PHOSPHORUS POLLUTION FOR LAWYERS AND OTHER IGNORANT PERSONS

(With a Bit about Nitrogen, Too)

ABSTRACT
A simple, but thorough, discussion of the quantification, causes, and effects of phosphorus pollution in freshwater rivers and streams.

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Contents

Cover Photo Credit: Midwest Environmental Advocates (Madison, WI)

INTRODUCTION

What follows is a vast simplification of the quantification, causes, and effects of phosphorus pollution (and, to a lesser extent, nitrogen pollution) in freshwater rivers and streams. It is not intended, however, to be an *over*simplification. The aim is to explain nutrient pollution in a manner that can be understood by all people, even those as math- and science-challenged as most lawyers. While simplified, this paper is more accurate than much of what is purveyed by state officials and others who attempt to make the problem seem so complex that nothing effective will ever be done about it.

This paper addresses the following:

- The basic arithmetic relevant to water quality standards and permits,
- Fundamental facts on water quality standard development,
- The basic science on how the effects of phosphorus and nitrogen pollution (collectively "nutrient pollution") compare to the effects of toxic pollution,
- An overview of aquatic plant and algal growth caused by nutrient pollution,
- A discussion of dissolved oxygen and how nutrient pollution affects it, and
- An overview of the effects of phosphorus and nitrogen pollution on aquatic life, drinking water supplies, and recreational uses of rivers, lakes and streams.

Armed with the knowledge you gain from the content of this paper and the supplemental *Πhosphatic Δialog* (Appendix), you should be able to informatively address comments from polluters and regulators you encounter as you work on this problem.

The author of this piece is well qualified to insult lawyers, having been a member of the Illinois Bar for over 35 years. He is also qualified to write this gross simplification regarding nutrient pollution after having worked on the subject as a lawyer for over 20 years and having endured countless slide show presentations by bored bureaucrats and numerous depositions of annoyed experts. The author has also reviewed large numbers of scientific and quasi-scientific papers authored by government agencies, dischargers, and even a few real scientists.

Most factual statements are supported in footnotes with references to government or scholarly sources so that readers will never have to cite this paper as a source (which might constitute malpractice). In some cases, footnotes serve to acknowledge simplifications so extreme that, if left unacknowledged, might lead even a fairly ignorant reader to stop reading.

This paper has been reviewed for rough accuracy by real experts on the subject of nutrient pollution. The author, however, has generally ignored suggestions to make the paper more precise by adding complicating detail.

While this paper's content deals mainly with water quality standards in general and the science regarding nutrient pollution, the author hopes to write a second piece that covers what should be done about nutrient pollution from a legal standpoint with regard to numeric water quality standards and permit limits for phosphorus (and maybe nitrogen).

1 BASIC CONCEPTS

1.1 Terminology

Dosis facit venenum. ("The dose makes the poison.")

– Philippus von Hohenheim
(a.k.a. Paracelsus, b. 1493 d. 1541)

Many seeking to excuse nutrient pollution will emphasize that phosphorus (P) and nitrogen (N) are natural in the environment and necessary for aquatic life. This is true, but only up to a certain magnitude. High concentrations of P in most water bodies are not natural. Also, too much P and N can cause too much of some types of aquatic life, a condition which can then preclude other beneficial types of growth and other beneficial uses of water. For example, some plant life is necessary for fish to eat. Too much plant life makes it impossible for fish to breathe. The condition of having too much plant life because there is too much nutrient presence is sometimes referred to in scientific literature and regulatory language as "cultural eutrophication," [1] a term the author avoids except when quoting someone or something else.

1.1.1 Loading *v.* Concentration

The first simplification in this paper is to focus on concentrations of pollutants in the water as opposed to looking at the total quantity, or "loading." Thus, for example, a lake might contain 1000 pounds of phosphorus but have a concentration of 1 part phosphorus per million parts in the sample. For most Americans, discussing concentrations requires a brief tutorial on the metric system. One milligram per liter (mg/L) of a pollutant is roughly equivalent to a concentration of one part per million (ppm). That may not sound like much, but for some pollutants it really is quite a lot.[2] Nutrient pollution is often discussed in terms of mg/L, but because small amounts of N and P pollution can have very bad effects, it is also discussed in terms of micrograms per liter (μg/L), or parts per billion (ppb). Thus, 1 ppm = 1

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[1] Walter K. Dodds & Matt R. Whiles, Freshwater Ecology (2d. Ed. 2010) at 471. "Eutrophication can be defined as an increase in the nutritive factor or factors that lead to greater rates of whole-system heterotrophic or autotrophic metabolism."; Christopher Mason, Biology of Freshwater Pollution (4th Ed. 2002) at 127. "*Artificial* or *cultural* eutrophication results from an increase in nutrients due to human activities, *natural* eutrophication results from an increase caused by a non-human process such as a forest fire."; See also Robert G. Wetzel, Limnology (3d. Ed. 2001) at 274-76 for a discussion of eutrophication; I think you can see, then, why we will avoid this term in the future.

[2] Ill. Admin. Code tit. 35, § 302.504(c); Wis. Admin. Code [NR] § 102.06(5)(b). The Illinois and Wisconsin phosphorus water quality criterion for Lake Michigan is 7 parts per *billion*.

mg/L = 1000 ppb = 1000 µg/L. Similarly, 75 µg/L = 0.075 mg/L, which happens to be the Wisconsin phosphorus criteria for streams.[3]

1.1.2 Water Quality Standards

In this paper, concentrations of N and P are discussed in two different contexts and it is important to keep them separate. The first context relates to what is deemed to be tolerable by state and federal authorities in the rivers, lakes, streams, or wetlands being protected. These water quality standards, or "criteria," apply either to broad categories of water bodies (e.g., rivers or lakes) or sometimes to specific, named water bodies (e.g., Lake Erie, the Wabash River, or Nippersink Creek).[4] The criteria, established by states with U.S. EPA oversight under Clean Water Act Section 303(c), are either numeric (e.g., "A total phosphorus criterion of 100 µg/L is established for the following rivers…"[5]) or narrative (e.g., "Waters of the State shall be free from…plant or algal growth, color or turbidity of other than natural origin."[6])

1.1.3 Effluent

The other context in which the concentrations of N and P must be considered relates to the concentration of the pollutant within a specific source of pollution, such as a pipe coming from a factory and discharging into a water body. Under the CWA, states issue National Pollutant Discharge Elimination System (NPDES) permits which often contain limits on the concentration of a pollutant allowed to come from a particular pollution source.[7] For example, under a treaty signed in the 1970s,

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[3] Wis. Admin. Code [NR] § 102.06(3)(b).

[4] The terms "water quality standards" and "criteria" are not used consistently by anyone, but there are federal definitions at 40 C.F.R. § 131.3. To use the federal definitions, water quality standards consist of state or tribal use designations for water bodies with water quality criteria sufficient to protect those designated uses and an antidegradation policy consistent with 40 C.F.R. § 131.12 (as stated at 40 C.F.R. § 131.6). Thus, for example, a state might designate a water body as having the uses of trout fishing and swimming. The state should then have criteria that apply to that water body for a) ammonia and dissolved oxygen stringent enough to protect trout and b) pathogens (a.k.a. harmful microbes or germs) to protect swimmers from getting sick. The official federal terminology which uses "criteria" to refer to one part of the standards will generally be used here. "Criteria" refers then to the chemical concentrations and/or descriptive narrative conditions designed to protect uses, but do not be surprised if quotes or rules also sometimes refer to "numeric standards" or "narrative standards."

[5] Wis. Admin. Code [NR] § 102.06(3)(a).

[6] Ill. Admin. Code tit. 35, § 302.203.

[7] As stated in 40 C.F.R. § 122.44(d)(1)(vi) and upheld in *American Paper Institute v. U.S. Environmental Protection Agency*, 996 F.2d 346, 350 (D.C. Cir. 1992), NPDES permits should contain numeric limits on

most U.S. and Canadian wastewater treatment plants discharging into the Great Lakes basin are to meet a limit that the concentration of phosphorus in the discharge be no more than 1.0 mg/L of phosphorus (= 1000 μg/L).[8]

1.1.4 Mixing Zones

One might ask why it is important to keep thinking about ambient water quality criteria mentally separate from effluent limits. After all, at the location where the pollution comes into the water body, the concentration in the water body will often be close to the concentration of the pollutant that was in the pipe. The answer is that under a federal regulation (40 CFR 131.13), "mixing zones" may be allowed by states. In other words, under the law, to some degree, "dilution can be the solution to pollution." When a mixing zone is allowed, the compliance of the water body with the water quality criteria is not measured at the point where the pollution source enters the water body, but is instead measured at a point at which the pollution source has had time to mix with the water body and become diluted.[9] Application of the mixing zone concept can be quite complicated and there are rules in states that specify the conditions in which mixing zones are allowed and where they are allowed.[10] A very simple example may be helpful to appreciate the concept.

