RESERVOIR MANAGEMENT APPROACHES EXEMPILIFIED

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An Ecosystem Approach to Raw Water Management in the Hemlocks Reservoir System, Bridgeport, Connecticut.

Two large storage reservoir systems occur in two very different geological settings, providing an opportunity to study interactions between hard- and soft-water systems. The water supply challenges include avoidance of phytoplanktonic blooms of Cyanobacteria, MIB and Geosmin production by benthic Cyanobacteria mats, accumulation of anaerobic respiration products, and both ecological and water quality impacts of an unintentionally introduced population of land-locked alewife. Winter drawdown and copper sulfate application at the benthic interface helped control benthic Cyanobacteria mats. Deep water releases from the distribution and depth-selective releases from the storage reservoir overcame the oxygen deficit rate, avoiding accumulation of iron and manganese. Use of the artificial circulation system was abandoned. Biomanipulation by piscivorous fish stocking in cooperation with the Department of Environmental Protection-fisheries unit has been initiated.

Biomanipulation, aeration with nutrient inactivation, and front-end permanganate treatment.

The loss of an effective piscivorous fishery resulted in increased zooplanktivory and a shift in phytoplankton to Cyanobacteria. Taste and odor complaints resulted in taking the source off-line. Stocking piscivorous fish (large-mouth bass and brown trout), low-dose nutrient inactivation treatments injected directly through aerators, and pilot testing of permanganate pre-treatment of withdrawn raw water was performed. Copper sulfate treatment frequency decreased, and source water quality improved significantly. The source remained on-line throughout the year following implementation.

Layer Aeration, Hypolimnetic Aeration

Although exhibiting mesotrophic phytoplankton productivity, allochthonous organic loads resulted in a eutrophic respiration rate and build-up of anaerobic respiration products in three small Connecticut reservoirs. Hypolimnetic aeration has been performed since 1984 to prevent water treatment problems caused by iron and manganese. In 1987, a multiple layer aeration approach was initiated in a large Connecticut reservoir which had been experiencing Cyanobacteria and Synura sp. blooms, resulting in very short GAC longevity and taste and odor episodes. Over the first three years, trophic status shifted from eutrophic to mesotrophic, summer Cyanobacteria blooms were eliminated, and *Daphnia sp*. returned as a dominant zooplankton population.

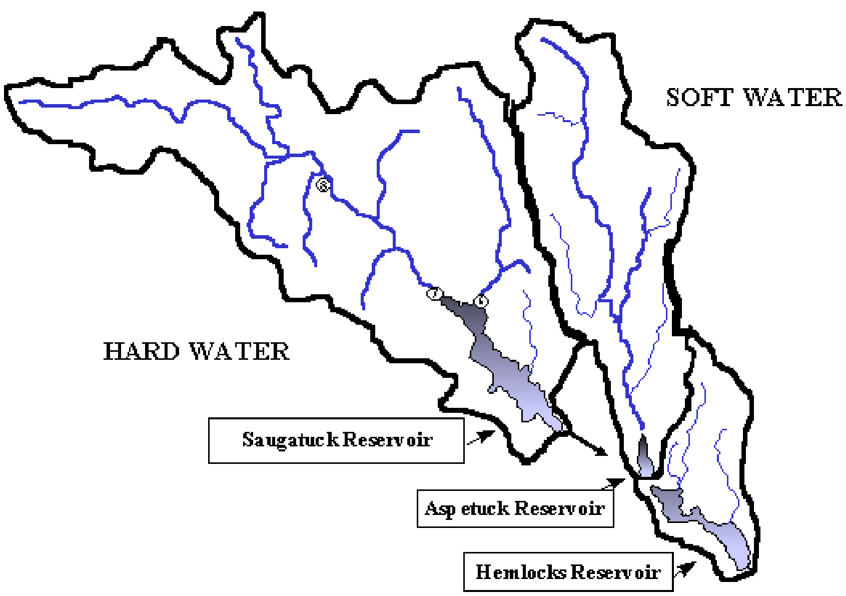
Case studies conducted since 1984 are used to illustrate the utility of depth-selective releases, reservoir sequencing and blending, reservoir partitioning-intake isolation, nutrient inactivation, biomanipulation, focused algaecide application, front-end treatment, and aeration strategies for water supply reservoirs.

Introduction

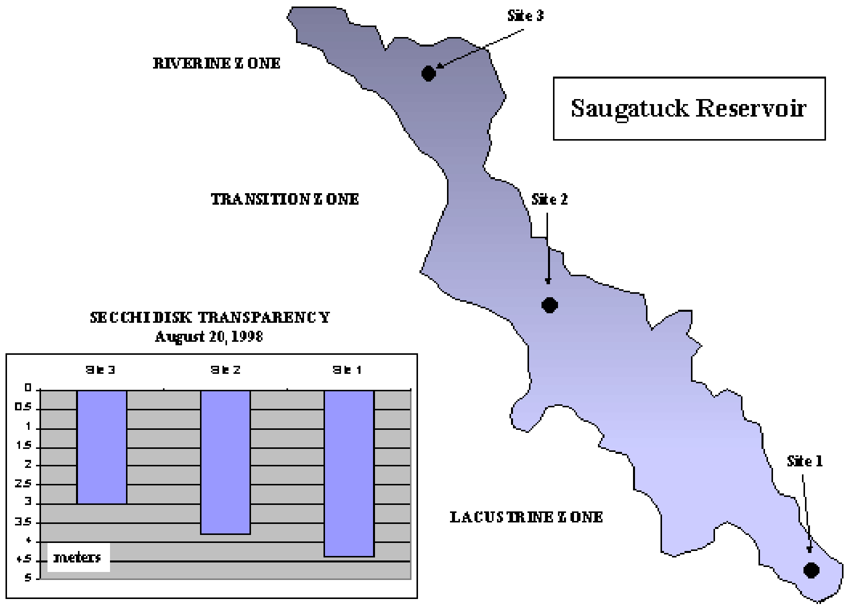
The limnology of a water supply reservoir is often very different from the limnology of a lake. Reservoirs exhibit greater longitudinal variability, allochthonous organic matter tends to be more important than autochthonous productivity, and managing the chemistry of raw water as it relates to the water treatment process is the primary objective of reservoir management. Reservoir limnology is effected by inter-reservoir diversions, releases from various depths, and water supply withdrawals. Source water reservoir systems are usually designed for water quantity (maximizing safe yield). However, once the limnological structure and function of a reservoir system is understood, and related to the specific water treatment process, significant improvements in raw water quality and treatment can usually be accomplished in the source water system. Reservoir management represents a potentially effective "first step in the water treatment process". A variety of reservoir management projects are described in order to exemplify the uniqueness of reservoir limnology, and cost-effectiveness of raw water quality improvement techniques.

Source System Operational Considerations

Hemlocks Reservoir Source Water System - Bridgeport Hydraulic Company, Connecticut



A multiple reservoir system provides water for a large distribution area in southwestern Connecticut. The hemlocks system consists of Hemlocks Reservoir (the direct source), Aspetuck Reservoir, and Saugatuck Reservoir (a large, deep storage reservoir). The watershed drainage to Aspetuck Reservoir and Hemlocks Reservoir is soft water, while Saugatuck Reservoir and its watershed consist of hard water. Multiple depth intakes are available at Hemlocks Reservoir, and multiple depth release gates are available at Saugatuck Reservoir for diverting water through Aspetuck Reservoir and into Hemlocks Reservoir.

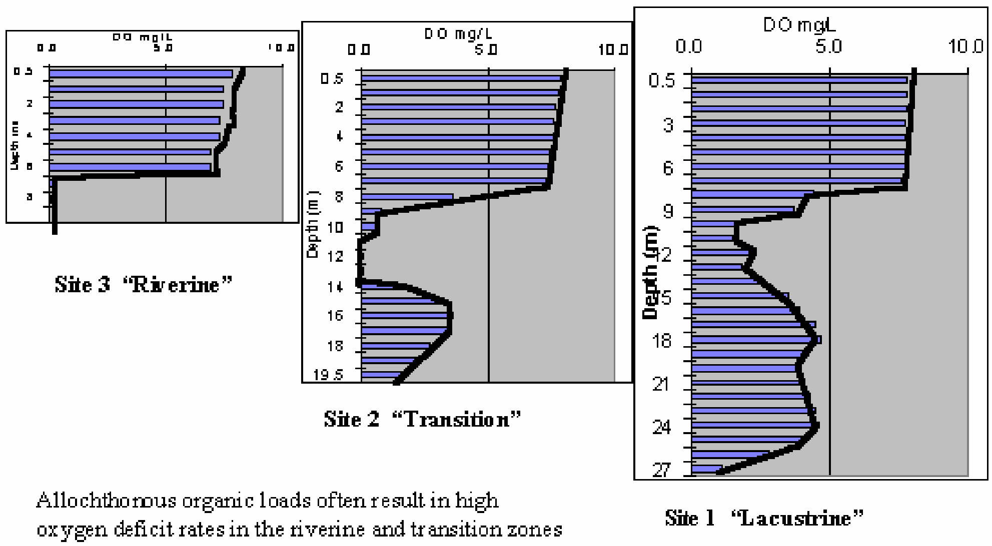


During the early 1990's, several water quality and treatment difficulties developed. Accumulation of anaerobic respiration products (iron and manganese) in bottom water resulted in high color and turbidity at the deep withdrawal gates. Bluegreen algae resulted in taste and odor episodes if shallow gates were used. An artificial circulation system was installed in an attempt to overcome the accumulation of iron and manganese. However, complete destratification was not accomplished and deep water temperatures increased significantly, stimulating the growth of benthic Cyanobacteria mats (which produce Geosmin and MIB). The attempt to control iron and manganese by destratification created suitable habitat conditions for a different taste and odor producing organism. Limnological studies were initiated in 1994 throughout the multiple-reservoir source system.

