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CDM
One Cambridge Place, 50 Hampshire Street
Cambridge, Massachusetts 02139
tel: 617 452-6000
fax: 617 452-8000

August 30, 2007

Mr. Paul A. Kennedy
Superintendent
Department of Wastewater
Government Center
77 Park Street
Attleboro, MA 02703

Dear Mr. Kennedy:

As you have requested, CDM has reviewed certain elements of the draft NPDES permit issued by the Environmental Protection Agency to the City of Attleboro.

We have prepared comments with respect to this permit, copies of which are attached hereto. Should you have any questions on these matters, please do not hesitate to contact me at 617-452-6246

Sincerely,

CAMP DRESSER & McKEE Inc.

John J Gall, Jr.
Vice President

Comments on the Revised Draft Permit for the City of Attleboro

The Environmental Protection Agency has proposed to modify the draft permit for the City of Attleboro originally issued in August of 2006 to incorporate revised limitations for the discharge of phosphorus. The newly proposed limit is 0.1 mg/l Total Phosphorus as a monthly average, as compared to the previously proposed limit of 0.2 mg/l total Phosphorus, as a monthly average. The City believed that it could achieve the phosphorus limits contained in the August, 2006 permit. Achieving the newly proposed limits is expected to require the addition of new treatment processes, at substantial costs to the City.

EPA bases its decision to revise the permit based on a reevaluation of the comments submitted by the Rhode Island Department of Environmental Management (RIDEM) on the draft permit issued in 2006 and on further evaluation of the administrative record.

RIDEM claims that the 0.2 mg/l limit is inadequate to provide for compliance with the Rhode Island Water Quality Standards and suggests that EPA should undertake a waste load allocation study. According to EPA, the Rhode Island Water Quality Standards require that:

> "Average Total Phosphorus shall not exceed 0.025 mg/l in any lake, pond, kettlehole or reservoir, and average Total P in tributaries at the point where they enter such bodies of water shall not cause exceedance of this phosphorus criteria, except as naturally occurs, unless the Director determines, on a site specific basis, that a different value for phosphorus is necessary to prevent cultural eutrophication." Rule 8.D. (2).

First, the Agency failed to establish that the John V. Turner Reservoir is in fact subject to the quoted Rhode Island Standard. Although it is named a reservoir, it no longer functions as such, and the Agency presents no information to support the assertion that the cited Rhode Island Standard applies to this water body. In its comments on the initial draft permit, RIDEM has asserted that the Reservoir meets RIDEM's definition of a lake. This definition reflects nutrient management guidance developed by EPA. As indicated by RIDEM, this guidance defines lakes as water bodies with a mean water residence time of 14 days or more. According to studies conducted by the Army Corps of Engineers the reservoir has a volume of 350 million gallons (See Attachment 1 hereto). Using this value, and the flow data from the USGS gage located immediately downstream of the John V. Turner Reservoir, the mean water residence time of this impoundment is 9.68 days. Thus, the impoundment does not meet the definition of a lake used by RIDEM to distinguish between bodies of water subject to the standard, and those that are not.

Secondly, in developing its proposed limits the Agency does not present any information to show how a 0.1 mg/l permit limit is necessary to keep the "Average Total Phosphorus" below 0.025 mg/l. Rather, it appears that the Agency has relied upon flow conditions associated with the 7 day, ten year low flow to develop the limit. In most systems, the seven day 10 year low flow is substantially below average flow, and represents a flow that happens very infrequently, far different from the "average" referenced in the state's water quality standards. The Agency then argues that dilution, and in-stream attenuation will serve to achieve compliance with the Rhode Island standard. But no information is presented to quantify these factors to show how this meets the Rhode Island standard.

The use of average concentrations over appropriately long periods is recommended by the Agency's guidance. In its "Ambient Water Quality Criteria Recommendations; Information Supporting the Development of State and Tribal Nutrient Criteria Lakes and Reservoirs in Nutrient Ecoregion XIV" EPA encourages States to

> "Identify appropriate periods of duration (how long) and frequency (how often) of occurrence in addition to magnitude (how much). EPA does not recommend identifying nutrient concentrations that must be met at all times; rather a seasonal or annual averaging period (e.g., based on weekly or biweekly measurements) is considered appropriate. However, these central tendency measures should apply each season or each year, except under the most extraordinary conditions (e.g., a 100-year flood)." See Attachment 2 hereto.

The use of seasonal averages would provide additional dilution, and would thus serve to lower the treatment requirements required of the City.

Third, the Agency failed to conduct a wasteload allocation as suggested by RIDEM on its comments of 2006, and failed to consider that other sources of phosphorus could represent significant contributions to the problems of the waterbody as referenced in the State's 2004 integrated waters list. In particular, there are several golf courses adjacent to the John V. Turner reservoir that could significantly impact the phosphorus loading on the Reservoir. TMDL's ought be established and waste load allocations adopted in order that to properly manage the waterbody. Although the Fact Sheet maybe technically correct that TMDL are not now underway for the Ten Mile River, the State of Rhode Island has indicated that it will be undertaking a TMDL of the Turner Reservoir, to be completed in 2012. (See Appendix B to Plan for Managing Nutrient Loadings to Rhode Island Waters, attachment 3 hereto). If the State of Rhode Island is content to wait that long to develop a TMDL for this system it would appear appropriate to stay with the 0.2 mg/l limit of the 2006 proposed permit until that time. The 0.2 limit contained in that proposed permit reflects an 80 % reduction in phosphorus as compared to the currently effective permit; the 0.1 mg/l limit would result in only a very small incremental load reduction – generally on the order of 1 pound per day.

Fourth, the Agency has agued that various literature references support the imposition of a 0.1 mg/l permit limit, including the criteria presented in the Gold Book (the 1986 Quality Criteria for Water); information presented in the technical guidance manual for Rivers and Streams; and Recommendations for Nutrient Criteria in Ecoregion IV, the region encompassing the Attleboro discharge.

None of these references support the application of their recommendations in the manner adopted by the Agency. The 1986 Quality Criteria for Water suggests a level of 0.1 mg/l as "a desired goal for the prevention of plant nuisances in streams or other flowing waters" and references a 1973 publication of Kenneth Mackenthun, a copy of which is included as attachment 4 to this document. However, that document does not present information concerning the development of the 0.1 mg/l "desired goal", but rather makes reference to a 1968 paper published in the Journal of the American Waterworks Association by the same author. A copy of the 1968 paper is included as attachment 5 to this document. The 1968 document indicates that " … A considered judgment suggests that to prevent biological nuisances, total phosphorus should not exceed 100 ug/l P at any point within the flowing stream, nor should 50 ug/l be exceeded where waters enter a lake, reservoir or other standing water body …" (Mackenthun, 1968 p 1053). A careful reading of this document suggests that it is referencing streams which are tributary to water supply reservoirs and lakes and standing waters that serve as sources of water supply. This would explain why it was published in what would otherwise be thought to be a journal about water supply, and not water pollution. Moreover, the 1968 document presents no information concerning the development of the recommendation – and so it presents no guidance on how it should be applied – seasonally, monthly, or over the growing season ?

Similarly the Agency's recommendations with respect to nutrient criteria for streams in Ecoregion IV is clearly an annual average value, because it was developed based on the 25th percentile of all seasons of data, and not a value associated with 7 day 10 year low flow conditions. It is thus inappropriate to apply this criterion to low flow conditions.

Finally, it is not clear that the set of values contained in the Nutrient Criteria Technical Guidance manual are intended to be applied at extreme low flow conditions. Moreover, that table is presented in a larger context dealing with guidance to the States as to how the States might develop state water quality standards; it is not presented as proscriptive limits that must be used. In that respect, EPA should await development of actual water quality standards for phosphorus by both Rhode Island and Massachusetts.

PLANNING ASSISTANCE TO STATES

TURNER RESERVOIR STUDY
EAST PROVIDENCE, RHODE ISLAND

February 2001

US Army Corps
of Engineers

New England District

C. Project Study Area and History

The study area is located in the city of East Providence on the Massachusetts-Rhode Island border with parts of the reservoir area extending into Seekonk, Massachusetts (see Figure 1). The James V. Turner Reservoir consists of a series of three (3) ponds with a combined surface area of 225 acres and is located at the end of the freshwater section of the Ten Mile River. The three ponds are individually named North, Central, and South Pond, but collectively known as Turner Reservoir. Below Turner Dam, at the south end of South Pond, the Ten Mile River flows about two miles to the Providence River. Total drainage area at the dam is 52.1 square miles.

