Evaporative Loss from Receiving Waters
Due to Heated Effluent Discharges

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Executive Summary

The task of quantifying evaporative loss from receiving waters due to heated effluent discharges is one of several being performed by ICPRB with funding support from Maryland Department of Natural Resources - Water Resources Administration under the general subject of freshwater inflows to the Chesapeake Bay. Most environmental studies of heated water discharges concentrate on the biological effect of the increased heat content of the receiving water. The focus of this study is on the determination of the unaccounted off-site evaporative loss of water from the receiving waters due to that increase in temperature. The methods and results described in this report will be useful in determining a portion of consumptive use which is expected to grow as the population and industrial activity expands in the Chesapeake Bay Basin.

Drawing a consensus from the references, the only significant heat budget terms which are affected by water temperature are back-radiation, conduction (convection), and evaporation. Since it is an increase in temperature brought about by the discharge of heated cooling water which is of concern in this study, the analysis is restricted to those three terms.

Again, drawing a consensus from the cited reference material; approximately 60 percent of total heat loss from lakes and rivers is by evaporation. The evaporative process can be

condensed and simplified by reliance on the fact that it is the latent heat of vaporization which ultimately governs evaporation.

Thus, the evaporative loss from receiving waters due to heated effluent discharges can be expressed as a function of discharge flow and temperature, and temperature of the receiving water.

$$m = (0.60\ f\ S\ dT) / (596 - 0.52\ Tr)$$

where:

m = mass of evaporated water, grams/day

f = mass of effluent discharge, grams/day

S = specific heat of water, 1 cal/gram/^oC

dT = difference in temperature between discharge and receiving water body, ^oC

Tr = temperature of the receiving water body, ^oC.

The necessary information for the calculation of off-site evaporative losses was compiled for fourteen plants which discharge into waters which eventually flow into the Chesapeake Bay. The plants are located on the Patuxent River, the Patapsco River, the Potomac River, and the Chesapeake Bay and include the major dischargers of heated effluent in Maryland.

The results of the analysis show that off-site evaporative loss in the summer months is close to 50 mgd and in the winter months close to 33 mgd. As percentages of the discharged water the evaporative loss on average represents about 0.6 percent of the total discharge from the cooling system in the summer and about 0.5 percent of the total discharge in the winter months. The percentages vary between 0 and 2.5 and are primarily dependent on the temperature difference between the discharge water and the receiving water. This is useful information for the estimation of future water needs.

Introduction

The task of quantifying evaporative loss from receiving waters due to heated effluent discharges is one of several being performed by ICPRB with funding support from Maryland Department of Natural Resources - Water Resources Administration under the general subject of freshwater inflows to the Chesapeake Bay. Most environmental studies of heated water discharges concentrate on the biological effect of the increased heat content of the receiving water. The focus of this study is on the determination of the off-site evaporative loss of water from the receiving waters due to that increase in temperature.

The combination of freshwater inflows and marine salt water under tidal influence makes the Chesapeake Bay a very productive estuary. Salinity is a major factor in determining the quality of water in the Bay and thus the quantity and variety of biological resources to be found there. An increase in salinity would aggravate the presence of MSX disease in oysters and reduce the spawning and nursery areas for the soft clam and several important varieties of finish. It would increase the range of the woodboring shipworm and reduce the habitat of food sources which are important to sportfish and waterfowl. Therefore, the need exists to ensure that future use will progress in an orderly and economically efficient manner, and to balance the demand for consumptive use of freshwater with the aggregate impact of that consumption on the resources of the Bay.

It is assumed that reductions in freshwater inflow to the Chesapeake are not desirable for the health of beneficial biological systems, but can be tolerated during average and high flow periods. However, severe stress and death may result from extreme low flows of even short duration.

The main causes of the disruption to the natural pattern of freshwater flow to the Bay include increased consumptive losses from its catchment, and land development leading to more flashy runoff and lower baseflows in its tributary streams and rivers. This report describes a method which helps quantify previously unaccounted losses of freshwater inflow to the Bay. It will be useful in determining a portion of consumptive use which is expected to grow as the population and industrial activity expands in the Chesapeake Bay Basin.

