J. ENVIRONMENTAL SYSTEMS, Vol. 22(2) 189-197, 1992-93

A SCHEME FOR GENERATION OF CONTROLLED WATER TEMPERATURE BEACHES

M. SEGAL
Iowa State University, Ames

ABSTRACT

The relatively low water temperature in subtropical sea beaches during fall and spring prevents bathing during fair weather days. Similarly, low water temperature limits the bathing period during the summer in many mid-latitude beaches. Generation of a warm water beach is suggested by using the cooling water of electric power plants. The concept is developed in this article in light of beach design considerations, water and air temperature climatology, the heat balance of the beach water, and warm beach attractiveness. It is concluded that in many locations in the United States development of thermally controlled beaches would extend the annual bathing period. The beach development and operational economic considerations are likely to vary significantly from one potential site to another, and would have to be examined in detail in future feasibility studies.

1. INTRODUCTION

Many conventional electric power plants (EPPs) are located at the seashores. EPP condensers are cooled by water pumped from the sea (termed henceforth thermal waste water—TWW). Local increases in seashore water temperatures often occur at beaches near TWW outfalls. However, offshore advection and diffusion of the TWW plume reduces the potential for significant increase in water temperature of such beaches. Various studies have quantified the effect of TWW on beach water temperature fields (e.g., studies reported in Sengupta and Lee [1]). The TWW temperature is determined by the EPP generator's mode of operation. If only a portion of the EPP electric load capacity is used, the increase in TWW temperature is typically only several °C. However, when the EPP generators operate at full capacity, the increase may reach as high as 10°C for conventional plants and 19°C for nuclear plants [2, 3]. Typically the hourly water outflow of TWW is very large;

doi: 10.2190/2YUF-XYTH-86DN-GMGW
http://baywood.com

for example, for a 1000 megawatt conventional EPP that operates in full capacity and with 30 percent thermal waste generation, the estimated TWW outflow is approximately 26,000 m^3 per hour.

Some uses for TWW have previously been considered, including: 1) desalinization of sea water, 2) maintaining temperature in agricultural greenhouses, and 3) controlling water temperatures for aquaculture during the cold season [1, 4, 5]. The economic aspects of these schemes for using TWW apparently have not been very attractive. There is room, then, for new ideas. This article suggests that TWW be used to make a controlled temperature beach (CTB) for bathing at subtropical seashores during the fall and spring, and at cool-water mid-latitude seashores during the summer.

On subtropical coasts, CTBs are likely to be considered if: 1) seawalls are constructed to prevent mixing of the TWW with the lower temperature coastal water; 2) the thermal losses of the CTB water are mild; and 3) fair weather conditions prevail during fall and spring (i.e., a high percentage of clear days with relatively high air temperatures and low wind speeds appropriate for bathing). In cool-water mid-latitude coasts, extension of the summer beach bathing period is mostly related to the applicability of 1) and 2). Considering the crowded beaches during the summer's comfortable water temperatures, it seems likely that artificially raised water temperatures would be attractive to many bathers. This article provides a preliminary analysis prospect for controlled thermal beaches. General evaluations of CTB thermal influx exchanges, environmental impacts, and design consideration are given in Section 2. Estimates of CTB thermal losses are presented in Section 3. General discussion is provided in Section 4.

2. GENERAL EVALUATION

The annual variation of beach water temperature follows patterns similar to those in deep-water offshore locations. However, the relatively shallow beach area water reaches 1°-2°C higher daytime temperatures in the summer, and about 1°-2°C lower temperature in the winter [6]. The shallow beach water also has characteristic diurnal temperature variations. Table 1(a) provides the monthly average satellite observed coastal water temperature, T_w, the maximum air temperature, T_a, and the daily global solar irradiance, R_{sd}, in several subtropical locations in the United States, for the period October-June. A 5° to 10°C increase in beach water temperature in these locations would generate reasonably warm water for bathing during much of the fall and spring. Average maximum monthly air temperatures imply that many days during this period are adequate for bathing in a CTB. In mid-latitude locations during the summer, the average daytime air temperature is ideal for beach recreational activity. As implied by Table 1(b), increase in T_w in these locations by developing CTB would improve beach conditions and extend the beach season. The potential is greatest for California beaches, where water temperatures are relatively low due to cold ocean currents.