Between 50 years and 100 years ago, a dam was constructed on the Ten-Mile River approximately 100 feet upstream from what is now Route 152 presumably to provide waterpower for a local mill. The resulting one-mile long impoundment is the area now known as Central and North Ponds, and consisted of approximately 100 acres of artificial lake. In 1930, another dam was constructed approximately 0.75 miles downstream from the original milldam as a water supply for the city of East Providence. The weir elevation of this new dam (Turner Reservoir Dam) was approximately 5 feet higher than that of the milldam upstream. The resulting impoundment was known as Turner Reservoir, and consisted primarily of the flooded pasture/wetland immediately downstream from the milldam (i.e. Route 152). It also included the upstream areas of Central and North Ponds, due to the higher weir elevation of the new dam, which raised the impoundment surface elevation above the previous level of Central/North Pond (i.e. overtopping the milldam). This formed the existing Turner Reservoir Central/North Pond complex. The remains of the mill dam (i.e. the water control structures) can be seen upstream from Route 152, and the weir still stands approximately 5 feet below the existing water surface.

During the period following the construction of the dam to 1969, Turner Reservoir was used as a water supply for the City of East Providence. It was discontinued due to odor and other aesthetic water quality problems. It is currently used for recreational fishing and boating.

3. Reservoir Description. James V. Turner Reservoir is located in East Providence on the Massachusetts-Rhode Island line, with parts of the reservoir extending into Seekonk, Massachusetts (See Figure 1). It consists of a series of 3 ponds with a combined surface area of 225 acres, located at the end of the freshwater section of the Ten Mile River. The route 152 causeway separates North and Central Ponds from South Pond. On some maps, North and Central Ponds are collectively labeled "Central Pond," and South Pond is labeled "Turner Reservoir." To avoid confusion, "Turner Reservoir" is used in this report to refer to all three ponds, which are individually referred to as "North," "Central," and "South" Ponds.

4. Reservoir Use. East Providence used Turner Reservoir as a public water supply source until 1969, when treatment with sand filtration followed by chlorination was no longer able to keep coliforms out of the treated water. The source of these bacteria was probably upstream wastewater discharges. Turner Reservoir is currently used for limited recreation, mainly fishing and non-motorized boating.

5. Land Use. Sections of the Ten Mile River watershed are heavily urbanized, including parts of East Providence, Pawtucket, Attleboro, and all of the urbanized area of North Attleboro. Other sections are still undeveloped, and much of this land is covered with wetlands including swamps, marshes, and open bodies of water. In additional to municipal wastewater treatment plants discharges, the Ten Mile River receives runoff from golf courses, including Slater Park, which is just upstream from Turner Reservoir's North Pond. In the past, the river also received industrial discharges including metal wastes from jewelry manufacturing. The main effects of municipal wastewater discharges and runoff from urban areas and golf courses would be to add nutrients to the river, leading to eutrophication in downstream impoundments. Urban runoff, and to a lesser extent municipal discharges, will also add coliform bacteria, metals, and organic chemicals to the river. The extensive areas of wetlands in the watershed will not remove these contaminants because the wetlands are upstream of the sources. The main effect of the wetlands in the upper watershed is to moderate flows in the river by storing and releasing runoff.

6. Reservoir Yield. Only a cursory analysis of potential water supply yield for Turner Reservoir is included in this study. The reservoir volume is not known, because siltation has undoubtedly reduced it since it was last used for water supply. However, the reservoir has a surface area of 225 acres, and very rough measurements during water quality sampling indicate it may have an average depth of 4 to 5 feet, which would give it an estimated volume of around 350 million gallons. Average daily flow can be calculated from the record at the USGS gage about 1.2 miles downstream from the dam. Using the 11-year record at the gage, from 1986 through 1997, and adjusting flows by drainage area, the average daily flow at the dam is 103 cfs (66 million gallons per day). Using a spread-sheet analysis of flow for each day of the eleven-year period of record at the gage, storage of 350 million gallons would have provided a safe yield of 16 million gallons per day. If used as a backup water supply, the reservoir could provide greater yields for shorter periods of time; however, during a serious drought the yield could be less.

United States
Environmental Protection
Agency

Office of Water
4304

EPA 822-B-01-011
December 2001

EPA

Ambient Water Quality Criteria Recommendations

Information Supporting the Development of State and Tribal Nutrient Criteria

Lakes and Reservoirs in Nutrient Ecoregion XIV

- Include variables that can be measured to determine if standards are met, and variables that can be related to the ultimate sources of excess nutrients.
- Identify appropriate periods of duration (how long) and frequency (how often) of occurrence in addition to magnitude (how much). EPA does not recommend identifying nutrient concentrations that must be met at all times; rather a seasonal or annual averaging period (e.g., based on weekly or biweekly measurements) is considered appropriate. However, these central tendency measures should apply each season or each year, except under the most extraordinary conditions (e.g., a 100-year flood).

3.0 AREA COVERED BY THIS DOCUMENT

This chapter provides a general description of the Aggregate Ecoregion and its geographical boundaries. Descriptions of the level III subecoregions contained within the Aggregate Ecoregion are also provided.

3.1 Description of Aggregate Ecoregion XIV—Eastern Coastal Plain

The **Eastern Coastal Plain** Ecoregion extends from Maine to Georgia and is a lowland dominated by woodland, urban areas, or marshland; less than 20% of the area is used as cropland and pastureland. Broad, nearly flat to depressional areas occur and have poorer drainage than neighboring nutrient regions. The northern portion of the Eastern Coastal Plain (XIV) has nutrient-poor soils and glacial drift deposits that usually mantle metamorphic and igneous bedrock; valleys contain glaciolacustrine, marine, and outwash deposits. The central and southern portions are underlain by sedimentary rock and are dominated by poorly drained soils, swampy or marshy areas, and meandering, low-gradient streams that are often tidally influenced. Urban, suburban, and rural residential, commercial, and industrial areas occupy a large and growing percentage of the region; such large human population concentrations are absent from Ecoregion VIII. Some of the biggest cities in the United States are scattered throughout the Eastern Coastal Plain (XIV) and have locally replaced the native woodland.

Lake quality in the Eastern Coastal Plain (XIV) has been significantly affected by urban, suburban, and industrial development as well as by poultry, livestock, and aquaculture operations. In Connecticut, bottom sediments have been contaminated by metals, organic compounds, and solid residuals from textile and paper mills. In Delaware, high levels of enterococcal bacteria and total nitrate concentrations occur and are the result of increasing population, wastewater discharge, and runoff from fertilized cropland, poultry operations, and urban areas. In Maine, dioxin from pulp and paper processing effluent and bacteria in untreated sewer overflow continue to be serious problems in some reaches. In Massachusetts, bacterial contamination and low dissolved oxygen concentrations persist. Throughout most of New Jersey, nutrient and fecal bacteria concentrations continue to exceed State water quality criteria. In the southern portion of Ecoregion XIV, urban areas are far fewer than in the north, and related lake water quality issues are also less. However, locally in the south, there are a large and growing number of intensive turkey, hog, and chicken operations along with associated water quality problems.

