

Eutrophication Control in Reservoirs

Vladimir Novotny¹

Abstract

This article outlines the potential of hyper eutrophication in the Švihov Reservoir, a primary source for water supply to the capital city, Prague. This potential is endemic to many reservoirs and ponds in the Czech Republic and has an overall severe impact on the uses of Czech and Moravian impoundments for water supply and recreation. The hyper-eutrophication is generally exhibited by blooms of cyanobacteria. The article also suggests general steps for developing a plan for prevention of the algal blooms and, hence, control of eutrophication or hyper-eutrophication. The plan should be tiered and include immediate and long term actions throughout the Želivka River watershed and in and around the impoundments.

Introduction

There are over 24,000 manmade reservoirs in the Czech Republic, ranging from centuries old ponds to deep stratified reservoirs built mostly in the last fifty to seventy years. In contrast, the country has only five small natural lakes (Hejzlar, 2006). As it is in many other countries, many reservoirs in the Czech Republic provide potable water for the population and their protection is of utmost importance. However, recent threats of excessive nutrient inputs and future threat of global warming present a great challenge not only to watershed managers but to the entire population. The situation is especially troublesome in the Czech Republic where 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 with severe impairment in the near future.

While, hydrologically both lakes and reservoirs are categorized as impoundments there are significant differences between the two. Dams markedly modify the biochemical, physical, and ecological features of the natural water bodies on which they are built. Manmade reservoirs usually lack natural ecological features such as viable littoral and riparian zones and a natural hydrologic regime. Dams cause fragmentation of the longitudinal exchange of biota in the river and impede spawning migration. Hence, defining manmade impoundments as lakes impounded by dams simply cannot be made because this would overlook the many hydrological and ecologic anthropological changes made by the impoundment and its management.

Artificial impoundments are multi use water bodies and the uses are very often conflicting. The most important uses are water supply, recreation (both in and on water), providing habitat and conditions for a balanced aquatic life, and flood control. The first three uses are protected by national and international laws such as the EU Water Framework Directive or the US Clean Water

¹ Professor, Department of Civil and Environmental Engineering, Northeastern University, Boston 02115, USA (on a sabbatical leave 2008-2009) . Fulbright Senior Specialist.

Act. Other uses include navigation, providing water for irrigation, cooling, and accepting pollution in amounts that would not be harmful to aquatic life or human health. Many impoundments, due to a combination of overuse a natural aging process, have become impaired, resulting in diminished ecological function. Also due to increased settling of sediments from natural land erosion and diffuse (nonpoint) pollution sources, the ecological life time of reservoirs is limited, often to few decades, or even less, after filling.

Another feature of the impoundments is chemical and biological interaction between the water column and sediments. Some important noxious microorganisms (e.g., some cyanobacteria) reside during their life phases both in water and in sediments, making the effects of water quality improvements alone less effective or the effect is delayed by years.

Problem with Nutrient Enrichment of Reservoirs

Eutrophication is a process of enrichment of the water bodies by primary productivity of organic matter that progresses from oligotrophic, mesotrophic, to eutrophic states. Characteristic of these three states are presented in Table 1. In today’s context, “eutrophication refers to the natural and artificial 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.

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

Water Quality	Oligotrophic	Mesotrophic	Eutrophic	Hyper-eutrophic*
Total P (µg/L)	<10	10-20	>20	> 50
Chlorophyll - <i>a</i>	<4	4-10	>10	>20
Secchi disc transparency depth (m)	>4	2-4	<2	<1
Hypolimnetic oxygen (% saturation)	>80	10-80	<10	0

* Calculated from the Carlson Index set as 60. See Novotny (2003)

Although eutrophication can be natural it is usually accelerated by anthropogenic activities, excessive nutrient inputs, and by global warming. 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 nonpoint sources after 1960, a category of *hyper-eutrophication* and *hyper-eutrophic* water bodies was added, which denotes a troublesome post eutrophication state of the water body exhibited by excessive algal development, especially of noxious species. Under certain favorable conditions these organisms can develop in large quantities (Figures 1 and 2) known as algal blooms. A “bloom” is massive accumulations (10^4 - 10^6 cells m^{-3}) of a single or coexisting nuisance species (Paerl, 1988). Blooms are frequently dominated by blue green algae, or cyanobacteria, which can be especially noxious and harmful to the ecosystem and human health. Cyanobacteria blooms can produce a range of toxins (Carmichael et al, 1985; Carmichael, 1992) which interfere with the uses of the water body for recreational (swimming, fishing, boating), drinking water supply, and aquatic resource (including commercial fishing and aquaculture) purposes (Paerl et al. 2001). The presence of cyanobacteria in large densities in an impoundment imposes excessive oxygen

