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EVALUATION OF THE SIMPL-1
HYBRID COMPUTER CONCEPT
ON A WATER QUALITY BENCHMARK PROBLEM

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HYBRID COMPUTER CONCEPT
ON A WATER QUALITY BENCHMARK PROBLEM

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November 1969

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R. A. Burnett and D. G. Daniels

ABSTRACT

As part of a study to evaluate the Battelle-Northwest SIMPL-1 hybrid computer concept in comparison to large digital techniques, a hybrid version of an all-digital Columbia River water quality simulation was developed. The discrete-time, discrete-space digital water transport model was transformed into a continuous-time, discrete-space analog model for use in the hybrid program. Identical river and weather parameters were input to both models for a performance comparison. The hybrid results matched the all-digital output almost exactly. A minimum speed advantage of 3.6 to 1 and a machine economic advantage of 55 to 1 was achieved by the SIMPL-1 hybrid program over the all-digital program. Although requiring longer initial setup time, the hybrid program eliminated turnaround time between successive runs and provided the operational conveniences of man-machine interaction and graphical output displays.

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INTRODUCTION

The SIMPL-1 concept⁽¹⁾ is a hybrid computer programming system which has been developed at Battelle-Northwest in order to optimally perform a wide range of simulation studies with the hybrid facility (Hybrid 1). To evaluate the effectiveness of SIMPL-1, several digital simulation programs currently in use at Battelle-Northwest were chosen as benchmark problems for an all-digital/SIMPL-1 comparison study. Points to be compared are: 1) accuracy; 2) time and costs, both man and machine; 3) operational convenience and flexibility; and 4) amount of computer equipment required to solve each problem. The water quality simulation (COL HEAT) discussed herein was chosen as one of the benchmarks. This program, coded in FORTRAN for the UNIVAC 1108 computer, calculates a history of the river temperatures at spaced intervals along a specified river reach. The basic mathematical models used in COL HEAT were successfully converted into a SIMPL-1 hybrid program, the current version of which is called RIVER4.

SUMMARY AND CONCLUSIONS

ACCURACY

Comparative results showed no detectable loss in accuracy. In fact, the integral of the squared error (ISE) over the length of the comparison run was slightly lower for the RIVER4 simulation than for the all-digital simulation. Figure 1 is a plot of the results of the comparison run. The ability of the

FIGURE 1. Grand Coulee-Priest Rapids River Reach:
Comparison of Hybrid and Digital Solutions.

hybrid model to closely duplicate a set of COL HEAT temperature calculations is thus demonstrated. A detailed analysis of the comparison run begins on page 15.

TIME AND COST

The total time required to develop and evaluate RIVER4 was 450 man-hr and \$2300 (120 hr) of computer time. The solution time for a run covering 168 days of real-time was 33.6 sec. This time scale was chosen for convenience of monitoring and recording the simulation. It could have been run at speeds up to 10 times faster, but this would gain only a few seconds. The cost of operating Hybrid 1 (\$27/hr or \$0.45/min) is so low that such action is economically insignificant. The COL HEAT solution time on the 1108 for a run of the same magnitude was approximately 2 min. The hybrid thus has a 3.6 to 1 minimum speed advantage. At \$7/min for the UNIVAC 1108, the hybrid has a 15.5 to 1 cost rate advantage for an overall machine economic advantage of 55 to 1. However, the time required to set up and initialize RIVER4 (including pot setting and analog checkout) is about 30 min. The cost of obtaining only one set of river temperatures is thus about equal for both models. For parameter surveys and model optimization studies, where a large number of consecutive runs must be made, the increased effectiveness of an engineer should be multiplied by the 55 to 1 machine advantage to produce the overall economic advantage to be gained by using the hybrid computer.

OPERATIONAL CONVENIENCE AND FLEXIBILITY

RIVER4 becomes a powerful tool for parameter surveys and optimization studies because of the ability to make rapid parameter and program changes and the availability of graphical output displays for immediate observation of the effects of these changes. Although COL HEAT is simple to set up, each

run requires 6 to 12 hr of turnaround time, resulting in a considerably longer delay between consecutive runs. Graphical output requires an additional 6 to 12 hr per COL HEAT run.

Reprogramming is simplified with the SIMPL-1 concept. If several parameter or program changes are made in the digital portion during a series of RIVER4 runs, and the operator desires to return the program to the same conditions at a later time, he can write part or all of the core memory contents to magnetic tape. The modified program, containing all of the changes up to that point, can then be recalled to memory whenever the operator so desires. Major programming changes requiring reassembly can also be made with a relatively small amount of time and cost.

COMPUTER REQUIPEMENTS

Approximately 50% of the 8K memory of the PDP-7 digital computer and 70% of the combined capacity of the EASE 1132 and 2133 analog computers are required by RIVER4 to simulate 21 river sections with two flow troughs in each section. Twelve 1132 multipliers are used, with the bulk of the analog portion of the simulation being handled by the 2133. A total of 42 integrators, 70 summer-inverter amplifiers, and 42 multipliers are required. About 30K of UNIVAC 1108 core memory was required to solve the same problem with COL HEAT. (Three troughs instead of two were used in the digital model; from an accuracy standpoint it appears that two troughs are sufficient.)

The hybrid model as presently constituted does not possess all of the capabilities of COL HEAT. However, consideration of the expansion area available and the existence of optimal programming techniques which can be used to condense the existing program, indicates that these capabilities could be added to RIVER4.

