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LONG-TERM SIMULATION OF THERMAL REGIME OF MISSOURI RIVER

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ABSTRACT: Riverine water temperature extremes have typically been analyzed using event-based simulations, for example the 10-year 7-day low flows, combined with record-high air temperatures and other extreme conditions relevant to the location (e.g., maximum power generation). Using this combination of extreme conditions, one can estimate the maximum water temperature that may occur on the river. However, this method does not allow for calculation of, for example, the probability of a given temperature exceedence, or the average duration of such an excursion event. Alternatively, long-term continuous simulation using historical and physically representative reconstructed data records provides a large database of realistic events, which can be used to analyze the thermal regime of a river and its variability under current and changing conditions. This study applies such a procedure to the Missouri River between Gavins Point Dam at Yankton, S.D.. and Rulo, Nebr. Along this reach, the thermal regime is influenced by six power installations, which release heated condenser cooling water to the main stem. Several scenarios were simulated numerically with the one-dimensional (ID) CHARIMA model to examine the effects of current power generation, as well as changing operational, hydrologic, and climatological conditions on the river thermal regime. Model simulations revealed that climate change and increased power demand may significantly affect the thermal regime of the Missouri River; however, the scenarios simulated in this study did not result in water temperatures that exceed the current temperature standards.

INTRODUCTION

The Missouri River along its Iowa border currently supplies once-through cooling water to several thermal power installations. The purpose of this study is to assess the river's capacity to accommodate variable energy production under changing climatological, hydrologic, and regulatory conditions. A trend of tightening environmental regulations has developed in recent years in nearly all aspects of water quality. Although the main focus has been on conventional chemical pollutants associated with agriculture and industry, the growing need for power in an industrialized society has threatened to alter the thermal regime of rivers, and thus the natural habitat available to biota. These tightening regulations, combined with possible global warming, changes in Missouri River flow releases from main-stem reservoirs, and increased power demand, result in the need for an analysis of the ability of the Missouri River to support existing and future power installations along its Iowa border.

The water temperature characteristics of an environment are very important to the organisms that inhabit it, and largely determine the composition of the aquatic community. Organisms have upper and lower thermal tolerance limits, optimum temperatures for growth, preferred temperatures in thermal gradients, and temperature limitations for migration, spawning, and egg incubation. The temperature of a waterway also determines its physical characteristics, such as viscosity, degree of ice cover, and oxygen capacity. The increased demand for cooling water for power stations has threatened to impact the thermal regime of waterways, and thus affect their aquatic composition. In anticipation of this, environmental consequences of temperature changes have been considered in assessments of water quality requirements for aquatic organisms. This has resulted in the establishment of regulatory water temperature criteria.

In this study, attention is focused on the temperature standards on the Missouri River. Current standards specify temperature rise criteria. Some standards are not applicable inside what the state has defined as a "regulatory mixing zone." In the past, power installations on the Missouri have been considered separate entities in the study of the river's thermal capacity, i.e., upstream power plants were assumed not to affect the intake water temperatures at downstream power plants. Therefore, power installation design and operation have been governed entirely by temperature-rise restrictions in well-defined, local mixing zones specified in the Iowa Administrative Code (567-61, 1990). Also, analyses of the thermal effects of the power installations were restricted to near field studies in the mixing zones.

However, in the future it may no longer be possible to operate the power installations under the assumption of independence from each other. At least one Midwest river is subject to cumulative rather than local temperatures (Bradley et al. 1998). This change in philosophy dictates that two other factors must be considered in the analysis of cooling capacity: (1) background river temperatures; and (2) meteorological conditions that control heat exchange with the atmosphere. The analysis of the cooling capacity of a river thus is expanded to consider all power installations as a "system," and to consider that each is affected by the generating schedule of the others upstream. In other words, the amount of power generation the Missouri can support is related not only to the amount of water released from the upstream reservoirs (Gavins Point Dam in this study) and short-term (diurnal) meteorological cycles, but also to how individual power plants are operated in concert to make the best possible use of the available dilution capacity of the river and diurnal meteorological cooling cycles. It may be argued that the power installations "compete" for the cooling opportunities provided by the hydrometeorological conditions, and thus should be considered jointly.

The goals of this study are the construction of a mathematical model and database of hydrology and meteorology, and the use of these to analyze the thermal regime of the Missouri River from the Gavins Point Dam at Yankton, S.D., to Rulo, Nebr. The mathematical model selected is the CHARIMA simulation code (Holly et al. 1990). It is capable of simulating

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hydrodynamics, contaminant transport, and thermal water-atmosphere interactions in networks of 1D channels. The calibrated and validated mathematical model and database are then used to analyze "what if" scenarios, such as decreased dam releases, potential global warming, and increased power demand. The results show the effect of these changes on the thermal regime of the river.

CHANGING CONDITIONS

There has been a great deal of concern in recent years that the increased emission of greenhouse gases may be causing a change in the climate on Earth. The Intergovernmental Panel on Climate Change (IPCC) (1996) reports that, based on general circulation model simulations, global mean air temperature, precipitation, evaporation, cloud cover, etc. would all be significantly affected by a doubling of the carbon dioxide concentration in the atmosphere. Also, global mean air temperature measurements have shown an identifiable increase over the past century, with many of the warmest years on record occurring recently. Although the changes are still considered within the natural variability of air temperatures, a discernible anthropogenic effect is suspected by many scientists (IPCC 1996). Hence, the possible future impacts of global warming need to be considered. It is obvious that a change in climate would have an effect on the thermal capacity of a river, since the exchange of heat between water and the atmosphere controls the heating and cooling of a waterway under natural conditions. Global mean temperature warming of the order projected by general circulation models could force the power installations to decrease output in order to comply with current and possibly stricter future standards.

Another factor affecting the thermal capacity of the Missouri River is the possible decrease in releases from Gavins Point Dam. The U.S. Army Corps of Engineers (COE) in 1989 undertook a major revision of the Missouri River Master Manual (U.S. 1990), which dictates all policy in the basin. The current navigation season is from 1 April to 1 December, but is further extended into December if excess water must be released from the reservoirs. During droughts, the navigation season is shortened to conserve water. The Master Manual–preferred alternative would shorten the season by one month every year and would shorten it sooner during droughts. This could affect the thermal capacity of the river below Gavins Point Dam. If the releases are cut back earlier in the year, and even earlier during droughts, this will decrease the dilution effects in the river during a warmer period of the year.

NUMERICAL MODEL

The CHARIMA computer code can be used to simulate 1D (longitudinal) steady or unsteady water flow, as well as contaminant and sediment transport in simple or complex systems of channels. Water movement (hydrodynamics) forms the core of a CHARIMA simulation. Mobile bed (sediment) and contaminant dynamics may be activated and deactivated. Channel systems may comprise a single channel, branched systems, or looped networks of arbitrary connectivity and flow direction.

Hydrodynamics is governed by the fully dynamic Saint-Venant (1871) equations. The 1D continuity and momentum equations are solved numerically by CHARIMA using the Preissmann four-point implicit finite-difference scheme (Preissmann 1961). The discretized continuity and momentum equations form a nonlinear system of algebraic equations, which are linearized by Taylor series expansion and solved using a Newton-Raphson iterative procedure. The solution is the discharge and/or water surface elevation at any user-defined computational point on the model reach, at any time.