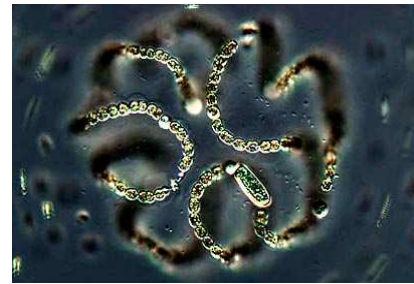
demand and hypoxia as sinking cells decay (Paerl et al. 2001). Both toxins and anoxia render the impoundments unsuitable for invertebrate prey (intermediate levels of the food web) and fish populations (Paerl et al. 2001; Paerl and Fulton 2006). As a result, in many nutrient-enriched freshwater habitats, those that have experienced parallel hydrologic modifications (impoundments and reservoirs), cyanobacteria constitute a major nuisance problem. During the hypereutrophic 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 night or cloudy days.

The anoxic hypolimnion and algal blooms have also adverse effects on fish residing in the reservoirs. Anoxic hypolimnion does not provide suitable habitat for game fish which is replaced by a rough fish population. Algal toxins generated by algal blooms, can also result in fish kills.



Figure 1 Sedlice reservoir on the Želivka River during blue green algae bloom. Picture taken in summer 2003 by the Biology Center of the Czech Academy of Sciences)

Figure 2 *Anabaena* – a bloom forming filamentous cyanobacterium



The phenomena of algal blooms and blue green algae occurrence have been known, studied and fought for years. For example, in the 1980s a hyper – eutrophic Lake Delavan in Wisconsin suffering from severe algal blooms was restored by a massive overhaul and clean – up that included control of point and nonpoint sources of phosphorus from the watershed, change of lake’s hydraulics, creating a headwater riparian wetland, massive and complete eradication of carp and buffalo fish overpopulation and subsequent restocking with a balanced fish population, phosphorus precipitation in water and sealing of sediment by application of aluminum sulfate (Wisc. DNR, 1989). However, only in the last fifteen years the problem has reached alarming proportions on a large scale. The problem with algal blooms of cyanobacteria has reached alarming proportions throughout the Czech Republic. It has been estimated that cyanobacteria blooms (Hejzlar, 2006) now impair 70 % of reservoirs in the Czech Republic. This was triggered by the “Green Revolution” that magnified dramatically the agricultural production by using large application rates of industrial fertilizers, expanded irrigation, and mechanization (Novotny, 2007). Also while in the US and many western European countries, use and selling of phosphate detergents was banned decades ago, it has been noted (Pečenka et al., 2007) that phosphate detergents are still sold in the Czech Republic, produced by chemical international conglomerates that shifted their detergent production from the US and elsewhere in western Europe to countries that have lax controls.

Idiosyncrasy of cyanobacteria

In order to prevent and control the occurrence of hyper eutrophication characterized by cyanobacteria blooms or even excessive eutrophication interfering with the use of reservoir water for drinking, one has to understand the peculiar behavior of these billions of years old resilient microorganisms. It is a known fact that blue – green algae are some of the first organisms on the earth and may be credited for bringing oxygen into the atmosphere three billion years ago. Cyanobacteria have several important ecological and physiological characteristics distinguishing them from other algal groups and provide competitive advantages in aquatic ecosystems. In addition to producing harmful toxins, they can control their buoyancy, enabling them to rapidly migrate between nutrient-rich deeper waters and surface waters, where blooms can “shade out” non-buoyant taxa (Paerl et al. 2001; Paerl and Fulton 2006). The filamentous and colonial nature of cyanobacterial bloom genera provides an impediment to grazing (c.f. Paerl and Fulton 2006), and some nuisance genera (*Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Nodularia*) are capable of converting atmospheric N_2 into biologically-available ammonia, enabling them to circumvent N-limited conditions. (Paerl et al. 2001). As a group, bloom-forming cyanobacteria prefer warm, stratified water (Fogg 1969; Vincent 1987; Paerl 1996), and hence may increase in dominance in response to global warming in eutrophic/hypereutrophic water bodies. Lastly, many cyanobacteria species have complex lifecycles that include resting stages (spores, akinetes, see Figures 3 and 4, that enable them to over-winter and survive long periods of sub-optimal growth conditions.