Table 1. Monthly Average Maximum Meteorological Shelter Temperature[a]

Location		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
(a) *Subtropics*										
Los Angeles, CA	T_a	27.9	21.7	18.6	17.6	18.6	21.7	25.6	29.8	32.8
	T_w	(18.8)	(16.5)	(15.0)	(14.9)	(14.7)	(14.0)	(14.5)	(14.7)	(15.0)
	R_{sd}	[18.5]	[13.7]	[11.3]	[12.0]	[16.0]	[20.8]	[24.5]	[28.0]	[29.5]
San Diego, CA		23.2	21.2	18.9	18.1	18.7	18.9	19.8	20.8	21.7
		(19.5)	(17.3)	(16.0)	(16.0)	(16.0)	(15.3)	(15.5)	(15.6)	(16.2)
		[18.7]	[13.9]	[11.8]	[12.5]	[16.3]	[21.0]	[24.8]	[28.2]	[29.6]
Brownsville, TX		29.5	25.0	22.3	21.4	22.9	24.9	27.9	30.6	32.6
		(26.8)	(24.1)	(22.0)	(22.1)	(21.0)	(21.0)	(24.1)	(26.8)	(29.1)
		[20.7]	[18.0]	[15.0]	[16.5]	[19.5]	[21.0]	[22.5]	[24.0]	[24.5]
Galveston, TX		27.9	21.7	18.6	17.6	18.6	22.1	25.6	29.8	32.8
		(26.0)	(23.1)	(19.9)	(19.0)	(18.5)	(19.0)	(22.8)	(26.0)	(28.5
		[18.7]	[15.0]	[11.7]	[12.0]	[17.3]	[21.5]	[24.5]	[27.7]	[27.7]
Miami, FL		29.3	26.8	25.1	24.3	25.0	26.6	28.1	29.7	31.1
		(26.7)	(25.0)	(24.8)	(24.5)	(24.2)	(24.5)	(25.2)	(26.9)	(28.2)
		[19.6	[17.2]	[15.0]	[16.5]	[19.3]	[20.5]	[22.3]	[24.0]	[24.3]

Location	May	Jun	Jul	Aug	Sep	Oct
(b) *Mid-Latitudes*						
San Francisco, CA	19.4	21.2	22.2	22.1	23.2	21.4
	(10.8)	(11.0)	(13.0)	(14.5)	(14.2)	(14.1)
Cape Hatteras, NC	23.8	27.6	28.8	28.6	26.6	21.8
	(22.0)	(25.1)	(27.0)	(27.1)	(28.0)	(25.3)
Atlantic City, NJ	21.7	26.2	28.8	27.9	24.4	19.2
	(15.0)	(20.0)	(24.8)	(25.0)	(22.0)	(18.0)
Nantucket, MA	15.5	19.9	23.5	23.6	20.7	—
	(10.0)	(15.0)	(20.0)	(20.0)	(17.0)	(—)
Portland, ME	—	22.8	26.4	25.8	21.2	—
	(—)	(12.0)	(15.0)	(16.0)	(15.0)	(—)

[a] T_a(°C) (based on [8]); monthly average near-shore sea-surface temperature, T_w(°C) (based on [10]), in parentheses; estimated clear-days average daily global solar irradiance, R_{sd} (MJ) (based on [11]), in brackets.

A scheme for CTB design is presented in Figure 1(a). It consists of the EPP and a water aqueduct (or pipe), A, transferring TWW to the CTB. The aqueduct length is assumed to be at most several kilometers, where the water flow is forced by gravity. The CTB is *enclosed* by a seawall (seawalls oriented parallel to the shore are common in many beaches and they can be supportive when applicable in the construction of the CTB). In the CTB locations, I and O indicate, respectively, the intakes and outlets for the TWW. Assuming, for example, CTB of 100 × 100 m size with an average depth of 1.5 m, then a volume of TWW sufficient to fill the CTB can be supplied by a 1000 megawatt conventional EPP within thirty-five minutes or so. Such an EPP can potentially support simultaneously the operation of several CTB sites of that size. Development of several adjacent CTBs in one location may provide economical and operational advantages. When electricity generation varies diurnally, corresponding variations in TWW temperature result. The timing of TWW replenishments of the CTB accordingly should take into account the diurnal temperature cycle of the TWW. Appropriate design of the TWW intake and the CTB water outlets should reflect TWW supply rates and desired discharge rates of the lower-temperature CTB water. One possible design is illustrated in Figure 1b: the density of the TWW inflow at point I is lower than the original CTB cooler water, and therefore accumulates as a top layer. The

