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Evaluation of Offshore Wastewater Outfall and Diffuser for Onondaga Lake, NY

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ABSTRACT

Outfall alternatives are evaluated for a municipal wastewater treatment facility that discharges effluent at the shoreline of an urban lake. Occurrence of plumes of poorly diluted effluent in adjoining portions of the lake is described. Alternatives considered include outfalls over a range of depth and various diffuser designs. Benefits and impacts on lake stratification and dissolved oxygen are evaluated for an array of design alternatives with a model which links a far field hydrothermal and transport submodel with a near field buoyant plume submodel. Outfall design features are described that: 1) reduce shoreline discharge of bypass flow of partially treated wastewater during major runoff events; 2) eliminate plumes of poorly diluted effluent; and 3) reduce loading of the effluent to the upper waters. A deep (10 to 14 m) outfall with a multiport diffuser would reduce the loading of the facility's effluent to the upper waters by approximately 40%, without noteworthy impact on stratification or dissolved oxygen.

Keywords: Mathematical Model; Outfall; Diffuser; Near Field Dilution; Eutrophication

1. Introduction

Placement of wastewater outfalls within the stratified layers of receiving lakes and the coastal ocean, below the well-mixed upper layers, is a potentially valuable design alternative. In these cases, a fraction of the effluent is "trapped" in the stratified layers [1], which reduces the transport of nutrients and other pollutants to the productive upper waters [2] and nearshore contact recreation areas [3]. Trapping is achieved by mixing the effluent, which is often warmer and buoyant relative to the stratified layers, with ambient receiving water, producing a cool diluted effluent that loses its buoyancy while rising through the stratified layers [4]. While buoyancy alone drives a moderate level of effluent mixing, use of a multiport diffuser increases mixing, dilution, and trapping efficiency. Diffusers force the effluent through an array of small diameter ports or nozzles, creating relatively high discharge velocity, enhanced turbulent mixing and dilution [4,5].

A related benefit of a diffuser is reduction of the size of the mixing zone, defined as the area or volume of the receiving water surrounding the outfall where initial dilution of the effluent occurs, and where water quality standards for individual pollutants may be exceeded [6]. Federal and various state regulations and guidelines recommend that the size of mixing zones be minimized, and that presence of a mixing zone in nearshore or other sensitive regions be avoided [7]. In New York State, a 10:1 dilution is recommended within the mixing zone of a point source of an oxygen-demanding pollutant [6].

In the application of a water quality model to evaluate the impact of a wastewater outfall, the receiving water may be divided into two regions [8]. The near field is the region immediately surrounding the outfall where transport processes are dominated by the momentum (velocity) and buoyancy of the discharge, while the far field is the region outside of the near field, where ambient or natural transport and mixing processes dominate. A common modeling approach is to employ separate near and far field submodels for these two regions [9]. Simulation of far field water quality requires realistic linkage of the submodels. In large water bodies such as the coastal ocean or the Laurentian Great Lakes, a one-way linkage, which neglects the influence of the effluent on ambient (far field) stratification, has been adopted [9,10], while more general strategies for two-way linkage have been used for smaller systems where there is potential for system-wide impacts [2,11].

This paper evaluates the potential benefits and impacts of an offshore outfall and diffuser for municipal wastewater discharges to a small urban lake (Onondaga Lake, NY) where shoreline outfalls continuously release treated effluent, and intermittently release partially treated wastewater during major runoff events (bypass flow). The impacts of moving the outfall to an offshore location are evaluated using a model which links a far field one-dimensional heat and mass transport submodel with the CORJET near field diffuser submodel [12,13]. A dissolved oxygen submodel for the lower waters of the lake, which considers sediment and water column oxygen demand, is developed and applied. The model is used to evaluate various offshore outfall/diffuser designs with regard to: 1) reduction in transport of effluent and associated loads to surface waters; 2) increasing effluent dilution; 3) impact on the lake's stratification regime; 4) reduction in shoreline discharge of partially treated bypass flow; and 5) impact on dissolved oxygen in the lake's lower waters. The predicted effects of operating an offshore outfall/diffuser in Onondaga Lake are considered in the context of the current lake rehabilitation program that targets reduction in phosphorus (P) loads to the upper productive waters.

2. System Description

2.1. Onondaga Lake

This lake is located (lat. 43˚6'54"; long. 76˚14'34") in metropolitan Syracuse, NY (**Figure 1**). It has a volume of 0.13 km^3, surface area of 12 km^2, and a maximum depth of 20 m. Onondaga Lake is dimictic, strongly stratifying during summer months [14]. The lake flushes about four times per year on average, and thus responds rapidly to changes in material loading [15]. While the lake was oligomesotrophic in the late 19th century [16], subsequent inputs of industrial and domestic wastes caused severe degradation [17]. By the late 1980s Onondaga Lake was described as the most polluted lake in the United States [18]. Comprehensive rehabilitation efforts for the lake are underway for both domestic waste and residual industrial contamination, with a combined cost approaching $1 billion.

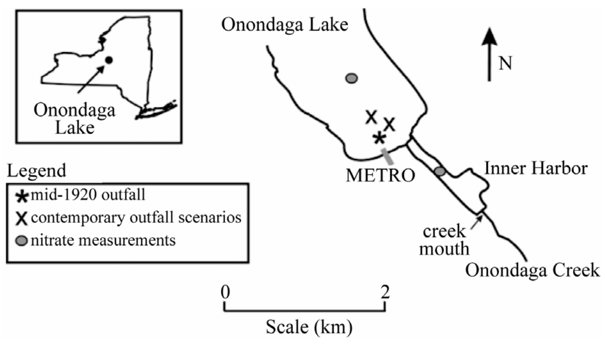

Figure 1. Onondaga Lake, harbor channel, and Inner Harbor, with locations of measurements of Metro nitrate signatures, mid-1920's outfall location and contemporary scenarios for locations of deep diffuser discharge.

2.2. Metro, Lake Impacts, and Partitioning Contemporary Phosphorus Loads

Treated wastewater from the Metropolitan Syracuse Wastewater Treatment Plant (Metro) has entered the southern end of the lake since 1921 (**Figure 1**). Influent wastewater is delivered by a combined sewer system. The contemporary Metro discharge to the lake (average of 3.0 m^3/s or 68 MGD) is comparable to other inflows from tributaries, representing about 20% of the total annual inflow. Metro inputs of P were responsible for the lake's cultural eutrophication and the associated degradations in its water quality [19].

The total P concentration of Metro effluent (TP_M) has decreased more than 100-fold since the early 1970s [19]. The most recent upgrade in P treatment (Actiflo®, micro-sand ballasted process) has reduced TP_M to <100 µg/L and transformed the lake's trophic status from hypereutrophy to upper mesotrophy, with improved clarity and oxygen resources [19], though the hypolimnion becomes anoxic by mid-summer. Presently 65% of TP_M is in a particulate form that is unavailable to support algae growth [20]. The regulatory goal for the lake's total P concentration is a summer average epilimnetic value (TP_E) of 20 µg/L [19], a level consistent with mesotrophy [20]. This goal is presently met irregularly. Management alternatives that would further reduce inputs to the epilimnion and more routinely meet the in-lake goal are of interest [20]. Related analyses have adopted an "effective" P loading approach (*i.e.*, representing factors, such as bioavailability, that diminish the availability of TP inputs to support primary production) for all lake inputs.

