Determining Phosphorus Load Reductions Needed to Reach Water-Quality Goals for Delavan Lake, Wisconsin

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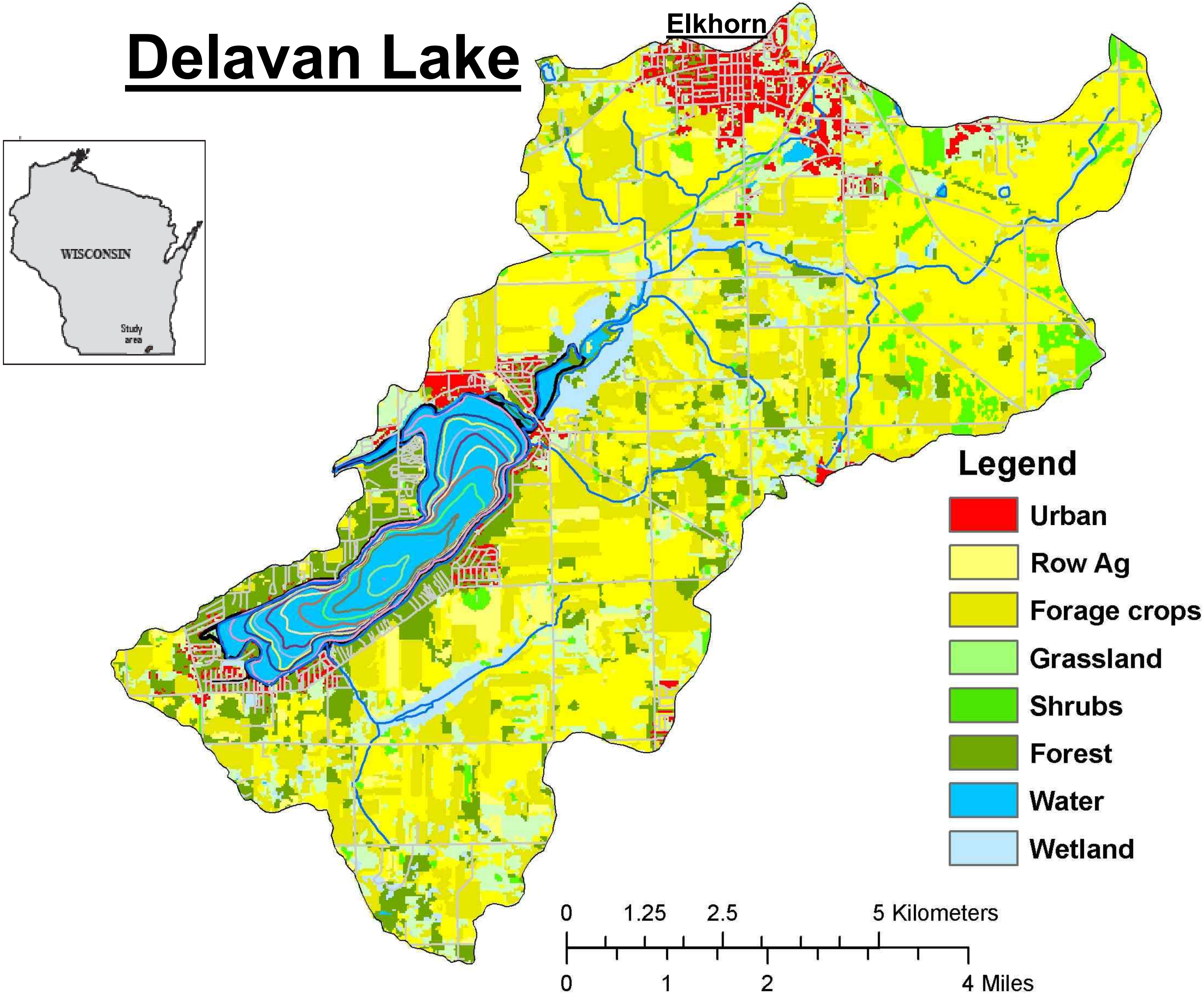
USGS

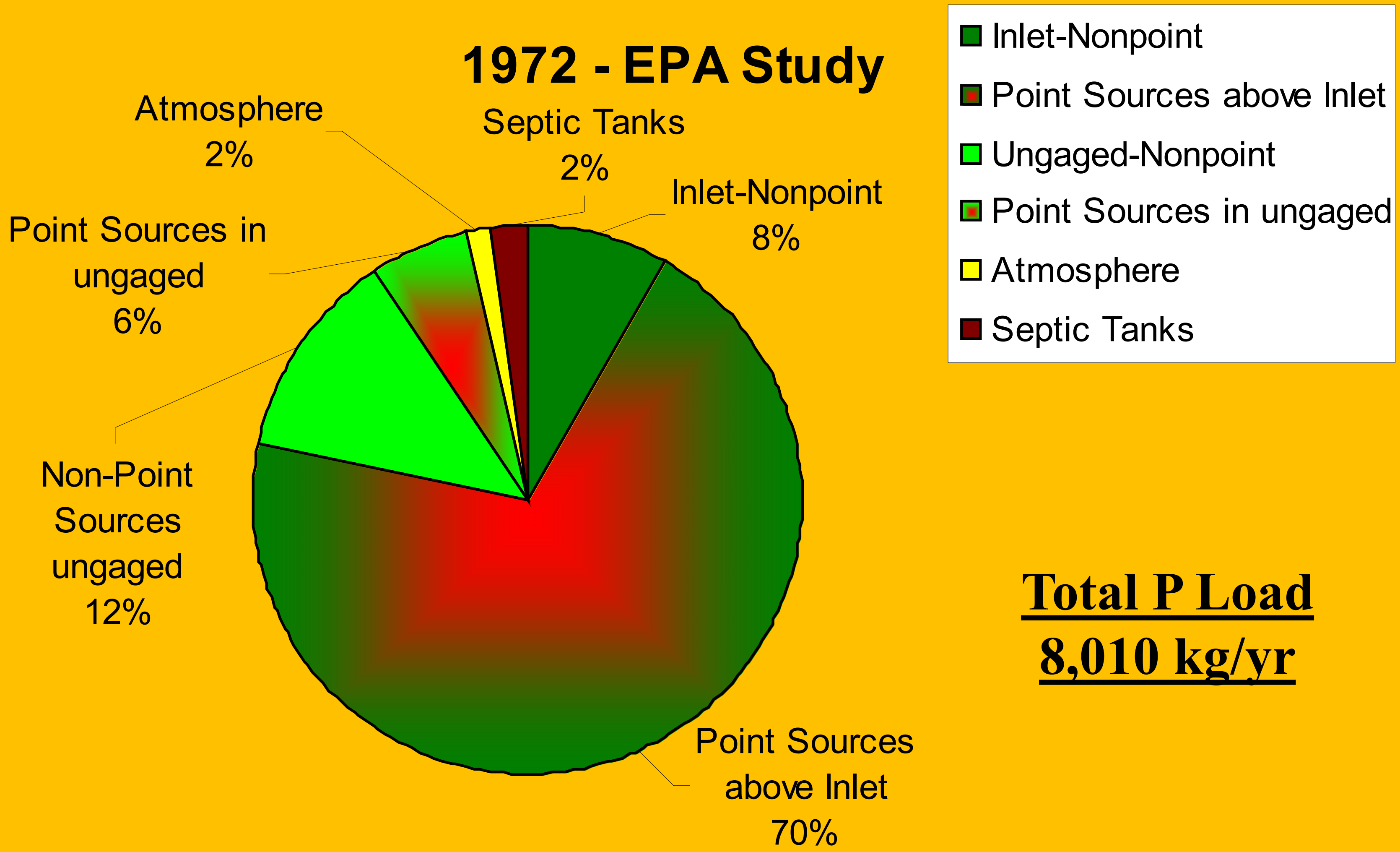
In Collaboration with:
Town of Delavan
Delavan Lake Sanitary District

Delavan Lake



Delavan Lake – ~1970s

Sources of External Phosphorus to Delavan Lake



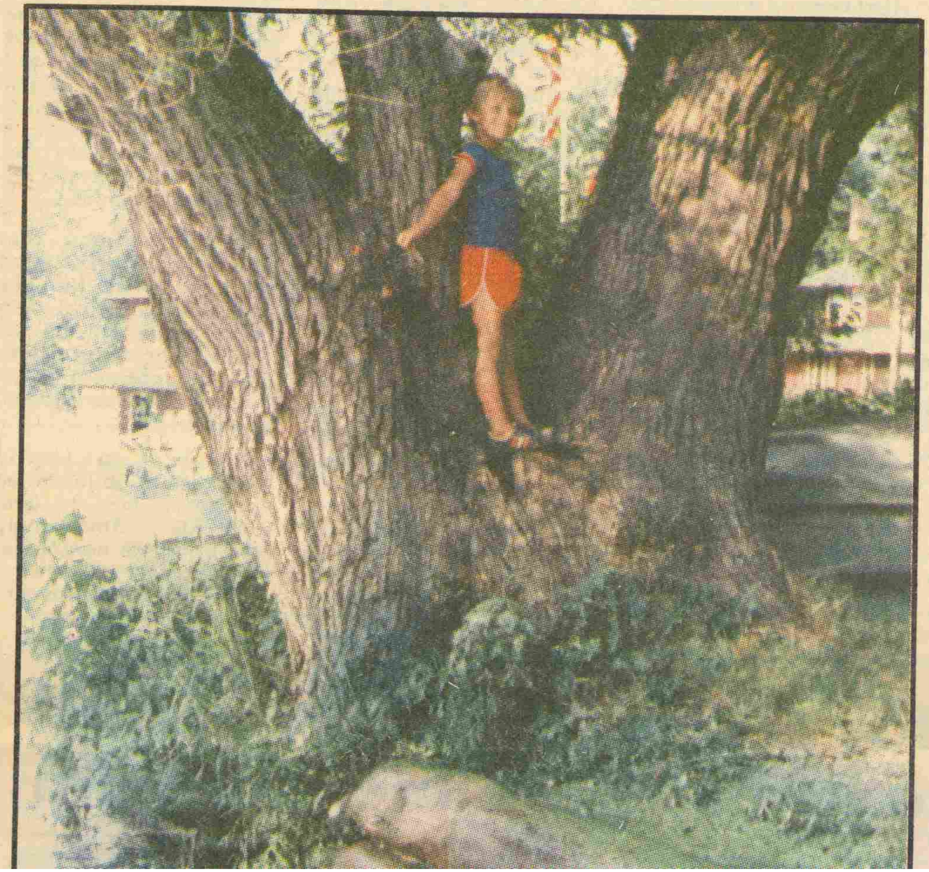
Total P Load 8,010 kg/yr

Point Sources Contribute ~76% of the Phosphorus Loading to the Lake

Wastewater Treatment Plant, WalCoMet, began treatment in 1981

WALWORTH COUNTY Week

Supplement to *The Janesville Gazette, published in Walworth County*—Tuesday, July 19, 1983



Algae in Delavan Lake triggers health worries, sends vacationers home

By Jon Henkes

DELAVAN LAKE— Year-round residents and vacationers at public and private beaches here have been warned that swimming in the lake may be hazardous to their health.

Concerned that decaying algae in the lake is emitting a toxic substance proven harmful to aquatic life, a state Department of Natural Resources official told lake residents last week to instruct their families and friends that swimming in Delavan Lake could produce gastrointestinal ailments such as nausea, vomiting and diarrhea.

That warning prompted the exodus of several vacationing families from the area, while prompting many others to drive to the city of Delavan's Mill Pond swimming area or to Geneva Lake to go swimming.

At the town of Delavan lakefront park, where major improvements have recently been made to attract summer vacationers, about 250 beachgoers drove away in disgust on the weekend of July 9-10.

That disaster occurred, however, three days before the DNR announcement about potential health problems.