Saugatuck Reservoir is a large storage Reservoir which exhibits significant longitudinal and vertical gradients. As is commonly found in large reservoirs constructed in a river valley, Saugatuck Reservoir exhibits a "riverine zone", "transition zone", and "lacustrine zone". Much of the external oxygen demand (allochthonous organics) and nutrient load (total phosphorus) impacts are expressed in the riverine and transition zones of the reservoir. Water clarity tends to increase from the inflow end of the reservoir to the deep "lake-like" lacustrine zone. The depth structure of the riverine and transition zones in relation to stratification boundaries (thermocline depth) is particularly important in water supply reservoirs.

An unintentional introduction of land locked alewife resulted in the decline of large-bodied Cladocera, which are most effective at grazing on phytoplankton. Phytoplankton biomass increased despite relatively low total phosphorus concentrations. An ongoing program of brown trout stocking is being conducted by the Connecticut Department of Environmental Protection in order to improve the piscivorous fishery and increase grazing pressure on algae by zooplankton.

Maintenance of suitable temperature and oxygen habitat conditions is important for fishery structure of the reservoir and raw water quality.



Allochthonous organic loads often result in high oxygen deficit rates in the riverine and transition zones of large reservoir impoundments. Depth structure and sediment areas in these zones often result in oxygen depletion occurring in the metalimnion and spreading longitudinally throughout the reservoir. This behavion can be managed by a variety of techniques including Layer Aeration, Reservoir Partitioning, and Depth-Selective Release.

Saugatuck Reservoir August 1998

At Saugatuck Reservoir, a large fraction of bottom area in the riverine and transition zone is within the depth range of the metalimnion. As a result, anoxia and the accumulation of iron and manganese, occurs first within the metalimnetic depth range, while the deeper hypolimnion remains aerobic and of higher quality. Anoxia develops within the metalimnion and spreads longitudinally from the transition zone throughout the lacustrine zone. Such a development of oxygen loss, and water quality impact, is common in large reservoirs. A variety of management techniques are available to prevent impacts from metalimnetic anoxia in the transition zone, including layer aeration, thermal partitioning, and depth-selective withdrawal.

Water releases from storage in Saugatuck Reservoir pass through a fountain aerator and into Aspetuck Reservoir prior to release into the direct source, Hemlocks Reservoir. As a result, when water is not flowing over the dam at Aspetuck Reservoir, water entering Hemlocks Reservoir is a blend of water from the Aspetuck River and Saugatuck Reservoir. During the summer low-flow period, a large fraction of Hemlocks Reservoir inflow is from Saugatuck Reservoir. In 1994, Aspetuck Reservoir exhibited substantial coverage by aquatic macrophytes (especially water milfoil). An old dam remains submerged within Hemlocks Reservoir, remnants of the earlier smaller storage reservoir. Water supply intakes are located at multiple depths at the southern end of Hemlocks Reservoir

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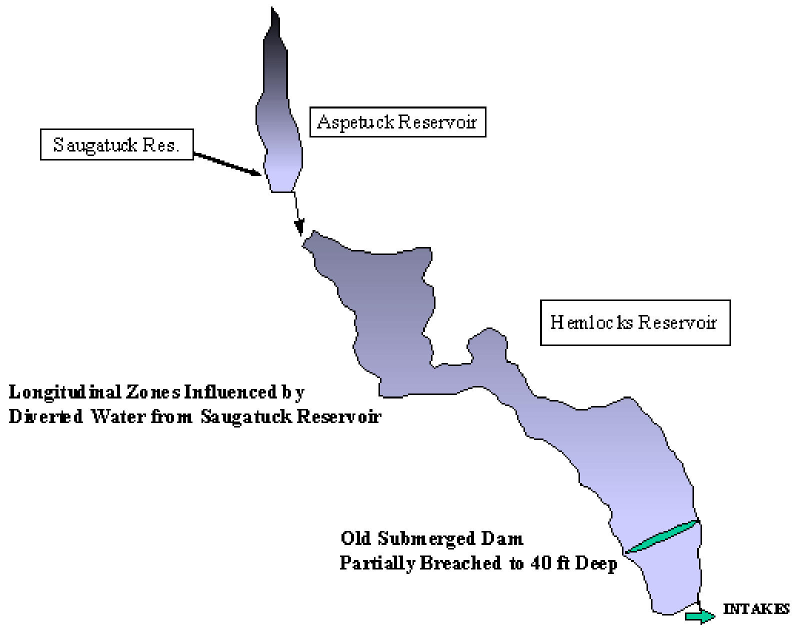
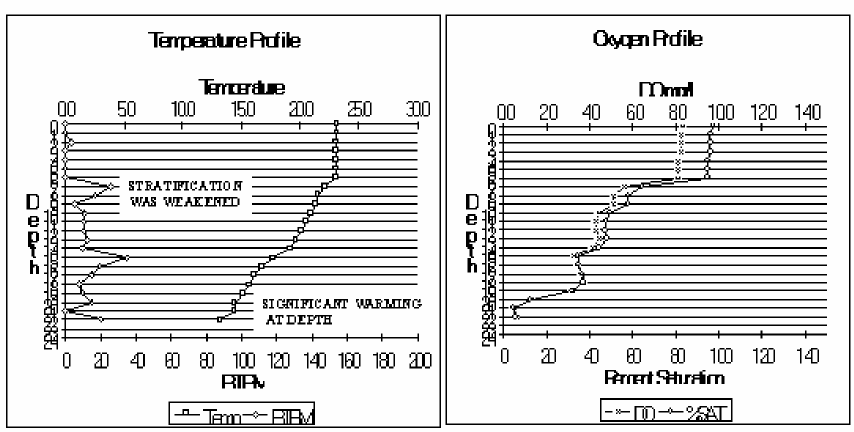


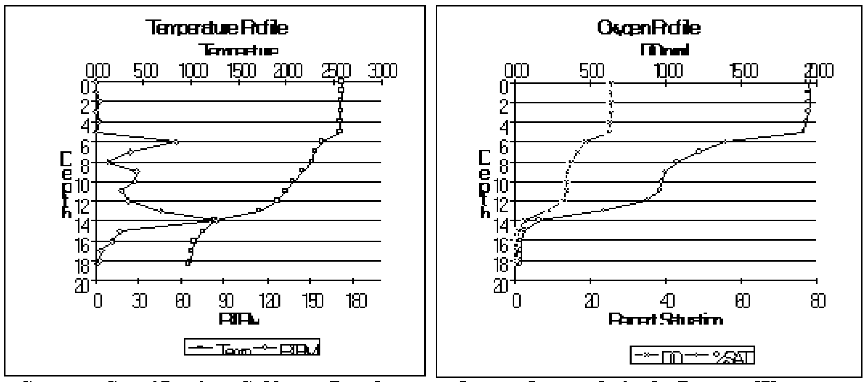
In 1994, an artificial circulation system remained in use. Although thermal stratification was weakened, enough stratification remained for anaerobic conditions to develop, resulting in the accumulation of iron and manganese in deep waters.



Hemlocks Reservoir August 23, 1994

Destratification (undersized) used below the Original, submerged Dam

Downward transport of heat resulted in significantly warmer temperatures at mid-depths. That stimulated the growth of benthic Cyanobacteria mats, which were observed at depths between 10 and 25 feet. Routine epilimnetic treatments using copper sulfate were needed to control bluegreen algae. Water treatment difficulties, and taste and odor episodes, were related to phytoplanktonic bluegreen algae, benthic mats, and the accumulation of anaerobic respiration products. Artificial circulation also reduced the utility of depth-selective withdrawal.



Stronger Stratification, Colder at Depth

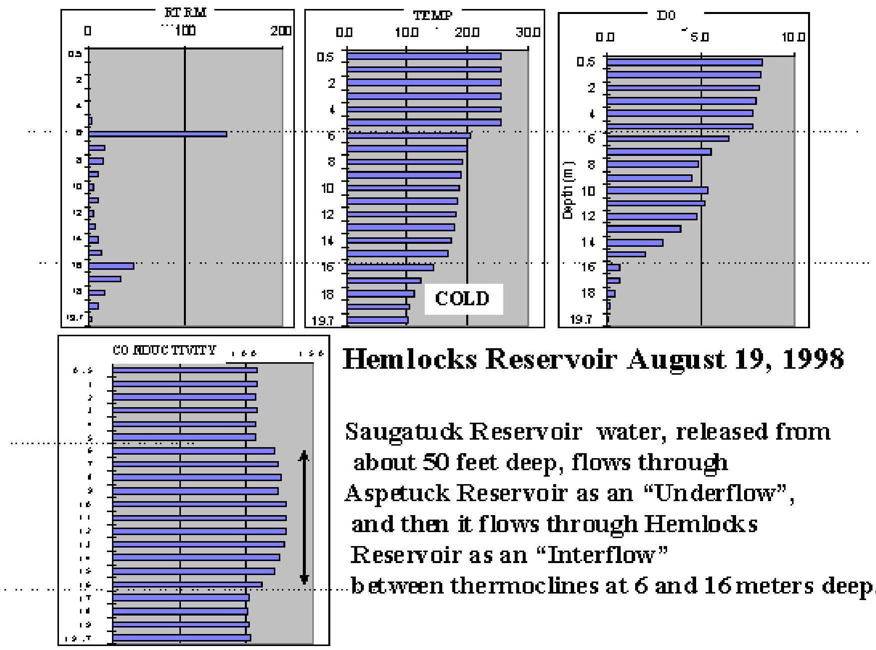
Oxygen Loss only in the Deepest Waters

Hemlocks Reservoir August 12, 1997

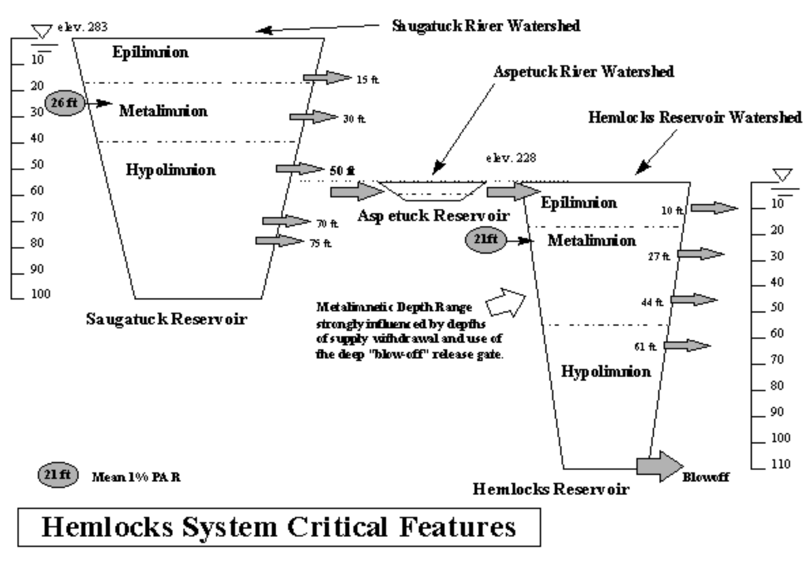
Destratification (undersized) - Use was Abandoned

During subsequent years, use of the artificial circulation system was abandoned in order to avoid stimulating the growth of benthic Cyanobacteria mats. Following several SCUBA surveys, a copper sulfate treatment was performed directly at the sediment interface at depths and locations where Cyanobacteria mats had formed. Follow-up SCUBA surveys indicated that treatment had significantly reduced the abundance of benthic Cyanobacteria mats. Subsequent benthic copper sulfate treatments have not been necessary since the use of the circulation system was abandoned. A winter water level drawdown was also performed at Hemlocks Reservoir to expose areas containing benthic mats for further control. SCUBA surveys have indicated no significant regrowth of benthic mats during the past three years.

