THEORETICAL STUDY OF THERMAL POLLUTION

RAUL ZALTZMAN* AND
GEORGE W. REID**

RESUMEN

Aproximadamente el 80% de toda el agua usada en la industria de los Estados Unidos lo es en operaciones de enfriamiento. Como resultado, la carga termal (calor) de los lagos y corrientes recipientes es más pesada cerca de los complejos industriales. Cuando la cantidad de calor en tales áreas comienza a desequilibrar el proceso acuático o a afectar las especies acuáticas, el resultado es la contaminación termal. Estimaciones teóricas sobre el exceso futuro de la producción del calor apuntan la necesidad de obtener más información en este problema vital.

Este estudio se refiere a los efectos de la contaminación termal y a los procesos termales en corrientes y lagos. Su objeto fue el de contribuir a la comprensión teorética de los procesos involucrados para que puedan desarrollarse planteamientos con criterio sólido. Con tal fin, un modelo matemático del proceso de contaminación fue desarrollado y evaluado.

ABSTRACT

Approximately 80% of all water used by United States industry is in cooling operations. As a result, the thermal load (heat) of receiving streams and lakes is heaviest near industrial complexes. When the quantity of heat in such areas begins to impair aquatic processes or kill

---

* *University of West Virginia*
** *University of Oklahoma*

aquatic species, the result is thermal pollution. Projected estimates on future excess heat production point up the need for more information on this vital problem.

This study concerns the effects of thermal pollution and thermal processes in streams and lakes. The objective was to contribute to the theoretical understanding of the processes involved in order that sound design criteria could be developed. Toward that end, a mathematical model of the pollution process was developed and evaluated.

INTRODUCTION

Investigation conducted at the University of Oklahoma for the U.S. Senate Select Committee on Water Resources on Low Flow Augmentation considered only the efects of dissolved oxygen (D. O.) (Reid, G. W., 1960).

However, the Select Committee studies indicated the severity of the thermal pollution problem and that more work should be done in this area.

The addition of a thermal load (heat) to a stream or body of water in quantities detrimental to beneficial activity constitutes thermal pollution. Aproximately 80% of all water used by United States industry is in cooling operations, with the result that discharge of large quantities of heat into the streams and lakes is commonplace. Projecting this situation into the future, industry is expected to double its excess heat production each decade until at least 1980. This in turn will create a greatly increased water demand – from 74 bgd in 1954 to an estimated 260 bgd for 1980. (Richardson, B., 1931).

The necessary requirement for temperature as a major factor of the physical environment of surface waters must be that it allow a level of activity commensurate with maintaining desirable aquatic species in acceptable numbers. Allowable temperatures are not within one specific range -- they fluctuate with season and other natural environmental factors. Present knowledge (or the lack of it) of nature's processes for maintaining a balance of life indicates that there can be no simple statement on thermal requirements of surface water.

Apparently the only feasible remedy to this situation is to develop specific and sound engineering design provisions to minimize thermal pollution from industrial sites. The objective of this study was to contribute to the theoretical understanding of such designs by deriving a mathematical model of the pollution process.

Effects of Thermal Pollution

The impact of thermal pollution on water conditions is exemplified by at least four distinct reactions:

(1) death or displacement of aquatic species
(2) environmental modification
(3) activity reduction
(4) impairment of stream self-purification

Lethal temperature levels among different species of fish vary markedly, in some instances as much as 31°F (Brett, J. R., 1960).

For example, with fish the critical limit for *Carassius auratus* is 106°F, while *Oncorhynicus gorbusha* cannot endure temperatures above 75°F. Stream temperatures which consistently exceed 70°F favor warm-water fishes rather than cold-water species such as the Salmonoids, (Belding, D. L. 1928). Increases in temperature of 2-3°F above the 70°F level have been observed to cause depopulation of *Salmonoids* to less than 10% of the total fish population. Minnows, suckers, and other warm-water species gradually replaced them under this condition (Tarzwell, M. C. and A. R. Gaufin, 1953).

