# DYNAMIC PREDICTION OF WASTEWATER AERATION BASIN TEMPERATURE

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**Abstract:** A dynamic model was developed to predict activated-sludge aeration basin temperature. The model accounts for hourly or more frequent changes in weather conditions and input parameters such as wastewater temperature, aeration, and biological reaction. The model was verified using data from full-scale treatment plants located across the United States. The various heat transfer terms are evaluated, and the relative contribution from each is shown. Evaporation from aeration can be a major component. Surface aerators cool the basin much more than diffused aeration systems. Diffused aeration systems are preferred for cold climates. The heat of biological reaction is small, except for very high rate processes. The effect of changing weather conditions, such as a cold front, can be predicted. Local relative humidity has a major impact on cooling. The impact of design changes, such as covering an aeration basin, insulating walls, or changing retention times, can be determined using the developed model.

## INTRODUCTION

Temperature is an important factor affecting microbial activity, which is critical for maintaining efficient biological wastewater treatment. The impact of temperature on treatment efficiency, especially for ammonia oxidation (nitrification) can be significant. It also affects other parameters such as dissolved oxygen saturation and solids settling velocity (Metcalf and Eddy 1992). Controlling temperature is not normally a consideration in the design of aeration basins, since heating or cooling is cost prohibitive; however, incorporating factors affecting aeration basin temperature in the process design can reduce the range of temperature extremes. In this way overall process operation can be improved by reducing temperature variations. Incorporating factors that affect temperature into plant retrofits can also improve process performance. Covering aeration basins for air-quality purposes and replacing existing aeration systems with high-efficiency, fine-pore diffusers can both dramatically affect basin temperature.

This paper presents a dynamic model that evaluates the heat exchange components in an activated-sludge process and allows the designer to manipulate various process and design variables to evaluate their effects on temperature. The research was conducted to meet four objectives:

1. To create an accurate dynamic model by extending steady-state models
2. To refine the individual heat exchange equations to improve accuracy
3. To validate the model and evaluate its use and accuracy
4. To compile these efforts into an easily usable computer code

The model can show the diurnal and seasonal changes in temperature as well as the effects of design and operating parameters on temperature. The dynamic model extends the steady-state model developed by Talati (1988) and Talati and Stenstrom (1990), which was developed in part from earlier models by Argaman and Adams (1977), among others. The model was validated using data gathered in several wastewater-treatment plants across the United States. The plants have different climates and operating conditions. A comparison of measured and predicted temperatures was made to assess the accuracy of the model.

## BACKGROUND AND LITERATURE REVIEW

Temperature-prediction models for the activated-sludge process and aerated lagoons were first developed by Eckenfelder (1966), Ford et al. (1972), and Argaman and Adams (1977). These researchers relied on earlier research and experience with spray cooling ponds for the various heat transfer components of their models. Talati and Stenstrom (1990) reviewed previous research and developed a steady-state spreadsheet-based model that integrated the best parts of each previous model. They also improved the accuracy and convenience of some of the procedures to minimize the need for site-specific information. Brown and Enzminger (1991) presented a model that in most respects is identical to the Talati model. Their steady-state model uses the same set of heat gain/loss terms, with some minor differences in the exact forms of individual equations. They applied the model to the evaluation of a high-strength industrial waste in aboveground basins. Only one dynamic temperature prediction model (unpublished) was found (see acknowledgments). Its concepts were reviewed and included in this model, where appropriate. Several improvements were made to the individual terms in the heat balance, and they have been noted in the model development section.

## MODEL DEVELOPMENT

The model presented herein is applicable to a completely mixed tank under non–steady-state conditions. The assumption of complete mixing implies uniform basin temperature at any given moment. Eq. (1) is the basic energy balance equation for non–steady-state systems. This equation is derived from the generic equation for overall energy balance

$$\rho_w V c_{pw} \frac{dT_w}{dt} = \Delta H + \rho_w q_w c_{pw}(T_i - T_w) \quad (1)$$

where $\rho_w$ = density of water (kg/m$^3$); $V$ = volume of basin (m$^3$); $c_{pw}$ = specific heat of water (cal/kg °C); $\Delta H$ = enthalpy change between influent and effluent streams (cal/day); $q_w$ = volumetric flow rate (m$^3$/day); $T_w$ = temperature of basin water (°C); and $T_i$ = temperature of influent stream (°C).

The change in enthalpy is equivalent to the net heat gain or loss (i.e., $\Delta H = Q_t$). The heat exchange is the sum of the components that represent the paths of heat transfer. This is represented by (2) and depicted in Fig. 1.

$$Q_t = Q_{sr} + Q_p + Q_b - Q_{lr} - Q_e - Q_c - Q_a - Q_{tw} \quad (2)$$

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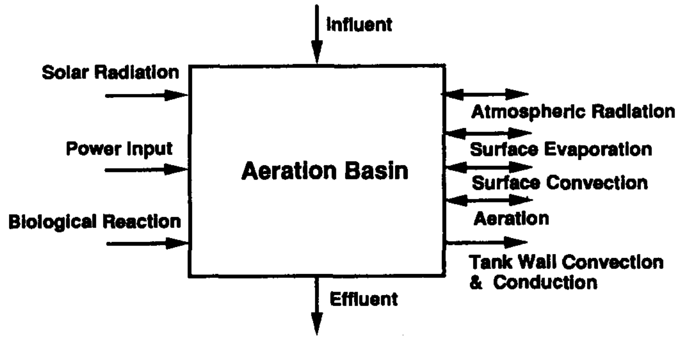


**FIG. 1. Temperature Model Heat Exchange Components**

where $Q_t$ = net heat gain or loss (cal/day); $Q_{sr}$ = solar radiation heat (cal/day); $Q_p$ = mechanical power heat (cal/day); $Q_b$ = biological reaction heat (cal/day); $Q_{lr}$ = long-wave (atmospheric) radiation heat (cal/day); $Q_e$ = surface evaporation heat (cal/day); $Q_c$ = surface convection heat (cal/day); $Q_a$ = aeration heat (cal/day); and $Q_{tw}$ = basin wall heat (cal/day).

The individual heat terms represent a heat exchange rate. Heat gain or loss is represented by the sign convention in (2), where the positive terms represent heat gains (increase in temperature) and the negative terms represent heat losses (decrease in temperature). The long-wave radiation, convection, evaporation, and basin-wall terms can be represented as gains or losses, with appropriate signs. The following sections discuss each term and improvements are noted.

## Solar Radiation

The method used by Talati (1988) is adapted from Thackston and Parker (1972), who used Raphael's (1962) approach. Raphael generated a function of solar insulation versus solar altitude from data collected by Moon (1940). A polynomial regress of his function was developed to facilitate calculation, as follows:

$$Q_{so} = (-0.06401 + 1.3341alt + 0.2008alt^2 - 0.0043alt^3 + 3.79e^{-5}alt^4 - 1.37e^{-7}alt^5)65102.26 \quad (3)$$

where $Q_{so}$ = clear sky solar radiation (cal/day); and $alt$ = solar altitude (degrees).

