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SIMULATION MODELING
OF THERMAL EFFLUENT
IN AN IRRIGATION SYSTEM

January 1970

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SIMULATION MODELING OF THERMAL EFFLUENT
IN AN IRRIGATION SYSTEM

D. E. Peterson and R. T. Jaske

Water and Land Resources Department
Environmental and Life Sciences Division

January 1970

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SIMULATION MODELING OF THERMAL EFFLUENT
IN AN IRRIGATION SYSTEM

D. E. Peterson and R. T. Jaske

ABSTRACT

Simulations of hourly average water temperatures along a 40 mile reach of the Phelps County Canal of south-central Nebraska were carried out by utilizing moving means of hourly regional weather data as input to the COLHEAT computer program. An analysis of the effects of steam plant thermal effluents on the canal indicates that irrigation canals may be an important future source of cooling water.

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SIMULATION MODELING OF THERMAL EFFLUENT IN AM IRRIGATION SYSTEM

D. E. Peterson and R. T. Jaske

INTRODUCTION

A test simulation was performed to ascertain whether the COLHEAT simulation system could be utilized to generate stream temperatures on an hourly basis with regional weather data. The study was concerned with the effects of steam plant discharges upon the thermal regimen of the Phelps County Canal of south-central Nebraska. Battelle-Northwest developed the COLHEAT system to simulate daily average water temperatures of the Columbia River. Made at the request of the Environmental and Sanitary Engineering Branch, Division of Reactor Development and Technology, United States Atomic Energy Commission, the study was a continuation of a series of tests which included simulations of daily average temperatures of the Deerfield, Illinois and Upper Mississippi Rivers (see Bibliography). A secondary purpose of the study was to determine if 10 years of irrigation with waters above equilibration temperatures had produced changes that attracted the attention of the people.

Three feeder canals, two of which are shown in Figure 1, make up the Central Nebraska Public Power and Irrigation District. With a length of 57 miles, the Phelps County Canal is the largest; its 380 miles of distribution laterals provide water to 74,600 acres of land in Phelps and Kearney Counties, approximately 65% of the total acreage in the District. Noted for high productivity, the area has annual direct irrigation benefits of \$15,000,000 for the 113,800 acres under irrigation.

Of special interest was the fact that the Canaday Steam Plant of the Central Nebraska Public Power and Irrigation District has used water from the supply canal for direct

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FIGURE 1. Central Nebraska Public Power and Irrigation District

cooling of condensers since 1958. With a 100 MW capacity, the Canaday Plant is a natural gas fueled generating unit located approximately 1 mile upstream of control structures designed to divert water along the Phelps County Canal and/or return it to the Platte River.

SUMMARY AND CONCLUSIONS

The essential purpose of the study was realized to an extent in keeping with the available data base. Good simulation of the hourly temperatures of the canal downstream of the operating thermal plant was achieved using weather data from a number of remote sources. The value of the overall heat transfer coefficient U_c was determined to be somewhat higher than values obtained from lakes and relatively swift rivers. Because of the absence of either a positive or negative history of the agricultural effect of the warmed water during the irrigation season, no significant effects could be determined for this case. The simulation of the addition of a 500% increase in heat rejection to the canal system indicated a large potential heat sink capability for future expansion of the system without extensive modifications of the simulated thermal history. In general, the study of the thermal dissipation of the canal system provided another successful test case for the use of the COLHEAT simulation system. The following specific conclusions are derived from the study:

- 1) A working test simulation of the hourly temperature history of a canal irrigation system using remote weather data was carried out. The success of the computer system in predicting temperatures within the error of measurement indicates that the basic assumptions used in the COLHEAT simulation model are good enough for the preliminary study of any moving water body with discrete boundaries. On this basis it appears that the use of multiparameter,

feedback coefficient, heat budget models are capable of deterministic prediction of a wide range of flowage and weather conditions. There should be little hesitation about the use of these models for the allocation and adjudication of incremental thermal increases on managed watercourses.