MODEL TRANSFORMATION

COL HEAT was developed under the direction of R. T. Jaske(2) as part of Battelle-Northwest's research effort in the water resources field. The program accepts geometrical and dimensional input data describing a particular river reach and sets up the simulation for that portion of the river. Based upon the daily weather and river flow data, the model then calculates a set of daily river temperatures at the outlet end of the reach. A weather and river flow forecast can thus be converted into a river temperature forecast. The transport and dispersion of impurity concentrations can be handled in a similar manner.

To effectively program the -river simulation on the hybrid computer, it was necessary to modify the COL HEAT mathematical model. The most significant modeling change was the conversion of the digital water transport model into an analog model. The COL HEAT difference equations were rewritten as continuous first-order differential equations, and these equations were programmed on the analog computer. This change could actually be expected to improve the accuracy due to the substitution of continuous integration for approximate numerical integration. In addition a great amount of digital bookkeeping and iteration was eliminated by this conversion.

The digital transport model divides the river reach into K sections, where K may not exceed 149. Each river section has either a rectangular or a trapezoidal cross section; the dimensions of the cross section at the inlet and outlet ends of the section need not be the same. The sections are then divided longitudinally into three channels or troughs. The inner trough normally contains half the volume of the section, with the central and outer troughs each containing one-fourth the section volume. The relative water velocities in the inner,

central, and outer troughs are then assigned; they are normally assigned a ratio of 3:2:1. At the end of each time step (24 hr), COL HEAT calculates an average temperature for each river section. This is done by examining the relative trough velocities, the section volumes, and the total volumetric flow rate for that time step, and from this information determining the previous location (24 hr ago) of the water in each trough of that section. Knowledge of its previous location determines the previous temperature of that chunk of water; its previous temperature and the weather data for that day determine its change in temperature over the past time step. In other words, during one time step the water in each trough is moved separately; then at the end of the time step, the program "uniformly mixes" the water in each section by calculating an average section temperature according to the volumetrically weighted temperatures of each trough.

Mathematically, the digital transport model is based upon the following difference equation:

$$T_{k,i} - T_{k,i-1} = \Delta T_{k,i} = \frac{Q_{k,i} S_k \Delta t}{\rho C_p V_k} + \frac{F_T \Delta t}{V_k} (T_{k-1,i-1} - T_{k,i-1}) \quad (1)$$

where $\Delta T_{k,i}$ is the change in temperature of the water in the k^{th} section during the i^{th} time step of duration Δt . The first term on the right hand side is the temperature change due to heat exchange at the surface. The second term accounts for displacement flow into section k from the section immediately upstream ($k-1$). This difference equation can easily be converted to continuous differential form by dividing both sides of the equation by Δt and taking the limit as Δt approaches zero:

$$\frac{dT_k(t)}{dt} = \frac{Q_k(t) S_k}{\rho C_p V_k} + \frac{F_T(t)}{V_k} [T_{k-1}(t) - T_k(t)] \quad (2)$$

Two troughs were implemented in the analog model. The central and outer troughs were combined into one trough and labeled the "bank" trough (identified by a subscript b), and the inner trough was renamed the "center" trough (identified by a subscript c). Both trough volumes are now equal to half the total section volume. The relative water velocity in the bank trough was set equal to the average of the velocities of the two digital troughs from which it was formed; the velocity ratio, center to bank, thus becomes 2:1. Two differential equations of the form of Equation (2) were thus required for each river section. The mixing concept was introduced by calculating the average effective temperature of section k-1 and using this as the temperature of the water flowing into both troughs of section k. The resulting analog transport equations are:

$$\frac{dT_{kb}(t)}{dt} = \frac{Q_k(t)S_{kb}}{\rho C_p V_{kb}} = \frac{F_{kb}(t)}{V_{kb}} \left[\bar{T}_{k-1}(t) - T_{kb}(t) \right] \quad (3)$$

$$\frac{dT_{kc}(t)}{dt} = \frac{Q_k(t)S_{kc}}{\rho C_p V_{kc}} + \frac{F_{kc}(t)}{V_{kc}} \left[\bar{T}_{k-1}(t) - T_{kc}(t) \right] \quad (4)$$

$$\bar{T}_k(t) = \alpha_{kb} T_{kb}(t) + \alpha_{kc} T_{kc}(t) \quad (5)$$

where

$$\alpha_{kb} = \frac{v_{kb}}{V_{kb} + RV_{kc}}$$

$$\alpha_{kc} = \frac{RV_{kc}}{V_{kb} + RV_{kc}} = 1 - \alpha_{kb}$$

$$R = \frac{\bar{v}_{kc}}{\bar{v}_{kb}} = 2$$

The bank and center flow rates F_{kb} and F_{kc} can be expressed in terms of the total volumetric flow rate F_T by a consideration of the following relationships:

$$F_{kb} = \bar{v}_{kb} A_{kb} = \frac{v_{kb} V_{kb}}{\ell_k}$$

Thus,

$$\frac{F_{kb}}{V_{kb}} = \frac{\bar{v}_{kb}}{\ell_k}$$

Similarly,

$$\frac{F_{kc}}{V_{kc}} = \frac{\bar{v}_{kc}}{\ell_k}$$

Now we observe that

$$F_T = F_{kb} + F_{kc} = \frac{\bar{v}_{kb} V_{kb}}{\ell_k} + \frac{\bar{v}_{kc} V_{kc}}{\ell_k} \quad (6)$$

$$\bar{v}_{kc} = R \bar{v}_{kb} \quad (7)$$

Substituting (7) into (6), we obtain

$$F_T = \frac{\bar{v}_{kb} V_{kb} + R \bar{v}_{kb} V_{kc}}{\ell_k} = \frac{\bar{v}_{kb}}{\ell_k} \left[V_{kb} + R V_{kc} \right]$$