Contributions of tributaries to effective P loading, as represented by summertime loading of total dissolved P (TDP_L; [20,21]), were relatively inconsequential compared to the Metro input until the most recent treatment upgrade, but are presently noteworthy ([21,22], **Figure 2**). Though the tributaries presently contribute about 62%

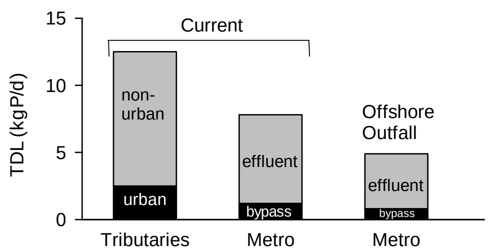

Figure 2. Partitioning the contribution of tributaries and Metro to the summertime loading of total dissolved phosphorus (TDP_L) to Onondaga Lake. Metro (future) is loading to the upper waters for an outfall/diffuser at a depth of 10 m (33 ft.).

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of the TDP_L (**Figure 2**), the extent to which substantial decreases in these inputs may be achieved is limited [22].

For example, inputs from the non-urban portions of the watershed are not considered to be sources where substantial reductions can be achieved [22,23]. Metro and urban tributary inputs (including leaky sewers and combined sewer overflows; **Figure 2**) remain targets for additional reductions.

Potential impact of a Metro discharge to stratified layers is an issue because the oxygen resources of the hypolimnion are an important management concern for the lake [24]. Following the recent treatment upgrades, the summer average dissolved oxygen (DO) concentration of Metro effluent is 9.7 mg/l, approximately saturated. Effluent concentrations of oxygen-demanding constituents in the fully treated effluent are low; summer average concentrations of 5-day biochemical oxygen demand (BOD_5) and total Kjeldahl nitrogen (TKN) are 3.7 and 1.2 mg/l (unpublished data Onondaga County), respectively. For the intermittent bypass flow, summer average concentrations are much higher (BOD_5 and TKN = 60 and 18 mg/l, respectively, unpublished data, Onondaga County).

2.3. Metro Discharge and Plumes

The primary point of discharge of the Metro effluent from 1921 to 1979 was located 520 m offshore (**Figure 1**) at a depth of 6.4 m (21 ft). This outfall pipe (diameter 152 cm or 60 in) has a multiport diffuser (4 ports of diameter 61 cm or 24 in). During wet weather, a second shoreline bypass outfall was used when the offshore outfall capacity was exceeded. These ~90 year-old facilities are collectively designated as outfall 002, as contained in the current effluent discharge permit granted by New York State. The primary point of discharge was changed to a new shoreline outfall, designated as 001 (**Figure 1**) in 1979, associated with treatment upgrades. A component of the upgrade was a co-treatment process that removed P utilizing calcium-rich saline wastewater generated by a local industry. A shoreline outfall was adopted to avoid the possible failure of lake turnover caused by the offshore discharge of saline, dense effluent. The closure of the industry in 1986 eliminated the co-treatment process and elevated effluent salinity. However, the shoreline outfall 001 continues to be the primary discharge location. This configuration, in combination with the absence of a diffuser, is unusual. The plant currently provides full treatment of flow up to 5.5 m^3/s (126 MGD). Flow exceeding this capacity, designated here as bypass, receives primary treatment and chlorine disinfection and is discharged via outfall 002. Assuming the 1987-2010 record of Metro inflow is representative of the future, bypass from the current plant would occur on average 7 days per year (average volume of 1.1×10^5 m^3 or 28 MG on those days), and 1 day per year during summer (June through September; **Table 1**). Over 24 years, bypass volume would be less than 1% of the plant inflow (**Table 1**), but bypass TDP load would be 15% of the total Metro TDP load (**Figure 2**).

In the absence of a diffuser, mixing of the current Metro discharge(s) within the lake relies primarily on ambient mixing levels and secondarily on the buoyancy of the effluent. This effluent is typically cooler (negatively buoyant) relative to the upper waters of the lake from late spring to late summer, and warmer (positively buoyant) thereafter through fall (**Figure 3(a)**), but substantially warmer than lower lake waters [21]. Based on in-lake observations of NO_3^- concentration, for which Metro is greatly enriched relative to other inflows and the lake [25], consistent signatures of poorly diluted (less than 4:1) Metro effluent are observed as interflow (metalimnetic peaks; **Figures 3(b)** and **(c)**) and overflow (on lake surface; **Figure 3(d)**) patterns in summer and fall, respectively, during low wind conditions. Moreover, wind from the northwest in late summer/early fall has been observed to drive the poorly-diluted (dilution ~2:1) buoyant effluent plume into the adjacent channel of nearby Onondaga Creek (**Figure 3(e)**), approaching the

Table 1. Volume of wastewater, including plant inflow, plant bypass, and nearshore relief for two offshore outfall/diffuser alternatives, based on 24-year historical (1987-2010) record of plant inflow. Baseline condition is release of all effluent at the shoreline. Volume units: $m^3 \times 10^{-4}$; frequency is days per year or days per summer.

Metro Flow Attributes	Annual	Summer (June thru Sept.)
Contemporary Conditions:		
plant inflow volume	227,000	66,700
average bypass[a] frequency	7 per year	1 per summer
partially treated bypass volume (% of total volume)	1910 (0.84%)	221 (0.33%)
Existing 6.4 m Depth Outfall 002:		
average relief[b] frequency	23 per year	4 per summer
nearshore treated volume (% of total treated volume)	4390 (1.9%)	402 (0.6%)
nearshore partially treated vol. (% reduction from baseline)	786 (59%)	72 (68%)
Offshore Outfall Scenario:		
average relief frequency	2 per year	<1 per summer
nearshore treated volume (% of total treated volume)	249 (0.1%)	0.758 (<0.01%)
nearshore partially treated vol. (% reduction from baseline)	143 (92%)	3.79 (98%)

[a]Partially treated (primary treatment only) bypass volume is generated when daily average plant inflow exceeds 5.5 m^3/sec (126 MGD); [b]Shoreline relief (bypass) occurs when total effluent flow (treated plus partially treated) exceeds hydraulic capacity of offshore outfall/diffuser.

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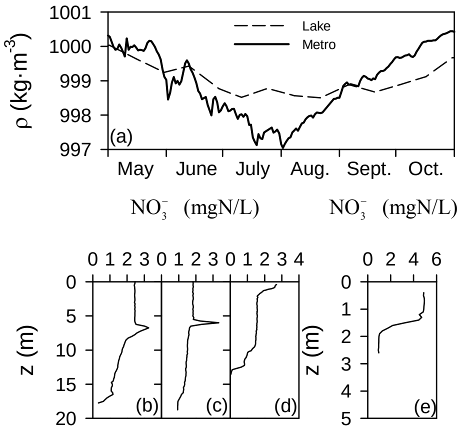

Figure 3. (a) Seasonal buoyancy (ρ = water density) of Metro effluent in 2006 comparing densities of the effluent and upper lake layers, and vertical signatures of poorly diluted effluent in the lake; (b) 4 August 2008; (c) 30 June 2011; (d) 9 October 2006 near south deep, and (e) 2 Sept 2006 in Onondaga Creek channel approaching the Inner Harbor. Metro effluent NO_3^- concentrations are ~10 mgN/L.

Inner Harbor (**Figure 1**), which is targeted for commercial and residential development.