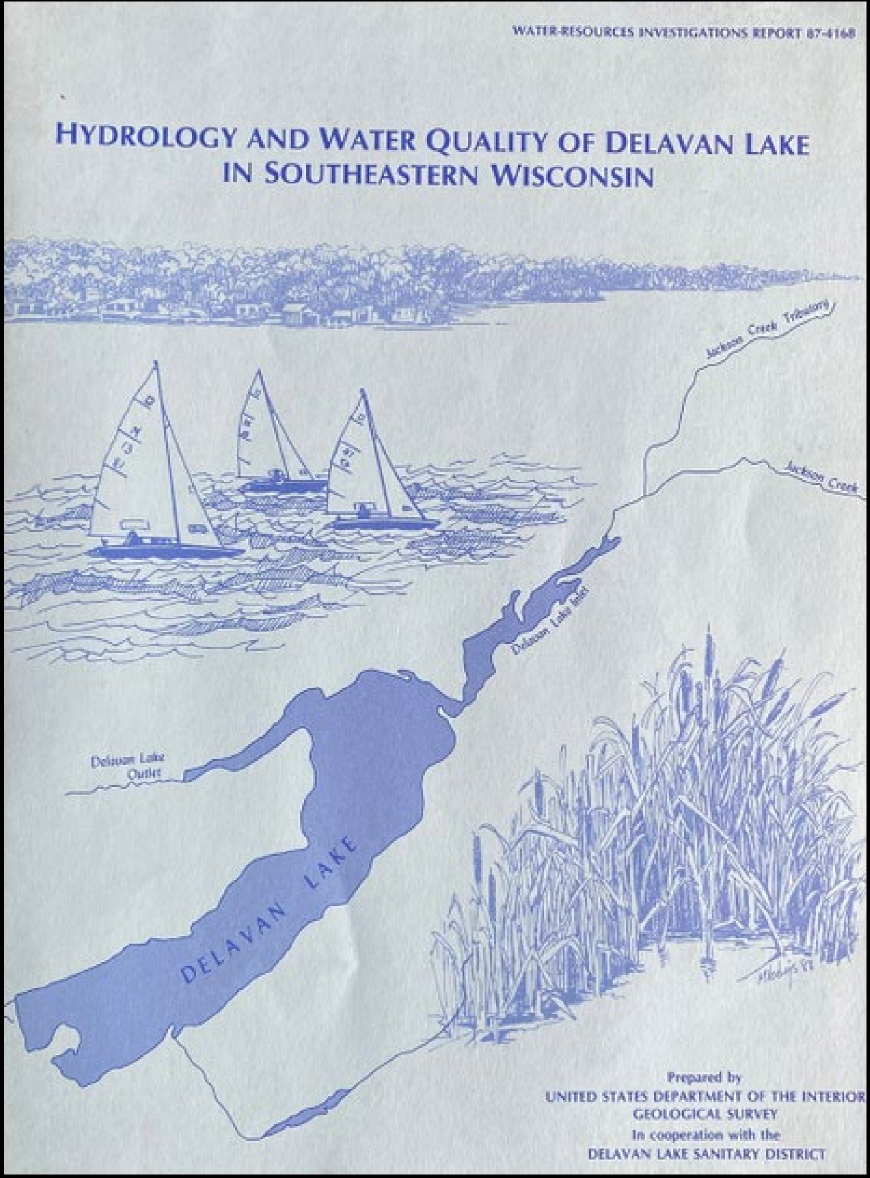
On July 9 and 10, a thick coating of dead algae permeated nearly the entire lake, the end result of the spraying of a chemical algaecide into the lake on June 30 and July 7.

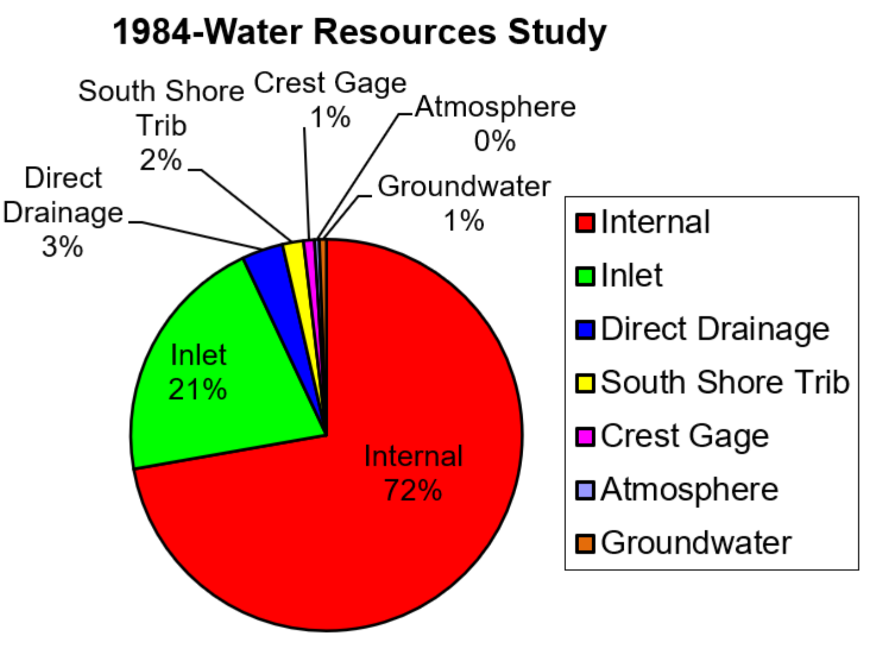
> *"Several families have requested refunds for their cottages and have packed their bags and left because of the algae. There were some children who became sick after swimming. The beach has been very quiet all week."*

Visually uninviting the lake was not known then to contain toxic dead algae. Year-round lake resident Bill Morelli said

Turn to page 10

U.S. Geological Survey Study to document the Water Quality of Delavan Lake and phosphorus input into the lake





Total – 15,400 kg/yr

Field and Duerk, 1988

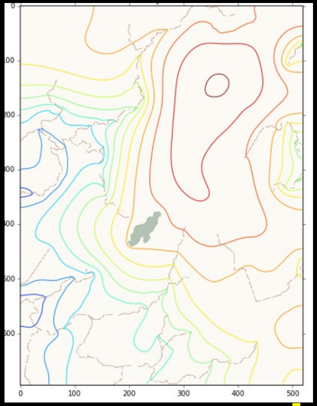
Where does all of the phosphorus being delivered to Delavan Lake come from and how much is there?

External Inputs

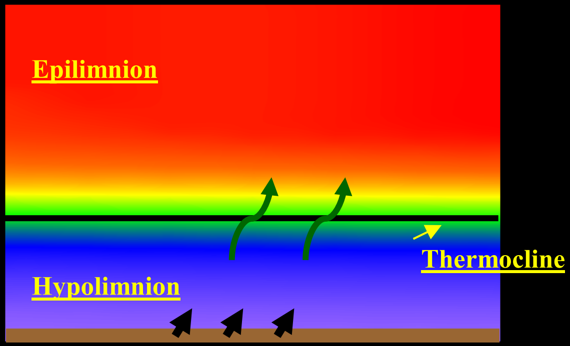
And What was Done to Reduce it

Tributary Inputs

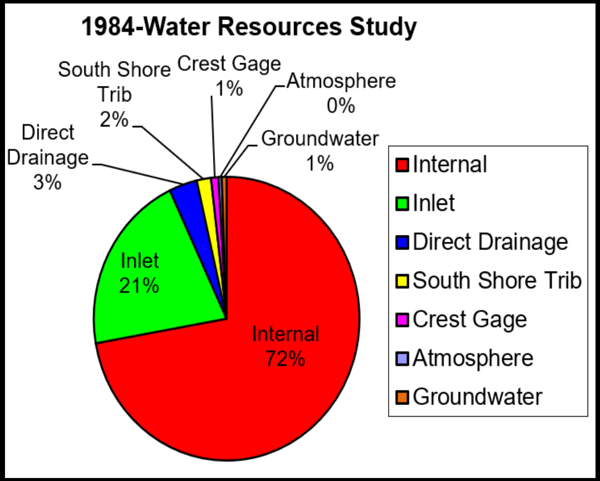
Groundwater



Sediment Input



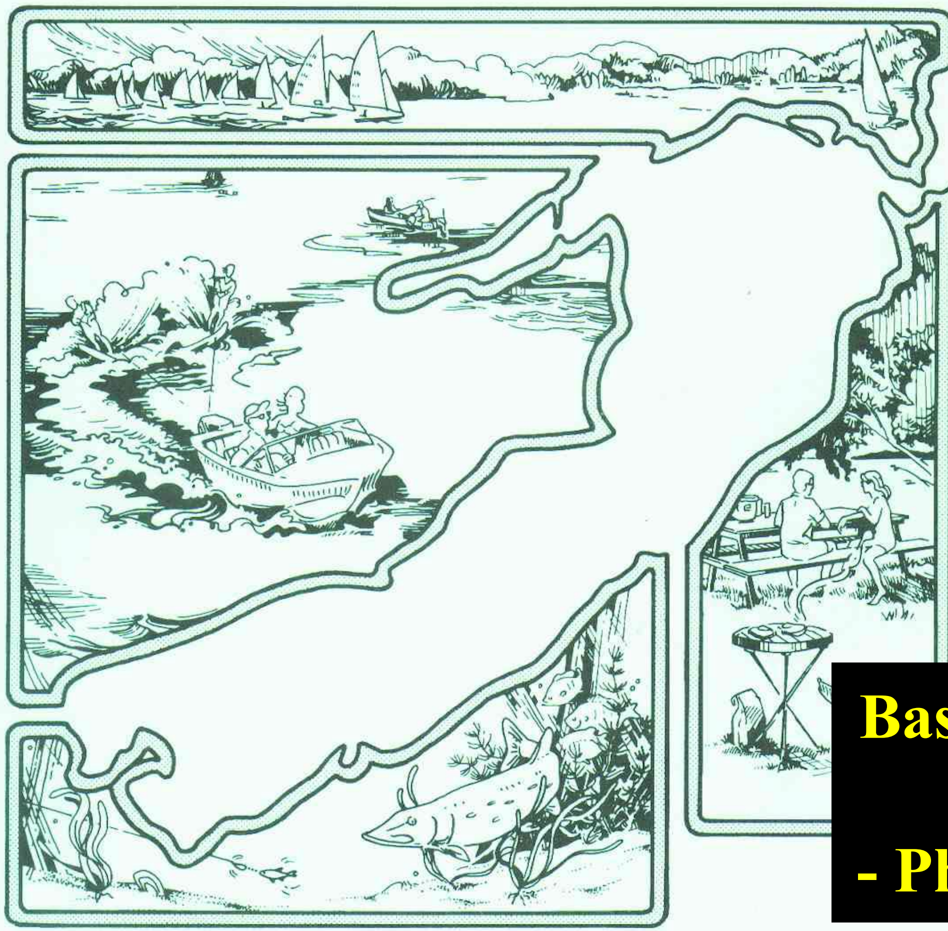
Septic Systems and Point Sources



Wastewater Treatment Plants

Delavan Lake: A Recovery and Management Study

Water Resources Management Workshop



Institute for Environmental Studies, University of Wisconsin—Madison
in cooperation with
Wisconsin Department of Natural Resources

September 1986

Based heavily on USGS studies

-Water quality

- Phosphorus budgets (sources)

Water Quality and Phosphorus Loading Goals for Delavan Lake Rehabilitation

Increase Water Clarity – Increase Average Summer Secchi Depth from 3 ft (~0.9 m) to at least 5 ft (1.5 m)

↑ Water Quality Model (Secchi Response with Lathrop et al, 1981
$SD = 5.19 \times Chl^{-0.468}$)

Decrease Productivty - Average Summer Chlorophyll a concentration from ~30 – 50 ug/L to 14 ug/L

↑ Water Quality Model (Chl Response with Dillon & Rigler, 1974
$\mathrm{Log(Chl)} = 1.45 \times \mathrm{Log(TP)} - 1.14$)

Decrease in lake P concentration from ~150 ug/L to about 34 ug/L

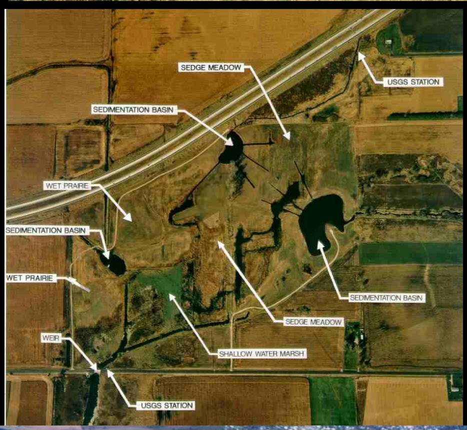
↑ Lake Loading Model (Phosphorus Response with Canfield &Bachmann, 1981
$TP = Z/(1.62\,(L/Z)^{0.458} + 1/\tau)$)

Decrease P Loading to the lake from about 15,400 kg/yr to ~2,300 kg/yr (~80%)

What was done to reduce the P loading to the lake?

