In-stream flow impact on river water temperatures
Impact de l'écoulement amont sur la température de l'eau d'une rivière

BASHAR A. SINOKROT, *Wenck Associates, Inc., USA and Department of Civil Engineering, Al-Isra' University, Jordan*

JOHN S. GULLIVER, *Saint Anthony Falls Laboratory, Department of Civil Engineering, University of Minnesota, Minneapolis, USA*

ABSTRACT

The Central Platte River often experiences high water temperatures during sunny, hot summer days. A 128-km reach of the Platte River downstream of two hydropower dams (Kingsley Dam and North Platte/Keystone Diversion Dam) was studied to determine the relationship between river summer water temperatures and river flow-rate, and the impacts of in-stream flow requirements upon peak water temperatures. This reach serves as a habitat for eight federally listed or endangered species, as well as over 300 species of migratory birds, including 500,000 sandhill cranes and 7-9 million ducks and geese. Hourly water temperatures were simulated using a dynamic numerical model (MNSTREM) with and without in-stream flow requirements. It was found that a clear relationship exists between river water temperatures and river flow-rate. In addition, it was found that the occurrence of high water temperatures can be attributed to low river flow-rate and can be reduced, but not eliminated, with minimum in-stream flow requirements.

RÉSUMÉ

Le cours médian de la Platte River présente souvent des températures d'eau élevées durant les jours d'été ensoleillés. Un bief de 128-km, à l'aval de deux barrages hydroélectriques (le Kingsley Dam et le North Platte/Keystone Diversion Dam) a été étudié pour déterminer une relation entre la température estivale de l'eau et le débit de la rivière, et l'impact des conditions sur les débits injectés en cas de pointe de température de l'eau. Ce bief sert d'habitat à huit espèces protégées par les lois fédérales ou exposées à des dangers, ainsi qu'à plus de 300 espèces d'oiseaux migrateurs comprenant 500000 grues littorales et de 7 à 9 millions de canards et d'oies. Les températures horaires de l'eau ont été simulées à l'aide d'un modèle numérique dynamique (MNSTREM) avec et sans conditions de débit entrant. On en a conclu qu'une relation claire existe entre la température de l'eau et le débit de la rivière. En plus, il a été montré que le fait de températures élevées de l'eau pouvait être attribué aux débits d'étiage, et que ce problème pouvait être atténué mais non supprimé par des conditions minimes sur les débits d'entrée.

I Introduction

The Central Nebraska Public Power and Irrigation District and Nebraska Public Power District were seeking license renewal from the Federal Energy Regulatory Commission (FERC) for two hydropower dams on the Platte River in western Nebraska. The dams are the Kingsley Dam and North Platte/Keystone Diversion Dam (Figure 1), more than 150 km upstream of the study reach. In 1992, FERC issued a draft environmental impact statement (EIS) for the license renewals and later submitted a revised EIS in March 1994. The U.S. Environmental Protection Agency (EPA) had some issues with the EIS. The issues of contention were related to the 240-km reach of the central Platte River downstream of the dams, which serves as a habitat for eight federally listed threatened or endangered species, as well as over 300 species of migratory birds, including 500,000 sandhill cranes and 7-9 million ducks and geese. The EPA believes that dam operations may have caused severe degradation of this internationally significant habitat. In particular, it is believed that the proposed operating alternative for the dams will cause persistent exceedances of the federally-approved state water quality temperature standard of 32°C in the central Platte River. According to the EPA, temperature exceedances (above the standard) are increasingly likely as river flow declines.

The importance of maintaining temperature standards is linked to the biological integrity of the Platte River, including the protection of forage fish species that are important to the survival of certain endangered bird species. High temperatures can generally result in increased metabolic activity of aquatic organisms, including fish, as well as decreased solubility of dissolved oxygen and increased biochemical reaction rates. If the temperatures are high enough, the results can be lethal to aquatic life. In fact, fish kills have been observed in five out of the six summers between 1985 and 1990 (Dinan, 1992). Decreased flow has the potential to increase daily temperature peaks in the central Platte due to the lower corresponding depth of flow. The solar radiation, for example, is applied over less depth in a shallower stream, causing a larger temperature increase during the daylight period.

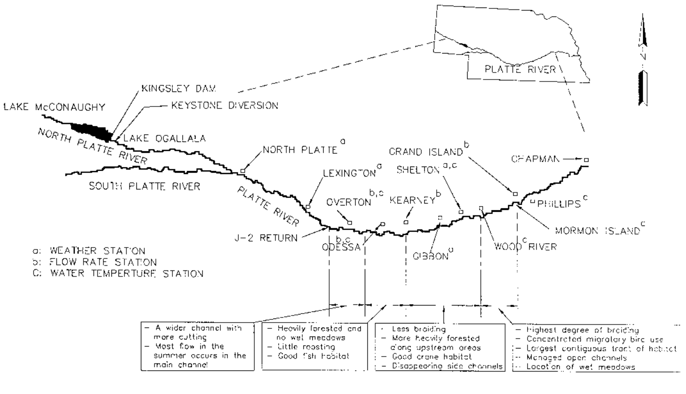

Fig. 1. Sketch of the central Platte River, location of relevant data stations, and description of stream segments.

Revision received April, 2000. Open for discussion till April 30, 2001.

This paper summarizes the results of a computational model study to determine the impact of various in-stream flow criteria upon the number of days that water temperature in the central Platte exceeds 1) the State standard of 32°C, and 2) 35°C (Sinokrot et al. 1996). The 35°C level is presumed to be a temperature at which the aquatic biota is more severely stressed than at 32°C. The 35°C level was also justified by Dinan (1992) as a temperature that is close to the “Critical Thermal Maximum” for many fish species found in the river basin. The study involved the application of a computational water temperature prediction model, MNSTREM, to the central Platte River. MNSTREM has been shown to accurately predict stream water temperature on an hourly time scale under highly unsteady conditions (Gulliver, 1977; Stefan et al., 1980; Sinokrot and Stefan, 1993), and has been adapted to incorporate all of the important aspects of natural rivers (Sinokrot and Stefan, 1992, 1993, and 1994). Calibration of a shading coefficient and a roughness coefficient, and verification took place through the comparison with four years of water temperature record at four stations on the Platte River. The model was then used with the same four-year weather record to predict the water temperatures that would have occurred with various minimum in-stream flow criteria applied to the reach. The impact of these in-stream flow criteria on water temperature was then predicted for the four-year period through comparison of computer simulations.

II Background on study reach and discharge

The study reach was a 128 km section of the central Platte River (Big Bend Reach) from Overton to Phillips, Nebraska. A map of the river with locations of discharge and weather stations is shown in Figure 1.

Currently, discharge in the central Platte River is highly managed. Central Nebraska Public Power and Irrigation District’s massive Tri-County Project, of which Kingsley Dam and the associated Lake McConaughy are the keystones, was designed to capture fall, winter and spring flows of the North Platte River for summer irrigation and for hydropower generation. Immediately below Lake McConaughy a significant portion of the river’s discharge is routed through the Keystone Diversion to cool the Gerald Gentlemen thermal power station, to supply hydropower for the city of North Platte, and to serve farmland in six irrigation districts. The remaining water is returned to the river near North Platte, Nebraska only to be diverted again by the Tri-County Diversion Dam below the confluence of the North and South Platte rivers. From this diversion, water is fed down canals to water cropland south of the Platte River, to power three hydropower plants and cool the Canaday thermal power station. On an average annual basis, about half of what was diverted below North Platte is returned to the Platte River at the Johnson-2 (J-2) return, which is immediately upstream from the Overton gauging station. The majority of the water is returned to the Platte in the October through April period. On average, the daily percent return in May through September is approximately 40 percent of that in October through April (Williams, 1978).