In order to avoid an increase in raw water iron and manganese concentrations, mid-depth supply gates were used at Hemlocks Reservoir, and deep water releases from Saugatuck Reservoir (ca. 50 feet) were routed through Aspetuck Reservoir as an "underflow", and into Hemlocks Reservoir as an "interflow". The interflow behavior of Saugatuck Reservoir water to the mid-depth water supply gates at Hemlocks Reservoir, was clearly observed in conductivity profiles (recall Saugatuck Reservoir is a hard water system, Hemlocks is soft water). As a result, water quality problems related to oxygen loss only occurred in a small volume below 16 meters deep, and did not effect raw supply water quality.



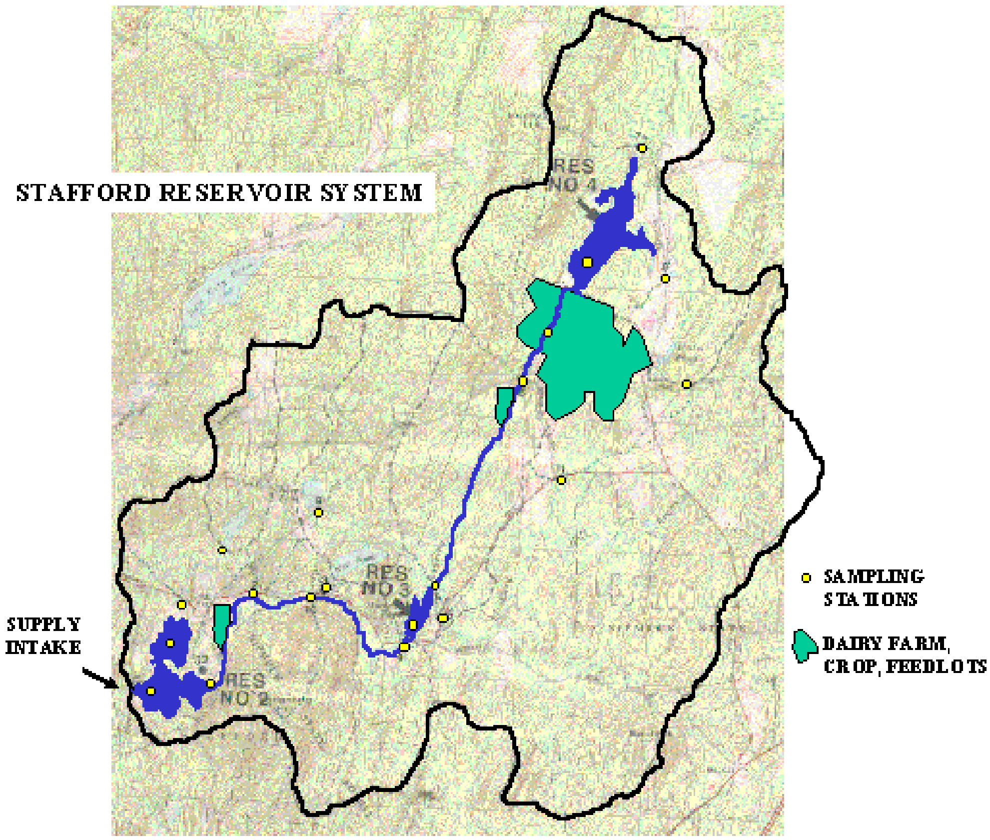
Water quality management in the Hemlocks Source system has included: Abandoning Destratification of Hemlocks Reservoir, Depth-selective Diversion of Saugatuck Reservoir Water to the mid-depth supply gates at Hemlocks Reservoir, Depth-Selective Withdrawal from Hemlocks Reservoir (seasonally), Area/Depth Selective Copper Sulfate Treatment at the sediment interface, Winter Drawdown, and Biomanipulation via piscivorous fish stocking. Taste and odor episodes have been avoided, epilimnetic copper sulfate treatments have not been needed, and color/turbidity related to iron and manganese has decreased.



Changes to source water system operations can help improve raw water quality and treatment. An understanding of the limnological behavior of the system, in relation to raw water quality parameters of concern, can lead to simple, inexpensive management options.

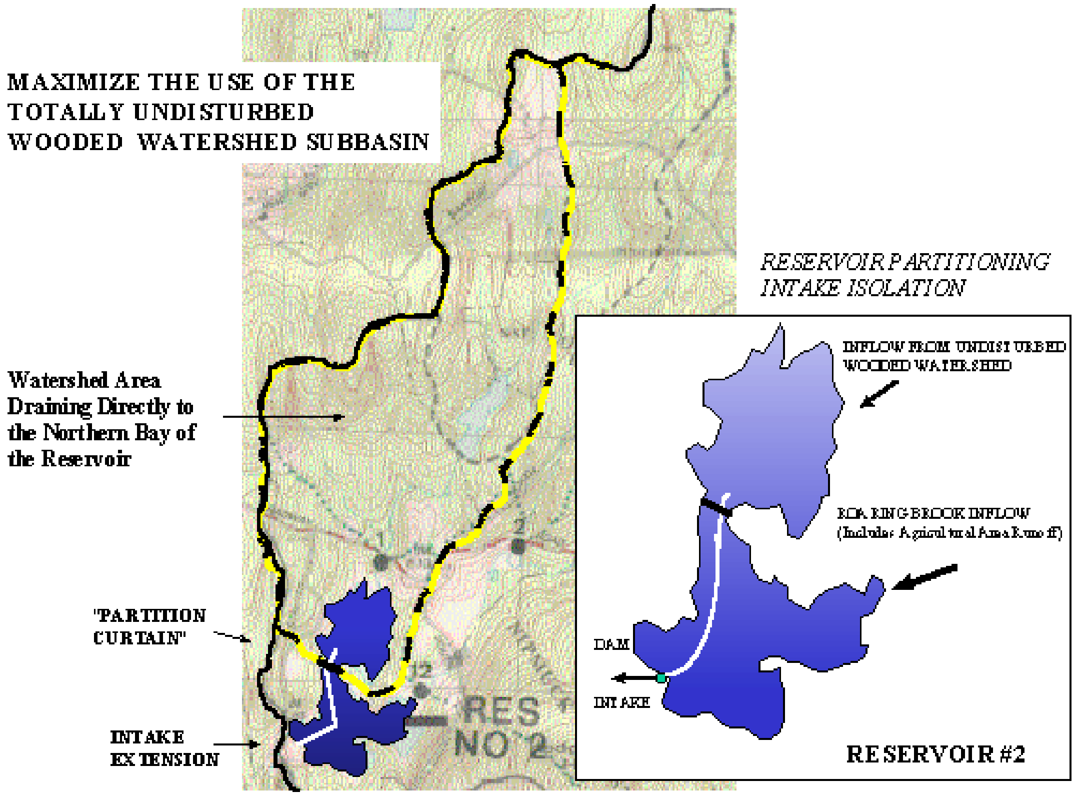
Reservoir Partitioning and Intake Isolation

Stafford Source Water System - Connecticut Water Company



The Stafford Source Water System supplies approximately 1 MGD of water to rural northeastern Connecticut. The source consists of a large, mostly wooded, watershed basin and three small shallow reservoirs in the flowline of Roaring Brook. Reservoir No. 4 is a small shallow impoundment located high in the watershed. Immediately below Reservoir No.4 is a large, expanding, dairy farm operation. Water quality downstream of the dairy farm is consistently poor, especially during storm runoff episodes. Reservoir No.3 lies approximately two miles downstream of the farm. Reservoir No.2 is further downstream, and is the direct source of raw supply water. Significant water quality impacts have been identified, including nutrient and organic loads, high coliform counts, color, metals, turbidity, and bluegreen algae blooms. Water treatment difficulties have included controlling taste and odor, meeting chlorine demands (especially during storm runoff peaks), and the formation of disinfection byproducts. Efforts to identify and implement agricultural best management practices (BMPs) to control runoff quality have progressed slowly due to private land ownership and implementation costs.

Small, deep water layer aerators (with biological substrates to enhance ammonia removal by nitrification) were installed in Reservoirs No. 3 and No. 2. The "indirect impacts" (iron and manganese, ammonia, and sediment P release) related to high organic loads were significantly controlled. However, water quality, especially during peak runoff episodes, remained difficult to treat.

