Strategy for Managing Waterbody Excessive Fertilization (Eutrophication) to Achieve TMDL Goals

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In 1998, one of the most frequent causes of listing a California waterbody on the Clean Water Act 303(d) list as an "impaired" waterbody was excessive fertilization. This listing established a requirement that the Regional Water Quality Control Boards initiate the development of a nutrient (nitrogen and/or phosphorus) load allocation among sources, and the establishment of a total maximum daily load (TMDL) of nutrients to the "impaired" waterbody. The managers of the sources of nutrients (urban and industrial wastewater and stormwater runoff, as well as agricultural stormwater runoff and tailwater) within the watershed must then control the nutrient discharge to the waterbody to ultimately eliminate its excessive fertilization. This paper presents guidance on how regulatory agencies, managers of nutrient sources, and others should proceed to develop technically valid, cost-effective TMDLs for the control of excessive fertilization of various types of waterbodies that are on the 303(d) list. Attention is given to determining the limiting nutrient or other factors that could, through nutrient control efforts, limit the excessive growths of aquatic plants in a waterbody. Also, information is provided on assessing the available forms of nutrients. In addition, a discussion is presented on how such factors as the hydraulic and nutrient residence times of waterbodies influence how a load of nutrients added to a waterbody affect its excessive fertilization. The role of sediments as a source of nutrients is also discussed . This review presents a synthesis of the authors'40 years of work on these topics at various locations within the US and other countries.

Water Quality Problems Caused by Nutrients (N and P)

Many Waterbodies Receive Sufficient Nitrogen and Phosphorus Compound Loads to Develop Excessive Growths of Algae and/or Water Weeds

- Impair Domestic Water Supply Water Quality
    - Tastes and Odors
    - Shortened Filter Runs
    - Increased Trihalomethane (THM) Precursors
        - Increased Carcinogens in Waters Disinfected with Chlorine
- Impair Recreation Use of Waters
    - Interfere with Swimming, Boating, Aesthetic Enjoyment
    - Odors and Decreased Water Clarity

Dissolved Oxygen Concentrations below Water Quality Standards
    - Diel DO Changes
    - Depleted Oxygen in Deeper Waters

- Increase Fish Production
    - Less Desirable Fish (*e.g.*, Carp) Loss of Cold Water Fisheries

Examples of Excessively Fertile Waterbodies

That Need Nutrient Input Control
Could Cost Nutrient Dischargers Many Tens of Millions of Dollars in Nutrient Control Programs

San Joaquin River Deep Water Channel

DO Depletion

- Violates Water Quality Standards
- Possibly Blocks Migration of Chinook Salmon to Spawning Areas
  - TMDL Must Be Implemented to Control Oxygen Demand Sources
    - Algae Are an Important Cause of Oxygen Depletion through Death and Decay

Sacramento/San Joaquin River Delta

Excessive Growths of Water Hyacinths and Attached Algae, Algal Blooms

- Impair Recreational Use
- Impair Water Supply Water Quality
  - Tastes and Odors, Shortened Filter Runs, Increased THM Precursors, Block Water Transmission

Not on 303(d) List–Could Be Listed

Nutrient Control in Delta in Conflict with Fish Production

- Delta Said to Have Inadequate Primary Production to Support Optimal Fisheries
- Role of Clams' "Harvesting" Algae Needed for Zooplankton Secondary Production

Upper Newport Bay, Orange County, California

Excessive Growths of Marine Algae

- Impair Recreational Use
- Cause DO Excursions below Water Quality Standard

TMDL to Control Nitrogen and Phosphorus Input to Be Developed

State of California, 1999

87 Waterbodies Listed as 303(d) Impaired, for Which TMDLs Needed

Will Require Massive Expenditures by Agriculture and Urban Nutrient Sources to Control Excessive Fertilization

TMDL Process

- Define Waterbody as Water Quality Use-Impaired
- List on State and US EPA Clean Water Act 303(d) List of Impaired Waterbodies
- Establish TMDL Goals–Desired Algal-Related Water Quality
  - In General, Poor Understanding of Relationship between Nutrient Loads and Algal Growth and Impaired Water Quality
    - Must Use Phased Approach
- Establish Estimated Total Nutrient Load to Achieve Desired Water Quality
- Allocate Nutrient Loads to Sources

- Implement Nutrient Control Programs
  - Phased Approach
- Monitor Algal Biomass for Several Years after Nutrient Load Reductions Achieved
- If TMDL Goal Not Achieved, Implement Phase II Nutrient Control Program

