SOLAR-POWERED RESERVOIR MIXING FOR IMPROVED DRINKING WATER QUALITY

Final Report

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ABSTRACT

Release of manganese from the sediments of small drinking water reservoirs can adversely affect operations at water treatment facilities and degrade the aesthetic quality of the water. The Town of Newburgh, NY operates a small reservoir known as Chadwick Lake Reservoir, which is one of two primary drinking water supplies serving the Town. Raw water from the reservoir is treated at the Chadwick Lake Water Filtration Plant through conventional filtration, chlorination, fluoridation, and addition of chemicals for corrosion control. Each summer and fall, the water treatment process and finished water quality are affected by the high levels of manganese in the reservoir. The levels of manganese are high enough to generate customer complaints of dirty water in the distribution system. An innovative technology of reducing manganese concentrations using solar-powered reservoir mixers was evaluated to attempt to control manganese and reduce operational impacts for the Town.

Four solar-powered mixers were installed in the reservoir and evaluated for their ability to enhance mixing, prevent or minimize stratification, enhance atmospheric oxidation and reduce plant influent manganese concentrations. The reservoir and plant influent water quality; plant operational data and energy consumption were monitored over a six month demonstration period to assess the efficacy of the mixers.

The results of the reservoir mixing study were summarized and compared to past plant performance data; and also compared with an equivalent diffused aeration system and other manganese treatment technologies. The results indicate that the mixers were capable of maintaining manganese concentrations in the shallow depths of the reservoir within levels treatable by the water filtration plant, however, they were unsuccessful in preventing stratification of the reservoir.

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SUMMARY

The Town of Newburgh, New York owns and operates the Chadwick Lake reservoir as part of their water supply system. Annually, the Town observes adverse impacts to the water treatment process at the Chadwick Lake Filtration Plant due to release of manganese from the sediments of the reservoir. During high manganese periods (typically summer and fall), the release of manganese from the sediments causes difficulty for the plant to oxidize and remove it from the water prior to its delivery to customers, resulting in increased treatment costs and complaints of colored water from customers.

Four solar-powered reservoir mixers were installed in the reservoir on April 30, 2003. The mixers consist of a thirty-six inch adjustable draft tube, twenty-four inch stainless steel impeller, brush style direct current motor, and three 4 ½ -square foot solar panels; all supported off a stainless steel support structure and high density polyethylene floats. Each mixer was adjusted to withdraw lower water at two to three feet above the reservoir bottom and were anchored to minimize lateral movement.

The performance of the mixers was monitored by the Town water plant operating staff and Stearns & Wheler over a six-month demonstration period. The mixers were maintained clear of aquatic growth during this time. During the demonstration period, water quality monitoring was performed in the reservoir using a multi-probe field instrument manufactured by Hydrolab®. Water quality parameters monitored by the Hydrolab® unit were water temperature, dissolved oxygen, pH, and specific conductance. Each of the four mixer stations and the area in the vicinity of the filter plant intake screen were monitored at approximate two week intervals (at half meter depths through the water column) to achieve depth profiles of each location. In addition, samples were collected at selected locations for analysis of manganese, iron, chlorophyll-*a*, and phosphorus. The analyses were conducted by Town personnel at the filter plant laboratory and an outside contracted laboratory. During the demonstration study, daily operational data from the water filtration plant was also collected in order to assess the impact of the mixers on plant performance in removing manganese and operational costs

Installation of the SolarBee® solar-powered reservoir mixers was intended to prevent the development of thermal stratification in Chadwick Lake, and thus, interrupt the process of oxygen depletion of the lower waters and its associated release of soluble manganese. The mixers were not effective in inducing mixing throughout the water column in the 2003 study period. The lower waters of Chadwick Lake remained isolated and anoxia was present in the lower strata for the entire summer. Anoxic conditions at the sediment-water interface resulted in manganese, iron, and phosphorus release into the water column.

As a result, manganese levels in the bottom waters, and at times surface waters (to a lesser degree), increased to concentrations problematic for treatment in the Town drinking water supply. Since recent

historical data are very limited, it was not possible to determine to what extent, if any, the mixers altered stratification or dissolved oxygen concentrations compared to typical conditions. However, even if the thermal and dissolved oxygen resources of Chadwick Lake were altered by the mixers, their deployment did not result in water quality conditions meeting the needs of the Town. To successfully destratify Chadwick Lake either additional solar mixers or a different, more energy intensive approach would be required. The Town anticipates deploying two additional mixers in 2004 and monitoring its performance to determine if more mixing energy will be necessary to destratify the reservoir to control manganese.

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SECTION 1

INTRODUCTION

1.1 DESCRIPTION OF STUDY

The Town of Newburgh water system serves about 17,000 people in the Town using two sources of supply: Chadwick Lake Reservoir and the Delaware Aqueduct Tap (a connection to the New York City Delaware Aqueduct). Chadwick Lake reservoir has a reported capacity of 820 million gallons, average depth of about ten feet, and surface area of 210 acres. Water from the reservoir is treated at the Chadwick Lake Water Treatment Plant. The plant treatment process consists of: pre-oxidation using potassium permanganate, THMR (trade name for peroxygen chemical), or chlorine dioxide (temporary system); coagulation, sedimentation, filtration, disinfection using sodium hypochlorite, fluoridation, and corrosion control. A process schematic of the filtration plant is shown on Figure 1-1. The design capacity of the plant is 3.4 million gallons per day (MGD), however, the plant generally produces about 1 MGD on average, as the extent of production is influenced by the performance of the plant in removing manganese. Average daily production in 2002 was 0.6 MGD and in 2003 was 2.0 MGD (during periods when the plant was in operation). The 2003 average daily production was higher than normal because the Delaware Aqueduct Tap was out of service for about three months.

The filter plant has historically experienced elevated manganese concentrations in the raw water from Chadwick Lake. The plant is generally capable of removing manganese to acceptable levels in the finished water when the raw water concentrations are less than 0.5 milligrams per liter (mg/L). However, raw water manganese routinely exceeds this limit, particularly in late summer and early fall, resulting in elevated manganese concentrations in the finished water and complaints of dirty water from customers.

The Town utilizes a diffused aeration system at the reservoir in the vicinity of the filter plant intake in order to oxidize manganese in the raw water prior to entering the plant. The system consists of a 25-horsepower compressor, air delivery piping, and perforated air diffusion piping. This system has proven to be ineffective for controlling manganese. Potassium permanganate, THMR, and more recently chlorine dioxide are also utilized to pre-oxidize manganese, however, these treatments have proven to be effective only while raw water manganese concentrations range from 0.5 to 0.8 (mg/L).

Each summer the reservoir stratifies thermally, resulting in low dissolved oxygen concentrations in the hypolimnion and release of manganese from the sediments. Raw water manganese concentrations in the treatment influent have been measured as high as 5 mg/L, however, typically range from 0.02 to 1.2 mg/L. Solar-powered reservoir mixers were identified as a potential low cost method to improve reservoir mixing and reduce reservoir stratification and manganese concentrations in the raw water.

To test this hypothesis, four solar-powered reservoir mixers were installed in the reservoir on April 30, 2003 and operated over a six month period. Water quality and temperature conditions in the reservoir and the plant influent were monitored during this period to evaluate the efficacy of the mixers. Along with water quality conditions, filter plant performance and energy consumption were monitored to assess the impact of the mixers on finished water quality and operational costs.

1.2 PURPOSE OF REPORT

The purpose of this report is to evaluate the efficacy of solar-powered reservoir mixers on the Chadwick Lake reservoir for reduction of raw water manganese concentrations and related water quality, operational, and energy benefits that may be achieved. A six-month demonstration study of four solar-powered mixers was performed using rented SolarBee® pond circulators. A product bulletin of the mixers is included in Appendix A.

The scope of services for this study included the following:

1. Hosted a project kickoff meeting held in the Town offices and attended by representatives of the Town and NYSERDA to review the project scope, schedule, and responsibilities; begin the data gathering process; and establish the critical success factors for the project.

2. Hosted progress meetings, held at strategic times during the study to review progress of work, to discuss issues related to the project and solicit input from NYSERDA.

3. Prepared and delivered to NYSERDA monthly progress reports of work completed, results, work anticipated, budget status, and problems and resolutions.

4. Collected available data from Town records on historic reservoir water quality and physical conditions; treatment process conditions; energy consumption related to the water treatment process; and chemical dosages, costs, and quantities. The Town collected the following additional data daily at the water treatment plant during the study period:

    - Plant Production
    - Electrical consumption (KWH and KW)
    - Chemical consumption
    - Pumping rates and durations
    - Volume of backwash water
    - Labor hours for plant maintenance
    - Residual disposal volume
    - Raw and finished water quality (particularly iron and manganese)
    - Customer complaints

5. Performed a six-month demonstration study of a solar-powered reservoir mixer utilizing four rented SolarBee® Model SB10000F pond circulators. The solar-powered pond circulators were installed in an array, shown on Figure 3-1, on April 30, 2003. Reservoir sampling took place during the period in accordance with the analytical program outlined in Tables 1-1 and 1-2. Most laboratory analytical work was performed by a contracted certified laboratory. Daily measurements of iron and manganese were performed by Town personnel in the treatment plant laboratory.