3. Methodology

3.1. Modeling Concepts

In the near field region that immediately surrounds the diffuser, the mixing and transport is dominated by the characteristics of the diffuser and effluent, such as the port velocity and effluent buoyancy. Characteristics of the ambient receiving water, such as currents and turbulent diffusion have no significant influence in the near field. In the far field, which surrounds the near field, the relative roles are reversed; ambient characteristics dominate while diffuser and effluent characteristics have much less influence.

While the average hydraulic residence time for Onondaga Lake is about 3 months, residence time in the near field of a diffuser plume is on the order of minutes. In addition, the horizontal scale of the near field is on the order of tens of meters, while the lake is two orders of magnitude larger. Due to this disparity in temporal and spatial scales, separate near field and far field submodels are commonly used to simulate the fate and transport of diffuser effluent in a receiving water body [9,10]. This approach is adopted here. The state variables in these submodels are water temperature, salinity, and mass concentration. Temperature (T) is simulated in order to represent the important characteristics of effluent buoyancy and thermal stratification in the lake. Salinity (S) has a smaller influence on both effluent buoyancy [21] and stratification in the lake [14], but is included to fully represent these effects. Mass concentrations for other constituents are simulated as described subsequently.

3.2. Near Field Submodel

The near field submodel used is CORJET [12,13], the simulation component of the widely used CORMIX expert system for discharges to surface waters [26]. The submodel assumes that effluent is discharged through an array of diffuser ports whose diameter, orientation, and spacing are identical, with uniform distribution of effluent to each port. The model uses the integral approach to jet mixing [1,5]. The relatively high velocity of the jet from a diffuser port induces turbulent mixing. The integral approach characterizes this mixing as entrainment, a bulk dilution of the effluent by ambient lake water from the surrounding far field.

Immediately after discharge from a diffuser port, a round jet is formed that is deflected upward by buoyancy along the centerline path length$s$ (**Figure 4**). At a port opening (s = 0), $Q_N = Q_W/N$, where Q_N is the discharge of an individual jet, Q_W is wastewater effluent flow and N is the number of diffuser ports. Entrainment causes the buoyant jet discharge Q_N to increase with s [13] as given by

$$\frac{\mathrm{d}Q_N}{\mathrm{d}s} = 2\pi b \alpha_1 U_N \tag{1}$$

where b is the radius of the jet, α_1 is the entrainment coefficient, and $U_N = Q_N / \pi b^2$ is the average velocity of the jet, so that the rate of entrainment is directly proportional to U_N [5,13]. Additional integral conservation equations for horizontal and vertical momentum, heat, and mass are solved for Q_N, b, jet trajectory angle θ, and near field temperature T_N, salinity S_N, and near field mass concentration as a function of s and vertical position z. Due to the short near-field detention time, the near field model contains no dynamic terms, and daily changes in effluent characteristics are simulated using a series of steady states. In addition, reactions involving mass concentrations in the near-field are neglected. The continuity (Equation (1)) and momentum equations predict that Q_N, b, and θ increase, while U_N decreases, with increasing s. At some value of s, the jet radius may increase to the point that $b = l$, where $l = L/(N - 1)$ is the spacing between adjacent alternating ports and L is the total diffuser length (**Figure 4**). At this point, the individual round jets merge to form an equivalent "slot" or two-dimensional jet [12] whose flow per unit diffuser length is $q_N = Q_N/2l$. Should this merging condition be met, the near field continuity equation then takes the form

$$\frac{\mathrm{d}q_N}{\mathrm{d}s} = 2\alpha_2 U_2 \tag{2}$$

where α_2 and $U_N = q_N / 2b$ are the entrainment coefficient and velocity in the merged or two-dimensional jet

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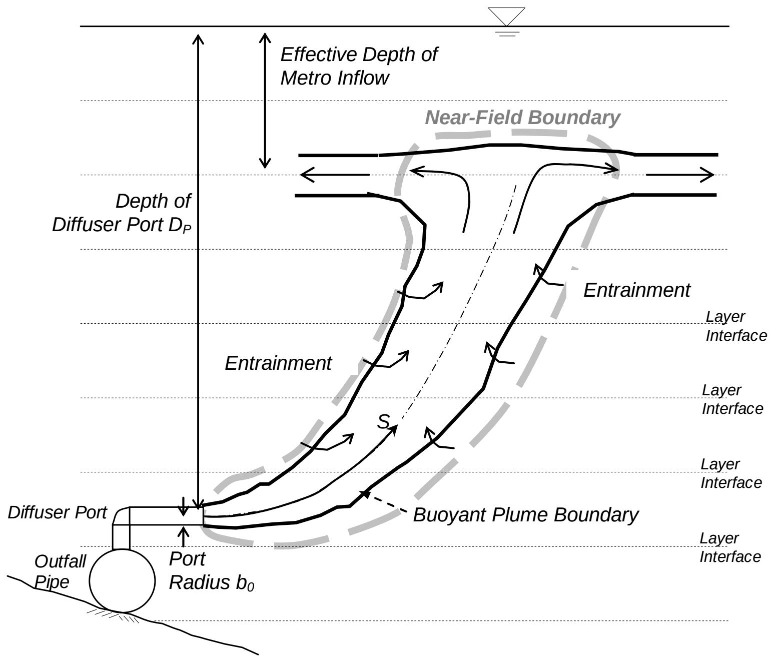

Figure 4. Schematic of a buoyant plume rising from the port of a diffuser. The layer interfaces define the model layers used by the far field submodel to describe vertical variations within the lake. Within the near field, velocity, temperature, salinity, and concentration vary continuously along the centerline position *s*.

region. When the lake is thermally stratified, solution of the near-field submodel leads to the result that, at some vertical position in the stratified layers, the jet density, determined by the near-field temperature T_N and salinity S_N, is no longer less than the density of the surrounding ambient water determined by the far field temperature T_F and salinity S_F. The plume exits the near field, and enters the far field, at this vertical position.

3.3. Far Field Submodel

The far field submodel is UFILS4, a one-dimensional (vertical) hydrothermal and mass transport model that simulates the dynamics of lake stratification and mixing. UFILS4 has been rigorously tested for Onondaga Lake for multiple years [4,27] and other water bodies [28]. UFILS4 allows temperature, salinity, concentrations and vertical mixing to vary in the vertical direction but these are assumed to be uniform in the horizontal plane. The lake is represented by a "stack" of layers of uniform thickness (1 m), with the exception of the surface layer whose thickness may change in time due to inflow and outflow. The submodel is based on conservation equations for water volume, temperature, salinity, and mass. For layers below the surface, the water volume conservation (continuity) equation is

$$w_{i+1} = \left(w_i A_i - Q_{oi} + \sum Q_{Ii} \right) \Big/ A_{i+1} \tag{3}$$

where w_i and A_i are the vertical velocity and lake plan area at the base of layer *i*, and $Q_{I\mathrm{i}}$ and $Q_{O\mathrm{i}}$ are the inflow to and outflow from layer *i*, with the summation indicating the multiple sources of inflow, and $i = 1, \ldots, n$, where *n* is the total number of layers. Equation (3) generally states that an imbalance in the inflow to and outflow from a model layer causes (vertical) water motion across the boundary between adjoining layers. For the tributaries and for Metro at its current shoreline location, the vertical distribution of inflow to individual layers $Q_{I\mathrm{i}}$ is determined by an algorithm within UFILS4 that considers inflow momentum and buoyancy. A similar outflow algorithm determines the vertical distribution of outflow to the single lake outlet (**Figure 1**).