For our example, let's say that Stream A has a constant flow of 10 million gallons per day and that Polluter X also has a constant discharge from its plant of 10 million gallons per day.[11] Let's us assume that the water quality criterion for a particular pollutant is 10 mg/L and that Stream A is perfectly clean at least as to that pollutant above the point of the discharge. In that case and depending on some other factors, Polluter X could possibly receive a NPDES permit allowing it to discharge wastewater containing up to 20 mg/L of the pollutant and Stream A would only be expected to meet the 10 mg/L criterion where the pollution had mixed with the clean water.

If Stream A already had some of the pollutant in it from upstream sources, Polluter X would not be able to discharge at the 20 mg/L level. If Stream A was already violating the water quality standard by having, for example, 15 mg/L of the pollutant, Polluter X in many states would be required to discharge

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the concentration of a pollutant coming from the effluent if there is a reasonable potential that the discharge might cause or contribute to a violation of water quality criteria, including narrative criteria.

[8] http://www2.epa.gov/glwqa#PHOSPHORUS LOAD REDUCTION

[9] Situations in which states may use mixing zones as well as potential limitations on mixing zones is discussed at length in the U.S EPA Water Quality Standards Handbook (EPA-820-B-14-008, September 2014), *available at* http://water.epa.gov/scitech/swguidance/standards/handbook.

[10] E.g., Ill. Admin. Code tit. 35, § 302.102.

[11] No real situation is ever this simple. Flows and discharges vary over time as do the concentrations of pollutants upstream and in the discharge. States have rules, written and unwritten, to address how to take such factors into account.

at no higher concentration than the water quality standard.[12] The terminology often used in such a case is that the discharge must meet water quality standards "at the end of the pipe" as opposed to having to meet standards "at the edge of the allowed mixing zone."

1.2 Criteria for Toxins and Other Pollutants

Another frequent refrain of those who do not want effective controls on nutrient pollution is that nutrient pollution is entirely different from and far more complex than toxic pollution. In fact, both toxic pollution and nutrient pollution criteria are complex. The only way that it has been possible to adopt criteria for toxins is to accept various fairly arbitrary assumptions and rough approximations. To understand this, one must understand how water quality criteria for toxins are developed.

It has been said that lovers of laws and sausages should not watch them being made. The same idea applies to water quality criteria. Indeed, it applies to water quality criteria for toxins, drinking water, and pathogens, as well as for nutrients.

Photo credit: Amy Goerwitz

Generally, "toxic" here means toxic to aquatic life. The basic way to test at what concentration a pollutant is toxic is by dropping fish, aquatic bugs (macroinvertebrates), and other critters into laboratory tanks containing various concentrations of the pollutant and determining how many of them die. If, on average, a concentration of a particular pollutant (e.g., ammonia) kills 50% of a particular fish species (e.g., fathead minnows) in a short period of time (e.g., hours) in a number of laboratory tests, that concentration is referred to as the LC_{50} (for Lethal Concentration 50%) for ammonia for fathead minnows. (Fathead minnows, however, are generally known to be pollution tolerant, so the water quality standard for most water bodies should be driven by much more sensitive species.[13])

Since we do not want to kill off 50% of a species we are trying to protect, a value of half the LC_{50} is generally used to set the acute standard for a toxic substance as the criterion that should never be exceeded. So, for example, if the LC_{50} for the most sensitive species to be protected is 10 mg/L, the

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[12] E.g., Ill. Admin. Code tit. 35, § 302.102.

[13] We do not generally require that our criteria protect the most sensitive species. It was decided arbitrarily that it is good enough to protect 95% of the species unless a member of the most sensitive 5% is particularly important for one reason or another.

acute criteria would be set at 5 mg/L.[14] The percentage of the members of the species that half of the LC_{50} will protect obviously varies from species to species and pollutant to pollutant.

Also, one cannot consider only what concentrations kill aquatic life in a short period of time. In some cases, a lower concentration over a longer period (e.g., days or weeks) may have detrimental effects like killing more slowly, preventing reproduction, or causing aquatic life to swim away from the stream segment or lake.[15] These sorts of chronic effects on aquatic life are generally harder to observe than immediate acute effects. It is harder to see when a fish is stressed than when it is floating belly up. Because of the general lack of chronic data for most species, coarse, rule-of-thumb, acute-to-chronic ratios are often assumed in setting chronic standards.

It gets still more complicated. Sometimes the presence of other chemicals in the water may raise or lower the toxicity of the pollutant being studied.[16] For example, many dissolved metals (e.g., zinc) are less toxic to aquatic life if the water has greater hardness. Temperature can also have an effect, with most toxins being more toxic when the water is warmer (although sometimes the opposite is true).[17]

There are also other types of uses that need to be protected with different criteria.[18] Drinking water supplies have criteria designed so that safe drinking water generally can be provided from the water body without having to spend too much on drinking water treatment. Recreation criteria are based on estimates of how many harmful microbes (germs) can be present in the water without swimmers getting sick along with various arbitrary cut-offs used to determine an acceptable number of sick swimmers. Certain criteria, most notably the human health criteria for mercury, are based on an estimate of how low the level of mercury must be in the water so that fish do not build up so much mercury in their systems that they become unsafe for humans to eat. Again, these criteria are

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[14] Mason, *supra* at 27; Rules and assumptions for determining water quality standards were set forth decades ago in U.S. EPA's Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses (PB85-227049, 1985), *available at* http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/85guidelines.pdf.

[15] Mason, *supra* at 34-37.

[16] Mason, *supra* at 32-33.

[17] E. B. Welch, Ecological Effects of Wastewater (2d. Ed. 1992), at 333; Hammer & Hammer, Water and Wastewater Technology (1996), at 137.

[18] 40 C.F.R. § 131.11(a). Criteria must protect the "most sensitive use" in the water bodies to which they apply. The same pollutant can have different criteria to protect different uses. For example, at 40 C.F.R. § 131.36 nickel criteria are provided to protect aquatic life in saltwater and freshwater and to protect human beings who drink water and eat fish from the water body and to protect human beings who eat the fish but do not drink the water.

determined by using arbitrary cut-offs regarding how many people it is acceptable to harm with mercury as well as estimates about how much fish people are expected to eat.[19]

It would be much more convenient if pollutants were perfectly safe up to a particular concentration, and then clearly impaired some uses. Then there would be no doubt as to the proper water quality standard to protect aquatic life, drinking water, or recreation. That is not our world. Instead, it is necessary to draw lines that are often hard to justify in order to prevent toxicity and other harmful effects.

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[19] The different types of criteria to be set and what they are supposed to do is discussed in the U.S EPA Water Quality Standards Handbook (EPA-820-B-14-008), Sept. 2014, *available at* http://water.epa.gov/scitech/swguidance/standards/handbook.

2 NUTRIENT LIMITATION AND EXCUSES FOR NUTRIENT POLLUTION OF LIMITED VALUE

It is true that nitrogen and phosphorus, insofar as they act as nutrients, have a different bad effect on the uses of water bodies than toxins.[20] Generally, their effect is to cause unnatural levels or types of plant, algal, or bacteria growth which, in turn, have various bad effects on other forms of aquatic life, drinking water supplies, and recreational uses.[21]

2.1 Liebig's Law

A number of distinctions must be made between forms of nitrogen and phosphorus and types of plant, algal, and bacterial growth that result from nitrogen and phosphorus pollution. However, the first concept that must be understood is Liebig's Law.

As you may recall from high school biology, the process of photosynthesis requires a number of inputs including sunlight, water, a place to live (habitat), and many different chemicals that work as nutrients, including nitrogen and phosphorus. Generally, whatever is in shortest supply relative to the needs of the plants dictates how much growth there can be. This is known as Liebig's law of the minimum. Under Liebig's Law, the input to plants and algae in shortest supply relative to their needs limits the total amount of growth,[22] so that input is said to be "limiting."[23] For example, if there is no sunlight, photosynthesis cannot occur no matter how much water and nutrients are present.[24]

Adding more of the inputs that are not limiting, or reducing the level of an input that is already present in a surplus to a level where it is still in surplus, will not generally affect plant or algal growth.[25] For example, adding more nitrogen is not going to help a plant that is not getting enough

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[20] Nitrogen has both a toxic and a nutrient effect.

[21] U.S. EPA, 75 Fed. Reg., No. 233, at 75,765-68 (Dec. 6, 2010).

[22] Dodds & Whiles, *supra* at 449; Walter R. Hill & Shari E. Fanta, *Phosphorus and Light Colimit Periphyton Growth at Subsaturating Irradiances*, Freshwater Biology 53, 2008, 215-25, at 216; Vladimir Novotny & Gordon Chesters, Handbook of Nonpoint Pollution (1981) at 54.

[23] Débora Figueroa-Nieves, Todd V. Royer, & Mark B. David, *Controls on Chlorophyll-a in Nutrient-Rich Agricultural Streams in Illinois, USA*, Hydrobiologia 568, 2006, 287-98 at 297.

[24] Todd V. Royer et al. *Assessment of Chlorophyll-α as a Criterion for Establishing Nutrient Standards in the Streams and Rivers of Illinois*, J. of Environ. Qual. 37, 2008, 437-47. Other types of growth may occur if given enough nutrients, such as algae that do not need much light.

