Journal of Water Sustainability, Volume 1, Issue 1, June 2011, 1–22

The Danger of Hypertrophic Status of Water Supply Impoundments Resulting from Excessive Nutrient Loads from Agricultural and Other Sources

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ABSTRACT

The effect of agricultural operations on nutrient losses with a specific focus on creating eutrophic and hypertrophic water quality in lakes and reservoirs providing water supply has been outlined. As a result of the intensification of agriculture and installing sewerage to growing communities, nutrient loads into receiving surface and ground waters have dramatically increased throughout the world. The article compares nonpoint loads of nitrogen and phosphorus in several countries. Two specific cases will illustrate the dilemma. The presentation will focus on the Švihov Reservoir on the Želivka River in the Czech Republic which is a primary source of potable water for Prague and Lake Tai (Taihu) in China. These impoundments are either threatened by or are already suffering from excessive nutrient loads by nonpoint agricultural and by point industrial and municipal sources. The problem is the hyper-eutrophic status exhibited by harmful algal blooms of cyanobacteria (Cyano-HAB) which is becoming endemic to many impoundments in Europe and Asia. The need for coordinated interdisciplinary research and an implementation remedial plan is outlined, discussed and developed into a concept of an ecoregion for multiple uses and purposes for water bodies and watersheds providing water supply to communities.

1.0 INTRODUCTION

The excessive overloading of soil with industrial fertilizers and uncontrolled discharges of nutrients (nitrogen and phosphorus) from municipal and industrial point source has had serious worldwide consequences in water quality. The situation is troublesome both in the Czech Republic and in China. In the Czech Republic, in the last three decades, the water quality of a majority of impoundments deteriorated to the point that the basic uses of these water bodies for recreation and water supply are now severely impaired or are threatened in the near future. The impairment has been caused by massive growths of blue-green algae also known as cyanobacteria nourished by high concentrations of nitrogen and phosphorus in surface and ground waters. Harmful algal blooms of cyanobacteria (Cyano-HAB), which are massive accumulations (10^4-10^6 cells/ml) of a single or coexisting nuisance species (Paerl, 1988), now impair 70 % to 80% of reservoirs in the Czech Republic (Hejzlar, 2006; Babica et al., 2006). Figure 1 shows the total fertilizer (N+P+K) use in the Czech Republic in kg/ha-year and nitrate concentrations in the Želivka River, which is the main supplier of potable water for 1.3 million people in the capital city Prague, and central Bohemia and Highlands re-

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gions. A significant portion of applied fertilizer is lost into surface and ground waters. The danger of hypertrophy in the water supply system of Prague was documented in Novotny (2009).

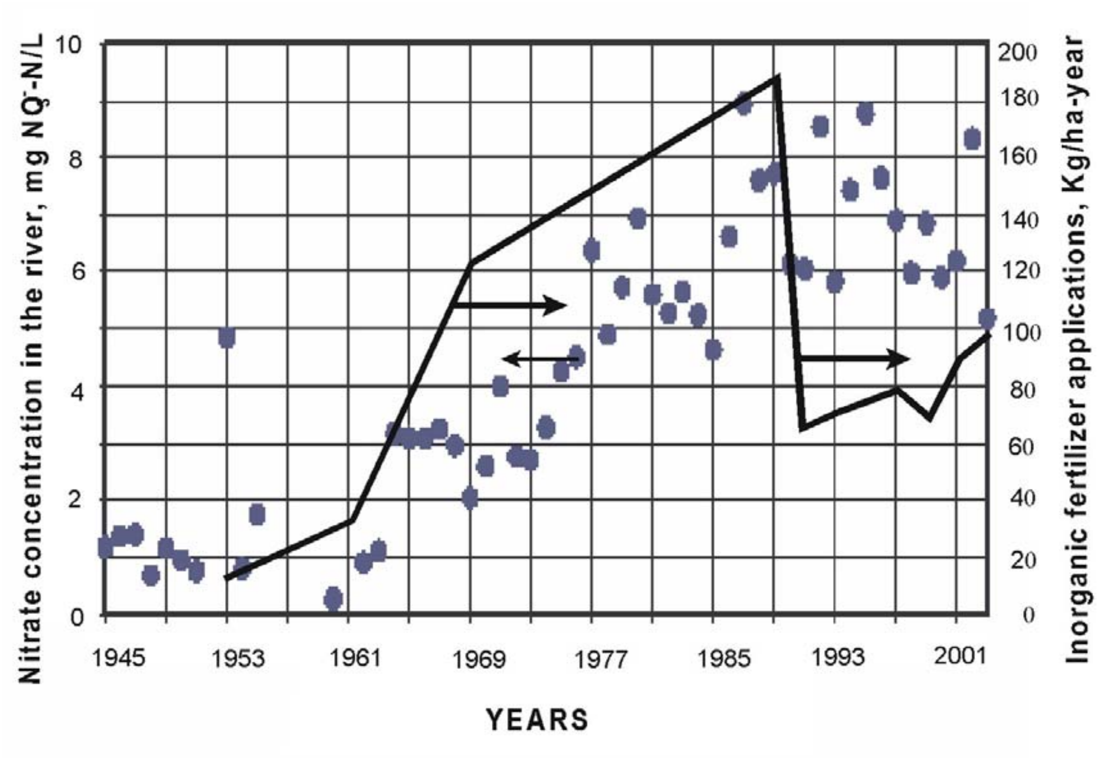


Figure 1 Concentrations of nitrate-N in the Želivka River in Švihov and total industrial nitrogen fertilizer (N+P+K) application in the Czech Republic. Data from the Czech Ministry of Agriculture and from Lexa et al. (2006)

A statistically noticeable reduction of industrial fertilizer occurred after the 1989 economical and political change in the Czech Republic (former Czechoslovakia). Before 1989, the price of fertilizers was heavily subsidized by the government to increase crop yields. After 1989 the subsidies were removed and the cooperatives responded by a significant reduction of purchases of the fertilizers (Holas, 1997; Holas and Hrnčíř, 2001). However, because of the soil overload by the N and P, a proportional sudden reduction in N (and also P) concentration in Czech streams did not occur and, at best, the response was gradual and slow (see also Novotny, 2003; Stalnacke et al., 2009) and crop yields were reduced only slightly. Some P reduction can be attributed to the ban on phosphate detergents regulation implemented in the Czech Republic in 2006.

Excessive use of fertilizers and subsequent water quality degradation and occurrence of Cyano-HABs are not limited only to the Czech Republic, the same proliferation of Cyano-HABs and loss of water resources are now plaguing China, Japan, the Netherlands and many other countries. Sixteen percent of lakes in Florida are hypertrophic with Cyano-HABs. In The Netherlands, most inland surface water bodies (canals and lakes) at the end of the last century were hypertrophic and groundwater nitrate concentration exceeded 10 mg N/L in the eastern half of the country (Van der Molen et al., 1997; Oenema et al., 2005). In China, the third largest freshwater lake, Taihu, has in the last five years anticipated severe algal blooms of the same cyanobacteria species (Microcystis) (Paerl et al., 2010; B. Maršálek, personal communication, 2009) as the reservoirs in the Czech Republic. Both Lake Tai and other lakes in China and water supply reservoirs in the Czech Republic also receive nutrient loads from municipal and industrial point and nonpoint sources.