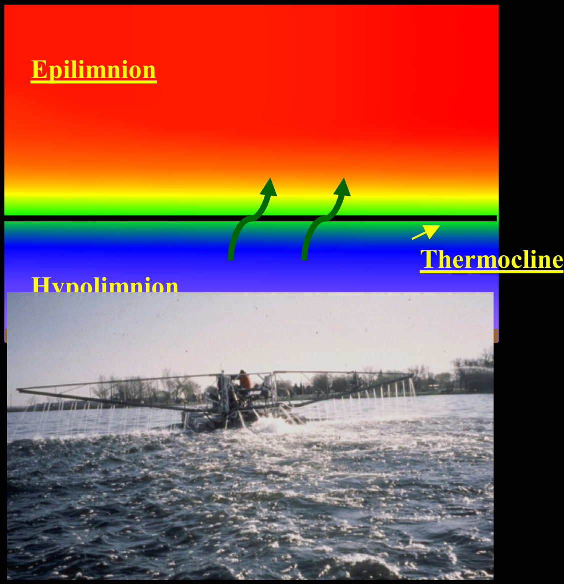
External Inputs

Tributary Inputs

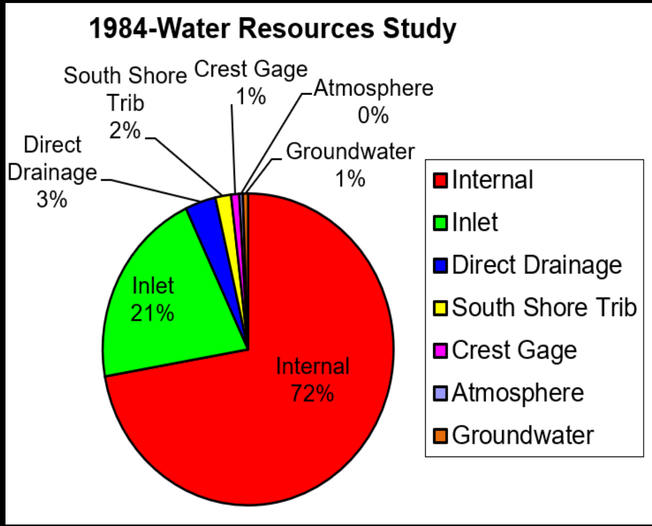


Groundwater

Sediment Input



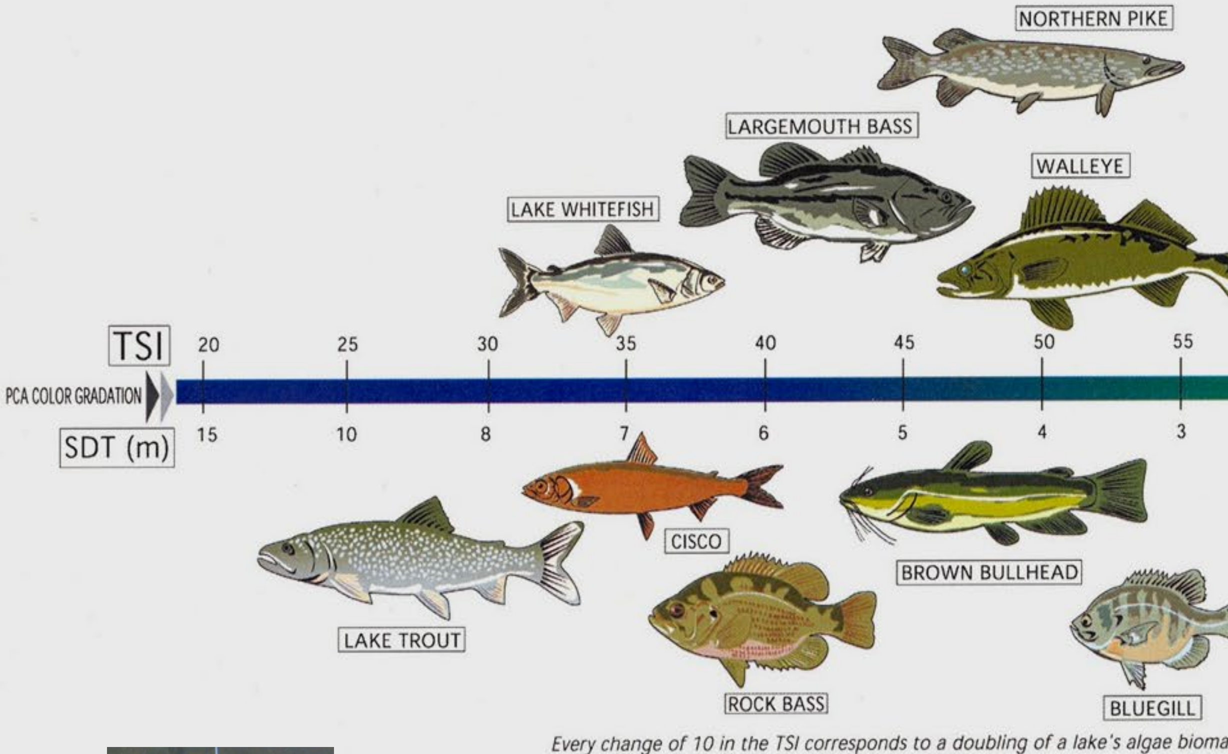
Septic Systems and Point Sources



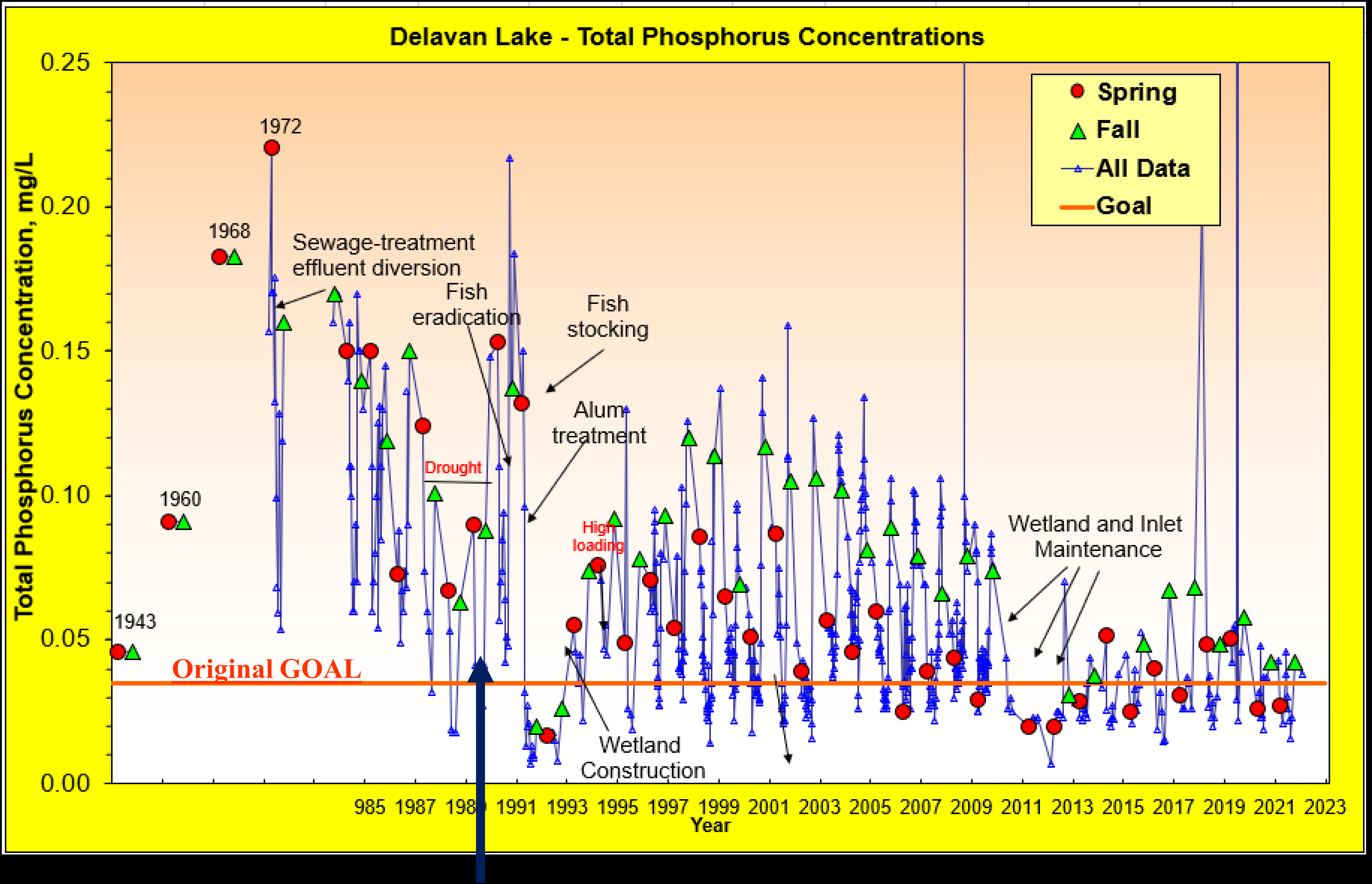
Wastewater Treatment Plants

Typical conditions associated with trophic status

Oligotrophic **Mesotrophic** **Eutrophic** **Hypereutrophic**



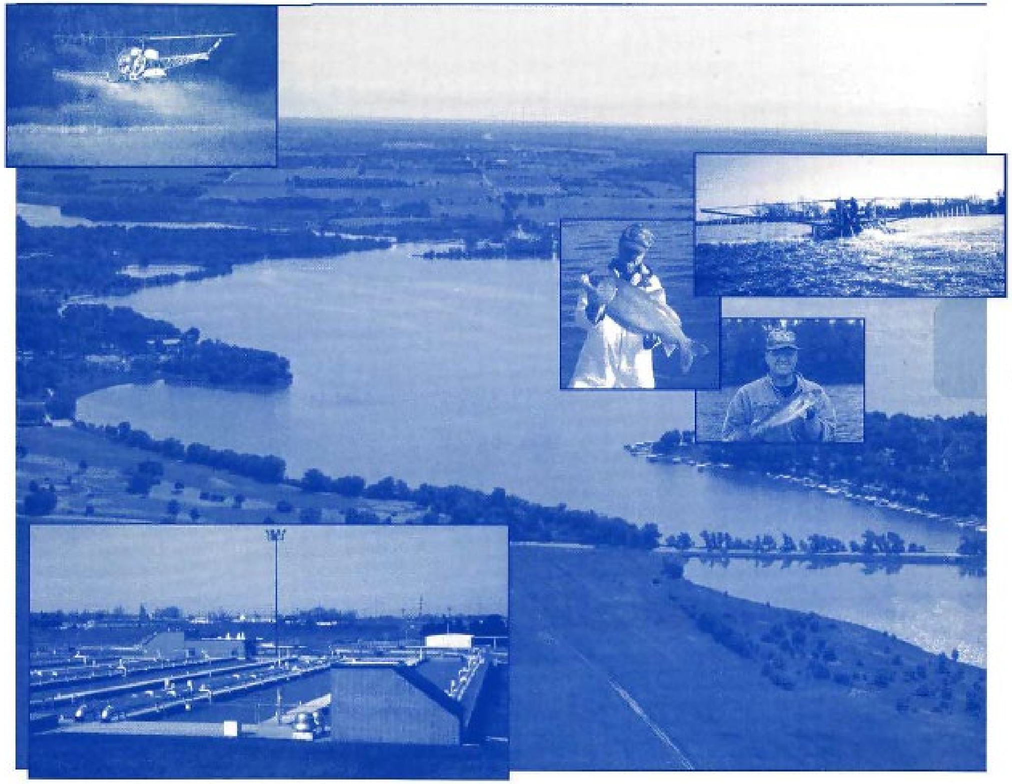
Based on work of De



Delavan Lake - Total Phosphorus Concentrations
Total Phosphorus Concentration, mg/L
0.25
0.20
0.15
0.10
0.05
0.00
1943
1960
1968
1972
Sewage-treatment effluent diversion
Fish eradication
Fish stocking
Alum treatment
Drought
High loading
Wetland Construction
Wetland and Inlet Maintenance
Original GOAL
Spring
Fall
All Data
Goal
985
1987
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Year