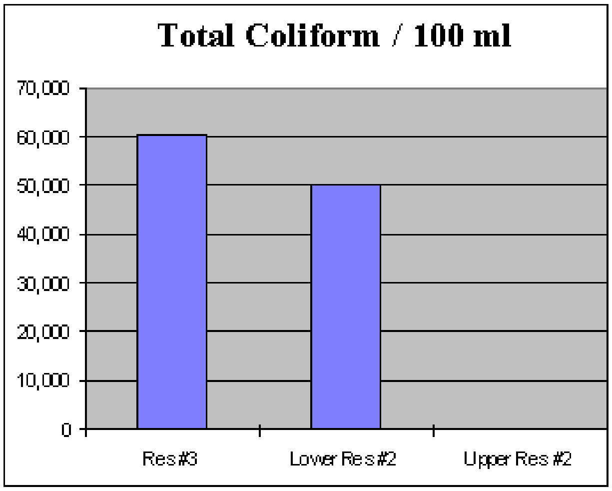


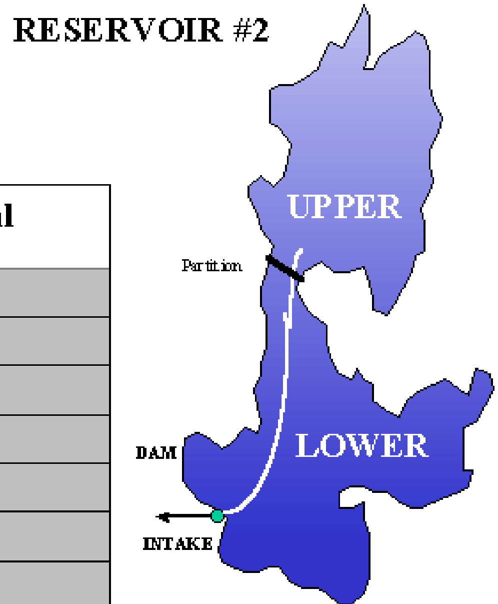
Reservoir No. 2 (the direct source of raw water) is a shallow reservoir consisting of two "bays". Roaring Brook (which carries dairy farm runoff) enters the lower bay, flows through Reservoir No. 2, and leaves either over the dam or through the supply intake. Approximately half of the reservoir volume and area lie in the upper bay. A narrow constriction connected the upper and lower bays of Reservoir No. 2. The watershed drainage basin which drains directly to the upper bay was entirely undisturbed woodland. In order to minimize supply water quality impacts of agricultural runoff carried by Roaring Brook the intake was extended to the upper bay of Reservoir No. 2, and a scrim-reinforced curtain was used to separate the upper and lower bays of the reservoir at the narrow constriction. The intent of this reservoir partitioning was to isolate the water supply intake as much as possible from the impacts of water quality in Roaring Brook, especially during storm episodes.

A comparison of water quality in Reservoir No. 4 (above the farm), Reservoir No. 3 (below the farm), lower Reservoir No. 2, and upper Reservoir No. 2, identifies the benefits of reservoir partitioning and intake isolation. Total coliform counts were very high at Reservoir No. 3 and lower Reservoir No. 2 following storms, yet remained low within upper Reservoir No. 2.

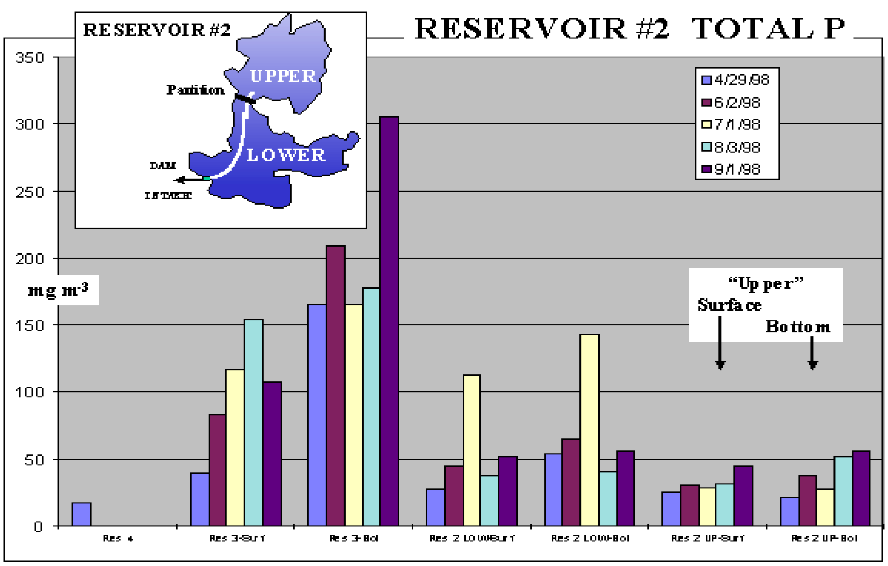
1998 Stafford Reservoir #2 and #3

	Total Coliform/100 ml 7/1/98
Res #3	60,500
Lower Res #2	50000
Upper Res #2	200



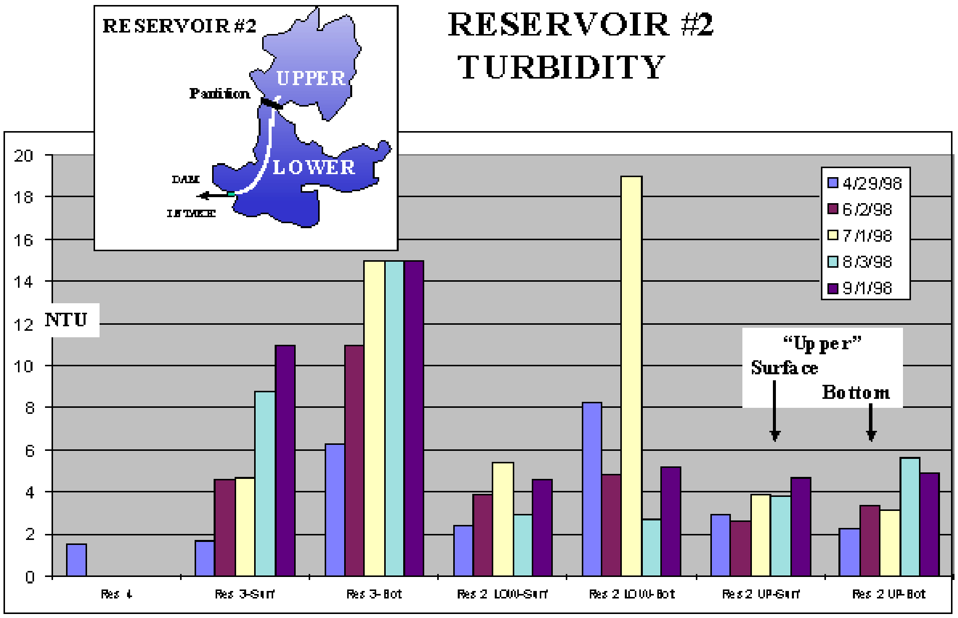


Total phosphorous concentration in surface and over-bottom waters remained lower in the isolated upper bay, compared to the lower bay which is exposed to Roaring Brook peak flows.

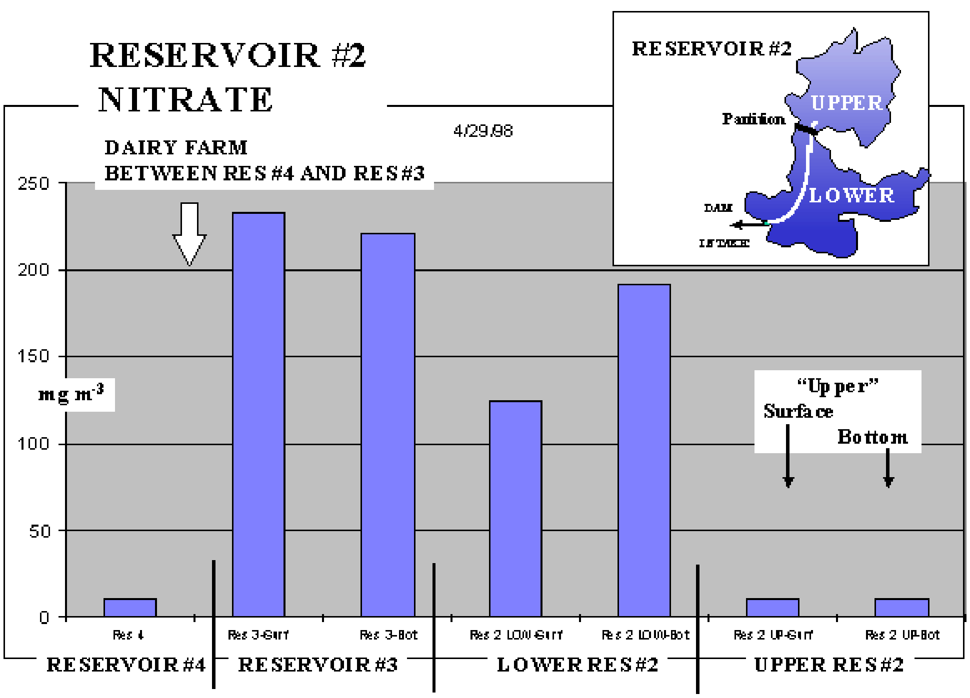


Although total phosphorous increased as the summer progressed, concentrations were lowest in the upper bay.