TMDL Goals

Significant Problems in Establishing Appropriate TMDL Goals

- Lack of Standards for Excessive Algae, Water Hyacinth, and Water Weeds
  - Goal Subjective, Depend on Region, and Especially Whether There Are High-Quality, Low Algal/Weed Waters in Region
- DO Depression with Depth and Associated with Diel Excursions below Standard
  - Poor Understanding of Significance of DO Excursions to Fisheries
- Nitrogen and Phosphorus Water Quality Standards
  - US EPA Developing Nitrogen and Phosphorus Nutrient Criteria
    - To Be Available in Year 2000 and Implemented by 2003
      - To Be Similar to Other Water Quality Criteria; Regionally Adjusted Nitrogen and Phosphorus Concentration Is Not to Be Exceeded
  - US EPA Proposed Approach for Developing Nutrient Water Quality Criteria Not Technically Valid
    - Site-Specific Evaluation Needed to Establish Appropriate Nutrient Loads to Protect Beneficial Uses of Waterbody

Information Base on Managing Excessive Fertilization

Large Amounts of High-Quality Research Conducted in the US, Canada, and Western Europe on Managing Excessive Fertilization in Lakes and Reservoirs in the 1960s and 1970s

- US EPA Stopped Supporting Research in the Late 1970s and Shifted Emphasis to Controlling Priority Pollutants–Rodent Carcinogens
- Recently US EPA Started to Address Excessive Fertilization Problems as Part of the Clean Water Action Plan
- Many of Those in Governmental Agencies, and Others Now Working in This Area Are Ignoring the Vast Information Base That Exists on Eutrophication Management
  - US EPA and Others Are Making Same Kinds of Mistakes Now as Were Made in the 1960s in Developing Eutrophication Management Programs
- Need to Become Familiar with Applied Limnology/Oceanography and Environmental Engineering/Science to Formulate Technically Valid, Cost-Effective TMDLs to Control Excessive Fertilization

Relationship between Nutrients and Algal Biomass

Limiting Nutrient

- Chemical Constituent That Is Present in the Least Amount Compared to Algal Needs
  - Typically Phosphorus in Midwest and East Coast Fresh Waterbodies
    - Surplus Nitrogen Available
  - West Coast and Marine Waters Algal Growth Typically Limited by Nitrogen Compounds

Available P = Soluble Ortho P + 20% of Particulate P

Available N = Nitrate, Nitrite, and Ammonia, +?% Organic Nitrogen

Must Focus Nutrient Control Programs on Available Nutrients, Not Total Nutrient Concentration

Most Waterbodies That Are Excessively Fertile Have Surplus N and P, Compared to Algal Needs

Light Limitation

Penetration and Duration

Not All Nitrogen and Phosphorus Equal in Promoting Algal Growth

Key to Effective Nutrient TMDL Development

Gain Waterbody-Specific Understanding of Nutrient Load–Algal Growth Response Relationship in Waterbody

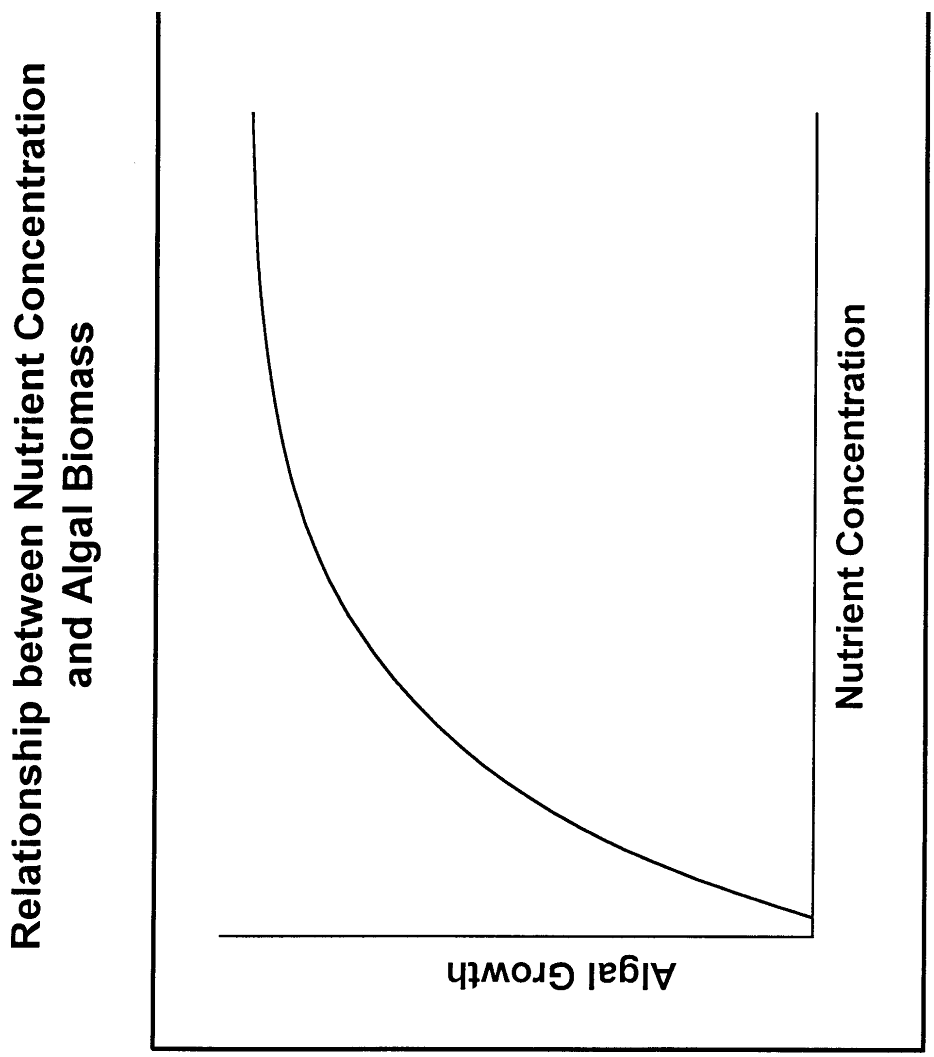
Must Understand How Nitrogen and/or Phosphorus from a Particular Source Promote Algal Growth That ***Impairs Water Quality***