Lake and Reservoir Management

Volume 16, No. 3, September 2000



an international journal of the

North American Lake Management Society

Lake and Reservoir Management 16(3):155-176, 2000

Rehabilitation of Delavan Lake, Wisconsin

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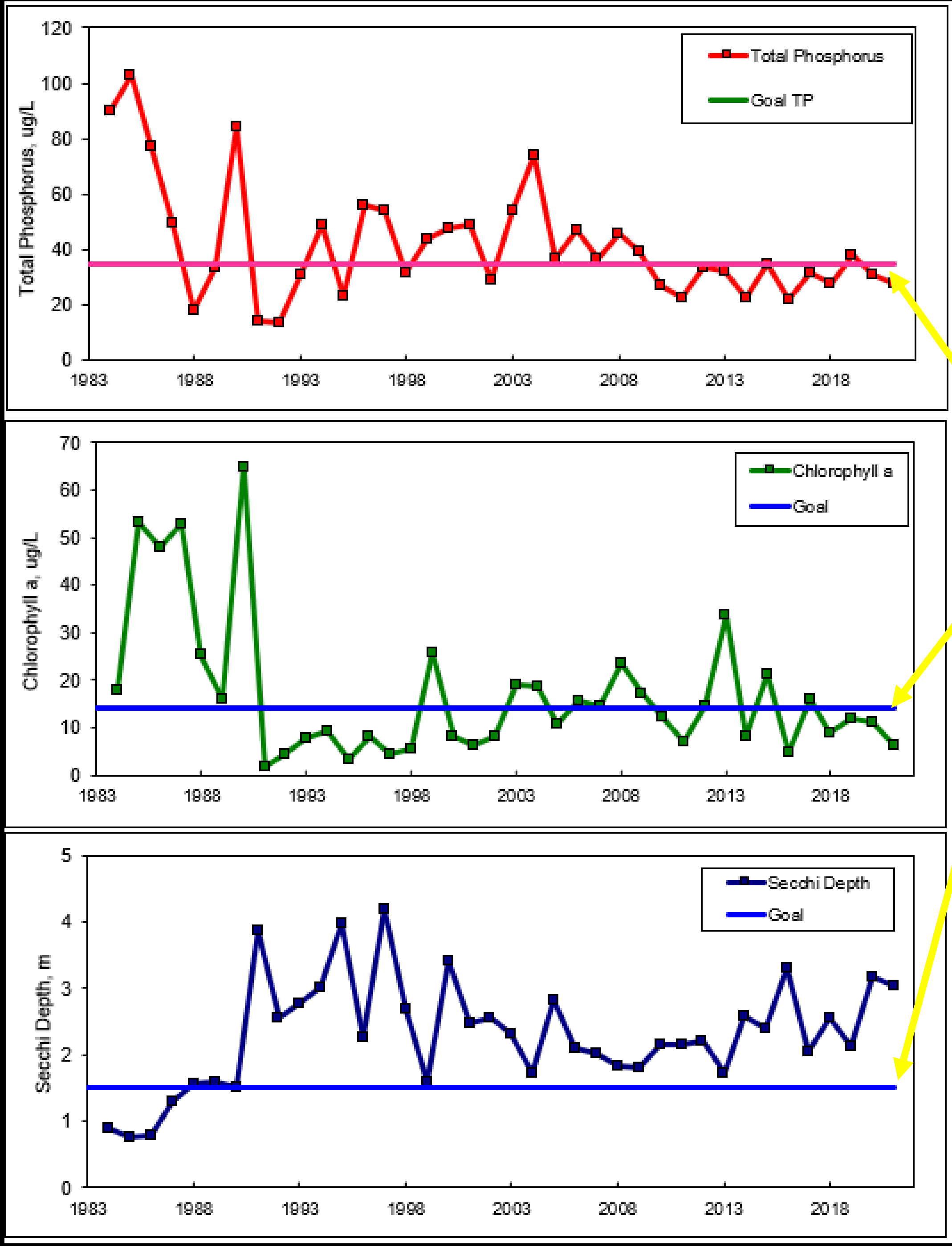
2021

Summer Average (June-Sept) Water Quality



(July-Sept)

(July-Sept)

Met all of the original Goals

How does the DNR view the recent water quality of Delavan Lake? Impaired?

Table 30. Recreation impairment thresholds for lake and reservoir natural communities.

Indicators	Min. Data Requirement (see text for details)	Exceedance Frequency (see text for details)	Impairment Threshold – LAKES & RESERVOIRS – Recreation Use				
			Shallow		Deep (Stratified)		
			Drainage[(1)] Lake	Seepage Lake	Drainage[(1)] Lake	Seepage Lake	Two-story fishery lake
Conventional physical-chemical indicators							
Total phosphorus (TP)	3 monthly values from each of two years from the period June 1 – Sept. 15	Lower bound of 80% CI of the mean exceeds threshold	≥40 µg/L		≥30 µg/L	≥20 µg/L	≥15 µg/L
Biological indicators							
Chlorophyll-*a*	3 monthly values from each of two years[(2)] from the period July 15 –Sept. 15	Lower bound of 80% CI of the mean exceeds threshold	> 30% of days in sampling season have moderate algal levels (> 20 µg/L)		> 5% of days in sampling season have moderate algal levels (> 20 µg/L)		
Aquatic plant metrics	Baseline aquatic plant survey	*N/A (one survey)*	*(reserved until guidance available)*				
Pathogenic indicator							
E. coli							

(1) "Drair
(2) Whe

Note: Fo
period ar

Number of samples required to meet assessment requirements

- For TP, a minimum of 6 monthly means over at least two qualifying years are required.
- For chlorophyll-*a*, the minimum number of monthly means and years required depends on whether the assessment is being used as a 'biology only' (i.e., standalone) impairment listing for chlorophyll-*a*, or whether it is being used in conjunction with TP for an impairment listing.
  - For a listing based on biology only (chlorophyll-*a*) exceedances, a minimum of 6 monthly means over at least two qualifying years are required.
  - For listing based on chlorophyll-*a* and TP exceedances, a minimum of 3 chlorophyll-*a* monthly means from at least one qualifying year is required.
- If three monthly means during a year are not available, multiple years may be used to assemble the minimum number of data points.

Delavan Lake IS LISTED as impaired for Chlorophyll a

Data from Mid July to Mid September

5 Years Current Conditions	2017-2021 Last 5 years of data	GeoMean	8.9
Mean Chla	10.6	log10 Chla	0.95
SD log10 Chla	0.268	SD log10 Chla	0.268

Date Monthly value	Chla (ug/L)	Log10 Chla	Chla	Exceedance Frequency	Chla	Exceedance Frequency
7/18/2017	16.8	1.23				
8/9/2017	20.5	1.31	5	89%	5	82.7%
8/16/2017	25.3	1.40	10	54%	10	42.8%
9/21/2017	7.9	0.90	20	15%	20	9.6%
7/11/2018	6.2	0.80	30	5%	30	2.5%
7/23/2018	15.3	1.18	40	2%	40	0.8%
8/9/2018	7.5	0.88	50	1%	50	0.3%
8/13/2018	4.2	0.62				
7/9/2019	16.2	1.21				
8/6/2019	6.1	0.78				
8/7/2019	3.5	0.54				
9/19/2019	14.8	1.17				
7/21/2020	11.7	1.07				
7/22/2020	7.4	0.87				
8/11/2020	5.1	0.71				
8/12/2020	9.0	0.95				
9/16/2020	17.3	1.24				
7/13/2021	10.0	1.00				
7/14/2021	10.9	1.04				
8/16/2021	4.1	0.61				
8/26/2021	3.0	0.47				

Impaired for Chlorophyll a >20 ug/L 9.6% of the time

Delavan Lake could also be listed as impaired

Average (Geometric) Total Phosphorus Concentrations - Up to 2021

	Total Phosphorus (June-September)	Chlorophyll a July-September	Secchi July-Sept
Average over past 16 years			
Center	0.033	11.7	2.2
Average over the past 10 years			
Center	0.029	10.80	2.44
Average over the past 5 years			
Center	0.034	8.94	2.38

There was a need to set New Goals for Delavan Lake Water Quality

Because with the old goals,

The lake is classified by the WDNR as impaired.

Goals of Modeling Study:

Determine what phosphorus loading is needed to get Delavan Lake off the Wisconsin Impaired Waters list (chlorophyll and total phosphorus concentrations).

Why was Delavan Lake listed as Impaired?
Chlorophyll a concentrations > 20 ug/L between mid July and mid September occurred more than 5% of the time: currently ~10% of the time. What load reduction is needed to reduce chlorophyll conc.?

Total phosphorus concentrations > 30 ug/L. What load reduction is needed to reduce TP conc.?

Approach

1. What is baseline? Quantify average water quality in lake and average P loading to lake for 2017-2021. Use most current 5 years of data (includes wide range in conditions).

----

2. Determine goals:
   a. Total phosphorus (WDNR criterion):
      Geometric Summer mean < 30 ug/L
   b. Chlorophyll a (Chl a) concentration (WDNR criterion):
      Chl a concentration so that it is > 20% ug/L less than 5% of the time?

Approach - continued

3. Develop Response Curves: Determine how Chl a and TP concentration respond to changes in P loading
4. Determine TP loading to get summer average TP concentration > 30 ug/L response curve (Canfield Bachmann relation).
5. Determine TP loading to get summer average Chl a to a specified concentration
   a. Use relation between Carlson TSI's for TP and Chl a to get response curve - A
   b. Use Jones-Bachmann model from TP to Chl a to get response curve - B
   c. Use Chl a response curves A&B to determine P loading to get desired concentration.

Determine Chlorophyll a Goal

Current frequency of Chl > 20 ug/L

Determine mean Chl a concentration needed to have Chl a > 20 ug/L less than 5%

5 Years Current Conditions — 2017-2021 Last 5 years of data — GeoMean 8.9

Mean Chla 10.6 — log10 Chla 0.95

SD log10 Chla 0.268 — SD log10 Chla 0.268

Date Monthly value	Chla (ug/L)	Log10 Chla	Chla	Exceedance Frequency	Chla	Exceedance Frequency
7/18/2017	16.8	1.23				
8/9/2017	20.5	1.31	5	89%	5	82.7%
8/16/2017	25.3	1.40	10	54%	10	42.8%
9/21/2017	7.9	0.90	20	15%	20	9.6%
7/11/2018	6.2	0.80	30	5%	30	2.5%
7/23/2018	15.3	1.18	40	2%	40	0.8%
8/9/2018	7.5	0.88	50	1%	50	0.3%
8/13/2018	4.2	0.62				
7/9/2019	16.2	1.21				
8/6/2019	6.1	0.78				
8/7/2019	3.5	0.54				
9/19/2019	14.8	1.17				
7/21/2020	11.7	1.07				
7/22/2020	7.4	0.87				
8/11/2020	5.1	0.71				
8/12/2020	9.0	0.95				
9/16/2020	17.3	1.24				
7/13/2021	10.0	1.00				
7/14/2021	10.9	1.04				
8/16/2021	4.1	0.61				
8/26/2021	3.0	0.47				

Future with specified percent reduction

5 years with percent reduction — GeoMean 7.2 — Fraction Remaining

Mean Chla 8.6 — Mean log10 Chla 0.9 — 0.81

SD log10 Chla 0.268 — SD log10 Chla 0.268 — CHANGE THIS

Date Monthly value	Chla (ug/L)	Log10 Chla	Chla	Exceedance Frequency	Chla	Exceedance Frequency	Reduction	0.81
7/18/2017	13.6	1.13						
8/9/2017	16.6	1.22	5	81.0%	5	72.6%	19.0%	
8/16/2017	20.5	1.31	10	40.3%	10	30.0%		
9/21/2017	6.4	0.81	20	8.5%	20	5.0%		
7/11/2018	5.1	0.70	30	2.1%	30	1.1%		
7/23/2018	12.4	1.09	40	0.6%	40	0.3%		
8/9/2018	6.1	0.78	50	0.2%	50	0.1%		
8/13/2018	3.4	0.53						
7/9/2019	13.1	1.12						
8/6/2019	4.9	0.69						
8/7/2019	2.8	0.45						
9/19/2019	12.0	1.08						
7/21/2020	9.5	0.98						
7/22/2020	6.0	0.78						
8/11/2020	4.1	0.62						
8/12/2020	7.3	0.86						
9/16/2020	14.0	1.15						
7/13/2021	8.1	0.91						
7/14/2021	8.8	0.95						
8/16/2021	3.3	0.52						
8/26/2021	2.4	0.38						

Assume the same variability in Chl Concentrations

New Goals >

Geomean summer (June-Sept) TP concentration < 30 ug/L
GeoMean Summer (July-Sept) Chl a concentration < 7.2 ug/L

To get these, we need to reduce P loading to the lake.