Thus

$$\frac{v_{kb}}{\ell_k} = \frac{F_T}{V_{kb} + R V_{kc}} = \frac{F_{kb}}{V_{kb}}$$

and

$$\frac{\bar{v}_{kc}}{\ell_k} = R \left(\frac{\bar{v}_{kb}}{\ell_k} \right) = \frac{R F_T}{V_{kb} + R V_{kc}} = \frac{F_{kc}}{V_{kc}}$$

Defining D_k as

$$D_k = V_{kb} + RV_{kc} ,$$

we can now rewrite the differential Equations (3) and (4) as

$$\frac{dT_{kb}(t)}{dt} = \frac{Q_k(t)S_{kb}}{\rho C_p V_{kb}} + \frac{F_T(t)}{D_k} \left[\bar{T}_{k-1}(t) - T_{kb}(t) \right] \quad (8)$$

$$\frac{dT_{kc}(t)}{dt} = \frac{Q_k(t)S_{kc}}{\rho C_p V_{kc}} + \frac{RF_T(t)}{D_k} \left[\bar{T}_{k-1}(t) - T_{kc}(t) \right] \quad (9)$$

This formulation requires only one D-to-A channel to carry the total flow rate function from a digital table to the analog computer; this value is then modified by separate pot coefficients for each river section. Equations (8), (9), and (5) were programmed on the analog computer for 21 river sections. Figure 2 shows the resulting analog diagram.

The surface heat exchange calculations are performed digitally in a manner similar to those in the COL HEAT model except that only one heat transfer rate, Q_k , is calculated for each section, based on the average effective temperature $\bar{T}_k$. The surface heat exchange equations are:

$$Q_k = Q_s - Q_{kh} - Q_{kB} - Q_{ke}$$

$$Q_s = K_s K_a Q_i$$

$$Q_{kh} = K_h U_P (\bar{T}_{ks} - T_a)$$

$$Q_{kB} = K_B \left[(\bar{T}_{ks} + 460)^4 - \beta (T_a + 460)^4 \right]$$

$$Q_{ke} = K_e U (e_{ks} - e_a)$$

$$\bar{T}_{ks}(t) = \bar{T}_k(t) + \Delta T_s(t)$$

FIGURE 2. Analog Diagram of RIVER4 Transport Model.

where all temperatures are °F. The term $\Delta T_s(t)$ is an empirical surface correction term to account for the effects of a thin film of warmer water at the surface; it is a sinusoidal function with a period of 1 year. The vapor pressures e_{ks} and e_a are functions of the water surface temperature $\bar{T}_{ks}$ and the dew point temperature T_d , respectively. The back radiation coefficient β is an empirical function of the cloud cover θ and the air vapor pressure e_a .

The basic differences between RIVER4 and COL HEAT can be summarized as follows:

- 1) The hybrid simulation contains a discrete-space, continuous-time transport model; COL HEAT is discrete-space, discrete-time,
- 2) RIVER4 uses two troughs; COL HEAT uses three.
- 3) The mixing effect between troughs is achieved on a spatial (sectional) basis in the hybrid model; the digital model does this on a temporal (daily) basis.
- 4) RIVER4 calculates a single heat input term Q_k for each section, based on the average temperature $\bar{T}_k$ of that section; COL HEAT calculates a separate Q for each trough of each section.

Figure 3 is a block diagram of the entire hybrid simulation. The simulation was run at a time scale of 1 sec = 5 days. The inlet water temperature, the flow, and the weather data were thus updated once every 200 msec (once each day of real-world time). For the simulation of K river sections, $2K$ differential equations and K algebraic equations are required to be solved on the analog portion. The digital portion handles $6K + 4$ algebraic equations which are solved repeatedly during the simulation.

FIGURE 3. Hybrid Computer Model. of Columbia River.

OPERATIONAL FEATURES AND CAPABILITIES

In addition to the basic model described above, COL HEAT is capable of handling advected heat inputs at each river section. The effects of the Hanford reactors on the Columbia River temperatures can thus be studied. The digital model can also check for the presence of density currents according to a criterion based on the critical Froude number; the surface heat input is reduced by a specified factor if a density current is detected. RIVER4 contains both of these capabilities, at a somewhat lesser degree of sophistication. COL HEAT can simulate tributary flows into and out of each section; RIVER4 cannot.

RIVER4 is currently limited to 22 river sections, compared to a maximum of 149 sections in COL HEAT. This limitation is imposed by the number of digital-to-analog conversion channels available. This is not a serious limitation, however, because the simulation can be operated iteratively, with the outlet temperature history being stored digitally and used as the inlet temperature function for the next run. In this manner a river reach of any length or any number of sections can be covered if enough runs are made.

COL HEAT can simulate the advection and transport of radioactive or nonradioactive material concentrations in addition to the temperature simulation. This capability is not currently present in RIVER4, but it could be added without much difficulty since the material concentration model is not as complex as the temperature model.

The amount of time and funding available for the study was limited; therefore, only one river reach was programmed and only one set of weather and flow data was used. The section volumes and surface areas were thus precalculated and

entered directly in digital tables along with the weather and flow information. A routine could easily be written which would allow new river sections and/or weather data to be read in either from punched cards or from tables stored on magnetic tape. New section volumes and surfaces would then be computer calculated from the section dimensions.