The environmental characteristics of the reach change gradually over the 128 km length, and are in a period of slow transition today. Beginning with the impoundment of the upstream reservoirs, the island, channels, and sandbars have slowly been colonized by trees and other woody vegetation. The reach between Wood River and Grand Island is probably the most similar to the classic braided river that existed before the dams and diversions. The upstream sections of the reach are more heavily forested with little roosting habitat. These general environmental characteristics are also identified in Figure 1. Topography of the Platte valley is relatively flat with a slope of 1.4×10^{-3} (Currier et al. 1985).

In-stream flows to protect the resources of the central Platte River have recently taken on a greater importance. In 1992 the Central Platte Natural Resources District received approval for an in-stream flow appropriation that was exclusive of releases from the Kingsley and Keystone Dams. In other words, once the flow is supplied to the river by these two dams, the in-stream flow appropriation is in effect. The current in-stream flow appropriation, however, cannot place requirements upon releases from the dams. It is not surprising that federal and state resource agencies would seek to intervene in the relicensing process for these two dams, to secure an in-stream flow appropriation that will provide some additional protection for the aquatic and terrestrial habitat in and near the central Platte River.

III Modeled period and historical record

Water temperature measured by the U.S. Fish and Wildlife Service, river discharge measured by the U.S. Geological Survey, and weather data measured by the High Plains Climatic Center exist for different periods and at different locations on the study reach. Hourly measured water temperature data exist at five stations along the study reach: Overton, Odessa, Shelton, Mormon Island, and Phillips. Figure 1 shows the location of these stations. Daily measured flow rates exist at four stations on the study reach: Overton, Odessa, Kearney, and Grand Island. These stations are also shown on Figure 1.

The data required for accurate modeling was recorded for most of the period extending from 1991 to 1994. This study focused on the summer period from June through August, since this period is believed to be most critical when considering maximum river water temperatures.

The variation in weather and river discharge over a three-month summer period are significant, and summers can generally be classified as warm, cool or normal; and as wet, dry, or normal. Water temperature, however, has more of a daily response to weather and discharge, rather than a seasonal response, and therefore these seasonal classifications lose their relevance when water temperature is concerned.

The question still remains, however, as to how the simulated four-year period compares to the historical record. Four years of summer data may not be sufficient to establish the expected mean values of river discharge and weather parameters. Gulliver (1991), for example, found that thirty years of record were required to establish a mean discharge for two rivers within 10 percent. Thus, the probability of obtaining a daily mean discharge or weather parameter (i.e., air temperature) will be estimated for both the study period and the fifty years of summer records from 1945-1994. The probability distributions for the two periods can then be compared to establish how four-year modeled period represents the historical record.

Discharge

A cumulative probability distribution histogram of discharge (flow duration curve) is given for both the study period and the June-August months of 1945-1994 in Figure 2. The histogram gives the probability of exceedance for various discharges on any given day during the period of interest. Put differently, the histogram identifies the percentage of time that a given river discharge can be expected to be exceeded. It is believed that a comparison of this data for the 1991-94 and 1945-94 periods will indicate whether the simulation period is representative of the longer period and may indicate any major changes in river discharge operation that may have occurred over the longer period.

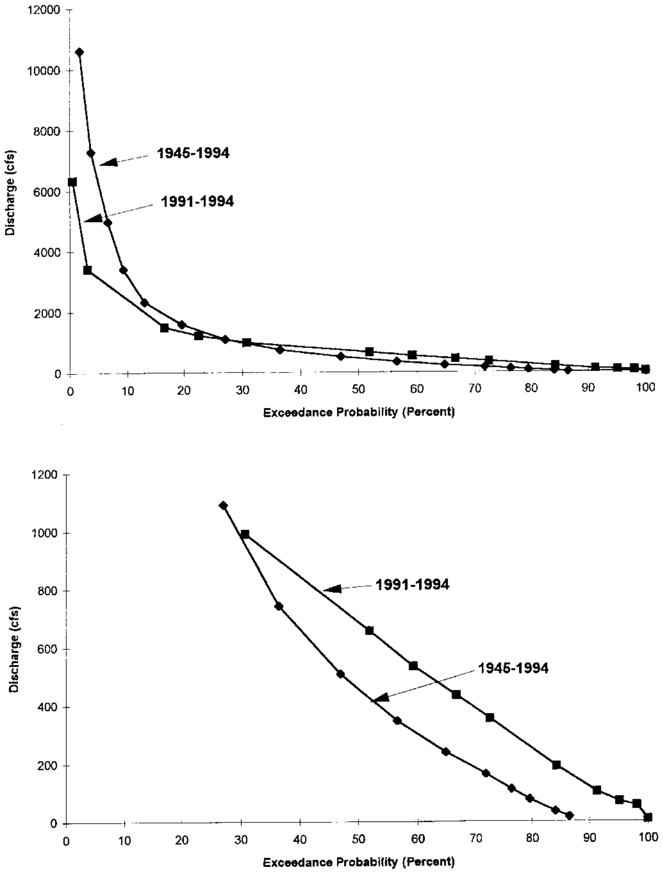

Fig. 2. Cumulative probability histograms of June, July and August for the four-year study period and the fifty-year period.

Some differences are, in fact, observed in Figure 2. During the study period, the low discharges occurred less frequently. For example, a discharge of 100 cfs was exceeded 90 percent of the time during the study period, but only 77 percent of the time during the 50-year period. In addition, zero discharge occurred 10 percent of the time in the 50-year period, but did not occur in the study period. The median discharge of the 50-year period was 456 cfs, while during the study period it was 651 cfs; and the 75 percent exceedance discharges were 310 and 126 cfs for the respective periods. Thus, the low flows were more frequent in the 50-year period than in the study period.

On the other hand, high discharges were also more frequent during the 50-year period than during the study period. For example, the 2 percent exceedance discharges were approximately 4000 cfs and 10,000 cfs for the study period and 50-year period, and the 5 percent exceedance discharges were 3000 cfs and 6200 cfs, respectively. In the end, the higher discharges and lower discharges of the 50-year period balance out, and the mean discharge of the 50-year period, 1150 cfs, was close to that of the 4-year study period, 1200 cfs.

It is difficult to determine what portion of these differences are accounted for by the change in operation of the river discharge, and what portion is indicative of a different runoff regime. As mentioned previously, the Platte River has a highly managed flow regime. Any change in the operating rules for release of water from the upstream reservoirs would alter the flow duration curve. It is also true that to have four years of discharge in a river precisely represent fifty years of record is difficult. Nevertheless, Figure 2 indicates that the historical record had less runoff during the low flow periods than the period that will be modeled, 1991-1994, although the median discharges are similar.