How much?

Approach to determine external P loading:
Determine Total Phosphorus concentrations needed and then translate Total Phosphorus concentrations to Chlorophyll a concentrations and Secchi Depths
(develop response curves between loading in water quality)

Canfield-Bachmann Model

$$\text{TP concentration} = \frac{L}{Z\left(1.62\,(L/Z)^{0.458} + 1/\tau\right)}$$

Where:

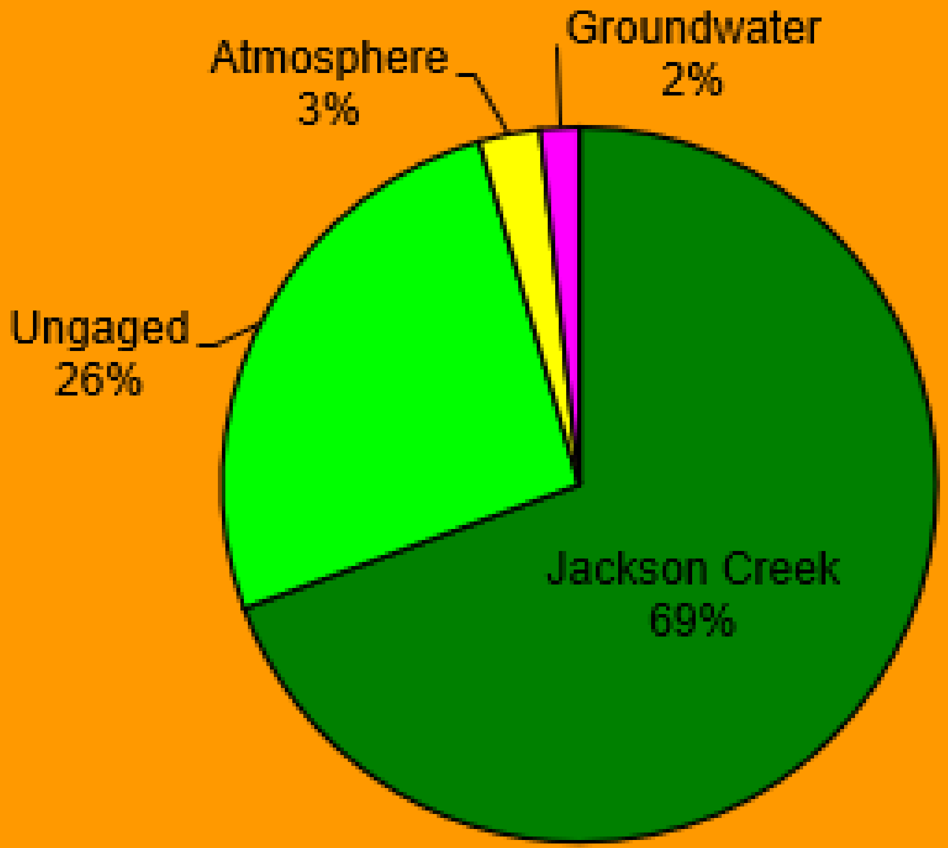
L = P loading

Z - Mean depth

τ = Residence time

Total Phosphorus Loading to Delavan Lake – 2017-2021

<u>External Loading</u>



<u>6,557</u> kg/yr

Determine how in-lake TP concentrations are related to external P loading

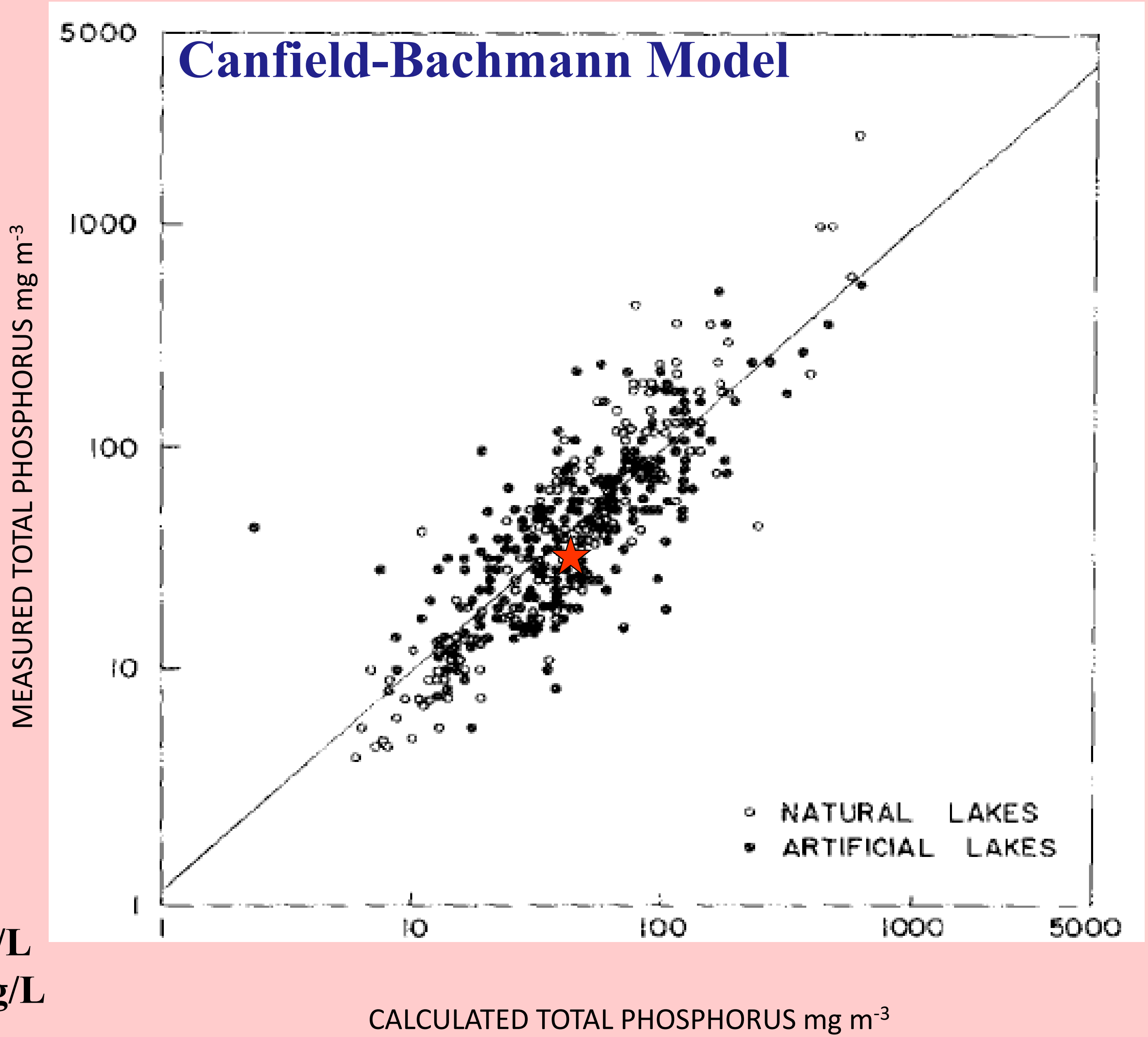
Canfield-Bachmann Model (natural lake model)

$$\text{TP concentration} = \frac{L}{Z\,(1.62\,(L/Z)^{0.458} + 1/\tau)}$$

Where: L = P loading

Z - Mean depth

τ = Residence time



How well does the model work for Delavan Lake?

Measured 33.7 ug/L
Calculated 49.7 ug/L

Adjust all predictions by the Percent difference – Multiply all model predictions by 0.68

Possible causes for the conversion factor needed:

1. Short circuiting of nutrients
2. Nutrients going into macrophytes instead of phytoplankton

Determine how in-lake TP concentrations are related to external P loading

Canfield-Bachmann Models (natural lake model)

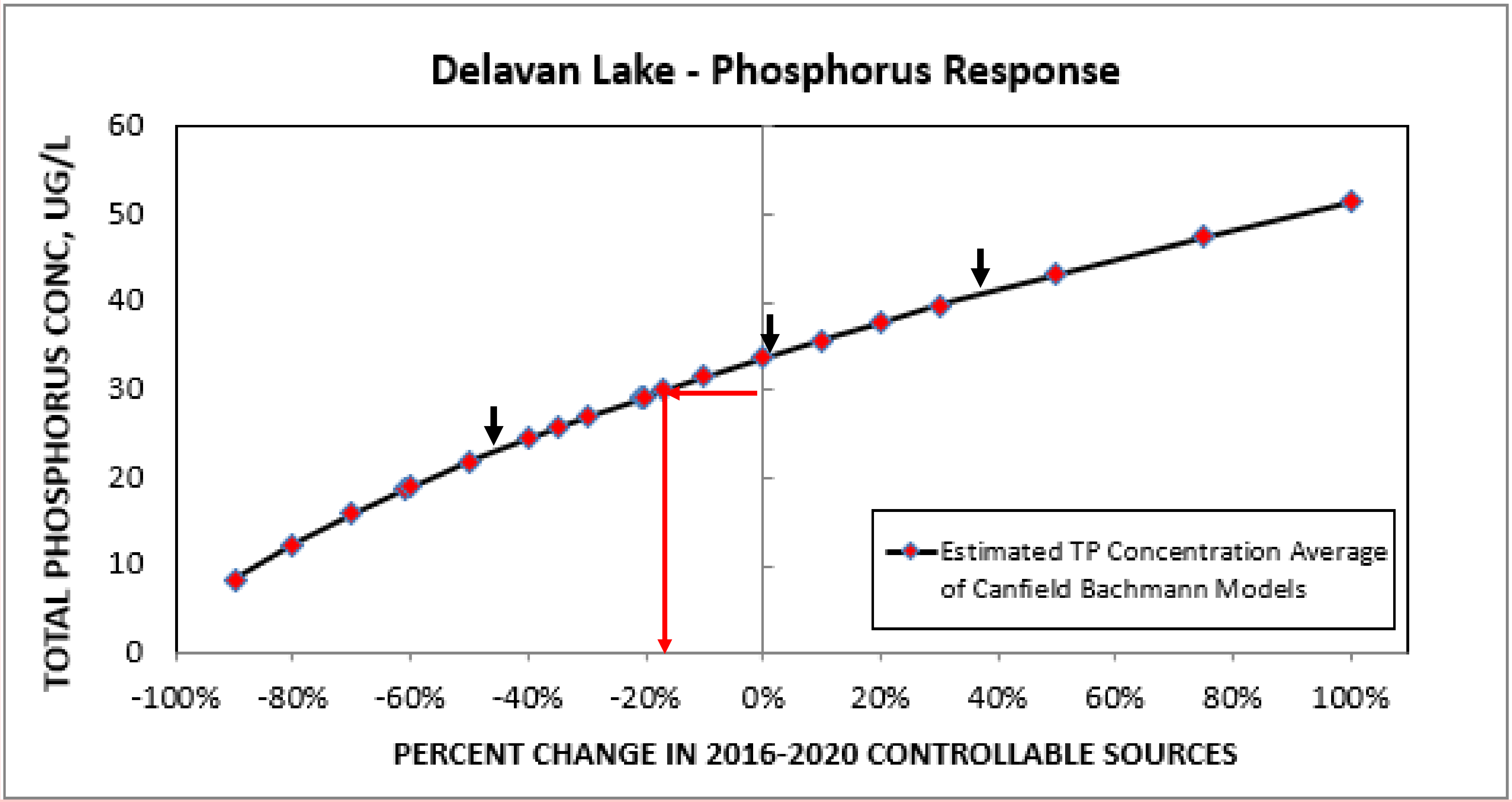
$$\text{TP concentration} = \frac{L}{Z\,(1.62\,(L/Z)^{0.458} + 1/\tau)}$$