- Limiting Nutrient and Available Nutrient Must Be Considered
- Hydraulic Residence Time

  Short Residence Time Waterbodies–Only Some of the Nutrient Loads Support Algal Growth during Critical Water Quality Impairment Periods

  - Nutrients Associated with High Flow Can Flush through the Waterbody and Not Be Available to Support Algal Growth during the Critical Time Period for Water Quality Impairment
  - Assess Nutrient Loads on a Monthly Basis

    Consider Those Loads That Lead to Excessive Growths of Algae That Impair Waterbody Uses



Assessing Limiting Nutrients

Algal Stoichiometry

100 C: 16 N: 1 P   Atomic Basis

7.5 N: 1 P   Mass Basis

Nutrient Ratios (Redfield Numbers) Not Reliable for Determining Limiting Nutrients

Must Assess Which Nutrient (If Any) Limits Algal Biomass during the Time When Algal Growth Significantly Impairs Waterbody Use

Some Fall, Winter, and Spring Algal Blooms Do Not Significantly Impair Waterbody Beneficial Uses

Typically, Summer Is the Critical Period

Determine Limiting Nutrient by Measuring Algal-Available Nutrient Concentrations at Peak Biomass

If the Soluble Ortho P >5 :g/L P and Nitrate + Ammonia >20 :g/L N, Algal Growth Rate and Biomass Is the Maximum That Can Occur for Those Conditions – i.e., Algal Growth Is Not Limited by the Available Phosphorus or Nitrogen

Most Excessively Fertile Waterbodies Have Nitrogen and Phosphorus in Surplus of Algal Needs at Peak Biomass – Maximum Water Quality Use-Impairment

Requires Appreciable N and/or P Control to Significantly Limit Algal Growth That Impacts Water Quality

Need at Least 25% Reduction in Load of Algal-Available P to a Waterbody to Cause Discernable Impact on Algal-Related Water Quality

"Every Little Bit" of Nutrient Control Does Not Necessarily Help Control the Impacts of Excessive Fertilization

Nutrient Sources

Nutrient Export Coefficients

For Each Type of Land Use or Activity, the Amounts of Nitrogen and Phosphorus Compounds Exported Per Year Are Relatively Constant

Can Estimate Amounts of Nitrogen and Phosphorus Contributed to a Waterbody Based on Land Use within the Waterbody's Watershed

Standard Nutrient Export Coefficients Need to Be Evaluated for Specific Areas Outside of Where They Were Developed

Amounts of Nitrogen and Phosphorus Contributed from Various Sources

Source	Nitrogen	Phosphorus	Units
Domestic Wastewater	3.2	0.9	kg/person/yr
Urban Drainage	0.5 (0.25[a])	0.1	$g/m^2/yr$
Rural/Agriculture	0.5 (0.2[a])	0.05	$g/m^2/yr$
Forest	0.3 (0.1[a])	0.01–0.001	$g/m^2/yr$
Manured Land (100 cows/mi^2, 15 tons manure/cow/yr)	0.34	0.11	$g/m^2/yr$
Drained Marsh	10.1	4.5	g/m^2
Rainfall and Dry Fallout	2.4	0.02	$g/m^2/yr$[b]

a = For Western US Waterbodies (after Rast and Lee, 1983)

b = Waterbody Area

Sediment as a Source of Nutrients

Generally, Waterbody Sediments Are Nutrient Sinks – Storage Areas

- Some Nutrient Recycling to Overlying Waters
  - Normally Associated with Mineralization of Recently Developed Dead Algae