The Corps of Engineers (1984;1) states that electric power generation in the Chesapeake Bay Basin will require a 25-fold increase in consumptive water use during the period 1965 to 2020. "This" it is claimed, "reflects both an increase in the amount of power to be generated and the trend toward the use of cooling towers." In once-through cooling systems, only 2 percent of the water withdrawn is not returned; whereas, approximately 13 percent is evaporated on-site when cooling towers are used, according to the Corps of Engineers (1984;2). The point appears to be missed, that in the overall induced heat and freshwater budgets of the Chesapeake Bay, off-site cooling by evaporation from receiving water bodies has been and continues to be ignored.

Functional relationships governing evaporation are discussed and adopted for this study. They are then applied to effluent discharge parameters in order to determine the subsequent loss from receiving waters due to increased temperature. Most references on the subject of evaporation and heat loss consider heat loss as the dependent variable and evaporation as the explanatory variable. In the course of this report, the terms describing heat lost by evaporation will be transformed to yield the increased quantitative evaporative loss of water as a function of the temperature difference between that of the discharge and the receiving water body.

Methodological Development

Giusti and Meyer (1977) compare types of cooling systems for nuclear powerplants in the United States. They develop a range of water requirements by converting all residual heat to the latent heat of vaporization and thus dissipating it by evaporation. The resultant evaporative water requirements vary from 31 cu ft/sec/1000MWe for closed systems with mechanical draft wet towers to 18 cu ft/sec/1000MWe for once through systems. The difference in water requirements is presumably inversely proportional to the amount of heat remaining in the water which is discharged back to the environment in the effluent. No consideration was given to the evaporative water requirement from the receiving water body in order to return it to background temperature conditions.

Brady, et al (1969) studied the heat assimilative capacity of the Chesapeake Bay. The surface heat exchange balance considered the following factors:

1. incident solar radiation
2. reflected solar radiation
3. incident atmospheric radiation
4. reflected atmospheric radiation
5. long-wave back-radiation
6. heat lost by conduction
7. heat lost by evaporation.

Of these seven terms, only three (back-radiation, conduction and evaporation) are dependent on the water surface temperature. Calculations for a 1oF rise in water temperature under summer conditions indicate that 25, 26 and 89 BTU/sq ft/day would be dissipated respectively by back-radiation, conduction and evaporation. Thus, the total heat loss is 140 BTU/sq ft/day/^{o}F, which is approximately linear with changes in temperature. It is important to note that 89/140 (64 percent) of the induced temperature rise is dissipated by evaporation.

Pickard (1963) in his discussion of the earth's oceans, also develops heat loss terms for radiation, conduction and evaporation: Qb, Qh and Qe respectively. However, actual radiation loss is less than clear sky radiation, as a function of cloud cover:

$$Qb \text{ actual} = Qb \text{ clear sky } (1 - 0.08\, C)$$

where:

C = cloud cover value, tenths.

From NOAA (1985) National Airport, mean annual C = 6.1.

Thus:

$$Qb \text{ actual} = \text{approx } 0.5\ Qb \text{ clear sky}$$

Pickard also indicates that the potential clear sky radiation loss is approximately the same value as evaporative heat loss.

$$Qb \text{ clear sky} = Qe$$

and from the previous equation:

$$Qb \text{ actual} = \text{approx } 0.5\ Qe.$$

Pickard (1963) gives values which imply that:

$$Qh = \text{approx } 0.1\ Qe.$$

Then by expressing total heat loss, Qt, in terms of evaporative loss:

$$Qt = Qb + Qh + Qe$$

$$Qt = 0.5\ Qe + 0.1\ Qe + Qe \qquad \text{(from Pickard)}$$

$$Qt = 1.6\ Qe$$

therefore:

$$Qe = 0.63\ Qt$$

The previous discussion of Brady's work leads to the following similar relation between evaporative and total heat loss:

$$Qt = 0.28\ Qe + 0.29\ Qe + Qe$$

$$Qt = 1.57\ Qe$$

$$Qe = 0.64\ Qt$$

Thus, the consensus of these apparently independent sources is that evaporation accounts for approximately 60 percent of heat dissipated from water in the environment.