Where: L = P loading

Z - Mean depth

τ = Residence time

Adjust all predictions by the Percent difference – Multiply all model predictions by 0.68



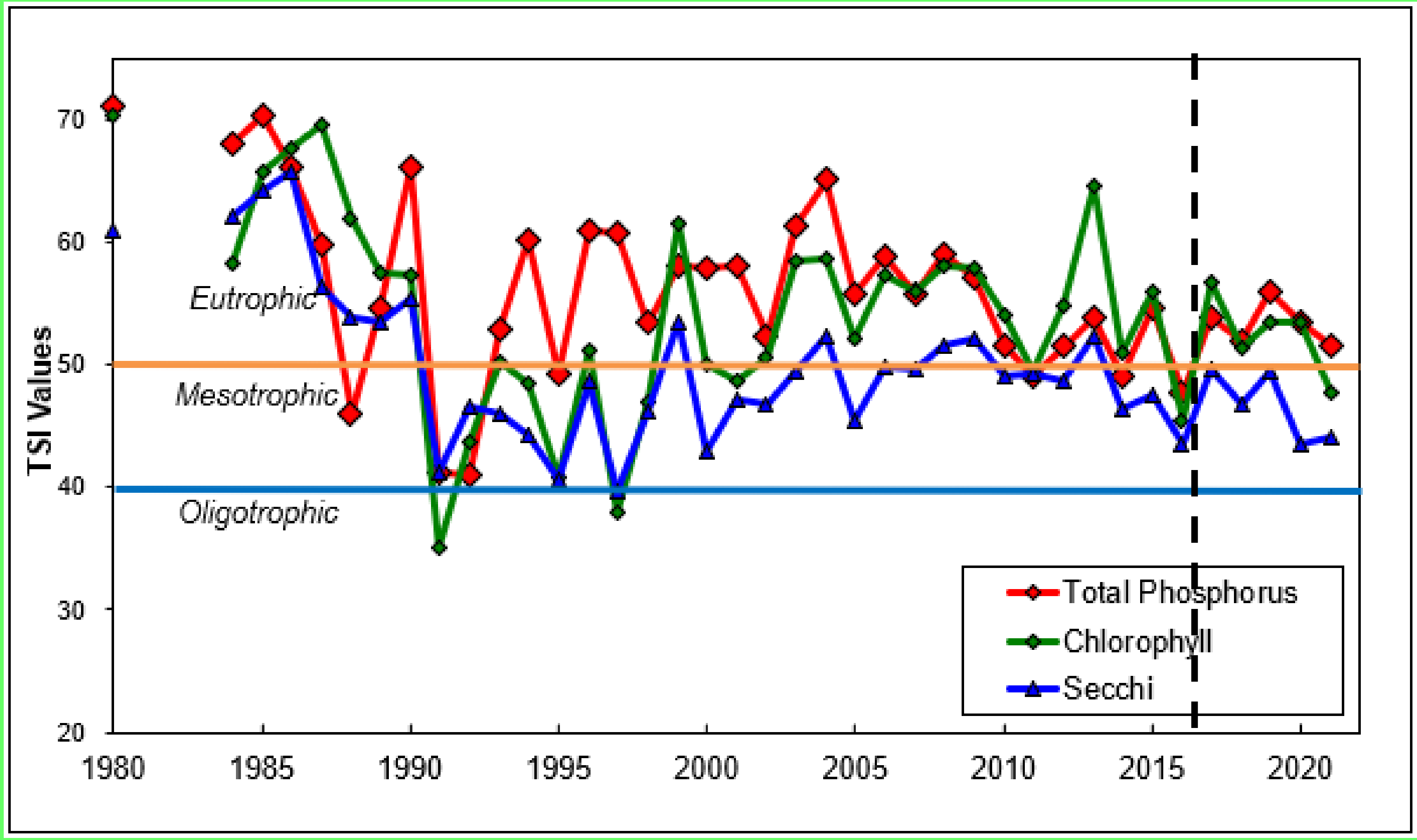
STEP 1 >> Calibrate (multiply all predictions by 0.68)

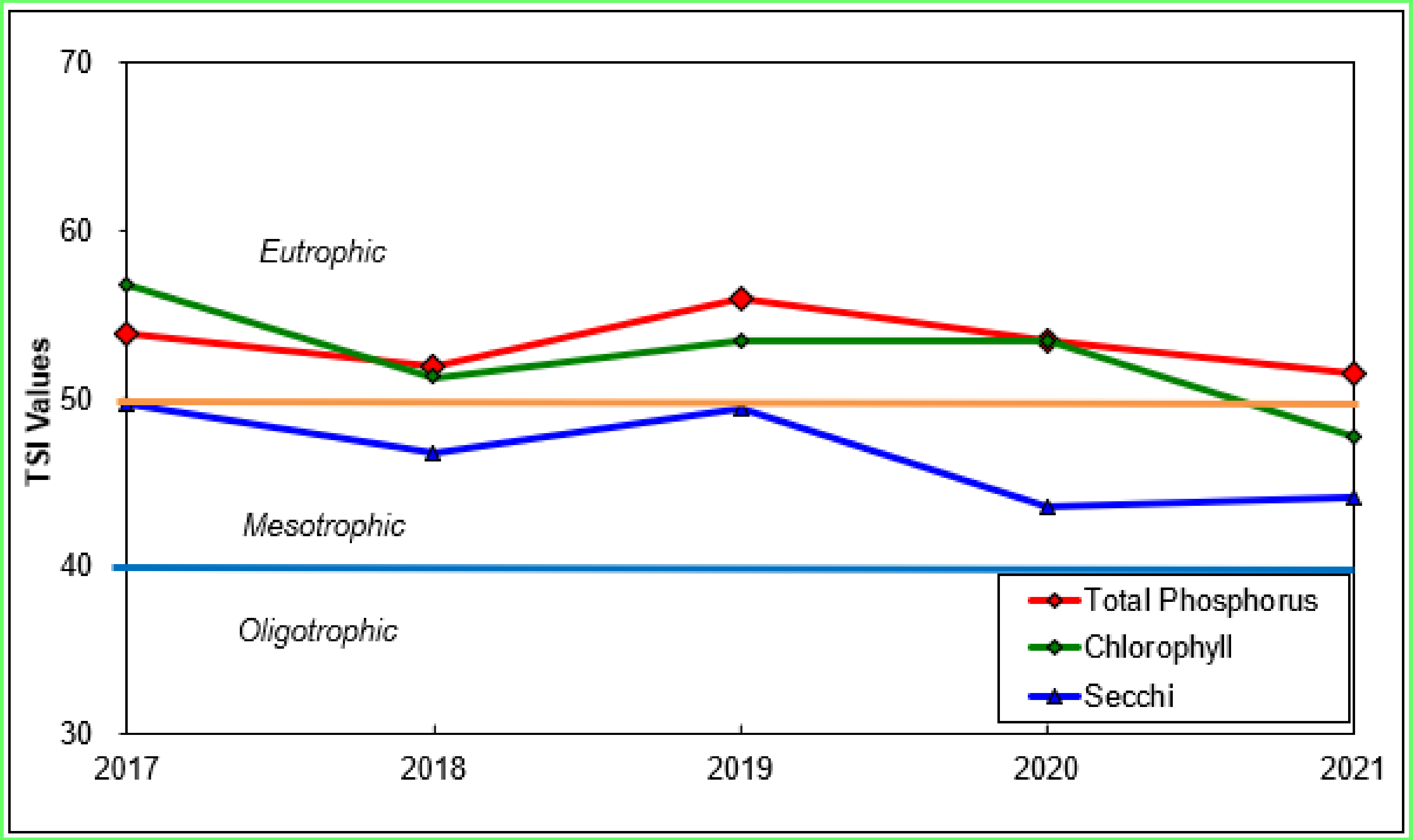
STEP 2 >> Predict TP concentrations for various load changes

STEP 3 >> Current TP = 33.7 ug/L. To get to 30.0 ug/L need to reduce external loading by 17% from that measured in 2017-21 (5,502 kg/yr)

How do we get response curves for Chl a?

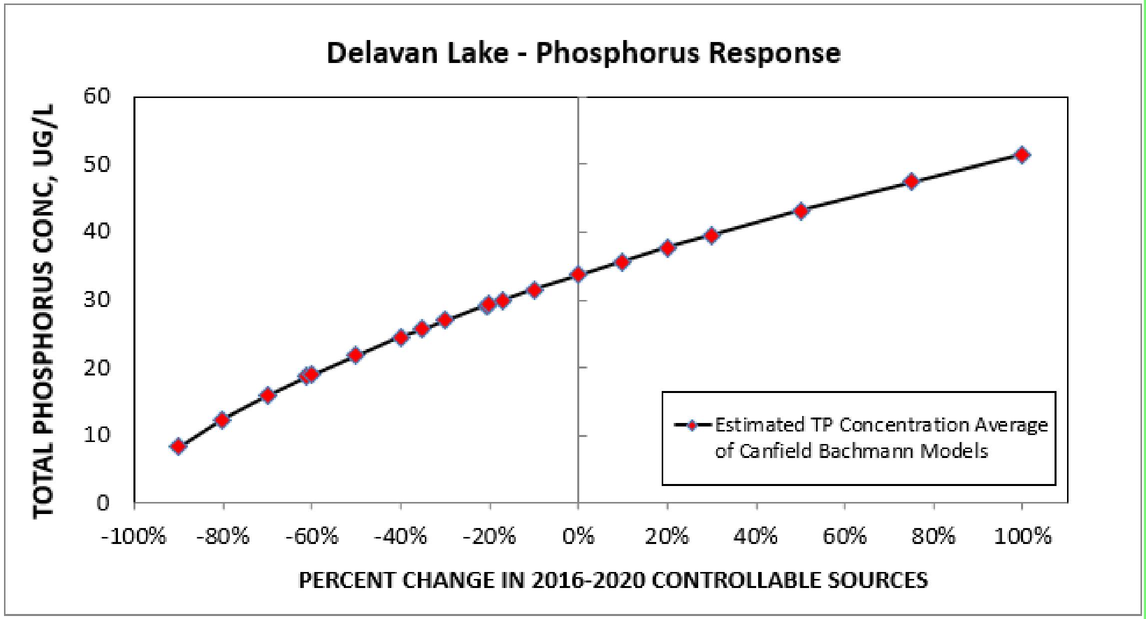
Step 1. Determine how summer average Chlorophyll a concentration and Secchi depth are related to phosphorus concentrations in the lake.