Pot settings are automatically set by a separate sub-program. The settings for the pots labeled " $5(D_{\min}/D_k)$ " and " $5R(D_{\min}/D_k)$ " in Figure 2 are calculated from the section volumes and the value of R specified by the programmer/operator. The other pot settings are stored in tables. The relocatable feature of the Hybrid 1 programming system allows the pot setting program to be read into a specified portion of memory only when it is needed. It can communicate with the part of the main program that is left in memory. Then the entire main program can be read back in to replace the pot setting program, and another simulation run can be made. Relocatability thus allows the user to make use of several programs which could not co-reside in memory due to limited core space. The same technique would also apply to the weather and section data read-in routine mentioned in the previous paragraph.

The increase in man-machine communications gained with the hybrid system make it a powerful tool for experimentation, parameter studies, and model optimization. Surface heat exchange coefficients and other parameters can be easily and quickly changed on-line between hybrid runs. The value of R can also be changed on-line, but this requires resetting of 2 pots per section which takes a slightly longer time (3 or 4 min). The same is true if the relative trough volumes or surface areas are to be changed.

The inlet and outlet temperatures and/or any of the intermediate temperatures can be monitored and visualized continuously during a run with the aid of a number of recording and display devices available, such as stripchart recorders, x-y plotter, digital voltmeter, storage oscilloscopes, etc. For example, the program could be modified to allow certain weather inputs for certain days to be analog variables, determined by hand-set pots. The time scale could be speeded up and the program run repetitively. Changes in the overall temperature curve could then be observed on the storage scope as the specific weather inputs for those key days were varied.

One disadvantage of the present hybrid system is the slowness of the teletype in printing output information. This situation will be greatly improved when the interfacing and installation of a recently purchased line printer are completed.

COMPARISON RUN

To obtain a direct comparison of the accuracy of COL HEAT and RIVER4, both models were programmed for a specific simulation. The conditions of this simulation were:

- 1) The river reach from Grand Coulee to Priest Rapids was divided into 21 sections, 13 rectangular and 8 trapezoidal. The temperature at Priest Rapids thus became the outlet temperature.
- 2) Weather and flow data from May 17 to October 31, 1965, were used.
- 3) A set of daily measured river temperatures at Priest Rapids covering the same time period was employed as the accuracy standard.
- 4) The density current checking subroutines were not used (that is, it was assumed that no density currents were formed).

5) There was no advected heat.

6) Surface heat coefficient values were:

$$K_a = 0.926$$

$$K_B = 1.66 \times 10^{-9}$$

$$K_e = 10.43$$

$$K_h = 0.00521$$

$$K_s = 3.6869$$

7) The transport models were set up as follows:

RIVER4

$$V_b = V_c$$

$$S_b = S_c$$

$$R \equiv \frac{\bar{v}_c}{\bar{v}_b} = 2$$

COL HEAT

$$V_{\text{outer}} = V_{\text{central}} = 1/2 V_{\text{inner}}$$

$$S_{\text{outer}} = S_{\text{central}} = 1/2 S_{\text{inner}}$$

$$R_1 \equiv \frac{\bar{v}_{\text{central}}}{\bar{v}_{\text{outer}}} = 2$$

$$R_2 \equiv \frac{\bar{v}_{\text{inner}}}{\bar{v}_{\text{outer}}} = 3$$

The maximum and minimum time constants for this simulation were 1.047 days and 7.2 min of real-time, respectively (0.2094 and 0.001 sec of hybrid computer time).

The results of this run are listed in Table 1 and displayed in Figure 4. The sampled hybrid temperature was within 0.05 °C of the digital temperature for 88% of the 168 days covered by the run. The two models were never more than 0.09 °C apart except for the first few days of the run during which time the models were eliminating a 1 °C error in the initial outlet temperature. The averages of the absolute value of the daily errors were 0.21 °C for both COL MEAT and RIVER4.

FIGURE 4. Comparison Run: Grand Coulee to Priest Rapids, 2965.

TABLE 1. Results of RIVER4 Versus
COL HEAT Comparison Run.