Dingman, Weeks and Yen (1968) also identified radiation, convection (largely due to conduction) and evaporation as the major factors in the loss of heat from the surface of rivers. Graphical plots of their calculations indicate that at water-air temperature differences of 10 °C, evaporative heat loss accounts for only between 24 and 36 percent of the sum of the three terms. The calculations are made for varying wind speed and temperature conditions, and assuming a clear sky. At low wind speeds, small differences between water and air temperatures, and actual cloud cover, the percent of evaporative heat loss would be greater.

With regard to heat loss from a cooling pond, Edinger (1969) states, "On relative magnitudes of the heat-loss terms, upwards of 80 to 85 percent of the heat loss could be by evaporation and the remaining 15 percent by radiation and conduction. This varies depending on the general temperature range; for example, if the body is between 80 and 90 or between 90 and 100 or between 70 and 80."

Shorney (1983) indicates that conventional coal-fired electricity power generating plants with wet-type cooling towers use approximately 79 percent of total station water needs for cooling system evaporation. He found that evaporation in towers removes approximately 2 percent of circulating cooling water; equivalent to approximately 1 percent of the water for each 10-degree (F) drop in water temperature in the cooling system.

This is a low figure compared to the 13 percent reported by the Corps of Engineers (1984;2).

Again, with regard to heat loss from a cooling pond, Edinger (1969) states, "The only place heat could be lost is to the atmosphere." This statement seems to reflect conventional wisdom on the subject of temperature-dependent heat loss from natural waters as depicted in the referenced material; that is, by radiation, conduction (convection), and evaporation. Dingman, Weeks and Yen (1968) consider other minor terms in the heat balance:

Q_s = heat lost to snow falling onto the water, cal.

Q_g = heat added by the flow of geothermal heat through the stream bed, cal.

Q_{gw} = heat added by the flow of ground water through the stream bed, cal.

Q_f = heat increase due to fluid friction, cal.

The sign of most of these terms could be reversed (lost:gained) depending on the circumstances, but in most cases the values would be negligible and their effects will be ignored in this analysis.

Drawing a consensus from the references, the only significant heat budget terms which are affected by water temperature are back-radiation, conduction (convection), and evaporation. Since it is an increase in temperature brought about by the discharge of heated cooling water which is of concern in this study, the analysis is restricted to those three terms.

The budget of heat in the discharged cooling water will be defined:

$$Qt = Qb + Qh + Qe$$

where, stated now more completely:

Qt = heat to be dissipated from discharge so as to render it to the same temperature as the receiving water, cal.

Qb = heat to be dissipated from discharge via back-radiation, cal.

Qh = heat to be dissipated from discharge via conduction (convection), cal.

Qe = heat to be dissipated from discharge via evaporation, cal.

Again, drawing a consensus from the cited reference material; approximately 60 percent of total heat loss from lakes and rivers is by evaporation.

Thus:

$$Qe = 0.60\ Qt$$

Most of the references on the subject provide complex formulae for the calculation of evaporation. It is dependent upon a number of hydrometeorological factors, including: vapor pressure, wind and water velocity, air and water temperature, and relative humidity. However, the process can be condensed and simplified by reliance on the fact that it is the latent heat of vaporization which ultimately governs evaporation.

Weast (1972-1973) defines latent heat of vaporization as "The quantity of heat necessary to change one gram of liquid to vapor without change of temperature, measured as calories per gram." In this case, the source of heat is the heated water discharge. Its formula is given in Pickard (1963) as:

$$Lt = 596 - 0.52\ T$$

where:

Lt = latent heat of vaporization, cal/gram

T = temperature of the water, ^{o}C.

This relationship is part of the equation for the energy (heat) of evaporation given by Beard and Hollen (1969):

$$Qe = Lt\ m$$

where:

m = evaporation mass (flux), grams (/day).

The consideration of flux rate (in units of time and area) will be ignored except that it be understood that all discharge flows are in units of average quantity per day.