In addition to transport associated with the vertical velocity *w*, turbulent diffusion between adjacent layers is simulated. The depth of a well-mixed surface layer is determined from a turbulent kinetic energy (TKE) balance that considers wind shear at the water surface as a source of TKE and multiple sinks including dissipation and buoyancy. Below the mixed layer, turbulent diffusion is driven by wind shear and is dampened by stratification. Conservation equations for heat and mass are solved to determine the far field temperature T_F, salinity S_F, and concentration for each layer at a daily time step. All conservation equations consider inflow and outflow, and vertical transport by advection (*w*, Equation (3)) and turbulent diffusion. Salinity is treated as conservative. Heat conservation considers the subsurface penetration of solar radiation, and exchange of heat at the water surface due to incident long wave and back radiation, evaporative exchange and conduction. The mass conservation equation for layer i is

$$\begin{aligned} V_i \frac{dC_i}{dt} &= Q_{Ii} C_I - Q_{oi} C_i + w_I A_I C_{i-1} \\ &\quad - w_{i+1} A_{i+1} C_i + E_{i+1} A_{i+1} \frac{C_{i+1} - C_i}{\Delta z_{i+1}} \\ &\quad - E_i A_i \frac{C_i - C_{i-1}}{\Delta z_i} + W_S \left(A_{i+1} C_{i+1} - A_i C_i \right) \\ &\quad - r V_i - f_B \left(A_{i+1} - A_i \right) \end{aligned} \tag{4}$$

where V_i is volume, C_i is concentration, E_i is the vertical diffusion coefficient, Δz_i is layer thickness, W_S is settling velocity, r is reaction or loss rate, and f_B is mass flux at the lake bottom, all for layer i. Equation (4) is used to simulate conservative ($W_S = r = f_B = 0$) and nonconservative ($f_B = 0$; $W_S \neq 0$ or $r = kC \neq 0$, where k is a first-order decay rate) tracers in order to evaluate trapping of Metro effluent in the water column. In addition, Equation (4) is used to evaluate the impact of an offshore discharge on dissolved oxygen in the lower waters by simulation of carbonaceous biochemical oxygen demand (CBOD; $W_S = f_B = 0$, $r = k_{CBOD}C_{CBOD}$), nitrogenous biochemical oxygen demand (NBOD; $W_S = f_B = 0$, $r = k_{NBOD}C_{NBOD}$), and dissolved oxygen (DO; $W_S = 0$, $r = k_{CBOD}C_{CBOD} + k_{NBOD}C_{NBOD}$, f_B = sediment oxygen demand).

Far field submodel inputs, specified at a daily time interval, are wind speed, incident solar radiation, air temperature and humidity, and stream characteristics of discharge, temperature, salinity, and constituent concentration. The validation for 19 y of historical conditions [14] included simulation of the existing shoreline Metro outfall using the same algorithm used to simulate the inflow of the stream tributaries. Simulations for the existing shoreline outfall were performed here to establish a baseline against which comparisons are made for offshore outfall alternatives.

3.4. Linkage of Near and Far Field Submodels

Various approaches to linkage of near and far field models have been described [2,8,10,11]. The approach taken here follows that used by Owens and Effler [27] and Choi and Lee [11] and utilizes a two-way linkage of the submodels. This approach is appropriate for the Metro discharge to Onondaga Lake, where the detention time of this discharge in the stratified layers is short (~3 months), and thereby has the potential to affect lake stratification.

Within each daily time step of the model, the near field and far field submodels are solved once and in that order. The near field submodel utilizes the far field solution for T_F, S_F, and far field concentration from the previous time step. The entrainment flows from surrounding far field layers into the near field, and the near field temperature T_N, salinity S_N, and concentration at increasing values of s and z (Equations (1) and (2)) are computed. Solution continues until the near field buoyancy vanishes, or the water surface is reached, where the wastewater effluent, diluted by entrainment, leaves the near field and becomes an inflow to the far field submodel. At this point, the near field dilution D is determined as the mixing of a unit volume of effluent with $D - 1$ volumes of lake water by entrainment.

The far field submodel for the same time step is then solved. Entrainment as computed by the near field submodel is treated as an outflow from appropriate far field layers. Entrainment-based outflow from the far field in stratified layers together with inflow of diluted effluent at the "top" of the near field leads to negative values of the vertical velocity w_i (Equation (3)) in stratified layers above the outfall location, resulting in downward transport of heat and mass. It is through these processes that a Metro discharge to stratified layers may modify thermal and salinity stratification, and the vertical distribution of mass concentrations.

3.5. Modeling Protocol and Preliminary Design Approaches

The linked UFILS4/CORJET model was used to evaluate offshore outfall and diffuser design features for the Metro effluent. A wide variety of outfall depths and multiport diffuser configurations were evaluated, including outfalls without a diffuser. Outfall depths over the range of 6 to 18 meters in depth were evaluated, as were diffuser port diameters in the range of 8 to 16 inches, number of ports from 20 to 50, and port spacing from 1 to 8 meters, resulting in a range of diffuser port velocities (**Table 2**). The existing offshore outfall/diffuser 002 was also evaluated (**Table 2**). In order to quantify the water quality benefit of an offshore outfall, conservative and nonconservative tracers were simulated, as follows. To track the transport of Metro effluent in the lake, an arbitrary constant tracer concentration (100 mg/l) was assigned to the effluent for all simulations, with zero concentration in all other inflows. The reduction in the tracer concentration in the upper waters of the lake relative to that predicted for the existing shoreline outfall (baseline) is the primary measure of benefit of a particular offshore outfall/diffuser design.

In addition to the receiving water modeling, head loss calculations for the various outfall/diffuser designs were performed. These calculations utilized the Darcy-Weisbach equation for pipe sections, and considered minor head losses associated with pipe bends, entrances and other fittings [29]. The outfall pipe diameter was selected to maintain a minimum velocity of 0.8 m/s (2.5 ft/s) at the average effluent flow rate. Flow is delivered to individual diffuser ports via a short riser pipe exiting the top

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Table 2. Diffuser designs considered in this analysis and associated port velocities for effluent flow rates of 3.0 and 5.5 m^3/s (68 and 126 MGD).

Port diameter cm (inch)	Number of diffuser ports	Diffuser port velocity m/s (ft/s)	
		3.0 m^3/s (68 MGD)	5.5 m^3/s (126 MGD)
20 (8)	35	2.6 (8.6)	4.9 (16.0)
23 (9)	35	2.1 (6.8)	3.8 (12.6)
25 (10)	35	1.7 (5.5)	3.1 (10.2)
31 (12)	35	1.2 (3.8)	2.2 (7.1)
41 (16)	35	0.7 (2.2)	1.2 (4.0)
[a]61 (24)	4	2.6 (8.4)	4.7 (15.5)
[b]244 (96)	1	0.8 (2.6)	1.2 (3.9)

[a]Existing offshore outfall/diffuser at depth of 6.4 m; [b]"No Diffuser" option: a 244-cm outfall pipe with open end; for this option, the velocity in the diffuser port and outfall pipe are equal.

of the diffuser manifold, with a 90˚ bend leading to a horizontal port orientation. The riser pipe diameter was roughly twice the actual port or nozzle size. Outfall/diffuser head loss was most sensitive to diffuser port diameter and outfall pipe length. The hydraulic capacity of a particular outfall/diffuser design was determined as the flow rate at which a critical water surface elevation is reached at the downstream-most unit process within Metro. When this elevation (375.66 ft; unpublished data, Onondaga County) is exceeded, plant operations begin to deteriorate. For a particular outfall/diffuser design, the occurrence of this critical condition is determined by wastewater flow and lake level (monitored continuously by the US Geological Survey).