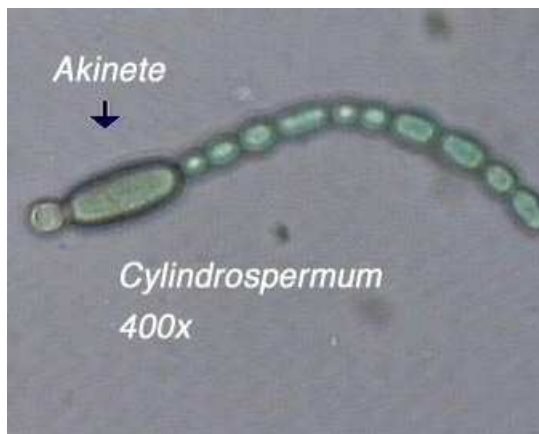


Figure 3 Resting stage (akinetete) of cyanobacteria (from www.botany.wisc.edu, 2007)

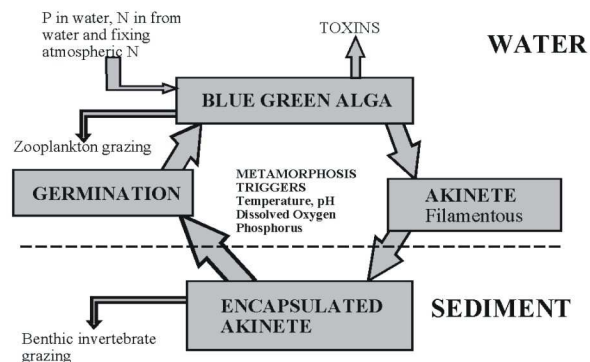


Figure 4 Life stages of some key species of blue-green algae

Those cells can over-winter in/on the sediment bed and inoculate the water column in the spring, often as a sudden, explosive bloom. Over billions of years of evolution these life characteristics helped them survive long periods of adverse growth conditions, including freezing, heating, desiccation, nutrient starvation, etc. This competitive advantage can significantly affect the ecology, water quality and habitat conditions of an impoundment (e.g. Baker, 1999; Head et al., 1999). However, the thresholds for reactivation triggers are not well known. As pointed out, the largest algal bloom in the aforementioned Lake Delavan occurred after a significant reduction of phosphorus loading was achieved by controlling the point sources discharging into the lake,

defying the outcome of a traditional Vollenweider (1975) model. Existing water quality models (e.g., WASP-Eutro; AQUATOX, QUAL-2E) typically do not explicitly consider cyanobacteria. If they do include them, they do so in a simplified manner, as a separate state variable in multi-species or –class models with different parameter values to reflect their unique behavior. The settling velocity can be reduced or set to zero to account for vertical motility, the nitrogen half-saturation constant can be set to zero to account for nitrogen-fixing ability, and the grazing rate can be reduced or set to zero to account for grazing resistance (e.g. Lung and Paerl, 1988; Robson and Hamilton, 2004). However, although the importance of resting stages has long been recognized, it is not included in eutrophication models. This severely hinders our ability to develop accurate TMDL (Total Maximum Daily Load) targets for water bodies that experience cyanobacteria blooms let alone predict when these blooms might take place.

The perseverance of these organisms, even in harsher conditions such as a short duration (up to five years) reductions of the nutrient content in water, indicates that controls are difficult after the hyper eutrophic condition develop. Hence, prevention of and control of cyanobacteria blooms requires a hierarchical forceful approach to reduce the loads of nutrients, protection of the reservoirs and their tributaries and control nutrient levels in the sediments before the onset of hyper –eutrophication. Recent research on an hyper-eutrophic Lake Taihu (“hu” means “lake” in Chinese) by Dr. Hans Paerl from the University of North Carolina (personal communication) indicates that a remediation program of already impacted water supply reservoirs must be on all fronts. i.e., availability of phosphorus and nitrogen must be reduced in water and sediment and the notion of focusing on a limiting nutrient only may not be enough. Lake Tai is the largest freshwater lake in China and provides drinking water to millions of people. Currently, excellent and cutting edge research is being conducted in the laboratories of the Czech Academy of Science in Brno (Dr. Maršálek) and České Budějovice (Dr. Hejzlar and others).