DATE	HYBRID TEMP.	MEASURED TEMP.	DIGITAL TEMP.	ERROR H HYB.-MEAS.	ERROR D DIG.-MEAS.
517	9.38	10.40	9.392	-1.02	-1.008
518	9.84	10.40	9.662	-0.56	-0.738
519	10.02	10.30	9.840	-0.28	-0.460
520	10.18	10.30	10.070	-0.12	-0.231
521	10.39	10.40	10.335	-0.01	-0.066
522	10.60	10.60	10.574	-0.00	-0.026
523	10.73	10.60	10.721	0.14	0.121
524	10.83	10.71	10.844	0.12	0.144
525	10.97	11.00	10.998	-0.03	-0.001
526	11.16	11.21	11.162	-0.05	-0.038
527	11.34	11.31	11.343	0.04	0.043
528	11.60	11.60	11.598	-0.00	-0.003
529	11.85	11.81	11.838	0.05	0.039
530	11.98	11.69	11.956	0.28	0.255
531	11.96	11.69	11.975	0.27	0.275
601	11.99	11.81	12.018	0.18	0.218
602	12.12	12.00	12.155	0.12	0.154
603	12.33	12.10	12.332	0.23	0.232
604	12.50	12.19	12.503	0.30	0.302
605	12.60	12.40	12.619	0.20	0.218
606	12.65	12.50	12.657	0.15	0.157
607	12.69	12.50	12.692	0.20	0.192
608	12.76	12.69	12.759	0.06	0.059
609	12.85	12.80	12.866	0.05	0.066
610	13.06	13.00	13.061	0.06	0.061
611	13.21	13.10	13.173	0.11	0.073
612	13.15	13.10	13.138	0.05	0.038
613	13.09	13.00	13.097	0.09	0.096
614	12.94	13.00	12.944	-0.06	-0.056
615	12.79	12.90	12.800	-0.11	-0.100
616	12.92	13.00	12.954	-0.09	-0.046
617	13.08	13.10	13.051	-0.03	-0.049
618	13.24	13.40	13.267	-0.16	-0.133
619	13.60	13.70	13.599	-0.10	-0.101
620	13.95	14.00	13.953	-0.05	-0.048
621	14.16	14.20	14.157	-0.04	-0.043
622	14.25	14.20	14.258	0.05	0.059
623	14.40	14.40	14.402	-0.00	0.003
624	14.55	14.50	14.522	0.05	0.021
625	14.51	14.60	14.490	-0.09	-0.110
626	14.22	14.30	14.212	-0.08	-0.089
627	13.96	14.30	13.985	-0.33	-0.315
628	13.96	14.40	13.989	-0.44	-0.411
629	14.12	14.60	14.154	-0.48	-0.445
630	14.38	14.60	14.415	-0.22	-0.186
701	14.69	14.80	14.703	-0.11	-0.096
702	14.97	14.91	14.979	0.06	0.079
703	15.11	15.50	15.105	-0.39	-0.395
704	15.25	15.30	15.264	-0.05	-0.035
705	15.49	15.30	15.504	0.20	0.204
706	15.78	15.41	15.789	0.38	0.389

TABLE 2. (contd)

DATE	HYBRID TEMP.	MEASURED TEMP.	DIGITAL TEMP.	ERROR H HYB.-MEAS.	ERROR D DIG*-MEAS.
707	16.04	15.91	16.043	0.14	0.143
708	16.05	15.70	16.034	0.35	0.334
709	15.87	15.80	15.862	0.08	0.062
710	15.60	15.70	15.605	-0.10	-0.095
711	15.32	15.50	15.316	-0.18	-0.185
712	15.23	15.30	15.220	-0.06	-0.081
713	15.39	15.50	15.373	-0.11	-0.127
714	15.66	15.70	15.640	-0.04	-0.060
715	15.93	15.80	15.921	0.14	0.121
716	16.21	16.01	16.204	0.21	0.204
717	16.46	16.20	16.447	0.26	0.247
718	16.54	16.39	16.520	0.15	0.120
719	16.47	16.51	16.469	-0.04	-0.032
720	16.28	16.20	16.276	0.09	0.076
721	15.94	16.01	15.929	-0.06	-0.071
722	15.76	16.01	15.807	-0.24	-0.193
723	15.86	15.91	15.895	-0.05	-0.005
724	16.08	16.01	16.093	0.08	0.093
725	16.44	16.30	16.447	0.15	0.146
726	16.84	16.70	16.817	0.15	0.117
727	17.21	17.10	17.190	0.11	0.090
728	17.55	17.39	17.543	0.16	0.143
729	17.81	17.60	17.810	0.21	0.210
730	18.02	17.80	18.035	0.22	0.236
731	18.25	18.00	18.285	0.24	0.284
801	18.55	18.20	18.561	0.35	0.362
802	18.65	18.30	18.617	0.35	0.317
803	18.63	17.80	18.587	0.83	0.787
804	18.66	17.70	18.597	0.96	0.899
805	18.69	17.90	18.638	0.79	0.738
806	18.81	18.20	18.766	0.61	0.566
807	18.95	18.70	18.930	0.24	0.230
808	19.09	19.00	19.084	0.10	0.085
809	19.19	18.90	19.200	0.29	0.300
810	19.29	19.00	19.290	0.29	0.291
811	19.25	19.00	19.242	0.26	0.242
812	19.06	19.00	19.041	0.06	0.041
813	18.90	18.80	18.916	0.10	0.116
814	18.79	18.80	18.819	-0.01	0.020
815	18.70	19.10	18.759	-0.40	-0.342
816	18.69	19.50	18.746	-0.81	-0.754
817	18.70	18.70	18.749	-0.00	0.049
818	18.77	18.40	18.796	0.38	0.395
819	18.69	18.40	18.656	0.29	0.256
820	18.58	18.20	18.593	0.38	0.392
821	18.65	18.30	18.640	0.35	0.341
822	18.58	18.30	18.555	0.28	0.255
823	18.42	18.30	18.391	0.12	0.091
824	18.35	18.30	18.363	0.05	0.064
825	18.29	18.20	18.268	0.09	0.069
826	18.15	18.10	18.172	0.05	0.071
827	17.99	18.10	17.950	-0.11	-0.150
828	17.59	17.60	17.571	-0.01	-0.029
829	17.41	17.30	17.415	0.11	0.114
830	17.39	17.39	17.400	-0.00	0.000

TABLE 1. (contd)