- 2) The investigation of the cooling capacity of the main canal system reveals a relatively large and previously untapped heat sink of considerable value in the planning for future power systems. The computed rates of heat transfer from the canal indicate overall coefficients as high as $700 \text{ Btu/}(\text{day})(\text{ft}^L)(^\circ\text{F})$. This is considerably higher than values calculated on open lakes and ponds which range from 100 to $200 \text{ Btu/}(\text{day})(\text{ft}^L)(^\circ\text{F})$. Net values on the Columbia River are higher than those for open lakes and ponds due to the turbulence of the surface. The high values obtained in the instant study are about twice the values nominally used for cooling ponds and may reflect the absence of boundary layer limits ordinarily expected on large lake surfaces. The results point up the importance of additional research in the determination of surface exchange coefficients in varying surface geometrical configurations to supplement the basic information derived from oceanographic sources.
- 3) The high heat transfer rates obtained from the simulation suggest that the use of an extensive canal system for the routine enhancement of agricultural production either by soil warming or boundary layer modification of the local weather may be considerably less appealing because of high investment costs in water distribution piping or insulation of main conduit to conserve heat. Conversely, the use of large artificial canal systems as part of pumped

storage nuclear and fossil power stations suggests a means of providing a large dependable energy base away from existing river systems.

SIMULATION MODEL

The COLHEAT simulation model, which was first utilized to simulate a reach of the Columbia River in August 1965, has been discussed in detail in a previous publication.⁽¹⁾ The model applies a heat budget to a given section of a river, or canal as follows:

$$\Sigma Q = Q_T = (Q_S - Q_R) - Q_b - Q_e \pm Q_h + Q_v$$

where

Net insolation

Q_S = incoming short wave radiation

Q_R = reflected short wave radiation from the water surface

Back radiation

$$Q_b = 0.970 \sigma (T_w^4 - \beta T_a^4) \text{ Btu/ft}^2/\text{hr}$$

σ = Stefan Boltzmann radiation constant

β = atmospheric radiation factor derived from cloud cover and vapor pressure

t_w = temperature of water surface in °K

t_a = temperature of air in °K

Evaporation

$$Q_e = 13.8 u (l_w - l_a) \text{ Btu/ft}^2/\text{hr}$$

u = wind speed in mi/hr

l_w = vapor pressure of water in inches of mercury

l_a = vapor partial pressure in inches of mercury

Conduction

$$Q_h = 0.00466 k p (t_a - t_w) \text{ Btu/ft}^2/\text{hr}; 0.00466 \text{ is a constant derived from Bowen ratio for quiescent lakes}$$

k = correction factor varying between (1-3) for rapid streams

u = wind velocity in mi/hr

p = atmospheric pressure in inches of mercury

t_a = mean air temperature in °C

t_w = mean water surface temperature in °C

Advected energy

Q_v = varies with heat source

(Term used to input discharge heat from thermal effluents, and in special cases to handle ice, sleet, rain, etc.)

The water temperature for a section is determined by means of the equation

$$T_w = \left[\frac{1}{V_r} \frac{Q_t A \theta}{62.5} + V_i (T_i - T_w) \right]$$

where

V_r = mean river section or reservoir volume

A = mean river section or reservoir surface area

θ = time increment

V_i = inflow volume per time increment

T_i = mean temperature of inflowing water

T_w = mean temperature of water in a given section of river or reservoir

Q_t = the net heat transport per time.