Now combining the previous three equations:

$$Qe = 0.60\ Qt$$

$$Lt\ m = 0.60\ Qt$$

and substituting:

$$Qt = f\ S\ dT$$

where:

f = mass (flow) of discharge, grams (/day)
S = specific heat of water, 1 cal/gram/^{o}C
dT = difference in temperature between discharge and receiving water body, ^{o}C.

Therefore,

$$Lt\ m = 0.60\ f\ S\ dT$$

$$(596 - 0.52\ Tr)\ m = 0.60\ f\ S\ dT$$

where:

Tr = temperature of the receiving water body, ^{o}C.

Thus, the evaporative loss from receiving waters due to heated effluent discharges can be expressed as a function of discharge flow and temperature, and temperature of the receiving water.

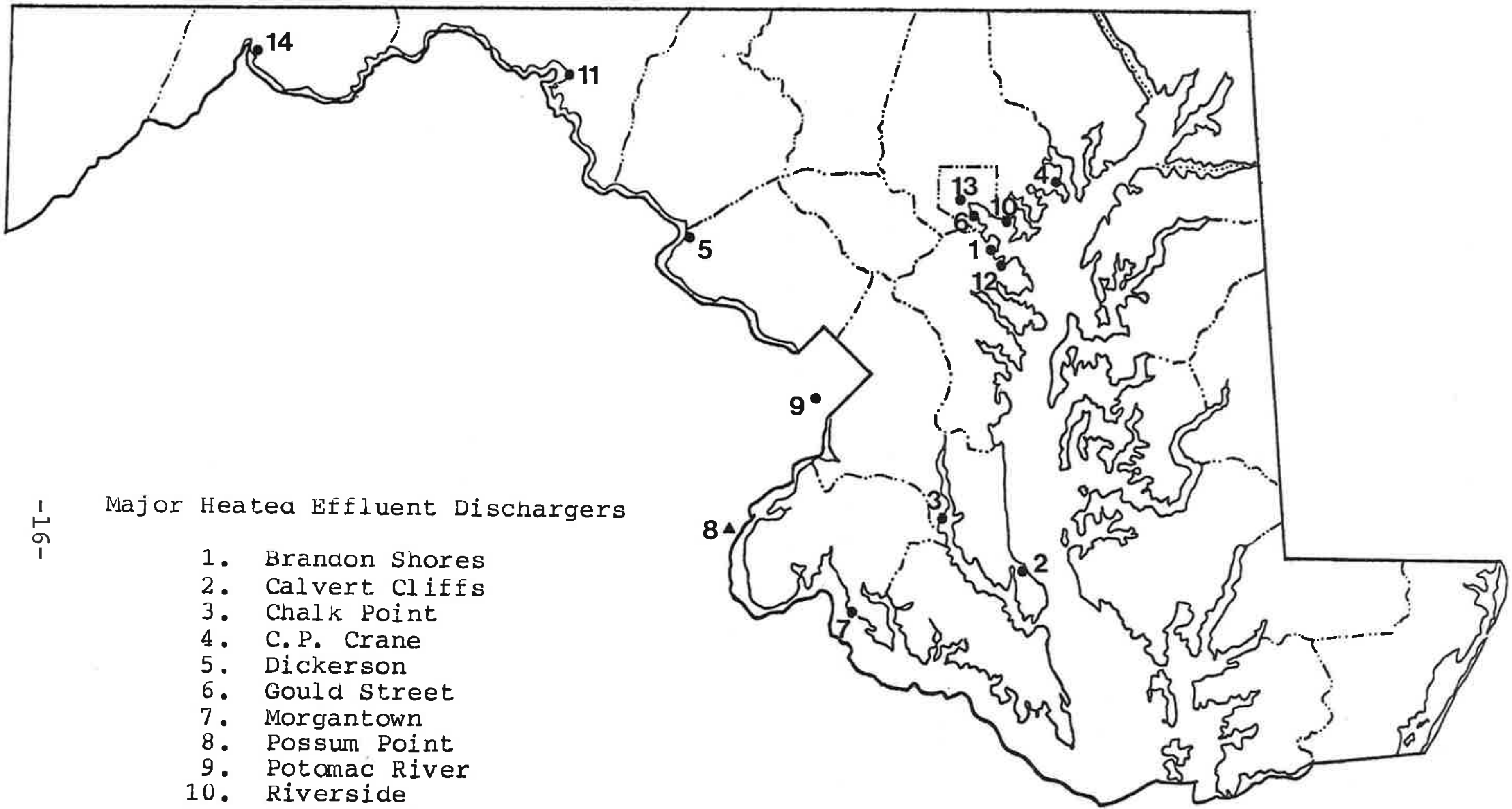
$$m = (0.60\ f\ S\ dT) / (596 - 0.52\ Tr)$$