Figure 2 shows the trends in the unit area industrial fertilizer use in several countries of Asia, Europe and in the US. These application rates are less than the total fertilizer use in the countries with large concentrated animal herds such as The Netherlands, France or India where a lot of manure is disposed on land. In The Netherlands, the manure fertilized application rates (Salomons and Stol, 1995; Novotny, 2003) ranged between 150 to 450 kg/ha. Note that the trend in eight countries is converging to the optimum value of 100 kg/ha. China's and Brazil's trends are increasing and Korea's rate remains steady and high. In The Netherlands, which has the highest application rates of fertilizers and all lakes are man-made, all lakes in the western most populated part of the country were highly eutrophic to hypertrophic at the beginning of this century (Ibelings, 2005). Dense Microcystic blooms were found not only in smaller regional waters, but also in the major lakes where the cyanobacteria surface scums can cover hundred of km^2 of the water surface.

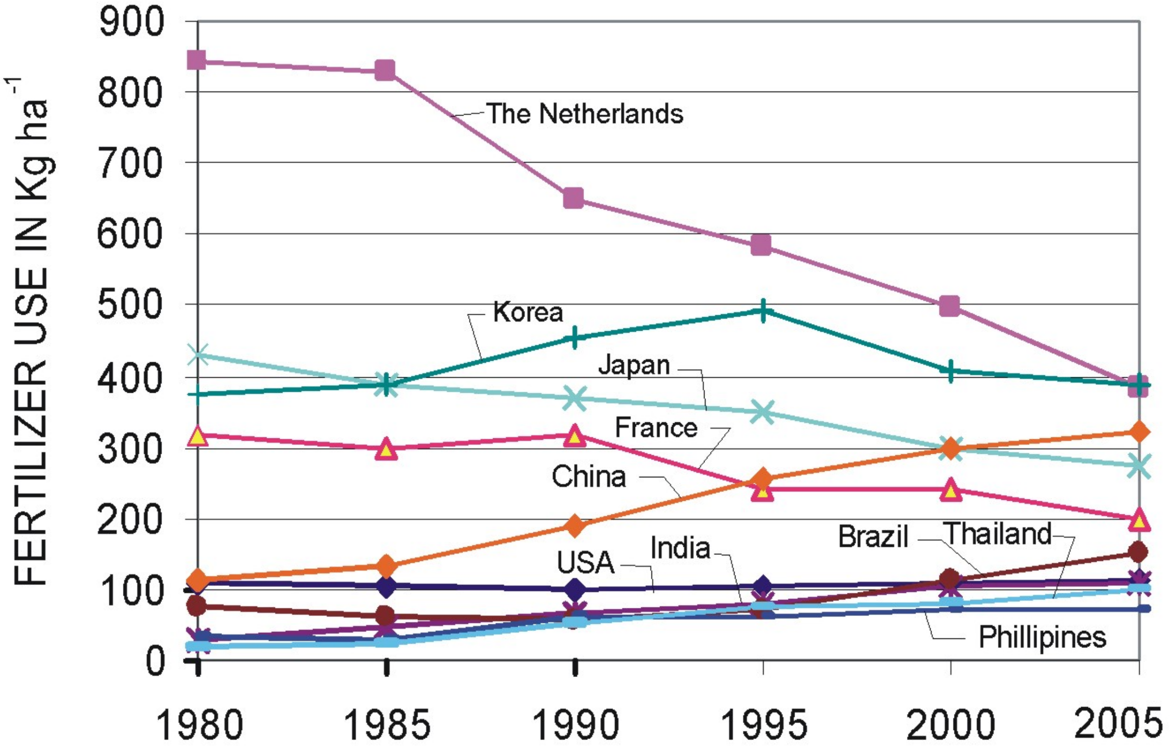


Figure 2 Industrial fertilizer unit area applications (Kg/ha-year) in ten countries. Based on IFIA and FAO STAT data (Novotny et al., 2010a)

When the trends of the fertilizer applications in China in Figure 2 and the Czech Republi

When the trends of the fertilizer applications in China in Figure 2 and the Czech Republic from Figure 1 are compared it will be noted, that before the economic and political changes in 1989 in Czechoslovakia (today Czech Republic), the trends and application rates were about the same. After 1989 the rates were dramatically reduced in the Czech Republic to the levels of the US, India, Thailand and other low use countries while in China's agricultural applications continued to raise. However, it is recognized that in the Czech Republic farmers generally grow annually only one crop while in southern China two harvests (and double fertilizer applications) may be common. Currently in China, the proportions of the industrial and organic fertilizers are about 75% inorganic and 25% organic, respectively (IPNI, 2007). Hence, of the total application rate of 426 kg/ha in China (based on 2005 data), 321 kg/ha is the application rate of industrial fertilizers.

It is obvious that the losses of nutrients (N + P) into receiving and ground waters are related to the fertilizer application rates. Generally, in high fertilized use countries 20 – 40% of the applied fertilizer is in excess and is lost into surface waters, ground water, or adsorbed by soils, or, in the form of nitrous oxides and ammonia volatilize into the atmosphere. According to De Haan et al. (1993) agriculture significantly contributes to the Dutch emissions of greenhouse gases (~15%), acid rain (~50%), by nitrous oxides and ammonia, and groundwater pollution by nitrates (~85%). As stated above, groundwater nitrate concentrations in the eastern half of The Netherlands exceed the WHO (World Health Organization) limit of 10 mg/L of nitrate N.

2.0 PROBLEMS WITH NUTRIENT ENRICHMENT OF IMPOUNDMENTS

Eutrophication is a process of photosynthetic enrichment of water bodies by primary productivity of organic matter by algae and also by cyanobacteria that progresses from oligotrophic, mesotrophic, to eutrophic states. Characteristics of these three states are presented in Table 1. In today's context, "eutrophication" refers to "natural and anthropogenic additions of nutrients to water bodies and to the effects of these added nutrients on water quality" (Rohlich, 1969). The stages of eutrophication may be related to the algal biomass or chlorophyll-*a* concentrations as shown in Table 1 or to the primary productivity of organic matter.

There are several indices for estimating trophic status of impoundments. The most common in the US is the Carlson's (1977) index developed for lakes that are phosphorus limited. Carlson based the formulation of his index on the fact that there are cross-correlations between the transparency expressed by the Secchi disc depth (meters), algal concentrations expressed as chlorophyll-*a* (μg/L) and vernal (spring) average concentrations of phosphorus (μg/L). The trophic status index (TSI) is then defined as (Carlson, 1977; Novotny, 2003; US EPA, 2011)

$$\text{TSI (SD)} = 60 - 14.41 \ln(\text{SD})$$

$$\text{TSI (Chl)} = 30.6 + 9.81 \ln(\text{Chl})$$

$$\text{TSI (TP)} = 4.15 + 14.42 \ln(\text{TP})$$

The overall TSI is calculated as an average of the three values. Secchi disc values can be distorted by high inorganic sediment concentrations. In such cases, the overall TSI is an average of TSI(Chl) and TSI(TP).

