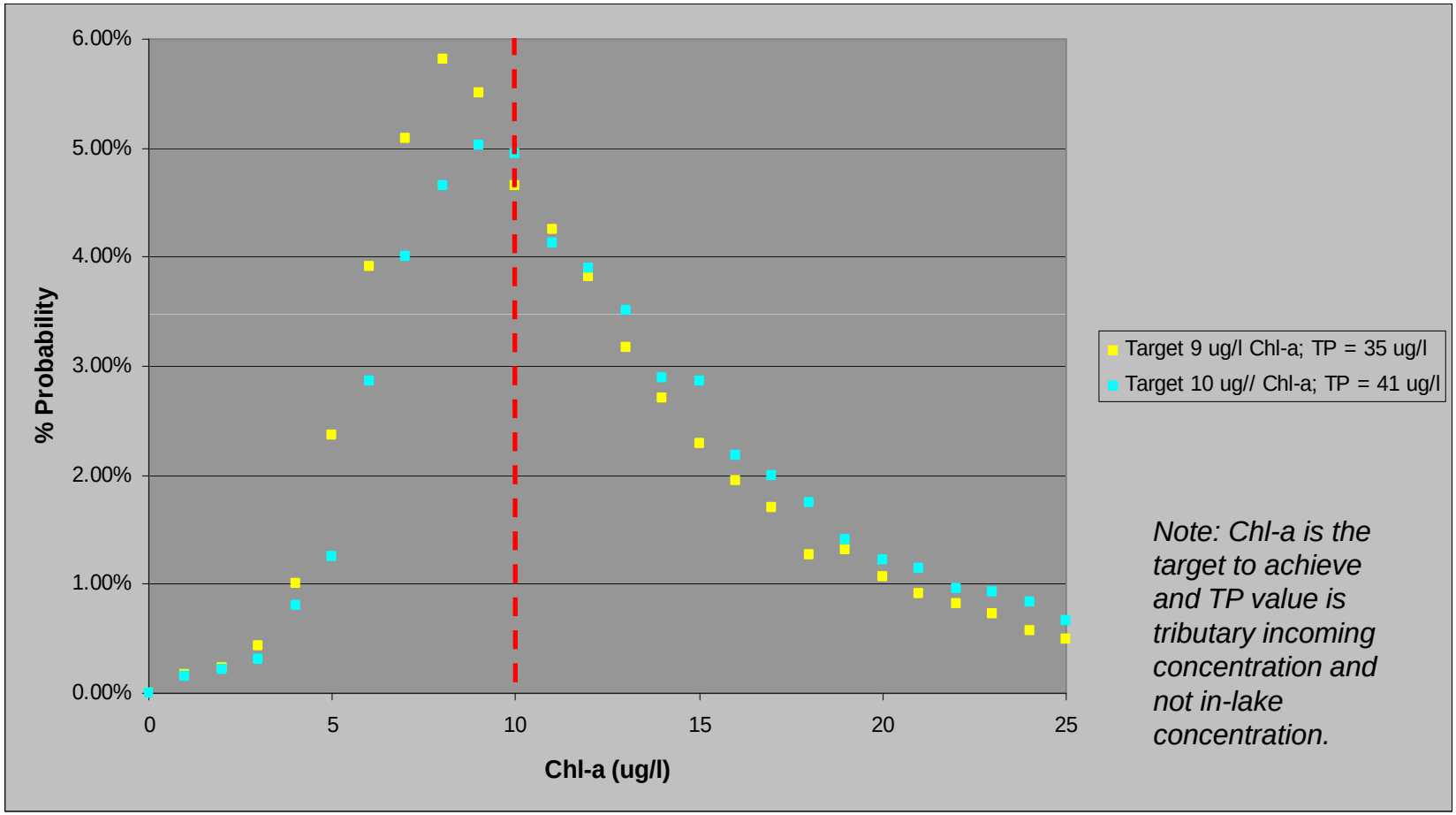
Parameter	Definition	Distribution
a	Non-algal turbidity (1/m)	Normal (Steed: mean = 2.21, std.dev. = 1.348; Rocky: mean = 2.33, std.dev. = 0.65)
CB	Calibration factor for chlorophyll-*a*	Normal (Steed: mean = 1.5, std.dev. = 0.25; Rocky: mean = 2.0, std.dev. = 0.25)
evp	Annual Evaporation (m/yr)	Normal (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)

Results are all preliminary and not to be quoted.