Quantification of Evaporative Loss

The necessary information for the calculation of the off-site evaporative loss resulting from the discharge of heated effluent into natural water bodies was compiled for fourteen plants. These plants are primarily steam generating power plants and include the major dischargers in the state of Maryland. The plants and their geographical locations are displayed in Figure 1; they are dispersed between the Potomac, Patuxent, and Patapsco River Basins.

Only plants that are operated and discharge heated water on a fairly continual basis were included in the analysis. Therefore, power plants used intermittently such as peaking power units were excluded. This is the case for the Benning Road plant operated by PEPCO.

The calculation of the evaporative loss using the methodology



Major Heated Effluent Dischargers

1. Brandon Shores
2. Calvert Cliffs
3. Chalk Point
4. C.P. Crane
5. Dickerson
6. Gould Street
7. Morgantown
8. Possum Point
9. Potomac River
10. Riverside
11. R.P. Smith
12. Wagner
13. Westport
14. Westvaco

Figure 1. Location of major dischargers

developed above requires the following three pieces of information:

1. the magnitude of the discharge,
2. the temperature of the discharge, and
3. the temperature of the receiving water.

The first two pieces of data were obtained through direct correspondence with personnel from the individual plants. When values for the temperature of the receiving water were not provided, the values were obtained from various regional water quality publications. The compiled data were aggregated into seasonal averages representing summer (using June, July, August, and September data) and winter (using December, January, February, and March data) seasons. When data were insufficient for seasonal differentiation, an annual average was determined. A summary of the data and the sources of the data is presented in Table 1. Specifically, the table lists the average discharge, the average temperature of the discharge, the water body receiving the discharge, the average temperature of the receiving water, the source of the receiving water temperature, and the period of the averaging.

The calculated off-site evaporative loss based on data reflecting actual plant operation is shown by plant and by season, when possible, in Table 2. This value may be compared to the magnitude of the discharge and to the difference in the temperature between the discharged and the receiving waters. This comparison is facilitated by examining the column which

Table 1. Discharge and receiving water information for surveyed plants

Plant	Discharge		Receiving Water			
	Flow (mgd)	Temp (°F)	Body	Temp (°F)	Source	Season (s/w/a)
BG&E						
Brandon Shores	17.	75.	Patapsco	54.	3	w
	25.	95.		82.		s
Calvert Cliffs	3500.	57.	Bay	50.	3	w
	3500.	90.		78.		s
Crane PP	478.	55.	Gunpowder	44.	3	w
	478.	94.5		81.		s
Gould St. PP	100.	55.5	Patapsco	54.	3	w
	100.	88.		82.		s
Riverside PP	196.	65.	Patapsco	54.	3	w
	315.	101.		82.		s
Wagner PP 001	550.	64.	Patapsco	54.	3	w
	550.	98.		82.		s
004	515.	59.		54.		w
	515.	91.		82.		s
Westport 001	144.	56.	Patapsco	54.	3	w
	144.	93.		82.		s
PEPCO						
Potomac River	315.	62.	Potomac Estuary	47.	1	w
	364.	88.		81.		s
Dickerson 001	119.	55.	Potomac	45.	1	w
	136.	89.		84.		s
002	128.	55.		45.		w
	130.	88.		84.		s
Chalk Point	346.	55.5	Patuxent	47.	2	w
	530.	77.		71.		s
Morgantown 001	455.	46.	Potomac Estuary	47.	1	w
	602.	84.		81.		s
002	454.	54.		47.		w
	700.	86.		81.		s
Potomac Edison						
R.P. Smith	59.5	61.	Potomac	41.	3	w
	59.5	104.		81.		s
VEPCO						
Possum Point 003	81.4	-	Quantico	48	4	w
	81.4	-		74		s
004	142.8	-		48		w
	142.8	-		74		s
Westvaco 001	7.5	80.	North Branch Potomac	60.	2	a
002	3.0	82.		60.		a
003	2.4	80.		60.		a
004	3.9	104.		60.		a
005	13.4	85.		60.		a

where sources are:

1 -- Potomac River Water Quality - 1984: Conditions and Trends in Metropolitan Washington, Department of Environmental Programs, Metropolitan Council of Governments, November, 1985.

2 -- Water Resources Data - Maryland and Delaware: Water Year 1984, U.S. Geological Survey, Towson, Md., 1985.

3 -- supplied through plant survey

4 -- Water Resources Data - Virginia: Water Year 1983, U.S. Geological Survey, Richmond, Va., 1984.

Table 2. Off-site evaporative loss (mgd) for surveyed plants

Plant	Disch. (mgd)	Average Observed			Season (s/w/a)
		Del T (°C)	Evap (mgd)	% disch.	
Brandon Shores	17.0	11.7	.20	1.19	w
	25.0	7.2	.18	.72	s
Calvert Cliffs	3500.0	3.9	13.82	.40	w
	3500.0	6.7	24.03	.69	s
Crane PP	478.0	6.1	2.96	.62	w
	478.0	7.5	3.70	.77	s
Gould St. PP	100.0	.8	.08	.08	w
	100.0	3.3	.34	.34	s
Riverside PP	196.0	6.1	1.22	.62	w
	315.0	10.6	3.43	1.09	s
Wagner PP 001	550.0	5.6	3.11	.57	w
	550.0	8.9	5.04	.92	s
004	515.0	2.8	1.46	.28	w
	515.0	5.0	2.66	.52	s
Westport 001	144.0	1.1	.16	.11	w
	144.0	6.1	.91	.63	s
Potomac River	315.0	7.8	2.49	.79	w
	364.0	3.9	1.46	.40	s
Dickerson 001	119.0	5.6	.67	.56	w
	136.0	2.8	.39	.29	s
002	128.0	5.6	.72	.56	w
	130.0	2.2	.30	.23	s
Chalk Point	346.0	4.7	1.66	.48	w
	530.0	3.3	1.81	.34	s
Morgantown 001	455.0	.0	.00	.00	w
	602.0	1.7	1.03	.17	s
002	454.0	3.9	1.79	.39	w
	700.0	2.8	2.01	.29	s
R.P. Smith	59.5	11.1	.67	1.12	w
	59.5	12.8	.78	1.32	s
Possum Point 003	81.4	-	1.50	1.84	w
	81.4	-	1.52	1.87	s
004	142.8	-	.01	.01	w
	142.8	-	.01	.01	s
Westvaco 001	7.5	11.1	.09	1.13	a
002	3.0	12.2	.04	1.25	a
003	2.4	11.1	.03	1.13	a
004	3.9	24.4	.10	2.49	a
005	13.4	13.9	.19	1.42	a
Total			32.9	.45	w
			49.3	.61	s

shows the off-site evaporative loss as a percentage of the total discharge. This percentages and the difference between the temperatures are highly correlated with the percentages varying between nearly zero and 2.5 depending upon the temperature difference or heat loading.

Table 2 shows that the total evaporative loss for the fourteen plants is 33 mgd on a winter day and 50 mgd on a summer day. This corresponds to .45 percent of the total discharge in the winter and .61 percent of the total discharge in the summer.

Conclusions

The results of the analysis show that off-site evaporative loss in the summer months is close to 50 mgd and in the winter months close to 33 mgd. As percentages of the discharged water the evaporative loss on average represents about 0.6 % of the total discharge from the cooling system in the summer and about 0.5 % of the total discharge in the winter months. The percentages vary between 0 and 2.5 and are primarily dependent on the temperature difference between the discharge water and the receiving water. This is useful information for the estimation of future water needs.

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