TABLE 1-1

Sampling Program Design

ISSUE	PARAMETERS FOR EVALUATION
Temperature, DO, pH, specific conductance, redox character of the reservoir	Profiles through the water column at 0.5 m intervals, biweekly samples, spring through fall mixing (four stations).
Chemical profiles with depth: Manganese and iron	Discrete samples water depths: 1m, 3m, 5m, 7m depths; all sampling dates (Station 2 only)
Phosphorus concentrations	Total Phosphorus and Soluble Reactive Phosphorus (SRP), 1m and 7m depths; all sampling dates (Station 2 only)
Trophic status indicators	Secchi disk transparency, measured from surface; all sampling dates (four stations)
	Chlorophyll-*a*, 1m depth; all sampling dates (Station 2 only)

TABLE 1-2

Sampling Program Analytical Summary

PARAMETER	LOCATIONS	DEPTHS	FREQUENCY	NUMBER OF SAMPLES*
Field parameters (Hydrolab profiles, secchi disk transparency)	4 stations	Profiles through water column (0.5-m intervals)	Biweekly: 4/14/03 through 10/15/03	14 events
Manganese	1 station	4 depths	Biweekly: 4/14/03 through 10/15/03	62 samples
Iron	1 station	4 depths	Biweekly: 4/14/03 through 10/15/03	62 samples
Total Phosphorus (P)	1 station	2 depths	Biweekly: 4/14/03 through 10/15/03	31 samples
Soluble Reactive Phosphorus (SRP)	1 station	2 depths	Biweekly: 4/14/03 through 10/15/03	31 samples
Chlorophyll-*a*	1 station	1 depth	Biweekly: 4/14/03 through 10/15/03	15 samples

*Sample numbers include 10 percent QC allowance.

The sampling program encompassed four stations on Chadwick Lake reservoir. Station 1 was at about a 15-foot depth just north of the filter plant raw water intake. Station 2 was at the deepest point of the lake's southern basin; Station 3 was at the deepest point of the lake's northern basin; and Station 4 was at the 15-foot contour, northern segment of the lake near the confluence of the northern tributary. Coordinates of the sampling stations were recorded using global positioning system (GPS) technology to ensure accurate locations during the sampling program. The depths and locations of sampling varied depending on findings at the time of equipment installation and due to minor movement of the mixers during operation.

6. Collected data were analyzed to determine the efficacy of the mixing system for achieving the desired increased DO and reduced manganese.

7. Prepared an estimate of the potential energy and cost saving for employing the solar-powered mixing system on Chadwick Lake Reservoir. The total cost to produce finished water (in dollars per million gallons) was determined for the study period and compared against previous years. A comparison of the costs and energy associated with the existing aerator to the solar-powered mixing was also performed along with an estimate of the potential payback period on capital investment for solar-powered reservoir mixing.

8. Provide a report detailing the findings of the study, utilizing NYSERDA standard formats.

1.3 ANALYSIS OF HISTORIC ENERGY USE

The Chadwick Lake Water Treatment Plant is served by a single 280 volt, 3-phase electrical service connection from CH Energy Group, Inc. (formerly Central Hudson Electric and Gas). An on-site step-down transformer provides 120-volt service for building facilities and smaller electric equipment. A single electric meter located in the filter plant workshop area provides consumption monitoring. Electrical consumption data was reviewed from the Town's monthly statements for 2002 and 2003 and selected information is presented in Table 1-3.

The power is used for the raw water aeration system, chemical feed equipment, mixers, high lift pumps, instrumentation and controls, backwash pumps, building lighting, hot water circulation pumps, and ventilation. Average daily plant production for the selected period was 1.39 MGD. Based on this data and 2002 electric billing records, electric consumption per million gallons of water produced was 44,283 KWhrs/MG.

The primary impacts that manganese treatment has on power consumption is in the raw water aeration system, chemical feed systems for preoxidants, and to a lesser extent backwash and high lift pumping. The existing aeration system consists of a 25-horsepower compressor that does not have its own electric meter. Based on its' continuous operation, the existing aeration system consumes an estimated 150,000 KWhrs of energy per year, resulting in an energy cost to the Town of about $12,000(1) annually.

(1) Estimated based on the Town's average total power cost of $0.08/KW-hr, inclusive of all consumption, demand and service charges, a 90% compressor efficiency, and 24-hour operation at 25 HP.

TABLE 1-3

2002/2003 Monthly Electric Consumption Chadwick Lake Water Treatment Plant

Year	Month	Production (MGD)	KW Demand	KW Hours	KW hrs/mgd(2)
2002	January	0.73	72	38,400	52,603
	February	0.73	72	38,400	52,603
	March	0.57	72	32,400	56,842
	April	0.43	60	27,000	62,791
	May	0.62	60	37,800	60,968
	June	0.36	60	45,000	-
	July	0			
	August	0	48	24,000	-
	September	0	30	18,600	-
	October	0	18	6,000	-
	November	0	24	6,000	-
	December	0	24	6,000	-
2003	January	0.29	114	118,200	69,734
	February	3.10			
	March	2.90	108	60,800	20,965
	April	2.83	128	62,400	22,049
	Period Average	**1.39**	**76**	**46,156**	**44,283**

(2) Not estimated for periods when the treatment plant was not in continuous operation.

SECTION 2

RESERVOIR ASSESSMENT

2.1 ENVIRONMENTAL SETTING

Chadwick Lake is currently a drinking water supply reservoir located in the Valley and Ridge Province of Orange County, in the Town of Newburgh, New York. This area is described by its low-rolling hills and large areas of agricultural lands. The area is underlain by layered sedimentary bedrock with extensive sand and gravel deposits. Land use within the watershed of the lake is a mixture of residential areas, forests and agriculture (Figure 2-1).

Chadwick Lake is located within the Hudson River drainage basin in Orange County. The impoundment is small, with a reported volume of 820 million gallons, with an average depth of about 10 feet and maximum depth of about 32 feet. The surface area of the reservoir is about 210 acres.

A large watershed area, extending over 8,380 acres to the north and east, drains into Chadwick Lake (Figure 2-2). Extensive wetland areas north of the lake are a significant component of the lake ecosystem as displayed in Figure 2-3. The outlet of the lake, Quaissaic Creek, flows to the south and east into the Hudson River. Overall, Chadwick Lake and its watershed provide good habitat conditions for a diverse assemblage of aquatic and wetland biota. Based on the watershed area, average precipitation, and runoff conditions, the water residence time of Chadwick Lake is estimated at 72 days. This is short water residence time, which results from the large watershed area and small lake volume.

Chadwick Lake is classified as dimictic, in that there are two periods of complete mixing each year (spring and fall), separated by periods of thermal stratification (summer and winter). The fact that Chadwick Lake develops thermal stratification has significant water quality implications. When the thermal gradient between the upper and lower waters develops, a sufficient density barrier to wind-induced mixing is created and the deeper waters become isolated from the atmosphere. While this occurs, the dissolved oxygen is consumed in this deep layer of the lake from decomposition of organic material and is not replenished by atmospheric exchange.

As lakes and ponds become more productive, increasing amounts of organic material such as algal cells settle into the lower waters where they are decomposed by the microbial community. The microbial community uses oxygen during decomposition. When the supply of oxygen is exhausted and the dissolved oxygen (DO) concentration in the deep waters approaches zero, the chemistry of the sediment surface is altered. The resultant chemical changes reduce iron and manganese complexes and soluble forms of the metals and phosphorus are released from the sediment and diffuse into the overlying water.

2.2 EXISTING WATER QUALITY

With the exception of routine monitoring of raw water at the Town of Newburgh supply intake, only limited historical data are available to document water quality conditions of Chadwick Lake. The following summary is based primarily on results of the 2003 monitoring effort conducted in support of this investigation. A detailed description of the 2003 results is presented in Section 5 of this report.

Chadwick Lake is a small, moderately productive impoundment. Water chemistry results indicate that the lake waters are alkaline and moderately well buffered. A prominent feature of the lake is the tea-colored tint to the water. Phosphorus and chlorophyll data were highly variable during the 2003 monitoring program, but were generally consistent with a lake of moderate productivity levels. Anecdotal information from Town personnel has indicated that the lake supports a warm water fish community. Macrophytes (aquatic vegetation) are present in the shallow regions of the lake.

As mentioned previously, the lake is deep enough to undergo thermal stratification and water quality conditions differ widely between the upper and lower waters. The upper waters, where light penetration supports photosynthesis and there is atmospheric exchange, exhibit higher concentrations of DO, chlorophyll-*a* (a plant pigment used to index algal abundance), and pH. The deeper waters, isolated from the atmosphere and affected by decomposition, were characterized by lower concentrations of DO and pH and detectable concentrations of soluble phosphorus and manganese.

2.3 DESCRIPTION OF MANGANESE PROBLEM

Elevated levels of manganese in the raw water to the Chadwick Lake Water Treatment Plant have historically been a problem for the Town. Raw water manganese concentrations have ranged from non-detectable levels to as high as 5 mg/L in recent years. Elevated levels typically occur during summer and fall when the reservoir exhibits thermal stratification.