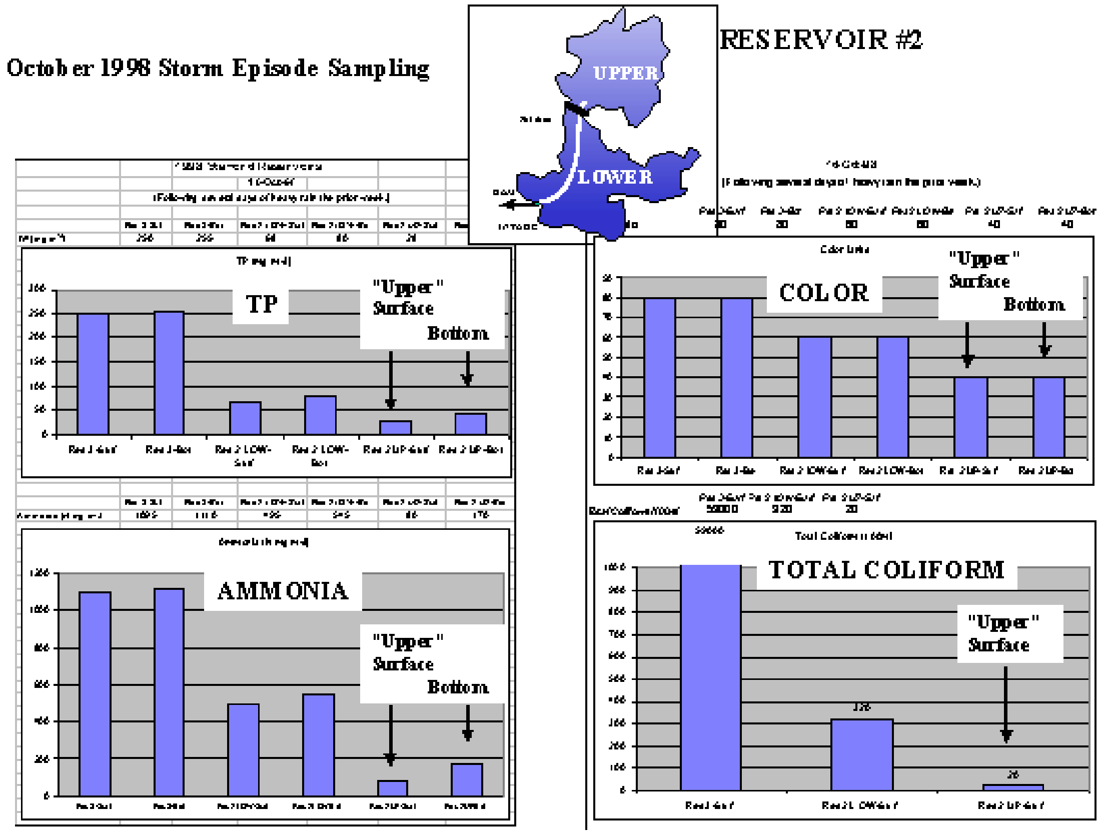
Turbidity also remained low in surface and over-bottom waters in the isolated upper bay, especially during storm events.



Row crops (e.g. feed corn) are a significant source of nitrate loads. Reservoir No. 3 and the lower basin of Reservoir No. 2 exhibited significant nitrate concentrations, while the upper basin of Reservoir No. 2 remained near the lower detection limit and nearly identical to Reservoir No. 4 (above the dairy farm).



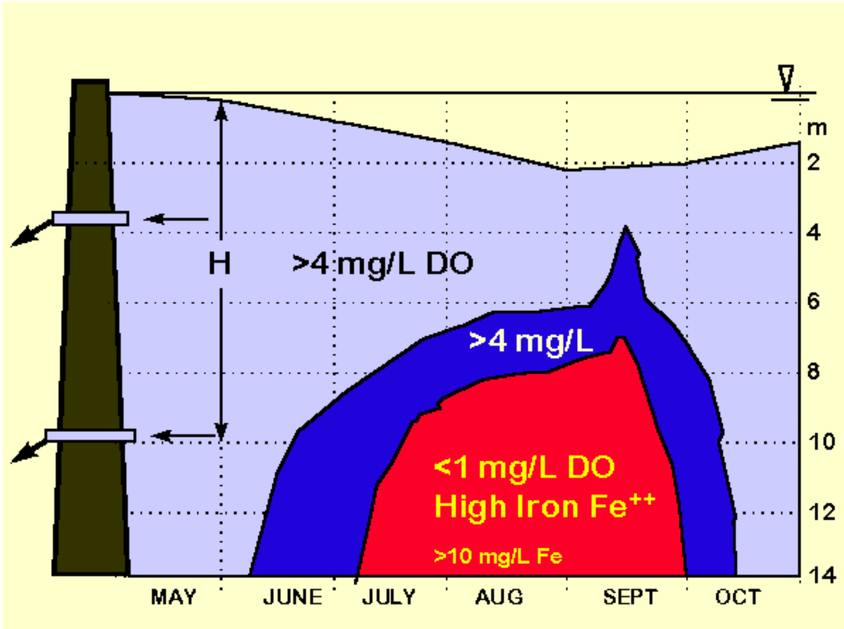
Storm episode sampling during October 1998 demonstrated that the isolated upper basin of Reservoir No. 2 exhibited the lowest total phosphorous, ammonia, color, and total coliform observations. Withdrawal of water from the isolated upper basin has avoided many of the impacts originating from agricultural runoff, and has improved the ability to treat raw source water in the system.



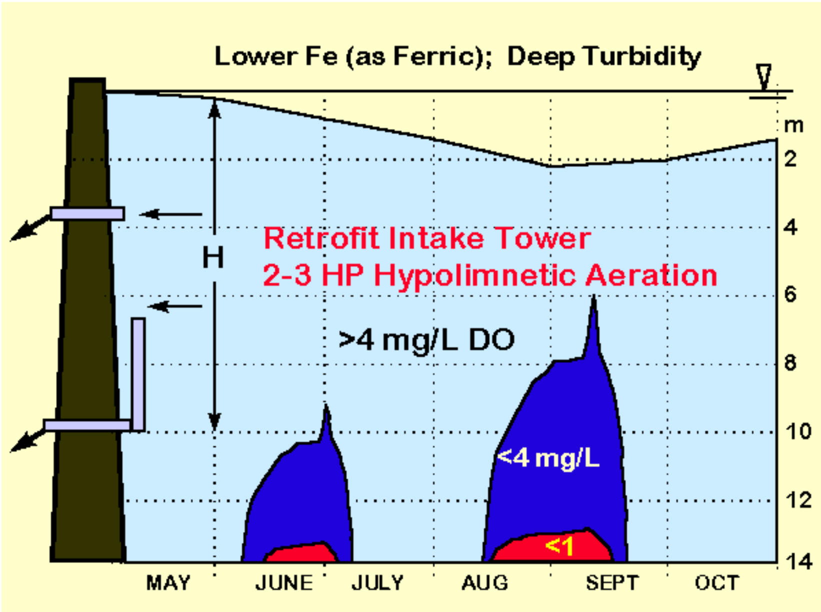
Hypolimnetic Aeration

Naugatuck Source System Reservoirs, Connecticut Water Company

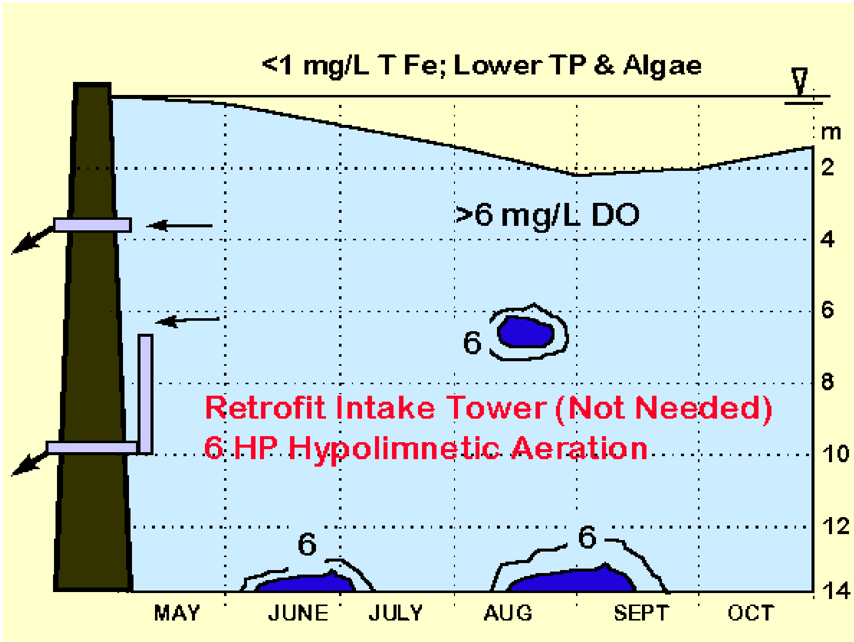
In 1983, three small water supply reservoirs in central Connecticut were examined in order to identify late-summer sources of high turbidity. All three reservoirs were found to be mesotrophic relative to total phosphorous concentration and algae productivity. However, using respiration rate as an indicator of trophic state (both oxygen deficit rate and carbon dioxide increment rate) each Reservoir would be classified as eutrophic. This is a common observation in Reservoir Ecosystems which have a disproportionately large supply of allochthonous organic matter compared to in-reservoir primary productivity. Longhill Reservoir was the most important supply source to be system. Two vertical release gates were available at approximately 4 and 10 meters deep. The 4 m gate was used most of the time. However, in late summer water level decreased by approximately 2 meters. Although still underwater, the head above the shallow intake was not adequate to release the volume needed immediately downstream at the water supply intake. Therefore, the 10 m gate was opened, releasing water containing more than 10 mg /L dissolved ferrous iron, which oxidized and cause very high turbidity at the water supply intake.



In order to prevent the late summer iron-turbidity problem, hypolimnetic aerators were installed to maintain aerobic conditions and prevent iron accumulation in deep water.



At Longhill Reservoir the aerators were driven by a total of 3HP compressor capacity (remaining from an abandoned destratification system) the first year, and a vertical extension tower was added to the deep release gate (functioning as a "cold water weir"). Iron and turbidity problems were significantly reduced, however airflow was not adequate to prevent a turbid layer from developing in the bottom waters of the Reservoir.