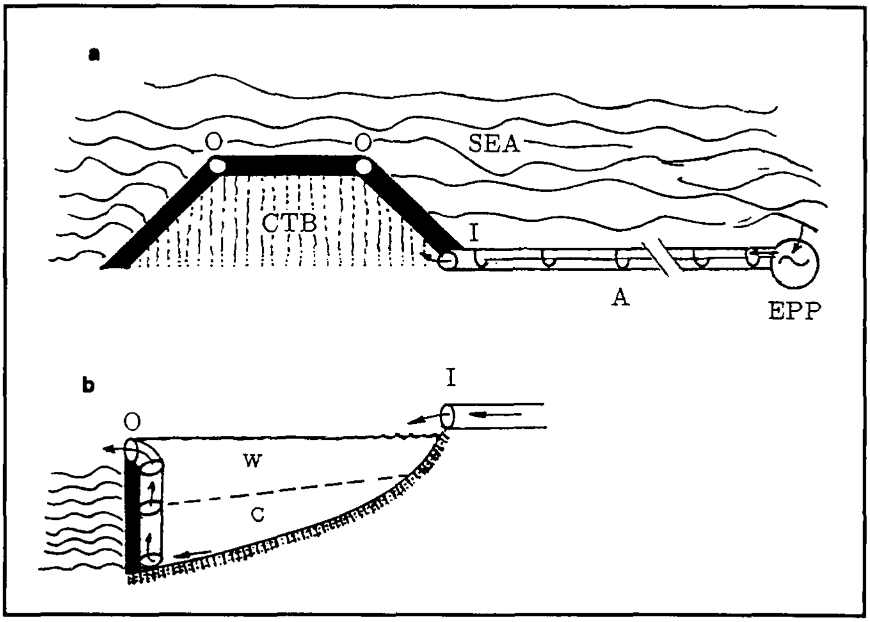

Figure 1.

increased hydrostatic pressure results in discharge of the cooler bottom water through the outlet pipes at the points O. Although no chemical treatment is needed, hygienic considerations may dictate replenishing of TWW to the CTB once a day (even when not needed due to thermal considerations).

3. HEAT BALANCE AT THE CTB

When the EPP operates at full capacity most of the day, the replenishing of peak temperature TWW can be done relatively quickly (meanwhile, the CTB can be closed to bathers). In these circumstances the CTB water easily can be maintained at a relatively high temperature. However, when the TWW has diurnal temperature and outflow variations, replenishing the CTB with warm water should be scheduled at specific times in order to maximize the thermal gain.

Evaluation of the potential water temperature increases in the CTB is provided in the following subsections.

Thermal Losses in the Aqueduct

The total thermal losses in the aqueduct are related to various parameters, including its length and vertical cross-section area, A, flow speed, U, and the thermal conductivity of its walls. Assume an open aqueduct that is buried in ground with $A = 1$ m^2, wall width of 0.1 m, wall thermal conductivity of 4 W·m^{-1}C^{-1} and temperature difference across the wall of 5°C. The corresponding thermal losses to the ground through the walls are ~200 W·m^{-2}, and ~600 W·m^{-1} for unit length of square-cross-section aqueduct. The losses from the aqueduct open water surface are estimated to be <325 W·m^{-2} (see the scaling in the next sub-section). Assuming also that the waterflow in the aqueduct has a speed $U = 4$ m·s^{-1} (which corresponds to elevation difference of ~3 m between the points EPP and I), then along a distance of $L \approx 1$ km (t = 250 s) the thermal losses, H_a from water volume of 1 m^3 correspond to ~$925 \cdot L \cdot (C_W \cdot U \cdot A)^{-1} \approx 0.05$°C, ($C_w = 4.17 \cdot 10^3\ J \cdot kg^{-1}$ is the water specific heat). Therefore, even if the aqueduct length is several kilometers, the total thermal loss is ≤0.2°C. For larger aqueduct cross-section area (which is applicable when large or multi-CTB development is considered), the water temperature decrease is even smaller.

Thermal Losses in the CTB

To estimate potential thermal losses in the CTB, as a first approximation we assume well-mixed water in the CTB and horizontal uniformity of the temperature field. The temporal change of T_ω is then given by

$$\frac{dT_w}{dt} = \frac{1}{\rho_w \cdot C_w \cdot d}\left[(R_S + R_I - R_O - H_S - H_L)_E - H_{LOS} + H_{GAIN}\right], \qquad (1)$$

where

ρ_ω	= water density ($kg \cdot m^{-3}$)
d	= the CTB average water depth (m)
R_S	= solar radiative flux reaching the water surface ($W \cdot m^{-2}$)
R_I	= incoming atmospheric long wave radiative flux to the water surface ($W \cdot m^{-2}$)
R_O	= (σT_ω) outgoing long wave radiative flux emitted from the water surface ($W{\cdot}m^{-2}$); σ = the Stefan-Boltzmann constant.
H_S	= the sensible heat flux at the water surface ($W{\cdot}m^{-2}$)
H_L	= the latent heat flux at the water surface ($W{\cdot}m^{-2}$)
H_{GAIN}	= heat gain by TWW inflow ($W{\cdot}m^{-2}$)
H_{LOS}	= heat losses through the bottom and the walls of the CTB.