In addition, the effect of altered flow regime on the geomorphic characteristics of the river was not determined. Changes in the cross-section shapes that include an increase in the width-depth ratio, loss of vegetation (shade) and shallowing of pools may occur as a result of altered flow regimes due to operating rules of the dams.

Air Temperature

A cumulative probability distribution histogram of air temperature is given for both the study period and the June-August months of the 50-year period from 1945 through 1994, in Figure 3. The purpose was to compare the weather, as it relates to water temperature, of the study period to the 50-year record. Miller (1992) and Zander (1996) found that daily peak water temperature is most strongly correlated with air temperature. The likely reason for this correlation is the cross-correlation of air temperature with solar radiation and longwave radiation. On sunny summer days, the air temperature tends to be high, and longwave radiation is also high. Thus, the apparent impact of air temperature is actually the impact of solar radiation, longwave radiation, and air temperature.

A comparison of these curves in Figure 3 indicates that the study period is representative of the 50-year period, although the modeled period is slightly colder than the normal year in the 50-year period. During the 1945-94 summers an air temperature of 23.4°C was exceeded or equaled with a 50% probability (the median), while a median air temperature of 22.2°C was observed during 1991-94 summers. The difference between the two curves was greater at lower exceedance probability levels, the largest being 2°C at a 20% exceedance probability.

The weather of the four-summer study period appears to be somewhat cooler than the 50-year period. We believe that this would tend to reduce the number of days that water temperature would exceed the 32°C and 35°C levels in the study period analysis as opposed to the 50-year period from 1945–1994.

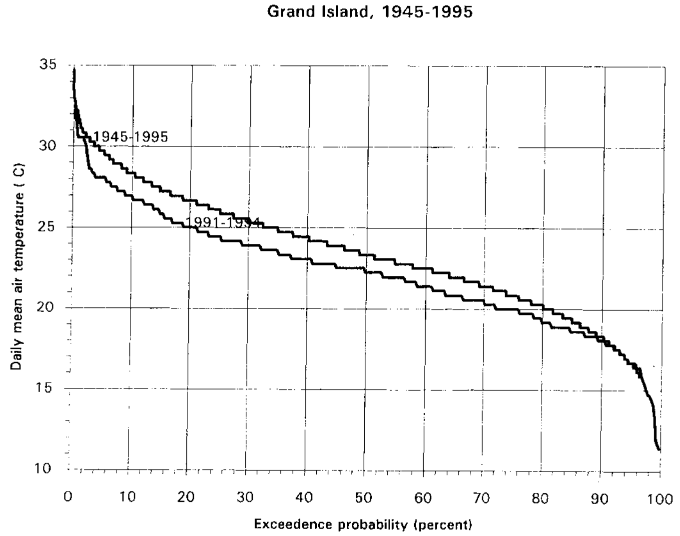

Fig. 3. Cumulative probalility histograms of air-temperature at Grand Island, Nebraska, for fifty summers (June through August) of record, 1945-1994, and for the 1991-1994 study period.

IV Computational model for water temperature prediction

The model used in this study is a modified version of the dynamic stream water temperature simulation model MNSTREM (Gulliver, 1977; Stefan et al., 1980). MNSTREM is a finite difference, implicit numerical model developed for the simulation of hourly water temperatures using the one-dimensional heat advection-dispersion equation and includes the heat exchange with the atmosphere. Sinokrot and Stefan (1994) extended MNSTREM to include streambed heat flux in the heat budget, side stream inflow, and groundwater inflow.

If stream cross-sectional area, *A*, surface width, *W*, and flow rate, *Q*, are variable along the *x* axis, the one-dimensional heat transport equation takes the form

$$A\frac{\partial T}{\partial t} + \frac{\partial (QT)}{\partial x} = \frac{\partial}{\partial x}\left(AD_L\frac{\partial T}{\partial x}\right) + \frac{WS}{\rho C_p} \qquad (1)$$

where T is water temperature, x is streamwise distance, t is time, D_L is a dispersion coefficient in the direction of flow (x direction), S is a source or sink term which includes heat transfer with the surrounding environment, ρ is the density of water, and C_p is the specific heat of water. The short time step (one hour) used in MNSTREM allows the use of more physically-based relationships that do not require the degree of empiricism that a daily time step would. Solar reflectance of the water surface, for example, varies throughout the day. This variation was incorporated into the simulations.

Equation 1 can be used to predict water temperatures in streams that have a relatively steady discharge and have no significant transverse temperature gradients. Stream cross-sectional area and width are a function of stream discharge, which can vary widely throughout the year.

The MNSTREM model requires three categories of data for the solution of Equation 1. These categories are: location, weather data, and stream data.

1. The location data are latitude and altitude.
2. The weather data are air temperature, relative humidity, solar radiation, wind velocity, cloud cover, and air pressure.
3. The stream data are total length of river reach, cross-sectional area and surface width as a function of discharge, upstream water temperature as a boundary condition, observed water temperature for calibration, stream flow rate, groundwater inflow/outflow, and initial streambed data (temperature profile in the sediment).

In the model simulations, daily values of Q are specified and the associated cross-sectional area (A) and stream width (W) are calculated from empirical power functions as commonly used in water quality modeling (Thomann and Mueller, 1987). It is also necessary to have hourly water temperature data to calibrate and validate the water temperature model.

The groundwater inflow/outflow between stations is calculated from a water balance. The temperature of shallow groundwater is set equal to the annual average air temperature.

A uniform streambed temperature profile in the sediment is used as an initial condition. The model calculates dynamic profiles based on the hourly stream water temperatures and then calculates the hourly streambed heat flux (Sinokrot and Stefan, 1993).

Longitudinal dispersion is normally not a significant transport mechanism for stream waters temperature modeling unless there are large spatial gradients in water temperature. For this application, the longitudinal gradients are not sufficiently large, and the longitudinal dispersion coefficient is simply determined from stream dimensions, roughness and flow (Fischer et al., 1979; McQuivey and Keefer, 1974).

V Model calibration and verification

A *Available Data*

Data input required by the model was obtained from a variety of sources. Stream location (latitude and altitude) was obtained from U.S. Geological Survey maps. Hourly weather data (except for cloud cover) from four weather stations (North Platte, Lexington, Gibbon, and Shelton) were purchased from the High Plains Climate Center, University of Nebraska, Lincoln. The cloud cover data were obtained from the National Oceanic and Atmospheric Administration (local climatological data for Grand Island, Nebraska). Hourly water temperature measurements for five stations (Overton, Odessa, Shelton, Mormon Island, and Phillips) on the Platte River were obtained from the Grand Island, Nebraska Office of the Fish and Wildlife Service, U.S. Department of the Interior. Manning coefficients (n) for different segments along the Platte River were obtained from the Mills, Wyoming Office of the Bureau of Reclamation, U.S. Department of the Interior. They were determined by measuring water surface slope, cross-sectional area, and wetted perimeter at various river discharges and back-calculating Manning's n from Manning's Equation (Equation 4). River and diversion flow rates data were obtained from the U.S. Geological Survey, State of Nebraska Department of Water Resources, and U.S. Bureau of Reclamation, through the U.S. Fish and Wildlife Service. As mentioned earlier, the model requires a functional relation between cross-sectional area A, surface W, and flow rate Q. Leopold and Maddock (1953), Richards (1982), and Jarvis and Woldenberg (1984) suggested the following forms of these relationships:

$$A = aQ^b \tag{2}$$

$$W = cQ^d \tag{3}$$

where a, b, c, and d are constants that depend on the shape of the stream's cross-section and can be determined from data for cross-sectional area, surface width, and stream flow rate. The stream surface width constants (c and d) for different segments of the Platte River were derived from morphology data supplied by the U.S. Fish and Wildlife Service, Grand Island, Nebraska, and were consistent with their values. The stream cross-sectional area constants were calculated for each segment using Manning's equation for fully rough, fully-developed boundary layer flow:

$$Q = \frac{1}{n}R^{2/3}AS^{1/2} \tag{4}$$

$$R = \frac{A}{P} \tag{5}$$

where S is the stream slope, R is the hydraulic radius, and P is the wetted perimeter. For wide open channels such as the Platte River, the wetted perimeter can be approximated by the surface width from Eq. 3. Then,

$$Q = \frac{1}{n}\left(\frac{A}{cQ^d}\right)^{2/3}AS^{1/2} \tag{6}$$

Substituting Equation 6 into Equation 2 results in the relationships:

$$a = \left(\frac{c^{2/3}n}{S^{1/2}}\right)^{3/5} \tag{7}$$

and

$$b = \left(\frac{2}{3}d + 1\right)^{3/5} \tag{8}$$

B *Calibration*

The model was calibrated using the measured water temperature data for June and July of 1994 and an average of weather data obtained at two stations, Lexington and Shelton. Sun-shading by the stream banks and its vegetation are considered most important when modeling stream water temperatures. Brown (1969), Rishel et al. (1982), Meisner (1990), and Sinokrot and Stefan (1993) previously illustrated the effect of sun shading on stream water temperature. Optimal values of sun-shading coefficient were established for each segment of the Platte River reach in concern by minimizing the standard error (SE) between measured (T_m) and computed (T_c) water temperatures. Sun shading ranged from 12 percent (between Wood River and Phillips) to 13 percent (between Kearney and Wood River) to 16 percent (between Overton and Kearney). This corresponds to an observed increase in the number of tree-lined channels and a reduction in the width of each. In addition to the sun shading calibration, the model was also calibrated for Manning's coefficient. The U.S. Bureau of Reclamation has supplied a range of Manning coefficients, which generally varied as a function of discharge, for different segments along the Platte River. The model was calibrated for a given Manning's coefficient for each segment that did not change with discharge. The Manning's coefficients used were in the range specified by the U.S. Bureau of Reclamation, as shown in Table 1.

Table 1. Manning's coefficients, and surface width and cross-sectional area parameters used in model simulations. Manning's coefficients are the range of Manning's coefficients determined from Bureau of Reclamation (BOR) measurements at a variety of stream discharges.

		Manning's Coefficient		Surface Width		Cross Section Area	
Segment	Reach Kilometers	MNSTREM	BOR	Constant	Exponent	Constant	Exponent
Overton Gage	0 - 12.6	0.030	---	71.96	0.3178	4.965	0.7272
Elm Creek A	12.6 - 18.5	0.030	0.023 - 0.041	68.84	0.2417	5.219	0.6967
Elm Creek B	18.5 - 23.4	0.030	0.025 - 0.040	82.17	0.2245	4.770	0.6898
Odessa	23.4 - 44.0	0.028	0.038 - 0.039	71.96	0.3178	4.856	0.7271
Kearney	44.0 - 62.6	0.026	0.026 - 0.041	94.36	0.3052	5.151	0.7221
Gibbon	62.6 - 66.0	0.030	0.030 - 0.047	101.3	0.2254	4.668	0.6902
Shelton A	66.0 - 73.3	0.025	0.023 - 0.049	117.4	0.1610	5.618	0.6644
Shelton B	73.3 - 77.0	0.030	0.027 - 0.045	110.4	0.2236	5.474	0.6894
Wood River	77.0 - 111.7	0.030	0.027 - 0.098	115.5	0.1872	6.226	0.6749
Grant Island	111.7 - 119.1	0.030	---	96.07	0.2953	5.963	0.7181
Phillips	119.1 - 128.7	0.030	---	223.7	0.1404	7.499	0.6562

C *Verification*

The model calibration was verified by comparing the standard errors of the calibrated period (June and July 1994) and the remaining of the study period (August 1994; July and August 1993; June, July and August 1992 and 1991). The standard errors for both of the calibrated period and the verification periods compared well. The standard errors of prediction ranged from 0.8°C at the Morman Island station in August of 1994 to 1.83°C at the Odessa station in June through August of 1991. It was difficult to reduce the standard error below 0.8°C for a 128 km stream reach, especially considering the variations in the weather parameters and stream morphology that can occur along the reach. The predictions were accurate to roughly 10 percent of the diurnal water temperature variation, which can be as high as 18°C in the central Platte River. An example of model simulations for the verification period is shown in Figure 4.

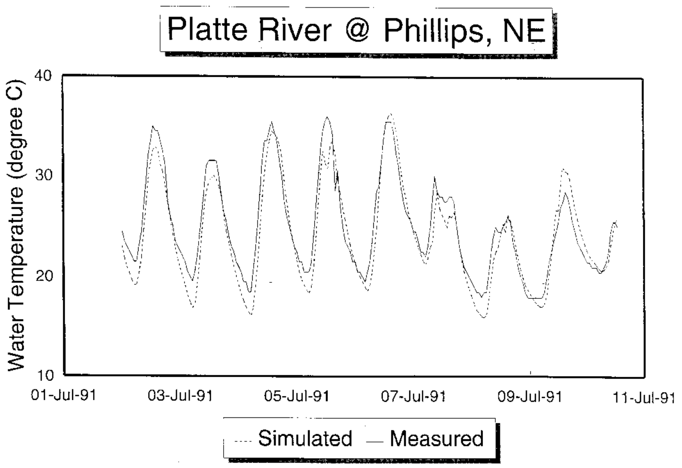

Fig. 4. Simulated and measured water temperatures for the 2–11 July 1991 period at the Phillips station.

Table 2 represents another form of model verification. The table compares the number of days with measured maximum water temperature that exceed 32 and 35°C to the number of days with simulated maximum water temperature that exceed 32 and 35°C at four stations on the Platte River. The number of days compared are below the total 368 days of the four-year, summer periods because both weather station malfunctions and water temperature station malfunctions caused “drop-outs” of measured data. Since the number of days that the water temperature exceeds 32°C and 35°C are the focus of the simulations, this comparison of measured and predicted number of days is judged to be the best verification for the simulations. Table 2 also lists the standard errors between measured and simulated maximum water temperature, which range from 1.4 to 1.9°C. This is considered good, especially when measured water temperatures showed diurnal variations as high as 18°C.

Table 2. Comparison of the total number of days that water temperature exceeds 32 and 35 degrees C. Simulations and measurements are compared over the same time period: 1991-1994.