Hypolimnetic Anoxic P Release Typically Not an Important Source of Phosphorus Leading to Waterbody Water Quality Problems

- Iron Chemistry Controls the Availability of Phosphorus

- Fall Overturn Blooms Usually Not a Significant Cause of Water Quality/ Use Impairment

- Laboratory and Micro/Mesocosm Studies on Nutrient Cycling Unreliable for Predicting Nutrient Behavior in the Environment
  - Must Examine the Total Nutrient Content (Mass), and Fluxes into and out of the Waterbody over Time to Determine the Role of Sediment Release in Contributing to Excessive Fertilization

Rate of Recovery of a Waterbody upon Nutrient Reduction

Misconception That the Nutrients in Sediments Will Prevent a Waterbody from Improving in Water Quality in Response to Nutrient Load Reduction

The Hydraulic Residence Time (Filling Time) of a Waterbody Is Not Reliable for Predicting Rate of Recovery of Waterbodies That Experience Nutrient Load Reductions

- Lake and Reservoir Water Quality Improves Much Faster Than Predicted Based on Hydraulic Residence Time
- Must Use **Nutrient** Residence Time:
  - Total Mass of Phosphorus or Nitrogen in a Waterbody, Divided by the Nutrient Load per Unit Time
- Studies on Lakes That Have Received Nutrient Reductions Have Demonstrated That Rate of Recovery Is Three Times the Limiting Nutrient Residence Time
  - Demonstrates That Sediment-Associated Nutrients Are Not a Major Factor in Controlling Algal Growth in Waterbodies

OECD Eutrophication Studies

$50 Million, 5-Year, 22-Country, 200-Waterbody Study Conducted in the 1970s Devoted to Assessing the Relationship between Nutrient Loads and Eutrophication Response, as Measured by Planktonic Algae

Found That the Planktonic Algal Chlorophyll in a Lake, Reservoir or Estuary Could Be Correlated with a Normalized Phosphorus Load

Based on Vollenweider Nutrient Load Normalizing Factor:

$$(L(P)/q_s)/(1+ (J_T)^{0.5})$$

$L(P)$ = Areal Annual Phosphorus Load (mg $P/m^2/yr$)

q_s = Mean Depth÷Hydraulic Residence Time=z/J_T (m/yr)

J_T = Hydraulic Residence Time (yr)

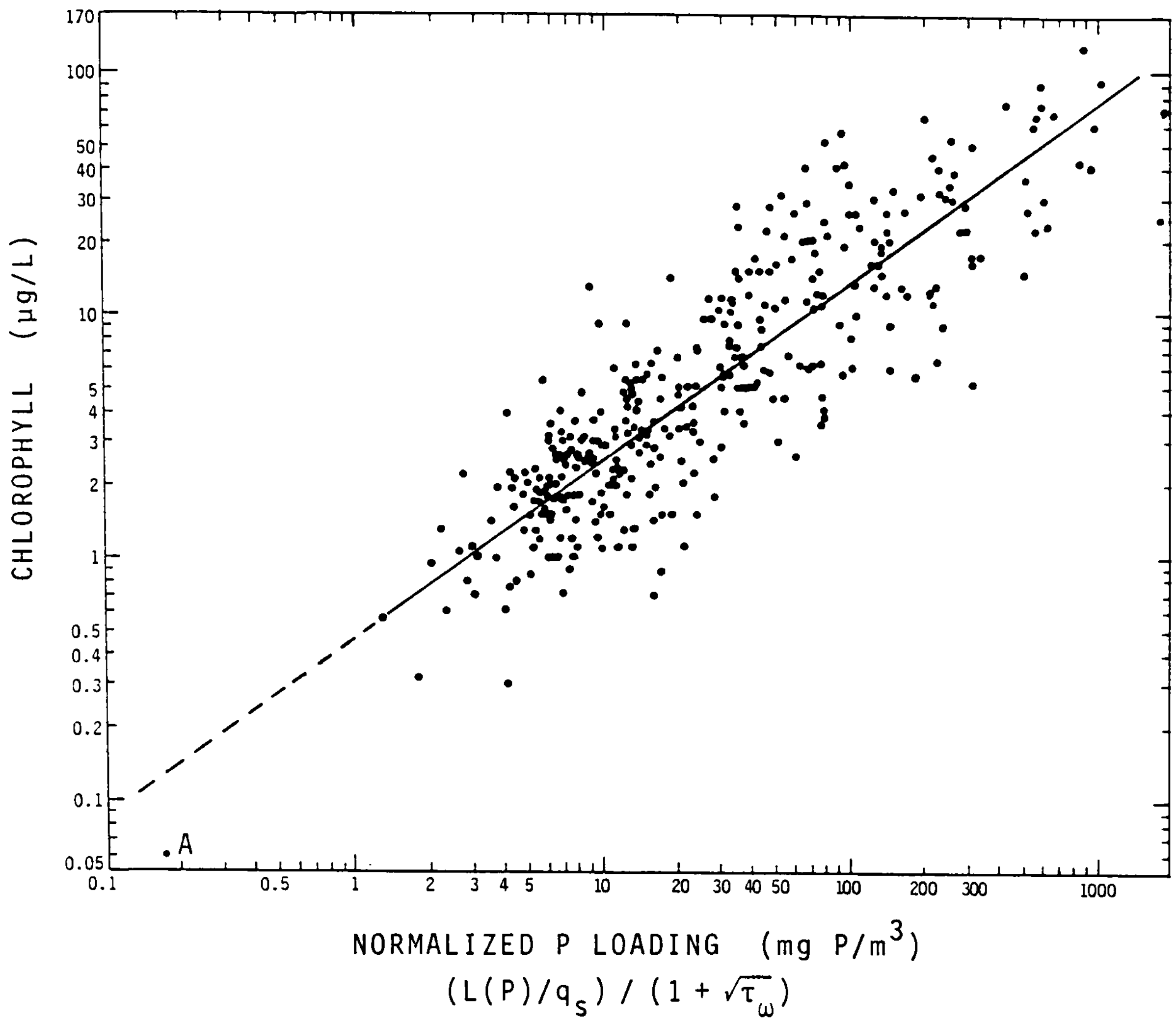
z = Mean Depth = (Waterbody Volume)÷(Surface Area)