The direct effect of cloud cover on solar radiation is presented empirically in (4)

$$Q_s = (1 - 0.0071CC^2)Q_{so} \quad (4)$$

where $CC$ = cloud cover in tenths (0–10).

## Long-Wave (Atmospheric) Radiation

The heat exchange from long-wave radiation is based on the Stefan-Boltzman's fourth power radiation law. The net effect of long-wave radiation is the difference between incoming and back radiation as expressed by (5)

$$Q_{lr} = [\varepsilon\sigma(T_w + 273)^4 A_s] - [(1 - \lambda)\beta\sigma(T_a + 273)^4 A_s] \quad (5)$$

where $A_s$ = aeration basin surface area (m$^2$); $\varepsilon$ = emissivity of the water surface (0.97); $\sigma$ = Stefan-Boltzman constant [$1.17 \times 10^{-3}$ cal/(m$^2$ day °K$^4$)]; $\lambda$ = reflectivity of water surface (0.03); $\beta$ = atmospheric radiation factor; and $T_a$ = ambient air temperature (°C).

The atmospheric radiation factor $\beta$ is a function of cloud cover, cloud height, and vapor pressure. Raphael (1962) modified the empirical equations for $\beta$, developed by Anderson (1954), to disregard cloud height. This produced a series of functions for different cloud covers. Talati (1988) determined the slope and intercept of each line and then required that $\beta$ be evaluated by picking values and evaluating the linear equation. A polynomial curve was fitted to the slope and intercept terms in the equations that represent the individual cloud-cover lines.

Anderson used data from a study performed in a cooler climate to make his correlations. The data are generally below a vapor pressure of 25 millibars (0.75 in. Hg). Raphael extrapolated Anderson's data to 2.54 cm Hg (1.0 in. Hg). In warmer temperatures, the vapor pressure can be even higher than 2.54 cm Hg, which requires even further extrapolation of Anderson's data to evaluate long-wave radiation. The effect of a changing $\beta$, including Raphael's extrapolation, on atmospheric heat and final aeration basin temperature, was evaluated to determine its significance on overall model accuracy.

The impact of $\beta$ on basin temperature is linear. $\beta$ can be expected to range from approximately 0.75 to 1.05. The heat-quantity change is $-2.65 \times 10^8$ cal/day for a change in $\beta$ of 0.1. The basin temperature has a rate of change of 0.019°C for 0.1 unit change in $\beta$, which, over the expected range of the extrapolation, translates to a 0.057°C temperature difference. Although this analysis does not address the validity of extrapolating $\beta$, it does indicate that the extrapolation from the largest measured value of $\beta$ (approximately 0.94) to an expected maximum of 1.05, for all the probable uses of the model, would change the basin temperature only 0.06°C. This accuracy is well within the overall accuracy of the model, and extrapolation of $\beta$ will not produce a significant error.

The values of emissivity $\varepsilon$ and reflectivity $\lambda$ used in (5) were not modified from Talati's analysis (1988).

## Surface Convection

Heat transfer by surface convection occurs as a result of the temperature difference between the water and the air above it. It is also influenced by the convective transfer coefficient, which is a function of wind velocity, and is assumed to be the same as the vapor transfer coefficient. Eq. (6) was developed by Novotny and Krenkel (1973) and modified to this final form by Talati and Stenstrom (1990)

$$Q_c = \rho_a c_{pa} h_v A_s (T_w - T_a) \quad (6)$$

$$h_v = 392 A_s^{-0.05} W \quad (7)$$

where $h_v$ = vapor phase transfer coefficient; $\rho_a$ = density of air (kg/m$^3$); $c_{pa}$ = specific heat of air (cal/kg °C); and $W$ = wind velocity at treetop level (m/s).

## Evaporation

Heat transfer by evaporation is a function of the water and air temperature difference, wind velocity, and humidity. Talati (1988) used the following equation developed by Novotny and Krenkel (1973), which has not been changed

$$Q_e = [1.145 \times 10^6(1 - r_h/100) + 6.86 \times 10^4(T_w - T_a)]\exp(0.0604T_a)WA_s^{0.95} \quad (8)$$

where $r_h$ = relative humidity (%).

## Aeration

Heat exchange from aeration consists of two components: sensible heat loss in the form of convection, and latent heat loss in the form of evaporation. The quantities of heat, the proportion of convective to evaporative heat exchange, and the exact form of the governing equation, are dependent on the type of aeration device—either surface or diffused. The total heat exchange from aeration is the sum of the sensible and latent heat components

$$Q_a = Q_{as} + Q_{al} \tag{9}$$

where $Q_{as}$ = sensible heat exchange; and $Q_{al}$ = latent heat exchange. The sensible or convective heat exchange for surface aeration is

$$Q_{as} = \rho_a c_{pa} h_v A_s (T_w - T_a) c_{time} \tag{10}$$

$$h_v = 392(NF)^{-0.05} W \tag{11}$$

where $N$ = number of aerators; $F$ = aerator spray area (m$^2$); and $c_{time}$ = conversion factor for time = 86,400 s/day.

Note the difference in the vapor-phase transfer coefficient as compared to its use in surface convection. In this case the basin surface area is replaced with the aerator spray area multiplied by the number of aerators. The vapor-phase coefficient $h_v$ is calculated using the spray area $NF$ as opposed to surface area $A_s$ shown in (7). The aerator spray area must be determined experimentally or obtained from the manufacturer. The spray area for one manufacturer's low-speed mechanical aerator as a function of aerator power was published by Talati and Stenstrom (1990).

The overall equation for heat exchange contains the basin surface area $A_s$. To be exact, this term should theoretically be the surface area of all water droplets in the spray. This area would be difficult to determine experimentally, and the basin surface area $A_s$ is used as a surrogate.

In the case of diffused aeration systems, the exit air temperature is assumed to be the same as the aeration basin liquid temperature, and the vapor-phase heat transfer is not needed. The temperature increase due to power input (temperature rise from air compression) is calculated as a power input, shown later. The heat exchange is calculated from

$$Q_{as} = q_a \rho_a c_{pa} (T_w - T_a) c_{time} \tag{12}$$

where $q_a$ = air flow rate (m$^3$/s).

The second component of the aeration heat exchange is the evaporation, or latent heat, term. This equation was developed by Novotny and Krenkel (1973) and modified to this final form by Talati (1988). It is used without further modification and is given by (13)

$$H_{al} = \frac{M_w q_a L c_{time}}{100R} \left\{ \frac{v_w[r_h + h_f(100 - r_h)]}{(T_w + 273)} - \frac{v_a r_h}{(T_a + 273)} \right\} \tag{13}$$

where $M_w$ = molecular weight of water; $L$ = latent heat of vaporization (cal/kg); $R$ = universal gas constant (62.361 mm Hg-L/gmole °K$^4$); $v_w$ = vapor pressure of water at basin temperature (cal/kg); $v_a$ = vapor pressure of water at air temperature (cal/kg); and $h_f$ = exit air humidity factor.