Manganese is a naturally occurring inorganic chemical that is objectionable in public water supplies for its aesthetic impacts, and to a lesser extent, objectionable taste. Manganese occurs naturally in water in its reduced state (Mn^{2+}), but when oxidized, forms manganese oxides (MnO_2) that can create staining of water fixtures and clothing and impart color to the water. Higher manganese concentrations can result in complaints of “black” or “dirty” water.” Reported literature values indicate that concentrations of soluble manganese of less than 0.05 mg/L are generally acceptable in public water supplies; at these low concentrations the aesthetic problems of characteristic black stains and deposits of manganese oxides do not occur (AWWA/ASCE, 1998).

The New York State Sanitary Code has established a maximum contaminant level for manganese of 0.3 mg/L. However, at this level, complaints will most likely occur due to aesthetic impacts. USEPA has established a secondary maximum contaminant level (non-enforceable) of 0.05 mg/L for manganese. As part of the Safe Drinking Water Act Amendments of 1996, manganese was placed on USEPA's candidate contaminant list for possible regulation. The contaminant candidate list is used to evaluate contaminants for possible regulation or to eliminate them from future consideration. Based on information in the USEPA website (www.epa.gov), we understand that USEPA will not regulate manganese related to health effects.

The Town's finished water manganese concentrations have generally been less than 0.05 mg/L in the winter and spring; however, levels above 0.05 mg/L have frequently occurred during most of the summer and during early fall. The Town indicated that natural springs are believed to contribute recharge to the reservoir during periods of low surface water inflow (i.e. groundwater recharge) and that this groundwater recharge may contain elevated levels of manganese. Elevated manganese concentrations have been measured during periods of high surface water flows as well.

The existing Chadwick Lake intake is a 24-inch stainless slotted steel screen supported from a 20-inch vertical riser pipe off the reservoir bottom (see Figure 2-4). The screen assembly is fitted with 2-inch stainless steel air supply piping in order to provide periodic air cleaning. The design drawings for the intake indicate that the top of the screen is 11'-0" below the maximum water surface elevation. However, field measurements on June 27, 2003 indicate that it is actually 8'-3" below the water surface (reservoir at spillway elevation 450.5' on this date). An area around the intake (approximately 2,000 ft^2) is aerated year round to attempt to reduce manganese concentrations. The aeration system consists of a 25-horsepower compressor and slotted air pipes laid on the reservoir bottom. The aeration system has proven ineffective in controlling manganese and consumes significant energy.

Another potential cause of increased raw water manganese levels in the lake over the last few years was the installation of a new intake in the reservoir in 1998. The new intake is deeper than the old intake, which was a surface withdrawal. While no data are available to verify in lake manganese levels prior to 1998, it is possible that the deeper intake is drawing from a water stratum with elevated concentrations of manganese. The Town water treatment plant operators have indicated that plant influent manganese concentrations have increased since the new intake was installed. Flushing of the raw water intake pipeline has occurred periodically since 2002. Since flushing was initiated, it does not appear as though deposits in the intake pipeline are a significant source of manganese.

The Town's current treatment for manganese reduction consists of potassium permanganate ($KMnO_4$) addition or THMR addition (a peroxygen chemical) to the raw water for oxidation of soluble manganese. Oxidized manganese is then removed through conventional coagulation/sedimentation and filtration. The use of $KMnO_4$ or THMR has been effective in controlling manganese at lower concentrations; however, has not provided effective control at manganese concentrations greater than about 0.5 mg/L. These chemicals are injected into the raw water just prior to rapid mixing. Both $KMnO_4$ and THMR are dry chemicals and are batched in a day tank for feed in slurry form. The current chemical feed facilities for $KMnO_4$ and THMR were installed in 1998.

In 2001 and 2002, the Town evaluated chlorine dioxide oxidation of manganese using a temporary chlorine dioxide (ClO_2) feed system. The ClO_2 is generated on-site from chlorine gas and sodium chlorite and can be injected at the raw water gate house (just downstream of the supply dam) or in the plant influent main. The use of ClO_2 has proven only marginally more effective than $KMnO_4$ and THMR; providing effective oxidation for raw water manganese concentrations of up to about 0.8 mg/L.

Because the Chadwick Lake Filtration Plant was upgraded in 1996, the Town has been seeking cost effective manganese control strategies to complement their upgraded conventional treatment facility. This study provides a potential cost effective solution to manganese control focused on control of manganese in the source water.

2.4 ALTERNATIVES CONSIDERED FOR WATER QUALITY IMPROVEMENT

The Town of Newburgh has considered changing the depth of the raw water intake at its filter plant to draw from a shallower lake stratum and avoid encountering elevated concentrations of manganese. Given the height in the water column with elevated manganese concentrations during the summer period, a shallow intake would be required. A near surface intake might reduce the manganese concentration in the raw water but would be vulnerable to other water quality issues, notably elevated organic carbon associated with algal growth.

The focus of this evaluation was to break the cycle of manganese release from the lake sediments. Elevated manganese concentration in lake water is a direct result of the manganese concentration in the sediments and the development of anoxic conditions at the sediment-water interface. As previously described, when the DO of the overlying waters is depleted, anoxic conditions are created that allow manganese (along with iron and phosphate) to be released to the water column. The options available for reducing undesirable impacts of manganese on the water supply are removing manganese from sediments or preventing the development of anoxic conditions at the sediment-water interface.

Removing manganese from lake sediments is not a feasible alternative, given its ubiquitous presence in the rocks and soils of the watershed. Thus, options for controlling the sediment release of manganese focus on maintaining DO concentrations at the sediment-water interface. There are two common methods to add oxygen to the deeper water: induce mixing (to enable atmospheric oxygen exchange), or inject oxygen to the lower waters. Mixing can result in destratification; the thermal structure of the lake is disrupted as the temperature and density gradient between the upper and lower waters is eliminated. Chemical changes in the lower waters due to anoxia and the related water quality degradation are prevented. Any cool or cold-water habitat that had adequate oxygen to support aquatic life could be eliminated as the lake is destratified. This alternative is typically considered only for relatively shallow systems that do not support cold water biota.

In contrast, injection of oxygen (or sometimes air) into the lower waters may increase deep-water DO concentrations while maintaining the thermal structure of the lake. To achieve this, sufficient oxygen must be supplied to satisfy the oxygen demand exerted at the sediment surface. This alternative is typically selected for deeper lakes as the oxygen delivery system itself can create sufficient turbulence to induce mixing in a shallow reservoir such as Chadwick Lake.

In general, there are two ways to circulate water in a lake: aeration and pumping. Aeration systems create vertical currents using the rising force of small bubbles to entrain the water column and draw water from deep in the lake towards the surface. There is little diffusion of oxygen from the air bubble to the water. Pumping systems use energy to draw bottom water to the surface through a pipe. Both techniques have the same goal - to break down thermal stratification so that oxygen depleted water from deep in the lake has an opportunity to reach the surface where atmospheric exchange can replenish the oxygen supply.

The main obstacles posed by circulators are:

- High capital cost for equipment and deployment.
- Continual energy costs and maintenance.
- Underpowered circulators will not adequately circulate water allowing the development of anoxia in bottom waters and can result in deterioration of surface conditions as well (NRC 1992, Holdren, et al., 2001).
- Possible increase in turbidity if sediments are disturbed (NRC 1992, Holdren, et al., 2001).
- Potential increase in phosphorus concentration in the upper, sunlit regions of the lake and an associated increase in algal growth (Holdren, et al., 2001).
- Highly variable water quality conditions can be challenging for water treatment (Ministry of Health, 2001).

Due to the energy consumption and high costs associated with running electrical pumps and aerators, several companies have developed solar-powered mixing machines for use in reservoir circulation. Pump Systems, Inc. is one of these companies; they construct and deploy solar-powered pond and lake mixers and agreed to participate in this study.

SECTION 3

SOLAR-POWERED MIXERS

3.1 TECHNICAL OUTLINE

The solar-powered mixers used during this study were four SolarBee® Model SB10000F floating circulators as manufactured by Pump Systems, Inc., Dickinson, North Dakota. These units are self-contained mixing machines specifically designed for circulation of small ponds and lakes. Each SolarBee® mixer is sixteen-feet in diameter and weighs three hundred pounds. The main components include a motor, impeller, solar panels, distribution dish, draft tube, and floats. A product bulletin for these mixers is located in Appendix A.

The SolarBee® mixer operates by capturing solar energy via an array of solar panels, converting the solar energy to electrical energy, and then delivering the electricity to a small motor to drive an impeller assembly. The impeller draws water in an upward direction through a flexible draft tube, which is fastened to the mixer unit and positioned beneath the water surface. Water enters the draft tube laterally through a deflector plate entrance fitting at its end, and then exits the tube through a distribution dish located between the impeller and water surface. A cable-crank unit mounted on the mixer frame can be used to manually adjust the depth of the draft tube. Three stabilizer arms mounted on top of durable high-density polyethylene floats support the mixer structure on the water surface. A cable drawn through the center of the draft tube and tethered to concrete blocks achieves anchoring of the unit.

The power supply to each mixer is generated by three tilted solar panels positioned in a triangular configuration atop the open-air portion of the structure. The angle of the panels promotes self-cleaning by rainfall runoff while the layout aims to maximize exposure to direct sunlight. A self-adjusting oscillating synchronizer controller converts the power from the solar panels into a form needed for the motor to achieve maximum revolutions per minute. A 165-watt direct current brush-style motor powers each mixer in conjunction with an integral gearbox. Each drive unit has an auxiliary connection to receive supplemental D.C. power from a land-based supply for utilization in applications that require continuous operation in the absence of sunlight (this feature was not utilized in this study).