In equation 1 the thermal exchange with the atmosphere is represented by the sum of the E terms. The gain of heat due to TWW is represented by H_{GAIN}, which can be easily determined based on the EPP operational data. In the following, the accumulated effect of the environmental terms on the CTB water temperature is evaluated for fair weather conditions separately for daylight and nocturnal hours. Conservative values are chosen for the input parameters.

Assuming an average daylight period of τ_d = 10 h for the *fall-spring period in the subtropics*, following Table 1(a) the daytime mean clear-sky solar radiation reaching the water surface is $\overline{R}_s \sim 300\ W{\cdot}m^{-2}$ in mid-winter and $\overline{R}_s \sim 600\ W{\cdot}m^{-2}$ in fall and spring. This radiation is almost entirely absorbed by the water and by the CTB bottom surface (most of the solar energy absorbed at the surface affects the water through heat conduction). For approximation of the net longwave radiation, ΔLW, at the water surface, the Brunt empirical formula [7] gives:

$$\Delta LW = R_I - R_O = \sigma T^4(1 - a - bq_a^{0.5}), \tag{2}$$

where q_a is the near-surface specific humidity, T is the average of T_ω and the near surface air temperature, T_a, and $a = 0.44$ and $b = 0.10$. Adopting $T_\omega = 22°C$, $T_a = 20°C$ for the daytime ($T_a = 10°C$ for the nighttime), and $q_a = 7g \cdot kg^{-1}$ (e.g., [8]), the average daytime value of ΔLW is $\sim -130\ W{\cdot}m^{-2}$.

The surface fluxes H_S and H_L can be estimated by the relations:

$$H_S = -C\rho_a C_p(T_a\text{-}T_\omega)U_a$$

$$H_L = -C \cdot \rho_a \cdot L(q_a - q_\omega)U_a, \tag{3}$$

where C is a transfer coefficient dependent on the air thermal stratification over the CTB, U_a the near-surface wind speed, ρ_a the air density, C_p the specific heat of air, L the latent heat of evaporation and q_ω the saturation specific humidity at the CTB water temperature. Following Kondo [9] and accounting for advection contributions, $C = 2 \cdot 10^{-3}$ is considered a high value which is appropriate for conservative evaluations.

The following atmospheric surface layer conditions are assumed as typical: $U_a \leq 4m \cdot s^{-1}$ (stronger wind speed would reduce bathers' attraction to the CTB); and $q_\omega \sim 16g \cdot kg^{-1}$. Based on equation 3, for these environmental conditions it is estimated that in the daytime $H_S + H_L \leq 220W \cdot m^{-2}$ and in the nighttime $H_S + H_L \leq 325\ W \cdot m^{-2}$. The thermal losses, H_{LOS} (at the CTB bottom through conduction into the soil and into the seawalls) are estimated to be $\leq 100\ W \cdot m^{-2}$. Using equation 1, assuming period $\tau = 10$ h of daylight and $d = 1.5$ m, and the thermal flux values indicated above, the mid-winter maximum daytime change in the CTB water temperature is given by

$$\Delta T_d = \frac{\tau \cdot 3600}{\rho_w \cdot C_w \cdot d}[R_s + \Delta LW - (H_S + H_L) - H_{LOS}] \geq -0.9°C \tag{4}$$

When fall and spring are considered, $\overline{R}_S \approx 600\ W \cdot m^{-2}$, resulting in $\Delta T_d \geq -0.9°C$.