While the change of temperature may be within the thermal tolerance of the particular fish, it may make *environmental conditions* unfavorable for essential food organisms and for certain developmental stages of fish life – it is known that the eggs of some daphnia have to be chilled or frozen before they hatch. Or the higher temperatures may favor competitors or predators of desirable species. Many other organisms go through resting periods or specific stages of development during certain seasons. Furthermore, certain diatoms are abundant only, at temperatures below 50°F. Thus, by elevating the temperature of a stream, the biota distribution may be changed and the entire food chain seriously disrupted (Tarzwell, M. C., 1957).

The observation was made in 1947 that water temperature affects *aquatic activity* through the process of metabolism in the life forms (Fry, F. E. J., 1947). Experiments were made to determine the effects of temperature and cruising speed of the *sockeye* to demonstrate this relationship (Brett, J. R., *et al.* 1958). The maximum sustaned swimming speeds of *sockeyes* at 10°C and 19°C are approximately equal. However, because of increased metabolic demand at the higher temperature, energy reserves of the fish were found to be exhausted 1 ½ to 2 times as quickly at 19°C (Brett, J. R., *et al.* 1958). From these studies it is apparent that the rate of activity is directly related to the water temperature and to the difference between resting metabolism and active metabolism Activity reduction aspects may be extended to man, who also experiences undesirable effects at higher temperatures. For example, the use of a stream for recreational purposes is reduced by excessive heat.

Bacterial growth rate in streams is maximum at 86°F. As a consequence, higher stream temperatures decrease the *self-purification capacity* of the stream. Addition of heat to surface waters increases the possibility of septic conditions and tends to make the water unsuitable for industrial reuse or for drinking purposes without expensive treatment.

The dissolved oxygen content of water, as noted in the introduction is a function of temperature, ranging from for example, 10 ppm at 59°F to 7.6 ppm at 86°F. This relationship has been noted in self-purification studies as well as the bacterial growth rate. It Should be stressed thath these conditions relate to equilibrium conditions and rarely occur in vivo.

The development of a theoretical formulation will give a broad idea of the assimilation capacity of thermal waste in a certain point of a stream thereby providing design criteria to help prevent pollution in an increasingly critical area.

ANALYSIS OF THE THERMAL BUDGET IN A BODY OF WATER

Study of thermal processes in water must begin by accounting for all significant factors. After this has been done, the *nature of functioning* can be analyzed and evaluated as performed below (Bowen, I. S., 1926. Richardson, B., 1931):

A. The continuty expression of the conservation of energy can be stated as:

$$H_e + H_h = H_v - H_i + H_s - H_r - H_b \qquad (1)$$

where

H_c = heat required for evaporation
H_h = heat loss due to conduction to the atmoshphere
H_v = net energy advected
H_i = increase in energy stored in the body of water
H_s = incident short wave radiation
H_r = reflected short wave radiation
H_b = net energy loss throuth exhange of long wave radiation

or if we evaluate these terms as a function of Insolation (Richardson, B., 1931), we find that Insolation is a positive quantity during the day, but at night is equal to zero. Evaporation is always positive, while the other terms (convection, sensible heat, conduction and radiation) may be either positive or negative. Expressed simbolically this is,

$$L \cdot E \cdot R + L \cdot E = I - S - C - B_r \qquad (2)$$

L = latent heat of vaporization of water (585.4 at 20°C)
E = quantity of water evaporated in cm of depth per day
R = ratio of convection evaporation (Bowen's ratio)
I = radiant power per unit area of earth surface from sun, calories per minute
S = detectable heat measured by warming or cooling of water, calories/day
C = conduction of heath through the walls of the container
B_r = radiation from water, calories/per sq. cm per day.

B. Effects of evaporation

From equation (2), heat loss by evaporation is:

$$H_{loss} = L \cdot E + L \cdot E \cdot R = EL(1 + R) \text{ with} \qquad (3)$$

$$R = \frac{0.46\,(T_o - T_a)\,P}{(P_1 - P_2)\,760} \qquad (4)$$

where

T_o = temperature of water °C
T_a = temperature of air °F
P_1 = vapor pressure of sat. vapor @ T_o – mmHg
P_2 = partial pressure of actual vapor in air – mmHg
P = atmospheric pressure

The effect of wind in evaporation has been disregarded because no detectable error results from neglecting it (Bowen, I. S., 1926).