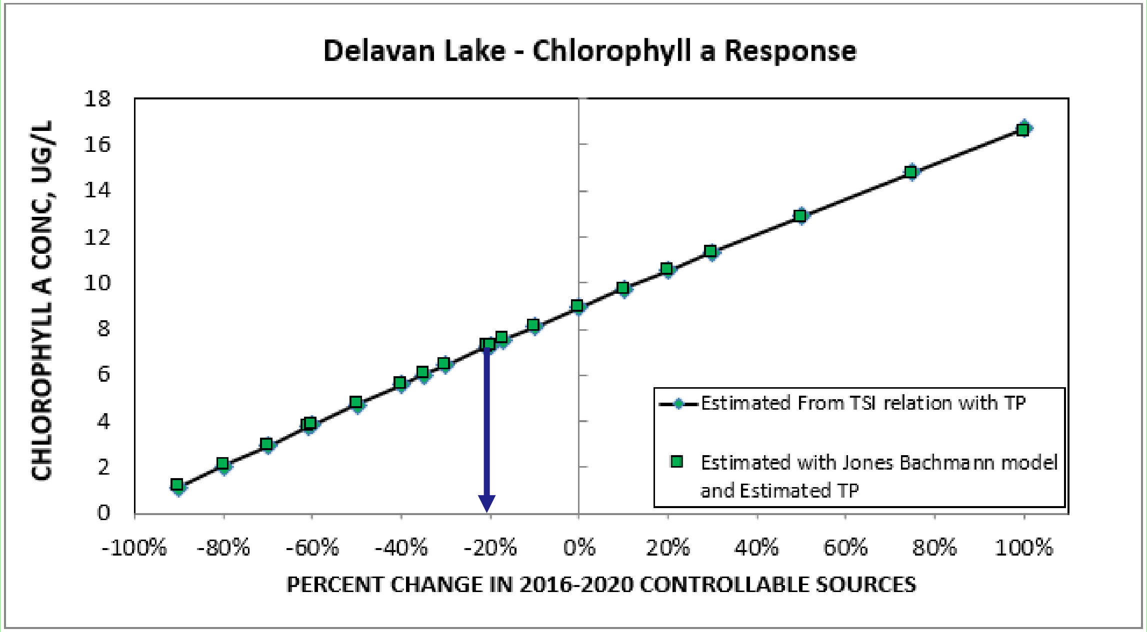




Site Specific Calibration

$$\mathbf{TSI_{Chl\ a} = TSI_{TP} \times \underline{1.003}}$$





Determining Response in Chl a to changes in TP – Approach 1

STEP 1a >> Determine Goal Summer Average Chl a concentration needed – 7.2 ug/L

STEP 2a: Develop response curves Carlson TSI relations – Model A

a. Compute TSI_{Chl} from TSI_{TP}

$$TSI_{Chl} = TSI_{TP} \times 1.003$$

b. Compute Chl from TSI

$$TSI_{Chl} = 30.6 + 9.81 * Ln(Chl)$$

c. Calibrate relation

$$Chl = Chl_{TSI} \times 0.74$$

STEP 3a >> Determine TP load reductions to get 7.2 ug/L

20.5 % reduction – 5,277 kg/yr

Step 2b. Approach 2: Find a way to convert predicted TP to predicted Chlorophyll a (Jones and Bachmann, 1976)

Model B

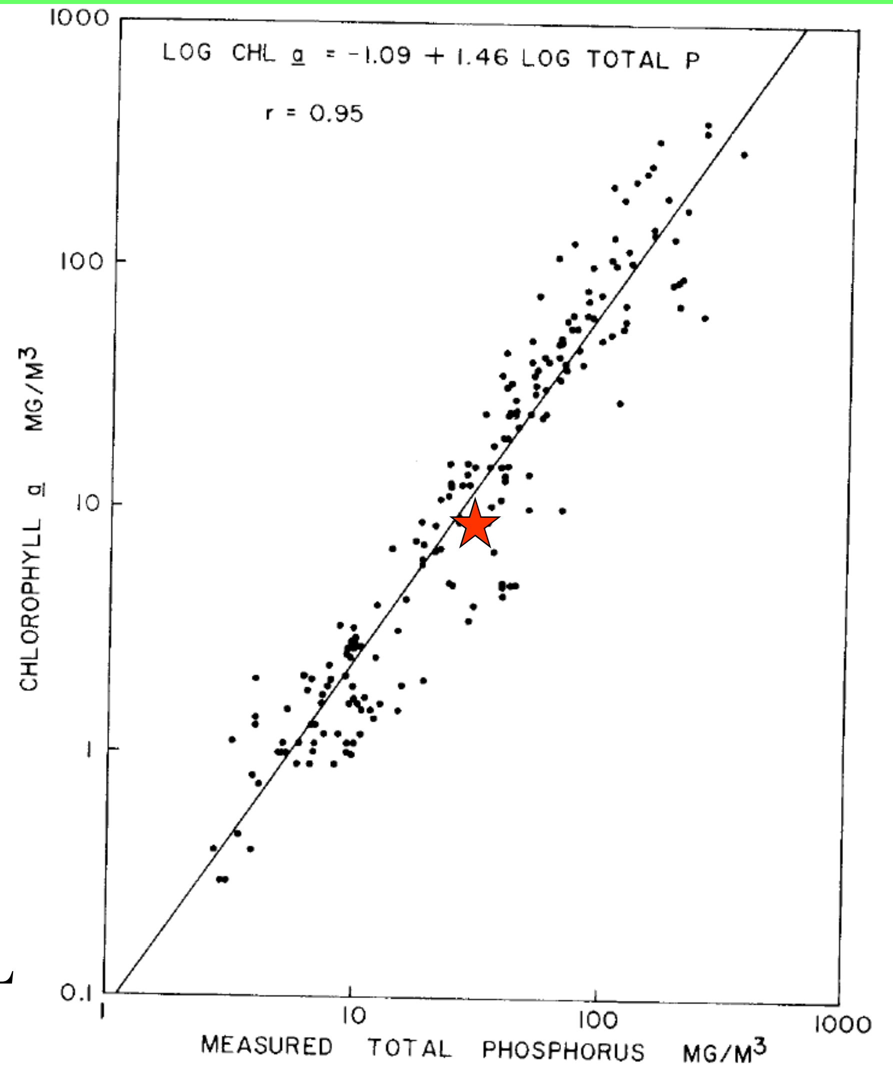
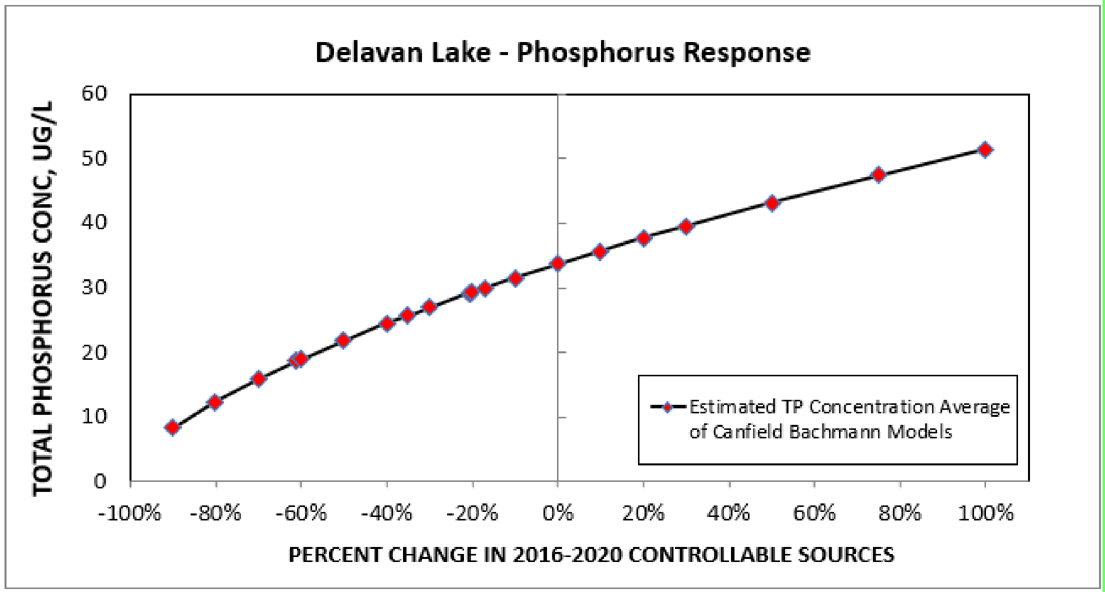


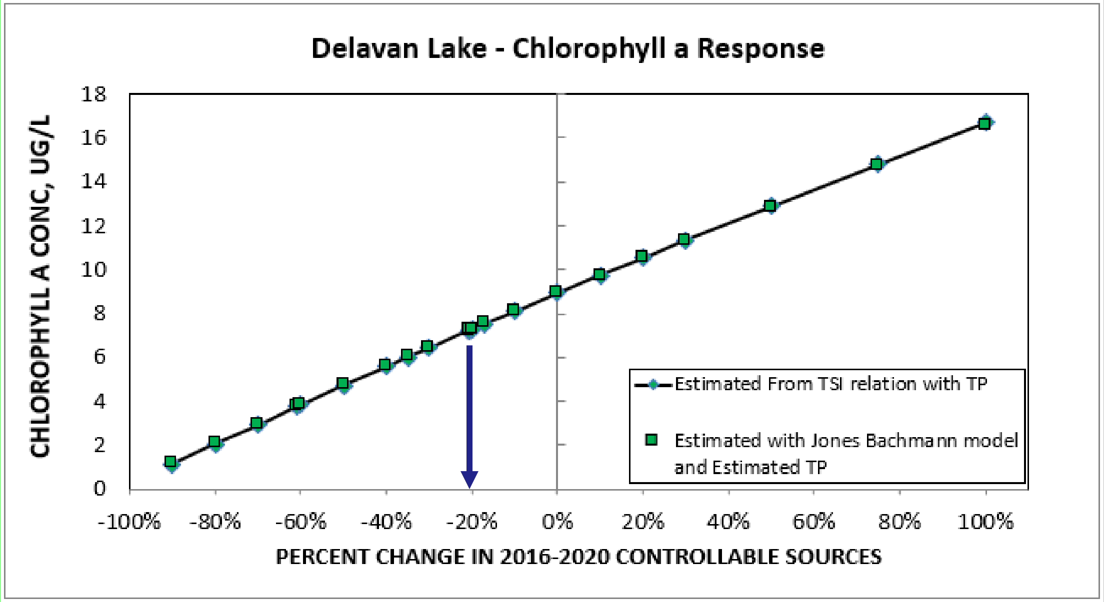
FIGURE 1.—Relationship between summer levels of chlorophyll *a* and measured total phosphorus concentration for 143 lakes.

How well does the model work for Delavan Lake?