Contaminant transport in CHARIMA is governed by the 1D longitudinal advection-dispersion equation. The longitudinal dispersion coefficient for the Missouri River has been observed to be approximately 1,500 m^2/s (Fisher 1973), and this is the value used throughout this study. The advection-dispersion equation is solved in two steps in CHARIMA. First, transport of the contaminant due to advection is solved using the Holly-Preissmann fourth-order method of characteristics scheme (Holly and Preissmann 1977). The diffusion effects are solved using the generalized Crank-Nicholson finite-difference scheme (Crank and Nicholson 1967). The two solutions are combined to produce the contaminant concentration due to advection and dispersion at any computational point, at any time. Concentrations are calculated at junctions (e.g., tributary inflows) as a discharge-weighted average.

When considering the fate of heat in any water system, one must consider interactions between the water surface and atmosphere. The source-sink term in the advection-dispersion equation then is the interaction between the water surface and the atmosphere. Heat exchange between the water and the bed or banks is judged to be insignificant, which is supported by investigations by Sinokrot and Stefan (1994). CHARIMA considers the following mechanisms when computing the surface-heat exchange between water and atmosphere: (1) incoming short-wave (solar) radiation; (2) incoming and outgoing long-wave radiation; (3) sensible heat exchange (conduction); and (4) evaporation and condensation. The empirical and geometrical relations used to quantify these heat exchanges are essentially those published by Huber and Harleman (1968).

CHARIMA calculates the temperature rise of condenser cooling water as proportional to the fraction of the rated load being carried by the plant. The temperature rise at rated load is a function of the nameplate heat rejection rate and the condenser flow rate of the particular unit.

Solution of the Saint-Venant equations requires spatial data such as channel cross sections, roughnesses, and plan-view connectivity. Temporal data required are inflow hydrographs at the upstream boundary points, and stage hydrographs (or rating curves) at downstream boundary points. Contaminant transport (e.g., thermal) simulation requires only temporal variations of contaminant inflow concentrations (temperatures) at upstream boundary points, and power-generation schedules. Thermal calculations also require temporal variations of air temperature, wind speed, cloud cover, and relative humidity.

The CHARIMA program is similar to other, more well known, 1D unsteady codes such as MIKE 11 and UNET. For detailed descriptions of computational solutions to 1D unsteady flow and contaminant transport and related assumptions, see Cunge et al. (1980) and/or Abbot (1979).

STUDY REACH

The model study reach is the stretch of Missouri River from Gavins Point Dam at Yankton to Rulo. Fig. 1 shows the model layout and geographic situation (Hagen and Holly 1994). The figure contains an index that defines the various symbols on the map. CHARIMA requires that the reach be broken down into several "links," and the links are separated by computational "nodes." Nodes are generally placed at inflow points or channel junctions, or are used to separate different link types. There are four possible types of links: fluvial, power plant, level control, or discharge control. A link must contain at least two "computational points." These are the spatial points at which the discretized equations are solved, and thus the simulation results (temperature, discharge, water surface elevation, etc.) are available at these points.

HYDRODYNAMICS CALIBRATION AND VALIDATION

Before any model can be used as a predictive tool, it must first be validated through comparison with measured data. The

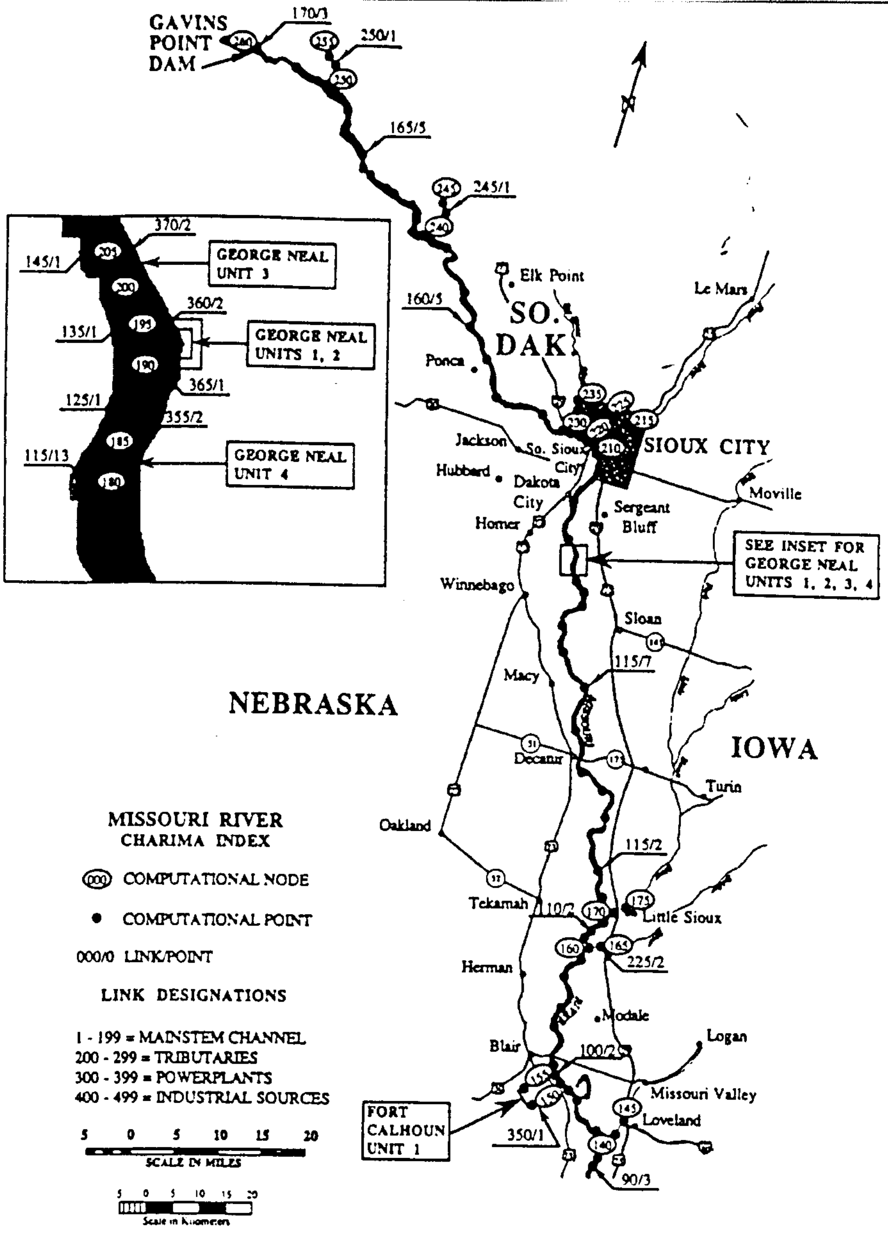

FIG. 1(a). Missouri River Model Layout

first step of this validation is to calibrate the model's uncertain physical parameters, then validate these parameters for different conditions. During calibration, a parameter is adjusted to achieve acceptable reproduction of known observed events. The calibrated parameters are then used to reproduce independent observed events, thus validating the model.

