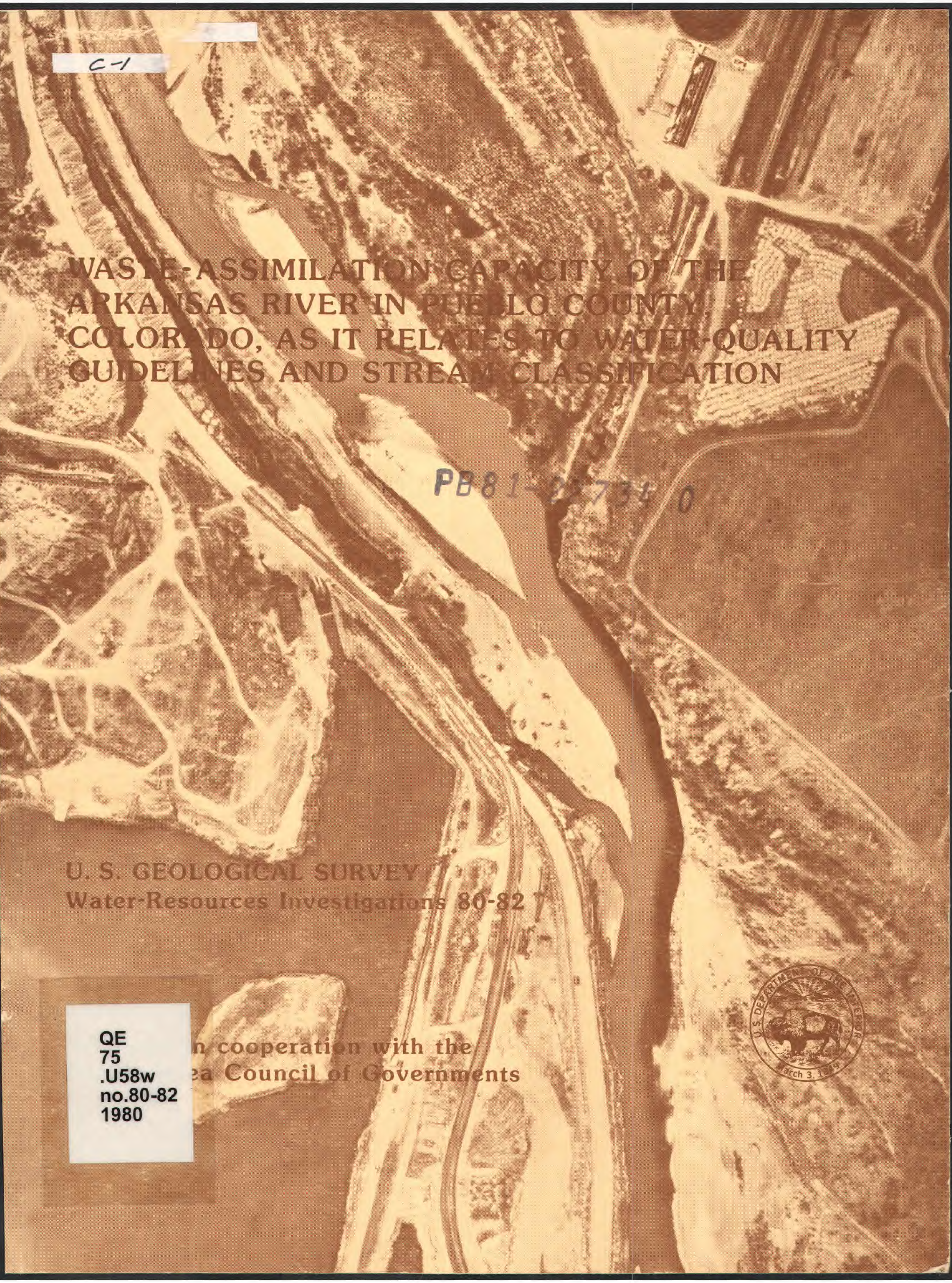

WASTE-ASSIMILATION CAPACITY OF THE ARKANSAS RIVER IN PUEBLO COUNTY, COLORADO, AS IT RELATES TO WATER-QUALITY GUIDELINES AND STREAM CLASSIFICATION

U. S. GEOLOGICAL SURVEY
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Waste-assimilation capacity of a 42-mile reach of the Arkansas River in Pueblo County was evaluated using a one-dimensional steady-state water-quality model calibrated and verified using hydraulic and water-quality data collected in 1976 and 1979. The water-quality constituents modeled were 5-day carbonaceous biochemical oxygen demand, total organic nitrogen, total ammonia, total nitrite, total nitrate, and dissolved oxygen. The model was used to simulate water-quality effects of 63 combinations of wastewater treatment, based on a 7-day low flow with a 10-year recurrence interval that occurs between August 15 and October 15 and on a winter low-flow period that occurs as a result of upstream storage of water. Evaluation of the mixing zone downstream from the Pueblo Wastewater Treatment Plant determined that complete lateral mixing of the effluent occurred 2.7 river miles downstream. Model simulations indicated some guidelines of constituents would be exceeded with projected effluent discharges and projected wastewater-treatment possibilities. Wastewater-treatment possibilities with projected discharge for the year 2000 which would result in both water-quality guidelines being met include land application of treated effluent and advanced secondary treatment at the Pueblo Wastewater Treatment Plant. Model simulations also included an evaluation of flow augmentation necessary to meet a water-quality guideline of 0.06 milligram per liter nonionized ammonia nitrogen. The flow augmentation necessary to meet the water-quality guidelines, based on the model simulations, is approximately 140 cubic feet per second.