The SolarBee® mixer is designed for simple handling and deployment utilizing a typical crew of no more than two people. The entire mixer structure can be raised out of the water and floated to position by simultaneously lowering all three control arms. This procedure is also used to access the impeller assembly for maintenance and mechanical work. Maintenance of the mixer is minimal and typically consists of removing weeds and debris from the impeller, cleaning the solar panels, and replacing motor brushes as required. The units are constructed of stainless steel and high-density synthetic materials, which provide for durable and long lasting operating equipment.

3.2 PERFORMANCE CHARACTERISTICS

Reservoir-Mixing Benefits

The SolarBee® mixers are designed to provide mixing in lakes through direct and induced flow. The flow generated by each mixer is aimed at improving water quality by enhancing natural biological and chemical processes. The following are characteristics that have been associated with the SolarBee® mixing technology as drawn from SolarBee® product literature:

1. Each mixer is reported to achieve up to 10,000 gallons per minute (gpm) with a low velocity through the draft tube (1 foot per second up the intake hose). SolarBee® estimates that about 3,000 gpm is drawn through the draft tube and about 7,000 gpm is moved through induced currents it creates.

2. Gentle mixing entrains water with higher DO and pH levels on the surface and efficiently mixes them throughout the water column to destratify the lake, or depress the thermocline, and increase DO in the lower waters.

3. Higher DO increases the oxidation of manganese and iron in the water column.

4. Higher DO near the silt layer minimizes the amount of metals re-entering the water column.

5. Small lapping waves associated with the surface renewal have been shown to increase gas (oxygen, nitrogen, and CO_2) transfer rates into and out of the reservoir at rates five to seven times greater than when surface film exists.

6. Near-laminar flow allows for a large sphere of influence on the reservoir (estimated up to 50 acres per high flow unit).

7. The radial surface renewal flow creates both vertical and horizontal mixing throughout the treated zone of the reservoir.

Energy Efficiency

The SolarBee® mixer is energy efficient in two ways: (a) it employs 165-watts of power to drive the motor and move the impeller; and (b) the continuous mixing action of the unit captures and employs more of the solar energy striking the surface area of the reservoir (about 3.5 MW per surface acre). The renewable energy used to drive the motor and impeller is generated by the three 55-watt solar panels.

3.3 DESIGN BASIS AND INSTALLATION

The SolarBee® technical specifications prepared by Pump Systems, Inc. for Chadwick Lake were based on the Town's goal to destratify the reservoir, increasing manganese oxidation to reduce raw water manganese levels entering the filter plant intake. This is achieved by aeration of the hyplomnion to introduce more DO in deep-waters to oxidize inorganic chemicals released from the sediment. Additional design criteria included reduction of blue green algae based on water quality concerns previously expressed by filter plant personnel.

Each SolarBee® is rated for 10,000 gallons per minute of combined direct and induced flow. The mixers operate from sunrise to sunset; during the summer period twelve hours per day of sunlight is typical. Based on the estimated volumes of the hyplomnion and mixed zone in the lake, and a design maximum allowable time to achieve turnover of each, a total of four SolarBee® Model SB10000F solar-powered mixers were specified to provide adequate mixing. To ensure that the lake was affected by the mixing, the machines were positioned equidistant, north to south, along the predominant flow channel of the reservoir (Figure 3-1).

The SolarBee® mixers were installed on Chadwick Lake on April 30, 2003 by field technicians of Pump Systems, Inc. It was important to install the equipment before the onset of thermal stratification, which was expected to occur in June. Prior to anchoring each unit in position, the installers took several depth readings to determine the deepest bottom elevation at each proposed location. The mixers were installed at these deep locations to provide maximum vertical mixing in the lake. Once installed, the draft tube on each was adjusted to provide 2 to 3 feet clearance above the bottom. This was done to prevent sediment suspension during mixing as well as bottom interferences from lateral movements of the machine during wind and wave action. Photographs of the reservoir and mixers are included in Appendix B.

CHAPTER 4
DEMONSTRATION STUDY DESIGN

4.1 WATER QUALITY PARAMETERS AND RATIONALE

The objective of the 2003 field-monitoring program was to evaluate the effectiveness of solar-powered mixing of Chadwick Lake for improving water quality criteria related to public potable supply. The field-monitoring program was designed to evaluate indices of thermal stratification and DO dynamics; Fe and Mn levels; and trophic state parameters (phosphorus, chlorophyll-*a*, and water clarity as measured by Secchi disk transparency); with a particular focus on manganese control. The sampling and analytical parameters were selected to characterize both the upper and lower waters of Chadwick Lake. Discrete samples for chemical analysis were collected at depths of 1, 3, 5 and 7 meters at select locations. Manganese and iron samples were collected at each depth. Total and soluble reactive phosphorus samples were collected at the 1 and 7 meter depths. Chlorophyll-*a* samples were collected at the 1 meter depth.

The reservoir was sampled approximately every two weeks from early May through October 2003. A total of four sites were sampled regularly and several locations were added to the sampling program as the study progressed. The main sampling sites, designated Station 1 through Station 4 (see Figure 3-1), correspond to each of the SolarBee® mixer locations, with sample parameters summarized in Table 4-1. These sites were sampled consistently throughout the study.

Reservoir sampling and analysis at the location of the filter plant intake and locations A through F (between the intake and Station 2), were added to the sampling protocol after the study had commenced (see Figure 4-1). The intake is located approximately 30 feet offshore of the Chadwick Lake dam. This earthen dam is located along the southeastern boundary of the lake. Sample locations A through F are six equidistant points along a transect from the intake to Station 2; three between the intake and Station 1 and three between Station 1 and Station 2. These sampling locations were included to determine if localized effects on water temperature and related water quality parameters were evident near the SolarBee® mixers.

Analytical Methods

The following analytical methods were used by the Town water treatment plant laboratory and the contract laboratory, Severn Trent Laboratories of Newburgh, for sample analysis during this study.

Metals. Manganese and iron samples collected from the lake were analyzed by the treatment plant laboratory using a HACH® PAN and FerroVer reagent methods, respectively. The PAN method is a highly sensitive and rapid procedure for detecting low levels of manganese. An ascorbic acid is used initially to reduce all oxidized forms of manganese to Mn^{2+}. An alkaline-cyanide reagent is added to mask any potential interferences. PAN indicator is then added to combine with the Mn^{2+} to form an orange-colored complex. Test results are measured at 560 nm. The FerroVer iron reagent converts all soluble iron and most insoluble forms of iron in the sample to soluble ferrous iron. The ferrous iron reacts with 1,10 phenanthroline indicator in the reagent to form an orange color in proportion to the iron concentration. Test results are measured in 510 nm.

Manganese and iron samples collected from the lake were analyzed by the contract laboratory using SM 18 3120B Inductively Coupled Plasma (ICP) methods. A sample aerosol is generated and injected into a plasma stream. The result is an almost complete disassociation of molecules and significant reduction in chemical interference is achieved. Ionization of a high percentage of atoms produces ionic emission spectra. This results in low detection limits for many elements. The light emitted from the ICP is focused onto either a monochrometer or a polychrometer to determine metal concentration based on wavelength. Filtered samples were obtained using a 0.45 micron filtering material.

Phosphorus. Total phosphorus (TP) and soluble reactive phosphorus (SRP) were analyzed using EPA 365.3 and SM 18 45000PE procedures, respectively. Total phosphorus is all of the phosphorus in an unfiltered sample that reacts with the chemical reagent molybate, after the sample has been digested with ascorbic acid to break down organic material. TP includes dissolved inorganic P, P in organic material, and P associated with particulate material. SRP is all the P in a filtered sample that reacts with ammonium molybate and potassium antimonyl tartrate without digestion. SRP includes dissolved inorganic P, some P associated with small particles, and some organic P.

Chlorophyll-*a*. The concentration of the plant pigment chlorophyll-*a* was determined using SM 18 10200H procedures. This analysis determines the concentration of chlorophyll-*a* from water samples that have been centrifuged, to concentrate algal mass, ground in a tissue grinder, and filtered. Pigments are extracted from the sample using aqueous acetone and the optical absorbance can then be correlated to a final concentration of chlorophyll-*a* in the sample.

TABLE 4-1

Summary of Field Monitoring Program
Summer 2003

Parameter	Locations	Depths
Field parameters (Secchi disk and Hydrolab profile of DO, temperature, pH, specific conductance)	All 4 stations	0.5 m profiles
Iron and Manganese	Station 1	1,3,5,7 m
Total Phosphorus (TP)	Station 1	1 m, 7 m
Soluble Reactive Phosphorus (SRP)	Station 1	1 m, 7 m
Chlorophyll-*a*	Station 1	1 m

4.2 RESERVOIR SAMPLING PROCEDURES

A multi-probe field instrument manufactured by Hydrolab® was used to measure and record water temperature, dissolved oxygen (DO), pH, and specific conductance at the sampling locations (Figure 4-1). The Hydrolab® Surveyor 3 system used in this investigation has multiple probes attached to 25-meters of cable and is able to measure at 0.5-meter depth intervals through the water column. The Hydrolab® was calibrated before each use. Water clarity was measured using a standard limnological Secchi disk at all sites.