New models are being developed such as Agent-Based Model (ABM) that better describes the lifecycle stages of the cyanobacteria (Hellweger et al., 2008). However, while ABMs have been used in other fields – economics, human behavior, traffic, they have never been in this context (eutrophication modeling) until recently. The dominant strength of the ABM agent-based approach is understandable description the life cycle of a large number of agents that behave in a prescribed manner when responding to multiple stresses and stimulants (nutrients). An agent-based model accounts for intra-population variability. This is one of the reasons why agent-based modeling is rapidly gaining popularity in ecological modeling of higher trophic levels, where the complex behavior of individual microorganisms has long been recognized as important. With an increased realization and understanding of the complexity of microorganisms, the extension of agent-based modeling to microorganisms is a natural progression.

Situation in the Švihov Reservoir and its Tributaries

The report by Pečenka et al. (2007) provides a bleak picture of the water quality in the Švihov Reservoir, the Želivka River and its tributaries. The author of this article has seen in the Czech Republic other water bodies severely impacted by cyanobacteria (e.g., Brno and Nové Mlýny reservoirs) and the fact that 70 % of impoundments are affected, including legendary Máchovo Jezero, indicates the problem is already beyond serious and must be taken as an emergency situation in the country. It was noted the water quality of nitrogen is judged based on the WHO standard for drinking water of 50 mg of NO₃-N/L (roughly equivalent of 10 mg of N/L standard in

the US) that is derived from the public health limit to prevent methaemoglobinemia (blue baby disease). Meeting this inappropriate standard in the context of controlling eutrophication gives authorities a false sense of security when an “average” N content is below the WHO limit. The limits for preventing eutrophication are much smaller, less than 1 mg-Total N/L during the vernal period.

Pečenka et al. (2007) document the average nitrate concentrations in the water from the Želivka Water Treatment Plant are higher than those in the Vltava River that already has hyper-eutrophic reservoirs (e.g., Orlik), cyanobacteria are already developing in the reservoir and its headwater basins. Note the pea soup appearance of the cyanobacteria bloom on Figure 1 showing Sedlice Reservoir on the Želivka River. The average concentrations of phosphorus and nitrogen in the key tributaries have already exceeded the limits for hyper – eutrophication. The use of average annual concentrations in judging the water quality status is misleading because the key period is vernal (Spring) which exhibits, as the Pečenka’s et al. report documents, the highest concentrations carried from diffuse (nonpoint) sources by runoff and snowmelt flows.

Control of Eutrophication

Adaptive Planning and Management

At the current state of water quality of the Želivka River and considering the very high magnitudes of the nutrient loads coming from the poorly treated point sources and uncontrolled nonpoint sources in the watershed, the first goal is to prevent and control hyper – eutrophication. The second goal, carried out contemporarily, is to plan for the attainment of the final goal which would be to bring the Švihov and other reservoirs (e.g., Sedlice) close to a mesotrophic status. Mesotrophic status would be synonymous to the EU “Good Ecologic Status” for drinking water impoundments. Hence 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 science and modeling regarding the impact of various control measures on the occurrence of cyanobacteria and algae in general. Therefore, it is paramount that the scientific centers in the Czech Republic fully participate and focus, in collaboration with international partners, on improving the level of the scientific knowledge and modeling the effects of nutrients on algal population of impoundments. As pointed out, the dramatic emergence of cyanobacteria bloom outbreaks throughout the world in the last two decades (earlier in the Czech Republic), has left, to some degree, scientists and planners unprepared. For example, in the US funding for this type of research is grossly inadequate, experts are few, and adequate models are now only being developed. The aforementioned laboratories of CAV are in the forefront of the research and recognized worldwide. This however, does not mean that the planners and managers responsible for water supply water bodies can wait. The situation is urgent now.

The complex and layered hierarchical schematic of impacts and processes affecting the biota in water bodies is shown on Figure 5. There are no comprehensive models that would describe the entire process.