The above equation, which applies to homogeneous, isotropic media, is modified for nonhomogeneous media by incorporating it into a computational system which uses intermittent transport and mixing with respect to the ratios of mean travel times of water masses through a fixed volume. In the form of the model used in this study the flow system is composed of an inner and outer trough with relative volumes B and $(1-B)$, respectively (Figure 2). The model sets up a series of difference equations and iteratively computes the downstream temperatures as a function of the input data in the following manner:

$$T_{i+1,j+1} = (1-B) \left(T_{i,j} + T_{i,j}^{(1)} + T_{i,j}^{(2)} \right) + B \left(T_{i,j-1} + T_{i,j-1}^{(1)} + T_{i,j}^{(2)} \right)$$

L VARIES AS RESERVOIR GEOMETRY AND FLOW
AND REPRESENTS A RESERVOIR LENGTH FOR THAT REGION
ONE FLOW DAY IN LENGTH

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FIGURE 2. Model of Channel Flow at Translational Instant

where

- $T_{i,j}$ = average water temperature of the beginning of the j^{th} flow increment at the end of the i^{th} time increment [flow day) $^{\circ}\text{C}$
- $T_{i,j}^{(1)}$ = the temperature change during the first half of the i^{th} time interval in the j^{th} flow increment as determined from surface heat exchange plus advected energy (heat budget) in $^{\circ}\text{C}$
- $T_{i,j}^{(2)}$ = same as above except for the second half of the i^{th} time interval, in $^{\circ}\text{C}$
- B = the fractional part of the water in the inner fast moving trough.

At the end of an i^{th} time interval the water in the inner and outer troughs of each section is mixed and an average temperature for the section is calculated. The process is then repeated for the $i + 1$ time interval.

Operation of the COLHEAT model requires the following data:

- River or reservoir dimensions reduced to equivalent non-parallel trapezoidal cross sections
- @Water temperatures at the upstream end of reach under study and also at downstream locations
- Streamflow at inlet and outlet of each canal section
- Meteorological data over the area of interest (wind velocity, mean air temperature, dew point, sky cover, incoming short wave radiation)
- Advected heat quantities.

These requirements provide a topical outline for the following discussion.

CANAL SECTIONS

The Phelps County Canal was originally constructed with a trapezoidal cross section having a 2:1 side slope. The section has been subject to natural modification since that time so that the present configuration resembles that of a natural

stream, with the exception of an absence of meandering. For simulation purposes it was assumed that the original cross section had remained unchanged. Surface widths and depths were obtained from data provided by the Central Nebraska Public Power and Irrigation District, supplemented with onsite examination.

WATER TEMPERATURES

Battelle-Northwest made an onsite study of point temperatures along the Phelps County Canal during 19, 20, 21 August 1968. To obtain representative average temperatures, the data were collected downstream of waterfalls and other control structures. In addition, hourly intake temperatures to Canaday Steam Plant condensers were made available for simulation purposes. The appendix has a summary of the data.

FLOW RECORDS

Input flows past the Canaday Steam Plant were obtained from hourly records of the Johnson No. 2, hydroelectric plant (Figure 3), which is located 2-1/2 miles upstream of the Canaday Steam Plant (Figure 4). Figure 5 shows a typical control structure. An accretion of approximately $50 \text{ ft}^3/\text{sec}$ due to seepage occurs between the Johnson No. 2 and Canaday Plants; this was added to Johnson No. 2 flows to obtain the flow past the steam plant. Additional records were available at the head end of the Phelps County Canal (Mile 0), 3-1/2 miles downstream of Johnson No. 2, and at Phelps Canal Mile 31.8. Data on diversions from the Phelps County Canal were available for 19 August 1968. Diversions for 20 and 21 August were assumed for simulation purposes to be proportional to those of the 19th.

METEOROLOGICAL DATA

The input data for operation of the simulation system include the five major variables involved in the heat budget

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FIGURE 3. Johnson Hydropower Plant No. 2

FIGURE 4. Canaday Steam Plant

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FIGURE 5. Phelps County Canal Control Gate

computation. Of these, solar radiation and dry bulb temperatures are dominant; the others have a lesser effect in the order of dew point, wind speed, and cloud cover. The latter is involved only in the estimate of long wave radiation exchange, since measured values of short wave (solar) radiation are used as input data.