Water samples were collected using a Van Dorn bottle on a calibrated line at designated locations. Samples were collected at discrete depths of 1, 3, 5 and 7 meters. Iron and manganese were analyzed at each sample depth. Total phosphorus (TP) and soluble reactive phosphorus (SRP) were analyzed at the 1 and 7 meter depths. Chlorophyll-*a* was analyzed only at the 1 meter depth. Unfiltered samples were added to bottles containing the appropriate preservative. Samples for soluble reactive phosphorus (SRP) and soluble metals were filtered in the water treatment laboratory within two hours of sample collection. The appropriate preservatives (nitric acid for metals, sulfuric acid for phosphorus) were added after filtration. Chain-of-custody procedures were observed and samples were kept on ice until delivered to Severn Trent Laboratory (STL) in Newburgh, NY for analysis; samples were delivered to the laboratory within 24-hours of collection.

4.3 TREATMENT PLANT PERFORMANCE TRACKING

To evaluate the effects of the solar-powered mixers on treatment plant performance, a daily plant-monitoring program was established at the beginning of the study, which coincided with the field monitoring at the reservoir. The goal of this program was to determine the effects, if any, the mixers had on the raw water entering the plant and the finished water produced, by tracking key water quality and treatment process parameters.

The plant-monitoring program was designed with two components: a daily sampling protocol at various locations in the plant for specified constituents; and daily record keeping of performance criteria relating to the treatment process. The sampling program included analysis for water quality parameters such as turbidity, color, manganese, iron, pH, and chlorine residual. The plant performance tracking included recording flows for high-lift pumping, backwash volumes; coagulant usage; sludge production; chemical (peroxidant) usage; sodium hypochlorite usage (disinfection); and plant power consumption. Outlines of the daily sampling and performance monitoring programs are presented in Tables 4-2 and 4-3, respectively.

Sampling and analysis for the daily plant monitoring program was performed by Town personnel at the water treatment plant. Raw water samples were taken from the raw water tap discharge, located in the plant laboratory, and the influent gate house, located directly downstream of the intake. The raw water tap is a connection to the supply line downstream of the gate house. Samples of filtered water were taken from the effluent trough located between the filters and the clear well. Finished water samples were taken from the domestic water tap; a connection to the distribution line in that discharges to the plant laboratory.

TABLE 4-2

Summary of Chadwick Lake Filter Plant
Daily Sampling Program
Summer 2003

Parameter	Locations
Turbidity	Raw, settled, filtered, finished
Color	Raw, finished
Manganese	Raw, influent, settled, filtered, finished
Iron	Raw, finished
pH	Raw, settled, finished
Chlorine Residual	Finished

TABLE 4-3

Summary of Chadwick Lake Filter Plant
Daily Performance Monitoring Program
Summer 2003

Criteria	Application
Pump Flow	Finished water production
Backwash Volume	Filter performance
Alum Usage	Coagulation efficiency
Sludge Production	Coagulation efficiency/sludge disposal
Chemical Usage (Cl_2, ClO_2, THMR, $KMnO_4$)	Oxidants for manganese treatment
Sodium Hypochlorite	Disinfection
Power Consumption	Energy efficiency

CHAPTER 5
DEMONSTRATION STUDY RESULTS

5.1 WATER QUALITY ANALYSIS AND RESULTS

The following section describes water quality and thermal conditions in Chadwick Lake during the field monitoring period of May 1, 2003 through October 30, 2003.

Water temperature

Chadwick Lake Reservoir developed stable thermal stratification during the study period. Contour plots of lake temperature at the four stations and the intake location are shown in Figures 5-1 and 5-2. These plots demonstrate the development and breakdown of thermal stratification, the increase in temperature of the upper waters through early August, and the subsequent loss of heat until the end of sampling in October.

Temperature regimes at the four lake stations, the intake location, and monitoring points A through F did not differ substantially (see Figure 5-3). Stratification at all sites began in early May and persisted through late September. The reservoir developed thermal layers, with an upper layer of warmer water (epilimnion) and a lower layer of cooler water (hypolimnion) separated by a transition zone of rapid temperature change (metalimnion). The temperature of the surface waters ranged from 11ºC to 28 ºC over the monitoring period, with the warmest temperatures occurring in the end of July and early August. Warmer water extended deeper within the reservoir as the summer progressed, although the deepest water remained close to 15°C until complete mixing was achieved in late September.

Dissolved Oxygen

Dissolved oxygen (DO) contour plots as a function of water depth and time indicate progressive oxygen depletion over the 2003 monitoring period in the deeper areas of the lake (Figures 5-4 and 5-5). DO concentrations were essentially identical for the four stations and at the water intake location. These data, coupled with the temperature data, indicate that the lowest waters of the reservoir remained isolated from the upper waters, and from atmospheric exchange, throughout the 2003 summer period.

DO was high at the beginning of the summer period, and remained close to saturation in the upper waters. As the season progressed, rapid DO depletion of the lower waters was evident. The rate of oxygen depletion at the 5.5 m and 7.0 m depth over the monitoring period is displayed in Figure 5-6 The anoxic environment at the sediment surface resulted in release of soluble iron, manganese and phosphorus by late May. Anoxic conditions persisted in the lower waters until fall turnover, which occurred in late

September. Dissolved oxygen levels at the four lake stations, the intake location, and monitoring points A through F, shown in Figure 5-3 (3m and 6m depths), do not indicate any localized effects on dissolved oxygen resulting from the mixers.

Trophic State Parameters

Lakes may be classified according to their trophic state, or level of productivity. High levels of nutrients and an abundance of plants and algae characterize eutrophic lakes. Oligotrophic lakes have low nutrient concentrations and low productivity. Mesotrophic lakes have moderate levels of nutrients and plants and are classified between eutrophic and oligotrophic lakes. While trophic state is a continuum, researchers and lake managers have adopted levels of trophic state indicator parameters to demarcate oligotrophic, mesotrophic and eutrophic systems. These parameters include: phosphorus (limiting nutrient for algal growth in most inland lakes in the northeast), chlorophyll-*a* (plant pigment used to indicate algal abundance), Secchi disk transparency (a standard measure of water clarity), and oxygen content of the deeper waters.

Demarcation of trophic state boundaries in lakes is not precise. Lakes are continually evolving towards a state of eutrophy. Often times lakes can exhibit characteristics of different trophic states. This is particularly common when data is limited. The unusual water quality characteristics of Chadwick lake in 2003, low phosphorus and moderate chlorophyll-a, indicate that Chadwick lake fits the description of both a mesotrophic lake and eutrophic lake. Results of the 2003-monitoring program suggest that Chadwick Lake falls in the intermediate eutrophic-mesotrophic level of productivity as summarized in Table 5-1. Additional discussion of the phosphorus, Secchi disk, and chlorophyll-*a* results is presented in the following sections.

Table 5-1

Trophic State Indicator Parameters

	Oligotrophic	**Mesotrophic**	**Eutrophic**	**Chadwick Lake (2003)**
Summer average total phosphorus, upper waters (µg/l)	<10	10-35	35 -100	**< 9**
Summer average chlorophyll-a, upper waters (µg/l)	<2.5	2.5 - 8	8 - 25	**12**
Peak chlorophyll-a (µg/l)	<8	8-25	25-75	**32**
Average Secchi disk transparency, m	>6	6-3	3-1.5	**1.6**
Minimum Secchi disk transparency, meters	>3	3-1.5	1.5-0.7	**1.0**
Dissolved oxygen in lower waters (% saturation)	80 - 100	10-80	Less than 10	**Zero**

Phosphorus

Total phosphorus (TP) and soluble reactive phosphorus (SRP) were measured at Station 1 in both the upper waters (1 m below the water surface) and lower waters (7 m below the water surface) of Chadwick Lake during the 2003-monitoring program. TP is operationally defined as all the phosphorus (P) in an unfiltered sample, after the sample has been digested with acid to break down organic material. TP includes dissolved inorganic P, P in organic material, and P associated with particulate material. Soluble reactive phosphorus (SRP) constitutes all the P in a filtered sample without digestion. SRP includes dissolved inorganic P, some P associated with small particles, and some organic P. Most investigators consider SRP to be nearly 100% biologically available.

In lakes and reservoirs that are limited by phosphorus, TP is a useful index of productivity, or trophic state. Low concentrations (less than approximately 10 - 15 µg/l) are typically measured in oligotrophic (low productivity) water bodies; moderate concentrations (between 15 – 25 µg/l) are considered typical of mesotrophic conditions; and concentrations in excess of 30 µg/l are considered indicators of eutrophic water bodies.

Results indicate that consistently low concentrations of TP and SRP were detected in the 1 m depth sample during the 2003-monitoring program. Results were reported less than the limit of detection (9 µg/l) as summarized in Table 5-2. The surface water phosphorus results were not consistent with the occasional high measurements of chlorophyll–*a*. Discussions with the contract laboratory, Severn Trent Laboratories, did not identify any factors that might have contributed to the anomalous results. SRP concentrations are typically low in surface waters in a phosphorus-limited system, as this nutrient is immediately incorporated into algal biomass. However, if the digestion procedure for the TP samples was complete, TP concentrations should have increased as algal abundance increased.