Plan for Managing Nutrient Loadings to Rhode Island Waters

State of Rhode Island
Department of Environmental Management

Prepared by the
Rhode Island Department of Environmental Management

Pursuant to RI General Law § 46-12-3(25)

February 1, 2005

[Edited February 10, 2005]

Appendix B

Schedule for Completing Water Quality Restoration Plans to Address Nutrient Impacts

WB Type	Waterbody Name	Target End Date
E	Apponaug Cove	2005
E	Brushneck Cove	2005
E	Buttonwoods Cove	2005
E	Greenwich Bay	2005
E	Greenwich Bay	2005
E	Greenwich Cove	2005
E	Greenwich Cove	2005
E	Palmer River	2005
E	Providence River	2005
E	Providence River	2005
E	Seekonk River	2005
E	Warwick Cove	2005
E	Warwick Cove	2005
L	Kickemuit Reservoir (Warren Reservoir)	2005
L	Mashapaug Pond	2005
L	Sands Pond	2005
L	Saugatucket Pond	2005
E	Greenhill Pond	2007
E	Mt. Hope Bay	2007
E	Mt. Hope Bay	2007
E	Mt. Hope Bay	2007
E	Mt. Hope Bay	2007
E	Potter Cove	2007
E	Tidal Pawcatuck River	2007
E	Upper Narragansett Bay	2007
E	Wickford Harbor	2007
L	Almy Pond	2007
L	Belleville Ponds	2007
L	Brickyard Pond	2007
L	Gorton Pond	2007
L	Hundred Acre Pond	2007
L	North Easton Pond (Green End Pond)	2007
L	Prince's Pond (Tiffany Pond)	2007
L	Roger Williams Park Ponds	2007
L	Sand Pond (N. of Airport)	2007
L	Scott Pond	2007
L	Spectacle Pond	2007

WB Type	Waterbody Name	Target End Date
L	Three Ponds	2007
L	Upper Dam Pond	2007
L	Valley Falls Pond	2007
L	Warwick Pond	2007
L	Barney Pond	2012
L	Chapman Pond	2012
L	Deep Pond (Exeter)	2012
L	Lower Sprague Reservoir	2012
L	Omega Pond	2012
L	Simmons Reservoir	2012
L	Slater Park Pond	2012
L	Turner Reservoir	2012
L	Turner Reservoir	2012
R	Cedar Swamp Brook	2012
R	Runnins River & Tribs	2012

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Eutrophication and Biological Associations

KENNETH M. MACKENTHUN

Director, Division of Applied Technology,
Environmental Protection Agency, Washington, D.C.

The enrichment of waters by nutrients through either man-created or natural means along with the attendant biological phenomena defines the term eutrophication. Present knowledge indicates that phosphorus and nitrogen are the chemical constituents usually responsible for the eutrophication phenomenon. Other elements are essential such as carbon, vitamins, and trace elements but often these are not limiting to nuisance biological development in natural lakes and streams.

Lund (48) in his thorough literature review stated that "Nitrogen and phosphorus can still be considered as two of the major elements limiting primary production. In some tropical and highly eutrophic temperate lakes, nitrogen may be a more important limiting factor than phosphorus. In many other lakes phosphorus is present in very low concentrations and seems to be the major factor limiting production. Evidence from the addition of fertilizers to fish ponds and from what is known about the eutrophication of lakes by sewage supports the view that phosphorus plays a major role in production." Carbon, as well as molybdenum, has been found to be limiting in particular natural waters (27, 42).

Evidence indicates that: (*a*) high phosphorus concentrations are associated with accelerated eutrophication of waters when other growth-promoting factors are present; (*b*) aquatic plant problems develop in reservoirs or other standing waters at phosphorus values lower than those critical in flowing streams; (*c*) reservoirs and other standing waters collect phosphates from influent streams and store a portion of these within consolidated sediments; and (*d*) phosphorus concentrations critical to noxious plant growths vary, and a given concentration will produce nuisance growths in one geographical area but not in another. Potential contributions of phosphorus to the aquatic environment have been indicated in the literature (Table 1).

The discharge of domestic sewage increases the concentration of phosphorus markedly. Organic phosphorus in the sewage and simple and complex

ƬABLE 1 Pounds of Phosphorus Contributed to Aquatic Ecosystems (51)

Major contributors
Sewage and sewage effluents: 3 lb/(capita) (year)[a]
Some industries, for example, potato processing: 1.7 lb/ton processed
Phosphate rock from 23 states (53)
Cultivated agricultural drainage: 0.35–0.39 lb/acre drained per year (24, 73, 86)
Surface irrigation returns, Yakima River Basin: 0.9–3.9 lb/(acre) (year) (81)
Benthic sediment releases
Minor contributors
Domestic duck: 0.9 lb/year (72)
Sawdust: 0.9 lb/ton (22)
Rainwater[b]
Groundwater, Wisconsin: 1 lb/9 million gal (40)
Wild duck: 0.45 lb/year (62)
Tree leaves: 1.8–3.3 lb/acre of trees per year (17)
Dead organisms; animal excretions

Various researchers have recorded the annual per capita contribution of phosphorus in pounds from domestic sewage as 2 to 4 (15), 2 and 3 (56), 1.9 (61), and ·.5 (75).

Influenced by pollution present in atmosphere "washed out" by rainfall.

ʰhosphates from synthetic detergents are the principal contributions. Decomposition of the organic material, along with soluble phosphates, esults in phosphorus concentrations in excess of the requirements for ·lant growth. The readily available soluble phosphorus often furnishes a ood source for nuisance biological growths.

EWAGE

ʾhe discharge of human wastes results in an abundance of nitrogen in all orms, causing an abrupt change in the nutrient balance of the stream. Vhen untreated domestic sewage is discharged to a watercourse, organic itrogen (proteins) and ammonia are the principal nitrogen constituents. ı the water, nitrifying organisms decompose the organic materials and xidize the ammonia to nitrite and nitrate. Since the nitrite ion is a transient orm it is usually present in very low concentrations.

Treated sewage has undergone partial oxidation in the treatment process. herefore the nitrite and nitrate forms are increased in well-treated sewage, hile the organic nitrogen and ammonia are reduced.

Phosphorus is added to receiving waters principally as a component of pollution. Once added, it is combined with other constituents in populations of bacteria, algae, vascular plants, and fish and in benthic sediments. Once nutrients are combined within the ecosystem of the receiving waters, their removal is tedious and expensive; removal must be compared to inflowing quantities to evaluate accomplishment. In a lake, reservoir, or pond, phosphorus is removed naturally only by outflow, by insects that hatch and fly out of the drainage basin, by harvesting a crop, such as fish, and by combination with consolidated bottom sediments. Even should adequate harvesting methods be available, the expected standing crop of algae per acre exceeds 2 tons and contains only about 1.5 lb of phosphorus. Similarly, submerged aquatic plants approach at least 7 tons/acre (wet weight) and contain 3.2 lb/acre of phosphorus. Probably only half of the standing crop of submerged aquatic plants can be considered harvestable. The harvestable fish population (500 lb) from 3 acres of water would contain only 1 lb of phosphorus.

Sawyer (74) discussed factors that influence the development of nuisance algal growths in lakes. The surface area is important since the accumulations of algae along the shoreline of a large lake under a given set of wind conditions could easily be much larger than on a small lake, under equal fertilization per acre. The shape of the lake determines to some degree the amount of fertilizing matter the lake can assimilate without algal nuisances since prevailing winds blowing along a long axis will concentrate the algal production from a large water mass into a relatively small area. The most offensive conditions develop during periods of very mild breezes that tend to skim the floating algae and push them toward shore. Shallow lakes, too, respond differently than deep stratified lakes in which the deeper waters are sealed off by a thermocline. In the nonstratified waters all the nutrients dissolved in the water are potentially available to support an algal bloom. In stratified waters, only the nutrients confined to the epilimnion are available except during those brief periods when complete circulation occurs.

Chu (18) found that optimum growth of all organisms studied in cultures can be obtained in nitrate–nitrogen concentrations from 0.9 to 3.5 mg/l. and phosphorus concentrations from 0.09 to 1.8 mg/l., while a limiting effect on all organisms will occur in nitrogen concentrations from 0.1 mg/l. downward and in phosphorus concentrations from 0.009 mg/l. downward. The lower limit of optimum range of phosphorus concentration varies from about 0.018 to about 0.09 mg/l., and the upper limit from 8.9 to 17.8 mg/l. when nitrate is the source of nitrogen, while it lies at about 17.8 for all the planktons studied when ammonium is the source of nitrogen. Low phosphorus concentrations may, therefore, like low nitrogen concentrations, exert a selective limiting influence on a phytoplankton population. The nitrogen concentration determines to a large extent the amount of chlorophyll formed. Nitrogen concentrations beyond the optimum range inhibit the formation of chlorophyll in green algae.

SEDIMENTS

Keup (43), in flowing water studies, found that phosphorus is temporarily stored in bottom sediments or transported as a portion of the stream's bed load after its removal from the flowing water. Long-term storage is affected when the phosphorus is pooled in deltas or deposited on flood plains. Keup reviewed the literature on phosphorus discharges by specific streams (Table 2).