Since water movement forms the core of a CHARIMA simulation, the first step in calibration of the model is calibration of the uncertain parameters affecting hydrodynamics. Hydrodynamics (e.g., velocity and water-surface elevation) must be accurate to drive reliable thermal calculations.

The CHARIMA simulation code hydrodynamics are based on the conservation of mass and momentum, and some deterministic, process-based empirical relations. Therefore, the only adjustable hydrodynamic parameter is the channel roughness (Manning coefficient), which determines the depth-discharge relationship. Manning's roughness coefficient generally has low uncertainty due to the large amount of work that has been done to estimate the roughness of open-channel waterways.

A study was conducted by the COE on a 7 mi reach of the Missouri River near Omaha, Nebr., where a complete set of observations was taken during the fall of 1966 (*Sedimentation* 1975). These data showed that the water surface elevation for a given discharge diminished appreciably, causing a decrease in n from 0.019 to 0.015 for a temperature drop from 24°C (76°F) to 5.6°C (42°F) from early September to early November. This variation of channel roughness with temperature can be explained. For a given flow depth and channel slope, bed forms are primarily governed by the fall velocity of the bed material. A change (e.g., decrease) in the water temperature causes a change (increase) in the kinematic viscosity of the water, and a change (decrease) in the fall velocity of the particles. Therefore, changes in water temperature affect the bed forms, which in turn affect the channel roughness as a dune regime transitions to a plane bed. The effects of water temperature on bed roughness were accounted for in model calibration by breaking the calibration data set into seasons, and calibrating n for each season.

The following strategy was adopted for calibration of Manning's roughness coefficient. Measured water surface elevations (WSELs) at Rulo, Omaha, Nebr., and Sioux City, Iowa, were available through the U.S. Geological Survey (USGS) from 1983 to the present. Mean daily flow records for all boundary points were also available from the USGS for this period. Table 1 shows the average flows for the tributary rivers and water treatment plant discharges (or withdrawals). The

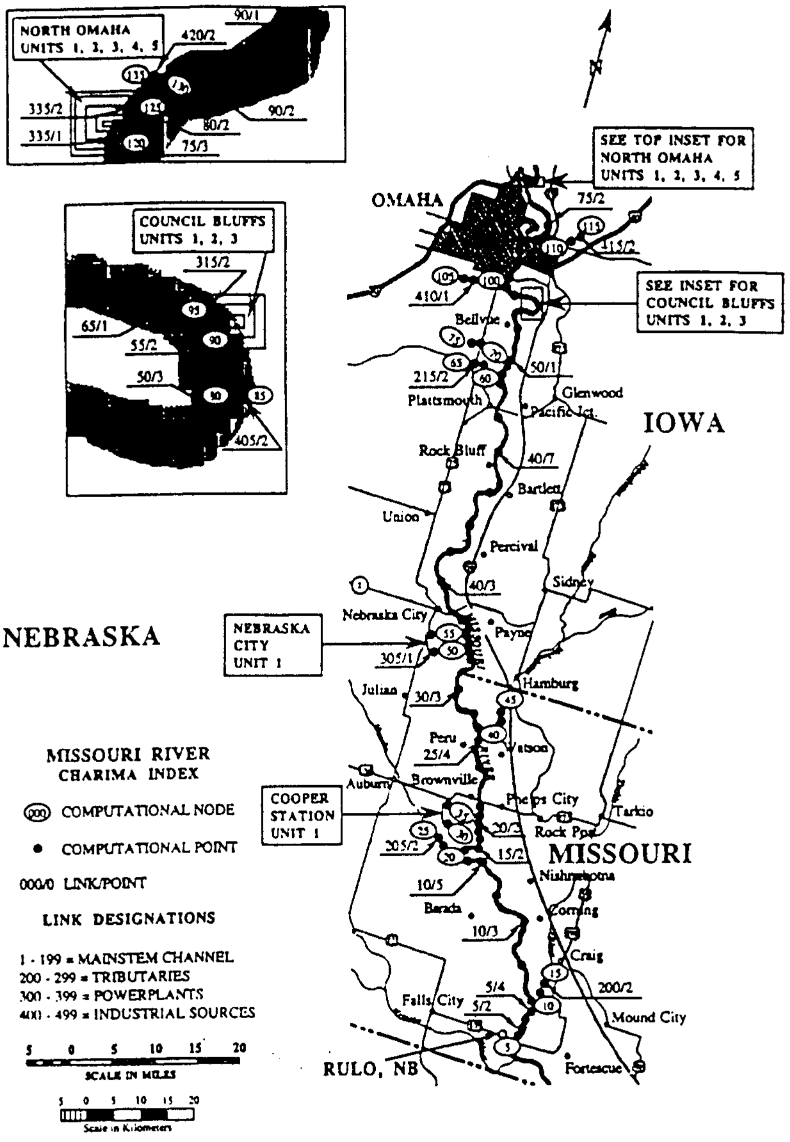

FIG. 1(b). Missouri River Model Layout (Continued)

TABLE 1. Tributary Average Flows

Tributary (1)	USGS station number (2)	Average flow [m^3/s (cfs)] (3)
James River	06478500	14.8 (521)
Vermillion River	06479000	3.5 (125)
Big Sioux River	06485500	33.3 (1,176)
Floyd River	06600500	6.9 (244)
Monona-Harrison Ditch	06602400	14.3 (506)
Little Sioux River	06607500	43.6 (1,541)
Soldier River	06608500	4.3 (151)
Boyer River	06609500	10.1 (355)
Platte River	06805500	197 (6,948)
Nishnabotna River	06810000	34.7 (1,227)
Little Nemaha River	06811500	8.9 (314)
Tarkio River	06813000	5.9 (208)
Sioux City Water Treatment	N/A	0.5 (19)
M.U.D. Water Works	N/A	−2.8 (−100)
Council Bluffs Water Works	N/A	−0.5 (−16)
Omaha Sewage Treatment Plant	N/A	1.5 (54)
Council Bluffs Sewage Treatment Plant	N/A	0.3 (12)
Papillion Treatment Plant	N/A	2.0 (70)

Note: N/A = not available.

Rulo WSELs were needed as the downstream boundary condition of the model. The Sioux City and Omaha WSEL records were used for comparison with simulated WSELs for calibration of the channel roughness. The years 1985, 1986, and 1987 were chosen arbitrarily as the calibration data set. Each year was separated into four seasonal time series. The model was then run for each of these periods, and the optimum value of Manning's *n* was determined. Simulated water levels were compared to measured water levels at Sioux City and Omaha as a combined root-mean-square error (RMSE). The range of calibrated roughnesses was 0.026–0.030, with a range of RMSEs of 0.24–0.59 m. It was decided to adopt a constant Manning's *n* equal to 0.029 (mean value), since a change of 0.001 in *n* resulted in a change of only 0.02±0.02 m in the RMSE.