DATE	HYBRID TEMP.	MEASURED TEMP.	DIGITAL TEMP.	ERROR H HYB.-MEAS.	ERROR D DIG.-MEAS.
831	17.47	17.60	17.474	-0.14	-0.125
901	17.54	17.70	17.505	-0.16	-0.195
902	17.45	17.50	17.409	-0.05	-0.091
903	17.38	17.20	17.332	0.18	0.131
904	17.43	17.20	17.405	0.23	0.205
905	17.53	17.30	17.470	0.23	0.170
906	17.48	17.39	17.438	0.09	0.038
907	17.52	17.60	17.482	-0.09	-0.119
908	17.59	17.70	17.566	-0.11	-0.134
909	17.64	17.60	17.612	0.04	0.012
910	17.70	17.80	17.692	-0.10	-0.107
911	17.80	18.00	17.775	-0.21	-0.225
912	17.85	18.10	17.837	-0.26	-0.262
913	17.91	18.20	17.874	-0.29	-0.327
914	17.79	17.90	17.732	-0.11	-0.168
915	17.41	17.50	17.337	-0.10	-0.164
916	16.83	17.10	16.783	-0.27	-0.317
917	16.53	16.89	16.580	-0.37	-0.320
918	16.65	16.89	16.676	-0.24	-0.225
919	16.71	17.00	16.754	-0.29	-0.247
920	16.80	17.00	16.817	-0.21	-0.185
921	16.84	17.10	16.887	-0.26	-0.212
922	16.97	17.20	16.980	-0.23	-0.220
923	17.00	17.10	17.009	-0.10	-0.091
924	17.05	17.20	17.055	-0.15	-0.145
925	17.08	17.20	17.051	-0.12	-0.149
926	16.98	17.10	16.939	-0.12	-0.161
927	16.87	16.80	16.832	0.08	0.032
928	16.84	16.70	16.804	0.15	0.104
929	16.82	16.60	16.792	0.22	0.192
930	16.87	16.70	16.870	0.17	0.170
1001	17.03	16.80	17.028	0.23	0.228
1002	17.09	16.89	17.070	0.20	0.170
1003	17.08	17.10	17.078	-0.03	-0.022
1004	17.04	16.89	17.009	0.15	0.109
1005	16.81	16.70	16.778	0.11	0.079
1006	16.58	16.51	16.580	0.08	0.081
1007	16.54	16.51	16.577	0.04	0.077
1008	16.68	16.70	16.693	-0.03	-0.008
1009	16.68	16.60	16.677	0.08	0.077
1010	16.53	16.39	16.522	0.14	0.122
1011	16.37	16.20	16.378	0.17	0.173
1012	16.32	16.01	16.326	0.32	0.326
1013	16.32	16.01	16.323	0.32	0.323
1014	16.16	15.91	16.091	0.26	0.191
1015	15.64	15.30	15.581	0.34	0.281
1016	15.21	14.91	15.208	0.30	0.308
1017	15.05	14.80	15.069	0.26	0.270
1018	14.97	14.50	14.941	0.46	0.442
1019	14.86	14.50	14.859	0.35	0.358
1020	14.86	14.50	14.839	0.35	0.339
1021	14.82	14.40	14.810	0.41	0.409
1022	14.76	14.30	14.727	0.46	0.427
1023	14.66	14.40	14.634	0.26	0.234
1024	14.66	14.30	14.629	0.37	0.329

TABLE 1. (contd)

DATE	HYBRID TEMP.	MEASURED TEMP.	DIGITAL TEMP.	ERROR H HYB.-MEAS.	ERROR D DIG.-MEAS.
1025	14.69	14.00	14.613	0.69	0.613
1026	14.65	13.90	14.583	0.75	0.682
1027	14.64	13.79	14.574	0.84	0.774
1028	14.62	13.90	14.552	0.72	0.652
1029	14.62	13.79	14.554	0.83	0.754
1030	14.66	13.90	14.583	0.76	0.683
1031	14.62	13.79	14.543	0.83	0.743

TABLE 1. (contd)

DATE	MODEL GAP HYB.-DIG.	DIFF. IN ABS. ERROR HYB.-DIG.	HYBRID PERCENT ERROR	DIGITAL PERCENT ERROR
517	-0.01	0.03	9.85	9.62
518	0.13	-0.17	5.40	7.03
519	0.13	-0.17	2.72	4.38
520	0.12	-0.10	1.19	2.12
521	0.06	-0.05	0.11	0.59
522	0.03	-0.03	0.00	0.22
523	0.01	0.03	1.26	1.02
524	-0.01	-0.01	1.14	1.25
525	-0.03	0.03	0.22	0.00
526	-0.00	0.01	0.43	0.32
527	-0.00	-0.00	0.32	0.32
528	-0.00	-0.00	0.00	0.00
529	0.03	0.01	0.40	0.30
530	0.03	0.04	2.39	2.09
531	-0.01	-0.00	2.30	2.30
601	-0.03	-0.03	1.55	1.76
602	-0.03	-0.03	1.01	1.22
603	-0.00	-0.00	1.92	1.92
604	-0.00	0.01	2.50	2.39
605	-0.01	-0.01	1.57	1.67
606	-0.00	-0.00	1.17	1.17
607	0.01	0.01	1.56	1.46
608	-0.00	0.01	0.48	0.38
609	-0.01	-0.01	0.38	0.48
610	-0.00	-0.00	0.46	0.46
611	0.04	0.04	0.83	0.55
612	0.01	0.01	0.37	0.27
613	-0.00	-0.00	0.65	0.65
614	-0.00	0.01	0.46	0.37
615	-0.00	0.01	0.84	0.76
616	-0.04	0.05	0.65	0.28
617	0.03	-0.03	0.18	0.37
618	-0.01	0.04	1.17	0.90
619	-0.00	-0.00	0.71	0.71
620	-0.00	0.01	0.34	0.26
621	0.01	-0.00	0.26	0.26
622	-0.01	-0.00	0.34	0.34
623	0.01	-0.00	0.00	0.00
624	0.04	0.04	0.33	0.08
625	0.03	-0.03	0.57	0.75
626	0.01	-0.01	0.50	0.59
627	-0.01	0.03	2.30	2.12
628	-0.03	0.04	3.04	2.79
629	-0.03	0.04	3.26	3.00
630	-0.03	0.04	1.50	1.25
701	-0.01	0.03	0.73	0.57
702	-0.01	-0.01	0.40	0.49
703	0.01	-0.00	2.52	2.52
704	-0.01	0.03	0.32	0.16
705	-0.01	-0.00	1.27	1.27
706	-0.00	-0.00	2.46	2.46