So far, no mention has been made of the artificial heating of the stream, but with it the value of R will change. As the values for E are known for the initial temperature (T_o) of the water, the value of R is good only for this condition. Thus when an increase of temperature in the stream has changed R To R', the geometric mean value of R is to be used, and equation (3) will be

$$H_{loss} = EL\,(1 + \sqrt{RR'}) \tag{5}$$

C. Capacity of thermal assimilation:

where using a consistent set of units,

Q_o = initial flow

Q_1 = final flow

ΔQ = added flow (waste flow)

$\frac{\Delta Q}{Q_o}$ = ratio of dilution

T_o = initial temperature

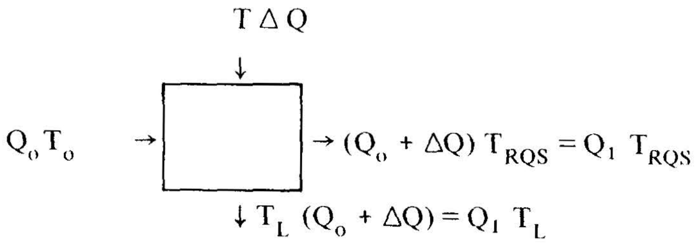
T_{RQS} = temperature of river quality standards, or final

ΔT_Q = allowable temperature change, or $T_{RQS} - T_o$

ΔT_w = allowable temperature difference between added flow and T_{RQS},

T_L = temperature loss
T = temperature od added flow
A = unit surface area of stream
V_S = subsidiance velocity, or Q/A
L = heat of vaporization of water at given temperature $1/2\,(t_o - t_{RQS})$

we have:



from eq (5)

$$Q_1 T_L = ELA(1 + \sqrt{RR'}) \tag{6}$$

if

$$A = \frac{Q + \Delta Q}{V_S}\text{, and } K = (1 + \sqrt{RR'}\,)\,EL$$

$$Q_1\;T_L = K\left(\frac{Q_o + \Delta Q}{V_S}\right) \tag{7}$$

then:

$$(Q_o + \Delta Q)T_{RQS} = T_o Q_o + T\Delta Q - K\left(\frac{Q_o + \Delta Q}{V_S}\right) \tag{8}$$

$$\Delta Q(T - T_{RQS}) = Q_o(T_{RQS} - T_o) + K\left(\frac{Q_o + \Delta Q}{V_S}\right) \tag{9}$$

if

$$\Delta T_W = T - T_{RQS}\,;\ \&\ \Delta T_o = T_{RQS} - T_o\,:$$

$$\Delta Q\,(\Delta T_w - K/V_S) = Q_o\,(\Delta T_Q + K/V_S) \tag{10}$$

then

$$\frac{Q_o}{\Delta Q} = \frac{\Delta T_W - K/V_s}{\Delta T_Q + K/V_s} \qquad (11)$$

and finally if $C = K/V_s$

$$\frac{Q_o}{\Delta Q} = \frac{\Delta T_W - C}{\Delta T_Q + C} \qquad (12)$$

Equation (12) them may be considered a working expression for calculating the effects on water thermal conditions from the addition of wastes having any given characteristics. For more information on the inter-relation of the variables in practical dynamic operation see Appendix A. To illustrate futher the use of Equation (12) see Appendix B which shows the determination of the thermal addition capacity of the Ohio Basin from data obtained from the Select Committee studies. (Reid, G. W., 1960). The solution is made graphically from Figures 1 and 2 (Appendix C). Figure 1 and 2 were developed from data presented in Appendix D.

RECOMMENDATIONS FOR ENGINEERING CRITERIA

In order to provide a reference basis of acceptable temperature ranges, it is recommended that aquatic species be allowed to have the benefit of at least 3/4 of their optimun total activity capability (or work capacity at most favorable temperature). This provision must take into account the living requirements of desirable species of the specific water body. For example, the adverse effects of a 3-5°F temperature rise on trout, forbid the discharge of significant amounts of heat into a stream in such a manner that a temperature block is created.