The seasonal change in roughness observed in the COE study was not strictly observed in this study. Small seasonal changes in the calibrated roughness are observed; however, the magnitude of change is smaller, and the magnitude of the roughness is larger. This is most likely due to the fact that the COE study reach was approximately 11.3 km (7 mi), while the study reach for this project is approximately 500 km (310 mi). Therefore, the COE measured roughness was localized, while no attempt was made to calibrate *n* locally in the CHARIMA model. There are sure to be variations in the roughness along a reach of this length. For example, upstream of Sioux City the river meanders greatly, then straightens out in the engineered channel between Sioux City and Omaha. This difference in plan view geometry affects the channel roughness. Also, differences in bed material along the reach precipitate overestimation of *n* in some locations and underestimation of *n* in others.

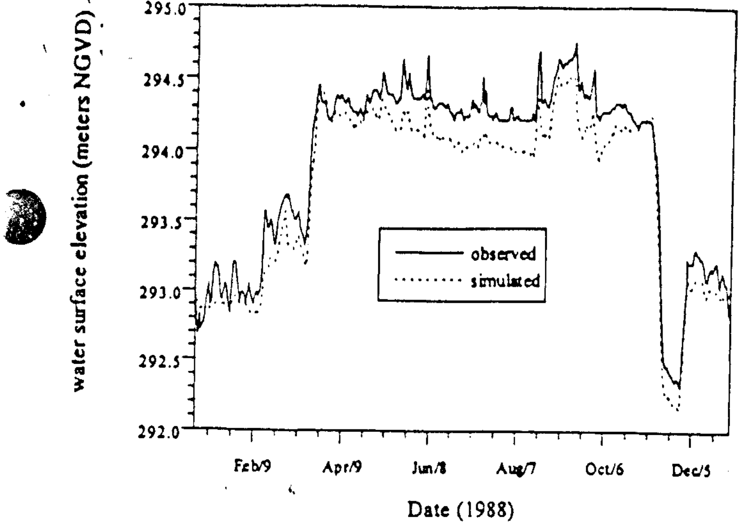

FIG. 2. Simulated and Observed Water Levels at Omaha for 1988

Validation requires the use of the calibrated value of roughness to reproduce an independent, measured event. The years 1988 and 1989 were chosen as the validation data set. The RMSEs for the validation periods were on the same order of magnitude as the errors for the calibration periods. Fig. 2 is a plot of the measured and simulated water surface elevations at Omaha for 1988. This plot and the RMSEs validate that the model can consistently reproduce a range of hydrologic events.

THERMODYNAMICS CALIBRATION AND VALIDATION

Once accepted calibration and validation of the hydrodynamic uncertain parameters have been achieved, it is necessary to calibrate and validate the thermodynamic parameters. The only adjustable thermal parameters in the CHARIMA code presently are the Area Reduction Factor (ARF), to account for the absence of surface heat exchange due to partial shading or coverage of the channel by vegetation and barges; and the Wind Reduction Factor (WRF), to account for any difference between the measured wind speed at a meteorological station and the effective wind speed governing evaporation and conduction heat-exchange processes at the water surface. In this study, a value of unity for the ARF was adopted, due to the minimum amount of barge cover on the large-surface-area river.

Ideal calibration of the WRF would require historical records of power generation from each of the power installations, historical records of streamflows and water levels, a historical record of meteorology, and historical records of water temperatures at all model inputs. It would also require records of water temperatures at one or more points along the reach, for comparison with simulated temperatures. Hourly records of meteorological data (air temperature, wind speed, relative humidity, and cloud cover) were obtained from stations at the Sioux City Gateway Airport and Omaha Eppley Airfield. The model reach was divided into two meteorological zones divided approximately at the midpoint between Sioux City and Omaha. Water temperature records were obtained from the USGS at the Sioux City and Omaha stations on the Missouri River. The temperatures have typically been recorded three or four times a month for the past 10 to 15 years. Also, hourly records of gross power generation were obtained for the George Neal, Fort Calhoun, North Omaha, Council Bluffs, and Nebraska City power installations (Fig. 1) for the arbitrary year of 1992. Table 2 gives information on the individual units of each plant. The simulations were then performed using historical records of mean daily flows, hourly meteorology, and a daily downstream water surface elevation. However, due to the absence of mean daily historical water temperature records, stochastically generated records were used as discussed in the next section of this paper.

The simulations were run for the full year of 1992. January was not used in calibration or validation, to allow the initial condition to stabilize. The months of February through July were chosen as the calibration period, leaving the remaining months for validation of the model. Through comparisons of measured and simulated water temperatures at Sioux City and Omaha, the WRF was calibrated to a value of 0.5, with seasonal mean errors on the order of 1.7°C (3.0°F). The mean errors are considered to be reasonable, given the deficiencies in the calibration data set. Also, the calibrated values are consistent with those for the Upper Illinois Waterway (Holly 1994; Holly and Bradley, 1995; Bradley et al. 1998). One possible explanation for having to reduce measured wind speeds by a factor of two is that the measurements were taken at the Sioux City and Omaha airports, where it is assumed that the measuring devices are located in exposed areas, while the north-south flowing Missouri River is protected from these winds by the very thin strip of riparian vegetation remaining along its banks.

The months of August through December were used for validation of the thermodynamics. The mean errors were on the same order as for the calibration runs. Fig. 3 shows the measured and simulated water temperatures at Omaha for 1992. The simulated temperatures are not consistently lower or higher than the observed temperatures, i.e., there is no systematic bias in the model results.

TABLE 2. Power Plant Operation Parameters

Station (1)	Rated load (MW) (2)	Condenser discharge [m^3/s (cfs)] (3)	Heat rejection rate (10^6 BTU/h) (4)	Temperature rise [°C (°F)] (5)
Cooper #1	835.6	35.1 (1,239.0)	5,016	10.0 (18.0)
Nebraska City Unit 1	615.9	18.9 (668.4)	2,841	10.5 (18.9)
Council Bluffs Unit 1	49	2.3 (80.2)	324.7	10.0 (18.0)
Council Bluffs Unit 2	81.6	2.8 (98.0)	396.8	10.0 (18.0)
Council Bluffs Unit 3	725.9	22.7 (802.1)	3,247	10.0 (18.0)
North Omaha Unit 1	73.5	3.8 (133.7)	631.5	11.7 (21.0)
North Omaha Unit 2	108.8	5.7 (200.5)	884.0	10.9 (19.6)
North Omaha Unit 3	108.8	5.7 (200.5)	1,015.0	12.5 (22.5)
North Omaha Unit 4	136.0	5.7 (200.5)	992.3	12.2 (22.0)
North Omaha Unit 5	217.6	6.9 (245.1)	1,246.0	12.6 (22.6)
Fort Calhoun Unit 1	502.0	19.6 (690.7)	3,340	11.9 (21.5)
George Neal Unit 1	147.1	4.5 (158.9)	893.3	13.9 (25.0)
George Neal Unit 2	349.2	7.5 (266.5)	1,858	17.2 (31.0)
George Neal Unit 3	549.8	17.4 (613.2)	2,620	10.6 (19.0)
George Neal Unit 4	639.9	20.6 (729.1)	2,624	8.9 (16.0)