Current OECD and Post-OECD Phosphorus Load – Planktonic Algal Chlorophyll Database Covers >750 Waterbodies Located throughout the World

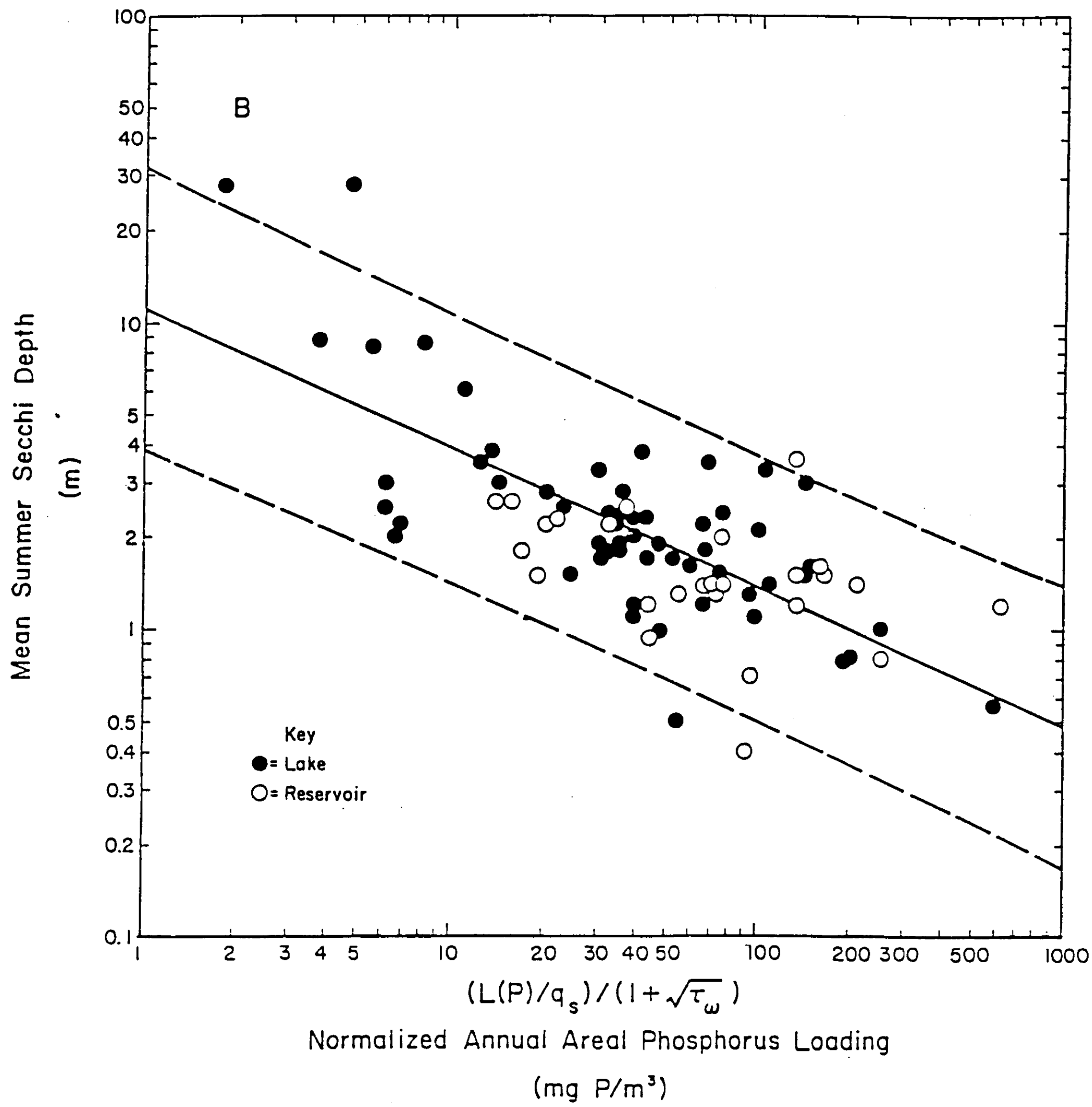
The Vollenweider OECD Relationships

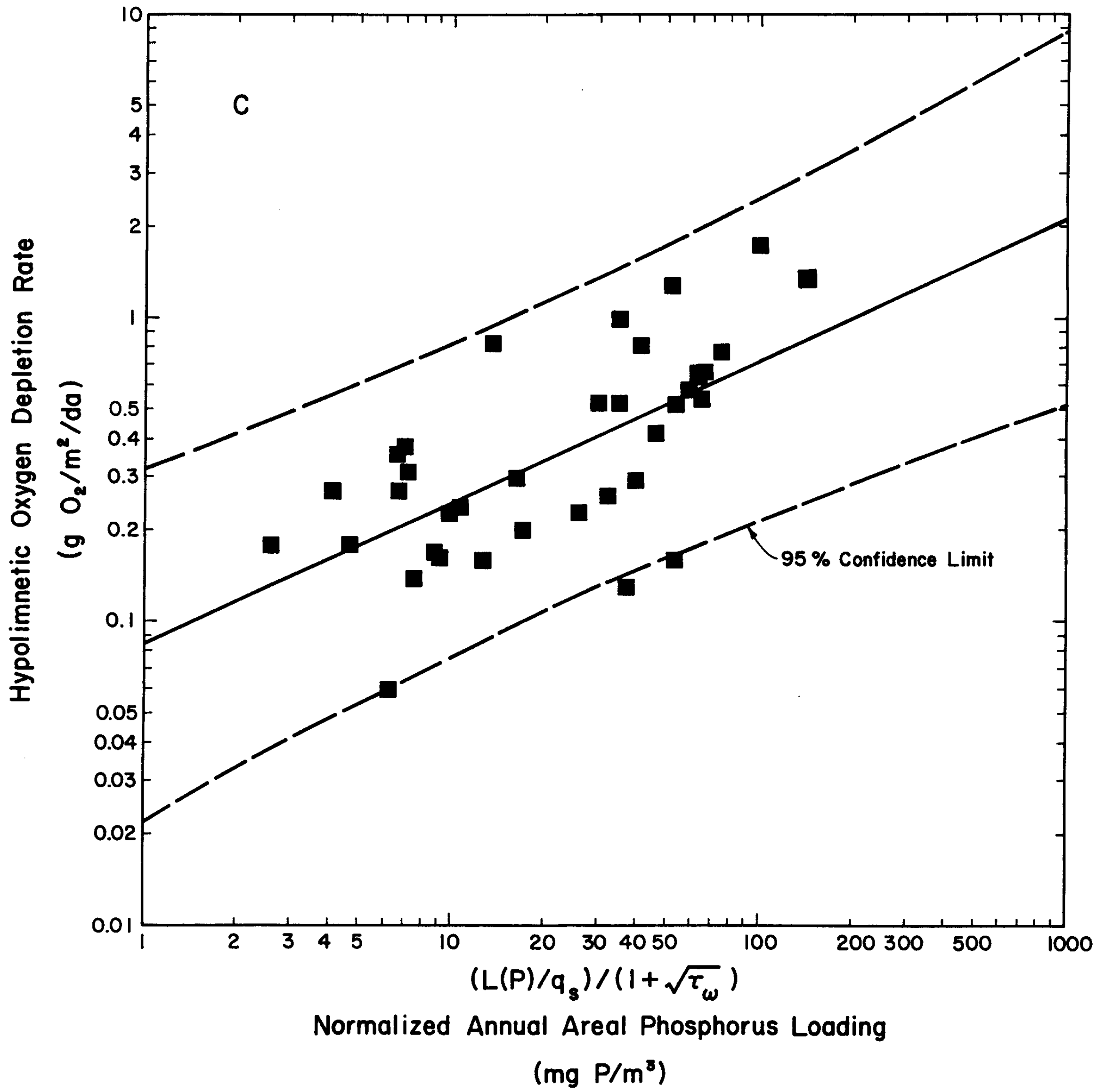
- Applicable to Lakes, Reservoirs, Estuaries, and Slow-Moving Rivers for Prediction of Planktonic Algal Biomass
  - Does Not Predict Water Hyacinth, Attached Algae, or Aquatic Weed Growth
- High Degree of Reliability in Predicting Recovery of Lakes after Altering of Nutrient Loads
- If Appropriately Applied, Is a Useful Water Quality Management Tool