For surface aerators the air flow rate must be estimated from the spray area and wind velocity as

$$q_a = NFW \tag{14}$$

The exit air humidity factor is a measure of the humidity of the air that exits through the aerator spray area. In subsurface systems the air has a longer contact time and is assumed to be water saturated as it reaches the surface of the basin; therefore, $h_f$ is assumed to be 1.0. For the surface aerators, the contact time is less and $h_f$ is less than 1.0. Values used were obtained from Talati (1988), who empirically fit this parameter to the data analyzed in his study.

## Power Input

Surface aerators are partially submerged in the basin and are in direct contact with the liquid. Hence, all the mechanical energy supplied to the impellers is available in the form of heat energy to the wastewater. The energy is initially in the form of kinetic energy, but is transformed to heat energy before it leaves the basin. In diffused aeration systems, heat is added to the air stream in the process of compression. As the gas rises through the liquor and expands it will also cool; therefore not all this heat is available for sensible transfer. The heat added is represented by the blower inefficiency (1 minus the efficiency). Heat losses in motors and gearboxes, which are perhaps 10–20% of the wire power, are neglected. This assumption is justified and will be confirmed in a sensitivity analysis herein. These heat exchange terms are represented by

$$Q_p = c_{hp} P(1 - \eta/100) \quad \text{for subsurface aeration} \tag{15}$$

and

$$Q_p = c_{hp} P(\eta/100) \quad \text{for surface aeration} \tag{16}$$

where $c_{hp}$ = conversion factor for horsepower to calories (1.54 × 10$^7$ cal/day/hp); $P$ = wire horsepower; and $\eta$ = efficiency (%). The efficiency $\eta$ is usually known from the aeration system design.

## Biological Reaction

Biological reactions provide heat to aeration basins because such reactions are exothermic. Heat released from a biological process depends on the composition of wastewater, the mass of organics removed, and the biomass produced. If experimental measurements are not available, cell yields can be used. Argaman and Adams (1977) assumed a cell yield of 0.25 grams volatile suspended solids (VSS)/gram of chemical oxygen demand (COD) removed. Their approach, after introducing a variable cell yield is represented by

$$Q_b = (3.3 - 5.865y)\Delta S \tag{17}$$

where $y$ = cell yield (g of VSS/g of COD); and $\Delta S$ = substrate removal rate (g of COD/day).

## Conduction through Basin Walls

Heat is lost from conduction and convection through basin walls and bottom. Municipal aeration basins are often below ground and industrial basins are often above ground, while some basins are a combination. The heat transfer coefficients for concrete to air and concrete to earth are different. Therefore, this model has included two terms: one for submerged wall area exposed to air and one for submerged area exposed to the ground. The ground term should also include the area of the basin bottom. Fig. 2 illustrates this arrangement. The governing equations are, for area exposed to air and to ground, respectively

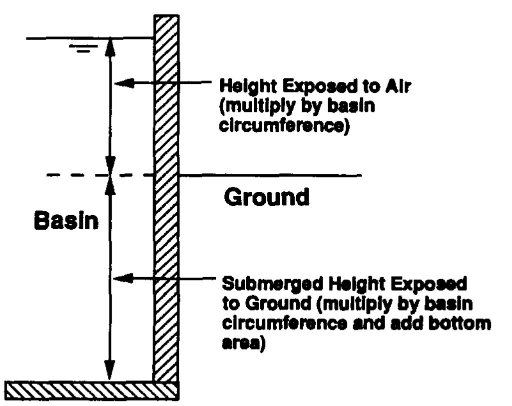


FIG. 2. Basin Wall and Bottom Schematic

$$Q_{tw} = U_a A_w (T_w - T_a) \quad (18)$$

$$Q_{tw} = U_g A_g (T_w - T_g) \quad (19)$$

where $U_a$ = overall heat transfer coefficient for conduction to air (cal/day m² °C); $A_w$ = area exposed to air (m²); $U_g$ = overall heat transfer coefficient for conduction to ground (cal/day m² °C); $A_g$ = area exposed to ground (m²); and $T_g$ = temperature of the ground (°C).

Determination of overall heat transfer coefficient is analogous to electrical resistance equations, and the approach in "Sewage" (1959) is used as follows:

$$U = \frac{1}{\frac{1}{K_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \cdots + \frac{1}{K_o}} \quad (20)$$

where $x_1$, $x_2$ = thickness of materials (cm); $k_1$, $k_2$ = thermal conductivity of materials (cal/day m² °C cm); $K_i$ = surface conductance at the air-surface area inside basin (cal/day m² °C); and $K_o$ = surface conductance at the air-surface area outside basin (cal/day m² °C).

The factor $1/K_i$ becomes zero if liquid is touching the surface of the wall (there would be a portion of wall in contact with gas in the case of an enclosed digester). If the outside wall is in contact with air an approximate value of $K_o$ is taken as $7.0 \times 10^5$ cal/m²day °C ("Sewage" 1959). If the wall is surrounded by an earth embankment greater then 3-m thick, $K_o$ becomes $1/17 \times 10^5$ cal/m² day °C ("Sewage" 1959).

### Integration Technique

The energy balance equation for this non–steady-state system, (1), must be solved for $T_w$. Once all the individual heat exchange equations described in the previous sections are summed together, as shown by (2), the overall equation is quite complex. An analytical solution would be difficult; therefore, a second-order Euler integration is used to solve for $T_w$. Eq. (1) is solved for $dT_w/dt$, which can then be evaluated. This procedure can be written in the following general form:

$$T_{1/2} = T|_t + \frac{\Delta t}{2} \frac{dT_w}{dt}\bigg|_t \quad (21)$$

$$T = T|_t + \Delta t \frac{dT_w}{dt}\bigg|_{t+\Delta t/2} \quad (22)$$

The initial condition is the initial basin temperature. Since this may not always be known, especially in a design problem, the steady-state form of (1) can be iteratively solved to obtain $T_w$. This is very similar to the technique used by Talati (1988).

## MODEL CALIBRATION AND VALIDATION

Five wastewater plants across the United States were solicited for their help in providing data to calibrate and validate the model. A questionnaire was sent to each plant to obtain all necessary operating data and plant design information. This information was requested for the months of July 1991 and January 1992. Summer and winter months were selected to evaluate two extremes of ambient conditions. A summary of the plants analyzed in this study is presented in Table 1.

The input data required for the model consists of time invariant data that falls into three groups: site-specific data, process data, and modeling information. Some of the parameters may vary with time, but have been approximated as constants for these examples if no dynamic information was available. These parameters, as they are presented in the data entry spreadsheet form, are listed in Table 2. Time varying parameters are shown in Table 3.

The meteorological parameters were obtained from the National Climatic Data Center (NCDC) in Asheville, North Carolina. Meteorological data for the five plant locations were requested on an hourly basis; plant operating data were only available as daily averages or single measurements. No direct solar radiation measurements were available; therefore, (3) and (4) were used to estimate solar radiation.