The linked modeling analysis adopted as an implicit assumption that lake water quality will be improved by utilizing the full capacity of an offshore outfall to release both fully treated effluent and intermittent partially treated bypass flow. In addition, when the hydraulic capacity of the outfall/diffuser is exceeded, excess flow would be diverted to a "relief" outfall located in shallow water near the shoreline. Accordingly, no effluent pumping would be required for any of scenarios considered here. In order to achieve this, the design involves combining fully treated effluent and bypass into a single conduit (**Figure 5(a)**). The combined flow would then be conveyed to a control structure, passing flows up to capacity to the offshore outfall, with excess diverted to the nearshore relief outfall (**Figure 5(a)**). This term "relief" was adopted here to differentiate it from the contemporary "bypass", as the constituent concentration would be substantially lower from the mixing with the fully treated effluent. When relief occurs, both the offshore and bypass outfalls would discharge, at different rates, the same mixture of fully treated effluent and partially treated bypass flow. Average contemporary bypass concentrations of TP and total ammonia (TNH_3) are 1200 µg/l and 8.0 mg/l (unpublished data, Onondaga County), respectively, both substantially higher than the fully treated effluent. Combining or mixing the effluent and bypass has the benefit of diluting the bypass flow.

Based on the assumption that historical weather and hydrologic conditions are representative of future conditions, the observed conditions for the spring to fall period of 22 years (1989 through 2010) were used as model inputs, to provide a probabilistic context for the simulations [30,31] that represents the effects of year-to-year variations in meteorology and hydrology. The potential for discharging all of the treated and bypass flow, or a portion of this flow, through an offshore outfall is also evaluated using the history of wastewater flow reaching the plant for the same 22 years. Simulations for each of these years began during the observed interval of spring turnover. Initial values of T_F, S_F, CBOD, NBOD, and DO were set to observed values, while the initial tracer concentrations C_o was given by

$$C_o = \frac{Q_W}{\left(Q_T + V_T k + A_s W_s\right)}\left(100 \text{ mg/l}\right) \tag{5}$$

where Q_W is Metro effluent flow, Q_T is total lake inflow (including Metro and all streams), V_T is total lake volume, and A_S is lake surface area. Simulations for each year continued until November 30, well after the onset of fall turnover. To evaluate the impact on dissolved oxygen in the lower waters of the lake, simulations of CBOD, NBOD, and DO were made using the linked model. For CBOD and NBOD, Equation (4) was used for the entire water column. For DO, Equation (4) was used for far field layers below the upper mixed layer, while DO was assumed to be at saturation in the surface mixed layer. Two levels of sediment oxygen demand (SOD), the dominant sink process in the hypolimnion [24], were considered, these being 0.9 and 0.5 g/m^2/day. These reflect current and future (after SOD reaches equilibrium with recent reductions in organic deposition) conditions [24], respectively.

4. Results and Discussion

4.1. Benefits of Mixing Treated Effluent and Bypass Flow within Metro

A design feature considered here is combining the treated effluent with bypass before these wastewaters reach the lake shoreline (**Figure 5**). Based on the 24-year record of plant inflow applied to the current plant, the average dilution, or ratio of fully treated effluent volume to bypass volume, would be 19:1 on those days that bypass occurs. Concentrations of mixed wastewater reaching the shoreline control structure (**Figure 5(a)**), that would exit via the relief, would be reduced from about 1200 to 160 ug/l

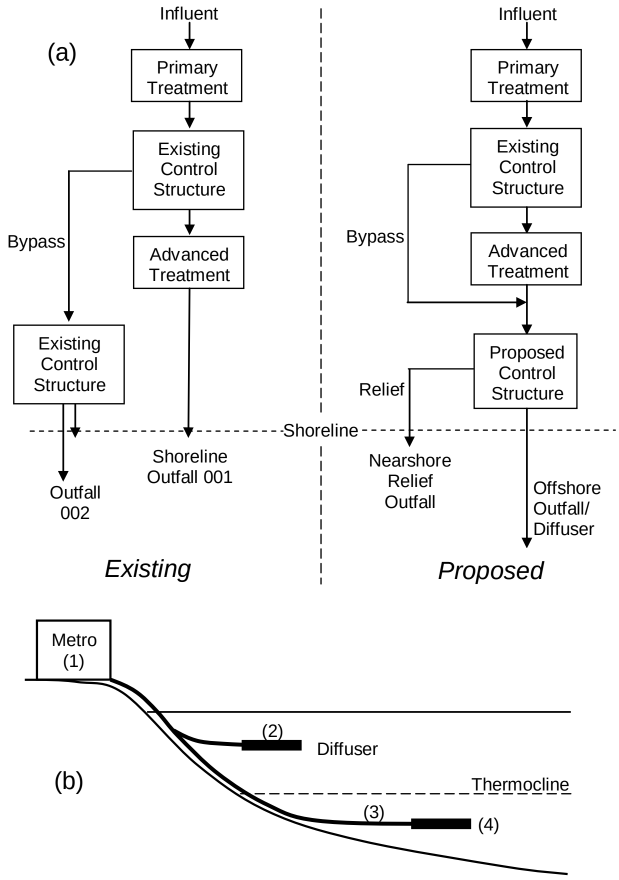

Figure 5. Schematic of alternatives for effluent and outfall: (a) mixing within Metro facility of bypass and fully treated effluent, and (b) all four components including (1) in-facility mix; (2) near shore outfall and diffuser; (3) offshore outfall without diffuser; and (4) offshore outfall with diffuser.

for TP, and from 8.0 to 1.4 mg/l for TNH_3, by adopting this proposed modification compared to the existing conditions (**Figure 5(a)**). These reduced concentrations are simply a result of dilution of the partially treated bypass with fully treated effluent.

4.2. Tracer Simulations

Far field submodel predictions of the variation of conservative tracer concentration in the upper waters for one (2009) of the 22 years show the important influence of outfall depth (**Figure 6**), for a diffuser with 31 cm (12 in) ports spaced at 1 m. Trapping is particularly effective from May through August; over this period upper water tracer concentrations would generally decrease over time. Tracer concentrations in the upper waters would increase in late September as the combined effects of a deepening thermocline and vertical diffusion bring previously trapped tracer into the upper waters. After fall turnover in early October, trapped tracer would be fully mixed into the water column of the lake, resulting in an increase in tracer concentration relative to the prediction for the shoreline outfall (**Figure 6**). The high flushing rate of the lake during the period from fall turnover to spring turnover [17] reduces water column concentrations back to levels consistent with inflows.