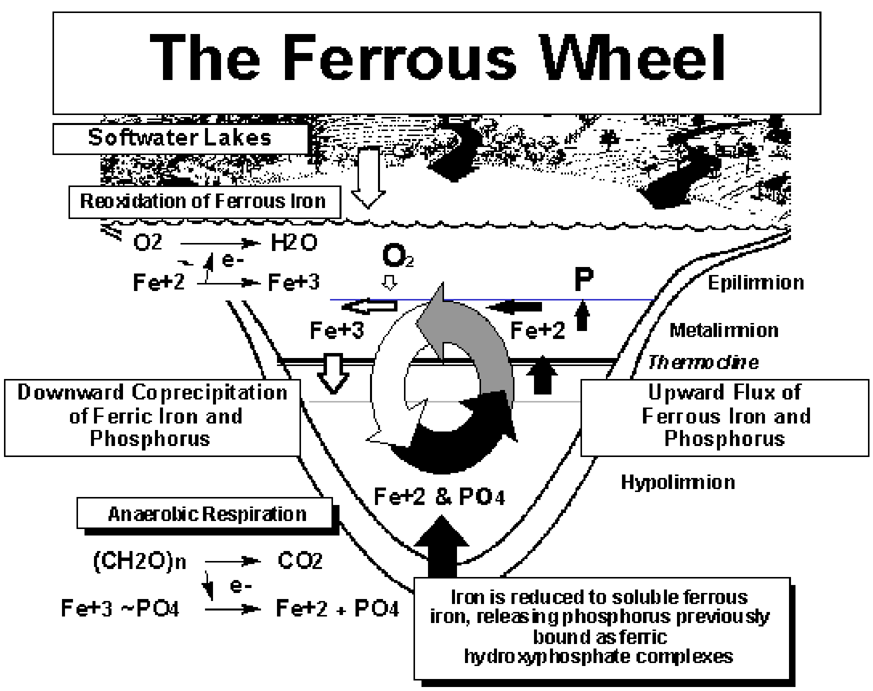
Subsequently, compressor capacity was increased to 6HP, which maintained highly aerobic conditions, low iron and manganese concentrations, and low turbidity. The retrofit gate extension was no longer necessary. Hypolimnetic aeration is particularly useful to avoid impacts from anaerobic respiration in the deepest waters of a Reservoir. The technique maintains cold bottom temperatures, habitat conditions, and can help to prevent treatment problems related to iron, manganese, hydrogen sulfide, and internal loading of phosphorous which can trigger bluegreen algae blooms. Hypolimnetic aeration only aerates water below the metalimnion. If oxygen loss occurs higher in the water column, within the metalimnion, hypolimnetic aeration will not be effective.

Aside: Internal Phosphorus Cycling Dynamics – Soft vs. Hard Water

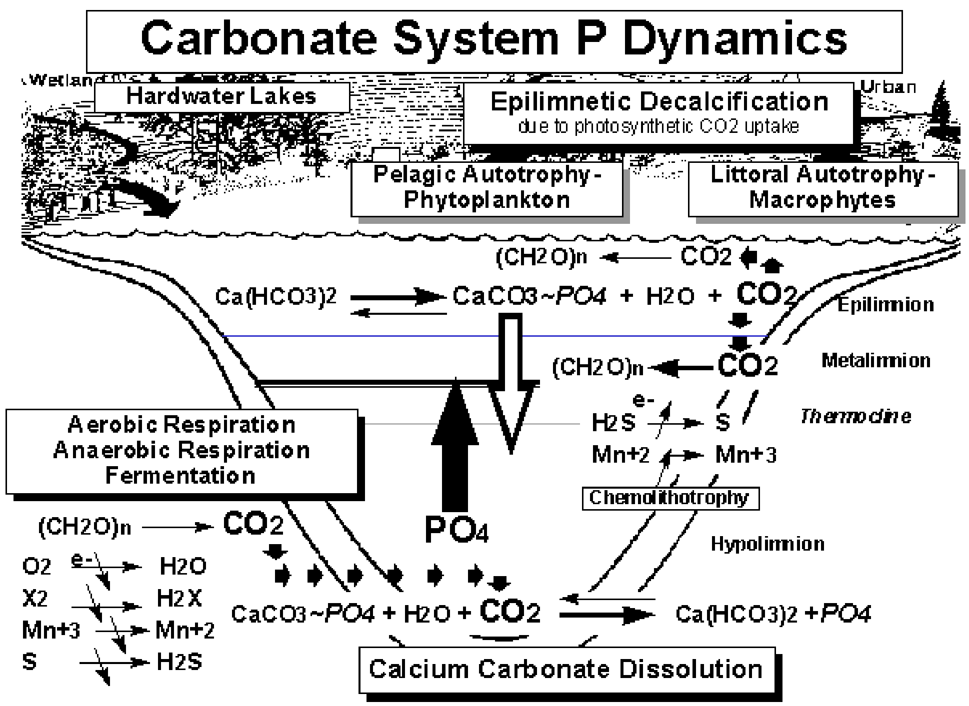
Phosphorus plays a central role in the bioenergetics of organisms and ecosystems; a role which no other atom can duplicate. Phosphorus is of paramount importance in lake and reservoir management because it most often limits the degree of phytoplanktonic autotrophy (algae growth). The mechanism of internal phosphorus cycling within a reservoir is very important to its quality. Large amounts of phosphorus are released from sediments of eutrophic lakes, especially when water in contact with sediment becomes depleted of oxygen. The mechanism by which sediment phosphorus flux occurs is different between soft water lakes rich in iron, hard water lakes with high alkalinity and conductivity, and soft- to moderately hard water lakes which have become deficient in iron.

Respiration is an "oxidation-reduction" reaction where organic matter is "oxidized" to carbon dioxide and another substance (X) is "reduced." In aerobic respiration, organic matter is oxidized to carbon dioxide and oxygen is reduced to water. Anaerobic respiration is the process by which organic matter is combusted (oxidized) using an alternate (ATEA). Some examples include dissimilatory nitrate reduction, manganese reduction, iron reduction, sulfur reduction, and fermentation. It is important to note that carbon dioxide is the common product of all lake community respiration processes; it is the product of the oxidation of organic matter regardless of what reduction reaction was coupled to it. This is one very important reason for measuring carbon dioxide during reservoir diagnostic studies.

As a lake becomes more eutrophic, more organic matter needs to be "combusted" via lake community respiration. This is first observed as a higher oxygen demand and more rapid consumption of dissolved oxygen (increased aerobic respiration). Once available oxygen is consumed, alternate compounds are used in place of oxygen (ATEAs). Increased lake community respiration is a consequence of eutrophication. As demand for respiration continues to increase, more ATEAs are used in respiration. The first ATEA used is nitrate (in dissimilatory nitrate reduction). While anaerobic respiration takes place in the nitrogen cycle no dramatic increase in phosphorus release from sediments occurs. (Nitrate is beneficial at the bottom of lakes.) However, as respiratory demand increases further, ferric iron acts as an ATEA, becoming soluble ferrous iron and releasing the phosphorus it had bound while it was oxidized. Further respiratory demand results in reduction of sulfur to hydrogen sulfide. Hydrogen Sulfide is extremely toxic to most biota and readily reacts with ferrous iron, permanently removing it as insoluble ferrous sulfide. Iron is no longer available to participate in respiration as an ATEA or to bind phosphorus. Accumulation of anaerobic respiration products (iron, manganese, sulfide) causes significant raw water quality problems and treatment difficulties, including shortened filter runs, taste and odor, discoloration, increased oxidant demand (permanganate, chlorine dioxide, etc.).



In soft water lakes (generally below about 50 mg CaCO3/L alkalinity), iron tends to control internal phosphorus dynamics. Oxidized ferric iron binds with phosphorus as ferric hydroxy phosphate complexes, giving sediments a capacity to bind phosphorus. When oxygen depletion occurs in bottom strata (for example, during lake stratification), alternate compounds are used by the biota for respiration. The use of alternate terminal electron acceptors (ATEAs) occur in a sequence of decreasing oxidation-reduction potential: first nitrate, then iron and manganese, then sulfur (producing hydrogen sulfide), and finally organic compounds in fermentation and methanogenesis. Once iron is used as an ATEA, both ferrous iron and previously bound phosphate are released to the water as soluble forms. Iron carries much of the anaerobic respiration in many softwater reservoirs. When ferrous iron again encounters oxygen, it is reoxidized and precipitates out of solution; carrying large amounts of phosphorus with it as ferric hydroxy phosphate complexes. This "ferrous wheel" controls much of the deep-shallow phosphorus exchanges in soft water lakes. Unfortunately, observed iron concentrations are low in many eutrophic reservoirs of moderate hardness. It is likely that iron has become deficient over years of eutrophication (it has been permanently removed from "redox availability" as ferrous sulfide). The release of phosphorus from sediments and chemical precipitation from the water column are directly due to oxidation-reduction reactions (the oxidation state of iron, hence its solubility).

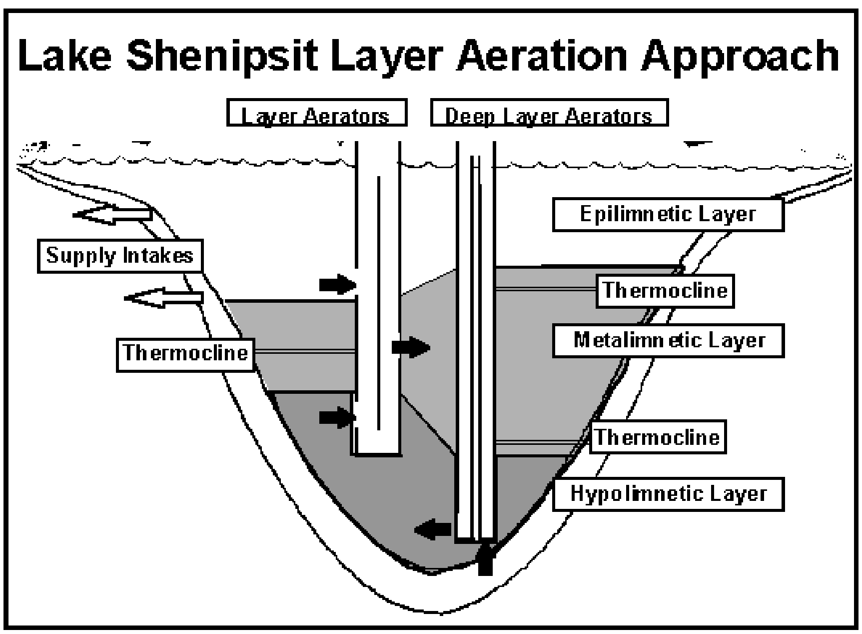


In a hard water reservoir, internal phosphorus cycling tends to be controlled by the carbonate buffering system. Water column removal of phosphorus (P) occurs when carbon dioxide (CO_2) is consumed by photosynthesis in surface waters. Removal of CO_2 disrupts the equilibrium between carbon dioxide and bicarbonate. Calcium carbonate precipitates from surface waters to reestablish equilibrium conditions. This process is called "epilimnetic decalcification" and results in the removal of large amounts of phosphorus associated with carbonate complexes. Unfortunately, this process doesn’t occur in softer water reservoirs (pH must exceed 8.3). Sediment P release in hard water lakes also tends to be a function of "non-equilibrium" of the carbonate system. As CO_2 increases in bottom strata, pH decreases due to carbonic acid formation, and a disequilibrium occurs in the opposite direction. Calcium carbonates are dissolved in order to reestablish equilibrium. This results in significant sediment phosphorus release from its previous association with carbonates. Phosphorus release from sediments, and precipitation from the water column, tend to be functions of carbonate system equillibria as effected by the accumulation of carbon dioxide by lake community respiration and photosynthetic carbon dioxide uptake, respectively. Unlike the "iron-controlled" system described above, neither sediment release nor water column removal is driven directly by oxidation-reduction reactions. Rather, these processes are driven by free carbon dioxide:carbonate equilibria as controlled the biological processes (respiration and photosynthesis).