TABLE 1. (contd)

DATE	MODEL GAP HYB.-DIG.	DIFF. IN ABS. ERROR HYB.-DIG.	HYBRID PERCENT ERROR	DIGITAL PERCENT ERROR
707	-0.00	-0.00	0.84	0.84
708	0.03	0.03	2.25	2.09
709	0.01	0.01	0.45	0.38
710	-0.00	0.01	0.61	0.54
711	0.01	-0.00	1.17	1.17
712	0.03	-0.01	0.39	0.48
713	0.03	-0.01	0.71	0.78
714	0.03	-0.01	0.23	0.30
715	0.01	0.03	0.84	0.69
716	0.01	0.01	1.30	1.21
717	0.01	0.01	1.57	1.50
718	0.03	0.04	0.89	0.66
719	-0.00	0.01	0.22	0.15
720	0.01	0.01	0.53	0.45
721	0.03	-0.00	0.38	0.38
722	-0.04	0.06	1.51	1.14
723	-0.04	0.05	0.30	0.00
724	-0.01	-0.01	0.45	0.53
725	-0.00	-0.00	0.89	0.89
726	0.04	0.04	0.87	0.65
727	0.03	0.03	0.64	0.49
728	0.01	0.03	0.90	0.77
729	-0.00	-0.00	1.17	1.17
730	-0.01	-0.01	1.23	1.30
731	-0.03	-0.04	1.36	1.55
801	-0.00	-0.00	1.94	1.94
802	0.04	0.04	1.93	1.73
803	0.05	0.05	4.66	4.38
804	0.08	0.08	5.45	5.03
805	0.06	0.06	4.43	4.09
806	0.05	0.05	3.34	3.08
807	0.03	0.03	1.30	1.17
808	0.01	0.01	0.51	0.44
809	-0.00	-0.00	1.55	1.55
810	-0.00	0.01	1.54	1.48
811	0.01	0.03	1.34	1.22
812	0.03	0.03	0.32	0.18
813	-0.01	-0.01	0.51	0.57
814	-0.03	-0.00	0.06	0.06
815	-0.05	0.06	2.10	1.78
816	-0.05	0.06	4.13	3.81
817	-0.04	-0.05	0.00	0.26
818	-0.01	-0.01	2.05	2.11
819	0.04	0.04	1.59	1.39
820	-0.01	-0.01	2.07	2.14
821	0.01	0.03	1.93	1.80
822	0.03	0.04	1.52	1.33
823	0.04	0.04	0.66	0.46
824	-0.01	-0.01	0.26	0.33
825	0.03	0.03	0.46	0.33
826	-0.01	-0.01	0.27	0.33
827	0.05	-0.04	0.60	0.81
828	0.03	-0.01	0.06	0.14
829	-0.00	-0.00	0.64	0.64
830	-0.00	-0.00	0.00	0.00

TABLE 1. (contd)

DATE	MODEL GAP HYB.-DIG.	DIFF. IN ABS. ERROR HYB.-DIG.	HYBRID PERCENT ERROR	DIGITAL PERCENT ERROR
831	-0.00	0.01	0.76	0.69
901	0.04	-0.04	0.89	1.10
902	0.05	-0.04	0.27	0.48
903	0.06	0.06	1.06	0.71
904	0.04	0.04	1.34	1.14
905	0.06	0.08	1.33	0.91
906	0.05	0.05	0.49	0.21
907	0.04	-0.03	0.48	0.62
908	0.03	-0.03	0.61	0.76
909	0.04	0.03	0.21	0.06
910	0.01	-0.00	0.54	0.54
911	0.03	-0.01	1.15	1.21
912	0.01	-0.00	1.42	1.42
913	0.04	-0.03	1.60	1.73
914	0.06	-0.05	0.61	0.88
915	0.08	-0.06	0.55	0.90
916	0.06	-0.05	1.56	1.86
917	-0.05	0.05	2.16	1.87
918	-0.03	0.03	1.44	1.30
919	-0.04	0.05	1.72	1.43
920	-0.01	0.03	1.21	1.07
921	-0.04	0.05	1.49	1.21
922	-0.01	0.01	1.34	1.27
923	-0.00	0.01	0.56	0.49
924	-0.00	0.01	0.84	0.77
925	0.04	-0.03	0.71	0.84
926	0.05	-0.04	0.71	0.93
927	0.05	0.05	0.43	0.14
928	0.05	0.05	0.87	0.57
929	0.04	0.04	1.32	1.10
930	-0.00	0.01	1.01	0.94
1001	0.01	0.01	1.38	1.31
1002	0.03	0.04	1.15	0.93
1003	-0.00	0.01	0.14	0.06
1004	0.04	0.05	0.87	0.57
1005	0.04	0.04	0.65	0.43
1006	-0.00	-0.00	0.44	0.44
1007	-0.04	-0.04	0.22	0.44
1008	-0.01	0.03	0.14	0.00
1009	-0.00	-0.00	0.44	0.44
1010	0.01	0.01	0.82	0.73
1011	-0.00	-0.00	1.05	1.05
1012	-0.00	-0.00	1.98	1.98
1013	-0.00	-0.00	1.98	1.98
1014	0.08	0.08	1.61	1.15
1015	0.06	0.06	2.23	1.83
1016	0.01	-0.00	2.04	2.04
1017	-0.01	-0.01	1.72	1.81
1018	0.03	0.03	3.20	3.03
1019	-0.00	-0.00	2.43	2.43
1020	0.03	0.03	2.43	2.27
1021	0.01	0.01	2.88	2.79
1022	0.04	0.04	3.23	2.98
1023	0.04	0.03	1.77	1.60
1024	0.04	0.04	2.55	2.30