Adaptive Planning, Implementation and Management

The planning process for controlling (hyper) eutrophication of the Želivka River system would be characterized in the US as the Total Maximum Daily Load process which is very similar to that under the EU Water Framework Directive (WFD). It progresses in the following steps:

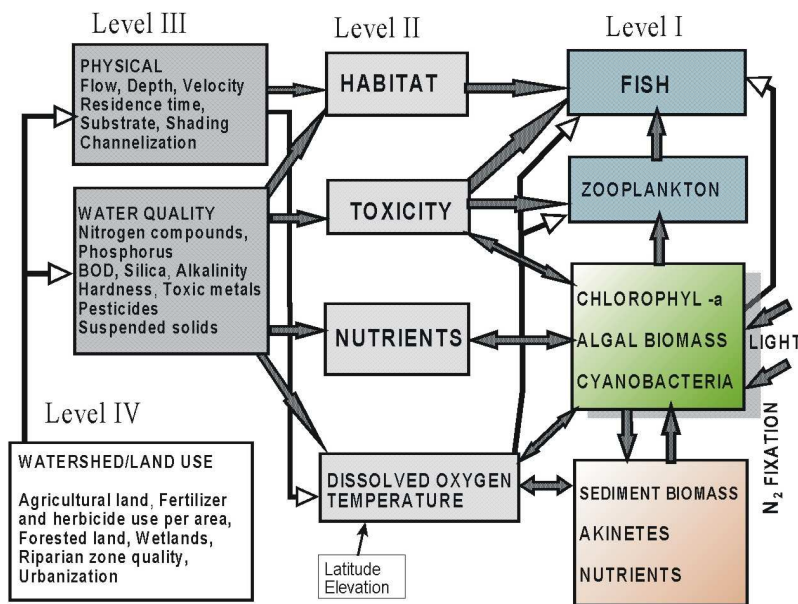


Figure 5 Hierarchical effect of stresses on occurrence and density of cyanobacteria

Define Standards. The adaptive planning process begins with a definition of goals and pertinent corresponding standard. The EU Water Framework Directive requires to define an ecologic potential of the impaired water body that would be based on reference conditions and its use. This is a prerequisite of a basin wide water quality management plan. Both nitrogen and phosphorus should be considered. Establishing the standards is not easy and the final standards may be a compromise. For example, in order to control eutrophication in thirteen reservoirs providing water

supply for the City of New York, developing Total Maximum Daily Load (TMDL) standards for these impoundments was in the 1990s a subject of a long litigation between the environmental stakeholders represented by the Natural Resources Defense Council (NSDC) and the agencies responsible for the implementation. Over the last one hundred years water from these reservoirs was only disinfected.

First, there were no standards in place and the water quality of many NY City water bodies was deteriorating rapidly. Some reservoirs east of the Hudson River and in the Delaware River basin were becoming eutrophic and some even reaching hyper – eutrophic conditions (Division of Water Quality Control, 1993). The cause of deterioration was uncontrolled urban development in some watersheds east of the Hudson River and agricultural practices in the Delaware basin. Reservoirs located west of the Hudson River in the Catskill Mountains had mostly forested watersheds and water quality was excellent. Under pressure and facing litigation, agencies proposed and used a phosphorus TMDL standard for the reservoirs as 20 µg/L of total P (NYSDEC, 1999). It was argued (Novotny, 2000; Committee, 1999) that this standard was not protective of the water supply use and would have essentially allowed the reservoirs to stay or become eutrophic. Furthermore, this standard would allow additional unrestricted development in the watersheds that had adequate water quality. Under a prolonged iterative negotiation process, the standard was established at 15 µg/L of total P, clearly in the middle of the mesotrophic state, for reservoirs providing unfiltered but disinfected water to the city’s water supply and the TMDL was based on this standard. Because this standard was not attainable, for various reasons in a few reservoirs east of the Hudson River, New York City has been implementing water treatment at a cost reaching \$ 1 billion. New York City has also embarked on a large program of buying riparian land surrounding the reservoirs and their tributaries and establishing protective buffer zones.

Because water from the Švihov reservoir is treated the standard could be somewhat higher (e.g., < 20 µg P/L during vernal growing season) but its magnitude would have to be established and confirmed by the scientific research and modeling. If the reservoir is already eutrophic this standard would not, however, bring the water quality into the mesotrophic zone.