Validation was performed by running the model with all required input data and comparing the output to the actual measured temperature values. For each of the five plants evaluated, it was necessary to make various assumptions to obtain a complete set of input files. Often, only biochemical oxygen demand (BOD) data were available; COD removal is the preferred model input, and assumptions were made to convert BOD to COD in these situations. The potential error in making many of the assumptions is negligible for these examples, which is shown later.

### Milwaukee

The evaluation of the South Shore WWTP (wastewater-treatment plant) in Milwaukee was one in which only assumptions of higher confidence were needed to create a complete set of input data. For some of the other plants, more assumptions were required to obtain a complete input data set. This plant treats approximately 4.38 m³/s (100 mgd) of wastewater with primary clarification, activated-sludge process, and final disinfection.

It was necessary to make the following assumptions to complete the input data set:

- The number of tanks in service varies and an average number of basins was used for calculating basin volume and surface area. The model is capable of using time-varying aeration tanks, but too little information was available for these examples.
- The wall area exposed to the ground is assumed constant, although varying the number of tanks in service changes the total area exposed to the ground.
- When COD was not measured, BOD data were converted using historical values for COD/BOD ratios.
- In calculating the cell yield, the total suspended solids (TSS) were multiplied by 0.7 (an approximation of VSS/TSS ratio for longer sludge age), and the calculated COD values were used.
- Compressor efficiency was assumed.
- Plant influent temperature, not aeration tank influent temperature, was supplied. No corrections were made to estimate the heat losses in the primary clarifiers, unless otherwise noted.
- Plant effluent temperature, not aeration basin effluent temperature, was supplied. Secondary clarifier and chlorine contactor areas were used to adjust for temperature change due to evaporation, convection, and long-wave and solar radiation.

A comparison of predicted to measured temperatures for January and July for the Milwaukee plant are shown in Figs. 3 and 4. January and July both show excellent fit for the predicted values; the residuals are mostly in the ±1°C range. The actual measured values for this plant were given in 1°F intervals, suggesting that the accuracy of the actual measurements are only ±1°F (±0.55°C).

### Sacramento

Sacramento has a high-purity oxygen activated-sludge plant with covered aeration basins. There is no long-wave radiation, solar radiation, evaporation, or convection from the surface.

TABLE 1. Treatment Plant Summary

| Plant (1) | Location (2) | Approx. capacity ($m^3$/day) (3) | Aeration type (4) | Primary[a] clarifiers (5) | Aeration[a] basins (6) | Secondary[a] clarifiers (7) |
|---|---|---|---|---|---|---|
| South Shore WWTP | Milwaukee | $3.8 \times 10^5$ | Diffused | 16; 12.2 × 49 × 3 | 28; 113 × 9.1 × 4.6 | 24; 34.1 dia. × 4.5 |
| Chino Basin Regional Plant 1 | Chino, Calif. | $5.7 \times 10^4$ | Surface | 10; 53 × 6.1 × 3.4<br>1; 30.5 dia. × 2.7 | 3; 73.2 × 39.6 × 5.4 | 4; 37 × 4.3<br>2; 39.6 × 1.2 |
| Terminal Island Treatment Plant | Los Angeles | $7.6 \times 10^4$ | Diffused | 6; 76.2 × 6.1 × 3.7 | 9; 91.4 × 9.1 × 4.6 | 18; 46 × 61 × 3.7 |
| Pulp mill | Maine | $1.3 \times 10^5$ | Diffused | 1; 67.1 dia. × 4.6 | Irregular shape area = 9,000 $m^2$<br>12; 3.8 deep | 3; 88 × 20 × 4.6 |
| Sacramento Regional Treatment Plant | Sacramento | $5.7 \times 10^5$ | Diffused-HPO | 12 | 8 trains of 4 basins; basin - 14.6 × 4.6 × 9.1 | 16; 39.6 dia. |

[a]Data shows number of devices followed by dimensions in meters.

TABLE 2. Time Invariant Parameters

| Parameter (1) | Units (2) |
|---|---|
| (*a*) Site-specific data | |
| Latitude of site | degrees |
| Longitude of site | degrees |
| Ground temperature | °C |
| (*b*) Process data | |
| Basin surface area | $m^2$ |
| Basin volume | $m^3$ |
| Submerged wall area exposed to air | $m^2$ |
| Heat transfer coefficient to air | cal/$m^2$/day/°C |
| Submerged wall area exposed to ground | $m^2$ |
| Heat transfer coefficient to ground | cal/$m^2$/day/°C |
| Power input to aerator | hp |
| Efficiency of aerator | % |
| Power input to compressor | hp |
| Efficiency of compressor | % |
| Cell yield | g VSS/g COD |
| (*c*) Modeling information | |
| Start date and time | m/d/yy h:mm |
| Duration of run time | days |
| Print time interval | h:mm |
| Initial basin temp. estimate | °C |

TABLE 3. Time Variant Parameters

| Parameter (1) | Units (2) |
|---|---|
| Aerator spray area | $m^2$ |
| Air flow rate | $m^3$/s |
| Air temperature | °C |
| Cloud cover | tenths (1–10) |
| Influent flow | $m^3$/day |
| Influent temperature | °C |
| Number of aerators | — |
| Relative humidity | % |
| Solar radiation | cal/day |
| Substrate removal rate | kg COD/day |
| Wind speed | m/s |

The sensible heat exchange is effected only by the flow of oxygen gas leaving the system, whereas the latent heat (evaporation) is effected by the entire gas flow leaving the process. This results because only dry oxygen is introduced to the covered aeration basins, and it is generally at a different temperature than the liquid temperature. The remaining part of the gas flow is evaporated from the liquid, and there is no sensible heat change, since it is assumed to be at the same temperature as the liquid. A comparison of predicted to measured temperatures for January and July are shown in Figs.