[25] Figueroa-Nieves et al., *supra* at 296.

sunlight to use the nitrogen it already has, and reducing the amount of nitrogen will not reduce growth.[26] This seems to indicate the lack of a typical dose-response relationship, a claim used by some to differentiate nutrient pollution from other types of pollution. But actually, there is not that great a difference between nutrients and toxins in this respect.

2.2 Dose-Response Relationship

It is generally true that toxins added to a water body in high enough amounts first kill the aquatic life most sensitive to them and, as more are added, they kill the less sensitive aquatic life until the only organisms that can live there are those which are totally immune to that toxin. So, for a range of concentrations, there is a dose-response relationship with a higher dosage meaning less aquatic life.

The claim that nutrient pollution is different from toxin pollution because there is no typical dose-response relationship is based on a false comparison. Note that many situations will cause there to be no dose-response relationship for toxins as well. For example, if a lack of habitat or a different pollutant has already killed off the species sensitive to the toxin, no change will be observed when the toxin is added. Also, above a certain concentration, everything that can be hurt by the toxin will be dead and there will be no further response from adding more of the toxin.

As will be discussed in greater detail below, in natural freshwater systems unaffected by sewage, fertilizer, or other pollution, the necessary input that is in shortest supply is normally phosphorus.[27] Under these circumstances, phosphorus is "limiting" under Liebig's Law. When phosphorus pollution is added to a natural freshwater aquatic system, plant and algal growth will increase with the increase in phosphorus until the point at which phosphorus is no longer limiting. Then some other input (e.g., physical factors, light, nitrogen, or space in which to grow) becomes the limiting factor.

This phenomenon was observed in Illinois by working scientists who reported that there was a strong correlation between total phosphorus (TP) levels and algae floating in the water column at sites with an open canopy (i.e., light was not limiting) up to a concentration of 0.2 mg/L TP.[28] Once TP was

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[26] JoAnn M. Burkholder & Patricia M. Glibert, *Eutrophication and Oligotrophication*, in Encyclopedia of Biodiversity (2d ed. 2013), 347-371, at 351. The lack of light may be due to the fact that the water body is suffering from sedimentation from agriculture or construction that is causing the water to be full of soil or other particles ("suspended solids" or "turbidity").

[27] *Id.* at 349; Dodds & Whiles, *supra* at 360; Mason, *supra* at 128.

[28] Royer et al., *supra* at 442; Linda M. Jacobson, Mark B. David, & Corey A. Mitchell, *Algal Growth Response in Two Illinois Rivers Receiving Sewage Effluent*, J. Freshwater Ecol., *23*(2), 2008, 179-187. The addition of sewage effluent did not matter to streams that already had phosphorus in great excess from agricultural sources; Michelle A. Evans-White et al., *Thresholds in Macroinvertebrate Biodiversity and Stoichiometry across Water-Quality Gradients in Central Plains (USA) Streams*, J. N. Am. Benthol.

above 0.2 mg/L (= 200 μg/L), it did not matter how much more TP was there. Simply put, at above 0.2 mg/L, phosphorus was not limiting.

One may often hear agency officials or nutrient polluters say that the nutrient in discussion is "not limiting" in the waters in question. The implication is that the pollutant is unimportant and therefore not affecting water quality. Generally, this suggestion is wrongheaded because although phosphorus is not now limiting, it *should be*. Without phosphorus pollution in the example above, phosphorus *would be* the limiting factor.

There are a few freshwater rivers or lakes that have so much natural background phosphorus that phosphorus pollution would not be limiting even if there was no pollution, but that is very rarely the case. Normally, if one reduces phosphorus pollution in freshwater systems to below the limiting level, it will reduce plant and algal growth. There have been numerous dramatic successes where improved water quality has resulted from reductions in phosphorus pollution.[29] However, the reduction in TP levels required for such a success may be bigger than state officials and dischargers want to contemplate.

Also, it might take a while to see the improvement because of the large amount of phosphorus pollution that settled out to the bottom mud (sediment) where it can continue to fuel plant and algal growth.[30] Reducing the levels of phosphorus from *way* too much to *merely* too much is unlikely to result in any improvement in water quality.[31] (It might help water quality downstream where phosphorus does become limiting, but does nothing visible in the area being targeted for cleanup.)

2.3 No Correlation, No Problem?

The supposed lack of correlation between phosphorus concentrations and plant and algal growth is the main argument of those opposing the establishment of protective criteria and permit limits for phosphorus. The basic absurdity of this pseudo-scientific defense of the status quo can be shown by analogy. In the 1929 St. Valentine's Day Massacre, all of the victims died even though some of them had been shot many more times than others. There is no correlation, then, between the number of times a victim was shot and death. According to the no-correlation-then-not-the-problem theory, one would conclude that shotguns and tommy guns did not affect the health of Chicago gangsters in the

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Soc., *28*(4), 2009, 855-868, at 866. Scientists looking at waters in Kansas, Missouri and Nebraska also found that most of the waters they studied had levels of TP above biologically significant thresholds.

29 Helen P. Jarvie et al., *Phosphorus Mitigation to Control River Eutrophication: Murky Waters, Inconvenient Truths, and "Postnormal" Science*, J. Environ. Qual. 42, 2013, 295-304 at 296.

30 *Id.* at 296-97.

31 *Id.* at 299; Royer et al., *supra* at 443.

20s. Even lawyers, at least those not being retained by polluters, can see that there is a flaw in that argument.

Unfortunately, Illinois, Indiana, Iowa and, to a lesser degree, other Midwestern states have very few waters that are not full of sewage, fertilizer, or both. The study of Illinois streams and rivers mentioned above found only eight sites out of 109 that had levels of TP below the limiting level; most had such high levels of phosphorus pollution that adding more phosphorus would not have affected plant and algal growth.[32] To put it another way, less than 10% of the Illinois streams and rivers studied had taken less than the number of bullets it took to kill members of the Bugs Moran gang.

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[32] Royer et al., *supra* at 442.

3 NITROGEN

Nitrogen is an element that makes up four-fifths (80%) of the gases in the atmosphere where it takes the form of N_2 gas and generally stays there. That nitrogen form is inaccessible to most life because most forms of life cannot break down the bond that nitrogen atoms form with other nitrogen atoms. For this reason, nitrogen is often a nutrient that limits plant growth because there is a lack of reactive or biologically available nitrogen.[33] The forms of nitrogen most relevant to the nutrient water pollution issues at hand are ammonia (NH_3), ammonium (NH_4^+), and nitrate (NO_3^-).[34]

Fritz Haber is one of the most important scientists in history, although few have heard of him. He is important for two discoveries: the Haber nitrogen fixation process ($N_2 + 3\ H_2 \rightarrow 2\ NH_3$,) and nerve gas.[35] The Haber nitrogen fixation process, also known as the Haber Bosch process, is responsible for creating fertilizers that help feed several billion people on Earth.[36] This biologically available form of nitrogen is applied to corn and many other crops in the form of anhydrous ammonia. In the environment this turns into ammonium (NH_4^+) and nitrate.[37] These are all forms of inorganic nitrogen and are readily used by corn and other plants. Unfortunately, ammonium and nitrate in particular are also readily used by aquatic plants and algae when these N forms reach water bodies.

Because nitrogen is generally the primary limiting nutrient (i.e., the nutrient algae run out of first, relative to their needs) in saltwater systems, nitrogen pollution causes algal blooms in oceans around the world. Along marine coasts, when the algae die and drop to the bottom mud, they rot and use up

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[33] Tim Loughheed, *Wrangling Reactive Nitrogen: Strategies for Mitigating Pollution*, Environ. Health Persp. 120(5), May 2012, A200-03; Alan R. Townsend & Robert W. Howarth, *Fixing the Global Nitrogen Problem*, Sci. Am., Feb. 2010, 64-71.

[34] Dodds & Whiles, *supra* at 347. Ammon*ium* (NH_4^+) acts as both a nutrient and a toxic substance depending on the concentration and other environmental conditions. Ammoni*a* (NH_3^-) toxicity criteria is a nascent water quality issue due to U.S. EPA's 2013 establishment of more stringent ammonia criteria to protect native mussels, *available at* http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/ammonia.

[35] Daniel Charles, Between Genius and Genocide: The Tragedy of Fritz Haber (2006).

[36] Townsend & Howarth, *supra* at 64-71.

[37] Some of it also becomes nitrite, which is highly toxic, but which will be left out of this paper that is already too long and complicated.

oxygen. This causes dead zones in many seas where there is too little oxygen for fish, shrimp and other aquatic life to live.[38]

Most of the unnatural nitrate in the environment comes from fertilizer applied to crops or lawns ("nonpoint" sources, diffuse over the landscape), but other sources are sewage and oil refineries. Ammonia and nitrate discharged from "point" sources (i.e., coming out of one place or point, like a pipe) are first a toxic problem because they are toxic to many forms of aquatic life.[39] Ammonia is usually toxic to aquatic life at much lower levels than nitrate.[40] Ammonia and ammonium also directly take out of the water the dissolved oxygen that fish need to breathe, although this effect is frequently ignored by permit writers who only consider the carbon component of the wastewater oxygen demand.[41]

Because ammonia can be a major toxic problem for aquatic life, many sewage treatment plants are built to change the ammonia in the wastewater to nitrate before the wastewater is discharged. This process is called "nitrification" ($NH_3 \rightarrow NO_3^-$). This is better than discharging highly toxic ammonia but not good enough, because nitrate also can act as both a toxin and a nutrient. What is needed is to take the nitrate and change it into oxygen and nitrogen that can then go back into the atmosphere as N_2. There are sewage treatment processes for doing this "de-nitrification," including the Ludzack-Ettinger process,[42] but a small percentage of sewage treatment plants in the United States take this further step.