TABLE 1. (contd)

DATE	MODEL GAP HYB.-DIG.	DIFF. IN ABS. ERROR HYB.-DIG.	HYBRID PERCENT ERROR	DIGITAL PERCENT ERROR
1025	0.08	0.08	4.87	4.36
1026	0.08	0.08	5.35	4.82
1027	0.08	0.08	6.10	5.57
1028	0.08	0.08	5.18	4.65
1029	0.08	0.09	6.01	5.40
1030	0.09	0.08	5.43	4.91
1031	0.09	0.10	6.01	5.30

AVERAGE ABSOLUTE ERROR, HYBRID: 0.21

AVERAGE ABSOLUTE ERROR, **DIGITAL:** 0.21

TIME AND COSTS

The computer and personnel time required for the various phases of the development of RIVER4 are listed in Table 2. The total computer cost was \$2300. A portion of the computer time was spent in program preparation, involving only the PDP-7, and in initial model studies, involving the PDP-7 and the 2133, at a cost of \$18/hr. The remaining time involved the use of all three computers, at a cost of \$27/hr.

TABLE 2. *RIVER4 Timetable*

<u>Task</u>	<u>Man-Hours</u>	<u>Computer Hours</u>
Model transformation	90	
Initial programming	120	
Debugging	60	60
Reprogramming	60	
Model evaluation and parameter studies	60	60
Documentation	<u>60</u>	<u> </u>
Total	450	120

REFERENCES

1. SIMPL-1: Simulation Implementing Machine Programming Language--Version 1, edited by R. D. Benham, BNWL-878. Battelle-Northwest, Richland, Washington, October 1968.
2. R. T. Jaske. An Evaluation of the Use of Selective Discharges from Lake Roosevelt to Cool the Columbia River, BNWL-208. Battelle-Northwest, Richland, Washington, February 1966.

APPENDIX

NOMENCLATURE

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
Subscript k	kth river section	
Subscript i	ith time step	
Subscript b	Bank trough	
Subscript c	Center trough	
A	Cross-sectional area	ft^2
C_p	Specific heat of water	$1 \text{ Btu}/(1\text{b})(^\circ\text{F})$
D_k	$V_{kb} + RV_{kc}$	ft^3
$D_{\min}$	Scale factor	3×10^8
$e_a(t)$	Vapor pressure of water vapor in the air	in. Hg
$e_{ks}(t)$	Vapor pressure of river water at the surface	in. Hg
$F(t)$	Volumetric flow rate	ft^3/day
$F_T(t)$	Total flow rate	ft^3/day
K_a	Radiation absorption factor	
K_B	Back (longwave) radiation coefficient	
K_e	Evaporation coefficient	
K_h	Conduction coefficient	
K_s	Solar radiation coefficient	
ℓ	Length	ft
P	Atmospheric pressure	in. Hg
$Q(t)$	Rate of heat transfer per unit of surface area	$\text{Btu}/(\text{ft}^2)(\text{day})$
$Q_B(t)$	Rate of surface heat transfer due to back (longwave) radiation	$\text{Btu}/(\text{ft}^2)(\text{day})$
$Q_e(t)$	Rate of surface heat transfer due to evaporation	$\text{Btu}/(\text{ft}^2)(\text{day})$
$Q_h(t)$	Rate of surface heat transfer due to conduction	$\text{Btu}/(\text{ft}^2)(\text{day})$
$Q_i(t)$	Amount of solar radiation received during a given day	Langleys
$Q_s(t)$	Rate of surface heat transfer due to solar radiation	$\text{Btu}/(\text{ft}^2)(\text{day})$

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
R	Ratio of center trough velocity to bank trough velocity	
S	Surface area	ft^2
$T(t)$	Water temperature	$^{\circ}\text{F}$
$\bar{T}(t)$	Average effective temperature	$^{\circ}\text{F}$
$T_a(t)$	Air temperature	$^{\circ}\text{F}$
$T_d(t)$	Dew-point temperature	$^{\circ}\text{F}$
$T_{in}(t)$	Inlet water temperature	$^{\circ}\text{F}$
$\bar{T}_{ks}(t)$	Adjusted surface temperature	$^{\circ}\text{F}$
$\Delta T_s(t)$	Surface temperature increment	$^{\circ}\text{F}$
t	Time	day
Δt	Time step	day
$U(t)$	Wind speed	mi/hr
V	Volume	ft^3
$\bar{v}(t)$	Velocity	ft/day
	Effective volume fraction	
$\beta(t)$	Atmospheric reflection factor	
ρ	Density of water	62.4 lb/ft^3
$\theta(t)$	Cloud cover	tenths of sky covered

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