Correlations of regional weather systems for various portions of the country show distinct regional patterns. According to studies of this series, a single station can represent daily average weather over a radius of 75 to 100 miles.

In this study, regional data were used in an attempt to simulate hourly average temperatures along the Phelps County Canal. The nearest U.S. Weather Bureau stations having hourly records are at Grand Island (approximately 60 miles to the east of the study area) and North Platte (approximately 65 miles to the west of the study area). The nearest station at which hourly solar radiation was normally collected was Lincoln, located approximately 125 miles to the east. Unfortunately no hourly data were recorded at Lincoln during the period of interest. Consequently, Dodge City, Kansas (225 miles south) solar radiation was used as input information to the COLHEAT model.

ADVECTED HEAT

As it is used in this and related studies, advected heat refers primarily to the waste heat entering streams or lakes as a result of direct cooling of steam plant condensers. On a national basis, over 80% of the waste heat dissipated to the environment comes from electrical generating units.

Hourly loads of the Canaday Steam Plant for the period of 19, 20, 21 August 1968 formed the input data for the Phelps County Canal simulation. The average thermal efficiency of

the plant during August 1968 was 35.7%; this value was used to determine hourly thermal loads to the stream. Additional information was available in the form of inlet and outlet water temperatures to and from the plant condensers. Two pumps, operating at capacity, provided a circulation flow of approximately $134 \text{ ft}^3/\text{sec}$ between the canal and the condensers.

RESULTS OF SIMULATION

Figures 6 through 9 illustrate computed and observed values of average canal temperatures at several points downstream of the Canaday Steam Plant. These results were obtained after three unsuccessful attempts with different combinations of Dodge City solar radiation and Grand Island and/or North Platte weather. The final results were obtained by using averaged Grand Island and North Platte weather in combination with Dodge City radiation in the form of a stochastic mean as input data to the model. The computed temperatures illustrated in Figure 6 are lower than the point observations at that location, 1 mile downstream of the Canaday outfall. Since the computed values were obtained using power load data, a check was made using a mass-temperature budget of condenser circulating water and canal flow. The results were in agreement with the temperatures computed by the COLHEAT program. The apparent explanation for the discrepancy is the fact that the outfall of the Canaday Plant directs the heated effluent toward the right (south) bank of the canal (Figure 4). Because of the low gradient (approximately 0.0001) of the canal, the water is not fully mixed until it passes through the tainter gate leading to the Phelps County Canal. The gate for return flow to the Platte River is located on the left bank on the upstream side of the Phelps Canal gate. As a consequence, a disproportionate quantity of cooler water traveling along the

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FIGURE 6. Phelps County Canal at Mile 0

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FIGURE 7. Phelps County Canal at Mile 9.7

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FIGURE 8. Phelps County Canal at Mile 20.5

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FIGURE 9. Phelps County Canal at Mile 31.8

left bank can be returned to the river. Measurements taken from a bridge midway between the Canaday outlet and the two control gates indicated that temperatures near the left bank were 0.6 to 0.8 °C lower than center and right bank temperatures.

Figures 7, 8, and 9, indicate good agreement between calculated and observed temperatures. Because of the natural decay of advected pulses and the dominance of solar radiation and weather, the differences noted at Mile 0 would normally diminish downstream. In order to estimate the distance of effective equilibration for the heat entering the system, the thermal load of the Canaday Plant was arbitrarily increased by a factor of three in one simulation run and by a factor of five in another (Figures 6 through 9). The results of these simulations (Figures 10 and 11) were then normalized with respect to natural background and averaged over the period of the test. Since solar radiation, weather, and surface area of the canal were identical for the three loads, a logarithmic normal analysis of the data could be made. The results indicate that the exchange coefficients for the three cases were in agreement for approximately 25 miles below the outfall. Beyond 25 miles, the coefficient associated with existing production level (100 MW) decreased to 85% of the coefficients for the hypothetical higher levels. This indicates that, for practical purposes and for the period of the study, the load was dissipated in 25 miles. The exchange coefficient for the period of study was calculated to be 700 Btu/(day) (ft²) (°F).