Station	Number of Days Compared	Number of days > 32°C		Number of days > 35°C		Standard Error of Maximums (C)
		Measured	Simulated	Measured	Simulated	
Odessa	256	21	34	1	2	1.4
Shelton	272	59	59	17	7	1.5
Mormon Island	279	101	84	26	28	1.8
Phillips	180	46	53	11	11	1.9

D *Model Sensitivity to Weather Parameters*

One of the challenges in simulating water temperature over a 128 km-long river reach is that the weather conditions vary over the reach, and the observations are at fixed locations. The weather stations along the central Platte River were not chosen with this modeling effort in mind but can be used to estimate the variability in each weather parameter along the reach.

The actual variation in weather that occurs along the river reach can be estimated by determining the standard deviation of each weather parameter as measured at four stations along the river. This will result in a standard deviation of each weather parameter (air temperature, solar radiation, wind velocity, and relative humidity) that varies over time.

The sensitivity coefficients represent the change of the dependent variable that results from a unit change of a model parameter while holding all other parameters constant. Mathematically, sensitivity coefficients are the partial derivatives of the dependent variable with respect to each of the parameters (Willis and Yeh, 1987). The influence-coefficient method was used here to calculate the sensitivity coefficients as in Sinokrot and Stefan (1994). The influence-coefficient method evaluates the sensitivity coefficients by perturbing each of the model parameters, one at a time. They indicate the change in water temperature at a given station that can be anticipated by a unit change in the weather parameter of interest.

Finally, an indication of the sensitivity of the Platte River water temperature to the variability in each of the four weather parameters is given by factoring the sensitivity coefficients and the standard deviations of each weather parameter. This results in a “sensitivity” of water temperature predictions.

The modeled water temperature for the central Platte River was most sensitive to the variability in the measurements of solar radiation and air temperature, as shown in Table 3. It is unusual for water temperature to be this sensitive to the variations in solar radiation (Sinokrot and Stefan, 1994). The probable cause of this high sensitivity is the shallow depth of the central Platte River during low flow periods. There is also significant sensitivity to the variability in the measurements of wind speed and relative humidity.

Table 3. Sensitivity of water temperature to various weather parameters.

	Weather Parameter			
	Air Temperature	Relative Humidity	Wind Speed	Solar Radiation
A. Sensitivity Coefficient	**(C/C)**	**(C/%)**	**(C/ m/s)**	**(C/ W/m^2)**
Odessa	0.71	0.063	0.57	0.016[a]
Shelton	0.88	0.078	0.99	0.019[a]
Mormon Island	0.89	0.078	1.01	0.020[a]
Phillips	0.89	0.079	1.05	0.020[a]
B. Standard Deviation	**(C)**	**(%)**	**(m/s)**	**(W/m^2)**
	1.34	6.46	0.86	66.2[a]
C. Sensitivity[b]	**(C)**	**(C)**	**(C)**	**(C)**
Odessa	0.96	0.41	0.65	1.06
Shelton	1.18	0.50	0.86	1.24
Mormon Island	1.20	0.50	0.87	1.31
Phillips	1.20	0.51	0.91	1.32

[a] Computer based upon 12 daylight hours

[b] Sensitivity = (Mean Sensitivity Coefficient)(Standard Deviation of the weather parameter over the four weather stations)

The sensitivities can be used to identify the variability in weather parameters along the central Platte River as an important factor in the standard errors of prediction seen in this study. It would be difficult to get a prediction of less than 1°C standard error with these sensitivities to the existing variations in air temperature, solar radiation, wind speed, and relative humidity.

An illustration of the predicted water temperature response for the central Platte River to input data from various weather stations is given in Figure 5. The measured water temperatures for a 10-day period are compared to that predicted using each of the four weather stations individually. For the most part, the water temperature predictions are within a fairly narrow 1°C to 3°C band, with the measured water temperatures in this band as well. Periodically, however, the weather variation over the central Platte River is much larger, such that the prediction band can reach 5 to 10°C as can be seen on 2 July 1994 in Figure 5.

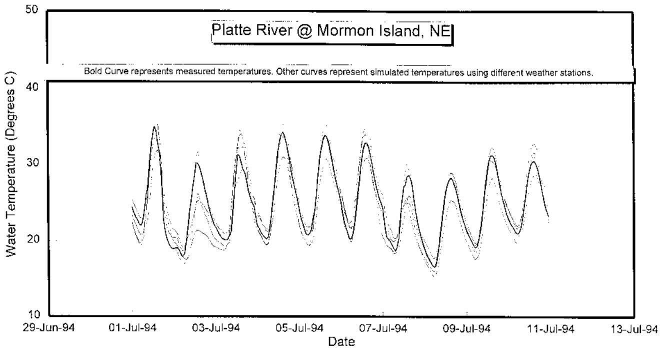

Fig. 5. Measured water temperatures at Mormon Island compared with those simulated using the weather input of the four weather stations on the central Platte River.

VI In-stream flow impact on water temperatures

The purpose of the calibration and verification of the dynamic water temperature computation model is to predict the impact of in-stream flow operation scenarios upon the occurrence of high water temperatures. This impact of in-stream flow on high water temperatures will be demonstrated by a determination of the number of days that the water temperature exceeds 32°C and 35°C. Although the increase in flow will be from reservoirs (potentially cool water), it is likely that the river would reach quasi-steady state temperatures by the time it reaches the first modeling station. The measured upstream temperatures for the study period were used as an upstream boundary condition in the in-stream flow operation scenarios.

There are a variety of in-stream flow constraints that have been suggested for the summer period in the Platte River. The Office of Environmental Affairs and the Fish and Wildlife Service of the Department of the Interior suggest a minimum discharge in the central Platte River of 1200 cfs during the wettest 75% of the years (wet and normal years) and 800 cfs in the driest 25% of the years (dry years). Habitat was the primary criteria in setting these recommendations, although water temperature was also considered. The Platte River Trust suggested a minimum discharge of 1000 cfs, and the U.S. Environmental Protection Agency, based solely on water temperature considerations, suggested a minimum discharge of 900 cfs. All of these flows were for the central Platte River, which will be assumed herein to indicate the discharge at the Grand Island station of the U.S. Geological Survey. The Nebraska Public Power District, on the other hand, suggests a minimum discharge of 200 cfs at Overton when the storage behind Kingsley Dam is less than 1.45 million acre-ft, and 400 cfs at Overton when the storage is greater than 1.45 million acre-ft. This storage level occurs roughly half of the time, in recent years.

The impact of these minimum stream flows constraints on the river discharge over the three-month period is difficult to predict. The discharges in the Platte River are highly managed, with flooding, irrigation, hydroelectric energy production, and environmental requirements all taken into consideration simultaneously. In addition, these considerations may change at any time, making past operation simulations obsolete. This study, therefore, will model what we consider to be the two extremes of system operation response to a minimum discharge constraint. The first is herein labeled the *minimum discharge operating scenario*. The second extreme is herein labeled the *constant discharge operating scenario*.

A *Minimum Discharge Operation Scenario*

Under the minimum discharge operating scenario, a given discharge release is added to the stream discharge of the four-year modeled period to meet the specified minimum stream flow constraint at Grand Island. This system operation response assumes that sufficient lake storage exists at Kingsley Dam to transfer released water from a wet season (spring) into a dry season (summer). Otherwise the stream discharge is identical to the historical operation in the summer months of 1991–1994. This scenario would likely to be closer to the actual operation at the lower constraints, such as 200 cfs, than at the higher constraints, such as 1200 cfs. The implications of this type of operation are indicated on the flow duration curve given in Figure 6.