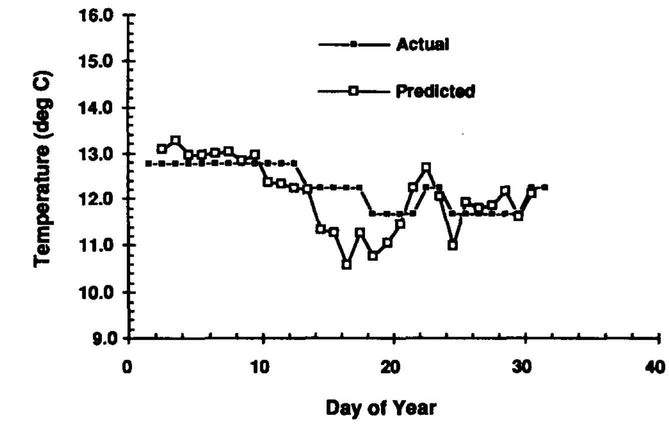


FIG. 3. Comparison of Actual and Predicted Temperatures for January at Milwaukee

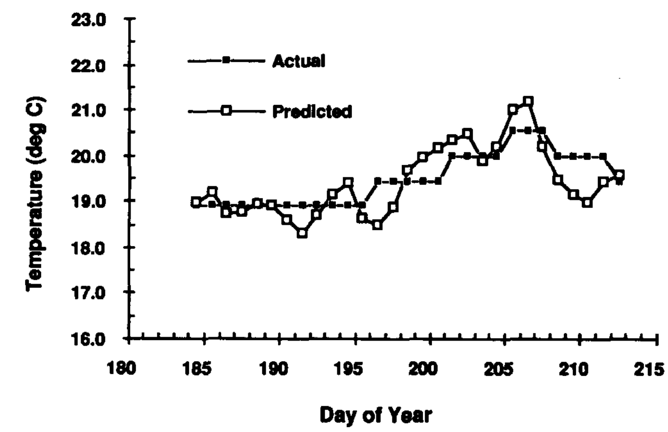


FIG. 4. Comparison of Actual and Predicted Temperatures for July at Milwaukee

5 and 6, respectively. January and especially July both show excellent fit for the predicted values.

## Chino Basin and Terminal Island

These two plants are located in Southern California and do not measure influent temperature, which is a critical input parameter. To produce a complete data set, a time-invariant influent temperature was assumed for the input, and various temperatures were evaluated by trial and error to produce the best fit. Both plants are otherwise excellent examples, as few additional assumptions were needed. Ground temperature, compressor/aerator efficiency, and VSS/TSS conversion

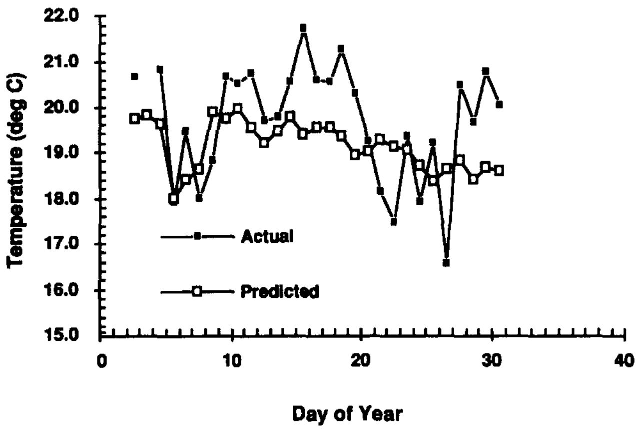


FIG. 5. Comparison of Actual and Predicted Temperatures for January at Sacramento

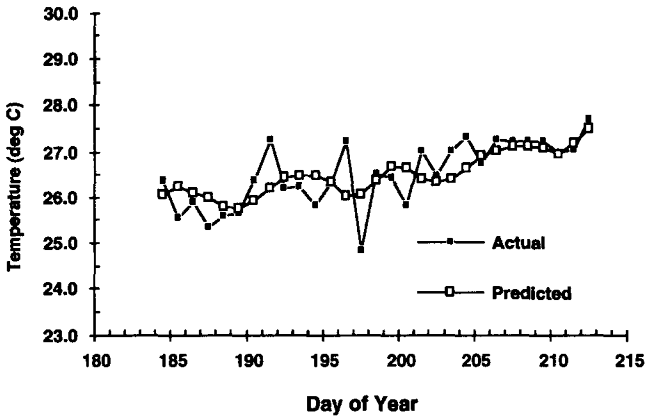


FIG. 6. Comparison of Actual and Predicted Temperatures for July at Sacramento

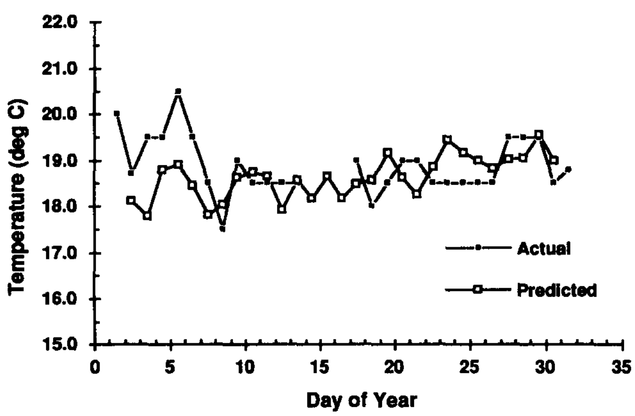


FIG. 7. Comparison of Actual and Predicted Temperatures for January at Chino Basin

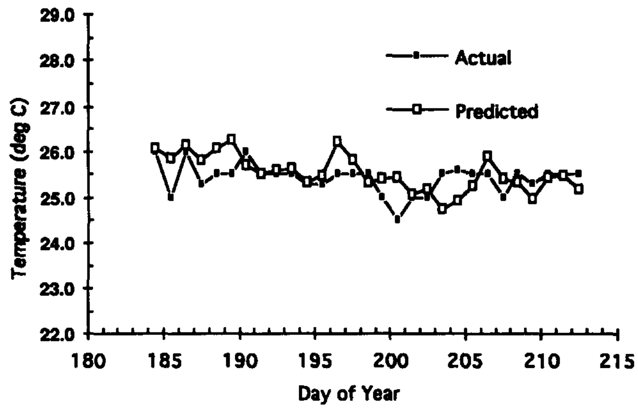


FIG. 8. Comparison of Actual and Predicted Temperatures for July at Chino Basin

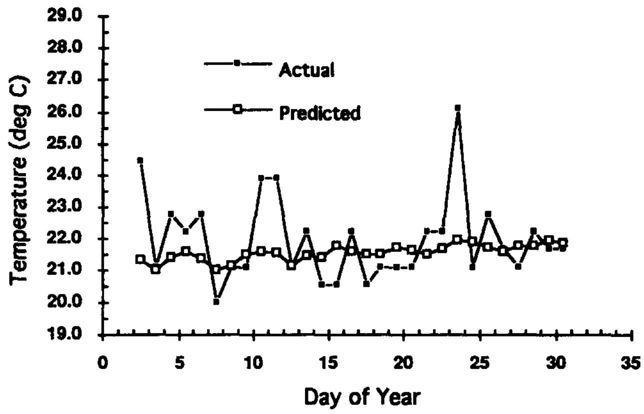


FIG. 9. Comparison of Actual and Predicted Temperatures for January at Terminal Island

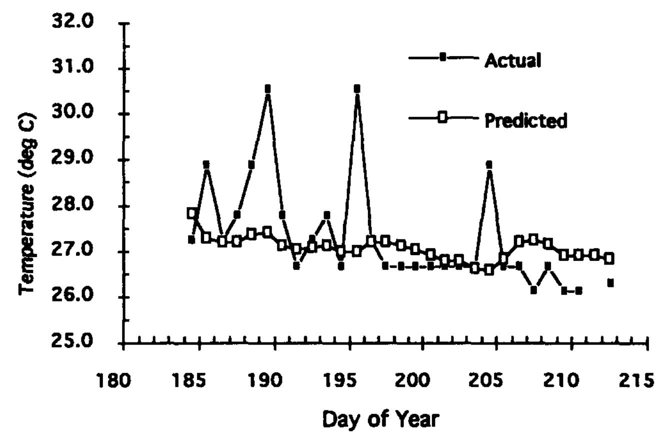


FIG. 10. Comparison of Actual and Predicted Temperatures for July at Terminal Island

were the only other assumptions made. Predicted temperature and residuals for both months and plants are shown in Figs. 7–10. The fits would probably be even better if influent temperature had been available. Terminal Island receives pretreated petroleum refinery wastewater, which can be over 40°C. This may have contributed to some of the variability in the measured temperatures.