Sediments may serve only to support the water, or they may have a profound effect on the quality of the water that comes in contact with them. In a lake which man has not polluted seriously, the lake bed will resemble the soils of the surrounding land. As man "civilized" an area by plowing fertilized fields, and by discharging sewage and industrial wastes to the watercourse, lake-bed sediments assumed different characteristics because of the materials that became a part of them. Concentrations of certain materials in the sediments became greater, the soil chemistry more complex, and biological populations more numerous and specialized.

Matter that can settle may transport nutrients to the sediments by ion-exchange and sorption mechanisms. As coarser and denser materials settle rapidly, large quantities of nutrients may be effectively removed and buried. Thomas (84) observed a phosphorus reduction (as P) from 2000 to 150 μg/l. as particulate matter settled from water passing through a 25-mi-long reservoir that received 6,629,000 tons of sediments annually. The particle size of the suspended sediment was very small and was comprised of 54% clay, 40% silt, and 6% sand. Also, once a dissolved nutrient is incorporated into an organism, the tendency is for it to deposit as a solid. Metabolic cycling may delay settling of some elements such as nitrogen, carbon, or phosphorus; for other elements such as silicon, when "fixed" as a diatom valve, the fate of deposition is nearly assured.

The contribution of nutrients and phosphorus in particular from consolidated lake-bed sediments to the water's biodynamic cycle is a variable factor that depends to a great extent on the physical-chemical aspects of the environment. There is evidence to indicate that in an undisturbed mud-water system the amount of phosphorus released to the superimposed water is very small (30, 87).

Nutrients in the sediment have been found to be more important as a growth c ibutor for sago pond weed than nutrients in the water (64).

TABLE 2 Phosphorus Discharged by Selected North American Streams (43)

Principal Land Use	River	Number of Analyses	Season of Sampling	Drainage Area (mi²)	Phosphorus (P) [lb/(annum)(mi²)]	Population Density (mi²)	Ref.
Forested	West Branch Sturgeon R. Mich.	27+	July	14	37	Sparse	8
	Pigeon, Minn.	4	Aug. and Sept.	600	28	Sparse	67, 68, 5
	Poplar, Minn.	4	Aug. and Sept.	114	21	Sparse	67, 68, 5
	Baptism, Minn.	4	Aug. and Sept.	140	42	Sparse	67, 68, 5
	St. Louis, Minn.	4	Aug. and Sept.	3430	58	Sparse	67, 68, 5
	Bois Brule, Wis.	4	Aug. and Sept.	113	97	Sparse	67, 68, 5
	Bad, Wis.	4	Aug. and Sept.	611	78	Sparse	67, 68, 5
	Montreal, Wis.	4	Aug. and Sept.	281	98	Sparse	67, 68, 5
	Black, Mich.	4	Aug. and Sept.	202	65	Sparse	67, 68, 5
	Presque Isle, Mich.	4	Aug. and Sept.	260	39	Sparse	67, 68, 5
	Ontonagon, Mich.	4	Aug. and Sept.	1290	44	Sparse	67, 68, 5
	Yakima, Wash.	?	Annual	182	473	Sparse	81
	Tieton, Wash.	?	7 months	237	492	Sparse	81
	Cedar, Wash.	?	Annual	125	204	Sparse	81
	Mulligan, Maine	12	4 seasons	21	4	Sparse	6
	Stetson, Maine	19	4 seasons	29	20	Sparse	6
	East Branch Sebasticook, Maine	56	4 seasons	56	128[a]	>63[b]	6
	Ellershe, Prince Edward Island	44	April–Dec.	10	113	Sparse	79
	Pigeon, N.C.	18	July	133	97	Light	This article
	Johnathans, N.C.	5	July	65	201	Light	This article
	Kankakee, Ind. and Ill.	6	June–Sept.	5280	139	28	34, 4
	Vermillion, Ill.	8	June–Sept.	1230	179	36	34, 4
	Fox, Ill. and Wis.	7	June–Sept.	2570	489	145	34, 4
Agricultural	Kaskaskia, Ill.	100	April–Dec.	5220	225	>174[b]	24
-ban	Streams near Madison, Wis.	?	?	?	235–262	?	73
	Du Page, Ill.	5	June–Sept.	325	18	380	34, 4
	Des Plaines, Ill. and Wis.						
	Above confluence with Chicago River	5	June–Sept.	635	570	1270	34, 4
	Total basin (includes Chicago River)	19	June–Sept.	2180	4020	2570	34, 4
	Chicago, Ill.	16	June–Sept.	810	6540	5650	34, 4

[a] One seasonal (9 months) industry contributes approximately 75%.
[b] Only sewered population known.

Plants with extensive root systems aid in recycling nutrients that have been buried below the interface and are otherwise unavailable to the overlying water.

BENTHIC ORGANISMS

Benthic organisms may transfer nutrients when that exchange is not reduced or prohibited by overlying materials. In a study on Connecticut lake sediments, Hutchinson and Wollack (36) found that diffusion of phosphorus from the mud may be aided by the metabolic activities of benthic organisms. Studies by Hooper and Elliott (33) on two species of protozoa indicated that organisms were capable of breaking down organic phosphates to inorganic phosphorus in aerobic conditions.

In addition to metabolic activities, benthic organisms may, through burrowing activities, resuspend or redeposit nutrients on the mud surface that would otherwise have been lost from the system. Aquatic oligochaetes may ingest quantities of material 2 to 3 cm below the interface, and midges may scrape up detritus from a depth of 5 to 10 mm (65). Aquatic organisms such as fishes also contribute to the overturn of bottom muds. In fish ponds located in Israel, phosphorus fixation was higher when mud was mixed with water by carp in the ponds (31). Other bottom-feeding fish such as catfish and bullheads probably contribute also to the overturn of bottom muds and the resultant release of nutrients as they disturb the bottom during feeding activities.

EFFECTS OF EUTROPHICATION

Jónasson (38) concluded that the bottom fauna fits into an ecological pattern set by primary production of algae, vertical distribution and abundance of macrophytes, dissolved oxygen, and nutrients. Increasing the supply of nutrients to the epilimnion causes increases in the standing crop and in the production of phytoplankton; transparency decreases; subsurface light dwindles; the macrophytes are excluded from deeper waters and eventually from the lake because of inadequate light; periods of dissolved oxygen deficiency become more prolonged; hypolimnionic pH decreases; and alkalinity increases. These environmental factors all have an adverse effect on benthos and may result in restricting the benthic inhabitants to a few midges and worms.

Larkin and Northcote (45) note that the eutrophication of lakes affects fish in many ways. These result primarily from the increase in production, the consequent deoxygenation of the hypolimnion and other waters, and the alteration of many other features of the biological environment that determine survival and abundance of various fish species. The abundance of food organisms caused by eutrophication may accelerate greatly the growth rate of the fish. On the other hand, eutrophic environments may force certain species such as ciscoes to live under undesirable conditions of temperature and dissolved oxygen, and they will fail to thrive even in the presence of abundant food (32).

When given the opportunity and because fish are mobile, they may respond to adverse environmental changes by moving from the area, to which they may return when conditions for existence become improved. On other occasions they may not be given the opportunity. Mackenthun *et al.* (52) reported an extensive mortality of fish resulting from the decomposition of algae that were flushed to the Yahara River through the control gates on Lake Kegonsa, Wisconsin. The lake was made eutrophic principally because of the inflow of treated sewage effluent. This, and particular climatological phenomena, resulted in a prolific algal growth that formed a thick scum several acres in area. When this decomposing mass was flushed to the river it eliminated the dissolved oxygen, and the water exhibited toxic properties.

As noted by Larkin and Northcote (45):

> More than 40 years ago, A. S. Pearse studied several lakes in Wisconsin, and his review on the ecology of lake fishes summarizes major differences in the quantity and species composition among the various lake types (63). Increasing eutrophy is associated with greater production. The largest oligotrophic lakes are dominated by salmonids and coregonines, whereas smaller oligotrophs support centrachids in abundance as well as coregonines. Such eutrophic lakes as Mendota, in Pearse's day produced large quantities of perch, largemouth bass, white bass, rock bass, carp, and buffalofish. The shallow Lake Wingra (maximum depth, 4.3 m) produced large quantities of carp, crappie, sunfish, dogfish, and perch. In the words of Pearse, 'Each lake presents a type in which one or more species of fishes may be at their best and become dominant.' It is scarcely surprising that with the changes attendant upon eutrophication, changes in fish populations should ensue.