It is important to diagnose the respiration pathways used in a water supply reservoir (especially anaerobic respiration) because they strongly influence raw water quality and treatment plant processes such as filtration, coagulation-flocculation, buffering, organics removal, oxidation and disinfection.

Layer Aeration

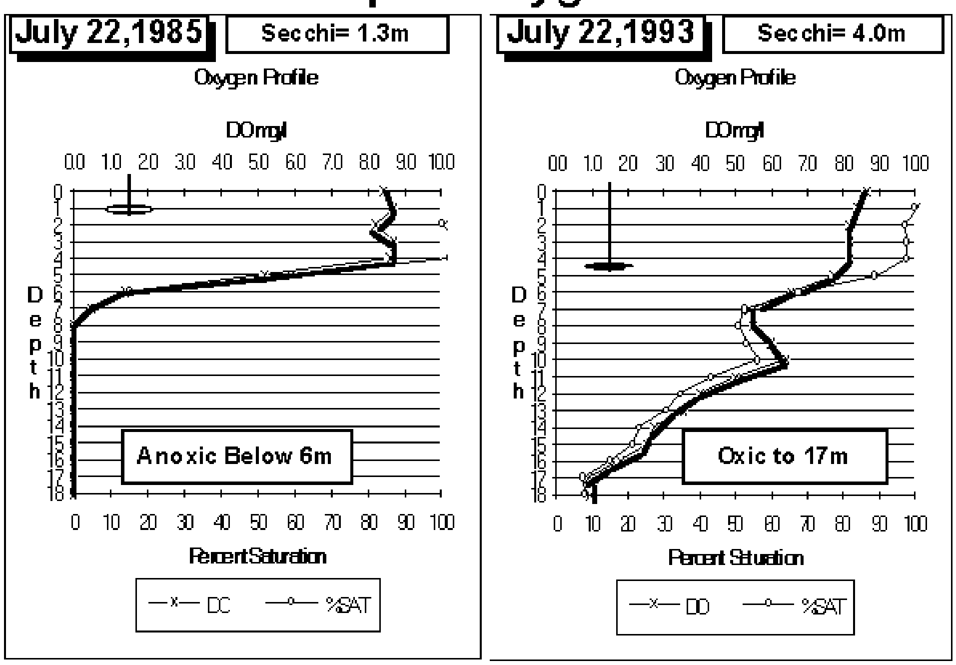
Lake Shenipsit, Connecticut Water Company



Lake Shenipsit provides source water to a treatment-distribution system serving a large population in north central Connecticut. The lake covers approximately 530 acres to mean and maximum depths of approximately 25 and 70 feet, respectively. The lake had become eutrophic, exhibiting blooms of bluegreen algae during the summer, and blooms of *Synura* during the fall and winter months. As a result, taste and odor episodes occurred and the GAC substrate lasted approximately 20 percent of its estimated design life. A diagnostic study of the lake identified intense oxygen loss throughout the hypolimnion and metalimnion. Internal nutrient loading was a significant contributor to phytoplankton productivity, stimulating blooms of *Anabaena* and *Aphanizomenon*. Hypolimnetic aeration was not selected as management technique because much of the anoxia occurred within the metalimnion and covered a substantial fraction of lake bottom area. Also, because the lake was large, significant compressor capacity would be needed for either hypolimnetic aeration or artificial circulation. A new aeration technique (Layer Aeration) was developed in order to create a high quality aerobic mid-depth layer during the summer, taking advantage of oxygen produced during photosynthesis to offset deeper respiratory oxygen demand. A small airflow was also delivered into the (now smaller) hypolimnion below the aerated layer, to reduce sulfide and phosphorus accumulation. The system is driven by two 30HP rotary screw compressors.

The Layer Aeration Process successfully aerated the design layer of the lake, creating several functional thermoclines and providing a high quality raw water withdrawal layer isolated from epilimnetic algae (above) and anaerobic respiration products (below). Summer blooms of bluegreen algae were eliminated after two summers of Layer Aeration. The frequency of fall-winter Synura blooms decreased, and when they occur GAC substrates control taste and odor more effectively. Prechlorination was no longer needed, which helped to control disinfection byproduct formation. The TOC of raw water decreased by approximately 1.5-2.0 mg/L on an annual basis (a full category in the TOC-Alkalinity matrix for enhanced coagulation). Transparency improved from a summer average less than 5 feet, to over 14 feet.

Lake Shenipsit Oxygen Profiles



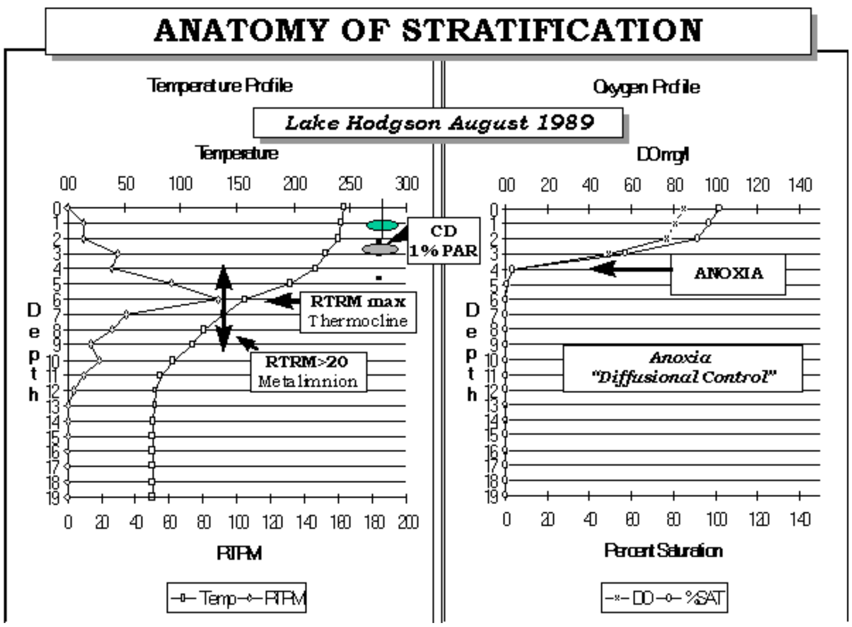
Lake Shenipsit is a soft water system. Layer aeration, with a small amount of aeration to the deepest water, used the iron cycle of the lake to maximize removal of P from the water column.

Layer Aeration and Hypolimnetic Aeration in a Hard Water Lake

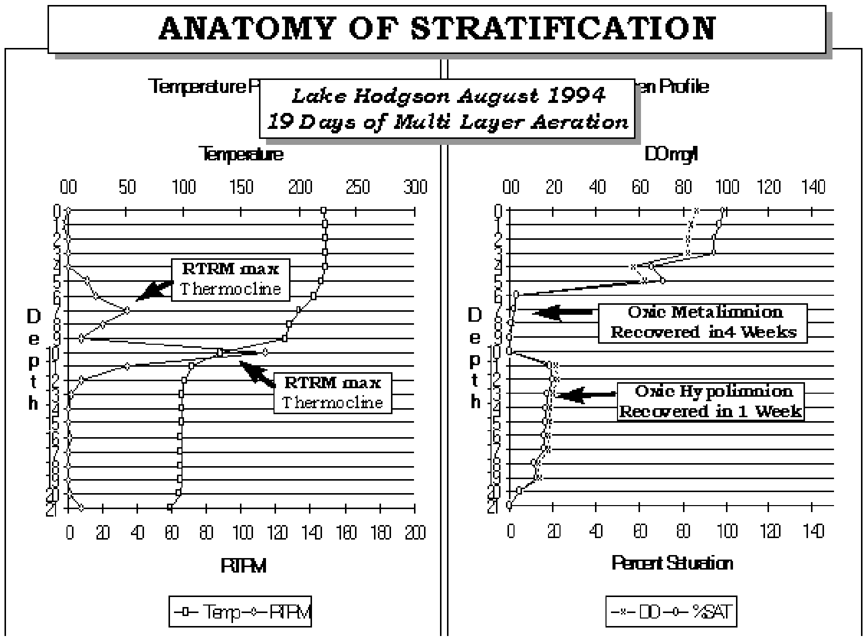
Lake Hodgson, Ravenna, Ohio

Lake Hodgson is a deep hard water supply lake in eastern Ohio. Water treatment difficulties developed as a result of intense anaerobic respiration and the accumulation of hydrogen sulfide, which required treatment with relatively large doses of permanganate. The source is hard water, anaerobic respiration is dominated by the sulfur cycle (not iron). The primary supply intake is deep within the hypolimnion in order to avoid epilimnetic bluegreen algae blooms, provide cold water to the distribution system, and optimize safe yield.

A hypolimnetic aerator was installed in order to maintain aerobic conditions and reduce treatment difficulties related to sulfide accumulation (and other anaerobic respiration products). Hypolimnetic aeration was very successful at maintaining deep hypolimnetic oxygen concentrations, and water treatment improved for most of the summer. However, the entire metalimnion still became anaerobic, covered a relatively large bottom area, and metalimnetic accumulation of phosphorus, sulfide, and manganese persisted. By late summer, supply withdrawals from the bottom had consumed much of the deep hypolimnetic volume and water treatment became more difficult.