## Pulp Mill

This plant is located in New England and treats approximately 1.53 $m^3/s$ (35 mgd) of wastewater with primary clarification, activated sludge, and final disinfection. Several assumptions had to be made to complete this data set

- Ground temperature, required for the losses through the walls and floor, was estimated based on the ambient temperature.
- The basin floor is earthen and walls are concrete; details and the exact construction are unknown. The heat transfer coefficient was estimated.
- COD was not measured; BOD removal data were converted to COD removal (COD/$BOD_5$ ratio ranged from 1.5 to 3.5) based upon literature references (DeLorme 1990).

- Compressor efficiency was assumed.
- Plant influent temperature, not aeration basin influent temperature, was supplied. No corrections were made.
- Plant effluent temperature, not aeration basin effluent temperature, was supplied. Secondary clarifier and chlorine contactor areas were used to adjust for temperature change due to evaporation, convection, and long-wave and solar radiation.

The initial simulation of this data set produced temperatures that were 2–3°C higher than measured. Inspection of the heat proportions showed a large contribution from biological heat. The estimate for the COD/BOD ratio of 2.5 was reduced to 1.5, and the subsequent simulation produced lower basin temperature estimates, which were still excessive. Since the closest location with meteorological data was from a location approximately 160 km (100 mi) from the plant, the data were adjusted to account for the change by modifying the ambient temperature and relative humidity, based on the average differences between the mill's location and the location with meteorological data. After adjustment, the measured and calculated data agreed relatively well, as shown in Figs. 11 and 12. The actual temperature had a large overall and daily fluctuation, which the simulation tracks very well. The actual measured values for this plant were given in 1°F intervals, suggesting that the accuracy of the actual measurements are only $\pm 1°F$ ($\pm 0.55°C$).

## Parameter Influence and Model Sensitivity

The relative influence of the individual heat exchange components varies greatly with type of aeration, the season, and all the various operating parameters. This section discusses the relative influence of each heat exchange term and the sensitivity of the model to the parameters.

The proportions of each heat exchange term for all plants during January and July are depicted in Fig. 13. Chino Basin, the only surface aeration plant evaluated in this study shows aeration heat as its major heat component. The other plants have a relatively small proportion due to aeration heat. Sacramento, Milwaukee, and the pulp mill all have dramatic changes between seasons. Chino Basin and Terminal Island, both in Southern California, where climatic changes are mild, are almost unchanged between seasons. This information dramatically points out the necessity of accounting for temperature in locations with changing seasonal meteorological conditions. The power component for all plants is relatively small; therefore, neglecting motor and gearbox inefficiency, which is perhaps 10–20% of the power shown in Fig. 13, is reasonable.

The sensitivity of the model to the input parameters was evaluated by selecting those heat components showing the most influence and then determining what variables in those equations were most significant. To make a comparison of relative effects, a baseline temperature and plant were selected. The July time-variant input data for the Milwaukee plant were averaged and used as a baseline. The model was run with this new set of input data to produce a baseline temperature. Different input parameters were then changed, one at a time, to evaluate their effects. The parameters evaluated were basin area, substrate removal rate, cell yield, and all four meteorological conditions.

Each parameter was varied to the extremes of its expected range or changed by a dramatic, but plausible, amount: basin