Monitoring. The monitoring program in the Želivka River has been conducted now for a number of years and has produced a large volume of valuable data. The Sedlice Reservoir is also a research water body for the Czech Academy of Science which produced a number of excellent research reports and articles. Monitoring and research must and will be continuous and, as a part of the planning process, it must be synthesized. The data are used for

- Ascertaining the water quality situation in the watersheds and its reservoirs and the degree of impairment
- Investigating the trends
- Investigating causes and thresholds of eutrophic and hypereutrophic conditions
- Developing and using models for:
 - calculating loads of nutrients from diffuse sources
 - describing attenuation of the nutrients in the receiving water bodies, also considering point source inputs
 - describing algae development and shifts (e.g., green → blue green) in the reservoirs that would consider water column, sediment, morphological characteristics and hydrology of the reservoirs
 - ascertaining the effect of the planned short and long term actions.

Model development is a continuing process to be carried out at the university, academy centers, and by the planners in a cooperative effort. Data and knowledge should be synthesized and directions of the research should be regularly updated. This will require coordination between the research centers and the water utility and watershed managers.

Ascertaining Loading Capacity of the Reservoir. The land based models will calculate and extrapolate the loads while the water quality models are used to determine the *Loading Capacity* of the water body for the pollutants, i.e., nitrogen and phosphorus. If the Loading Capacity minus a Margin of Safety (=Allowable Load) is less than the load to the water body, the allowable load is then allocated among the sources and the loads are then restricted to the allocated load.

Development of a tiered adaptive plan. WFD (TMDL) planning process is either continuous or repetitive. Because of uncertainty inherent in the outcomes of the models the process is iterative and connected to the development of the models. As more data is collected and actions are implemented, models are improved and finely tuned which will result in a reduction of the Margin of Safety. The committee of the US National Research Council on TMDL (Committee, 2002) recommended the planning process *contains immediate common sense actions and long term actions.*

Immediate common sense actions can be implemented in a relatively short and fixed time span after the beginning of the implementation process. Examples include:

- *Implementing immediately and fully a ban on phosphate detergents.*

- *Reduction of effluent phosphorus from wastewater treatment plants to less than 1 mg/L. This can be done simply and quickly by adding precipitating chemicals into the activated sludge tank; the chemical is typically a byproduct of iron and steel manufacturing.*
- *Reducing nutrient losses from agriculture by rapidly implementing soil conservation best management practices and stopping overfertilization.*
- *Implementing wetland treatment of wastewater in rural communities and controlling loads from feedlots and animal husbandry.*

In many cases, common sense actions are beneficial not only to the users of the potable water but also to those causing the pollution. For example, treating wastewater by wetlands provide habitat for water fowl, controlling loads from feedlots saves money to farmers (cooperatives) on purchasing more fertilizers. Similar savings can be achieved by soil conservation practices and proper matching of fertilizer use with plant needs.

After a certain but not long time period the monitoring program should focus on ascertaining the effect of the short term actions on water quality and trophic status. Meanwhile the process of continuous research will lead to better understanding of the eutrophication process and will lead to better models.

Examples of long term but still common sense actions are:

- *Conversion of existing and building new wastewater treatment plants for larger communities that would be based on Bardenpho technology.* Such plants remove both nitrogen and phosphorus and use less energy than the conventional activated sludge wastewater treatment plants. Adding more advanced wastewater treatment technologies based on microfiltration can attain effluent water quality commensurate to water quality of a relatively unpolluted or mildly polluted receiving surface water body.
- *Land use changes by acquiring more land surrounding the water bodies, including tributaries, and restoring or building riparian wetlands.* Forested uninhabited watersheds provide the best protection and yield best water quality. However, vegetated buffer strips (Figure 6) or restored wetlands (Figure 7) are also very effective for removing nitrate-N (more than 90 %) and phosphorus (about 50%). Wetlands are more efficient than traditional ponds but a wetland-pond combination provides the greatest benefits. Constructing wetlands in these zones or planting vegetation that is efficient for removing pollutants could also be effective. The Czech Republic has a tradition with implementation of “passive” buffer and protection zones around the reservoirs but not necessarily around the tributaries where the pollution from diffuse sources enters the surface water body.

The TMDL report of NRC (Committee, 2002) recommends a 5-6 year evaluation cycle for assessing the efficiency of the measures that have been implemented and evaluating the accuracy and state of the art of the models, future trends, etc.

Attaining the goal of an already impaired water body

The planning process for a reservoir that has already been impaired, i.e., it is already in an eutrophic or even hyper-eutrophic state, needs additional components. Reducing simply the loads of pollutants (N and P) simply to the borderline level of the criterion may not be effective because of pollutants and the akinetes may be already in the sediment in large quantities. Hence, reducing

the loads below the loading capacity will not have an immediate effect and it may take years before significant effects are noticed. The restoration process must be comprehensive and must include actions that would immobilize first and then remove the nutrients stored in the water body.