Because of data limitations, the simulations over the final 17 miles of the Phelps County Canal (total length 57 miles) were not representative. Since the primary purpose of this reconnaissance study is the simulation of the known data, more research on the ultimate capacity of the system needs to be done through other sponsorship.

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FIGURE 10. Thermal Capacity of Phelps County Canal System

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FIGURE 11. Cooling Rate Versus Heat Load

EFFECTS OF THERMAL EFFLUENTS ON AGRICULTURE

County agriculture service personnel and a number of farmers were contacted to ascertain if there had been any apparent changes after the Canaday Steam Plant had gone into operation in 1958. As far as they could tell, neither benefits nor liabilities resulted from water temperature modifications. The effects, if any, appear too subtle to be delineated by anything less than a detailed research program.

ACKNOWLEDGMENT

The authors appreciate the full cooperation of the personnel of the Central Nebraska Public Power and Irrigation District. Data, diagrams, and information were generously given, and without this assistance the investigation could not have been concluded within the scope of this program.

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APPENDIX

STEAM PLANT DATA AND TEMPERATURE OBSERVATIONS

TABLE A.1. Canaday Steam Plant Data

<u>Time</u>		<u>Canal Flow, ft³/sec</u>	<u>Intake Temperature, °C</u>	<u>Plant Load,* MWe</u>
Aug 19:	100	550	23.4	81
	200	550	23.4	73
	300	550	22.8	72
	400	530	22.8	72
	500	530	22.8	70
	600	530	22.8	64
	700	530	22.8	69
	800	480	22.8	80
	900	850	22.8	93
	1000	850	22.8	104
	1100	850	22.8	110
	1200	900	22.8	110
	1300	900	23.4	110
	1400	900	23.4	110
	1500	900	23.9	110
	1600	900	23.9	110
	1700	1210	24.5	110
	1800	1210	24.5	110
	1900	1210	24.5	110
	2000	1210	24.5	110
	2100	860	24.5	110
	2200	860	23.9	110
	2300	860	23.9	110
	2400	675	23.9	110
Aug 20:	100	610	23.4	109
	200	600	23.4	106
	300	550	23.4	98
	400	550	23.4	100
	500	550	23.4	90

* Thermal Efficiency 35.7%

TABLE A. 1 (contd)

<u>Time</u>		<u>Canal Flow, ft³/sec</u>	<u>Intake Temperature, °C</u>	<u>Plant Load,* MW_e</u>
Aug 20:	600	550	22.8	85
	700	550	22.8	83
	800	1000	22.8	91
	900	1000	22.8	99
	1000	1000	23.4	104
	1100	975	23.4	110
	1200	990	23.4	110
	1300	990	23.9	110
	1400	990	23.9	110
	1500	975	24.5	110
	1600	975	24.5	110
	1700	975	24.5	110
	1800	975	24.5	110
	1900	985	24.5	110
	2000	990	23.9	110
	2100	975	23.9	110
	2200	975	23.9	110
	2300	970	23.4	110
	2400	650	23.4	108
Aug 21:	100	650	23.4	92
	200	650	23.4	85
	300	650	23.4	87
	400	650	23.4	82
	500	650	23.4	82
	600	650	23.4	82
	700	650	23.4	82
	800	650	22.8	90
	900	1290	22.8	95
	1000	1290	23.4	100
	1100	1290	23.4	100
	1200	1290	23.4	110