Table 1 Trophic status of impoundments (Source US EPA, 1974 and 2011)

Water Quality	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic*
Total P (µg/L)	<10	10-20	20-70	>> 70
Total N (mg/L)	<0.3	0.3 -0.6	0.6 - 1.5	>1.5
Chlorophyll – *a* (µg/L)	<10	4-10	10-40	>>40
Secchi disc transparency depth (m) during summer	>4	2-4	1 - 2	<1
Hypolimnetic oxygen (% saturation)	>80	10-80	<10	0
TSI (Carlson)	<40	40 – 50	50 – 65	>65

*Calculated from the Carlson Index set as 65, rounded and added to the original table by the author.

Figure 3 Sedlice Forebay on the Želivka River system during cyanobacteria Microcystis bloom. Picture taken in summer 2003 by the Biology Center of the Czech Academy of Sciences

Figure 4 Microcystis aeruginosa – a common bloom forming cyanobacteria (Source Czech Academy of Science)

Figure 5 Cyanobacteria Microcystis outbreak and dead fish in Taihu photo taken by a student of Wuxi University. The repeating outbreaks are due to excessive nutrient inputs from industrial and agricultural sources.

Although eutrophication can be natural, it is usually greatly accelerated by anthropogenic activities, excessive nutrient inputs, and by global warming because cyanobacteria prefer warmer temperatures for growth. Originally, only three stages of eutrophication were used in the literature and in assessments of the organic enrichment of water bodies. With the exponential increase of the nutrient inputs from agricultural and urban point and non-point sources after 1960, a category of *hypertrophy* and *hypertrophic* water bodies was added, which denotes a troublesome post eutrophication state of the water body exhibited by excessive algal development, especially of noxious species of cyanobacteria (Chorus and Barton, 1999; Vollenweider and Kerekes, 1980; Paerl et al., 2010). Under certain favorable conditions these organisms can develop in large quantities as Cyano-HABs (Figures 3and 5) exhibited by scum, failure of filtration systems in water treatment plants by excessive clogging; smell of water due to anoxic conditions resulting in emanation of hydrogen sulfide, “pea soup” appearance, and bad aesthetics. They also cause rashes to swimmers and are toxic to animals. Chlorophyll a concentrations of dense Cyano-HABs can exceed 3 mg/L (Chorus and Bartram, 1999). Walker and Havens (1995) summarized the experience and eutrophication criteria for Minnesota, Florida, South Africa and other states and countries and concluded that chlorophyll a concentrations exceeding 40 μg/L were associated with severe “algal nuisance conditions” typical for HABs at which “no swimming” advisories are issued.

In June 2007 a large bloom of blue-green algae (mostly cyanobacteria Microcystis) in Tai Lake (Taihu) in China caused severe deterioration of water quality. For months, water supply systems for the city of WuXi (population 4 million) and other large cities relying on Tai Lake were decommissioned. Altogether, 10 million people rely on the water supply from Taihu. Figure 5 is a web picture by an unknown student from the university in WuXi that aroused the attention of the Chinese public and officials to the cyanobacteria problem. In November 2009, The World Lake Congress in Wuhan (China) featured many papers on the problems of Tai Lake. The surface area of Taihu is 2338 km^2 and its average depth is 2 meters. The population in the 10 000 km^2 watershed is 10 million. Over the last 30 years the trophic status progressed from mesotrophic diatoms dominated status to hypertrophic status with toxins producing Microcystis as the dominating species (Paerl et al., 2010).

Cyano-HABs produce a range of toxins (Carmichael, 1992, 1997; Chorus and Barton; 1999; Bláha et al., 2006; Bláha and Maršálek, 2009) and interfere with the uses of the water body for recreation (swimming, fishing, boating), drinking water supply, and other aquatic resource (including commercial fishing and aquaculture) uses (Paerl et al. 2001). Microcystis produces the dangerous toxin Microcystin. The presence of cyanobacteria in large densities in an impoundment imposes excessive oxygen demand, causing hypoxia as sinking cells die and decay. They also impose oxygen demand by their own heterotrophic metabolisms in the absence of light (Paerl et al. 2001; Šejnohová and Maršálek, 2006). Both toxins and anoxia render the impoundments unsuitable for invertebrate prey (intermediate levels of the food web) and fish populations (Paerl et al. 2001; Paerl and Fulton 2006; Bláha and Maršálek, 2009). They are also toxic to fowl (Skočovská et al., 2006), other organisms, and humans (Babica et al., 2006; Bláha and Maršálek, 2009). As a result, in many nutrient-enriched freshwater habitats, especially those that have experienced parallel hydrologic modifications (impoundments and reservoirs), cyanobacteria constitute a major nuisance problem. During hyper-eutrophic conditions, Secchi disc transparency often drops below 0.5 meters and the hypolimnion becomes anoxic, while in the epilimnion, dissolved oxygen concentrations exhibit large diurnal fluctuations exceeding saturation during the day and approaching hypoxia during late nights or cloudy days.

Helleweger et al. (2007) reported that the behavior of the cyanobacteria bloom development and perseverance is defying the rules and concepts of the traditional Vollenweider (1975) eutrophication model that relates eutrophication to phosphorus load and hydraulic characteristics of the lake or reservoir (depth, residence time). This severely hinders our ability to develop accurate TMDL (Total Maximum Daily Load) or European Community Water Framework Directive targets for water bodies that experience cyanobacteria blooms, let alone predict when these blooms might take place. *Hypertrophic* conditions**,** created by cyanobacteria blooms**,** are also different from eutrophic or better conditions and will also require approaches other than just lowering the inputs of phosphorus into the impoundment.

3.0 SITUATION IN THE ŠVIHOV RESERVOIR AND ITS TRIBUTARIES

Novotny (2009) summarized the Czech literature on eutrophication status and a danger of hyper-trophy in the country's reservoirs, particularly in the Želivka River watershed which is the main supply of potable water for the capital city Prague and surrounding Central Bohemia and Highland regions. The Švihov Reservoir on the Želivka River, one of the largest in the Czech Republic, is the main source of potable water. The reservoir and the Želivka River watershed are presented on Figure 6. Pečenka et al. (2007) documented the average nitrate concentrations in the water from the Želivka Water Treatment Plant are higher than those in the Vltava (Moldau) River that already has hyper-eutrophic deep reservoirs (e.g., Orlík, Slapy); and cyanobacteria are already developing in the headwater and upper reaches of the Švihov Reservoir as shown on Figure 3 showing the Sedlice forebay (upstream sedimentation reservoir) which is one of the headwater reservoirs on the Želivka River (Figure 6). The concentrations of phosphorus and nitrogen in 2006 in the key tributaries have already exceeded the limits for hypertrophy, exceeding 100 μg/L phosphorus and 10 mg/L of NO_3^--N, respectively (Table 2 and 3). The latter value is the WHO standard for potable water which is sometimes erroneously applied to water supply impoundments as a criterion of “good” ecological water quality. Water quality deteriorates and water supplies are decommissioned by Cyano- HAB developments at N concentrations that are much smaller than the 10 mg NO_3^--N/L criterion.