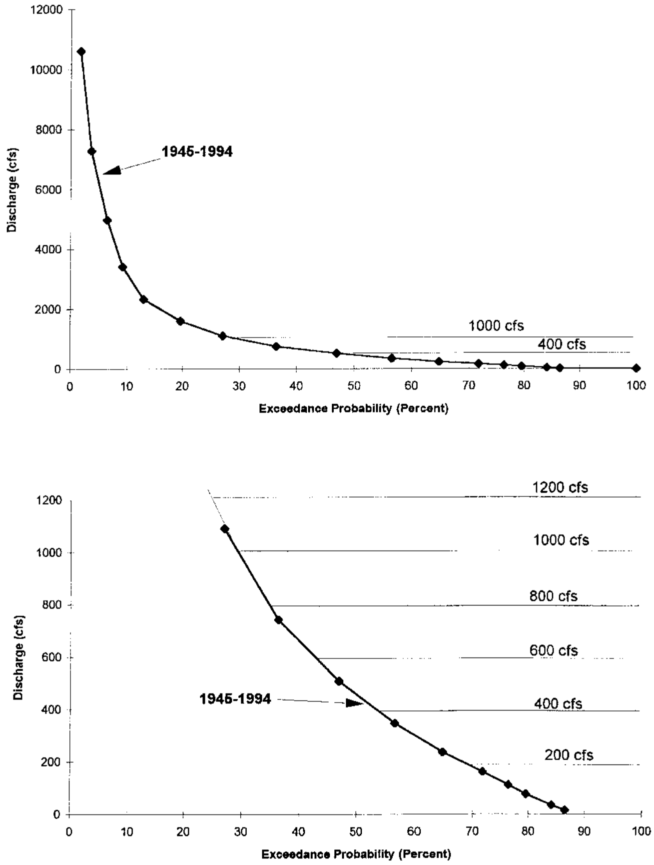

Fig. 6. Cumulative probability distribution curves for 50-years period and the adjustment to this curve that would be caused by the minimum discharge operating scenarios. June, July and August discharges at Grand Island, Nebraska.

A typical example of the impact of minimum discharge operating scenario on peak daily water temperatures is given in Figure 7, which shows the resulting days that the simulated water temperature exceeded 32°C and 35°C at Shelton. Exceedances above 32°C tends to decrease at close to a constant rate throughout the range from 0 to 1200 cfs, reaching 35 out of 290 days at 1200 cfs. This is still 12% of the June, July, and August days. The 35°C exceedances show a slope reduction versus discharge at 600 cfs, and drop to zero exceedances at 900 cfs.

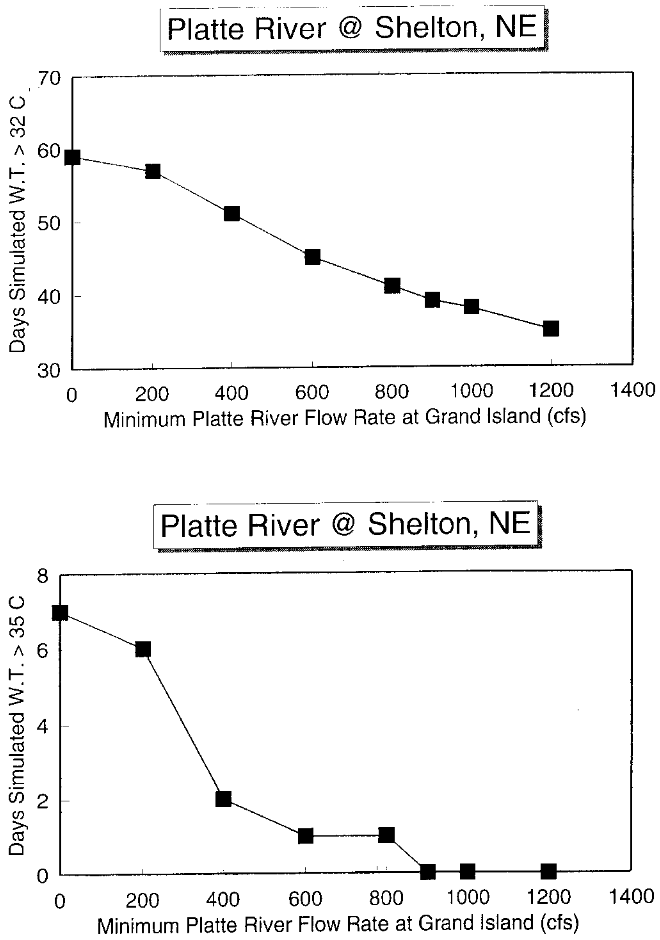

Fig. 7. Number of days that simulated water temperature exceeded 32°C (above) and 35°C (below) in the Platte River at Shelton for the minimum discharge operating scenario; 290 days simulated from 1991 through 1994.

The results of the minimum discharge simulations are summarized in Table 4 and can be compared readily in this table. the exceedances of 32°C approach zero only at Odessa. However, the exceedances of 35°C are reduced to zero at Odessa (800 cfs) and Shelton (900 cfs) and are reduced significantly with increasing discharge at Mormon Island and Phillips. For this operation scenario, increasing the in-stream flow standard to 1200 cfs would only decrease the total exceedances of the four stations to 60% of the base flow value. The total exceedances of 35°C, however, are reduced to 88% (200 cfs), 64% (400 cfs), 39% (600 cfs) 29% (800 cfs), 25% (900 cfs), 21% (1000 cfs), and 16% (1200 cfs) of the base flow value at the respective discharges. At the higher in-stream flows, this is a significant reduction in the exceedance of 35°C.

Table 4. Number of days that simulated water temperature exceeds 32 degrees C and 35 degrees C for the minimum discharge operating scenario. Total number of days simulated = 290, during June, July and August 1991-1994.

Odessa	**Base**	**Minimum 200 cfs**	**Minimum 400 cfs**	**Minimum 600 cfs**	**Minimum 800 cfs**	**Minimum 900 cfs**	**Minimum 1000 cfs**	**Minimum 1200 cfs**
T > 32 C	34	28	20	12	9	4	4	2
T > 35 C	2	2	2	1	0	0	0	0

Shelton	**Base**	**Minimum 200 cfs**	**Minimum 400 cfs**	**Minimum 600 cfs**	**Minimum 800 cfs**	**Minimum 900 cfs**	**Minimum 1000 cfs**	**Minimum 1200 cfs**
T > 32 C	59	57	51	45	41	39	38	35
T > 35 C	7	6	2	1	1	0	0	0

Mormon Island	**Base**	**Minimum 200 cfs**	**Minimum 400 cfs**	**Minimum 600 cfs**	**Minimum 800 cfs**	**Minimum 900 cfs**	**Minimum 1000 cfs**	**Minimum 1200 cfs**
T > 32 C	87	86	83	80	72	67	64	62
T > 35 C	28	24	18	11	8	8	7	5