The median and standard deviation of the reduction in summer average tracer concentration in the upper waters was determined for each outfall/diffuser alternative from the simulations for 22 years (**Figure 7**). Increasing the outfall depth resulted in progressive decreases in tracer concentration (*i.e*. greater trapping) over the depth range from 6 to 18 meters, although the incremental improvement began to decrease at 10 m depth and was small beyond a depth of 14 meters (**Figure 7(a)**). The existing offshore outfall (002) provided a reduction in tracer concentration that is similar to a new diffuser at the same depth (6.4 m; **Figure 7(a)**). The variation of summer average tracer concentration associated with natural variations in weather and hydrology (vertical bars) was substantial relative to the reductions associated with outfall depth (**Figure 7(a)**). The median values of percent reductions relative to the baseline (existing shoreline outfall) for depths of 10, 12, and 14 m were 38, 44, and 48%, respectively, for a diffuser with 25 cm (10 in) diameter

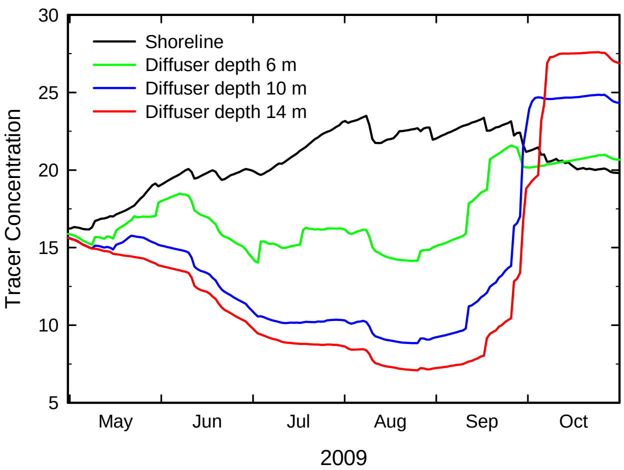

Figure 6. Predicted tracer concentration in the upper waters of Onondaga Lake for 2009, for the existing shoreline outfall and for outfall/diffusers located at 6, 10, and 14 meters depth, for a diffuser with 31 cm (12 in) ports.

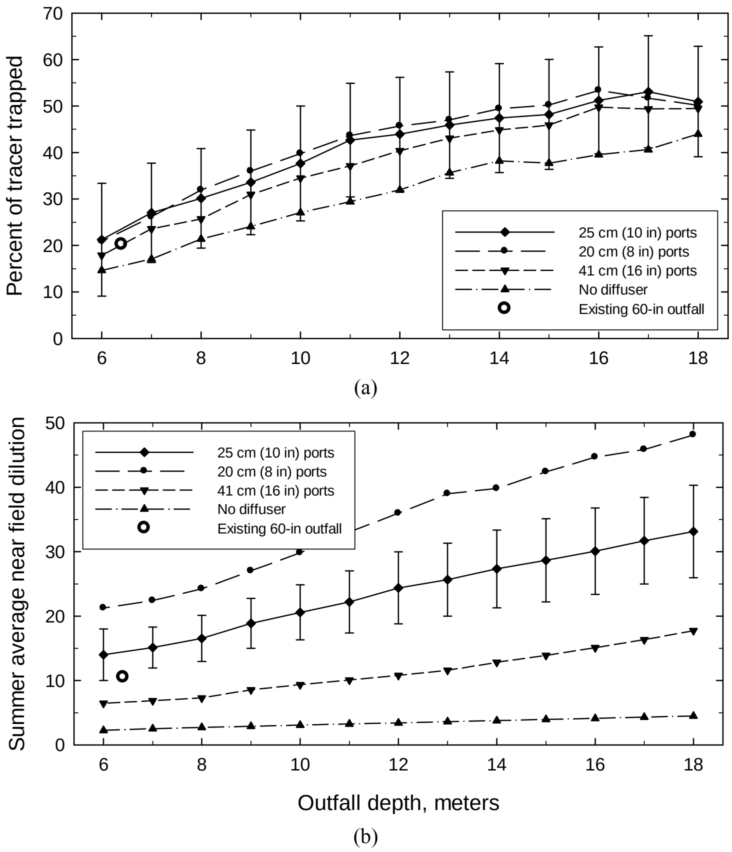

Figure 7. Model predictions of the median (for 22 years) of summer average conditions for various outfall/diffuser designs: (a) percent of conservative tracer trapped, and (b) near field dilution of effluent. These predictions are for a diffuser with 35 ports with 1 meter spacing. The vertical bars represent +/− one standard deviation for 22 summer average prediction, for a diffuser with 25 cm (10 in) ports.

ports. Simulations were made for a range of nonconservative (either settling velocity $W_S \neq 0$, or decay rate $k \neq 0$) tracers. In all cases, increasing W_S or k consistently resulted in greater reductions in tracer concentration associated with an offshore outfall/diffuser relative to the shoreline prediction for the same tracer. The predictions for a conservative tracer represent a lower bound for the reduction in a constituent concentration (*i.e.*, the benefit) such as TP or TDP.

All outfalls with multiport diffuser port diameters less

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than 31 cm (12 in) achieved average summer near field dilution (*D*) greater than 10. Average summer *D* progressively increased with outfall depth (**Figure 7(b)**). The existing offshore outfall (002) produced an average summer *D* of 11 (**Figure 7(b)**). The predicted *D*s, in the range of 2 to 4, for the existing shoreline outfall 001 (see no diffuser case, **Figure 7(b)**) were consistent with contemporary NO_3^- monitoring observations of the Metro effluent plume in the lake (**Figure 3**, [21]). Near field dilution was the feature most strongly affected by the port diameter (**Figure 7(b)**), through its direct effect on port velocity.

4.3. Stratification Regime and Hypolimnetic Oxygen Simulations

Predicted effects on thermal stratification (**Figure 8**) relative to the shoreline outfall were most sensitive to changes in outfall depth and, to a lesser extent, diffuser characteristics that changed the port velocity (diameter and number of ports). Both tracer concentrations and stratification were relatively insensitive to changes in port spacing or to concurrent changes to diameter and number of ports that do not change port velocity. As a result, model predictions for a range of outfall depths and port diameters are presented, with the number of ports fixed at 35. The duration of summer stratification (time interval from spring to fall turnover; **Figure 8(a)**) and average summer lake bottom temperature (**Figure 8(b)**) were predicted to not be affected by outfall depths less than about 10 meters. The depth of the thermocline is not substantially affected by an offshore outfall/diffuser (**Figure 8(c)**). The predicted impact on lake stratification for outfall depths of ≤14 m was far less than the interannual variation associated with natural variations in weather and streamflow conditions (**Figure 8**). For outfall depths of 16 or 18 m, the decrease in duration of stratification and increase in temperature at the lake bottom were of a magnitude that may be of concern to regulators because these approach the bounds of prevailing natural variations. These findings, in combination with the diminished trapping benefits for depths greater than 14 m (**Figure 7(a)**), indicate 14 m is a reasonable upper bound depth for the Metro outfall.

There was no noteworthy impact predicted for an offshore outfall/diffuser on dissolved oxygen in the hypolimnion (**Figure 9**) for both contemporary and projected future levels of SOD (0.9 and 0.5 g/m^2/day, respectively). The low oxygen demand of the effluent is offset or satisfied by its nearly saturated DO content. As the outfall is moved beyond 10 m depth, a modest increase in DO was predicted (**Figure 9**), associated with changes in vertical transport induced by the buoyant effluent plume that also affects thermal stratification. The predicted absence of negative impacts on hypolimnetic DO depended critically on the high quality of the contemporary effluent with respect to oxygen demand. Using typical secondary effluent concentrations for CBOD and NBOD (20 and 5 mg/l, respectively) instead, resulted in negative DO impact (approaching 1 mg/l DO decrease).