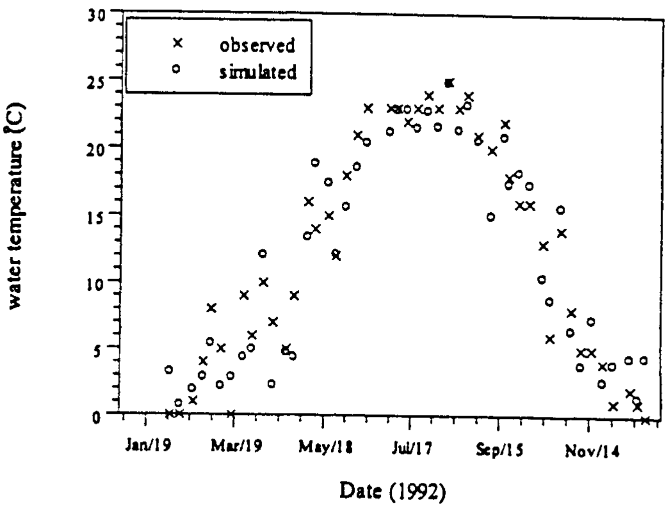

FIG. 3. Simulated and Observed Water Temperatures at Omaha for 1992

LONG-TERM DATABASES AND CONTINUOUS SIMULATION SCENARIOS

Several possible scenarios were identified that could alter the thermal regime of the Missouri River along its Iowa border. The first is a possible increase in the demand for power, resulting in increased output from each of the existing power stations or construction of new installations. The second is the lessening of the dilution effect during the late summer/early fall months due to a shortening of the navigation season. The third is the effect of projected global climate change.

Daily Flow Records

Most of the mean daily flow records available from the USGS for external boundaries to the model extended through water year 1993. Gauging of the Tarkio River was discontinued at the end of 1990 due to lack of funds. However, since its discharge magnitude is small compared to the main-stem flow, and due to the desire to include these relatively warm years and the 1993 flood, it was decided to extend this record through water year 1993. The Platte River record was the shortest, dating back only to January 1954. The Platte is the largest tributary to the main stem along the study reach, and it was thus decided not to attempt to extend its record. Therefore, an approximately 40-year period of record from 1 January 1954 through 30 September 1993 was chosen for the long-term continuous simulations. However, before any of the simulations were performed, some stochastic modeling was done to synthesize tributary and upstream boundary water temperatures and to extend the Tarkio streamflow record. Also, a record of water surface elevations was constructed at Rulo.

Tributary and Boundary Water Temperatures

Several methods have been proposed for estimating river water temperature based on meteorological data (Cluis 1972; Song et al. 1973; Kothandaraman 1974; Tasker and Burns 1974; Song and Chien 1977; Smith 1981; Krajewski et al. 1982; Bravo et al. 1993; Stefan and Preud'homme 1993). Stefan and Preud'homme (1993) have shown that water temperatures can be related to air temperatures by a simple linear regression model

$$T_w = mT_a + b + \varepsilon \qquad (1)$$

where T_w and T_a = water and air temperature, respectively; m and b = slope and y-intercept of the linear regression, respectively; and ε = model error. It was apparent from a plot of James River water temperature versus air temperature (1960–1981 daily record) (Fig. 4) that a single linear relationship between the two for the entire year was not sufficient. Therefore, a separate relation was derived for each month. Table 3 compares the monthly water temperature statistics of the James River from the historical 21-year (1960–1981) daily record with the monthly statistics from the synthesized record. The monthly regression method does an excellent job of reproducing the statistics. Although the synthesized record has slightly less variability, it captures the trend, and also reproduces monthly average temperatures almost identical to the historical record.

The model errors are the residuals from the linear regressions. Analysis of the correlation structure of the residuals revealed that they follow an autoregressive process. An order one process was determined to be sufficient. The AR(1) process can be represented as follows:

$$\varepsilon_t = \phi_1\varepsilon_{t-1} + Z_t \qquad (2)$$

where ε_t = residual at time t; ε_{t-1} = residual at time $t - 1$ (previous day); ϕ_1 = estimated AR(1) parameter; Z_t = random noise from

$$N[0, (1 - \phi_1^2)\sigma_\varepsilon^2] \qquad (3)$$

and σ_ε = standard deviation of the residuals. The linear regression relations and model error parameters for each month are presented in Table 4.

Unfortunately, the James River is the only tributary with a daily record long enough to justify use of this method with confidence. The data available for the remaining tributaries

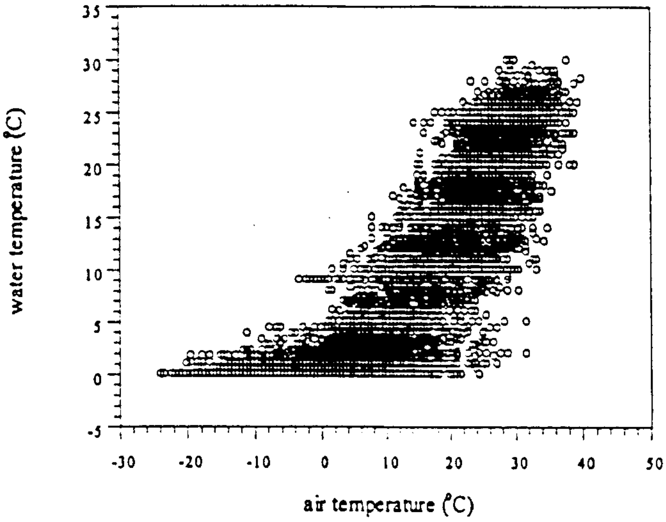

FIG. 4. Relationship between Water Temperature In Jame[illegible] River and Air Temperature at Its Confluence with Missouri Riv[illegible]

TABLE 3. Comparison of Monthly Mean Water Temperature Statistics from Historical and Synthesized Records for James River

	Historical Record		Synthesized Record	
Month (1)	Mean temperature [°C (°F)] (2)	Standard deviation [°C (°F)] (3)	Mean temperature [°C (°F)] (4)	Standard deviation [°C (°F)] (5)
January	0.50 (32.9)	0.78 (1.41)	0.56 (33.0)	0.43 (0.77)
February	0.72 (33.3)	1.06 (1.90)	0.72 (33.3)	0.51 (0.91)
March	1.72 (35.1)	1.76 (3.16)	1.78 (35.2)	1.03 (1.86)
April	8.11 (46.6)	3.99 (7.18)	8.00 (46.4)	3.34 (6.01)
May	15.6 (60.1)	3.28 (5.91)	15.7 (60.2)	2.83 (5.09)
June	21.7 (71.0)	2.63 (4.73)	21.9 (71.5)	2.35 (4.23)
July	24.7 (76.4)	1.71 (3.08)	24.9 (76.8)	1.26 (2.27)
August	23.2 (73.9)	2.15 (3.87)	23.3 (73.9)	1.67 (3.00)
September	17.2 (62.9)	3.63 (6.54)	17.2 (63.0)	3.16 (5.68)
October	10.5 (50.9)	3.19 (5.74)	10.4 (50.7)	2.52 (4.53)
November	3.00 (37.4)	3.21 (5.77)	3.39 (38.1)	2.03 (3.65)
December	1.00 (33.8)	1.79 (3.23)	1.06 (33.9)	0.86 (1.55)