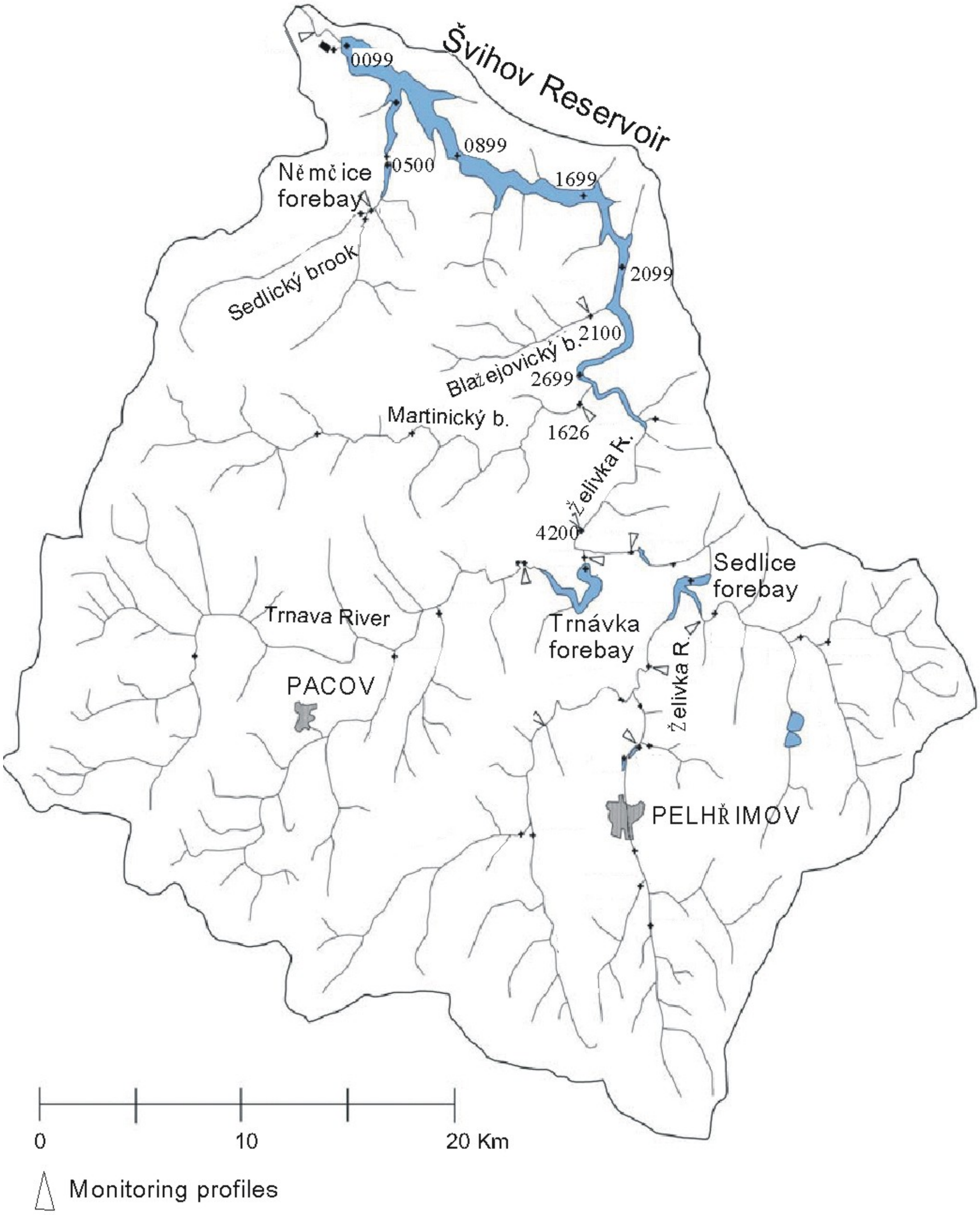


Figure 6 Želivka River watershed and Švihov reservoir (Repotted from and Courtesy of Hejzlar et al., 2006)

Table 2 shows the 90 percentile maximal concentrations of phosphorus and nitrogen in the direct tributaries of the Švihov Reservoir. These concentrations are in the hypertrophic range. All main monitoring points in the five year monitoring period reported by Pečenka et al. (2007) have exceeded total P concentrations of 100 μg/L. 90th percentile values in the report by Hejzlar et al., (2006) are used in the Czech Republic for evaluation of water quality. Also groundwater throughout the watershed exhibits very high nitrate concentrations exceeding 10 mg NO_3^--N/L.

Table 3 shows the progression of the eutrophy through the Švihov Reservoir from the entry point of the Želivka River into the impoundment (profile 2699) to the dam (profile 0099) in 2005 published in the Vltava Watershed Agency report by Hejzlar et al. (2006). It can be seen that indications of hypertrophy are already noticeable in the upper profile, exhibited also by a higher pH typical of excessive algal growths; however, pH of HABs can be as high as 10. The reason for pH increase is the fact that algae derive the inorganic carbon in the photosynthesis from bicarbonate ion (HCO^-_3) which generates hydroxyl ion (OH^-). The middle sections of the reservoir, based on the numbers in Table 3, could be classified as eutrophic and the water intake profile (0099 Dam) would be mesotrophic. However, this may not be a true classification because the values in Table 3 are annual averages while the key time period is the month or two just before the cyanobacteria outbreak for phosphorus and during the bloom outbreak for Secchi disc transparency. For example, if transparency during the bloom is less than 1 meter (hyper-eutrophic) and those before and after the bloom (winter) are 3 meters, which give the average Secchi disc greater than 2 meters, the profile is hyper-eutropic (high eutrophic) and not mesotrophic.

New data and information on water monitoring in the Želivka River watershed for the period 2006-2010 were published by Liška and Duras (2011). The data showed decreasing trends of phosphorus in the Sedlický brook, Martinický brook and the upstream Želivka River and a steady high concentration for nitrates. In 2010 the average values of total P were below 100 μg/L. Of note in the Liška and Duras (2011) paper is also information on the concentrations of a very potent algaecide *terbuthylazine* in the Sedlický Brook, ranging from 0.01 to 8 μg/L. This pesticide in a combination with other pesticides (acetochlor, glyphosphate, metolachlor, and others) is used in the watershed to control weeds on fields growing corn and colza. Typically a “cocktail” of 3-4 pesticides are applied. Toxicological studies (Pesticide info, 2011) revealed that the chronic toxic concentration of this herbicide for green algae and diatoms are in the rages of 6-10 μg/L and that for blue greens (cyanobacteria) is about 50 μg/L, respectively. A “cocktail” toxicity effect would be noticed at smaller concentrations because the toxicity effects are additive.

All headwater reservoirs (e.g., Sedlice, Trnávka River) and arms of the main Švihov Reservoir have already been infested by cyanobacteria. Blooming upstream headwater reservoirs (e.g., Figure 3) are actually a source of cyanobacteria to the main reservoir rather than a sink. Furthermore, all eighteen river systems forming the Želivka River system in 2009 were classified as having poor (unacceptable) water quality according to the Water Framework Directive guidelines.