Uncertainty Analysis and Margin of Safety

- Monte Carlo Simulations

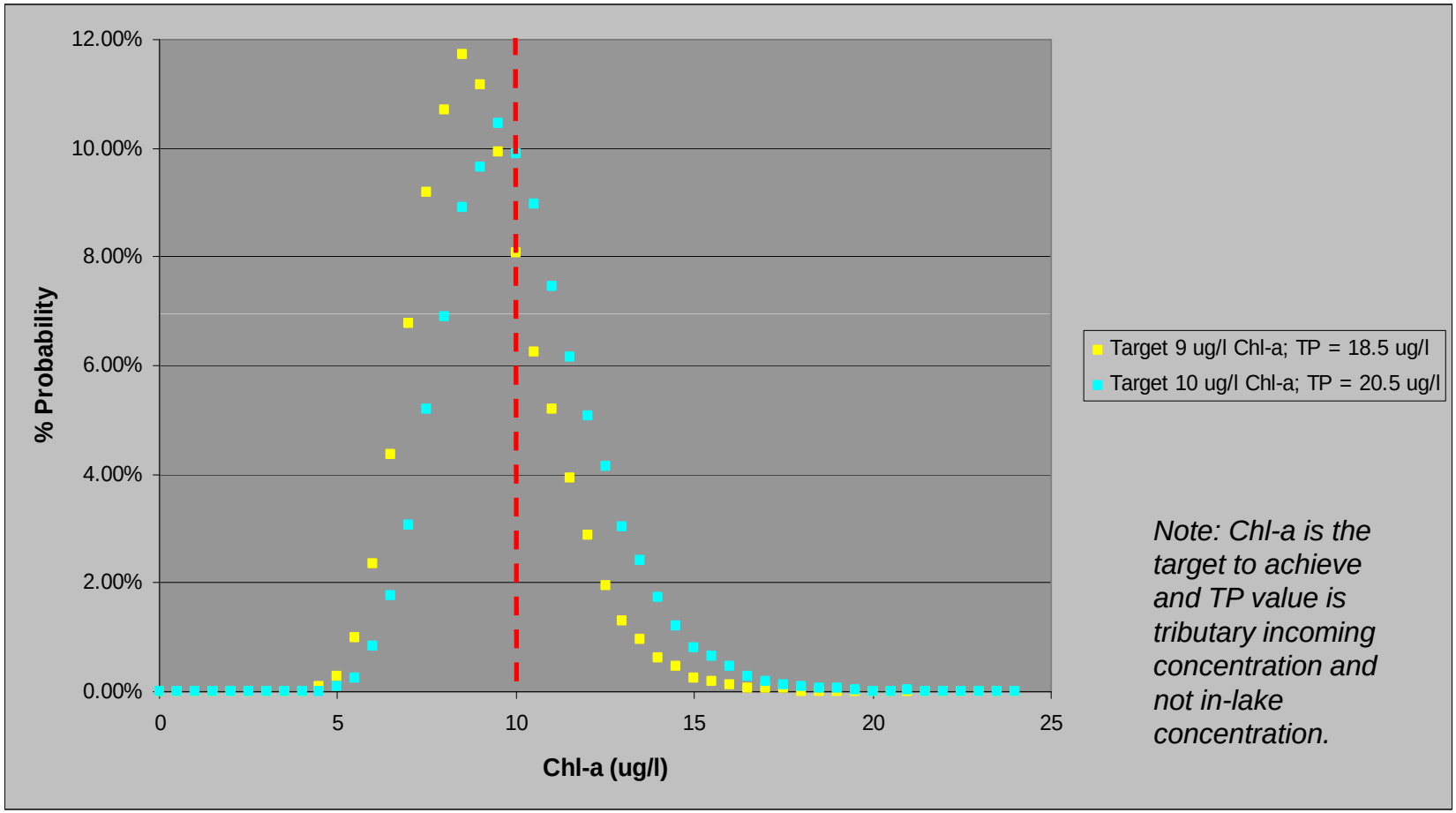
Lake Tom Steed Probability Plot of Chlorophyll-*a* Concentrations Obtained from 20,000 MC Samples



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

Results are all preliminary and not to be quoted.

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

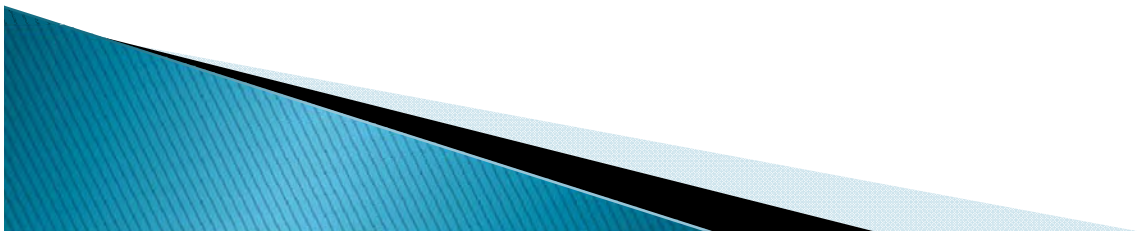
Results are all preliminary and not to be quoted.