TABLE 4. Monthly Water Temperature Synthesis Parameters for James River

Month (1)	Linear regression (2)	ϕ_1 (3)	σ_ε (4)
January	$T_w = 0.024T_a + 32.5$	0.827	1.37
February	$T_w = 0.019T_a + 33.1$	0.872	1.89
March	$T_w = 0.083T_a + 32.5$	0.814	3.00
April	$T_w = 0.469T_a + 24.0$	0.732	5.48
May	$T_w = 0.450T_a + 32.8$	0.733	4.54
June	$T_w = 0.417T_a + 42.0$	0.710	3.85
July	$T_w = 0.256T_a + 57.6$	0.752	2.73
August	$T_w = 0.322T_a + 50.8$	0.708	3.29
September	$T_w = 0.528T_a + 30.5$	0.685	4.73
October	$T_w = 0.382T_a + 31.3$	0.763	4.55
November	$T_w = 0.303T_a + 27.4$	0.838	4.84
December	$T_w = 0.074T_a + 32.1$	0.894	3.10

were typically two or three temperature measurements per month for a very limited amount of time. It was therefore assumed that the remaining tributaries exhibit the same relationship with air temperature as the James River does, allowing for the use of the James River monthly regression model parameters to synthesize the remaining tributary temperature records. This also allowed for the use of different air temperature records to account for the spatial variability of the tributary rivers. Air temperature records were linearly interpolated or extrapolated from Sioux City and Omaha records for each of the points where tributary inflows exist. These air temperature records were then used, along with the monthly regression model of the James River, to construct daily mean water temperature records for the remaining boundaries. The use of the James River parameters may not reflect the relationship between air and water temperature for the water being released from the reservoir at Gavins Point Dam. However, comparison between a small data set of measured release temperatures (approximately one measurement per month from 1969 through 1994) with the simulated release temperatures showed good agreement (mean difference = 2°C), indicating that thermal stratification of the reservoir is not affecting release water temperatures. For the several municipalities located along the reach, the temperature record of the nearest tributary was used. This is somewhat inaccurate for the releases from wastewater treatment plants, as their temperatures may be quite different than natural surface water. It is assumed that this inaccuracy is minor and acceptable due to the large magnitude of difference between main-stem discharge and municipality releases.

Water Surface Elevations

The water surface elevation is the boundary condition required at the point of the model that is furthest downstream —Rulo. USGS records of daily water levels were available at this location for the time period of 1 October 1983 through 30 September 1995. The rating curve for this location and the continuous daily discharge record were obtained from the USGS and used to reconstruct the water surface elevation record for the 40-year simulation period. The rating curve used was the curve used by the USGS at the time of this study. This curve can and does change over time due to bed and bank evolution. Unfortunately, the USGS was only able to supply the current rating curve. However, it is noted that gauges are by design generally located at relatively stable locations.

Tarkio River Record Extension

The database of available USGS streamflow records at the time of this study ran through water year 1993 (30 September 1993), except for the Tarkio River. The Tarkio River record runs only through 31 December 1990, due to a loss of funding to operate the gage at Fairfax, Mo. Therefore, the record was extended through water year 1993, in order to match the length of the other records. Hirsch (1982) compared four techniques for streamflow record extension that exploit the correlation between the station of interest and some nearby base station. The methods are regression, regression plus noise, and maintenance-of-variance extension types 1 and 2 (MOVE.1 and MOVE.2). He concluded that regression and regression plus noise have serious deficiencies as record extension techniques. MOVE.2 is shown to be marginally better than MOVE.1, and was the method used to extend the Tarkio streamflow record.

Changing Hydrologic, Meteorological, and Operational Conditions

Three changes in meteorological, hydrologic, and power-generation conditions have been identified as described earlier: increased power demand, a shortened navigation season (decreased releases from Gavins Point Dam), and global warming. To examine the effect of increasing power demand, three power production scenarios were formulated: (1) all plants off-line; (2) all plants operating at maximum capacity; and (3) all plants operating at a projected daily load cycle. A projected daily load cycle was developed for each power installation by averaging the power generation on an hourly basis, using all available hourly power schedules for each installation (plant downtimes were excluded from averaging).

The new Missouri River Master Manual has recommended a shortening of the navigation season. The COE-preferred alternative suggests a shortening of the navigation season by one month. To simulate this effect, the releases from Gavins Point Dam were analyzed to determine when the navigation season ended each year. The flows were than adjusted to end the navigation season one month earlier. The same procedure was applied to adjust the flows at Rulo, and the record of water surface elevations was reconstructed using the adjusted flows and the stage-discharge rating curve. This procedure accounts for the lag between the time when flows are decreased at Gavins Point and the time when the decrease is seen at Rulo.

There is some speculation on the climatic effects of increased greenhouse-gas concentrations. While month-to-month air temperature comparisons between general circulation models (GCMs) can sometimes show large disagreements, circulation models from several agencies have in general shown similar climate change results. In 1988 the U.S. Environmental Protection Agency (EPA) published a report (Smith and Tirpak 1988) detailing the potential effects of a doubling of the atmospheric carbon dioxide concentration, which may occur over the next half-century according to a 1983 U.S. National Research Council report (Eaton et al. 1995). The EPA report outlines the results of three GCMs on a regional basis for the United States. The three GCMs compared in the study were developed at the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamic Laboratory (GFDL), and Oregon State University (OSU). Table 5 shows the predicted annual changes in temperature and precipitation for each GCM, for a doubling of CO_2. The values are averages of the Great Plains grid points used by the models.

It was decided to adopt the GISS result for this analysis, since it reports the most extreme changes in precipitation. The average annual rainfall is 2.11 mm/day at the Omaha Eppley Airfield and 1.77 mm/day at the Sioux City Gateway Airport (Leeden et al. 1990). The GISS GCM predicts an approximately 15% decrease in the annual precipitation in the Midwest region of the United States.

Changes in precipitation and evaporation can cause large changes in hydrology. These changes will be complicated by the direct effect of increasing carbon dioxide on vegetation. Controlled experiments have shown that increased CO_2 levels cause the stomata of plants to close down, decreasing their rate of transpiration and increasing their water use efficiency. A reduction of evapotranspiration could lead to more runoff, and balance the effect of decreased precipitation. Wigley and Jones (1985) have studied the effect of changes in precipitation

TABLE 5. Potential Changes in Annual Air Temperature and Precipitation from Selected GCMs for Doubling of CO_2 Climate Scenario

GCM (1)	Change in air temperature [°C (°F)] (2)	Change in precipitation (mm/day) (3)
GISS	+4.5 (8.1)	−0.26
GFDL	+4.9 (8.8)	−0.12
OSU	+3.3 (5.9)	Slight increase

and CO_2 concentration on streamflow. The percent change in runoff is a function of the percent change in precipitation, the runoff ratio of the basin, and the percent change in evapotranspiration, assuming nonevaporative losses are small and the mean annual water balance of a river catchment states that runoff is equal to precipitation minus evapotranspiration. The fractional change in evapotranspiration is caused by a change in climate, a change in the area of vegetated cover, and the direct CO_2 effect on evapotranspiration. The projected change in evapotranspiration can have a large effect on the amount of runoff. For example, for a doubling of CO_2, and for a maximum direct effect on evapotranspiration (a 30% decrease for 100% vegetative cover), the runoff will increase by 120% for a 15% decrease in precipitation. Comparatively, if changes in evapotranspiration are neglected, the runoff will decrease by 50% for a 15% decrease in precipitation. This analysis is done using a value of 0.1 for the runoff ratio for the Missouri River basin (Korzun 1978).