Phillips	**Base**	**Minimum 200 cfs**	**Minimum 400 cfs**	**Minimum 600 cfs**	**Minimum 800 cfs**	**Minimum 900 cfs**	**Minimum 1000 cfs**	**Minimum 1200 cfs**
T > 32 C	84	84	80	73	69	66	65	58
T > 35 C	19	17	14	9	7	6	5	4

Base: Simulations are based on historical river flow rate.
Minimum 200 cfs: Minimum river flow rate at Grand Island is 200 cfs
Minimum 400 cfs: Minimum river flow rate at Grand Island is 400 cfs
Minimum 600 cfs: Minimum river flow rate at Grand Island is 600 cfs
Minimum 800 cfs: Minimum river flow rate at Grand Island is 800 cfs
Minimum 900 cfs: Minimum river flow rate at Grand Island is 900 cfs
Minimum 1000 cfs: Minimum river flow rate at Grand Island is 1000 cfs
Minimum 1200 cfs: Minimum river flow rate at Grand Island is 1200 cfs

The effect of minimum flow operating scenarios on water temperature can be further visualized by placing the sequence of discharge and simulated daily maximum water temperature onto one chart. As an example, in the summer of 1991, the Platte River experienced very low July and August discharges with the corresponding high water temperatures. Figure 8 shows the filling in the low flow periods with the minimum discharge reduced both the frequency and magnitude of high water temperatures.

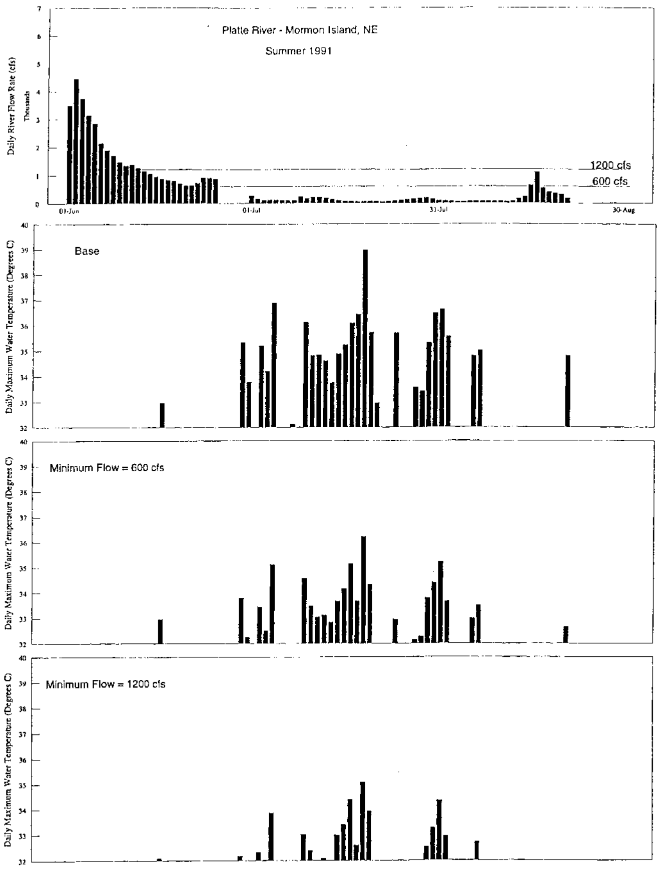

Fig. 8. Daily maximum water temperature for three simulated discharge operation scenarios and river discharge at Mormon Island versus days of the year for the summer of 1991. Zero river flow rate periods signify gaps in the data.

B *Constant Discharge Operation Scenario*

Instead of increasing the low discharges at Grand Island up to the minimum streamflow constraint, the river discharge at all four U.S. Geological Survey gauging stations is held at the minimum streamflow throughout the summer period of the years 1991-1994. In addition, there is no discharge into the Kearney diversion. All other diversions are uncontrolled and would continue to be governed by the stage-discharge relations of the Platte River. This assumes that all other discharges that occurred in the Platte River were stored to fill in the lower flow periods and to increase reservoir storage. Only the minimum streamflow was released. This is a fairly extreme alteration in the operation of the river during the summer months of 1991-1994, but may be representative of future reservoir releases during "dry" years, if a relatively high (1200 cfs) minimum streamflow is adopted. A constant discharge release would probably not be implemented for reservoir/irrigation canal operation if the lower minimum streamflow constraints are adopted for the Platte River.

The MNSTREM model was again run for the summer months of 1991-1994, except that the minimum streamflow criteria with the constant discharge operating scenario was instituted.

Figure 9 shows the simulated water temperature exceedances at Shelton. For the 32°C exceedances, a slight "knee" is shown at 600 cfs. The 35°C exceedances are reduced to zero at 900 cfs. The lower constant discharge exceedances (less than 600 cfs) are higher than the minimum discharge exceedances at both Odessa and Shelton, while the high discharge exceedances (above 800 cfs) are similar for the two scenarios.

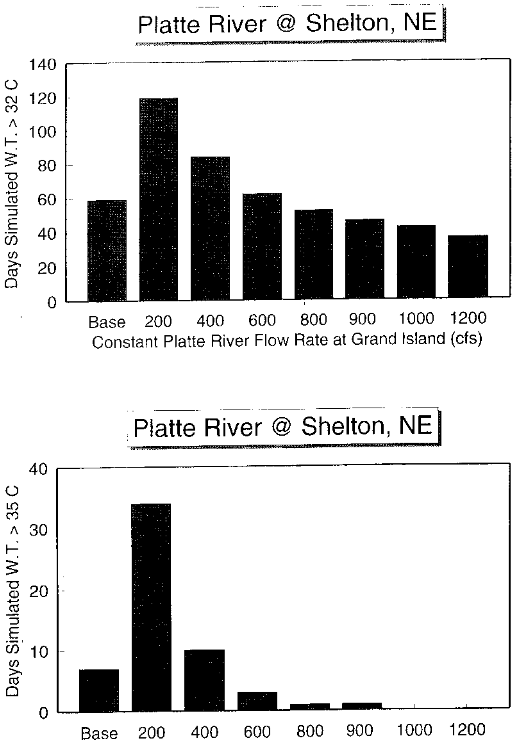

Fig. 9. Number of days that simulated water temperature exceeded 32ºC (above) and 35ºC (below) in the Platte River at Shelton for the constant river discharge operating scenario; 290 days simulated from 1991 through 1994.

The results of the simulations for the constant flow operating scenarios and the seven in-stream flow standards are summarized in Table 5. Significant reductions in the number of days exceeding 32°C are only possible at Odessa, using this operating scenario. The number of days that exceed 35°C, however, is significantly reduced with an increase in discharge at all stations. The constant flow scenario at 1200 cfs reduces the 35°C exceedances at all four stations to 25 percent of those at the base flow condition. At a constant flow scenario of 900 cfs, the exceedances are reduced to 48 percent of their base flow value. As in the minimum flow operating scenario, the effect of the constant flow operating scenarios on water temperature can be further visualized by placing the sequence of discharge and simulated daily maximum water temperature onto one chart. Figure 10 shows the predicted maximum water temperatures for the summer of 1991 at the Mormon Island location. Three operating scenarios, base flow, 600 cfs constant discharge, and 1200 cfs constant discharge are shown on the figure.

Table 5. Number of days that simulated water temperature exceeds 32 degrees C and 35 degrees C. Total number of days simulated = 290. 1991-1994.