Options for Margin of Safety

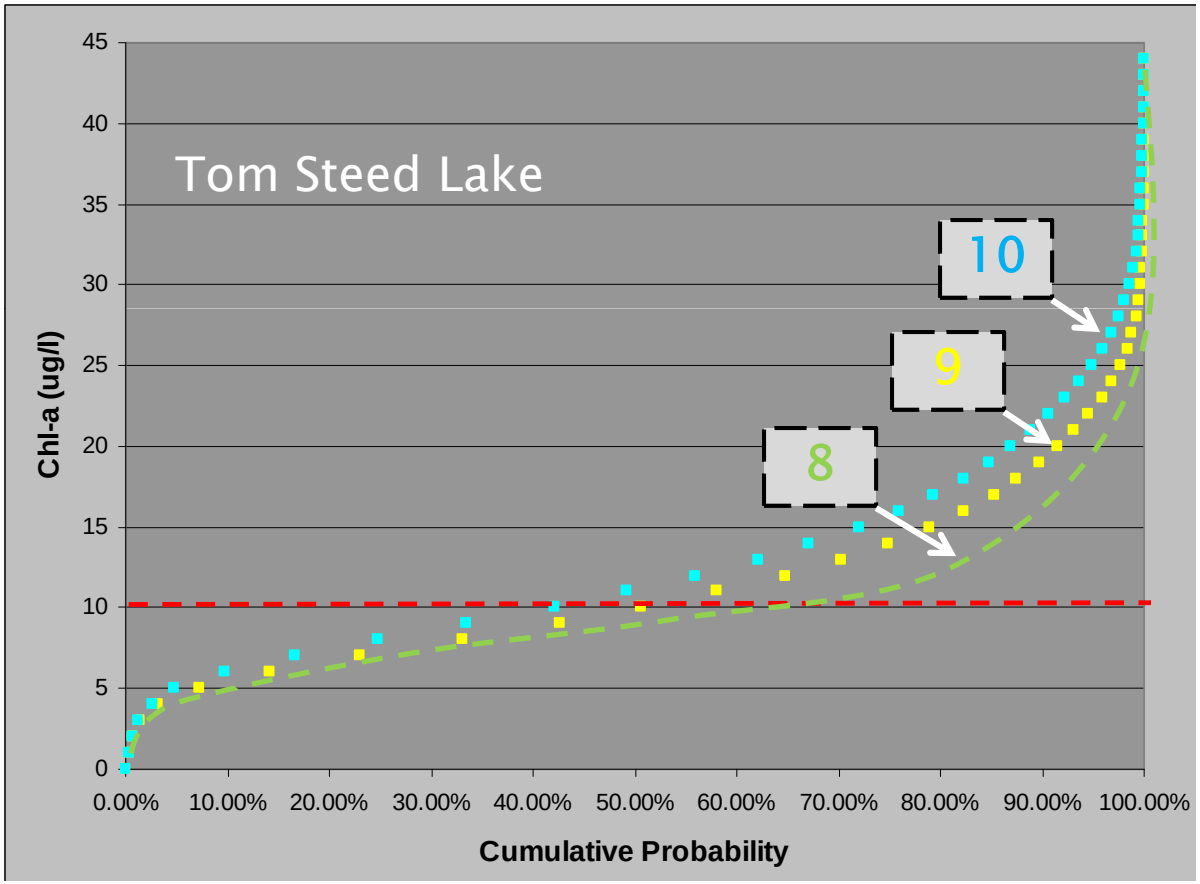
1. Explicit: lower target Chl-*a* level in the lake by a percentage (MOS) until achieving a certain target probability level (e.g., 51 or 67%)

2. Implicit (1): probability-reduction table

3. Implicit (2): 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%

Results are all preliminary and not to be quoted.

Implicit MOS (1)

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

Results are all preliminary and not to be quoted.

Implicit MOS (2)

Load Reduction Goals

	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%**

Results are all preliminary and not to be quoted.

Preliminary TMDL

- What is the MOS?

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	?
	TN	22	0	22	?
Tom Steed Lake	TP	48	0	48	?
	TN	98	0	98	?

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

Results are all preliminary and not to be quoted.

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
- Multiple options for MOS

Results are all preliminary and not to be quoted.

Questions?