Unfortunately, the magnitude of climate-related change in evapotranspiration due to changes in CO_2 is unknown. Changes in evapotranspiration can result from several competing factors: warmer temperatures, changes in the length of the growing (evaporative) season, changes in wind speed, changes in cloud cover, etc. These factors may cause either increases or decreases in evapotranspiration. At this point, the only guides available are the GCMs. All GCMs predict an increase in the intensity of the global hydrologic cycle. This means that, on a global average, precipitation and evaporation will increase, though precipitation is predicted to decrease in the Midwest. The GCMs predict a range of global mean evaporation increases of about 3 to 11% (Wigley and Jones 1985), much less than the maximum direct CO_2 transpiration effect. So the problem exists to somehow combine the effects of changing precipitation, evaporation, and transpiration. For this study, the most interesting scenario would involve a large decrease in annual runoff, thus decreasing the dilution capacity of the river. It was therefore assumed that increasing evaporation and decreasing transpiration will approximately balance, causing zero net change in evapotranspiration. Then a 15% decrease in precipitation will result in a 50% decrease in runoff in the Missouri River drainage basin.

The following changes were made to the data set to simulate the effects of global warming. First, the change in temperature was linearly applied to the air temperature record over the 40-year simulation period. Also, the synthetic water temperature records at model inputs were regenerated using the adjusted air temperature records. The discharge time series records at model inputs (except Gavins Point Dam releases) were adjusted to reflect the change in runoff. The discharge records were separated into base flow and runoff using a recursive digital filter commonly used in signal analysis and processing (Nathan and McMahon 1990). Once the base flow was separated, the runoff was linearly decreased by 50% over the 40-year period, and the discharge records at model inputs were reconstructed. For this study, it was assumed that the decrease in precipitation caused a decrease in direct runoff. It is possible, if not probable, that over time the decrease in precipitation would also cause a decrease in base flow. However, the writers are unaware of any research or consensus on how the decrease in precipitation would be distributed between runoff and base flow. Finally, the technique was also applied to the discharge record at the downstream boundary, and the water surface elevation record was reconstructed by use of the stage-discharge rating curve.

Simulation Scenarios

Five scenarios were selected to test the response of the river [illegible] changes in hydrologic, meteorological, and operational conditions discussed previously. The scenarios are presented in Table 6 and summarized as follows:

1. Historical flows, WSELs, and meteorology; synthesized water temperatures; all plants off-line
2. Historical flows, WSELs, and meteorology; synthesized water temperatures; all plants operating at projected daily load cycles
3. Historical flows, WSELs, and meteorology; synthesized water temperatures; all plants operating at 100% of capacity
4. Flows and WSELs adjusted for shortened navigation season; historical meteorology; synthesized water temperatures; all plants operating at projected daily load cycles
5. Meteorology, flows and WSELs, and synthesized water temperatures adjusted for global warming; all plants operating at projected daily load cycles

REVIEW OF UNCERTAINTY AND LIMITATIONS

Before the results of the simulations are presented, it is useful to recall the uncertainties involved and limitations of the model. The assumption of complete mixing may distort the results at points immediately downstream of heated water releases. The model is unable to simulate the dynamics of the plume, where the water will locally be much warmer than the cross-sectional average temperature.

CHARIMA treats the relationship between power generation and temperature rise as strictly linear. In reality there is considerable scatter around this line. Although this uncertainty may be unbiased, ignoring it decreases the variability of the results, i.e., added variability to input data will increase the variability of results. For example, for an extreme summer event, if the temperature rise was underpredicted as a result of the use of the strictly linear relationship, the model may underpredict the maximum water temperatures. Conversely, if the model overpredicts the temperature rise, it will overpredict the maximum temperatures. It is impossible to quantify the

TABLE 6. Long-Term Simulation Scenarios

Variant (1)	Scenarios Selected for Simulation: Plants off-line (1)	Current generation (2)	Maximum capacity (3)	Short navigation (4)	Global warming (5)
(*a*) Flows					
Historical	✓	✓	✓		
Adjusted for shorter navigation season				✓	
Adjusted for global warming					✓
(*b*) Water surface elevations					
Historical	✓	✓	✓		
Adjusted for shorter navigation season				✓	
Adjusted for global warming					✓
(*c*) Water temperature boundaries					
Synthesized from historical air temperatures	✓	✓	✓	✓	
Synthesized from air temperatures adjusted for global warming					✓
(*d*) Power plant operations					
All power plants off-line	✓				
Plants operating at current loads		✓		✓	✓
Plants operating at 100% capacity			✓		

effects without Monte Carlo sampling or other stochastic treatment of the power versus temperature rise relations as random variables.

Errors in simulation of water surface elevations are inevitable due to uncertainty in measured data used for calibration of the roughness coefficient. Although the errors may be unbiased, they may still cause errors in water temperatures. For example, simulated elevations greater than the actual elevations would cause a decrease in water temperature due to increased dilution for the increased cross-sectional area. However, this would also cause a decrease in the mean velocity, which means further heating or cooling due to increased exposure time to atmospheric heat exchange. During extreme summer conditions, when atmospheric heat exchange is heating the water, this might cause the model to overpredict maximum water temperatures. In contrast, underpredicting the water surface elevations may cause underestimation of maximum temperatures during extreme summer events.

It was stated earlier that the WRF is a physically based parameter accounting for differences between wind speeds at measured locations and applied wind speeds at the water surface. Although this definition is clear, it may be argued that the WRF may be masking a systematic bias in the model formulation or model input. Since the input water temperatures to the model were simulated stochastically and not measured, the possibility of a bias exists. It is impossible to determine if the WRF is masking such a bias. However, statistical analysis of measured and synthesized water temperature records showed no systematic bias.