Relationship Between Normalized Phosphorus Load and Chlorophyll Relationship
(After Jones and Lee `1986)

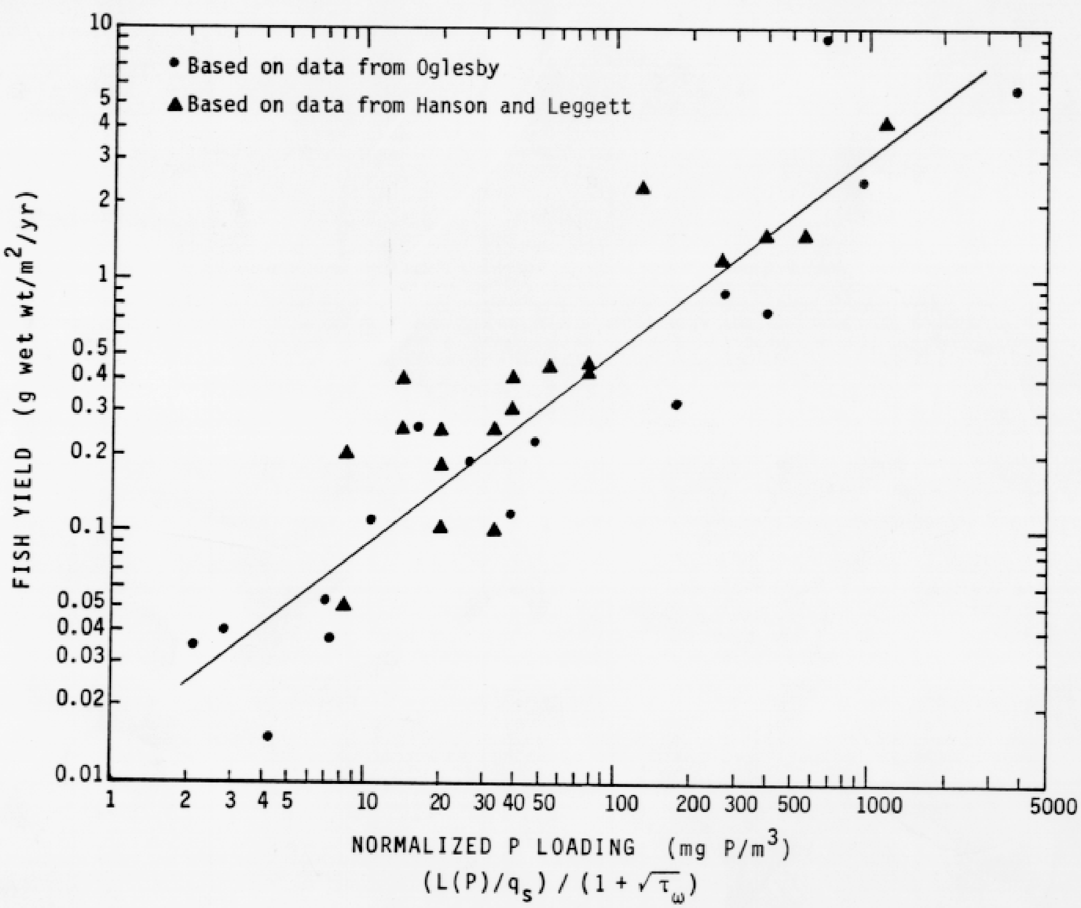

CHLOROPHYLL (µg/L)
170
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.1
0.5
1
2
3
4
5
10
20
30
40
50
100
200
300
1000
A
NORMALIZED P LOADING (mg P/m³)
(L(P)/q_s) / (1 + √τ_ω)

Relationship between Normalized P Loading and Water Clarity (Secchi Depth)