Figure 6
Vegetated stream buffer zone
in Iowa. Source Natural
Resources Conservation
Service



Figure 7
Riparian constructed
(restored) wetland in Iowa
Source NRCS

Olem and Flock (1990) and Novotny (2003) describe methods for evaluating and controlling symptoms of eutrophication and hyper-eutrophication. They have been for the first time used comprehensively in the restoration of Lake Delavan in southern Wisconsin. The obvious step is the above described process of reducing nutrient inputs from the watershed and reducing their availability in the water body which includes various watershed management and in-reservoir treatments. The relative merits and effectiveness of each depend on the relative importance and the level of the nutrient source relative to the impact on the impoundment as shown on Figure 5. Watershed management reduces external nutrient loadings while internal reservoir treatment procedures eliminate internal nutrient sources and/or their availability/mobility. In general, in-reservoir treatment, without reducing external sources, has only a short duration effect. In conjunction with a plan for improved watershed management, in-reservoir treatment may serve to

accelerate the process of the water body recovery. The following types of in-reservoir treatments have demonstrated to reduce nutrient availability effectively, at least in some circumstances:

1. *Chemical precipitation of phosphorus.* Aluminum salts have a strong affinity to adsorb and absorb inorganic phosphates and remove phosphorus containing particulate matter from the water column. The settled aluminum-phosphate complexes also create a seal layer over the bottom sediment that reduces the phosphorus release from the bottom. This process also improves dramatically clarity of the water body (and may also result in the emergence of macrophytes).
2. *Sediment removal.* Sediment with large concentrations of phosphorus and nitrogen (organic and ammonia) serve as an internal nutrient source and could be removed. However, dredging can disturb the sediment and cause nutrient release into the water column.
3. *Aeration.* This technique keeps the hypolimnion aerobic which reduces the phosphorus and ammonia release from the anoxic bottom sediments. This reduces the nutrient content in water and their availability.
4. *Sediment oxidation.* Oxidation of the sediments may also reduce the remobilization of phosphorus into the water column. Instead of aerating the sediment (a highly counterproductive process) a solid granular oxidant such as calcium nitrate can be added to the sediment as an oxidizing agent. Obviously use of this chemical would make sense only if phosphorus is a limiting nutrient.
5. *Fish management.* Sometimes fish management that would enhance grazing of phytoplankton has been practiced. Also in a hyper-eutrophic impoundment, game fish is absent and is replaced by rough bottom feeding fish species that stir the sediments and increase phosphate release. Complete rough fish eradication was done on Lake Delavan and the lake was restocked with a balanced fish population.

Conclusions

Protection of the Švihov Reservoir that provides water for the Prague water supply system requires comprehensive and symbiotic planning and research processes that include (1) watershed management leading to a significant reduction of nutrient loads from point and non point sources, (2) establishing protective buffer zones around the reservoirs and tributaries, (3) in-reservoir nutrient management. The planning process is tiered and hierarchical and will require use of sophisticated land based and water quality models.

The major problem threatening the reservoir is either existing or potential occurrence of nuisance algal blooms of blue green algae (cyanobacteria). The nutrient levels in the tributaries are already at levels that would indicate hyper eutrophic potential. The first step to prevent these nuisance blooms and keep water quality acceptable for water supply is to define appropriate water quality standards for nutrients, most likely for both phosphorus and nitrogen.

Because of uncertainty in models and estimates, the planning process and watershed and water body management must be adaptive, recurrent and include common sense immediate actions and also long term plans.