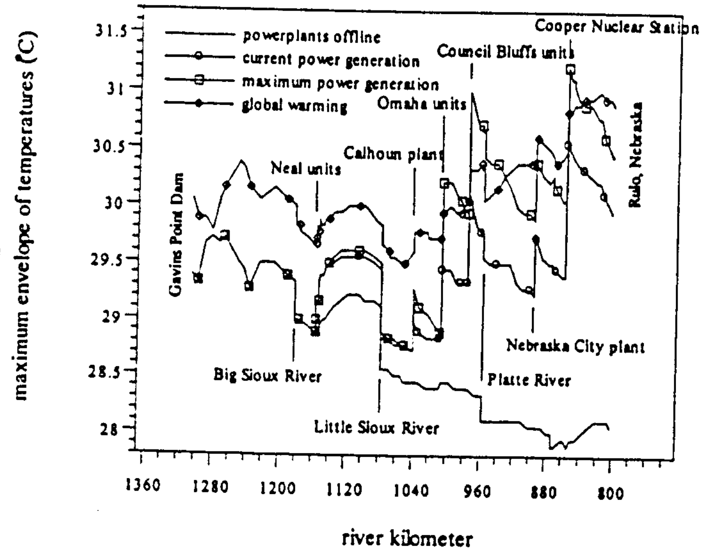

FIG. 5. Maximum Envelope of Water Temperatures over 40-Year Simulation Period

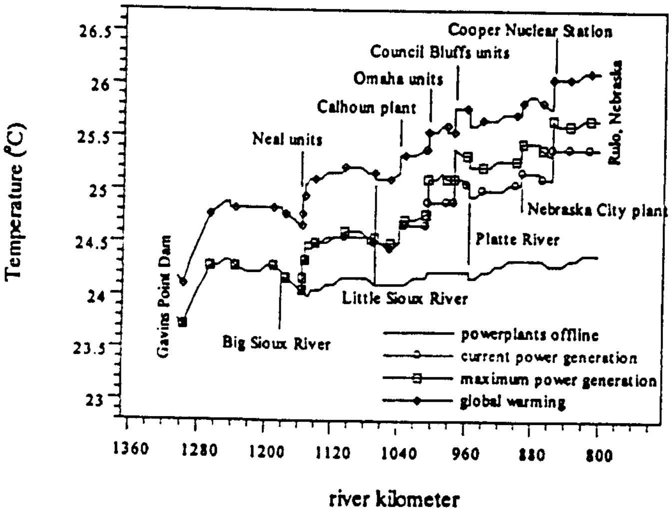

FIG. 6. Average of Maximum Daily Water Temperatures for August Conditions over 40-Year Simulation Period

SIMULATION RESULTS

Two longitudinal profiles of temperatures are presented. Fig. 5 is a plot of the maximum envelope of temperatures through the 40-year simulation, and Fig. 6 shows the averages of the maximum daily temperatures for August (arbitrarily selected to represent typical summer conditions) conditions over the 40-year simulation period. Several observations can be made with respect to the longitudinal temperature profiles. Pertaining to the longitudinal profile of the maximum envelope of temperatures (Fig. 5):

1. The tributaries cause a local decrease in the cross-sectional average temperature for these extreme conditions, directly related to the magnitude of discharge of the particular tributary. For the four scenarios in which the plants are operating, this can be explained by the fact that the main stem is in an artificially elevated thermal regime, i.e., its temperature is above natural conditions. For the scenario with all plants off, the tributary cooling is still seen because the tributary temperature records are daily averages, while main-stem temperatures reported in Fig. 5 are absolute maximums. So while the main stem is at its maximum temperature (mid-afternoon), the tributary inflows are mean daily temperatures, which will be slightly cooler.
2. The power plants cause a local increase in the cross-sectional average temperature. This is consistent with the model's treatment of the power plants.
3. For the scenario with all plants off-line, the tributary dilution effect caused an overall decrease in temperature from the upstream boundary to the downstream boundary.
4. For all other scenarios, the local temperature increase due to the power plants overpowered the dilution effect to cause an overall increase in temperature from upstream boundary to downstream boundary. This supports the hypothesis that the plants work as a system to increase the average temperature of the river, and that the local increase is not dissipated in the mixing zone.
5. Normal plant operations caused a 1.9°C (3.5°F) increase in the maximum temperature reached at Rulo as compared to the scenario with all plants off-line.
6. A shortened navigation season showed no significant effects.
7. Plants operating at maximum capacity caused a 2.4°C (4.3°F) increase in the maximum temperature at Rulo as compared to the scenario with all plants off-line.
8. The global warming scenario showed a 2.9°C (5.2°F) increase at Rulo.
9. The temperature did not exceed the 32°C (90°F) State of Iowa standard.

Similar observations can be made from the longitudinal profile of the averages of maximum daily temperatures for August conditions (Fig. 6):

1. As with the maximum envelope, the tributaries cause a local decrease and the power plants cause a local increase in the cross-sectional average temperatures for the August conditions. Again the local tributary cooling is seen for the scenario with all plants off-line, which can again be explained by the fact that their temperature records are daily averages, while the temperatures reported in Fig. 6 are averages of maximum daily temperatures. As

expected, these local differences are much less for the average conditions, and thus so are the overall changes in temperatures at Rulo.

2. Normal plant operations (and shortened navigation season) caused a 0.9°C (1.7°F) increase from the scenario with all plants off-line in the average maximum daily temperature for August at Rulo.
3. Maximum capacity plant operations caused a 1.3°C (2.3°F) increase in temperature at Rulo.
4. Global warming caused a 1.7°C (3.1°F) increase at Rulo.
5. The average maximum daily temperatures for August increase from upstream to downstream due to the increase in air temperature from upstream to downstream, and the low water temperature releases from Gavins Point Dam.
6. The average maximum daily temperatures never exceed the 32°C (90°F) standard; in fact, they never exceed 27°C (80°F).

One significant difference in the two plots is apparent. For the natural conditions simulation (all plants off-line), the maximum envelope of temperatures and average maximum August temperatures show different longitudinal gradients, i.e., the maximum temperatures decrease in the downstream direction, while the average maximum August temperatures increase in the downstream direction. One might expect the results regarding the average maximum August temperatures, due to increasing air temperatures and thus tributary water temperatures as the Missouri flows south. The behavior of the maximum envelope of temperatures is less obvious. The first thing that should be noted is that the plot presents the absolute maximum temperature that occurred at each point of the 40-year simulation, and does not necessarily represent one event. In other words, the points plotted in Fig. 5 may have all occurred at different points in time in the simulation. In the absence of power plants, one would expect the maximum river temperatures to be nearly constant or slightly increasing in the downstream direction, assuming water temperatures are driven by air temperatures. If the temperature decreases at the tributaries are eliminated from Fig. 5, this would indeed be the case. In fact, the temperature decreases at the tributaries in Fig. 5 are not physically explainable, and are due to the synthesized water temperature records. Table 3 shows that the synthesized record monthly standard deviations are consistently slightly less than for the measured record. Therefore, during extreme air temperature events, the tributary water temperatures are underestimated, thus causing the artificial mainstem temperature decreases seen in Fig. 5.

CONCLUSIONS

The most important findings of this study are as follows:

1. The computer code CHARIMA was able to successfully simulate the unsteady hydrodynamics and thermodynamics of the Missouri River along its Iowa border. The model was calibrated and validated by comparison with measured data, and can be used confidently in the future to analyze other possible changes in power plant operating policies, climatology, and hydrology.
2. The power plants, operating at their current normal loads, are significantly affecting the thermal regime of the river by releasing heated once-through condenser cooling water. Also, the power plants work as a system, not as isolated entities, to steadily increase the river temperature in the downstream direction.
3. Shortening the navigation season by one month, as recommended in the new Missouri River Master Manual, will have little or no effect on the thermal regime.
4. Both increasing power demand and global warming could cause a further increase in the average and extreme temperatures realized over this reach.
5. Average maximum daily temperatures in the summer were still well below the State of Iowa 32°C (90°F) standard for all scenarios for the 40-year period of record used for long-term simulation.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b = y-intercept of linear regression fit;
m = slope of linear regression fit;
T_a = air temperature;
T_w = water temperature;
Z_t = random noise;
ε = model error or residual;
ε_t = residual at time t;
ε_{t-1} = residual at time $t-1$;
σ_ε = standard deviation of residuals; and
ϕ_1 = order 1 autoregressive process parameter.