Both TP and SRP were present at detectable concentrations in the sample collected at 7 m from about mid-July to late September. Concentrations in the deeper water were generally high (TP mean 204 µg/L, SRP mean 273 µg/L) from July to the end of September. The high concentration in the lower waters reflects two inter-related mechanisms: decomposition of organic material such as algal cells in the lower waters, and phosphorus release from mineral complexes as the bottom sediments become anoxic. After the lake mixed from late September turnover, one would expect the concentrations in the upper waters of the lake to show an increase in concentration as water high in P was mixed with low P surface waters. This did not occur (note that the October TP at 1 m continued to be reported as less than 9 µg/l in Table 5-2).

Three other data anomalies were noted with regards to phosphorus concentrations in the Chadwick Lake data set. First, on September 24, 2003 SRP was reported at four times greater than TP at the 7 m depth.

This is an error; SRP is operationally defined as a fraction of TP. It was concluded that the SRP sample bottle was contaminated at some stage of the sampling and analytical process. Second, on July 11, 2003, the TP at 7 m was 0.149 mg/L while SRP was at undetectable levels (<0.009 mg/l). This is inconsistent with the other deep-water samples, where SRP was a substantial fraction of TP during the period of stratification and anoxia.

The third anomaly occurred on September 11, 2003 when both TP and SRP were recorded at as non-detectable (< 9µg/L) at the 7 m depth, yet the previous and subsequent samples were high in both fractions of phosphorus. It is highly unlikely P concentrations could decrease to un-detectable levels then increase to the levels observed in the samples. A discussion with the laboratory verified the results of the water samples as well as spiked samples. A significant wind induced mixing event could have resulted in temporary destratification and thus P release to the upper waters, but this would have likely resulted in detectable P concentration throughout the water column which did not occur and in addition the temperature and DO profiles do not indicate that such a mixing event occurred.

Table 5-2

Station 1
Total Phosphorus (TP) &
Soluble Reactive Phosphorus (SRP)

	Depth	2-May	15-May	29-May	17-Jun	27-Jun	11-Jul	29-Jul	14-Aug	26-Aug	11-Sep	24-Sep	8-Oct	30-Oct
TP (µg/L)	1m	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	7m	ND	ND	ND	ND	ND	149	340	210	210	ND	110	ND	ND
SRP (µg/L)	1m	ND	N/A	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	7m	ND	N/A	ND	ND	ND	ND	260	190	170	ND	470*	ND	ND

ND= non-detect. N/A= data not available
Note: SRP at 7 m on September 24, 2003 is likely biased high

Secchi Disk Transparency and Chlorophyll-a

An index of light penetration, Secchi disk transparency, was monitored throughout the 2003 field-sampling program. The data demonstrate a gradual decline in transparency of the reservoir as the monitoring season progressed with stabilization of readings after mid-August (Figure 5-7).

Secchi disk measurements indicate the presence of particulate material in the water column and are highly correlated with algal abundance in most lakes and ponds. The plant pigment chlorophyll-*a* is also used to indicate algal abundance. In the Chadwick Lake results, Secchi disk transparency was not closely related to the concentration of chlorophyll-*a* during the 2003 monitoring period. For example, the highest concentrations of chlorophyll-*a* were measured in mid to late May; these measurements correspond with the some of the deepest Secchi disk measurements recorded (indicating clear water) as shown in Figure 5-8. It is likely that the brown tinge to the lake water, imparted by tannic and humic acids, served to decouple the relationship between water clarity and algal abundance.

Specific Conductance and pH

The pH of the reservoir varied substantially both with depth and with time (Figure 5-9). This could be due to algal blooms, which may cause temporal variation at the surface. Algal blooms will typically increase pH as algal cells draw carbon dioxide from the water during photosynthesis.

The specific conductance data are consistent with a moderately buffered system. There was an accumulation of dissolved salts in the deepest areas of the lake in late summer that resulted in an increase in specific conductance during the 2003 monitoring period (Figure 5-10). The accumulation of dissolved mineral salts in the deeper waters is likely a result isolation of deeper waters of the reservoir during periods of thermal stratification.

Manganese

In-lake Manganese. Manganese concentrations in the lake were elevated during the summer in the lower waters, following the same temporal pattern of anoxia in 2003 (Figure 5-11). Manganese was first detected in the lower waters as oxygen levels fell close to zero in this region in mid to late May. Concentrations in the lower waters increased through the summer as the chemical reduction process of sediments released manganese. The highest manganese concentrations were measured on September 24, 2003, when filtered samples collected at 7 m contained 3.7 mg/L and unfiltered samples contained 5.0 mg/L (Tables 5-3 & 5-4). A split sample was taken at the 7 m depth at Station 1 on May 15, 2003 and was sent to STL Laboratories for comparative analysis. The result of the STL split analysis was a manganese concentration of 0.83 mg/L versus 0.26 mg/L for the sample analyzed by treatment plant laboratory. Variation in these sample results is likely subject to laboratory techniques and equipment.

Manganese was also detected in surface water samples during the summer, indicating that some manganese that was released to the lower waters reached high into the water column. This was likely due to both diffusion and entrainment. Concentrations near the surface were variable, but generally less than 0.5 mg/L. Manganese concentrations decreased rapidly after fall turnover, but were still at detectable levels into late October.

A similar temporal pattern was observed between manganese concentrations at the intake and Station 1 locations (Figure 5-11). Notable differences between the two locations are that elevated manganese concentrations appeared to occur earlier at Station 1 and the intake location had slightly higher concentrations near the surface than Station 1 did. A manganese concentration of 23 mg/L was recorded at a depth of 7 meters on September 11, 2003 at the intake location. This data point is abnormally high compared to other samples and was judged to be an anomalous outlier that was not used during data interpretation.

Examination of filtered and unfiltered samples indicates that a high proportion of the manganese measured both at the intake and Station 1 during the 2003 monitoring period was in the soluble form, thus eliminating the possibility that elevated manganese at the intake was due to sediment disturbance and entrainment of particulate materials. Some filtered samples were noted to have higher concentrations than corresponding unfiltered samples. Since, by definition, the filtered sample is the soluble portion of the unfiltered sample this should not occur. The higher filtered concentrations appears to have occurred frequently in the 1 and 3 meter samples where concentrations were generally low. This could indicate that there may be either detection limit issues at lower concentrations or filtering of samples was incomplete prior to analysis.

Table 5-3

Station 1
Filtered & Unfiltered Manganese

Sample	Depth	2-May	15-May	29-May	17-Jun	27-Jun	11-Jul	29-Jul	14-Aug	26-Aug	11-Sep	24-Sep	8-Oct	30-Oct
Filtered Mn (mg/L)	1	NT	0.038	0.30	NT	NT	0.08	0.63	0.25	0.40	0.23	0.35	NT	0.03
	3	NT	0.037	0.09	NT	NT	0.08	0.24	0.15	0.30	0.13	0.23	NT	0.03
	5	NT	0.039	0.14	NT	NT	0.50	0.23	0.90	2.97	0.13	0.20	NT	0.03
	7	NT	0.255	1.00	NT	NT	1.92	1.50	1.85	2.70	0.58	3.72	NT	0.03
Unfiltered Mn (mg/L)	1	NT	0.16	0.35	0.03	NT	NT	0.77	0.21	0.10	0.12	0.24	0.08	0.07
	3	NT	0.17	0.11	0.03	NT	NT	0.16	1.65	0.30	0.11	0.24	0.08	0.07
	5	NT	0.13	0.19	0.04	NT	NT	0.63	2.10	3.71	0.23	0.50	0.09	0.07
	7	NT	1.06	1.50	1.51	NT	NT	1.05	3.50	3.35	4.43	5.00	0.17	0.07

NT= Not Tested

Table 5-4

Filter Plant Intake (in-lake)
Filtered & Unfiltered Manganese

Sample	Depth	17-Jun	27-Jun	11-Jul	29-Jul	14-Aug	26-Aug	11-Sep	24-Sep	8-Oct	30-Oct
Filtered Mn (mg/L)	1	NT	NT	0.14	0.17	0.20	0.20	1.36	0.63	NT	0.14
	3	NT	NT	0.12	0.13	0.10	0.37	0.84	0.38	NT	0.18
	5	NT	NT	0.08	0.66	0.06	2.81	1.10	0.67	NT	0.15
	7	NT	NT	0.20	1.40	0.10	2.97	23.00	3.48	NT	0.24
Unfiltered Mn (mg/L)	1	0.10	NT	0.06	0.07	0.20	0.16	1.12	0.19	0.10	0.08
	3	0.22	NT	0.09	0.11	0.15	0.24	0.71	0.24	0.07	0.07
	5	0.31	NT	0.78	2.35	2.65	3.60	1.61	0.96	0.09	0.09
	7	1.42	NT	2.96	2.38	2.10	3.72	23.25*	3.75	0.40	0.10

NT= Not Tested

*Judged to be an anomalous data point, thus not used in data analysis.

Groundwater Manganese. Groundwater samples were taken from two nearby residential wells and analyzed for manganese by the contracted laboratory. The intent of this procedure was to determine whether local levels of manganese in groundwater might be contributing to in-lake manganese levels. As shown in Table 5-5, one well tested above the laboratory detection limits and although almost all of the manganese is in dissolved form, the results are not significant enough to correlate to elevated in-lake manganese levels.