As mentioned, nitrogen is generally the primary limiting nutrient for plant and algal growth in marine waters unless there is pollution. There are freshwater bodies where nitrogen is limiting, but generally phosphorus is the most important limiting nutrient in rivers, streams, lakes and wetlands.[43]

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[38] Townsend & Howarth, *supra* at 68; National Research Council Committee on the Mississippi River and the Clean Water Act, *Mississippi River Water Quality and the Clean Water Act: Progress, Challenges and Opportunities*, 2008, at 44-45, 74, *available at* http://nap.edu/catalog/12051.html.

[39] Burkholder & Glibert, *supra* at 366.

[40] See 2013 U.S. EPA ammonia criteria, *available at* http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/ammonia.

[41] Rodger Baird & Roy-Keith Smith, Third Century of Chemical Oxygen Demand 116-17 (2002).

[42] U.S. EPA, Municipal Nutrient Removal Technologies (832-R-08-006) § 2.2.2 (Sept. 2008), available at http://water.epa.gov/scitech/wastetech/upload/mnrt-volume1.pdf. I cannot forego mentioning that Morris B. Ettinger was my father, but I must assure the reader that I will not receive any financial remuneration if the spread of wisdom contained in this paper leads to greater use of the L-E process.

[43] Daniel J. Conley et al., *Controlling Eutrophication: Nitrogen and Phosphorus*, Sci. 323, 2009, 1014-15. There are also freshwater systems where nitrogen and phosphorus are said to be "co-limiting," as well as freshwater systems that are naturally phosphorus-limited, but have received so much phosphorus

4 PHOSPHORUS

Phosphorus is also an element. Unlike nitrogen, it cannot be returned to the atmosphere. Phosphorus can be tied up, settled deep into sediment, or otherwise become biologically unavailable for aquatic life. Under natural conditions, nearly all of the phosphorus is tied up, and it is often the most limiting nutrient in freshwater systems.

But few American water bodies are in anything like a natural condition. It has been said, "Indoor plumbing has been an environmental catastrophe for European and North American Rivers."[44] Phosphorus levels throughout much of the United States are greatly elevated above background conditions by sewage effluent and agriculture. [45]

There are a lot of different types of phosphorus compounds. For present purposes, the forms of phosphorus can be divided into total phosphorus (TP) and biologically available phosphorus (BAP). Total phosphorus is just what it sounds like, the total amount of phosphorus in the water. It includes phosphorus attached to soil particles or already taken up by algae or aquatic plants. BAP is loose phosphorus that can be readily taken up by plants and algae. Although slightly different or measuring a slightly different thing, soluble-reaction phosphorus (SRP), ortho-phosphorus, and inorganic phosphate (PO_4^{-3}) all fit into the category of BAP.

A major error can be made if one does not distinguish total phosphorus from BAP. Scientists have written papers and regulatory agency officials have said in conferences that there was high plant or algal growth although phosphorus levels were low, but plants and algae simply cannot grow without adequate levels of phosphorus.

One of two things would have led to such a statement that plant or algal growth was high although P was low.[46] First, the scientist or state official's view of what constitutes a low level of phosphorus may have been distorted by years of studying extremely polluted waters. As was seen in the discussion of Liebig's Law, a water body can have high levels of algae if it has *enough* phosphorus even if it does not have *way too much* phosphorus, just as a gangster might be dead with two bullet wounds as well as 25.

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pollution that nitrogen has become the primary limiting nutrient. This does not happen often, though, because generally there is nitrogen pollution where there is phosphorus pollution and, with so much nutrient pollution, something else (e.g., light or space) is limiting.

44 Perry Rahn, Engineering Geology: An Environmental Approach 574 (1996).

45 L. E. Gentry et al., *Phosphorus Transport Pathways to Streams in Tile-Drained Agricultural Watersheds,* J. Environ. Qual. 36, 2007, 408-415 at 408.

46 There are actually other possibilities, but venality and stupidity are beyond the scope of this paper.

The other possibility is that the scientist or state official who said phosphorus levels were low meant that *biologically available* phosphorus (e.g., SRP) was low. As noted, measures of SRP or other forms of BAP in the water do not include the phosphorus that has been taken up by the plants or algae. That is, what remains dissolved in the water is just a snapshot of the total supply that is available since most of it has been taken up by the plants and algae. Thus, even though concentrations of BAP are low, supply may be high.[47] One cannot measure how phosphorus has affected a water body solely by measuring only the BAP left around any better than one can determine how much pizza was delivered to a frat party just by looking at how many slices are left at the end of the night.[48] Much of the pizza is now in the frat boys.

BAP dissolved in the water is snapped up by plants and algae, often in seconds, in any water body in which phosphorus is limiting. Thus a water body with low levels of BAP still might have, and in U.S. waters usually does have, excessive phosphorus and excessive plant and algal growth compared to what there would be without phosphorus pollution. On the other hand, a freshwater body with a high level of BAP is probably one in which phosphorus is not now limiting, but if there was less pollution, *would* be limiting. As a leading scientist in the area said with regard to the SRP measure of BAP, "If SRP values are very high (>0.1 mg/L), then they likely make up much of the TP and indicate a very P-enriched system (e.g., in sewage effluent)."[49]

It should also be understood that, because BAP can be immediately used by plants, algae, and bacteria, it is a far more potent source of phosphorus pollution than phosphorus attached to particles, or particulate phosphorus. For this reason, per unit of TP, sewage treatment plants that do not treat adequately for P are generally a worse problem than agriculture. Phosphorus from sewage comes mainly in the form of BAP while most of the P coming from row crop agricultural pollution comes in the particulate form.[50]

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[47] Walter K. Dodds, *Misuse of Inorganic N and Soluble Reactive P Concentrations to Indicate Nutrient Status of Surface Waters*, J. N. Am. Benthol. Soc. *22*(2), 2003, 171-181.

[48] If a lot of pizza is left over, one knows that something other than the amount of pizza available limited consumption at the party, and that too much pizza was ordered. To decide if the frat boys over-ate, one might compare the number of frat boys who attended the party to the number of empty pizza boxes – but phosphorus pollution does not normally come in a box.

[49] Dodds (2003), *supra* at 179.

[50] Helen K. G. R. Millier, Peter S. Hooda, *Phosphorus Species and Fractionation – Why Sewage Derived Phosphorus is a Problem*, J. Env. Mgt. 92, 2011, 1210-1214; Helen P. Jarvie, Colin Neal, & Paul J. A. Withers, *Sewage-Effluent Phosphorus: A Greater Risk to River Eutrophication than Agricultural Phosphorus?* Sci. Total Environ. 360, 2006, 246-53. Phosphorus that comes through the tile drains from farms is often biologically available phosphorus.

5 NUTRIENT POLLUTION-FUELED GROWTH

One way in which nutrient pollution causes problems for aquatic life and people is by causing the growth of unwanted species or the potentially harmful *excess* growth of otherwise-harmless species of algae and plants. These species are not inherently evil. Even cyanobacteria, which will be seen as a villain in what is to come, are natural and helpful up to some level. Indeed, it appears that the heaviest hitters are cyanobacteria, which began their work billions of years ago and are responsible for there being free oxygen in the atmosphere.[51] However, just as national park bears can become a nuisance when fed by tourists, algae, plants, and bacteria fed by pollution can also become a problem, only on a much larger scale.[52]

Photo credit: Christian Fischer, licensed under CC BY-SA 3.0 via Wikimedia Commons

5.1 Growth Distinctions

When considering nutrient pollution-caused growth, a number of distinctions must be made. The first such distinction is between form of growth that photosynthesize and those that do not. Plants and algae (including cyanobacteria, or blue-green algae) photosynthesize, which means that during the day, when sunlight is available, they will take in carbon dioxide and produce oxygen, causing dissolved oxygen (DO) levels in the water to rise.[53] Alternately, when no sunlight is available, the DO levels will drop. These fluctuations of DO levels due to photosynthesis are called *diel* (24-hour) oxygen swings.[54]

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51 David Biello, *The Origin of Oxygen in Earth's Atmosphere*, Sci. Am., Aug. 19, 2009, *available at* http://www.scientificamerican.com/article/origin-of-oxygen-in-atmosphere.

52 E. C. Pielou, Fresh Water 234-36 (1998): discussion of bacteria and the effect of phosphate on bacteria and quality impacts of increased bacteria growth.

53 Steven Stanley, Earth and Life through Time 256-58 (1986). I am certain you are dying to know that cyanobacteria are not true algae because they are prokaryotes, single-celled organisms without a membrane-bound nucleus, while true algae are eukaryotes that have a nucleus.