It is further recommended that close attention be paid in the design of facilities to careful studies of the species which are intended to inhabit the water. Under no circumstances should peak endurance temperatures prevail for more than 8 hours of each 24 hours period. Fishways must be provided when these aceptable conditions cannot otherwise be met.

In conclusion, the authors hope that this report will stimulate interest in this important problem and that this interest will lead to the collection of urgently needed field data. The acceptance or rejection of the theoretical considerations made for this study should provide the insights needed to help solve this "fast growing problem."

APPENDICES

APPENDIX A

ANALYSIS OF THE VARIABLES IN EQUATION No. 12

Equation 12 as stated says:

$$\frac{Q_o}{\Delta Q} = \frac{\Delta T_w - C}{\Delta T_Q - C}$$

where:

$$C = \frac{K}{V_S}$$

in therms of depth "d" we have:

$$V_S = \frac{vd}{l}$$

where:

v = velocity of the stream (in units of distance per day).
d = average depth of the stream.
l = total distance traveled by the water in one day.

Then the dimensiones of V_S for a given period of time are:

$$(v = \frac{L}{\theta}\ ;\ d = L_1\ ;\ l = L)$$

$$V_S = \frac{L/\theta \cdot L_1}{L} = \frac{L_1}{\theta} = d/\text{time} = d_\theta$$

where:

time = unit,

or in other words,

The loading rate in our study is equal to the average depth per unit of time (one day).

Therefore:

$$C = \frac{K}{d_\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{“A”*}.$$

---

* Expression "A" will give the formula (12) in terms of the average depth of the stream in the section in study.

WORKING INTER-RELATION OF VARIABLES

	INCREASE	DECREASE	ΔT_w	K/E	C	ΔT_o	Q/ΔQ
T	X	–	Inc.	Inc.	Inc.	N/C	Inc.
T_{RQS}	–	X	Inc.	N/C	N/C	Dec.	Dec.
T_{RQS}	X	–	Inc.	N/C	N/C	Dec.	Dec.
Depth	X	–	N/C	N/C	Dec.	N/C	Dec,
Depth	–	X	N/C	N/C	Inc.	N/C	Inc.

Inc. = Increase, Dec. = Decrease, N/C = No Change

APENDIX B

DILUTION WATER REQUIREMENTS OF THE OHIO BASIN

1. A graphical solution of the equation (12) can be made by using Figure 1 and Figure 2 (Appendix C).

2. *Required Data:*

T_o = Average seasonal temperature of the water in the basin (for the warmest).
T_{RQS} = Maximum temperature allowable of the water in the basin.
T = Average temperature of the waste water.
T_{air} = Average temperature of the air in the layer in contact with the body of water.
E = Average evaporation in the basin (Yearly average will be good).
d = Average depth of the basin.

3. *Available Data:*

T_o – in print 29, = 75°F pág. 6. (Reid G. W., 1960)

$T_{RQS} - T_o = 5.4°F = \Delta T_Q$ – in °C = 3°C (Assumed 9°F)
$T = 95°F$ Assumed temperature of the waste water – (To be given by the plants).
$T - T_{RQS} = \Delta T_w$ – in °C $= \Delta T_Q$ in °F/1.8 $= \Delta T_Q$ in °C
d – in print, 29, pg. 6 (Reid, G. W., 1960)
E – in print 13, Class A pan evaporation (Reid G. W., 1960)

4. *Solution for the Ohio Basin:*

a. Find $T - T_{air} = 20°F$
b. Go with this value of 20°F to Figure (1) and find: K/E = 846
c. Go with this value of 846 to the nomogran (Figure 2) and solve for E = 45 inches/year, drawing a straight line through the pivot line, then draw another straight line. . .
d. . . . from the point in the pivot line through d = 4' and find a value for C (8 hour period) = 0.73.
e. In equation (12),

$$\frac{Q_o}{\Delta Q} = \frac{(\Delta T_w - C)}{(\Delta T_Q + C)}$$

we have that:

$$T_o = 75°F \qquad C = 0.73$$

$$\Delta T_w = T - T_{RQS}$$

$$T_{RQS} = T_o + 5.4 = 75.0 + 5.4 = 80.4$$

$$\therefore \Delta T_w = 95 - 80.4 = \underline{14.6°F} = 8.0°C$$

$$\Delta T_Q = T_{RQS} - T_o = 80.4 - 75.0 = 5.4°F = \underline{3°C}$$

$$\frac{Q_o}{\Delta Q} = \frac{8 - 0.73}{3 + 0.73} = \frac{7.27}{3.73} = 1.92$$

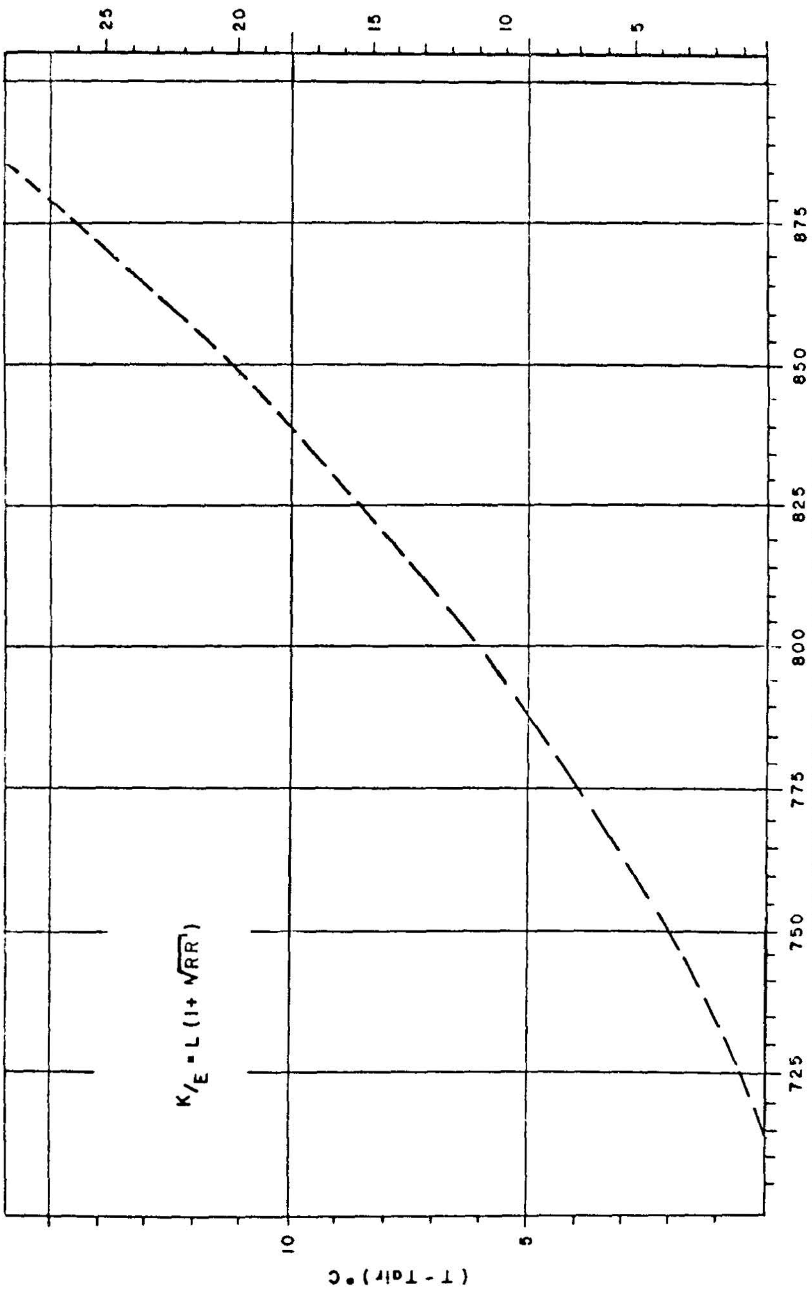
and from Table (1):

$$\Delta Q_{low-1980} = 19{,}121$$

$$\therefore Q_o = \Delta Q(1.92) = 19{,}121 \text{ x } 1.92 = \underline{\underline{36{,}712.32}}$$