Table 5-5

Residential Well Sampling
Filtered & Unfiltered Manganese

Sample	Well ID	Result
Filtered Mn (µg/L)	1	15.7
	2	ND
Unfiltered Mn (µg/L)	1	15.9
	2	ND

ND= Not Detected

Iron. Iron concentrations in water are typically controlled by the same mechanisms as manganese. Iron is released from sediments as the DO in the overlying waters decrease to zero. As a result, iron concentrations in Chadwick Lake during the 2003 monitoring period followed the same general temporal and spatial patterns as manganese (Figure 5-12). Iron was first detected in the lower waters as DO approached zero in the lower waters in May 2003. Concentrations in the lower waters increased through the summer as the chemical reduction of sediments released iron. The highest iron concentrations were measured on August 14, 2003 when samples collected at 7 m contained 3.9 mg/L (Table 5-6).

Table 5-6

Station 1
Iron Concentrations (mg/l)

Depth	2-May	15-May	29-May	17-Jun	27-Jun	11-Jul	29-Jul	14-Aug	26-Aug	11-Sep	24-Sep	8-Oct	30-Oct
1	NT	0.04	NT	0.14	NT	0.02	0.05	0.11	0.34	0.29	0	0.05	0.29
3	NT	0.13	NT	0.17	NT	0.02	0.22	0.17	0.27	0.06	0.1	0.05	0.21
5	NT	0.09	NT	0.15	NT	0	0.2	0.16	0.71	0.2	0.03	0.05	0.14
7	NT	0.64	NT	0.98	NT	0.82	3.7	3.94	*	1.3	2.46	0.07	0.18

NT= Not Tested
* Out of range

5.2 TREATMENT PLANT PERFORMANCE

During the 2003 study period plant performance monitoring was limited. The plant temporarily ceased operations on June 19, 2003 when raw water entering the plant reached manganese levels in excess of 2 mg/L. The plant continued to flow raw water to waste after June 19th and subsequent plant raw water manganese concentrations during the study period ranged between 0.5 and 3.5 mg/L. For a majority of the time, levels were above 1.0 mg/L. Manganese levels decreased to below 0.5 mg/L in early October when the reservoir turned over, however, the plant remained offline for the remainder of the year as personnel continued to work on repairs and maintenance of process equipment.

Manganese levels above 0.5 mg/L are difficult and costly for the plant to treat as shown in previous manganese treatment evaluations and demonstration studies completed by Stearns & Wheler. Currently, the plant does not have technology to treat manganese levels in excess of 0.5 to 0.8 mg/L and achieve a finished water goal of 0.05 mg/L. To supply water with acceptable manganese levels, the plant switched over to the Delaware Aqueduct tap as its' primary source of water supply for the Town during this period of elevated manganese levels.

Given that the treatment plant was only operating for one month during the study, the operational data that were collected, including flows for high-lift pumping, backwash volumes; coagulant usage; sludge production; chemical usage; and sodium hypochlorite usage were not extensive enough to correlate to the use of the SolarBee® mixers. Therefore, they have not been incorporated into this report. The plant-sampling program did continue through the duration of the study, although only for turbidity, color, manganese, iron, and pH related to the raw water supply, of which only the manganese data were used for comparison to available historical plant records.

Average monthly raw water manganese concentrations (sampled from the gatehouse), were compiled by plant personnel from records taken during 2001, 2002, and 2003 (Figure 5-13). In-lake levels taken at the intake depth on specific dates during the study period were superimposed on this chart for comparison. From this figure the annual trends for plant influent manganese appear somewhat consistent, however, there is clearly no correlation between this data and the in-lake concentrations. Based on this data observation, a possible cause of the discrepancy in manganese concentrations may be due to a mechanical problem with the intake structure in which water is entering the influent piping from manganese rich deeper waters.

5.3 INTAKE INSPECTION

The initial sampling results showed that the manganese level in the plant influent was significantly higher than in the lake at the intake screen or at Station 1 (3 meter depth). This prompted the Town to conduct an underwater inspection of the intake structure to see if there was leakage into the intake pipe from the lower depths. A profile of the intake screen and pipe, from the construction documents, is shown as Figure 2-4.

Hunt Underwater Specialties conducted an underwater inspection on October 21, 2003. Based on the review of their inspection report and videotape, the following were noted:

1. The 20-inch diameter intake pipe was covered with sediment. The diver uncovered the pipe but did not identify cracks or defects in the pipe.

2. There was a slight air leak in the 2-inch diameter air pipe, which only occurred at the initial activation of the air system.

3. The intake screen, located about 8 feet below the water level, is a “T-screen” style with flat ends. At the start of the inspection, the top of the screen was heavily covered with debris and sediment while the bottom appeared to be less covered (with sediment).

4. The diver used a brush to remove the sediment from the screen and air was injected through the 2-inch air system. The video, however, did not show a “burst” of air, but more of a steady stream of air that flowed from the top of the screen, at relatively low velocities.

The T-type screen is more typically utilized in rivers where channel velocities provide some cleaning effect. A drum-type screen is more often used in lakes and reservoirs. The drum type has a cap on top and draws horizontally from the sides of the screen. With the debris on the top of the screen, the plant may be drawing water primarily from beneath the T-screen. Higher inlet velocities may be drawing water from deeper waters which contain higher manganese levels.In early spring 2004, the Town should retain a diver to clean the intake screen again. At this time, the plant should operate at maximum flow and the diver should perform dye testing to determine the “radius of influence” of the T-screen inlet (particularly from below). Dye testing should also be conducted along the inlet piping to determine if water is being drawn in at lower depths through cracks. In conjunction with this work, the Town should also improve the intake air system, to provide for a “burst” of air for cleaning (as opposed to the current steady stream of air). Depending on the results of the investigations (along with manganese levels in summer of 2004), the Town could consider replacing the T-screen with a drum-type screen. This could include a new piping system that would allow the intake to draw-off the reservoir at multiple depths according to different seasons. In addition, a drain pipe would be installed at the bottom of the reservoir to allow accumulated sediments to be drawn-off in the vicinity of the intake.

5.4 ENERGY & ECONOMIC SUMMARY

Energy consumption and plant production for the 2003 study period are shown in Table 5-7. The energy data was taken from monthly electric billing statements and electric consumption per million gallons of water produced for May and June 2003 was 19,334 kWh/MGD, as compared to 44,283kWh/MGD for the prior period of January 2002 through April 2003. Average daily plant production for the study period was 1.19 MGD as compared to 1.39 MGD in the prior period. The existing intake aeration system was not in use at any time during the study.

The decrease in energy consumption per million gallons produced is primarily due to the limited production of the plant during the study period. The plant was not in service during the remainder of the study (July through December 2003) due to elevated levels of manganese in the raw water. During this period the plant discharged raw water to waste, by gravity, and water was supplied solely by the Delaware Aqueduct tap. Energy consumed by the Delaware Aqueduct tap site likely increased during this period, however, this data was not provided nor was it included in the scope of this study. Because of limited plant operation during the study period, conclusions could not be directly drawn as to the benefits of mixers on plant energy use.

Table 5-7

2003 Monthly Electric Consumption During Study Chadwick Lake Water Treatment Plant

Month	Production (MGD)	KW Demand	KW Hours	KW hrs/mgd[1]
May	0.94	114	18,600	19,787
June	1.43	120	27,000	18,881
July	0	24	4,800	-
August	0	12	4,200	-
September	0	12	4,200	-
October	0	18	6,000	-
November	0	18	6,000	-
December	0	12	5,400	-
Period Average	**1.19**	**117**	**22,800**	**19,334**

(1) Not estimated for periods without continuous operation.

The economic benefits of the SolarBee® mixing technology (when effectively used) are apparent and easily quantified. Table 5-8 presents our opinion of 20-year present value costs of a properly sized reservoir diffused aeration system to solar-powered mixing in Chadwick Lake. While the Town currently operates a 25 HP aerator, with ineffective results, the analysis in Table 5-8 assumes a new larger compressor array of diffusers would be required.

The opinions of cost in Table 5-8 indicate that the solar-powered mixing system is more cost effective and less energy intensive than a comparable new aeration system. The existing aeration system employed by the Town is ineffective in controlling manganese and incurs an annual operating cost of about $12,000 per year (±150,000 KWhrs per year). This system will require significant expansion in order to more effectively control manganese.

The economic benefits of solar-powered mixing are fairly straightforward to measure. There are no annual power costs as compared to a similarly sized aeration system. The concentration of manganese in the raw water dictates the subsequent treatment required to remove it. Costs associated with subsequent treatment to reduce manganese to acceptable levels can be estimated through chemical costs, power costs, manufacturer equipment quotes, and engineering estimates. As presented in Table 5-8, the energy benefits of solar-mixing technology for the Town of Newburgh are a reduction of an estimated 115,000 kWh/year (or about $9,000/year) for a properly designed aeration system, or ±150,000 kWh/year ($12,000/year) for the current aeration system (operated year-round) by the Town. In addition, reduced energy and costs of subsequent treatments will be realized, such as reduction in chemical usage and avoidance of capital and operational costs associated with more advanced treatment methods including ozonation and greensand filtration.