It may only be the large volume of the Švihov Reservoir and the plug flow in the reservoir augmenting phosphorus settling into sediments, assisted perhaps by herbicides, preventing for the time being the Cyano-HAB infestation reaching the dam and the intake into the water treatment plant of the Prague water supply system located near the dam.

Lake Tai in China which has a full blown hyper-eutrophy status is shallower than the Švihov reservoir. The average depth of the Švihov Reservoir is about 50 meters at the dam while average depth of Taihu is 2 meters. However, the concentrations of nitrogen and phosphorus in Taihu and those in the tributaries to the Švihov Reservoir and in the Vojslavice (2699) profile of the Švihov lake are about the same. Total average nitrogen in Taihu in 2009 was 2.3 mg N/L and that of Total Phosphorus was about 50 µg P/L (Paerl et al., 2010), respectively, which are actually less than those in the Želivka River and other tributaries of the Švihov Reservoir. The similarity of the concentrations is significant.

Table 2 Characteristic values of C90% (C10% for DO) in the monitoring profiles of the direct tributaries of the Švihov reservoir. Data from the Vltava Watershed (Povodi) Agency by Hejzlar at al. (2006)

Parameter	**Monitoring Profile**			
	Želivka River 42000	**Martinicky brook 3000**	**Blažejovský brook 2100**	**Sedlický brook 0500**
BOD_5, mg/L	3.7	3.1	5.0	4.0
Chlophyll *a,* µg/L	26	23	28	38
pH	8.0	7.9	7.9	8.5
$N\text{-}NH_4^+$, mg/L	0.37	0.17	0.20	0.44
$N\text{-}NO_3^-$, mg/L	10.3	12.4	9.3	13.8
Total P, µg/L	170	180	180	140
Range of terbuthylazine concentrations, µg/L$^+$				0.01-8

$^+$ Herbicide monitoring in the Sedlice Brook water 2006-2010 published in Liška and Duras (2011)

Table 3 Average annual water quality characteristics throughout the Švihov Reservoir. Data from the Vltava Watershed (Povodi) Agency by Hejzlar at al. (2006)

Parameter	**Profile and River Km (from the Sázava River)**				
	Dam (0099) RKm. 4.7	**Kralovice (0899) RKm. 15**	**Budeč (1699) RKm. 24.2**	**Zahrádka (2099) RKm 29.2**	**Vojslavice (2699) RKm 36.5**
Transparency, meters	5.1	4.3	3.4	3.2	2.0
pH	8.1	8.1	8.1	8.4	8.2
Total P, µg/L	20	24	32	28	61
Chlorophyll *a*	8	7	10	21	15
Classification	MT	MT-E	MT-E	E	E

MT-mesotrophic, E-eutrophic, H-hypertrophic

4.0 CAUSES OF WIDELY SPREAD HYPERTROPHY OF CZECH RESERVOIRS IN THE LAST 20 YEARS

Fifty years ago rural streams in the agricultural watershed of the Czech Republic were relatively clean and reservoirs were devoid of algal blooms. In the Švihov Reservoir watershed about the same area of land was cultivated (see Table 4) as today and rural communities typically had neither sewers nor wastewater treatment facilities. The dramatic changes in water quality after 1960 were triggered worldwide by the "Green Revolution" that magnified agricultural production by using large application rates of industrial fertilizers, expanded irrigation, drainage of wetlands and mechanization (Novotny, 2007) and, in central and eastern Europe and China, by formation of large agricultural cooperatives. In the same period, small family farmers in the US, due to market pressures, were forced to sell their land to large agricultural conglomerates practicing monocultural farming relying on industrial fertilizers. Agricultural cooperatives in the Czech Republic continue in a different economic market oriented European Union environment because farming today cannot sustain small farms, with the exception of organic community sponsored and supported farms representing only a small fraction of the e agribusiness.

Table 4 Land distribution in the Želivka River watershed in %

Arable land	47.8
Meadows and pastures	12.3
Forests	29.0
Urban (built)	1.2
Other	9.7

Figure 1, at first glance, would clearly indicate the increased applications of industrial fertilizers are the reason for the dramatic increase of nitrate concentrations in the tributaries of the Želivka Reservoir. However, Lexa et al. (2006) documented the multiplicity of causes of the increased nitrate nitrogen and phosphorus concentrations, most of them related to the intensification of agriculture. These are:

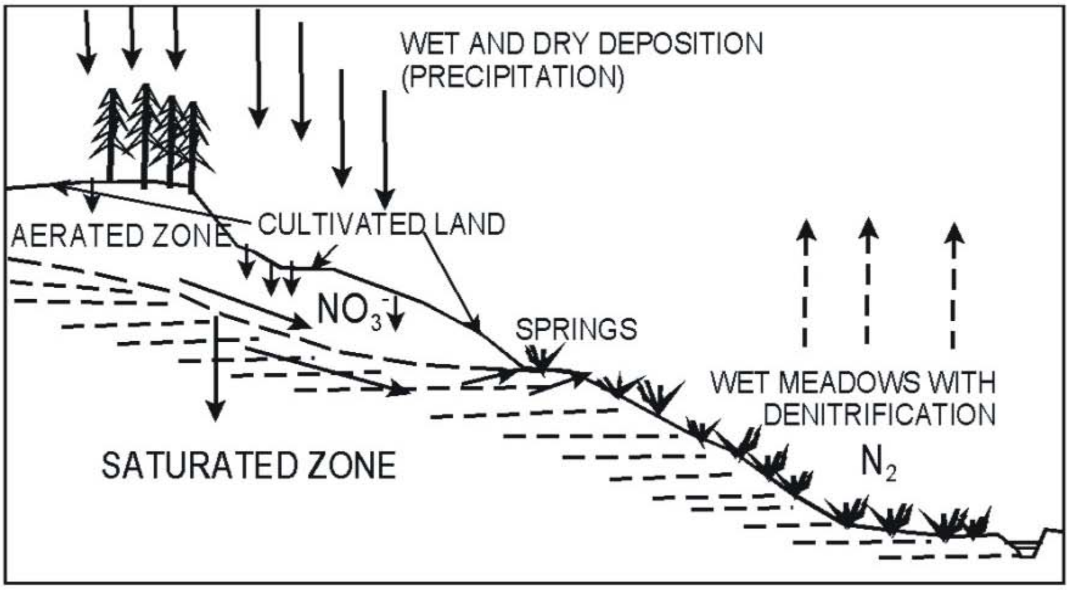
- *Inorganic fertilizer applications.* Figure 1 shows inorganic fertilizer applications in the Želivka River in the Czech Republic (Czechoslovakia before 1993) increased from less than 10 kg/ha in 1950/51 to highest applications of 186 kg/ha in 1989/90 (Ministry of Agriculture, 2011), then dropped to 65 kg/ha in 1999 and increased to 110 kg/ha in after 2007 (Ministry of Agriculture, 2011). The maximal total application of industrial fertilizers (N+P+K) before 1989 was more than 200 kg/ha which would have put the Czech Republic into the midrange of worldwide industrial fertilizer user, greater than that in the US (Figure 2).
- *Feedlots.* Although the number of cattle and hogs did not change significantly from the pre-collectivization and pre-intensification times, these animals were transferred from individual farms and pastures to high density operations in cattle feedlots and hog farms. Feedlot operations house hundreds of animals or thousands of birds in a confined to relatively small area. They are generally considered point sources but their treatment is often very poor consisting of poorly functioning storage

lagoons and manure storage pits with subsequent disposal on near farmland. In Holland, soils are overloaded with solid and liquid manure and oversaturated with nutrients and cannot accept and attenuate additional nutrient loads (Salomons and Stol, 1995).