4.4. Hydraulic Capacity and Outfall Alternative Considerations

The combinations of lake level and wastewater flow rate that define the hydraulic capacity of an offshore outfall/diffuser are shown in **Figure 10** for the existing offshore outfall 002, and for three 244-cm (96 in) diameter outfall scenarios (depth = 6, 10, and 14 m), each with 35 ports of diameter 25 cm (10 in). The historical record of lake level and daily average wastewater inflow at Metro for 1987-2010 (**Figure 10**) was used to evaluate the performance of offshore outfall/diffuser configurations with regards to: 1) hydraulic capacity; 2) occurrence and quantity of bypass (or relief); and 3) occurrence, frequency and volume of fully treated effluent and partially treated bypass at a nearshore relief outfall. Applying the 24-year (1987-2010) record of daily plant inflow, a total of 1894 × 10^4 m^3 (5.0 billion gallons) of bypass flow would occur (for the 5.5 m^3/s treatment capacity), which represents 0.84% of the total plant inflow (**Table 1**). For summer (June through September), the bypass volume would be 220 × 10^4 m^3 (0.58 BG), or 0.33% of total inflow (**Table 1**). For the example outfall/diffuser design, nearshore relief (hydraulic capacity of offshore outfall exceeded, points above the outfall lines of **Figure 10**) would occur on average only 2 days per year and <1 day per summer. Accordingly, the volume of partially treated bypass discharged nearshore would be greatly reduced (92% annually, 98% for June-September; **Table 1**). As a result, most of the bypass would experience much greater immediate dilution due to diffuser-induced mixing, and be discharged at a location that is a greater distance from the shoreline generally, and specifically from the mouth of Onondaga Creek (**Figure 1**), compared to contemporary conditions. Benefits would be observed even for the case of using the existing smaller offshore outfall 002. Bypass relief would occur on average 23 days per year, and 4 days per summer, and nearshore discharge of this partially treated wastewater (but mixed with fully treated effluent) would be reduced 59% annually and 68% in summer (**Table 1**). These hydraulic capacity analyses demonstrate that fully treated and bypass flows from Metro can be effectively delivered to stratified depths through a diffuser by gravity, without pumping the effluent.

The modifications to outfall facilities investigated here

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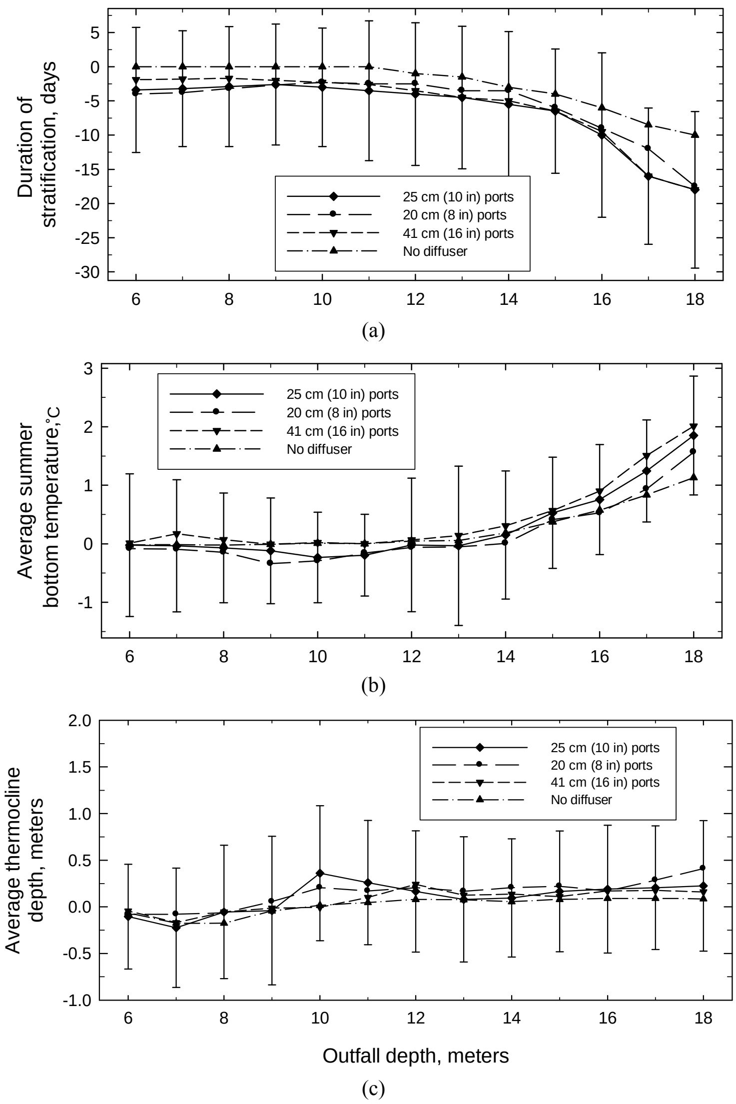

Figure 8. Model predictions of the median (for 22 years) change in stratification conditions for various outfall/diffuser designs relative to the existing shoreline outfall location: (a) duration of summer stratification; (b) average summer bottom temperature; and (c) average summer thermocline depth. These predictions are for a diffuser with 35 ports with 1 meter spacing. The vertical bars represent +/− one standard deviation for 22 summer average prediction for a diffuser with 25 cm (10 in) ports.

can be viewed in an additive or progressive manner, with alternative 1 through 4 (**Figure 5(b)**). As the alternative number increases the lower number alternatives are assumed to be included; *i.e*., these become components. The first alternative is the mixing of fully treated effluent with partially treated bypass. Nitrate monitoring that lead to identification of poor effluent dilution in the lake (**Figure 3**) did not take place during periods when bypass was occurring; the plumes detected were of fully treated effluent from outfall 001. Under contemporary high runoff conditions, the bypass discharge at outfall 002 leads to poorly diluted plumes containing higher pollutant concentrations [21] relative to plumes of fully treated effluent. Mixing of fully treated effluent with bypass (alternative 1, **Figure 5(b)**) would dilute the bypass by an average of 19:1, thereby substantially reducing the concentration of TP, TNH_3, and other pollutants in a poorly diluted effluent plume formed during a bypass period.

The existence of poorly diluted effluent plumes in the south end of the lake and the Onondaga Creek channel (**Figure 3**) is a result of not only the shoreline position but also the absence of a diffuser. If the outfall were extended away from the shoreline, but remained in the nearshore region (depth ≤ 6 m) with a diffuser (alternative 2, **Figure 5(b)**), the additional benefit of increased near field dilution of the mixed effluent with ambient lake water would be achieved. Additionally, the size of the near field mixing zone would be reduced, and its po-

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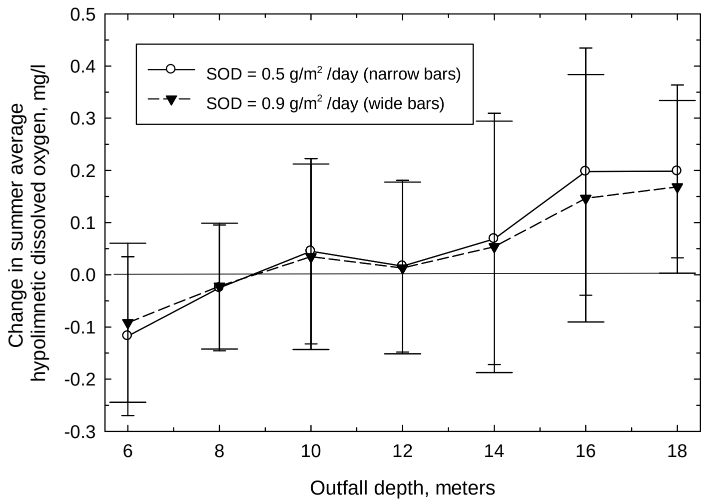

Figure 9. Model predictions of the median (for 22 years) change in summer average hypolimnetic dissolved oxygen concentration for a diffuser with 25 cm (10 in) ports associated with moving the outfall from the shoreline to an offshore depth, for SOD equal to 0.9 g/m^2/day (contemporary conditions), and 0.5 g/m^2/day (future conditions). The vertical bars represent +/− one standard deviation for 22 summer average predictions.