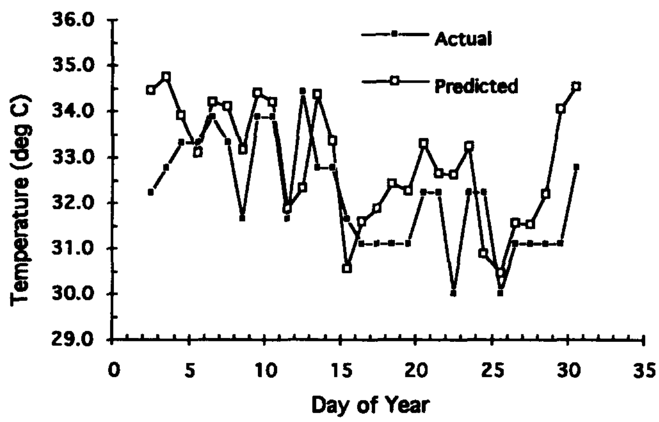


**FIG. 11. Comparison of Actual and Predicted Temperatures for January at Pulp Mill**

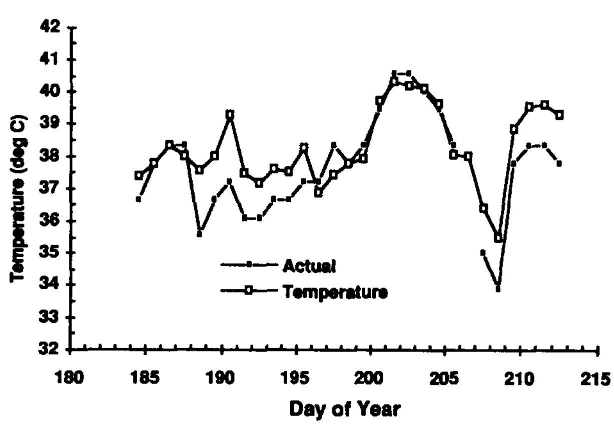


**FIG. 12. Comparison of Actual and Predicted Temperatures for July at Pulp Mill**

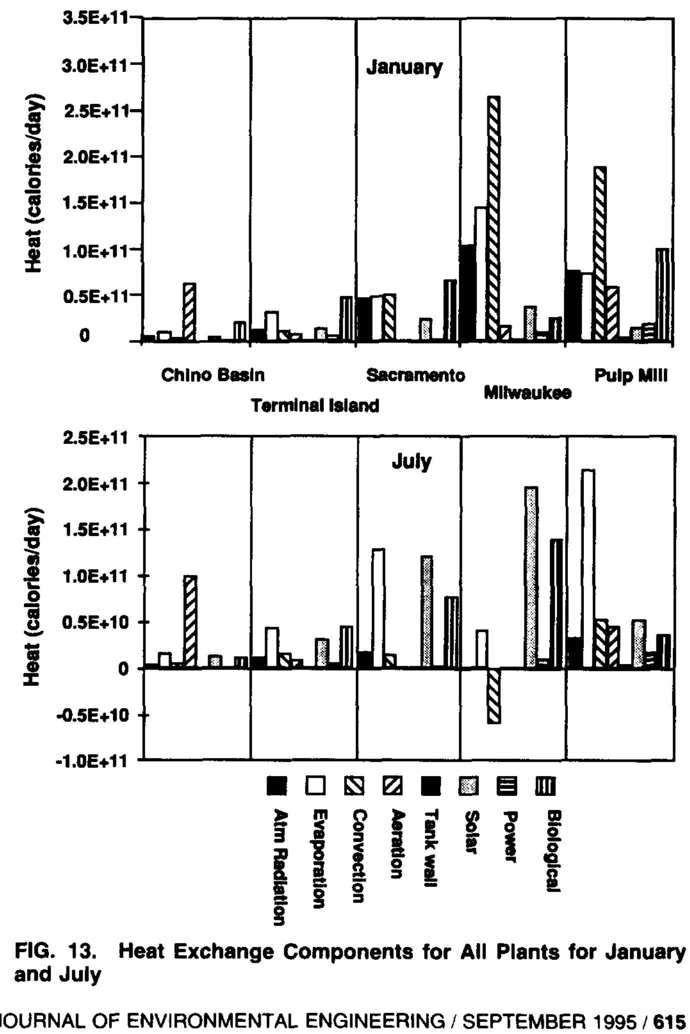


**FIG. 13. Heat Exchange Components for All Plants for January and July**

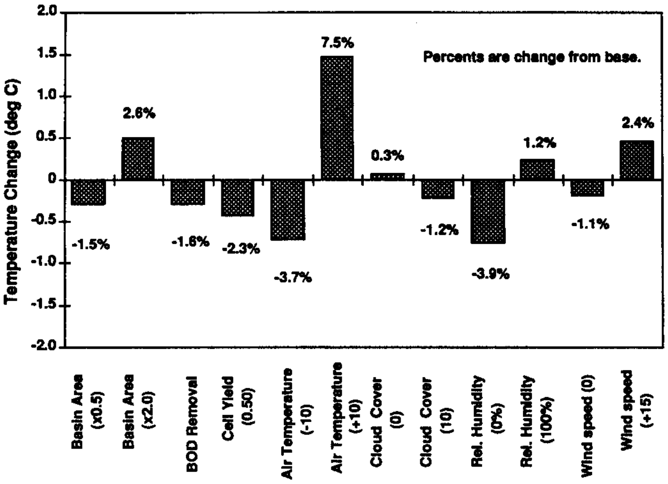


FIG. 14. Heat Transfer Sensitivity Analysis

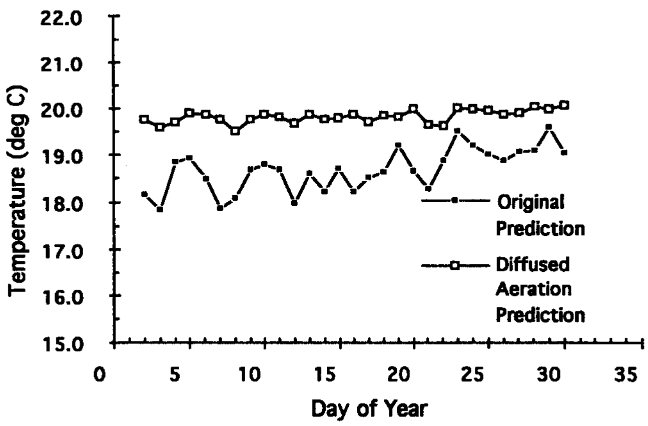


FIG. 15. Effect of Changing Chino Basin to Diffused Aeration (January)

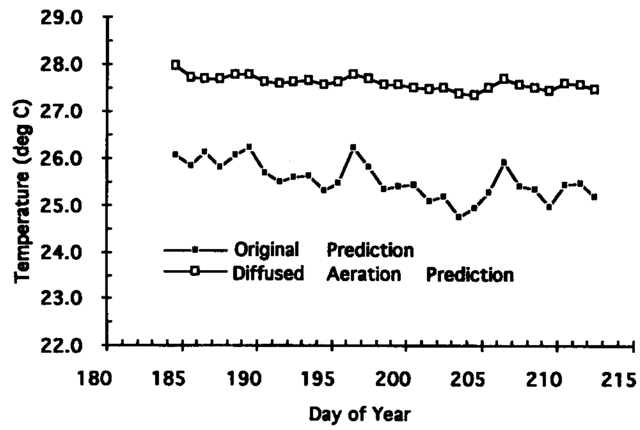


FIG. 16. Effect of Changing Chino Basin to Diffused Aeration (July)

area at one-half and twice the normal area; substrate removal rate using BOD instead of COD; cell yield at 0.5 instead of 0.23; ambient temperature at ±10°C of average; cloud cover at 0 and 10; relative humidity at 0% and 100%; and wind speed at 0 and 20 m/s. The results of these evaluations are shown in Fig. 14. The ambient temperature has the most significant effect on predicted temperature. Many of the other parameters produced aeration basin temperature changes as much as 0.5°C.

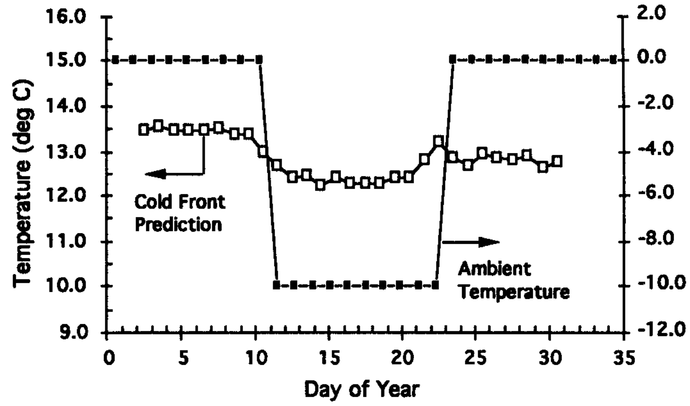


FIG. 17. Effect of a Cold Front on Aeration Basin Temperatures in Milwaukee

## ENGINEERING SIGNIFICANCE AND DISCUSSION

In this section the model is used to evaluate the effects of changing physical and operational parameters as well as the effects of changing meteorological conditions. This analysis shows the sensitivity of basin temperature to each parameter, and could be used to assist engineers in including more or less cooling in their treatment-plant designs. Three scenarios were evaluated: changing surface aeration to diffused aeration and vice versa; covering an aeration basin; and sudden ambient temperature drop due to abnormal weather. The objective of this analysis is to demonstrate the impact of certain key design decisions on aeration basin temperature.

### Aeration Type

Conversion between surface and diffused aeration was accomplished by assuming a process oxygen transfer efficiency of 1.1 kg $O_2$/kW·h (1.8 lb $O_2$/hp-hr) for surface aerators. An oxygen transfer efficiency for fine bubble diffusers was assumed for the diffused system; values of 18% and 10% were assumed for Chino Basin and Milwaukee, respectively. Surface aerators evaporate more water than subsurface aerators; therefore, surface aeration should cool a basin more than a diffused aeration system.