APPENDIX C

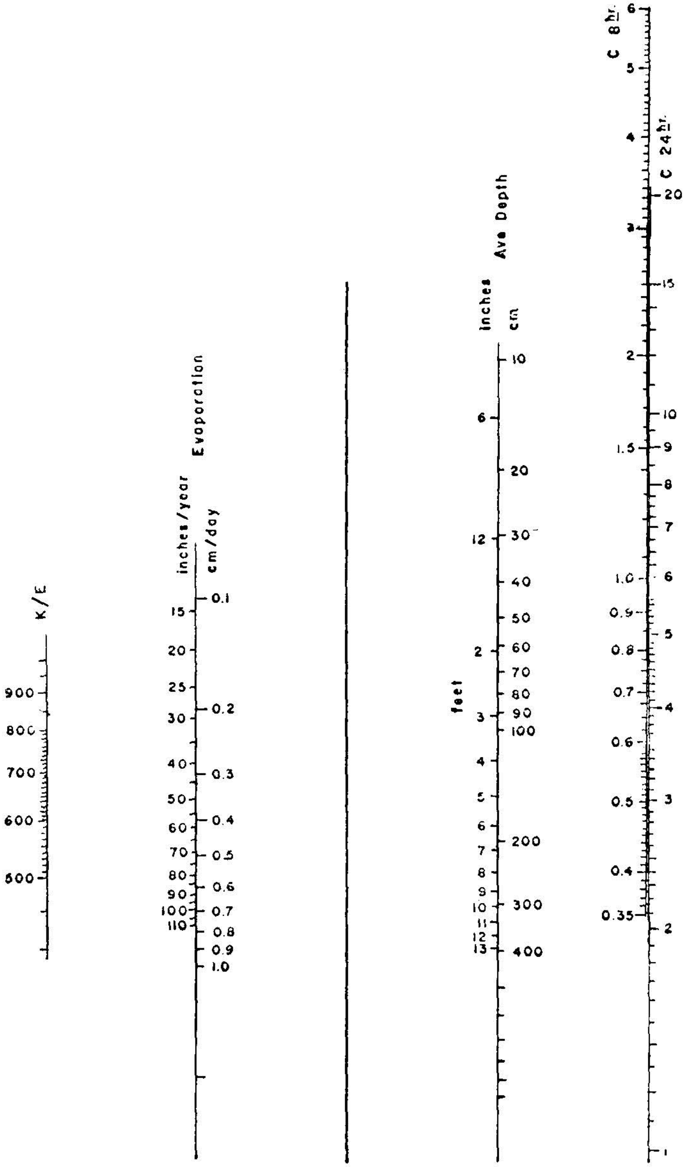
APPENDIX D



DETERMINATION OF THE CORRECTED HEAT OF VAPORIZATION

VALUES OF $K/_E$

FIGURE 1



NOMOGRAPH FOR SOLUTION OF EQUATION 12

FIGURE 2

TABLE 1

SEQUENCE OF THE SOLUTION OF FORMULA 12

ASSUME: $T_o = T_{air}$, $T = 100$, $T_{RQS} - T_o = 5.4^\circ F$

BASINS (NUMBER)	av. T_o	T_{RQS}	$T-T_{air}$	K/E	E (in/year)	av. depth (feet)	$T-T_{RQS}$
1	70	75.4	25.0	869	30	4.0	19.6
2	70	75.4	25.0	869	40	3.0	19.6
3	68	73.4	27.0	877	35	3.0	21.6
4	70	75.4	25.0	869	35	3.0	19.6
5	73	78.4	22.0	856	45	5.0	16.6
6	75	78.4	20.0	846	45	4.0	14.6
7	73	78.4	22.0	856	48	3.0	16.6
8	78	83.4	17.0	830	50	4.0	11.6
9	83	88.4	12.0	805	57	5.0	6.6
10	74	79.4	21.0	851	44	3.0	15.6
11	80	85.4	15.0	821	56	4.0	9.6
12	68	73.4	27.0	877	60	3.0	21.6
13	74	79.4	21.0	851	55	3.5	15.6
14	78	83.4	17.0	830	91	2.0	11.6
15	82	87.4	13.0	811	60	3.5	7.6
16	85	90.4	10.0	791	85	4.0	4.6
17	83	88.4	12.0	805	90	1.5	6.6
18	80	85.4	15.0	821	80	2.0	9.6
19	75	80.4	20.0	846	70	1.0	14.6
20	65	70.4	30.0	889	40	4.0	24.6
21	68	73.4	27.0	877	70	4.0	21.6
22	83	88.4	17.0	830	110	0.5	11.6