Enrichment may cause both an increase and a decrease in fish growth in different stream sections. Environmental changes resulting from enrichment influence the total stream length inhabited by particular associations of fish. The coarse fishes normally associated with downstream reaches tend to move into the enrichment zone and often the finer fishes are reduced substantially or eliminated.

ASSESSMENT OF NUTRIENT PROBLEM

To assess a nutrient problem properly, consideration should be given to all of those sources that may contribute nutrients to the watercourse. These sources could include sewage, sewage effluents, industrial wastes, land drainage, applied fertilizers, precipitation, urban runoff, soils, and nutrients released from bottom sediments and from decomposing plankton. Transient waterfowl, falling tree leaves, and groundwater may contribute important additions to the nutrient budget. Flow measurements are paramount in a study to assess quantitatively the respective amounts contributed by these various sources during different seasons and at different flow characteristics. In the receiving lake or stream the quantities of nutrient contained by the standing crops of algae, aquatic vascular plants, fish, and other aquatic organisms are important considerations. A knowledge of those nutrients that are harvested annually through the fish catch, or that may be removed from the system through the emergence of insects, will contribute to an understanding of the nutrient budget.

The interaction of specific chemical components in water, prescribed fertilizer application rates to land and to water, minimal nutrient values required for algal blooms, vitamins required, other limiting factors, and the intercellular nitrogen and phosphorus concentrations are likewise important. Usually, it is necessary to determine that portion of the nutritive input attributable to man-made or man-induced pollution that may be corrected as opposed to that input that is natural in origin, and therefore usually not correctable. A nutrient budget is used to determine the annual input to a system, the annual outflow, and that which is retained within the water mass to recycle with the biomass or become combined with the solidified bottom sediments. The carbon, nitrogen, phosphorus, and their respective ratios are important values to aid in the identification of a material, to calculate the amount of major nutrients contained within a segment of the biomass or a stratum of sediment, and from which to judge the relative input of nutrients to the water mass when the ecosystem component undergoes decomposition, or natural chemical change (Table 3).

FIELD INVESTIGATIONS

The conduct of a field investigation to define the effects of eutrophication on the living aquatic resource involves a number of important sequential considerations. These considerations are formulation of objectives to define the problem and delimit the scope of the study; planning in detail the logical

TABLE 3 Carbon, Nitrogen, and Phosphorus in Freshwater Environmental Constituents (50)

Constituent	Standing Crop (lb/acre) Wet	Dry	%C[a]	%N[a]	%P[a]	Ratio C:N	N:P	Ref.
Phytoplankton	1,000–3,600	100–360						
								11
				6.8	0.69		10	26
			39	6.1	0.64	6.5	10	54
Attached algae	2,000	200		9.0	0.52		17	11
								59
Vascular plants	14,000	1,800		2.8	0.14		2	11
								69, 70
Myriophyllum				1.8	0.18		10	28
Vallisneria				3.2	0.52		6	11
Potamogeton				1.8	0.23		8	77, 78
Castalia				1.3	0.13		10	77, 78
Najas				2.8	0.27		10	77, 78
Myriophyllum				1.9	0.30		6	77, 78
Bottom organisms				3.0	0.5		6	2
Midges	200–400	40–80						
Chironomus								21, 58
Hyalella				7.4	0.9		8	14
Hirudinea				7.4	1.2		6	11
Sialis				11.1	0.8		14	11
Fish	150–600			8.1	0.6		14	11
								80
				2.5[b]	0.2[b]		10	9
				2.8	0.18–0.49			13
					0.19			46

TABLE 3 (continued)

Constituent	Standing Crop (lb/acre) Wet	Dry	%C[a]	%N[a]	%P[a]	Ratio C:N	N:P	Ref.
					0.20			55
					0.29			82
				2.6–3.3	0.18–0.24			37
Domestic wastes[a]					5.1–10.6[d]			24
				45[d]	8[d]		6	55
				20–40[d]	5.3–10.6[d]		4	15
				61.3[d]	10.7[d]		6	60
				18–28[d]	3.5–9.0[d]			7
Sediments								
Lake Tahoe			0.6–19.8	0.6–1.6		4–25		55
Wisconsin lakes			4.4–40.5	0.6–3.6	0.12–0.6	8–14	5–6	12, 41
Madison, Wisconsin lakes				0.7–0.9	0.1–0.12		6–9	76
Green Lake				0.6	0.17		4	82
Lake Sebasticook			10–34	0.3–1.8	0.06–0.16	8–44	5–16	54
Klamath Lake			8.6	1.2		7		Thomas, N. A., unpublished[f]
Boston Harbor			2.3–5.0	0.06–0.41				Stewart, R. K., 1968[e]
Organic river sediments			0.03	0.0027		12		25
Pulp and paper wastes in river			5.3	0.23		22		25
Untreated domestic wastes			3.54	0.3		12		25
Untreated chemical and fertilizers and domestic wastes			3.15	0.12		26		25
No tributary wastes			0.55	0.05		11		25
Sand: silt; clay; loam			0.4–2.1	0.02–0.10		20		Ballinger and McKee, unpublished[f]
Stable sludge; peat; organic debris			2.0–5.0	0.10–0.20		20–25		Ballinger and McKee, unpublished[f]
Paper mill wastes			6–15	0.10–0.30		50–60		Ballinger and McKee, unpublished[f]
Packinghouse wastes			2.8–4.3	0.30–0.50		8–10		Ballinger and McKee, unpublished[f]
Fresh sludge; decaying algae; sewage solids			5–40	0.70–5.0		7–8		Ballinger and McKee, unpublished[f]
Log pond bark			50.6	0.5	0.02	100	25	Thomas, N. A., unpublished[f]
Sewage sludge in river			5.8	0.28	0.18	21	2	Thomas, N. A., unpublished[f]
Algae; sawdust; sewage			14.6	0.93	0.11	16	9	Thomas, N. A., unpublished[f]

TABLE 3 (continued)

Constituent	Standing Crop (lb/acre) Wet	Dry	%C[a]	%N[a]	%P[a]	Ratio C:N	N:P	Ref.
Leaf litter			28.3	1.63	0.11	17	15	Warner, R. W., *et al.*, 1969[g]
Sand			0.2	0.02	0.005	10	4	Warner, R. W., *et al.*, 1969[g]
Loam			2.7	0.19	0.02	14	10	Warner, R. W., *et al.*, 1969[g]
Muck			7.3	0.52	0.04	14	13	Warner, R. W., *et al.*, 1969[g]
Floating waste wool			37–43	3.4–4.7	0.08–0.09	9–11	38–58	[h]

[a] As the total element in percentage of the dry weight, unless specified otherwise.
[b] Calculated on wet weight.
[c] Average sewage flow can be calculated at 100 gal per capita per day.
[d] mg/l.
[e] *Biological Aspects of Water Quality, Charles River and Boston Harbor, Massachusetts*, by R. K. Stewart, Technical Advisory and Investigations Branch, Cincinnati, Ohio, 1968.
[f] Technical Advisory and Investigations Branch, Cincinnati, Ohio.
[g] Analyses of soil types from *Black Water Impoundment Investigations*, by R. W. Warner, R. K. Ballentine, and L. E. Keup, Technical Advisory and Investigations Branch, U.S. Department of the Interior, Cincinnati, Ohio, 1969.
[h] *Fertilization and Algae in Lake Sebasticook, Maine*, Department of Health, Education, and Welfare, Technical Advisory and Investigations Activities, Cincinnati, Ohio, 1966.

events that will lead to a successful study and the many details necessary t ensure success in each phase of the investigation; data collection, whic involves a selection of sampling sites, a judgment of the required number (samples, and a decision on the proper time, type, periodicity, and extent (sample collection; sample and data analyses and interpretation; and reportin of results with conclusions, recommendations, and predictions.

The first field study in the United States to address itself to the comple problem of determining a lake nutrient budget was that of Sawyer *et al.* (76) The essence of this report was later published (73). This 2-year study showe that Lake Waubesa, at Madison, Wisconsin, received at least 75% of it inorganic nitrogen and 88% of its inorganic phosphorus from sewage effluen One facet of this study was historic because from it came the now famous an oft-quoted conclusion that a 0.30 mg/l. concentration of inorganic nitrogen (N and a 0.010 mg/l. concentration of soluble phosphorus (P) at the start of th active growing season could produce nuisance algal blooms. This conclusio was based on the correlation of results of monthly nutrient and algal sampl examinations from 16 southeastern Wisconsin lakes. Although these obser vations were confined to one geographical area, they have been substantiate reasonably well in subsequent field and laboratory studies on waters i which the total methyl orange alkalinity exceeds 40 mg/l.