Figs. 15 and 16 show the effect of switching Chino Basin plant to diffused aeration. The temperature rose by approximately 1.5°C in January and 2°C in July.

For Milwaukee the model shows that surface aerators would not be practical in winter, with the temperature dipping to nearly 0°C. Interestingly, the effects in July are just the opposite, and the temperature rises. Due to high ambient temperature there is a convective heat transfer to the aerator spray. High ambient humidity reduces the cooling effects of evaporation; cooling would be expected if the relative humidity were low.

### Aeration Basin Covering

To simulate covering an aeration basin the only change necessary was to set the basin area to zero. Basin area is a multiplier in long-wave radiation, solar radiation, evaporation, and convection; setting basin area to zero essentially eliminates those terms from the calculation. For the Milwaukee plant in July, the temperature was lowered by approximately 0.5°C. The temperature difference in this case may be smaller than expected in other situations. The high ambient humidity in Milwaukee in July makes evaporation less insignificant. If the analysis had been conducted for a less humid climate, evaporation heat losses would have been significant.

### Cold Front

The effects on basin temperature of a sudden change in ambient temperature may be significant. A sudden drop in aeration basin temperature may impact nitrification and treatment efficiency. The ambient temperature for the Milwaukee plant in January showed a cold front. To clearly see the impact of this change on aeration basin temperature, two step changes were simulated. The step changes were selected to approximate the magnitude of the cold front observed in Milwaukee. A 10°C and 20% relative humidity change was simulated, and the results are shown in Fig. 17. The rate of decline and recovery of basin temperature can be observed; the changes appear to take 2–3 days to fully manifest themselves. This indicates that a short-duration aberration in weather conditions may not have a significant impact, but longer than 2–3 days may cause a significant drop in basin temperature. The slight increase in temperature on day 22 results because of influent wastewater temperature change.

## CONCLUSIONS AND SUGGESTED FUTURE WORK

A dynamic model was developed and validated to predict activated-sludge aeration basin temperature. Data were collected from five treatment plants and the NCDC. In cases where insufficient plant data were available, appropriate assumptions were made. The model predicted both average and dynamic changes in aeration basin temperature usually within ±1°C accuracy, except for Terminal Island. Improved calculation procedures for solar radiation input, ranges of the physical parameter regressions, and biological heat calculation had an overall effect of improving model accuracy, as compared to previous models (Talati and Stenstrom 1990).

Several major conclusions were made from the application of this model:

- Surface aeration plants can have a major portion of their heat loss from evaporation due to the impact of the surface spray. Diffused aeration evaporation losses are much less.
- Ambient temperature is a significant factor affecting several heat components and the model output.
- A sudden change in ambient temperature, such as a cold front, may take 2–3 days to impact the basin temperature. Therefore, operators should be aware of the potential drop in basin temperature and plant performance under these circumstances.
- Covering aeration basins seems to have a minimal effect on basin temperature of diffused systems where the ambient humidity is high, and, hence, evaporation is low.
- Accuracy of temperature predictions was ±0.5°C for Milwaukee, Chino Basin, and Terminal Island, and ±1.0°C for Sacramento and the pulp mill. The Terminal Island predictions were more variable, perhaps because of industrial wastewater contributions.

Plants expecting to upgrade or expand their facilities should perform a temperature analysis to determine if process design options can materially impact plant aeration basin temperature and plant performance. To perform such an analysis, additional data beyond what are normally collected may be required. Aeration basin influent and effluent temperatures are required. Our experience is that only one daily measurement is usually collected. Meteorological data are required as well as other process data, such as COD destruction rate and blower/motor efficiencies.

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

$alt$ = solar altitude (degrees);
$A_g$ = area exposed to ground (m$^2$);
$A_w$ = area exposed to air (m$^2$);
$CC$ = cloud cover (0–10);
$c_{hp}$ = conversion factor for horsepower to calories (cal/hp);
$c_{pa}$ = specific heat of air (cal/kg °C);
$c_{pw}$ = specific heat of water (cal/kg °C);
$F$ = aerator spray area (m$^2$);
$\Delta H$ = enthalpy change between influent and effluent streams (cal/day);
$h_f$ = exit air humidity factor;
$h_v$ = vapor phase transfer coefficient;
$k_1$, $k_2$ = thermal conductivity of materials (cal/hr m$^2$ °C cm);
$K_i$ = surface conductance at the air-surface area inside basin (cal/hr m$^2$ °C);
$K_o$ = surface conductance at the air-surface area outside basin (cal/hr m$^2$ °C);
$L$ = latent heat of vaporization (cal/kg);
$M_w$ = molecular weight of water;
$N$ = number of aerators;
$P$ = wire horsepower;
$Q_a$ = aeration heat;
$Q_{al}$ = latent heat exchange (cal/day);
$Q_{as}$ = sensible heat exchange (cal/day);
$Q_b$ = biological reaction heat (cal/day);
$Q_c$ = surface convection heat (cal/day);
$Q_e$ = surface evaporation heat (cal/day);
$Q_{lr}$ = long-wave (atmospheric) radiation heat (cal/day);

$Q_p$ = mechanical power heat (cal/day);
$Q_{so}$ = clear sky solar radiation (cal/day);
$Q_{sr}$ = solar radiation heat (cal/day);
$Q_t$ = net heat gain or loss (cal/day);
$Q_{tw}$ = basin wall heat (cal/day);
$q_a$ = air flow rate ($m^3$/s);
$q_w$ = volumetric flow rate ($m^3$/day);
$R$ = universal gas constant (62.361 mm Hg-L/gmole °K);
$r_h$ = relative humidity (%);
$\Delta S$ = substrate removal rate (g COD/day);
$T_a$ = ambient air temperature (°C);
$T_g$ = temperature of the ground (°C);
$T_i$ = temperature of influent stream (°C);
$T_w$ = temperature of basin water (°C);
$U_a$ = overall heat transfer coefficient for conduction to air (cal/day $m^2$ °C);
$U_g$ = overall heat transfer coefficient for conduction to ground (cal/day $m^2$ °C);
$V$ = volume of basin ($m^3$);
$v_a$ = vapor pressure of water at air temperature (cal/kg);
$v_w$ = vapor pressure of water at basin temperature (cal/kg);
$W$ = wind velocity at treetop level (m/s);
$x_1, x_2$ = thickness of materials (cm);
$y$ = cell yield (g of VSS/g of COD);
$\beta$ = atmospheric radiation factor;
$\varepsilon$ = emissivity of water surface (0.97);
$\eta$ = efficiency (%);
$\lambda$ = reflectivity of water surface (0.03);
$\rho_a$ = density of air (kg/$m^3$);
$\rho_w$ = density of water (kg/$m^3$); and
$\sigma$ = Stefan-Boltzman constant [$1.17 \times 10^{-3}$ cal/($m^2$ day °$K^4$)].