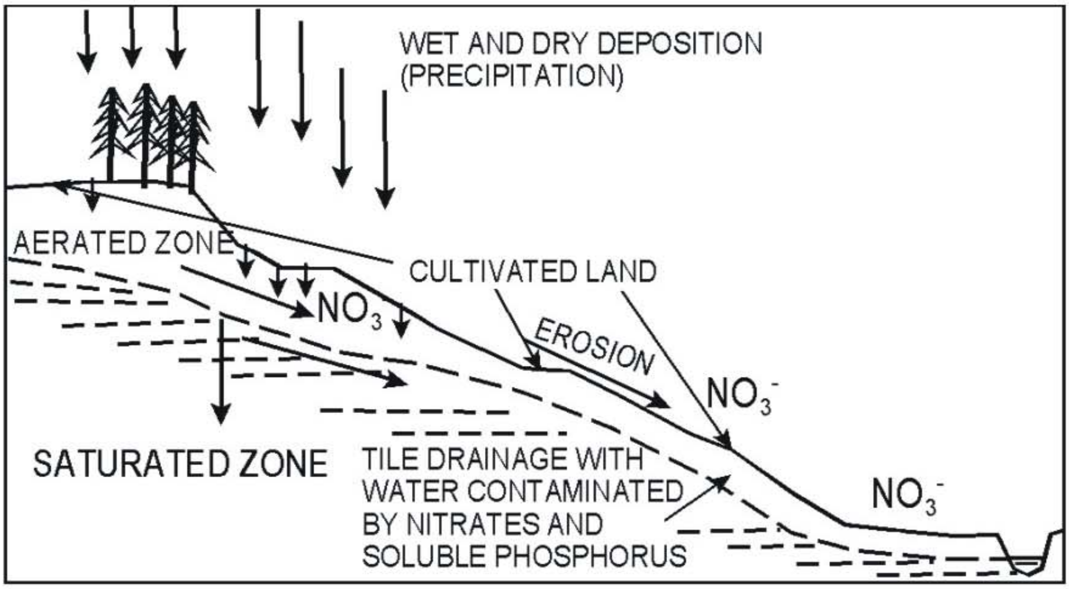
- *Agricultural tile drainage.* Lexa et al. (2006) and Doležal and Kvítek (2004) documented the loss of the denitrification capability of agricultural systems caused by installing tile drainage in lowland saturated soils that, before the agricultural green revolution, were mostly wetland meadows and woods with springs adjoining the streams. At that time (before 1960) saturated lowland alluvial soils, wetlands or saturated meadows, provided denitrification of nitrate, brought by shallow groundwater flow from upland cultivated lands, which converted nitrate into nitrogen gas. Hydrologically, cultivated upland soils were groundwater recharge areas where nitrate fertilizer entered the groundwater zone and the lowland alluvial wetlands and meadows were discharge zones of shallow ground water (Figure 7A). Installing tile drainage in wet riparian soils and draining wetlands coincided with the intensification of agriculture, starting in the 1950s and essentially ending in 1989.

After installing tile drainage, wet saturated soils were drained and became aerated; hence they lost their denitrification capability requiring anoxic conditions provided by soil saturation and the nitrate concentrations in shallow ground water and surface tributaries significantly increased (Figure 7B).

- *Urban drainage and sewage disposal.* With collectivization of agriculture and expansion of urban and agricultural communities came combined sewers that conveyed a part of untreated wastewater and mixed with stormwater into the receiving waters. Hejzlar et al. (2004) reported that municipal as well as other communal wastewater discharges contributed (prior to 2006) 90% of phosphorus to the receiving water bodies in the Želivka River watershed and about 15 % of nitrogen. It should be noted that currently most communities with a population of 2000 or more within the watershed have Bardenpho type wastewater treatment plants (WWTPs) removing nitrogen but combined sewer overflow (CSOs), representing 50% of the load to the receiving waters, are typically not controlled. Also use of phosphate detergents was banned in 2006 but high P loads could have persisted for some time after the ban. The phosphate detergent ban can be credited with the significant reduction of phosphate loads in the Želivka River after 2006.
- *Erosion.* Erosion is also a natural process accelerated by land use practices of humans. Anthropogenic erosion occurs as a result of agricultural practices of plowing the land**,** urban construction and landscaping. Both can reach high erosion rates of up to 50 tons of soil lost per hectare in a year, or more than 10 tons/ha in a single event in the absence of erosion control practices (Novotny, 2003). In the hilly Želivka watershed most of the agricultural erosion occurs in uplands and is strongly related to the type of soils and plowing techniques. Best management and soil conservation practices have not been implemented. The worst plowing practice resulting in the largest sediment load is so called, up and down slope, which seems to be favored by farmers therein because of ease of plowing on hilly fields. Also the grassed field borders (balks), trapping sediments between fields, disappeared during collectivization that turned small fields with balks into large area monocultural fields without border buffers. Without soil conservation practices, farmers compensate the soil nutrient losses by increased application of industrial fertilizers.



A) Water and nutrient regime before tile drainage



B) Water and nutrient regime after tile drainage

Figure 7 Water and nitrate movement before and after drainage. Before drainage wet water saturated riparian meadows and wetlands denitrified nitrates carried from fields by groundwater flow. (Adapted and replotted from Lexa et al. 2006)

5.0 NEED FOR AN EXPEDITED COMPREHENSIVE AND SUSTAINABLE SOLUTION - DEVELOPING PROTECTIVE BARRIERS

5.1 Is There A Limiting Nutrient for Estimating Loading Capacity and Its Controls?

The key step in preparing watershed plans to protect or restore and maintain good ecologic potential of the water supply lakes and reservoirs is estimation of the environmental (both water and land) *Loading Capacity (LC)* for safe assimilation of nutrients and other potential pollutants. As pointed out previously, the traditional lake models fail when applied to cyanobacteria and hyper-eutrophy Cyano-HABs. Traditionally, phosphorus has been considered as the limiting nutrient for controlling eutrophication of inland impoundments and even more so for hyper-trophic water bodies with CyanoHABs because some species, for example, filamentous cyanobacteria Anabaena flos-aquae, can fix atmospheric dissolved N_2 and convert it into ammonium.. It was generally assumed that excessive N loads promoted non-N_2 fixing cyanoHABs, including buoyant Microcystis, while excessive phosphorus loads would lead to N_2 fixing cyanoHABs. Hence, the N:P ratios in loads were used to estimate the limiting nutrient. Oh et al (2000) measured the organic C, N, and P of *Microcystis aeruginosa* and found that the concentration of C, N, and P varied with the growth rate of the cyanobacteria which is related to the phosphorus. At a low growth rate, 0.1 g/g-day the cellular contents of C/N/P (in mg/g of dry biomass) were 305/8/0.85 and the N/P ratio was 9.4. At a high growth rate of 0.8 g/g-day, C/N/P was 380/27/2.5 and N/P = 10.8. Hence, for the N_2 non-fixing Microcystis one can postulate that if N/P ratio of nutrients in water is more than 10-12, phosphorus would be a growth controlling nutrient, while if it is less than 7, nitrogen would be controlling. Generally, eutrophication of inland freshwater lakes and reservoirs is limited by phosphorus while most of coastal waters are nitrogen limited.