PRESERVATION

To prevent biological nuisances in most waters, total phosphorus shoul not exceed 100 μg/l. P at any point within the flowing stream, nor shoul

TABLE 4 Total-to-Soluble Phosphorus Ratios in Water

Water	Total P to Soluble P	Ref.
Western Lake Erie	3.5	16
Detroit River mouth	5–7	PHS Detroit Project
Linsley Pond, Conn.	10.0	35
Northern Wisconsin lakes	7.0	40
Northeast Wisconsin lakes	2–10	39
Ontario lakes (8)	17	71
Southeast Wisconsin lakes (17)	9	Mackenthun, unpublished
Rock River, Wis.	2–15	Mackenthun, unpublished
Sebasticook Lake, Maine	2.8 Winter	54
	12.7 Spring	54
	7.0 Summer	54
	4.1 Fall	54

Lake	State	Nitrogen (N) Loading [lb/(year acre)]	Nitrogen (N) Retention (%)	Phosphorus (P) Loading [lb/(year acre)]	Phosphorus (P) Retention (%)	Ref.
Washington	Wash.	280	—	12		1
Mendota	Wis.	20[a]	—	0.6[b]		3
Monona	Wis.	81[a]	48–70	7.5[b]	64–88	44
Waubesa	Wis.	435[a]	50–64	62.8[b]	−26–25	44
Kegonsa	Wis.	162[a]	44–61	35.9[b]	−21–12	44
Tahoe	Calif.	2	89	0.4	93	47
Koshkonong	Wis.	90	80	40	30–70	Mackenthun, unpublished
Green	Wash.	—	—	4.8	55	82
Geist	Ind.	440[a]	44	28	25	Mackenthun, unpublished
Sebasticook	Maine	—	—	2	48	Mackenthun, unpublished
Ross R. Barnett	Miss.	—	—	32	—	Mackenthun, unpublished

[a] Inorganic nitrogen only.
[b] Soluble phosphorus only.

50 μg/l. be exceeded where waters enter a lake, reservoir, or other ... .ding water body (49). Those waters now containing less phosphorus should not be degraded because even lower concentrations may be critical in very low alkalinity waters. Adequate phosphorus controls must now be directed toward treatment of nutrient point sources and to wastewater diversion around the lake or dilution within the lake, where feasible.

PHOSPHORUS SOLUBILITY DISTRIBUTION

Total-to-soluble phosphorus ratios may vary from 2 to 17 or even 90%, dependent on the particular water, season, aquatic plant populations, and probably other factors (Table 4). These ratios are of value when they can be determined periodically within the same water body and changes in them correlated with volumetric response changes within the algal mass.

The nutrient loading to the lake on a unit basis gives some measure of comparability among various water bodies (Table 5). Likewise, a lake or reservoir usually retains a portion of those nutrients that it receives from its various sources. The amount or percentage of the nutrients that may be retained by a lake or reservoir is variable and will depend on (*a*) the nutrient loading to the lake or reservoir; (*b*) the volume of the euphotic zone; (*c*) the extent of biological activity; (*d*) the detention time within the basin or time allotted for biological activity; and (*e*) the level of the penstock or discharge from the basin.

Long-term remedial measures might be focused on reducing the nutrient concentration in troublesome areas or in altering some aspect of the topography that concentrates or fosters the development of nuisance algae or aquatic weeds. Such measures often involve costly physical modifications to correct existing conditions, as well as future planning to assure wise use of the area's natural aquatic resources.

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Phosphorus and Ecology

CLAIR N. SAWYER, PhD

Consultant, Sun City, Arizona

"OHNE PHOSPHOR KEIN LEBEN" ANONYMOU

ECOLOGICAL CONSIDERATIONS

In considering the ecological aspects of phosphorus, or any other element for that matter, it is well to remember that a finite amount of each exists and that the Law of Conservation of Matter applies to all, save the radioactive ones. Seldom are the elements per se of significance in environmental considerations, except for mining and refining operations involved in winning the elements from their ores. Of vastly greater importance are the compounds that are generated from the elements to meet the demands of our modern civilization. Although these compounds are usually widely disseminated throughout populated, and sometimes unpopulated, areas of the world, some of them, unfortunately, tend to become concentrated in certain areas. The soluble phosphate compounds are a classical example.

PHOSPHORUS DISTRIBUTION IN VARIOUS ECONOMIES

Agrarian

Cropping of land exerts a constant drain upon the phosphorus resources of the soil. Table 1 shows the phosphorus content of a wide variety of crops and food products derived from them. Continual removal of crops without recycling results in a depletion of available phosphorus in the soil, and crop yields eventually become limited by the amount released by natural weathering action of the soil.

providing only an approximation for floc size-density relationships.

2. Laboratory measurements of the densities of iron(III) flocs indicate that a size-density variation does exist. Moreover, the size-density relationship observed was, for flocs smaller than about 1 sq mm in projected area, comparable to that predicted by the Vold model.

3. The laboratory observations of the floc size-density relationship support

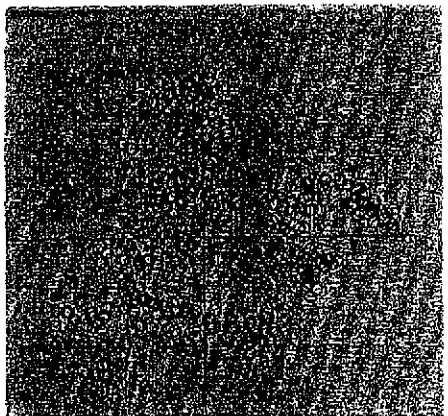

Fig. 6. Floc Aggregates

These third level floc aggregates are comprised of 601 primary particles.[5]

the hypothesis (advanced by others) of multiple levels or stages (at least three) of floc aggregation.

4. The intensity of agitation provided during flocculation does not affect floc density significantly, size-for-size. It does, however, alter the floc size-frequency distribution and thereby the density characteristics of the suspension.

5. Limited studies with the coagulant aid mentioned above indicate that this polyelectrolyte, used in small concentration along with ferric sulfate, does not alter floc densities, size-for-size, but does increase floc strength as indicated by the observation that larger flocs were formed when it was used.

6. Floc size distributions obtained from settling column analyses should be viewed with considerable skepticism unless the floc size-density variation was taken into account.

Acknowledgment

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The Phosphorus Problem

Kenneth M. Mackenthun

A contribution submitted to the JOURNAL *on Jun. 7, 1968, by Kenneth M. Mackenthun (Active Member, AWWA), Acting Chief, Bio. and Chem. Section, Tech. Advisory and Investigations Branch, Div. of Tech. Services, FWPCA, US Dept. of the Interior, Cincinnati, Ohio.*

"REDUCE phosphorus in waste-water sources" has become a slogan to those who would decelerate cultural eutrophication. Phosphorus is a nutrient that often is limiting to aquatic plant growths. When present in excess of a critical concentration, however, and when other environmental conditions are favorable, phosphorus can stimulate plant growths that produce scums and odors and destroy water uses. Although present in sewage, phosphorus concentrations in domestic and industrial wastes can be reduced by treatment, for unlike nitrogen, another essential plant nutrient, phosphorus cannot be fixed from the atmosphere by plants and added to the aquatic ecosystem.

Eutrophication

Eutrophication is a term meaning enrichment of waters by nutrients through either man-created or natural means. Present knowledge indicates that the fertilizing elements most responsible for lake eutrophication are phosphorus and nitrogen. Iron and certain "trace" elements are also important. Sewage and sewage effluents contain a generous amount of those nutrients necessary for algal development.

Lake eutrophication results in an increase in algal and weed nuisances and an increase in midge larvae, whose adult stage has plagued man in Clear Lake, Calif., Lake Winnebago, Wis., and several lakes in Florida. Dense algal growths form surface water scums and algal-littered beaches. Water may become foul-smelling. Filter-clogging problems at municipal water installations can result from abundant suspended algae. When algal cells die, oxygen is used in decomposition, and fish kills have resulted. Rapid decomposition of dense algal scums, with associated organisms and debris, gives rise to odors and hydrogen sulfide gas that creates strong citizen disapproval; the gas often stains the white lead paint on residences adjacent to the shore.