Measured TP 33.7 ug/L
Calculated Chl 13.79 ug/L
Measured Chl 8.94 ug/L

Determining Response in Chl a to changes in TP





STEP 1b >> Determine Summer Average Chl a concentration needed – 7.2 ug/L

STEP 2b:
Jones Bachman model
Model B

a. Compute Chl_{JB}

$Log(Chl) = 1.46 \times Log(TP) - 1.09$

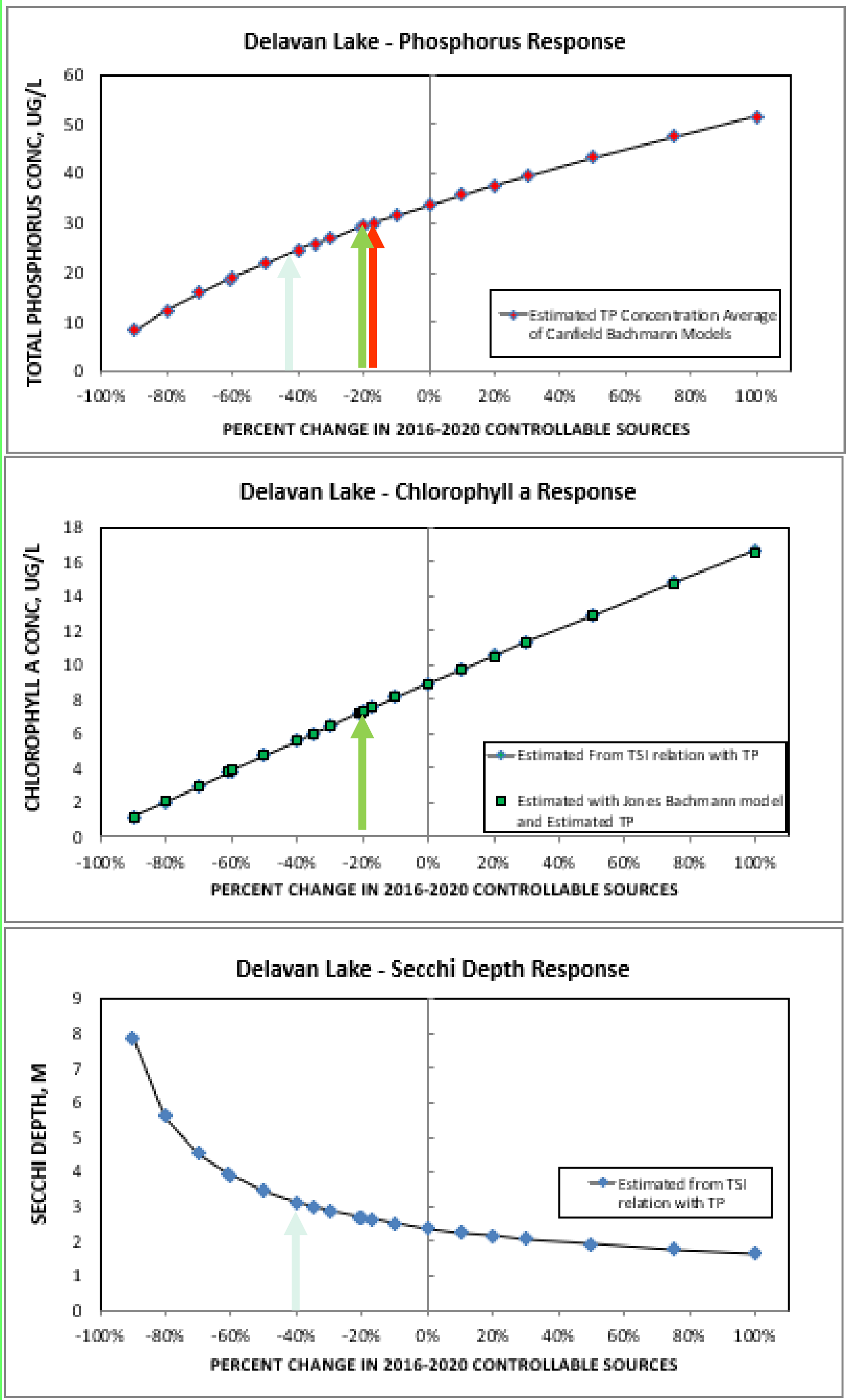
b. Calibrate relation

$Chl = Chl_{JB} \times 0.65$

STEP 3b >> Determine TP load reductions to get 87.2 ug/L

20.7 % reduction – 5,264 kg/yr

How does this all fit together??



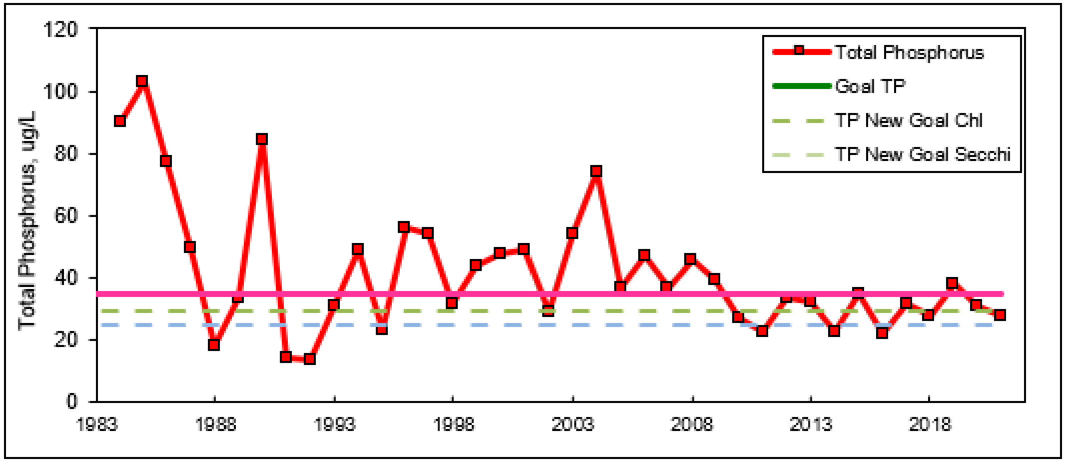
GOAL
30 ug/L Total Phosphorus
17% Reduction

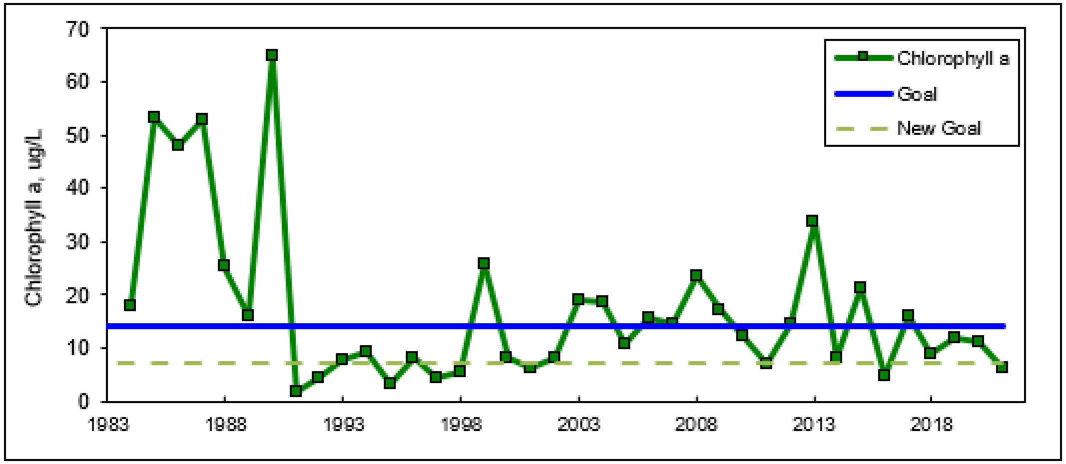
New GOAL ??
24.5 - 30 ug/L Total Phosphorus
20.7 - 40% Reduction
External loading > 4,060 kg

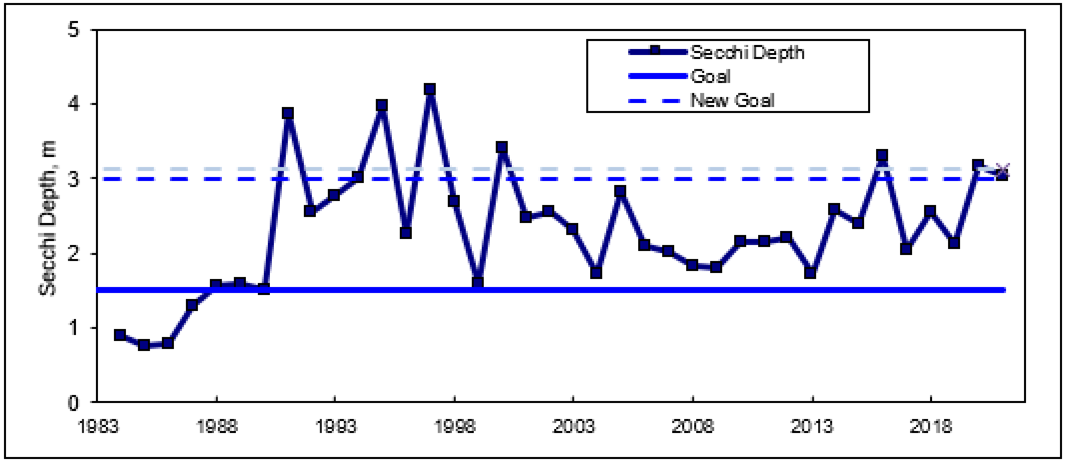
GOAL
7.2 ug/L Chlorophyll a
20.5-20.7% Reduction

GOAL
3.0 m Secchi
40% Reduction

New Goals for Delavan Lake







Conclusions:

Suggested New Goals:
Total Phosphorus conc.: June – Sept. of 24 ug/L
Chlorophyll a conc.: July – Sept. of 7.2 ug/L
Secchi depth: July – Sept. of 3.0 m

Controllable phosphorus loading needs to be reduced by 40 % from that measured during 2017-2021 (total external loading change from 6,600 kg to about 4,060 kg to get TP conc < 30 ug/L, less than 5% of the days with chl a concentrations > 20 ug/L, and average July-September Secchi depth > 3 m.

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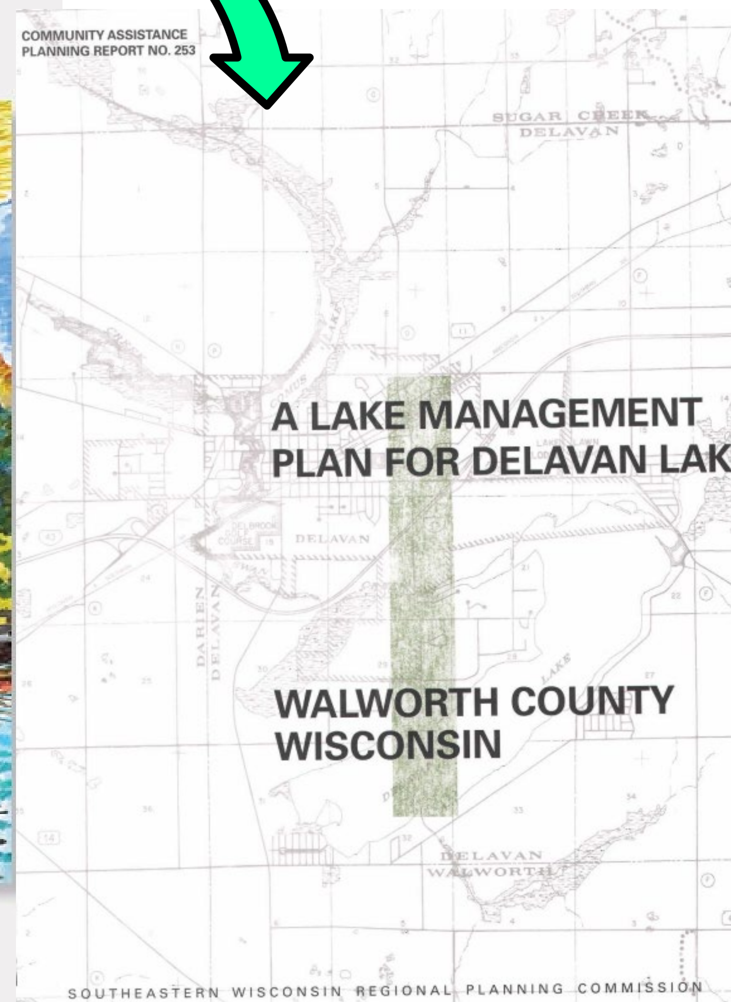
Prepared in cooperation with the Town of Delavan and the Delavan Lake Sanitary District

Response in the Water Quality of Delavan Lake, Wisconsin, to Changes in Phosphorus Loading—Setting New Goals for Loading from its Drainage Basin

Scientific Investigations Report 2023–5073

U.S. Department of the Interior
U.S. Geological Survey



COMMUNITY ASSISTANCE PLANNING REPORT NO. 253

A LAKE MANAGEMENT PLAN FOR DELAVAN LAKE

WALWORTH COUNTY WISCONSIN

SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

Determining Phosphorus Load Reductions Needed to Reach Water-Quality Goals for Delavan Lake, Wisconsin

Questions??

June 12, 2025

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References and Web pages:

1. Delavan Lake: Hydrology, water quality, and biology - https://www.usgs.gov/centers/upper-midwest-water-science-center/science/delavan-lake-hydrology-water-quality-and-biology

2. Robertson, D.M., Goddard, G.L., Helsel, D.R., and MacKinnon, K.L., 2000, Rehabilitation of Delavan Lake, Wisconsin, Lake and Reservoir Management, v. 16, no. 3. p. 155–176. https://www.tandfonline.com/doi/abs/10.1080/07438140009353961

3. Robertson, D.M., Siebers, B.J., and Fredrick, R.A., 2023, Response in the water quality of Delavan Lake, Wisconsin, to changes in phosphorus loading—Setting new goals for loading from its drainage basin: U.S. Geological Survey Scientific Investigations Report 2023–5073, 28 p., *https://doi.org/10.3133/sir20235073*.