However, the fact that both N_2 fixers (Anabaena flos-aquae) and non-fixers Microcystis are present in water and sediments of Taihu (Paerl et al., 2010) and also in the majority of affected Czech reservoirs (Bláha and Maršálek, 2003, 2009), including forebays of the Švihov Reservoir, could have led to a conclusion that control of N loads was inconsequential and the remediation should mainly focus on reducing P loads, mostly associated with sediment loads and agricultural and urban erosion. The premise that eutrophication cannot be controlled by reducing N inputs included in Schindler et al. (2008) was based on the observation that many systems exhibiting advanced eutrophication (hypertrophy) also contain significant N_2 fixing Cyano-HAB population and on the assumption that its N_2 fixing can meet the system N requirements.

Paerl et al (2010), in a seminal study of Taihu, quoted diverse studies and also proved by their bioassays and lake monitoring that only a fraction of the system N demand, far less than 50% can be met by N_2 fixing species. N_2 fixation rates are very low and supply little new N, even when N fixing cyanobacteria are present. The fact that Microcystis sp. were not replaced by N_2 fixing CyanoHABs during N limited but P sufficient summer periods in Taihu is evidence that predictions of successions from non-N_2 fixers to N_2-fixing taxa based on N:P stochiometry may not apply to hypertrophic lakes. Excess inputs of both N and P, combined with internal cycling of both nutrients may overwhelm the ability of a single nutrient to control increasing eutrophication and bloom intensification (Paerl et al., 2010). Paerl et al. also concluded that P input reductions are an important component of lake management and restoration in larger lakes and reservoirs; however, failure to control N inputs may result in continued serious eutrophication problems caused by non-N_2 fixing Cyano-HABs. As discussed in the previous section, controlling P focuses on control of sediment loads from fields, construction erosion, WWTP effluents and CSOs while N loads arrive to the receiving bodies both in surface runoff as organic N and ammonium (TKN), dissociated nitrate, and subsurface nitrate flows. Hence, both N and P must be controlled in the Czech reservoirs suffering Cyano-HABs.

In developing control and landscape nutrient attenuation measures, phosphorus and nitrogen controls may not be the same, but they may overlap. Phosphorus from agricultural, urban and highway construction or open lands is associated primarily with soil and soil particles and that from WWT is both dissolved (dissociated) and particulate. Hence, control measures must be focused on minimizing soil pollution by nutrients, soil losses and removal of particulates from effluent and runoff flows. Phosphorus from effluents is removed by chemical precipitation and sedimentation or biologically.

Nitrogen exists in several forms: (a) organic nitrogen is mostly particulate, (b) ammonium is both particulate and dissolved and there is an equilibrium between NH_4^+ adsorbed on organic and clay particulates and the dissolved fraction (Novotny, 2003), and (c) nitrate ions (NO_3^-) which are strictly dissociated in soil water and move with surface and ground water. Consequently, there are no single simple controls; the same controls that will be used for controlling phosphorus will also remove particulate nitrogen. However, dissolved and also some particulate nitrogen is removed generally by nitrification/denitrification processes that can occur in treatment plants and in nature in wetlands and sediments of impoundments. Denitrification converts nitrate to dinitrogen gas N_2 or sometimes to nitrous oxide (NO_2) gas. While the former is benign, the later is a potent GHG pollutant that also affects the stratospheric ozone layer.

Both dissolved nitrogen and phosphorus can also be removed by biological uptake into sludge, vegetation, or algae, followed by algae removal and vegetation harvesting. In this way the nutrient removal stimulates biomass production which sequesters carbon and can be used for energy production in a form of methane based biofuel and electricity. Interestingly, denitrification also sequesters carbon dioxide by converting it into alkalinity (Novotny, 2012).

After the reduction of phosphorus (and nitrogen) loads below the hypertrophic level, water quality of smaller impoundments can be improved and maintained by lake water quality management that includes hypolimnetic aeration preventing phosphate release from the sediments, phosphorus reduction in the water column by alum coagulation and adsorption, and by fish management (Novotny, 2003).

5.2 Developing A Sustainable Watershed Plan

There is a need to change the ecology in the Želivka River surface and ground water system from highly vulnerable into a sustainable and ecologically healthy system that guarantees good water to the citizens of Prague and Central Bohemia and Highlands (Vysočina) regions as well as restores the aquatic ecology of the receiving water bodies to a good ecological status. Similarly, there is a need to reverse hypertrophic conditions of Taihu. Considering also that some of the past, present and potential future ecological changes may be irreversible (Folke et al., 2005), the current situation in both watersheds is highly unsustainable. The economic damage by the current (Taihu) or potential future (Švihov) losses of the system for water supply, even temporarily during the Cyano-HAB season, are tremendous.

Traditional solutions of fifty years ago were to declare the water supply watershed as a highly protected area and forbade all polluting and most development activities. Boston's large Quabbin Reservoir, providing water to more than 2 million people living in the metropolitan Boston region (City of Cambridge has its own water supply system relying on local smaller lakes), had in its watershed in 1930 several communities. People from some communities were (forcefully) relocated, farming was abandoned and most of the original farming was converted to forest land or flooded by the waters of this large reservoir. Recreation activities on the lake and access to it are greatly curtailed. Such solutions may not be possible in advanced countries today, even in China this solution is not applicable in the 40 000 km^2 Taihu watershed which has 40 million inhabitants (Paerl et al, 2010). A better solution is to ascertain the assimilation capacity of the water body and the watershed, and develop protection zones and barriers with advanced pollution controls and enhancement of the assimilation of the residual pollution and buffering capacities of landscape. The water body itself with its complex attenuation processes and dilution as well as emergency treatment of water impacted by HBAs is the last line of defense and it cannot be the only one.

5.3 Goals and Objectives for Reversing the Trends in Threatened and Restoration of Impaired Water Supply Impoundments and Watersheds

Considering the current state of water quality of the Želivka River in the Czech Republic, Taihu in China and hundreds of other impaired water supply impoundments throughout the world, the first goal should be to prevent and control hyper – trophy. The second goal, carried out contemporarily, is to develop a plan for the attainment of a water quality status that would bring the impoundment and its tributaries to the "Good Ecologic Status" for drinking water sources. This also includes, restoring the integrity of these waters by providing conditions for a balanced aquatic life, and supporting (limited) recreation, fishing, and aesthetics. The approach must be tiered and recurrently adaptive. The adaptive planning, implementation and management approach is needed because of the uncertainty of the current state of the art of the science and modeling of the impact of various control measures on the occurrence of cyanobacteria and algae in general.