For the nocturnal period ($\tau = 14$ h), with $\Delta LW = -130\ W \cdot m^{-2}$ and $H_S + H_L \leq 325\ W \cdot m^{-2}$ the corresponding cooling of the CTB water for the extreme input values is

$$\Delta T_n = \frac{\tau \cdot 3600}{\rho_w \cdot C_w \cdot d}[\Delta LW - (H_S + H_L) - H_{LOS}] \geq -4.5°C \tag{5}$$

Based on the above evaluation, it is suggested that the extreme nocturnal TWW temperature reduction in mid-winter due to the H_A, and the E and H_{LOS} terms is $\geq -4.5°C$ compared with its value at the EPP outlet. However, in most situations the TWW replenishment is likely to occur in the morning hours before the CTB opens to bathers, so that the nocturnal temperature fall usually would be irrelevant. In general, during the daylight hours slight increase in the TWW temperature can be considered in fall and spring compared with mild decrease in mid-winter. Overall, thermal losses are estimated to be small considering the contribution of H_{GAIN} (which may reach the equivalent of 10°C for conventional EPP) and the operational needs of CTBs. It is worth noting that when the CTB consists of several adjacent and separate bathing areas, the timing of TWW supply can be flexible (when one of the bathing areas is closed due to replenishing of TWW, the others can be used by the bathers).

Considering the *summer in mid-latitudes*, the daytime environmental thermal gains are higher than those evaluated for the fall-spring period, whereas the nocturnal thermal loss are lower. Thus CTB thermal management for these situations is improved.

4. CONCLUSIONS

Generation of CTBs is suggested in: 1) subtropical locations where extension of the bathing in beaches to the fall and spring can be achieved, and 2) mid-latitude locations with relatively cool water beaches during the summer. Such beach resorts are likely to attract considerable recreational activity and related tourism, thereby contributing to the local economy. CTBs would provide extended period of bathing similar to that found in regular beaches in the summer. This activity is prevented in the subtropics primarily because of uncomfortably low beach water temperatures. In the summer, CTB would extend beach activity of earlier morning hours, and appropriate illumination could allow bathing in evening hours. In the relatively cool water of the high mid-latitudes CTB may provide an improved and extended period of bathing during the summer (in the U.S. most notably in the beaches of California). This article examined the water heat balance in the CTB. It was concluded that thermal losses in CTBs are likely to be small during a 12h period (within such periods it is assumed that the water is in any case replenished).

More detailed feasibility studies for CTBs at particular sites should assess:

1. comfort perceptions of the bathers, taking into account the local climate, sea water temperatures, and diurnal and monthly variations in TWW temperatures.
2. The direct revenue from the CTB operation and its contribution to the local economy, compared to development, capital, and maintenance costs. Economic considerations are likely to vary significantly from one potential CTB site to another, mostly because of differences in the construction costs. Factors such as the size of the CTB and the length of the aqueduct clearly are economically significant.
3. Operational aspects of the CTB, including: 1) coordination with the electric utility supply of TWW; 2) management of an appropriate water exchange in the CTB that prevents development of algae or any health hazards; 3) appropriate timing and amount of inflow of TWW to the CTB.

ACKNOWLEDGMENTS

The author thanks R. Arritt, R. Kubesh, A. Keamel, M. Poreh, K. Oliver, and L. Stadler for their comments and R. Solwa for preparation of the manuscript.

REFERENCES

1. S. Sengupta and S. S. Lee (eds.), *Waste Heat Utilization and Management*, Hemisphere, Washington, 1010 pp., 1983.
2. J. R. Clark, *Coastal Ecosystem Management*, John Wiley and Sons, New York, 928 pp., 1977.
3. T. Wildi, *Electric Power Technology*, John Wiley and Sons, New York, 698 pp., 1981.
4. M. Olszewski (ed.), *Utilization of Reject Heat*, Marcel Dekker, Inc., New York, 190 pp., 1983.
5. J. D. Keenan and R. N. Amundsen, Assessment of Waste Heat Utilization Technologies Overview, *Journal of Environmental Systems, 19*, pp. 115-134, 1990.

6. G. L. Picard, *Descriptive Physical Oceanography*, Pergamon Press, Oxford, 233 pp., 1979.
7. G. J. Haltiner and F. L. Martin, *Dynamical and Physical Meteorology*, McGraw Hill, 470 pp., 1957.
8. *Climates of the States*, NOAA, Gale Research Company, Detroit, Michigan, 1185 pp. (2 Volumes), 1978.
9. J. Kondo, Air-sea Bulk Transfer Coefficients in Diabetic Conditions, *Bound. Layer. Meteor., 9*, pp. 91-112, 1975.
10. *Oceanographic Monthly Summary*, National Weather Service, National Environmental Satellite, Data, and Information Service, Vol. 12, 1991.
11. *Solar Radiation Energy Resource Atlas of the United States*, SERI/SP-642-1037, SERI, Golden, Colorado, 167 pp., 1981.

Direct reprint requests to:

M. Segal
Department of Agronomy
Iowa State University
Ames, IA 50011-1010