Ozonation and greensand filtration are both effective technologies for controlling manganese levels in raw water entering a treatment facility, however, both require relatively high capital and operational costs. Ozone is a powerful oxidant formed by the high voltage activation of oxygen. An ozonation facility could be incorporated into the existing plant design without significant alterations to the process layout. However, ozone generation is associated with high power consumption, and from an operational standpoint this is reflected in power costs. As shown in Table 5-8, a savings of $11,000/year in power costs and $6,000/year in maintenance costs are realized utilizing solar-mixing technology compared to an ozonation facility.

Greensand is a naturally occurring ion exchange resin. Manganese is preoxidized using chlorine (or another oxidizing agent), and then as solids precipitate they are collected on the greensand. Due to space and hydraulic requirements, a greensand system at the current plant site would be constructed as a separate facility and require additional pumping for process flow and backwashing. A greensand filtration system would be associated with high power consumption and increased power costs. Solar-mixing offers a savings of $9,000/year in terms of power costs and $8,000/year for maintenance costs versus greensand filtration.

TABLE 5-8

Opinion of Present Value Cost for Manganese Treatment Alternatives

Aeration		**Comments**
HP of aeration	40	Based on 30 cfm/10^6 ft^2 per USEPA *Evaluation of Aeration/Circulation on a Lake Restoration Technique*, 1981
Run time (hours/day)	24	
Duration (day/year)	180	Warm water periods
KWh/year	115,000 at 90% compressor efficiency	
Unit power cost ($/kWh)	$0.08	Per Town of Newburgh
Annual power cost	$9,000	
Annual maintenance cost	$1,000	One manufacturer's representative visit with minimal parts.
System installation cost	$300,000	Based on Stearns & Wheler's January 2001 Manganese Treatment Evaluation for the Town of Newburgh, updated to February 2004 costs, with allowance for contingencies and engineering administration costs.
20-year present value	$425,000	5% rate of return; 5% inflation
Solar-Powered Mixing		**Comments**
Number of mixers	4	One per 50 surface-acres.
Run time (hours/day)	See comment	Will vary based on available sunlight.
Duration (day/year)	180	Warm water periods.
Annual power cost	$0.00	
Annual maintenance cost	$1,000	One manufacturer's representative visit per year with minimal parts.
Installed system cost	$110,000	Based on manufacturer's September 20, 2002 quote for delivery and installation and startup.
20-year present value	$125,000	5% rate of return; 5% inflation
Ozonation		**Comments**
Capacity	3.2 MGD	Existing peak capacity of treatment plant.
Run time (hours/day)	24	
Duration (day/year)	180	Warm water periods.
Annual power cost	$11,000	Based on average production of 2 MGD with Town of Newburgh electric rate ($0.08/kWh).
Annual maintenance cost	$6,000	Based on general maintenance requirements.
Installed system cost	$1,250,000	Includes costs for mobilization, construction, engineering, and contingencies.
20-year present value	$1,450,000	5% rate of return; 5% inflation

TABLE 5-8 (cont.)

Green Sand Filtration		**Comments**
Capacity	3.2 MGD	Existing peak capacity of treatment plant.
Run time (hours/day)	24	
Duration (day/year)	180	Warm water periods.
Annual power cost	$15,000	Based on average production of 2 MGD with Town of Newburgh electric rate ($0.08/kWh). Includes power for pumping, heating and electrical in greensand filtration plant.
Annual maintenance cost	$10,000	Includes costs for media replacement, chemicals, pump, and general maintenance.
Installed system cost	$3,150,000	Includes costs for mobilization, construction, engineering, and contingencies.
20-year present value	$3,500,000	5% rate of return; 5% inflation

5.5 SUMMARY OF REMAINING DATA GAPS

Temperature and water quality data collected during 2003 indicate that the solar-powered mixers were not effective in preventing development of thermal stratification in the reservoir. Without historical reservoir data, however, it is difficult to ascertain whether the mixers had any effect on the duration of stratification or the reservoir’s overall heat budget.

An anomalous feature of the 2003 water quality data was the apparent lack of correlation between phosphorus concentrations and algal abundance. Some of the problems were clearly related to laboratory data quality. However, the larger issue remains the source of the sediment oxygen demand that depletes the lower waters and creates conditions of elevated manganese in the raw water. One working hypothesis is that sediment oxygen demand is the direct result of algal decomposition. However, the 2003 data were not completely consistent with this conceptual model, as chlorophyll-*a* concentrations indicated a relatively low standing crop of algal biomass.

An area for further investigation is the potential role of dissolved and particulate organic carbon, entering the reservoir through its large watershed and extensive wetland complexes, in contributing to oxygen depletion of the lower waters. Finally, the potential role of groundwater in causing or contributing to the elevated concentrations of manganese has not been fully explored. Additional groundwater testing may help identify the significance of this potential source.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

1. Chadwick Lake is a borderline eutrophic-mesotrophic reservoir with moderate levels of nutrients and plants. The lake is classified as dimictic, in that there are two periods of complete mixing each year (spring and fall), separated by periods of thermal stratification (summer and winter). The fact that Chadwick Lake develops thermal stratification has significant water quality implications. When the thermal gradient between the upper and lower waters develops, a sufficient density barrier to wind-induced mixing is created and the deeper waters become isolated from the atmosphere. While this occurs, the dissolved oxygen is consumed in this deep layer of the lake from decomposition of organic material and is not replenished by atmospheric exchange.

2. Installation of the SolarBee® solar-powered reservoir mixers was intended to prevent the development of thermal stratification in Chadwick Lake, and thus, interrupt the process of oxygen depletion of the lower waters and its associated release of soluble manganese. The mixers were not effective in maintaining fully mixed conditions throughout the water column in the 2003 study period. The lower waters of Chadwick Lake remained isolated and the supply of dissolved oxygen was rapidly depleted by the sediment oxygen demand Anoxia was present for the entire summer and extended from the bottom of the reservoir to about three meters from the surface. In addition, localized or lake-wide effects of the solar mixers was not shown in figures created from data collected during the study.

3. Anoxic conditions at the sediment-water interface results in manganese, iron, and phosphorus release into the water column. As a result, manganese levels in the bottom waters, and at times surface waters (to a lesser degree), increased to concentrations problematic for treatment in the Town drinking water supply. Since historical data are very limited, it is not possible to determine to what extent, if any, the mixers altered stratification or dissolved oxygen concentrations compared to typical conditions. However, even if the thermal and dissolved oxygen resources of Chadwick Lake were altered by the mixers, their deployment did not result in water quality conditions meeting the needs of the Town. To successfully destratify Chadwick Lake either additional solar mixers or a different technological approach would be required.

4. The intake screen is a “T-screen” style with flat ends. Underwater inspection of the intake screen and piping on October 21, 2003 did not reveal any cracks or defects in the structures. Debris and sediment was removed from the screen by the diver at the time of inspection. During the

inspection, the 2-inch air system for intake cleaning was activated and videotape observations revealed that the air was being released in a steady stream instead of a “burst”; the latter being more desirable for cleaning purposes.

5. Testimony from Town personnel has indicated that the algae blooms during the 2003 season have not been as severe or prolonged as in previous years. Although the Town has not needed to use copper sulfate for the past two years to control algae, these observations of reduced algae growth during the 2003 season may be related to the use of the SolarBee® mixers. The field data collected during the study period does not conclusively support these observations.

6. The water treatment plant is one of two sources of draw-off from Chadwick Lake, the other being the spillway to Quassaic Creek. Because the treatment plant was not in operation for a majority of the study period, it is difficult to determine the impact this reduced draw-off (typically up to 2.8 MGD) may have had on lake stratification characteristics.

6.2 RECOMMENDATIONS

1. Continue to use SolarBee® mixers in 2004, including addition two more units, in order to determine if additional mixers will provide the required mixing energy to destratify the reservoir or depress the thermal gradient. Pump Systems, Inc. has offered to provide the revised layout and additional mixers at no cost to the Town

2. Continue monitoring the performance of the mixers in 2004, including influent manganese, temperature, and DO and profiles of manganese, temperature, and DO at 1m, 3m, 5m, and 7m depths at the location of the intake.

3. The Town should retain a diver to clean the intake screen again and dye testing should be conducted along the inlet piping to determine if water is being withdrawn at lower depths through cracks or is influenced by the lower waters. In conjunction with this work, the Town should also improve the intake air system to provide for better air burst cleaning of the screen. The Town should consider replacement of the existing screen with a drum type screen and installing a reservoir drain to allow for removal of accumulated sediment in the vicinity of the intake.

REFERENCES

AWWA/ASCE, 1998. Water Treatment Plant Design, 3rd Edition.

Holdren, C., W. Jones, and J. Taggart. 2001. “Managing Lakes and Reservoirs.” NAm. Lake Manage. Soc. and Terrene. Inst., in Coop. with Off. Water Assess. Watershed Prot. Div. U.S. Environ. Prot. Agency, Madison, WI.

Ministry of Health, Wellington, New Zealand, June 2001. Public Health Risk Management Guide. Pre-treatment process-destratification. Version 1, Ref P4.2.

National Research Council. Committee on Restoration of Aquatic Ecosystems-Science, Technology, and Public Policy, 1992. Restoration of Aquatic Ecosystems. National Academy Press.

Pump Systems, Inc., SolarBee® Pond Circulators Technical Bulletins, 2002. Dickinson, ND.