TABLE A.2. Temperature Observations

<u>Station No.</u>	<u>Temp, °C</u>	<u>Time</u>	<u>Remarks</u>	<u>Mile Coding Used With Canal Model</u>
<u>August 19, 1968</u>				
Ph-2	25.5	1125	Mile 0 - Phelps Co. Canal mixed zone below drop; 100% overcast	100.0
	24.5	1130	Bridge - 0.55 mile below Canaday outfall; temp taken near left (north) bank of canal	100.5
	25.1 to 25.3	1135	Bridge - 0.55 mile below Canaday outfall; temp's taken 10' from left bank to right bank	
Ph-2	25.2	1140	Flow in canal increased after reading	
J-2	23.9	1330	Johnson No. 2 Hydro Plant - mixed zone in tailwater; scattered clouds since noon	103.5
Ph-1	23.4 to 23.5	1350	Bridge near Canaday Plant - 50' upstream of plant outfall; temp range across stream indicated	101.1
Ph-2	26.25	1355		
Ph-3	26.40	1410	Mile 1.8 - Phelps Co. Canal - mixed zone at downstream end of siphon	98.2
Ph-4	25.85	1442	Mile 9.7 - Phelps Co. Canal - mixed zone at downstream end of siphon	90.3
Ph-5	25.95	1500	Mile 16.7 - Phelps Co. Canal - mixed zone below control gate	83.3
Ph-6	26.4	1508	Mile 20.5 - Phelps Co. Canal - mixed zone below drop	79.5
Ph-7	26.3	1523	Mile 23.2 (4 miles north of Holdrege) Phelps Co. Canal - mixed zone below drop	76.8

TABLE A.2. (contd)

<u>Station No.</u>	<u>Temp, °C</u>	<u>Time</u>	<u>Remarks</u>	<u>Mile Coding Used With Canal Model</u>
<u>August 19, 1968</u>				
J-2	24.85	1625	Continued scattered clouds	
Ph-1	24.2 ± 0.1	1635		
Ph-2	26.80	1640		
Ph-3	27.50	1650		
Ph-4	26.55	1715		
Ph-5	26.30	1735		
Ph-6	26.70	1745		
Ph-7	26.90	1755		
<u>August 20, 1968</u>				
J-2	24.00	0850	10% to 20% cloud cover, scattered	
Ph-1	23.6 ± 0.1	0900		
Ph-2	26.20	0905		
Ph-3	25.90	0920		
Ph-4	25.50	0938		
Ph-5	25.90	1004		
Ph-6	25.90	1012		
Ph-7	25.80	1019		
Ph-8	26.20	1224	Mile 31.8 (1/2 mile north of Funk) - Phelps Co. Canal - mixed zone below drop; 50% to 60% overcast	68.2
Ph-9	26.30	1255	Mile 38.6 (1 mile northwest of Axtell) - Phelps Co. Canal - mixed zone below drop	61.4

TABLE A. 2. (contd)

<u>Station No.</u>	<u>Temp, °C</u>	<u>Time</u>	<u>Remarks</u>	<u>Mile Coding Used With Canal Model</u>
<u>August 20, 1968</u>				
Ph-10	27.30	1325	Mile 51.1 (2 miles north of Minden) - Phelps Co. Canal - mixed zone below drop; 10 to 20% overcast	48.9
	27.65	1515	Mile 36.2 (Loomis) - E65 Canal - mixed zone below drop on 36.2N lat	
	27.40	1540	Mile 28.2 (1 mile east of Bertrand) - E65 Canal - mixed zone on south side of highway	
	25.3	1600	Mile 16.9 (Northeast Corner of Smithfield) - E65 Main Canal - readings from bridge; no noticeable variation in temp across canal	
J-2	24.80	1617		
Ph-1	24.8 ± 0.1	1626		
Ph-2	26.90	1631		
	25.50	1650	Mile 20.1 - E65 Main Canal - mixed zone below drop	
	26.00	1712	Mile 23.7 - E65 Canal - mixed zone below drop	
	26.75	1730	Mile 9.7 - (E65 - 23.7) Canal	
<u>August 21, 1968</u>				
Ph-1	23.4 ± 0.1	0950	Clear skies	
Ph-2	25.60	0955		

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