Certain algae are known to be toxic to animals. Water in which certain blue-green algae have bloomed may produce death in mammals and fish, even when the algal cells themselves are excluded. Humans who have accidentally swallowed several mouthfuls of lake water containing an algal scum have suffered severe gastrointestinal distress.

Nitrogen and phosphorus are necessary components of an environment in which excessive aquatic growths arise. Algal growth is influenced by many varied factors: vitamins, trace metals, hormones, auxins, extracellular metabolites, autointoxicants, viruses, and predation and grazing by aquatic animals. Several vitamins in small quantities are requisite to growth in certain species of algae. In a freshwater environment, algal requirements are met by vitamins supplied in soil runoff, lake and stream bed sediments, solutes in the water, and metabolites produced by actinomycetes, fungi, bacteria, and several algae.

Evidence indicates that: (1) high phosphorus concentrations are associated with accelerated eutrophication of waters, when other growth-promoting factors are present; (2) aquatic plant problems develop in reservoirs or other standing waters at phosphorus values lower than those critical in flowing streams; (3) reservoirs and other standing waters collect phosphates from influent streams and store a portion of these within consolidated sediments; and (4) phosphorus concentrations critical oxious plant growths vary producing such growths in one geographical area, but not in another.[1]

Micronutrients (iron, manganese, copper, zinc, molybdenum, vanadium, boron, chlorine, colbalt, silicon) are generally present in freshwater environments in the small concentrations sufficient for plant growth. Vitamins are synthesized by several organisms. Phosphorus, however, is an element found in large quantities in municipal and some industrial wastewaters, and with other water quality characteristics, when it is introduced into the aquatic ecosystem in amounts greater than those found in unpolluted environments, plant problems develop. Using contemporary techniques, phosphorus can be more feasibly reduced in wastewaters than can other constituents essential to the development of aquatic plants. It is logical, then, that diligent effort be made to minimize phosphorus inflows into waterways if they

TABLE 1

Pounds of Phosphorus to Aquatic Ecosystem

Controllable		Uncontrollable	
Major	Minor	Major	Minor
Sewage: 3/capita/yr*	Domestic duck: 0.9/year[11]	Phosphate rock, 23 states[6]	Rainwater**
Some industries, e.g., potato processing: 1.7/ton processed	Sawdust: 0.9/ton[12]	Cultivated agricultural drainage: 0.35–0.39/acre drained/year[7,8,9]	Groundwater, Wis.: 1/9×10⁶ gal[14]
		Surface irrigation returns, Yakima River Basin: 0.9–3.9/acre/year[10]	Wild duck: 0.45/year[15]
		Benthic sediment release	Tree leaves: 1.8–3.3/acre of trees/year[16]; Dead organisms; fecal pellets

* Various researchers have recorded the annual/capita contribution of phosphorus in pounds from domestic sewage as 2 to 4 (2), 2, 3 (3), 1.9 (4), and 3.5 (5).
** Influenced by pollution present in atmosphere "washed out" by rainfall.

are to be preserved in a usable state, both for recreative and other essential purposes.

Sources

Depending on their contributions to the aquatic ecosystem (not to sustain life, but to encourage its production to nuisance proportions), sources of phosphorus may be classed as major and minor. Phosphorus amounts in these sources are controllable or incontrollable, within the limits of economics and present technology (Table 1).

In the ecosystem, phosphorus is found in solution and is bound in bacteria, algae, zooplankton, vascular plants, benthos, fish, and fecal pellets (Table 2). Some phosphorus bound in this manner is in "temporary storage" and, upon death of the organism, becomes available to support life within the standing body of water.

Watt and Hayes[24] found that organic phosphorus compounds were released into solution from dead or dying organisms. Rapidly growing populations of bacteria and green plants did not release organic phosphorus compounds. Dissolved organic phosphorus compounds were absorbed by bacteria and broken down, and inorganic phosphorus was released.

Animal excretions are a major source of plant nutrients in the sea and also contribute nutrients in fresh water. According to Johannes,[25] the rate of excretion of dissolved phosphorus per unit weight increases as body weight decreases. As a result, microzooplankton may play a major role in planktonic nutrient regeneration. Although data are not available on quantitative nutrient excretions from these organisms in the freshwater ecosystem, the importance of this as a continuing nutrient source must be considered.

Cultures of bacteria and mixed microorganisms have been found to actively release a large portion of their phosphorus to the medium in a matter of hours, when kept under anoxic conditions. Only phosphorus is lost, probably as orthophosphate and apparently from the acid-soluble fraction of the cells. The process is completely reversible under aeration.

TABLE 2

Standing Crop Per Surface Acre in Lakes

	Phytoplankton	Attached Algae	Submerged Vascular Plants	Fish	Midges
Wet weight—*lb*	1,000-3,600 (16)	2,000 (17)	14,000 (18)	150-600 (19)	200-400 (20)
Dry weight—*lb*	100-360	200	1,800	—	40-80
Percentage N (dry wgt)	6.8 (21)	2.8 (16)	1.8 (22)	2.5 (23)	7.4 (16)
Percentage P (dry wgt)	0.69	0.14	0.18	0.2	0.9
N in crop—*lb*	7-25	6	32	3.8-15	3-6
P in crop—*lb*	0.7-2.7	0.3	3.2	0.3-1.2	0.4-0.7
Harvestable N—*lb*	—	—	16	1.0-3.8	0.2-0.4
Harvestable P—*lb*	—	—	1.6	0.1-0.3	0.02-0.04

Nuisance Plant Growths

Important factors affecting aquatic growths include temperature, sunlight and its penetration in water, size, shape, type of substratum, and contour of lake basin, and water quality. The total supply of an available nutrient depends on the total volume of water and concentration of the element in the water. The surface area is important because accumulations of algae along the shoreline of a large lake, under a given set of wind conditions, could easily be much larger than on a small lake, under equal fertilization per acre. The shape of the lake determines to some degree the amount of fertilizing matter the lake can assimilate without algal nuisances, for prevailing winds, blowing along a long axis, will push the algal production of a large water mass into a relatively small area. The most offensive conditions develop during periods when very mild breezes send floating algae toward windward shores. Shallow lakes, too, respond differently than deep, stratified lakes, where the deeper waters are seasonally confined as separate volumes by a thermocline. In nonstratified waters all nutrients dissolved are potentially available to support algal bloom. When waters stratify, only nutrients confined to the epilimnion are available, except during those periods when complete circulation occurs.

Sawyer [8] studied the southeastern Wisconsin lakes and concluded that a concentration of 300 μg/l of inorganic nitrogen (N) and 10 μg/l of soluble phosphorus (P) at the start of a growing season may help produce nuisance algal blooms. Chu [27] found that optimum growth of organisms studied in cultures can be obtained in phosphorus concentrations from 90 to 1,800 μg/l, while a limiting effect on organisms occurs when phosphorus concentration is 9 μg/l or less. The lower limit of optimum growth occurred in phosphorus concentrations from about 18 to about 90 μg/l, which may exert a selective limiting influence on a phytoplankton population.

Experiments by Ketchum [28] with the diatom, *Phaeodactylum*, show a reduction in rate of cell division, when phosphate in the medium is less than 17 μg/l P. Strickland [29] states that the limiting phosphorus concentration in some cultures is less than 5 μg/l. The problem is complicated, because auxiliary compounds may affect the availability of phosphate to a plant cell. Sylvester [19] found that nuisance algal blooms began in Seattle's Green Lake (a very soft-water lake) when nitrate nitrogen (N) levels were above 200 μg/l and soluble phosphorus (P) levels were greater than 10 μg/l.

Because the ratio of total phosphorus to that form of phosphorus readily available for plant growth is constantly changing, it is desirable to establish limits on the total phosphorus, rather than on that portion that may be available for immediate plant use. Most relatively uncontaminated lake districts are known to have surface waters that contain 10–30 μg/l total phosphorus (as P); in waters that are not obviously polluted, higher values may occur.[30] Data collected by the FWPCA, Division of Pollution Surveillance, indicate that total phosphorus concentrations, principally in streams, exceeded 50 μg/l (P) at 48 per cent of the stations sampled across the nation and averaged less than 50 μg/l at 52 per cent. Some potable surface water supplies now exceed 200 μg/l (P). Turbidity in many of the nation's streams, however, negates the algal-producing effect of high phosphorus concentrations.