54 Burkholder & Glibert, *supra* at 351. "Diel" refers to a 24-hour period which is what is being discussed here; Wetzel, *supra* at 154. Oxygen fluctuations caused by photosynthesis are also referred to as "diurnal", although that term refers to daytime and the fluctuation occurs over a period of day and night. It sometimes seems like scientists are not a whole lot better at keeping their terminology straight than lawyers and agency officials.

On the other hand, most types of bacteria and some other forms of growth that can be promoted by nutrient pollution do not photosynthesize. These forms of life (heterotrophs) do not cause diel swings in DO levels because they are net users of oxygen at all times.

Of the things that photosynthesize, there is algae, a term that refers to primitive organisms that photosynthesize but do not have higher plant organs such as roots, stems, flowers and leaves.[55] Then there are plants, some of which are nicer than others. Some plants are invasive species that have aggressively taken over many lakes and streams, such as Eurasian Watermilfoil, Curly Leaf Pondweed, Brazilian Elodea and Hydrilla.[56]

5.2 Cyanobacteria

Special notice must be taken of certain types of nutrient pollution-fueled growth that have some particular ill effects. One such nasty species is cyanobacteria, a type of bacteria that photosynthesizes and has been on the planet many years. Cyanobacteria are not inherently bad any more than scorpions, mosquitoes or kudzu were created by Sauron, but they have several nasty features that make it undesirable for most of them to dominate a water body. Cyanobacteria that create toxins and noxious blooms and that are inferior food for fish are favored by high levels of phosphorus and nitrogen in freshwater.[57]

Photo credit: Michael Ely, licensed under CC BY-SA 2.0 via Wikimedia Commons

There is a wide variety of cyanobacteria that may react differently to different levels of phosphorus and different ratios of nitrogen to phosphorus in the water.[58] It is generally understood that having more phosphorus will lead to greater levels of cyanobacteria.[59] It also has been shown that lakes (at least in Europe) are more likely to violate the World Health Organization standards for cyanobacteria toxins as phosphorus levels rise

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[55] Linda Graham, James E. Graham & Lee W. Wilcox, Algae (2d. Ed., 2009).

[56] Pictures of these monsters can be found at http://www.rtrcwma.org/wetland.pdf.

[57] Burkholder & Glibert, *supra* at 357.

[58] Andrew M. Dolman et al., *Cyanobacteria and Cyanotoxins: The Influence of Nitrogen versus Phosphorus* PLOS ONE 7(6), 2012, *available at* http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0038757.

[59] Pielou, *supra* at 35. "…pollution of a lake with added phosphates causes rampant blooms of blue-green bacteria, whose growth was previously checked by lack of phosphate."

from 0.016 mg/L to 0.054 mg/L.[60] Because some species of cyanobacteria can pull nitrogen from the air, nitrogen is unlikely to be limiting for those species which is why phosphorus pollution frequently favors cyanobacteria.[61] Cyanobacteria are also likely to become more prevalent in areas that global climate change has caused to become warmer.[62]

Unfortunately, there is no easy test for the amount of cyanobacteria in the water nor any easy way to determine how much toxin a given amount of cyanobacteria will produce.[63]

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60 Laurence Carvalho et al., *Sustaining Recreational Quality of European Lakes: Minimizing the Health Risks from Algal Blooms through Phosphorus Control*, J. Appl. Ecol. *50*(2), Apr. 2013, 315-323.

61 Dodds & Whiles, *supra* at 349; Mason, *supra* at 138. "Blooms of cyanobacteria form where nutrient loading is high, where the ratio of nitrogen to phosphorus is low, where conditions in the water are warm and still and where large-bodied grazers such as *Daphia* are scarce."

62 Cayelan C. Carey et al., *Eco-Physiological Adaptations that Favour Freshwater Cyanobacteria in a Changing Climate*, Water Res. 46 (2012), 1394-1407; Hans W. Paerl & Jef Huisman, *Blooms Like it Hot*, Sci. 320, 2008, 57-58.

63 The level of toxins created by the cyanobacteria can be measured and on May 6, 2015, U.S. EPA published a guidance on the levels of certain toxins deemed to be unhealthy. http://yosemite.epa.gov/opa/admpress.nsf/0/547DC50C15C82AAF85257E3D004D7F67.

6 FACTORS TO CONSIDER IN DETERMINING WHETHER A WATER BODY HAS BEEN IMPAIRED BY NUTRIENT POLLUTION

When determining if a water body has a harmful level of nutrients (nutrient impairment), one may look at its chlorophyll or DO levels because a high level of chlorophyll or low levels of DO can show excess, harmful growth. But again distinctions must be made, as the following sections illustrate.

6.1 Chlorophyll

All plants and algae that photosynthesize have the universal plant pigment chlorophyll *a* that is essential to the process. Rivers with high levels of nutrients generally have high levels of floating or suspended algae in the water column (a.k.a. "sestonic" algae or "phytoplankton") and, thus, high measures of chlorophyll α (> 10 μ/mg), a good indication of excessive algal growth.[64]

However, the absence of such high sestonic chlorophyll does *not* mean there is not a problem.[65] This is because there is chlorophyll in the water that is typically not measured. The chlorophyll in large aquatic plants and algae, such as those attached to the bottom of the water body, or to rocks, or floating on top of the water, is not included in a typical chlorophyll α measurement due to the sampling difficulty. Collecting all those plants and floating or bottom-attached algae in a measured area, and scraping the bottom of water bodies and rocks, is tiresome work. On the other hand, getting a sample for chlorophyll α in sestonic algae just requires dipping a jar into the water and shipping the sample to a competent laboratory.[66]

Not only that, but in general, larger (non-wadeable) streams have much higher suspended algal chlorophyll α concentrations per unit of total phosphorus than wadeable streams because typically the

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[64] Steven Heiskary & Howard Markus, *Establishing Relationships Among Nutrient Concentrations, Phytoplankton Abundance, and Biological Oxygen Demand in Minnesota, USA, Rivers*, Lake Reserv. Manage. *17*(4), 2001, 251-262; Erwin E. Van Nieuwenhuyse & John R. Jones, *Phosphorus-Chlorophyll Relationship in Temperate Streams and Its Variation with Stream Catchment Area*, Can. J. Fish. Aquat. Sci. 53, 1996, 99-105; I am sorry about using the term "sestonic" around lawyers who normally think of anything involving "tonic" as something to be mixed with gin. It is easier, though, than writing "floating or suspended" a lot of times and is the term your expert may want to use.

[65] For those of you who have somehow failed to learn Greek, α is the Greek letter "alpha" and here denotes a biochemical form of the chlorophyll molecule.

[66] Robert G. Wetzel & Gene E. Likens, Limnological Analyses (3d. Ed., 2010); Note that finding a competent laboratory is not always so easy.

flow in smaller streams is faster and the floating algae get washed away.[67] Smaller, wadeable streams tend to respond to nutrients through increased growth of algae growing on rocks or anchored to other places (periphyton, or benthic algae), or floating in large clumps (filamentous algae), rather than suspended microscopic algae (seston).[68] Thus, one cannot look at chlorophyll *a* levels, as chlorophyll is normally measured, and conclude that a stream has not been impacted by phosphorus.

There is no easy way to fix this problem because there is no simple correlation between attached and floating clumps of algae and the chlorophyll level in suspended microscopic algae.[69] Aquatic plants and floating clumps of algae or attached algae growing along the bottom of a waterbody can have almost all the negative effects of sestonic algae as well as negative effects that sestonic algae do not have (e.g., snagging a fishing hook).[70]

6.2 Dissolved Oxygen

Dissolved oxygen refers to oxygen in the water that is available for fish and other aquatic life to breathe. The classic effect of nutrients on DO is to cause crashes in the DO levels. How this happens is a bit different in the Gulf of Mexico than in freshwater lakes and streams, but the basic problem is the

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67 Brian A. Whitton, River Ecology: Studies in Ecology (Vol 2, 1975); Van Nieuwenhuyse & Jones, *supra* at 99-105.

68 Figueroa-Nieves et al., *supra* at 296.

69 Royer, *supra* at 442; Kirk Lohman & John R. Jones, *Nutrient-Sestonic Chlorophyll Relationships in Northern Ozark Streams*, Can. J. Fish Aquat. Sci. 56, 1999, 124-30.

70 Robert J. Miltner, *A Method and Rationale for Deriving Nutrient Criteria for Small Rivers and Streams in Ohio*, Environ. Manage. *45*(4), 2010, 842-55.

same in both cases.[71,72,73] The nutrients cause too much growth of plants, algae, or bacteria that take too much DO out of the water. [74]

6.2.1 DO Fluctuations

Photosynthetic plants and algae, as mentioned, put out DO while the sun shines. During the nighttime, plants and algae on balance consume a lot of oxygen.[75] This process of mostly putting out oxygen during the day and taking it in during the night can cause a large fluctuation (> 3 mg/L) in DO levels over the course of 24 hours.[76] This diel oxygen swing is a characteristic of many of the waters polluted by nutrients.[77]

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[71] Nancy N. Rabalais, R. Eugene Turner, & Donald Scavia, *Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River*, BioScience *52*(2), 2002, 129-142, at 134; Townsend & Howarth, *supra* at 64-71; In the Gulf of Mexico and a number of other marine dead zones, nitrogen and phosphorus can stimulate a bloom or overgrowth of algae that dies and falls to the bottom sediments where bacteria use oxygen to decompose them.