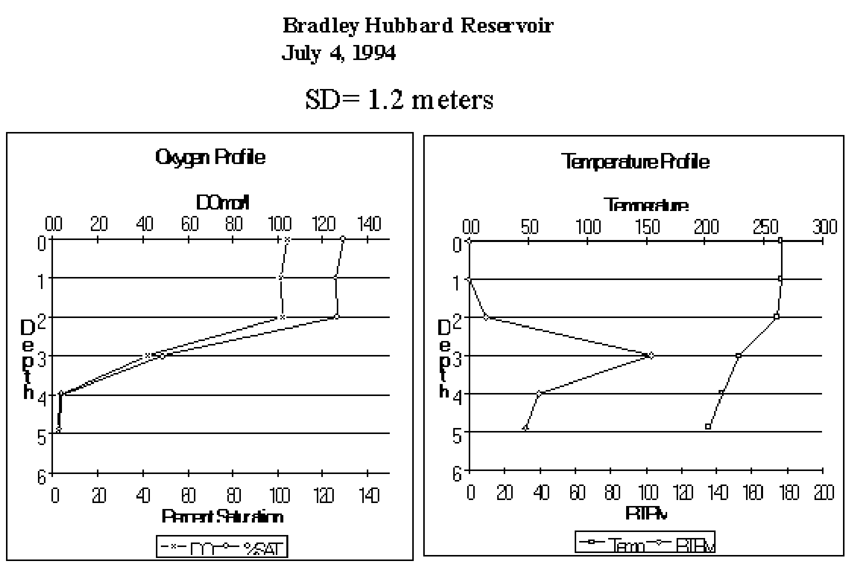
After several years of operating the hypolimnetic aerator it needed to be replaced. The in-lake aerator was replaced with a full-lift hypolimnetic aerator (so aeration depth range was established relative to water surface, and to optimize oxygen transfer efficiency). A second, small layer aerator was installed to reduce accumulation of anaerobic respiration products and phosphorus in the metalimnion. The replacement system (both aerators) are driven by the original compressor (only the aerator was replaced).



The replacement aerators were installed after anoxia had developed, and were able to recover oxic conditions and reduce accumulated sulfide and manganese. Water treatment improved.

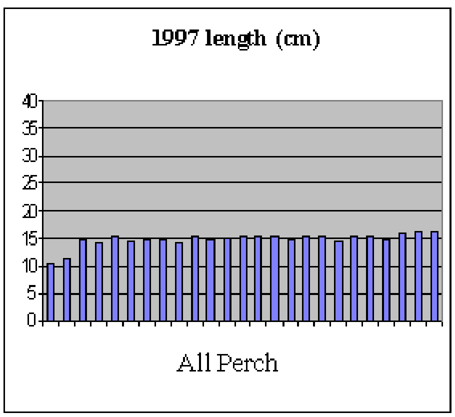
Integrated Methods

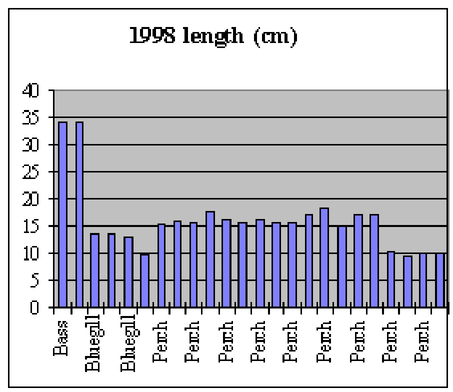
Bradley Hubbard Reservoir, City of Meriden, Connecticut



Bradley Hubbard Reservoir is a small, shallow supply source with an entirely undisturbed wooded watershed. It began being used as a supply source when a package treatment plant was put on line. The reservoir then began to exhibit raw water quality problems, especially bluegreen algae blooms, which forced the source to be taken off-line by early June. Diagnostic studies identified internal nutrient loading of phosphorus from anoxic sediments and an imbalance in the food web of the reservoir as main causes of bluegreen algae blooms. Over half of the reservoir sediment surface experienced coverage by anoxic water and sediment-P release more than doubled surface water P concentrations from spring to fall (stimulating *Anabaena* blooms). Fishery census collections revealed a lack of piscivorous species (predators, "fish eaters") and size classes. Hence, an overabundance of small fish which eat zooplankton (which control algae biomass by grazing) occurred. Algae were no longer controlled by grazing. The reservoir is very poorly buffered (very low alkalinity), and it was hypothesized that when the source began to be used, copper sulfate treatments and/or spring runoff episodes caused a pH decrease which impacted the fishery.

Bradley Hubbard Reservoir



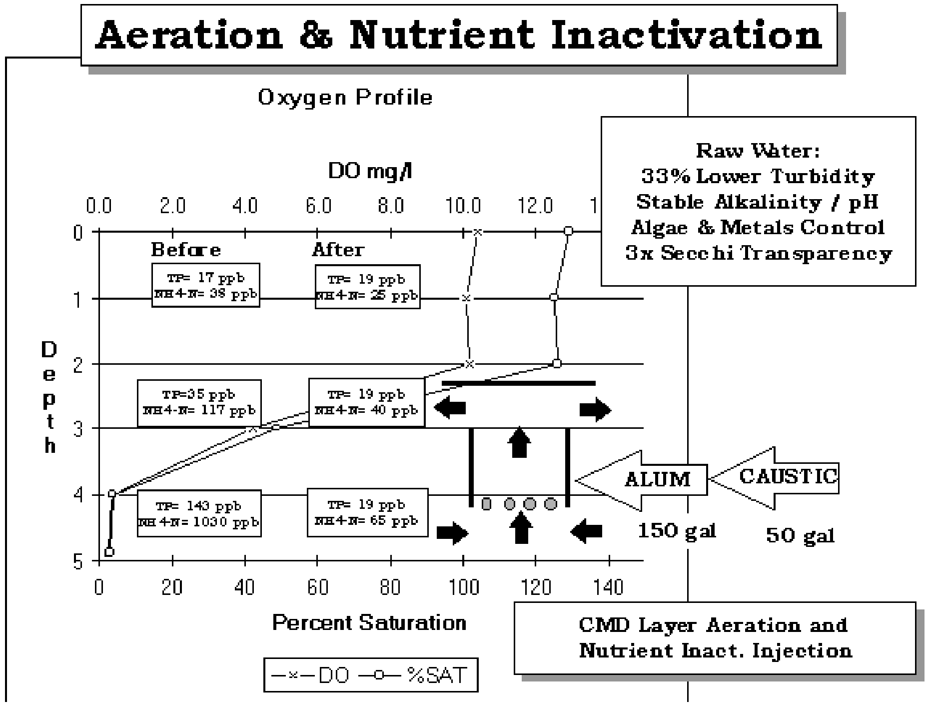


Very low piscivory,
only small yellow perch trapped

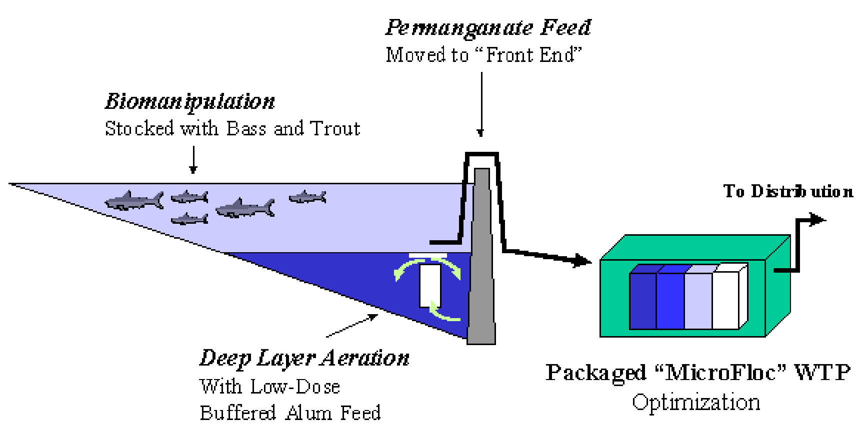
After stocking with Bass and Brown Trout,
CPUE decreased for Yellow Perch, several
large Bass were trapped (released)

A program of stocking with bass and brown trout was implemented to restore a more balanced food-web (to increase grazing, decrease algal biomass, and improve raw water quality).

A small, deep water layer aeration system was also installed, and fitted with a feed system for injecting small doses of buffered nutrient inactivation treatments directly into the bottom water layer (to overcome internal nutrient loading and reduce bluegreen algae bloom potential).



An evaluation of treatment plant operations and points of chemical feed resulted in several treatment modifications including moving permanganate feed to the gate house to increase time for oxidation treatment (in the transmission line).



Bradley Hubbard Reservoir 1998

City of Meriden,CT; Metcalf & Eddy; ECS,Inc.

The water supply source did not need to be taken off-line. Bluegreen algae blooms were less intense, reservoir transparency more than doubled. Management of this system is ongoing.

Summary and Discussion

No reservoir management technique exists that will remedy all raw water quality problems. Indeed, without a good diagnostic understanding of the limnology of the source water system and how it relates to the treatment process, implementation of a "treatment" may cause more water quality problems. Recall the problem of benthic Cyanobacteria mats stimulated by artificial circulation, the loss of grazing and stimulation of bluegreen algae by copper sulfate treatment, etc. Raw water supply limnology needs to be the first step.

Reservoir management of the source system can be a very effect first step in water treatment. Raw water quality improvement can be accomplished by changes to how a source system is utilized (for example diversion and interflow of high quality storage water), by modest structural changes (for example the reservoir partitioning and intake isolation), or by more aggressive treatments (a variety of aeration techniques, nutrient inactivation, biomanipulation, etc.)

Acknowledgements

I sincerely thank the Water Utilities (Connecticut Water Company, Bridgeport Hydraulic, City of Meriden, City of Ravenna) who have directly contributed to source water management and the pioneering of raw water management techniques for many years. I also thank all those who have directly and indirectly contributed to an improved understanding of managing source water systems (too numerous to acknowledge individually).

Selected Sources of Additional Information

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