To prevent biological nuisances, total phosphorus concentrations should not exceed 100 μg/l at any point within a flowing stream, nor should 50 μg/l be exceeded where waters enter a lake, reservoir, or other standing water body. Waters now containing less than the specified amounts of phosphorus should not be degraded by the introduction of additional phosphates.

When waters are detained in a lake or reservoir, the phosphorus concentration is reduced by precipitation or uptake by organisms, with subsequent deposition in sediments as fecal pellets or dead organism bodies. Some receiving waters may experience algal nuisances at and below the proposed phosphorus level in influent streams. Suggested phosphorus limits will restrict noxious aquatic plant growths in flowing waters and should restrict such growths in other waters that receive these flowing streams.

Control

Many measures have been proposed to limit the eutrophication problem in lakes, ponds, and reservoirs. Some of these are: dredging, algal harvesting, tertiary treatment of wastewaters, fish harvesting, diversion of wastes around lakes, dilution of standing waters with waters of lower nutrient concentrations, treatment of inflowing streams to remove phosphates, and sealing off benthic sediments with inert materials. Within the present state of the art, adequate controls are limited to treatment of point sources to remove nutrients and to diversion or dilution, where feasible.

The relationship of the total volume of water in the lake or reservoir to the area of land drained is important. For example, when the 3-month inflow of nitrogen and phosphorus from nonpoint waste sources within the drainage basin exceeds the quantity of those elements within the receiving waters, eutrophication deceleration may be impossible without drastic land management changes. The critical ratio of lake volume (acre-feet) to land drainage (square mile) will depend on detention time within the lake, lake depth, interchange with lake bed sediments, and the pounds of inflowing nutrients. In fertile agricultural areas, where runoff may contribute 250 lb of phosphorus per square mile of watershed per year, 1,800 acre-ft of storage might be necessary for each square mile of drainage area to prevent nuisance algal blooms from runoff alone. This assumes a detention time approximating 1 year and a 50 per cent reduction of inflowing phosphorus per year within the lake.

Once nutrients are combined within the ecosystem of the receiving waters, their removal is tedious and expensive; removal must be compared to inflowing quantities to evaluate accomplishment. In a lake, reservoir, or pond, phosphorus is removed naturally only by outflow, by insects that hatch and fly out of the drainage basin, by harvesting a crop, such as fish, and by combination with consolidated bottom sediments. Even should adequate harvesting methods be available, the expected standing crop of algae per acre exceeds 2 tons and contains only about 1.5 lb of phosphorus. Similarly, submerged aquatic plants could approach at least 7 tons/acre (wet weight) and contain 3.2 lb/acre of phosphorus (Table 2). Probably only half of the standing crop of submerged aquatic plants can be considered harvestable. The harvestable fish population (500 lb) from 3 acres of water would contain only 1 lb of phosphorus.

Dredging has often been suggested as a means of removing the storehouse of nutrients contained within the lake bed sediments. These sediments are usually rich in nitrogen and phosphorus, for they represent the accumulation of years of settled organic materials. Some of these nutrients are recirculated within the water mass and furnish food for a new crop of organic growth.

Hasler[31] found that, in an undisturbed mud-water system, the percentage of nutrients, as well as the amount of phosphorus that is released to the superimposed water, is very small. In laboratory experiments, when P^{32} is placed at various depths in the mud, the diffusion into the overlying noncirculating water is negligible, if the phosphorus is placed more than 1 cm in the mud. Application of lime to the water or mud reduces the amount of soluble phosphorus released. Acidification of previously alkalized mud will, upon agitation, increase the amount of phosphorus entering solution. In an aquarium experiment, circulation of the water above phosphorus-rich mud, with the aid of air bubbles, increased the phosphorus in solution.

Zicher *et al.*[32] found in laboratory experiments that the percentage of phosphorus released to water from radioactive superphosphate fertilizer placed in an undisturbed mud-water system was very small, with virtually no release of phosphorus from fertilizer placed at depths greater than ½ in. below the mud surface. Radiophosphorus placed ½ in. below the mud surface showed only a very slight tendency to diffuse into the water, while the radiophosphorus placed at a 1-in. depth did not diffuse into the water at all.

Dredging deepens an area within a lake and can be beneficial if the increased depth is sufficient to prevent growth of larger nuisance plants. Dredging uncovers yet another soil strata that will contain phosphorus in some quantity, subject to solution in water. The newly dredged area immediately begins to receive organic fallout from waters above, forming a new interface at which nutrient exchange is substantial. Sediments disturbed during a dredging operation liberate nutrients at a rate more rapid than sediments left undisturbed and all of these factors must be considered when recommending dredging for nutrient removal. Based entirely on nutrient considerations, dredging can be advantageous only when it removes sediments that contain a higher concentration of nutrients than the interface likely to be formed by fallout.

The chemical precipitation of phosphates as a treatment supplemental to conventional secondary processes is now feasible, both technologically and financially. Without question, other technological advances in nitrogen and phosphorus removal from wastewaters will be forthcoming. Wastes usually are discharged initially into flowing waters. These waters often enter lakes and reservoirs before their added nutrients are spent. To maintain receiving waters in a condition satisfactory for multiple use, maximum phosphate removal must be practiced at the waste source. If eutrophication is to be decelerated, removal of nutrients must be accomplished before wastes are permitted to enter receiving waters.

Summary

Wastewater phosphorus inflows to receiving waters must be reduced to check accelerating cultural eutrophication. A considered judgment suggests that to prevent biological nuisances, total phosphorus should not exceed 100 μg/l P at any point within the flowing stream, nor should 50 μg/l be exceeded where waters enter a lake, reservoir, or other standing water body. Those waters now containing less phosphorus should not be degraded.

Adequate phosphorus controls must now be directed toward treatment of nutrient point sources and to wastewater diversion around the lake or dilution within the lake, where feasible. Once nutrients are combined within the ecosystem of the receiving waters, their removal is tedious and expensive. Results of harvesting an aquatic crop, dredging, or other means to remove nutrients after they have reached receiving waters must be compared to inflowing nutrient quantities to evaluate accomplishments.

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New Developments in Automatic Cathodic Protection for Water Storage Tanks

Van Dyke J. Pollitt

A paper presented on Jun. 4, 1968, at the Annual Conference, Cleveland, by Van Dyke J. Pollitt, Mgr., Systems Service Div., Electro Rust-Proofing, a division of Wallace & Tiernan Inc., Belleville, N.J.

In earlier years, cathodic protection systems for water storage tanks and other water utility structures were hit-or-miss propositions. Although it was known that a potential could be achieved on submerged steel that would render its surface corrosion-free, little was known about the effect of applied currents on protective coatings, and system adjustment was rarely based upon actual field conditions and requirements.

Cathodic protection requirements change from time to time and from place to place. For any given water utility structure, the amount of cathodic protection current required to achieve and maintain a protection condition changes scores of times each day. Given two identical storage structures with identical coatings and storing identical waters, differing degrees of cathodic protection need will exist.

There are literally scores of variables that have a direct effect on the rate of corrosion activity within a structure, and these variables cannot be assumed to remain stable and reproducible. They include:

1. *Water resistivity changes.* These can be caused by changes in water source or treatment, changes in chemical content, changes in temperature, and so on.

2. *Water corrosivity changes.* Variations in DO, chloride ion content, and so on, affect a given water's propensity to support galvanic corrosion.

3. *Accumulated ampere hour effect.* Less cathodic protection current is required to maintain a protection effect than is required to achieve it. This variable is also related to the quality of applied paint coatings.

4. *Loss of coating effectiveness.* Paint coatings are applied to submerged steel surface areas for the sole purpose of isolating the steel from the corroding medium. All coatings are subject to deterioration in service due to water absorption, abrasion, bond failure, delamination, ice damage, and so on.

5. *Anode consumption in service.* Anode material is consumed as direct current flows from it. As the anodes are consumed, the circuit resistance of the cathodic protection system is increased. This necessitates changes in applied voltage to maintain a protection effect.

6. *Water level fluctuation.* Naturally, the current required to protect a given tank or other structure varies as more or less steel is exposed to the water electrolyte.

It is not enough to recognize that these changes occur without the cor-