[72] Mark B. David et al., *Denitrification and the Nitrogen Budget of a Reservoir in an Agricultural Landscape*, Ecol. Appl. *16*(6), 2006, 2177-2190, at 2177. A large portion of the nitrogen contributing to the Gulf dead zone originates from agricultural states in the Midwest, including Iowa, Illinois, Indiana, and Ohio.

[73] Todd V. Royer, Mark B. David & Lowell E. Gentry, *Timing of Riverine Export of Nitrate and Phosphorus from Agricultural Watersheds in Illinois: Implications for Reducing Nutrient Loading to the Mississippi River*, Environ. Sci. Technol. 40, 2006, at 4126-31. Addressing nutrient pollution to control effects on the Gulf of Mexico probably involves different steps than controlling nutrient pollution to protect Midwest waters. Controlling nutrients in the spring high stream flows to reduce total loadings is most important to protecting the Gulf, but it is the drier periods with high nutrient concentrations that are probably most critical to protecting Midwest waters.

[74] Pielou, *supra* at 181-82. There are also climate change effects. "The lack of oxygen that results from overnourishment of a lake often yields unwanted by-products. In the absence of oxygen, bacteria that produce methane and hydrogen sulfide go to work. Methane is a powerful 'greenhouse' gas that is believed to contribute appreciably to global warming."

[75] Burkholder & Glibert, *supra* at 351. Actually, plants and algae use oxygen during the daytime also, but produce much more than they use. At night, they use a lot of oxygen for energy through respiration, just as animals do; See also Vladimir Novotny & Gordon Chesters, Handbook of Nonpoint Pollution 50 (1981).

[76] Wetzel, *supra* at 154. Because having some plants in the water is healthy, nutritionally balanced waters also have a diel DO level fluctuation but it is on the order of 2 mg/L.

[77] Wetzel, *supra* at 153-54.

Thus, the fact that there are large DO swings over the course of a 24-hour day is a strong indication that the waters have too much nutrient pollution. On the other hand, as discussed below, the lack of such diel DO swings does not disprove the possibility of nutrient pollution, because the nutrient pollution may be having other bad effects.

6.2.2 Water Temperature, Oxygen Saturation and Supersaturation

A short excursion must be made into the topic of oxygen saturation and supersaturation. Basically, there is oxygen in healthy waters and oxygen in the air. If one took a glass of clean water and let it sit on a shelf, it would either give to or receive oxygen from the air until it reached an equilibrium that is determined mainly by the altitude and the temperature of the water. At that point the water is said to be saturated. Basically, the lower the temperature, the higher the concentration of oxygen under equilibrium conditions.[78] When the water is freezing, saturation at standard air pressure is about 14.6 mg/L but at 86°F saturation is about 7.6 mg/L.[79] This means that with completely clean water one would expect some variation in the DO level as water temperature changes. It also means that summer is the critical time for low DO.

That is for clean water. If the water has something in it that rots and takes up oxygen (biochemical oxygen demand, or BOD), this causes lower DO levels and less saturation until whatever is in the water fully decays.[80] If the water has something in it that photosynthesizes, it might have more than 100% saturation (supersaturation) during the day when plants are putting out oxygen. When there is darkness and photosynthesis cannot work, the water with respiring plants would have lower DO and might have well under 100% saturation.[81]

There are two morals of this story. The first is that one should not look at high DO levels during the winter and decide everything is ok. DO levels are almost always high enough when the water is cool. Also, one should not decide everything is fine based on high daytime DO levels (> 8 mg/L or 14 mg/L depending on the temperature). The high DO levels might be the result of excessive plant or algal growth and may actually be harmful.

Because a lot of state employees and other people who do water quality testing do not like to get up very early in the morning[82] and 24-hour DO monitoring equipment is comparatively expensive, most

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78 Dodds & Whiles, *supra* at 301-02; Wetzel, *supra* at 151-52.

79 Wetzel, *supra* at 152; Hammer & Hammer, *supra* at 17.

80 Dodds & Whiles, *supra* at 329.

81 Wetzel, *supra* at 154.

82 Considering the salaries and levels of respect many state environmental officials get from our politicians, it is hard to blame them.

of our water bodies have been tested only during daylight hours. During these hours one would not expect to find low DO levels caused by nutrient pollution fueled plant or algal growth.

6.2.3 DO Levels Just Below Sewage Treatment Plants

You may be told by state officials that there is no nutrient pollution problem because the DO levels just below a sewage treatment plant are fairly high all the time. This is wrong. DO levels in plant discharges are generally high because the treatment stirring and mixing process adds DO to the effluent so that the DO concentration is artificially high.[83]

Sewage treatment plant discharge contains substantial organic materials which require a lot of oxygen for bacteria to decompose.[84] Sewage discharge also includes various chemicals, such as ammonia, that use up oxygen when they convert to other chemicals such as nitrate. As previously noted, these oxygen-using organic materials and chemicals are referred to as biochemical oxygen demand (BOD).[85]

Thus, if a sewage treatment plant discharges water with 7 mg/L of DO and 4 mg/L of BOD, leaving aside other possible effects, the level of DO in the water will be 3 mg/L after the BOD has had time to use up DO. In a stream or river, this effect will not be observed right below the discharge but rather some distance downstream. Depending on the flow, the pollution can affect the DO levels in the water many miles below the plant without appearing to cause a DO problem at the discharge point at all.[86]

Most relevantly here, if the sewage discharge contains nutrient pollution that causes an algal bloom in flowing water, the bloom will not appear immediately at the point of discharge. It will appear well downstream after the algae have had time to use the nutrients to grow into a bloom.

6.2.4 Flat DO Levels and Periods without Supersaturation

Wide diel DO fluctuations and daytime DO supersaturation are clear signs of phosphorus pollution but one should not read too much into the absence of such DO effects.

It is not true that nutrients only affect DO levels by stimulating growth of algae, plants, and cyanobacteria that photosynthesize. Nutrient pollution can also fuel increased growth of bacteria that do not photosynthesize (they are heterotrophic, or animal-like) and thus do not cause the diel DO

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83 Joseph P. Wellner, Jr. & James S. Dinger, *Dissolved Oxygen Profiles at Major Wastewater Dischargers and Hydroelectric Dams on the Ohio River*, Ohio J. Sci. *89*(5), 1989, 164-71.

84 Pielou, *supra* at 235.

85 U.S. EPA, Water: Monitoring & Assessment 5.2, http://water.epa.gov/type/rsl/monitoring/vms52.cfm (last updated Mar. 6, 2012).

86 Mason, *supra* at 110.

fluctuations and supersaturation caused by organisms that have chlorophyll *a*. Increased bacterial growth and oxygen consumption can occur in waters that do not receive much sunlight.[87]

Further, the upward diel fluctuation caused by photosynthetic activity during the day can be dampened by BOD pollution that depresses DO levels. Thus, in a water body being harmed by both nutrient and BOD pollution, one can see DO levels fluctuate between 2 mg/L and 7 mg/L when perhaps if the only problem was nutrient pollution, the DO would have fluctuated between 4 and 9 mg/L.[88] Bad DO levels that are bad all the time, are probably the result of forces other than nutrient pollution. DO levels that show a large diel fluctuation with higher levels of DO occurring during daylight hours indicate that there is a nutrient issue no matter between what levels the DO levels fluctuate.[89]

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[87] Michael A. Mallin et al., *Factors Contributing to Hypoxia in Rivers, Lakes and Streams*, Limnol. Oceanogr. *51*(1, pt 2), 2006, 690-701; U.S. EPA, Region 4, Technical Support Document for U.S. EPA's Final Rule for Numeric Criteria for Nitrogen/Phosphorus Pollution in Florida's Inland Surface Fresh Waters 142 (2010); Walter K. Dodds, *Eutrophication and Trophic State in Rivers and Streams*, Limnol. Oceanogr. *51*(1, pt 2), 2006, at 676-77.

[88] Seok Soon Park & Yong Seok Lee, *A Water Quality Modeling Study of the Nakdong River, Korea*, Ecol. Model. 152, 2002, 65-75.

[89] DO readings showing high levels during night hours and low levels during the day probably mean that somebody's timer is busted or there is some other equipment problem.

7 EFFECTS OF NUTRIENT POLLUTION ON HUMANS

The nasty effects of nutrient pollution are many and varied. A good summary of some of the effects was provided by the U.S. EPA.

> Inputs of nitrogen and phosphorus lead to over-enrichment in many of the Nation's waters and constitute a widespread, persistent, and growing problem. Nitrogen/phosphorus pollution in fresh water systems can significantly impact aquatic life and long-term ecosystem health, diversity, and balance. More specifically, high nitrogen and phosphorus loadings result in harmful algal blooms (HABs), reduced spawning grounds and nursery habitats, fish kills, and oxygen-starved hypoxic or "dead" zones. (75 Fed. Reg. 75,762 at 75,765)

Moreover, it affects drinking water.