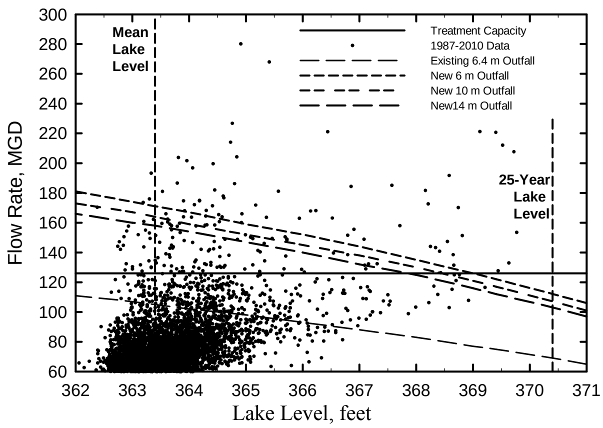

Figure 10. Hydraulic analysis of offshore outfall. Symbols show daily average flow and lake level for 1987-2010. Solid horizontal line is the treatment capacity (5.5 m^3/s or 126 MGD); sloping lines represents hydraulic capacity of the existing (outfall 002 at 6.4 m depth) and new outfall/diffuser alternatives at 3 depths with 25 cm (10 in) diameter ports.

sition would be moved away from the shoreline. When combined with mixing of treated effluent and bypass (both alternatives 1 and 2), a nearshore outfall/diffuser would effectively eliminate poorly diluted plumes of treated effluent, or of mixed effluent/bypass, from the south end of the lake and the Onondaga Creek channel. A particular case of a nearshore outfall/diffuser investigated here is the existing outfall 002 (example of alternative 2), which was the only outfall for this facility prior to 1979. The diameter of this existing outfall pipe (152 cm or 60 in) is smaller than that considered for newly constructed outfall scenarios (244 cm or 96 in). As a result, the existing outfall has lower hydraulic capacity, so that the frequency of shoreline relief for this outfall would be larger than for a new outfall. Due to the small number of ports (4), the existing diffuser achieves trapping and dilution that is moderately lower than what would be achieved for a new outfall at the same depth (**Figure 7**). The present condition of this existing 90-year old outfall pipe and pile foundation is also an important consideration. Contingent upon its condition, the existing outfall could represent a lower cost alternative to new construction. It would achieve an average trapping efficiency of 21% (**Figure 7(a)**) and near field dilution of 11:1 (**Figure 7(b)**).

Extension of a new outfall beyond the nearshore region to a position in stratified layers (depths > 7 m) would increase trapping in the summer months (**Figure 7(a)**), even for the case of no diffuser (alternatives 3, **Figure 5(b)**). The benefits of adding a multiport diffuser to a deep outfall (alternative 4, **Figure 5(b)**) are increased effluent trapping during the critical summer months (**Figure 7(a)**) and near field dilution (**Figure 7(b)**). Head loss in the diffuser would be a large component of the total outfall/diffuser head loss, though the frequency of occurrence of nearshore relief would be low (**Figure 10**).

4.5. Water Quality Benefits of a Deep Offshore Discharge

The potential benefits of a deep offshore discharge are considered in the context of the contemporary TDP_L budget for the lake, for the case of a 10 m depth outfall and diffuser with port diameter of 25 cm (**Figure 2**). This case was predicted to achieve a 38% reduction in loading from Metro to the upper productive layers for conservative constituents. This is the lower bound, or minimum, benefit because of the conservative assumption in the analysis. This would result in a nearly 14% reduction in the total summertime TDP_L (**Figure 2**); larger than is likely achievable from any single management action on the tributaries [22,23], but perhaps approachable through multiple tributary initiatives [32].

This representation of the potential benefit of a deep Metro outfall/diffuser is understated for at least two reasons. First, TDP would not behave conservatively at these metalimnetic depthsthat are below the vertical range of phytoplankton growth. TDP has two components, soluble reactive P (SRP) and dissolved organic P (DOP). The SRP fraction (15% of TDP in the Metro effluent) would be subject to multiple loss processes in such waters [33,34], particularly given the ongoing program of nitrate addition that blocks SRP release from the sediment [35]. Enzymatic losses of DOP are well known in productive (*i.e.*, upper) layers [17,21]. However, the behavior of DOP at these metalimnetic depths is more uncertain. Bacteria mediated losses are likely operative, though not presently quantified. Secondly, the contemporary tributary contributions to the summertime TDP_L to the upper waters (**Figure 2**) are overestimated because these do not accommodate the effects of plunging that prevails to varying extents for important tributaries [35-37].

This analysis has been considered in the context of potential implications for P loading because it is an important contemporary issue (e.g., irregular compliance with goal of 20 µg/l) for this urban lake. However, the general trapping benefit applies to all constituents of the effluent, such as pharmaceuticals [38], potentially toxic organics, and others, that may be of concern for other potential lake uses in the future.

5. Summary and Recommendations

Metro's unusual shoreline outfall, without a diffuser, offered a rare opportunity to demonstrate the benefits of diffuser-based discharge to stratified layers to achieve increased dilution and trapping. Alternate strategies from the existing outfall configuration were evaluated with two linked models, CORJET, a near-field diffuser submodel, and UFILS4, a far field one-dimensional heat and transport submodel. The two-way linkage was a critical feature, as a deep (near-bottom) discharge via a diffuser was demonstrated to significantly influence the lake's stratification regime. Outfall design features developed through application of the linked models were presented that would have the following benefits: 1) major reductions in the shoreline discharge of partially treated bypass flow during runoff events; 2) elimination of plumes of poorly diluted effluent; and 3) reduction of summertime loading of the effluent to the upper productive layers.

Key features of the design included mixture of the irregular bypass flow and fully treated effluent, extension of the outfall to metalimnetic depths, and addition of a multiport diffuser. Positioning the outfall in the metalimnetic depth interval between 10 and 14 m would reduce the summertime loading of conservative substances from Metro to the upper layers by approximately 40%, without significant effect on the stratification regime or the lake's hypolimnetic oxygen resources. Greater loading benefits would be realized for nonconservative constituents such as TDP. A minimum (conservative assumption) average reduction in total summertime TDP_L (*i.e.*, including tributaries) of approximately 15% would be achieved through implementation of the deep diffuser-based discharge strategy. Hydraulic capacity analyses established the fully treated effluent and bypass flows from Metro can be delivered to the targeted metalimnetic depths through a diffuser by gravity (*i.e.*, no pumping required). Topics not considered in this paper will be important to address as part of related management deliberations, including cost-benefit analyses, and improved kinetic insights on the behavior of TDP, and other constituents of interest, in metalimnetic depths.

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