Hence, the goal is to reverse the current practices of overuse and misuse of land and convert the watershed into a functioning ecologic system and, potentially, the cities and villages in the watershed into "eco-communities" with minimal discharges of nutrients and other pollutants into surface and groundwater systems.

The strategy of abatement and related research must be hierarchical and progress from the pollution source areas to the receiving water body and include also restoration of the water bodies themselves. The progression of reducing the pollution (nutrient and pesticide) inputs and establishing protective multiple barriers can be characterized as follows:

In the agricultural areas:

1. Identification of hazardous lands and land use practices that emit high levels of nutrients and propose controls such as

- Selection of crops and crop rotation that would minimize nutrient losses
- Matching applications to the crop needs and implementing erosion and soil conservation best management practices and, conversely, reducing the applications of industrial fertilizers currently compensating for the nutrient losses in the sediments

- Conversion of highly hazardous lands to closely grown crops (e.g., wheat, alfalfa), grass land, woodland and potentially using the grown biomass to produce biogas and biofuel
- Judicious manure management, storage and spreading. Manure cannot be applied onto frozen soils or snow covered fields
- Implementing crop management that would increase organic content of soils (for example, no till best management practices)
- Disconnection of drainage and conversion of the land to wetland stimulates denitrification in ground water and carbon sequestration by growing trees and brush for energy. Wetland meadows due to their root depth are not as efficient for nutrient removal from contaminated deeper grou ndwater. Long root woods can be grown for biogas and energy

2. Land best management practices aimed at intercepting the pollutant movement from the source areas to the receiving water

- Grass and vegetative borders
- Riparian buffers zones with fast growing woods
- Grassed swales
- Ponds

3. Consider organic farming using organic fertilizers, including those produced by the ecoregion resource recovery system (e.g., struvite, humus)

In urban and highway zones

1. Continue and expand nutrient removal in the WWTP
2. Develop sludge handling co-digestion systems that would also accept harvested vegetation and wood grown on the converted hazardous lands, produce biogas and recover phosphorus (struvite).
3. Discontinue using combined sewers which may represent a substantial portion of the nutrient load, especially phosphorus
4. Urban runoff conveyance should be converted from fast conveyance in sewers into surface storage oriented systems, including ponds, bioswales, and wetlands
5. Develop sustainable disposal systems for used water (and possibly reuse) and excreta for small distributed communities other than standard septic systems that have very poor nutrient removal efficiencies
6. Consider converting the communities into "ecocities and ecovillages" that would minimize emission of pollutants to zero or very low levels with recovery of nutrients (especially phosphorus), reclaim water for various uses such as irrigation, toilet flushing as well as energy from used water. It should be pointed out that such a system of ecocities and ecovillages as well as land conversion to nonpolluting lands is now being implemented in the watershed of the Miyun Reservoir supplying most of the drinking water to Beijing, the capital city of China.
7. Develop a regional integrated resource recovery facility (Novotny et al., 2010b) that would accept and co-digest sludge from WWTPs, high concentration organic liquid (landfill leachate, concentrate black water) and solid wastes, vegetation from riparian wetlands, and other organic residues, and recover biogas, struvite (ammonium magnesium phosphate), organic solids, energy, and heat.

6.0 CONCLUSIONS

Widely spread harmful algal blooms (CyanoHAB) and hypertrophic conditions of impoundments occurred in the last thirty to forty years are a result of intensification of agriculture exhibited by increased use and overuse of industrial fertilizers, use of phosphate detergents, tile drainage and often lack of adequate point sources treatment. They affect both inland impoundments and coastal waters where they cause large areas of hypoxia. In the same period, agriculture in many countries has changed from small family farms to often monocultural agricultural conglomerates relying heavily on the use of industrial fertilizer. However, the situation with widespread noxious cyanobacteria blooms is not ubiquitous to all industrial countries. In the US some lakes, including Great Lakes Erie and Ontario affected by eutrophication in the 1970s, were dying but the situation has improved due to abatement at the end of the last century. Nevertheless, the latest development of water quality and trophic status of Lake Erie shows signs of relapse. Today, hypertrophy on a large scale is typical only for a few countries like China, Holland, Korea and the Czech Republic but spreading in many countries (Chorus, 2005) on all continents.

The nutrient loads in the Želivka River watershed and the Švihov Reservoir are extreme examples comparable to the situation in China with Lake Tai (Taihu) because they affect or can affect a large number (more than million) of users. In the Švihov Reservoir the barriers to excessive pollution (control of diffuse sources, best management practices, buffer strips, denitrification through the watershed, erosion control, phosphorus removing practice for urban runoff and CSOs) are either not in place or are insufficient. The only barrier that keeps the reservoir from reaching the hypertrophic conditions throughout the entire lake is the volume of the Švihov Reservoir, phosphorus settling into sediments and, possibly, the herbicide inputs into the reservoir (a dubious alternative).

The change from mesotrophic/eutrophic status to hyper-eutrophic with harmful cyanobacteria blooms (Cyano HAB) is not gradual, it is highly non-linear and when the switch occurs, reversing back to an acceptable status is difficult and very costly. Some changes may be irreversible and/or may require more reduction of the phosphate load than the load that caused the change to the hypertrophic status (Folke et al., 2005). The state of the knowledge on abatement of various sources causing the problem and landscape/watershed remedial measures are known for both point and nonpoint sources and have been extensively researched. There is a need for an interdisciplinary international effort, to attack the problem by proposing and implementing rapidly the solutions that will prevent the impending severe water supply catastrophe.

In contrast to the traditional approach of forbidding most of agriculture and reducing other economic activities, transforming the water supply watersheds into an ecoregion with a sustainable nutrient attenuating landscape dotted with ecocities and ecovillages would not only reduce dramatically nutrient inputs to the reservoir, its tributary streams and groundwater, it would also significantly reduce GHG emissions from the landscape, communities and economic production processes taking place within the watershed.

ACKNOWLEDGMENT

The author appreciates and acknowledges the opportunity given to him by the US Fulbright Foundation-US Department of State, University of Chemical Technology (VŠChT) in Prague and A.R.C. Corporation in Prague to study the problem, work with colleagues from the Czech Republic and present his views. He appreciates collaboration and comments of Professor Jiří Wanner of VŠCHT, Ing, Jiří Holas of A.R.C. sro., Professor Blahoslav Maršálek of the Center for Cyanobacteria and their Toxins at Masaryk University in Brno, and Professor Josef Hejzlar from the Hydrobiological Institute of the Czech Academy of Sciences (ČAV) in České Budějovice. The author also acknowledges the cooperation with Professor Chengqin Yin from Chinese Academy of Science in Beijing who organized the site visits of Taihu watershed and the provincial government of Beijing sponsoring his participation and invited presentation at the World Lake Congress in Wuhan in No-

vember 2009. This article is an expanded version of the author's presentation at the Wuhan Congress. The views expressed in this paper are solely those of the author.

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