Odessa	**Base**	**Constant 200 cfs**	**Constant 400 cfs**	**Constant 600 cfs**	**Constant 800 cfs**	**Constant 900 cfs**	**Constant 1000 cfs**	**Constant 1200 cfs**
T > 32 C	34	94	48	22	7	5	4	1
T > 35 C	2	10	0	0	0	0	0	0

Shelton	**Base**	**Constant 200 cfs**	**Constant 400 cfs**	**Constant 600 cfs**	**Constant 800 cfs**	**Constant 900 cfs**	**Constant 1000 cfs**	**Constant 1200 cfs**
T > 32 C	59	119	84	62	52	46	42	36
T > 35 C	7	34	10	3	1	1	0	0

Mormon Island	**Base**	**Constant 200 cfs**	**Constant 400 cfs**	**Constant 600 cfs**	**Constant 800 cfs**	**Constant 900 cfs**	**Constant 1000 cfs**	**Constant 1200 cfs**
T > 32 C	87	197	148	125	113	102	95	78
T > 35 C	28	110	59	36	23	15	10	8

Phillips	**Base**	**Constant 200 cfs**	**Constant 400 cfs**	**Constant 600 cfs**	**Constant 800 cfs**	**Constant 900 cfs**	**Constant 1000 cfs**	**Constant 1200 cfs**
T > 32 C	84	147	126	113	98	93	85	74
T > 35 C	19	56	38	29	16	11	10	6

Base: Simulations are based on historical river flow rate.
Constant 200 cfs: Constant river flow rate at Grand Island is 200 cfs.
Constant 400 cfs: Constant river flow rate at Grand Island is 400 cfs.
Constant 600 cfs: Constant river flow rate at Grand Island is 600 cfs.
Constant 800 cfs: Constant river flow rate at Grand Island is 800 cfs.
Constant 900 cfs: Constant river flow rate at Grand Island is9200 cfs.
Constant 1000 cfs: Constant river flow rate at Grand Island is 1000 cfs.
Constant 1200 cfs: Constant river flow rate at Grand Island is 1200 cfs.

The number of 32°C exceedances is larger for the 600 cfs constant discharge than for the base flow, while the 35°C exceedances are lower. Figure 10 demonstrates the cause of this apparent anomaly. The high discharges in June contributed to the base flow having only one exceedance of 32°C, while the 600 cfs scenario had seven 32°C exceedances (in June). In July, however, the low base flow discharges contributed to the occurrence of a number of 32°C and 35°C exceedances. The 1200 cfs scenario indicates a reduction in both of these exceedances, primarily due to the large supplement in river discharge during July and August.

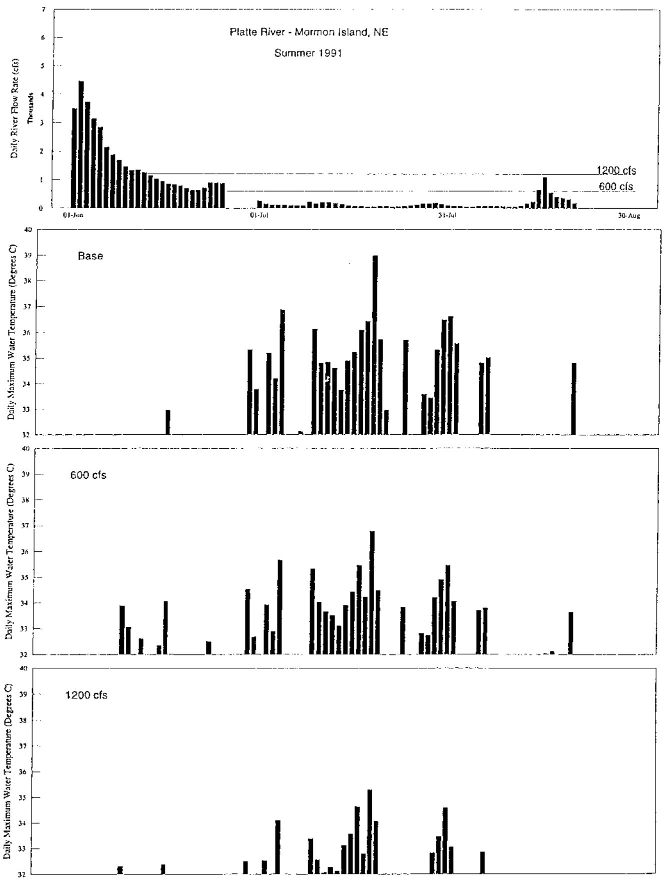

Fig. 10 Daily maximum water temperature for three simulated discharge operation scenarios and river discharge at Mormon Island versus day of the year for the summer of 1991.

VII Conclusions

In general, large rivers tend to be wide and deep, and smaller rivers tend to be shallow and narrow. The central Platte River is unusual in that it is both shallow and wide. This subjects the water to more rapid rates of heating and cooling due to the high surface area to volume ratio. Thus, solar radiation has a significant effect upon water temperatures, because of the low shading and shallow depth, and diurnal variations are commonly above 10 °C. The impact of discharge on water temperature occurs primarily through the associated increase in depth and the increased thermal inertia of the river. Thus, at higher discharges the amplitude of water temperature variation is decreased, where the high temperatures are reduced, and the low temperatures are increased. In a river that experiences up to 18 °C diurnal variation in water temperature, this reduction in the amplitude of water temperature variation is believed to have significant benefits for the aquatic biota.

The simulations of future operations with in-stream flow constraints indicated that there is a fairly strong correlation between the in-stream flow standard selected and the occurrence of river temperature greater than 35 °C. The correlation between in-stream flow standard and the occurrence of river temperatures greater than 32 °C was not as strong, occurring primarily at the upper two stations, Odessa and Shelton. It may be difficult to maintain water temperatures below the 32 °C state standard in the central Platte River, but the magnitude of the water temperature peaks above 32 °C can be reduced with an increase in stream discharge.

These and other observations on the simulations have led us to make two uncommon conclusions with regard to water temperature in the central Platte River: first, stream discharge does have a significant influence on peak water temperatures during low flow periods in the summer months; and second, the occurrence of these high water temperatures can be reduced with an increased in-stream flow.

The results of this study are related to a larger in-stream flow issue--the protection of the aquatic habitat in the central Platte River. This paper does not address the impact of these high temperatures on the aquatic biota, nor did it address the impact of various in-stream flow requirements on irrigation demands and hydroelectric power production in the Platte River watershed. The paper also did not address other aquatic habitat issues related to in-stream flows, such as roosting and nesting habitat for cranes, terns, and plovers. It, therefore, represented one piece in a large puzzle – the relationship of stream discharge to river water temperature as it relates to the protection of the aquatic habitat in the central Platte River.

VIII Acknowledgement

The study discussed in this paper was funded by District Eight of the U.S. Environmental Protection Agency, X998311-01. The authors would like to thank Bruce Zander, who provided encouragement and extensive review, and the members of the review panel, Steven C. McCutcheon of the U.S. Environmental Protection Agency in Athens, GA; Frank L. Parker of Vanderbilt University; and Larry A. Roesner of Camp. Dresser and Mckee, Inc.

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