= 95°F C	°F T_{RQS}-T_o	°C T-T_{RQS}	°C T_{RQS}-T_o	(T-T_{RQS}) – C	(T_{RQS}-T_o) + C	$\frac{(T-T_{RQS}) - C}{(T_{RQS}-T_o) + C}$
.50	5.4	10.8	3	10.30	3.50	2.80
.90	5.4	10.8	3	10.30	3.90	2.64
.80	5.4	12.1	3	11.30	3.80	2.97
.79	5.4	10.8	3	10.01	3.79	2.64
.59	5.4	9.2	3	8.61	3.59	2.41
.73	5.4	8.0	3	7.27	3.73	1.92
.07	5.4	9.2	3	8.13	4.07	2.00
.80	5.4	5.9	3	5.10	3.80	1.34
.70	5.4	3.7	3	3.00	3.70	0.81
.98	5.4	8.6	3	7.62	3.98	1.91
.87	5.4	5.3	3	4.43	3.87	1.14
.00	5.4	12.1	3	11.10	4.00	2.77
.05	5.4	8.6	3	7.55	4.05	1.86
.90	5.4	5.9	3	3.00	5.90	0.51
.05	5.4	4.2	3	3.15	4.05	0.77
.37	5.4	2.6	3	1.23	4.37	0.28
.80	5.4	3.7	3	– 0.10	6.80	–0 –
.49	5.4	5.3	3	2.81	5.49	0.51
.50	5.4	8.0	3	3.50	7.50	0.46
.68	5.4	13.7	3	13.02	3.68	3.54
.27	5.4	12.6	3	11.33	4.27	2.65
.01	5.4	5.9	3	– 4.11	13.01	– 0–

TABLE 2

DILUTION WATER REQUIREMENTS FOR THE BASINS OF THE UNITED STATES

BASINS (NUMBER)	TOTAL WASTE WATER (M. G. D.)				
	1980			2000	
	LOW	MEDIUM	HIGH	LOW	MEDIUM
1 New England	8,911	12,219	21,507	10,893	18,819
2 Delawere Hudson	19,807	27,607	47,974	23,584	44,090
3 Eastern Great Lakes	11,354	15,862	27,628	13,612	25,708
4 Western Great Lakes	21,082	29,032	50,721	26,322	48,558
5 Chesapeake Bay	15,963	22,951	39,917	20,089	39,404
6 Ohio	19,121	26,922	47,225	23,409	44,418
7 Cumberland	40,515	57,119	100,406	47,845	90,737
8 Tennessee	155	239	364	589	1,096
9 Southeast	7,511	10,583	18,454	11,321	21,436
10 Upper Mississippi	12,126	16,664	29,452	14,265	26,072
11 Lower Mississippi	3,410	4,826	8,295	4,300	8,230
12 Upper Missouri	5,370	7,353	12,998	6,665	12,106
13 Lower Missouri	1,367	1,872	3,311	2,072	3,762
14 Upper Arkansas & Red	4,026	5,526	9,711	4,652	8,507
15 Lower Ark. Red, & White	2,978	4,026	7,067	3,352	6,208
16 Western Gulf	17,740	25,721	42,812	26,225	53,242
17 Río Grande & Pecos	1,336	1,838	3,241	1,572	2,865
18 Colorado	2,629	3,598	6,398	4,480	8,133
19 Great Basin	1,366	1,887	3,346	1,572	2,895
20 Pacific Northwest	3,909	5,409	9,388	10,320	18,876
21 Central Pacific	10,181	13,926	24,542	14,380	26,092
22 South Pacific	8,298	11,330	19,852	10,565	19,093
TOTALS	219,155	306,510	534,669	282,084	531,347