C
95 % Confidence Limit
Hypolimnetic Oxygen Depletion Rate
(g O2/m2/da)
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.01
1
2
3
4
5
10
20
30
40
50
100
200
300
500
1000
(L(P)/qs)/(1+√τω)
Normalized Annual Areal Phosphorus Loading
(mg P/m3)

Relationship between Normalized P Load and Fish Yield



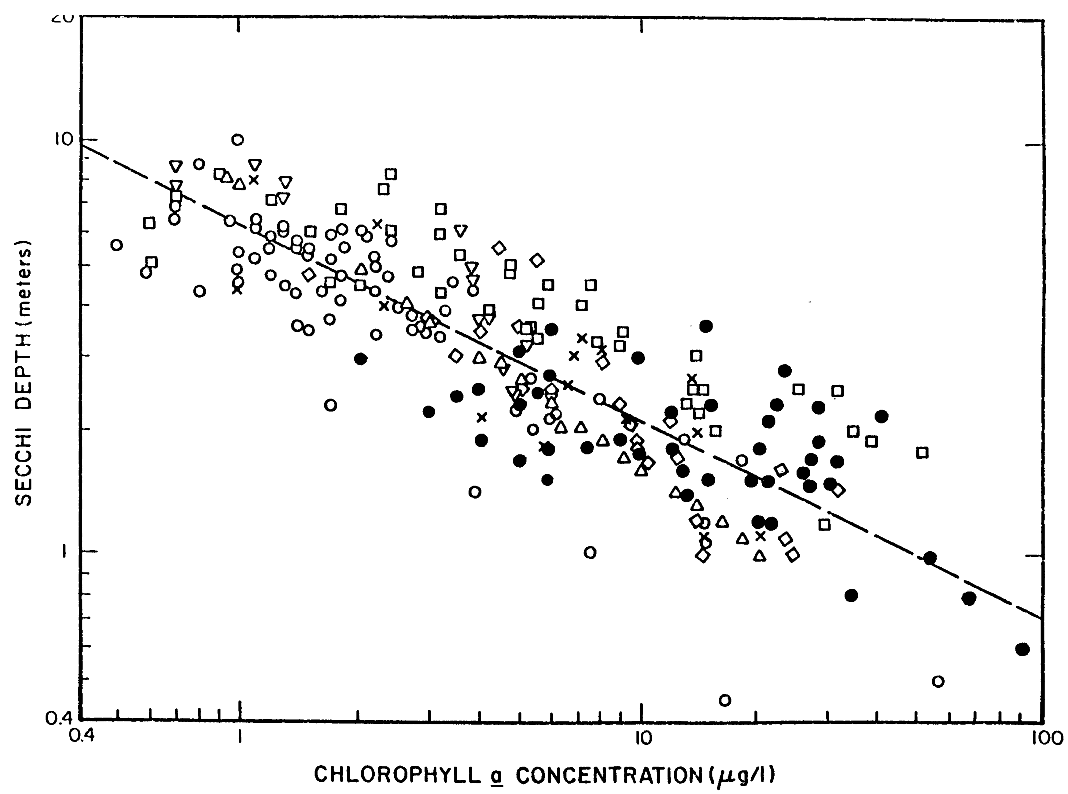


Figure 3. Relationship between Secchi Depth and Chlorophyll Concentration (after Rast and Lee, 1978)

Eutrophication Modeling

Dynamic Models Based on Differential Equations Developed to Describe How Nutrients Added to a Waterbody Result on Algal Biomass

Can, through Tuning, Be Used to Formulate Nutrient Load – Eutrophication Response Relationships

Relationships Developed for One Set of Nutrient Load Conditions May Not Be Applicable to Significantly Altered Nutrient Loads

Poor Prediction of Load–Response Relationships after Significant Change in Nutrient Loads

Conclusions and Recommendations

- Many Waterbodies Experience a Water Quality/Use Impairment Due to Excessive Growths of Algae and/or Water Weeds
- Activities of Man in a Waterbody's Watershed, Such as Urbanization, Farming, Animal Husbandry, and Some Industrial Activities Increase the Nutrient Loads to Waterbodies – Cultural Eutrophication
- Proper Development and Implementation of a Nutrient Control TMDL Requires Substantial, High-Quality, Waterbody-Specific Information on Nutrient Sources and Their Impacts on Algal-Related Water Quality

  Current TMDL Process Does Not Allow Adequate Time and/or Provide the Resources Required to Develop Needed Information
- Substantial Reliable, Pertinent Information Exists in the Eutrophication Management Literature That Should Be Used to Formulate Technically Valid, Cost-Effective TMDLs for Managing Excessive Fertilization of Waterbodies

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Many of the above-listed papers and reports are available from Dr. Lee's web site www.gfredlee.com.