> Public health concerns related to nitrogen/phosphorus pollution include impaired surface and groundwater drinking water sources from high levels of nitrates, possible formation of disinfection byproducts in drinking water, and increased exposure to toxic microbes such as cyanobacteria. (Ibid.)

Nutrient pollution also affects recreation as sport fishing areas are lost, swimming is made dangerous or unpleasant, mounds of aquatic vegetation pile up on beaches and rivers, and streams are turned to unattractive green gunk.

7.1 Effects of Phosphorus Pollution on Macroinvertebrates and the Sport Fish that Rely on Them

7.1.1 DO Effects

Fish need to be able to breathe 24/7. Fish can take lower levels of DO for some part of the day. It is clear, though, that low DO levels caused either at dawn (because all the plants, algae, and animals used up the oxygen at night) or all day (by bacteria growth if there is not enough light for much oxygen production from photosynthesis) will kill fish or limit their growth.[90] If DO falls below 5 mg/L, a lot of the higher-quality sport fish will have trouble surviving, and their young will be even less able

[90] U.S. EPA, Ambient Water Quality Criteria for Dissolved Oxygen (EPA-440-5-86-003), 1986; Welch, *supra* at 304-11; Dodds & Whiles, *supra* at 620.

to survive in low oxygen.[91] Further, there is considerable evidence that large diel fluctuations in DO levels will also cause stress on fish and other aquatic life that results in lower biodiversity.[92]

Finally, fish can get too much of a good thing. Very high levels of DO supersaturation (> 120%) can also be bad. High levels of DO can cause gas bubble disease in fish.[93]

7.1.2 Species Changes, Food Web Effects, and Other Effects

Aquatic life is affected by nutrient pollution in a number of ways in addition to effects caused by low or erratic DO levels. For example, nutrient pollution generally promotes a decrease in species diversity and more string chains of algae (filamentous algae and cyanobacteria)[94]

7.2 Drinking Water

7.2.1 Cyanobacteria and Drinking Water

Cyanobacteria can create toxics that will harm people who drink the water. This problem became national news when cyanobacteria shut down water supplies to 500,000 people living in the Toledo area in August 2014.[95] Even when not toxic, cyanobacteria can cause taste and odor problems in drinking water.[96] Finally, there is now some evidence that links living near bodies of water with cyanobacteria blooms to the occurrence of ALS (Lou Gehrig's Disease)[97]

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[91] U.S. EPA, Ambient Water Quality Criteria, *supra* at 17. The larval stage is the most sensitive to low DO.

[92] Steven Heiskary et al., Minnesota Nutrient Criteria Development for Rivers, Draft, Jan. 2013, *available at* http://images.webofknowledge.com/WOK46/help/zh_CN/WOS/L_abrvjt.html.

[93] Don E. Weitkamp, Total Dissolved Gas Supersaturation, Summary of the Literature 1980-2007 (2008), *available at* http://www.ecy.wa.gov/programs/wq/tmdl/ColumbiaRvr/062308mtg/TDGeffectsLitRev080615.pdf.

[94] Burkholder & Glibert, *supra* at 352-53; Evans-White, *supra* at 855, 866-67.

[95] Carl Zimmer, *Cyanobacteria are far from Just Toledo's Problem*, N.Y. Times, Aug. 7, 2014; Mason, *supra* at 149 (cyanobacteria suspected of killing 43 people in Brazil in 1996).

[96] Royer et al., *supra* at 437; Welch, *supra* at 166 (taste and odor problems in water supplies); For a World Health Organization discussion of this issue and potential standards for acceptable levels of toxins in drinking water, *see* http://www.who.int/water_sanitation_health/resourcesquality/toxcyanchap5.pdf.

[97] Lindsey Konkel, *Closing in on ALS? Link Between Lethal Disease and Algae Explored*, Environ. Health News, Dec. 11, 2014, *available at* http://www.environmentalhealthnews.org/ehs/news/2014/dec/als-and-algae.

7.2.2 Total Organic Carbon and THMs

Chlorine and other chemicals used to disinfect source water can form carcinogenic compounds when they react with organic matter. These compounds become a serious problem when nutrient overloads trigger recurrent and persistent blooms of algae that contaminate source water. The reaction between chlorine and algal organic matter generates trihalomethanes and haloacetic acids, two types of disinfection byproducts that are federally regulated, as well as many other types of toxic byproducts. The treatment of algal contamination in drinking water with chemical disinfectants such as chlorine can produce carcinogenic disinfection byproducts that are not currently regulated.[98] As explained by U.S. EPA, "some disinfection byproducts have been linked to rectal, bladder, and colon cancers; reproductive health risks; and liver, kidney and central nervous system problems."[99]

7.2.3 Nitrate

Nitrate is also bad for drinking water by causing "blue baby" syndrome in newborns.[100] For this reason, many states have water quality criteria designed to protect drinking water sources of 10 mg/L NO_3^-.[101]

7.3 Recreation, Aesthetic Effects, and Tourism

Low or highly fluctuating DO levels that harm sport fish obviously harm recreation.[102] Another major effect of nutrients is that the plant overgrowth they fuel can clog waters with aquatic weeds, including invasive species. The algal overgrowth can turn the water to something that looks like pea soup from outbreaks, or blooms, of cyanobacteria. [103]

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98 Olga V. Naidenko, Craig Cox, & Nils Bruzelius, *Troubled Waters: Farm Pollution Threatens Drinking Water*, Environmental Working Group, 2012, *available at* http://www.ewg.org/research/troubled-waters.

99 U.S. EPA, 75 Fed. Reg., No. 233, at 75,768 (Dec. 6, 2010).

100 Mason, *supra* at 138-39.

101 E.g., Ill. Admin. Code tit. 35, § 304.

102 U.S. EPA, 75 Fed. Reg., No. 233, at 75,766 (Dec. 6, 2010).

103 Welch, *supra* at 166. Cyanobacteria can form "scums on the water surface that are very unsightly and odiferous."

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This effect is a bit hard to quantify. Obviously, no one should swim in waters with high levels of toxins that are caused by cyanobacteria.[104] Cyanobacteria "frequently result in deaths of domestic animals."[105] As far as aesthetic effects, it is generally thought that some people are much more tolerant of green, slimy water than others. However, one poll showed that virtually no one wants to swim in water that has sestonic chlorophyll *a* levels greater than 30 μg/L, and few want to swim in water with over 20 μg/L.[106]

CONCLUSION

Nutrient pollution is a serious worldwide problem. The science regarding nutrient pollution is complex, but even lawyers can understand the basic science. Many principles are well established.

Determining water quality criteria for phosphorus is not that much harder than determining criteria for other pollutants and there are a number of tests that can be used to show that a particular water body has been adversely affected by pollutants. Many of the things that have been said or written to minimize the problem or make it appear that the science of nutrient pollution is hopelessly complex were probably motivated more by a desire to make the problem seem harder than it is so that the public will throw up its hands in despair and give up on protecting our waters.

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104 Jolanda M. H. Verspagen et al., *Benthic-Pelagic Coupling in the Population Dynamics of the Harmful Cyanobacterium* Microcystis, Freshwater Biol. 50, 2005, 854-867, at 854; For a World Health Organization discussion of this issue as well as potential standards for acceptable levels of toxins in drinking water, *see* http://www.who.int/water_sanitation_health/resourcesquality/toxcyanchap5.pdf; Mason, *supra* at 149.

105 Welch, *supra* at 166.

106 M. V. Hoyer, C. D. Brown & D. E. Canfield, Jr., *Relation Between Water Chemistry and Water Quality as Defined by Lake Users in Florida*, Lake Reserv. Manage. *20*(3), 2004, at 245.

APPENDIX. Πhosphatic Δialog

Dialog between a Midwest State Official (MSO) and The Truth (TT)

MSO: I don't know why you insisted on having this meeting. I thought we'd agreed to just study nutrient pollution until after I am retired.

TT: I never agreed to that, and under the Clean Water Act you can't just keep issuing permits that allow discharges of phosphorus that are causing violations of dissolved oxygen standards and the narrative standards against eutrophication or excessive or unnatural plant and algal growth.

MSO: We have gotten away with it, though, for a long time. Anyway, why do we have to do anything about phosphorus pollution in Illiowiana? Phosphorus is not limiting plant or algal growth in 90% of the waters of Illiowiana, or any of the other 'I' states for that matter.

TT: Phosphorus is not now limiting plant or algal growth, but it should be. Under Liebig's Law of the Minimum, growth is limited by the most limiting resource. In Illiowiana, the rivers, lakes and streams are pretty much awash in phosphorus. In most freshwater systems that are not polluted, the scarcity of phosphorus generally limits the plant and algal growth so that there is enough growth, but not too much growth, and not of the wrong kind like Eurasian water milfoil and outbreaks of cyanobacteria, also known as blue-green algae. We have so much nutrient pollution in Illiowiana water bodies that they are choked with invasive plants, lousy biodiversity scores for fish and microinvertebrates, and sometimes nasty "blooms" of cyanobacteria that put out toxics that ruin drinking water sources, make swimming impossible and kill pet dogs that go into the water. A lot of our water bodies are just gross.