1 Source: Senate Select Committee and University of New Mexico Studies on Resources for the

2 Whenever heated water is to be dumped in the stream it is recommended to raise the weir to a

		DILUTION WATER REQUIREMENTS (M. G. D.)					
		1980			2000		
HIGH	$\frac{Q_o}{\Delta Q}$ (Eq 12)	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
44,627	2.80	24,950	34,213	60,219	30,500	55,493	124,955
99,083	2.64	52,290	72,882	126,651	62,261	116,397	261,579
58,210	2.97	33,721	47,110	82,055	40,427	76,352	172,883
109,190	2.64	55,656	76,644	133,903	69,490	128,193	288,261
90,437	2.41	38,470	55,311	96,199	48,414	94,963	217,953
101,141	1.92	36,712	51,690	90,729	44,945	85,282	194,190
206,972	2.00	81,030	114,238	200,812	95,690	181,474	413,944
2,459	1.34	207	320	487	789	1,468	3,295
48,799	0.81	7,511	10,583	18,454	11,321	21,436	48,799
58,965	1.91	23,160	31,828	56,253	27,246	49,797	112,623
18,397	1.14	3,887	5,501	9,456	4,902	9,382	20,972
27,286	2.77	14,874	20,367	36,004	18,462	33,533	75,582
8,479	1.86	2,542	3,481	6,158	3,853	6,997	15,770
19,193	0.51	4,026	5,526	9,771	4,652	8,507	19,193
14,012	0.77	2,978	4,026	7,067	3,352	6,208	14,012
119,442	0.28	17,740	25,721	42,812	26,225	53,242	119,442
6,425	– 0 –	1,336	1,838	3,241	1,572	2,865	6,425^2
18,407	0.51	2,629	3,598	6,398	4,480	8,133	18,407
6,567	0.46	1,366	1,887	3,346	1,572	2,895	6,567
42,585	3.54	13,837	19,147	33,233	36,532	66,821	150,750
58,693	2.65	21,989	36,903	65,036	38,107	69,143	155,536
42,591	– 0 –	8,298	11,330	19,852	10,565	19,093	42,591^2
201,960	35.93	449,209	634,144	1,108,136	585,357	1,097,674	2,483,729

uture.

inimum of 21 (total depth of water)

BIBLIOGRAPHY

BELDING, D. L. 1928. Water Temperature and Fish Life. *Trans. Hm. Fish. Soc.*, Vol. 58, pp. 98-105.

BOWEN, I. S. 1926. The Ratio of Heat Losses by Conduction and Evaporation from any Water Surface. *Phys. Rev.* Vol. 27, pp. 779-787.

BRETT, J. R. 1960. Thermal Requirements of Fish – Three Decades of Study, 1940-1970. R. A. Taft Sanitary Engineering Center, T. Rep. W60-3 pp. 110-116.

BRETT, J. R. et al. 1958. Effects of Temperature on Cruising Speed of Young Sockeye and Coho Salmon. *Jour. Fish, Res. Bd.*, Canada 15 (5).

FRY, F. E. J. 1947. Effects of the Environment on Animal Activity. Univ. of Toronto, Student Biology Service, 55, Public Ont. Fish Res. Lab.

REID, G. W. 1960. Methods of Approximating Dilution Water Requirements as a Supplemental Measure for the Control of Water Quality in Rivers, U. S. Senate Select Committee on National Water Resources, Print No. 29.

RICHARDSON, B. 1931. Evaporation as a Function of Insolation. *Am Soc. Civil Eng. Trans.*, Vol. 95, pp. 996-1019.

TARZWELL, M. C. 1957. Water Quality Criteria for Aquatic Life. U. S. Dept. of H. E. W., pp. 248-251.

TARZWELL, M. C. and A. R. GAUFIN. 1953. Some limportant Biological Effects of Pollution Often Disregarded in Stream Surveys. U. S. Dept. of H. E. W., pp. 295-298.