References

- Baker, P. D. 1999. Role of akinetes in the development of cyanobacterial populations in the lower Murray River, Australia. *Mar. Freshwater Res.* 50: 265-79
- Carmichael WW (1997) The cyanotoxins. *Advances in Botanical Research.* 27:211-256
- Carmichael, W.W. (1992) A Status Report on Planktonic *Cyanobacteria* (Blue-green algae) and their toxins. EPA/600/R-92/079, U.S. Environmental Protection Agency, Washington, DC, 141 pp.
- Committee to Review the NY City Watershed Management Strategy (1999) *Watershed Management for Potable Water Supply: Assessing New York City's Approach*. National Research Council, National Academy Press, Washington DC
- Committee to Assess the Scientific basis of TMDL (2001) *Assessing the TMDL Approach to Water Quality Management*, National Academy Press, Washington, DC
- Division of Drinking Water Quality Control (1993) *Implications of Phosphorus Loading for Water Quality in NYC Reservoirs*. NYC Department of Env. Protection
- Fogg GE (1969) The physiology of an algal nuisance. *Proc. R. Soc. London B.* 173:175-189
- Head, R. M., Jones, R. I., Bailey-Watts, A. E. 1999. An assessment of the influence of recruitment from the sediment on the development of planktonic populations of cyanobacteria in a temperate mesotrophic lake. *Freshwater Biology* 41: 759-769.
- Hejzlar, J. (2006) Management options to control ecological potential of reservoirs, *Proc. The 5th Internatl. Conf. Reservoir Limnology and Water Quality*, August 27-31, 2006, Brno, Czech Republic, Institute of Botany of the Czech Academy of Sciences
- Hellweger, F., E. Kravchuk, V. Novotny and M. Gladyshev (2008), Agent-based modeling of a complex lifecycle of cyanobacterium (*Anabaena*) in a shallow lake, *Limnol. Ocean.* 53(40):1227-1241
- Lung, W. S., Paerl, H. W. 1988. Modeling Blue-Green Algal Blooms in the Lower Neuse River. *Wat. Res.* 22: 895-905
- Novotny, V. (1999) *Evaluation and Comments on Proposed Phase II TMDLs for New York City Water Supply Reservoirs*, A report submitted to the Natural Resources Defense Council, New York, NY, AquaNova International Ltd., Mequon, WI
- Novotny, V. (2003) *WATER QUALITY: Diffuse Pollution and Watershed Management*, J. Wiley, Hoboken, NJ
- Novotny, V. (2007) Diffuse pollution from agriculture: Ecological sustainability or food production of both, *Water* 21, April
- NYSDEC (1999) *Proposed Phase II Phosphorus Total Maximum Daily Loads for Reservoirs in the New York City Watersheds*, New York State Department of Environmental Conservation, Albany, NY
- Paerl, H.W (1988) Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnol. Oceanogr.* 33:823-847
- Olem, H., and G. Flock, (eds.) (1990) *The Lake and Reservoir Restoration Guidance Manual*, 2nd Ed., EPA-440/4-90-006, US Environmental Protection Agency, Washington, DC
- Paerl HW (1996) A comparison of cyanobacterial bloom dynamics in freshwater, estuarine and marine environments. *Phycologia* 35(6):25-35
- Paerl, H.W. and R.S. Fulton III. 2006. Ecology of harmful cyanobacteria. Pp. 95-107, In E. Graneli and J. Turner [Eds.]. *Ecology of Harmful Marine Algae*. Springer-Verlag, Berlin.

- Paerl, H.W., R. S. Fulton, P.H. Moisander and J. Dyble. 2001. Harmful Freshwater Algal Blooms, With an Emphasis on Cyanobacteria. *The Scientific World* 1:76-113.
- Pečenka, M., J. Holas, J. Wanner, and R. Vojtěchovský (2007) Zhodnocení Zátěže Povodí Vodárenské Nádrže Švihov Nutrienty (Evaluation of watershed loads of the Reservoir Švihov by nutrients), University of Chemical Technology (VŠChT), Prague
- Robson, B. J., Hamilton, D. P. Three-dimensional modeling of a *Microcystis* bloom event in the Swan River estuary, Western Australia. *Ecological Modeling* 174: 203-222
- Rohlich, G.A. (1969) *Eutrophication: Causes, Consequences, Correctives*, National Academy of Sciences, Washington, DC, pp. 307
- U.S. Environmental Protection Agency (1974) *The Relationship of Phosphorus and Nitrogen to the Trophic State of Northeast and North-central Lakes and Reservoirs*, National Eutrophication Survey Work, Paper 23, U.S. EPA, Washington, DC
- Vincent WF [Ed.] (1987) Dominance of bloom forming cyanobacteria (Blue-green algae). *N.Z. Jour. Mar. and Freshwat. Res.* 21(3):361-542.
- Vollenweider, R.A. (1975) Input-output models with special reference to the phosphorus loading concept in limnology, *Schweiz. Z. Hydrol.* 37:53-83
- Wisconsin Department of Natural Resources (1989) *Environmental Impact Statement - Delavan Lake Rehabilitation Project*, Madison, WI