MSO: Picky, picky, picky. Well, we ran an experiment once in which we got a sewage treatment plant to treat phosphorus down to the point that there was only 0.6 mg/L in the small river to which the plant discharged, a lot lower than what it is in most of the state, but we couldn't see any improvement in terms of plant or algal growth. So, phosphorus cannot be the problem.

TT: 0.6 mg/L is extremely high compared to natural levels that are less than a tenth of that. Experts say that anything above 0.2 mg/L and phosphorus probably is not limiting. If you get the levels below 0.2 mg/L and give the river some time, maybe years, for all the phosphorus in the stream to flow downstream, get covered by sediment, or otherwise become inaccessible to plants and algae, you should start to see improvement. This has happened in a few places where the people in charge actually took action to control phosphorus pollution.

MSO: I've got a lot of things to do. A bunch of guys collected a lot of data on our streams once and found no overall correlation between phosphorus levels and either algal growth or the biological health of the water body. If there was any difference in the sites, it seemed to be based on habitat. So, again, I don't see that we have a phosphorus problem.

TT: Of course, we should try to work on the habitat, too, but as I mentioned, Illiowiana waters are flooded with phosphorus. Most of the waters you are looking at have different levels of way too much. If you compared the health of people who were shot 40 times with those who'd been shot 20 times, you probably would not find much difference.

Studies that have concentrated on those few streams in Illiowiana that have less than 0.2 mg/L total phosphorus have found a pretty good fit between phosphorus levels and biological measurements. In the statewide studies, those numbers are outweighed by the huge number of data points comparing the effects of different levels of way too much.

MSO: Well, we've got to deal with the water bodies we've got.

TT: All but a few of your waters are messed up. You should look at data from states with more healthy waters if you want to make large-scale comparisons of waters that are polluted with ones that are not polluted.

MSO: We have a few streams with high levels of phosphorus that look just fine. Doesn't that refute the theory that phosphorus is a problem here?

TT: There are some people who have lived to be 100 despite smoking three packs of cigarettes a day. That does not mean that everyone should take up smoking.

You may not have been looking for the right things in the streams you think are fine, but it is possible that the light and flow conditions in those few examples you cite are such that it is hard for bad things to get started. In the places where that is true, you can bet that the phosphorus is flowing downstream to slower and less shaded water bodies or stream segments and is making a mess there.

MSO: You and EPA say that a problem with phosphorus is that it causes dissolved oxygen levels to go down and the poor little fishies can't breathe, but we checked DO levels and they look just fine, over 6 mg/L below the sewage treatment plants. So there can't be a problem.

TT: That's like saying that cannons are harmless because no one was hurt at the place where the cannon was fired. When you put phosphorus into a river, it causes plants and algae to start growing more than they would if phosphorus was limiting, but the plants and algae do not show up until a long way below the sewage treatment plant. You don't expect a growing thing to pop up immediately after being fertilized do you? In fact, the big obvious mess might not appear until miles downstream when the algae have had time to bloom and the flow slows down behind a dam or in another area where the water has the right flow and sun.

Just downstream of the sewage treatment plants, the water is full of DO from the aerated discharge, and the phosphorus and the other pollution that causes oxygen levels to fall, called biological oxygen demand, hasn't had time to work.

MSO: Ok, but we have looked at DO levels in a few of our waters well below sewage treatment plants and they are just great. We even got levels like 16 mg/L in the afternoon in the summer. That's 10 mg/L over the state DO standard. Things are just great.

TT: Apparently, you did not pay too much attention in your high school biology class or you have forgotten a lot. The plants and algae fueled by phosphorus photosynthesize. That means that they put out oxygen during the day when the sun is out. They respire all day and then during the night, when they cannot photosynthesize, they take in a lot of dissolved oxygen. If you check DO levels just before dawn, there may be very low levels of DO at the location you thought was so great in the afternoon.

MSO: You want me to get up at 4 in the morning on my salary? And the Governor says I am overpaid and I should not have a union? Forget it.

It so happens that we do have data at a few sites where some really overpaid professors and their indentured grad students measured DO levels at dawn and found violations at some of the places that had high levels in the afternoon. So maybe there is a problem at those places. But at some of those locations, the DO never gets very high. It is around 1 or 2 mg/L at 4 AM and 5 or 6 mg/L at 4 PM. It does not seem like phosphorus pollution causing photosynthesis is causing the problem there.

TT: I did not say that phosphorus pollution was the only problem in the state. In the waters with the low levels of DO during the day and even lower DO levels during the night as you describe, phosphorus is not the whole problem, but rather just part of the problem. The DO levels are being depressed by some other pollution (biochemical oxygen demand) all the time. Then the phosphorus is causing plant or algal growth that is causing the DO fluctuations that are causing really low levels during darkness when photosynthesis isn't working. Also, the phosphorus is probably helping fuel some bacteria that do not photosynthesize but that still use DO all the time.

MSO: We got someone to measure the chlorophyll-α levels in some streams and they found that the level was only 7 parts per billion. That's not bad is it? So why do we have to quit putting phosphorus in those streams?

TT: 7 parts per billion (7 μg/L) is not particularly good. The U.S. EPA recommendation for *average* streams is about that. What did you see in the water where you got those average chlorophyll levels?

MSO: Well, the stream was full of long stringy plants and the rocks were all covered with hairy looking mossy green crud. There were even plants growing on some of the plants.

TT: The long stringy plants and hairy looking mossy green crud are all using up DO just like floating algae in the water column would. The floating algae, called sestonic algae, which are what is usually measured for chlorophyll-*α*, don't grow well in streams because the current is too fast and they can't hold on. So in faster flowing waters where there is enough light, plants and algae that can hold on to the stream bottom or rocks will predominate. If you want to measure the plant and algal growth in those faster-moving streams, you have to pull up all the plants and scrape all the rocks to figure out the amount of chlorophyll for a known amount of area.

MSO: Not happening on our budget.

TT: Maybe not, but don't tell me you don't have a problem in a stream when you have not done the right tests.

MSO: Well, we did test phosphorus levels and the lab said there was only 0.2 mg/L soluble reactive phosphorus or phosphate or ortho-phosphate or whatever you call it. So according to the expert you mentioned, there can't be a problem.

TT: No, No. First, 0.2 mg/L of ***total*** phosphorus is where phosphorus stops being limiting on growth, and adding more does not make an apparent difference. The growth fueled by phosphorus starts way down at something like 0.03 mg/L and one continues getting more growth and nastier species of growth until around 0.2 mg/L where you stop getting more growth from adding phosphorus.

Also, here you have confused the types of phosphorus. Soluble reactive phosphorus and the other forms of phosphorus you mentioned are just a portion of the total phosphorus that algae and plants use the best. It is the phosphorus that is easily available right away, called "biologically available." What do you think is in all those long stringy plants and green crud you mentioned? That's right, phosphorus. You have to measure *total* phosphorus to know what is going on and it is the *total* phosphorus that needs to be kept well below 0.2 mg/L if you don't want a lot of invasive plants, cyanobacteria and other headaches.

The fact that you are finding 0.2 mg/L of the kind of "loose" phosphorus that's used by algae and plants right away means that there is so much phosphorus in the water that the plants and algae there can't even use all of the best kind. The excess is sailing *en masse* downstream to make a mess there.

MSO: I might agree with you that we could get phosphorus from the sewage treatment plants down to below 1.0 mg/L. At least, they have been doing it in the Great Lakes for a while. It is not too expensive to get sewage treatment plants down to 0.6 mg/L of phosphorus as opposed to the 3 or 4 mg/L that they often put out. But we don't have money to get phosphorus down below 0.2

mg/L. If it won't do any good to get levels down to 0.6 mg/L, why don't we just give up and let the levels stay at 3.0 or 4.0 mg/L and spend the money on habitat or paying the governor's appointees better?

TT: Well, if you don't give a damn about water quality, we will just take this discussion to federal court. If you do care, then you should get the sewage treatment plants down to 0.6 mg/L as a first step and work down from there. In some water bodies, even in Illiowiana, there is enough clean water so that getting the sewage treatment plants down to 0.6 mg/L will get the ambient level–that is, what's in the water after the river dilutes the effluent–down below 0.2 mg/L. Also, EPA has said that getting sewage treatment plants to use biological nutrient treatment to get total phosphorus levels down to 0.6 mg/L is a good first step that can be built on to get phosphorus levels lower. Also, getting the levels down in small rivers and streams will reduce the time it takes those waters to recover and help downstream waters including dammed rivers and the Gulf of Mexico.

MSO: Ah, but agriculture is the real problem, isn't it? Why should we do a lot of work at sewage treatment plants when agriculture is the problem?

TT: Actually, sewage treatment plants are the main problem causing bad levels of phosphorus in a lot of waters. There are many waters in Illiowiana in which there is a lot of sewage discharge and not much agricultural phosphorus run off. Also, the types of phosphorus put out by sewage treatment plants is the worst kind that is used right away by plants and algae. It causes harmful algal blooms and other problems, much more pound for pound than agricultural phosphorus pollution.

I am not saying, though, that you shouldn't work on phosphorus from agricultural sources also. That is another long effort that you should start now. And sometime very soon, we should discuss nitrogen.

MSO: Oh, brother. Can't wait to hear what *else* is wrong.

The 31st day of August, MMXV