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1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

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METRIC CONVERSION FACTORS

Inch-pound units in this report may be expressed as metric units by use of the following conversion factors:

To convert inch-pound unit	*Multiply by*	*To obtain metric unit*
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
mile	1.609	kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pounds per day (lbs/d)	0.4536	kilograms per day

WASTE-ASSIMILATION CAPACITY OF THE ARKANSAS RIVER IN PUEBLO COUNTY, COLORADO, AS IT RELATES TO WATER-QUALITY GUIDELINES AND STREAM CLASSIFICATION

By Doug Cain, U.S. Geological Survey;
Duaina Baldridge, Pueblo Area Council of Governments; and
Patrick Edelmann, U.S. Geological Survey

ABSTRACT

The waste-assimilation capacity of a 42-mile reach of the Arkansas River in Pueblo County, Colo., was evaluated using a one-dimensional steady-state water-quality model. The model was calibrated and verified using hydraulic and water-quality data collected in 1976 and 1979. The water-quality constituents modeled were 5-day carbonaceous biochemical oxygen demand, total organic nitrogen, total ammonia, total nitrite, total nitrate, and dissolved oxygen. Model calibration was acceptable for all constituents except total organic nitrogen, and verification was acceptable for all constituents except total organic nitrogen and total nitrite. A relationship between nonionized and total ammonia was defined to provide simulation capability for nonionized ammonia.

The model was used to simulate the water-quality effects of 63 combinations of wastewater treatment. The water-quality effects were evaluated with respect to water-quality guidelines that may be applied based on possible stream-use classifications. Model simulations were based on a 7-day low flow with a 10-year recurrence interval that occurs between August 15 and October 15 and on a winter low-flow period that occurs as a result of upstream storage of water.

The mixing zone downstream from the Pueblo Wastewater Treatment Plant outfall was evaluated to determine where the water-quality guidelines should apply for the model simulations. Complete lateral mixing of the effluent from the Pueblo Wastewater Treatment Plant occurred 2.7 river miles downstream from the outfall.

Model simulations indicated a water-quality guideline of 0.06 milligram per liter nonionized ammonia nitrogen would be exceeded at the end of the mixing zone for $Q_{7,10}$ conditions with secondary treatment at the Pueblo Wastewater Treatment Plant and a projected effluent discharge for the year 2000, and that a water-quality guideline of 0.5 milligram per liter total

nitrite nitrogen would be exceeded for winter conditions and the same wastewater-treatment possibility. Wastewater-treatment possibilities with a projected discharge for the year 2000 which would result in both water-quality guidelines being met include land application of treated effluent and advanced secondary treatment at the Pueblo Wastewater Treatment Plant with conversion of ammonia to nitrate to result in an effluent total ammonia nitrogen concentration of 5.4 to 10.6 milligrams per liter, depending on the quality of effluent from the downstream discharge from the CF&I Steel Corp.

Model simulations also included an evaluation of flow augmentation necessary to meet a water-quality guideline of 0.06 milligram per liter nonionized ammonia nitrogen. The evaluation was made for the $Q_{7,10}$ period, secondary treatment at the Pueblo Wastewater Treatment Plant with a projected discharge for the year 2000, and effluent water quality at a downstream discharge which could contain twice the estimated ammonia concentration allowable for best available technology treatment for the iron and steel industry. The flow augmentation necessary to meet the water-quality guideline, based on the model simulations, is approximately 140 cubic feet per second.

INTRODUCTION

Planners and public officials in Pueblo County, Colo., presently (1980) are making decisions about management of stream-water quality. The development and implementation of area-wide water-quality management plans was mandated by Public Law 92-500, Federal Water Pollution Control Act Amendments of 1972. Section 208 of this law provides grants to planning agencies for development and implementation of water-pollution controls to reduce degradation of streams to conditions suitable for recreation and fish propagation by 1983. Section 208 of Public Law 92-500 directs the Pueblo Area Council of Governments to coordinate such studies in Pueblo County.

The Arkansas River enters Pueblo County near Portland, just east of the Front Range of the southern Rocky Mountains (fig. 1). The quality of water in the Arkansas River upstream from Portland is generally suitable for all forms of recreation and the propagation of fish. As the river flows across the plains through Pueblo County, it is affected by point and nonpoint waste discharges from agricultural, municipal, and industrial sources. The Pueblo Wastewater Treatment Plant (WWTP) is the major municipal waste discharger to the Arkansas River in Pueblo County. The major industrial waste discharge is the effluent from the CF&I Steel Corp. (a steelmaking facility). The study documented in this report was conducted by the U.S. Geological Survey, in cooperation with the Pueblo Area Council of Governments, during a 15-month period from July 1979 to September 1980 and expands upon an investigation by Goddard (1980).

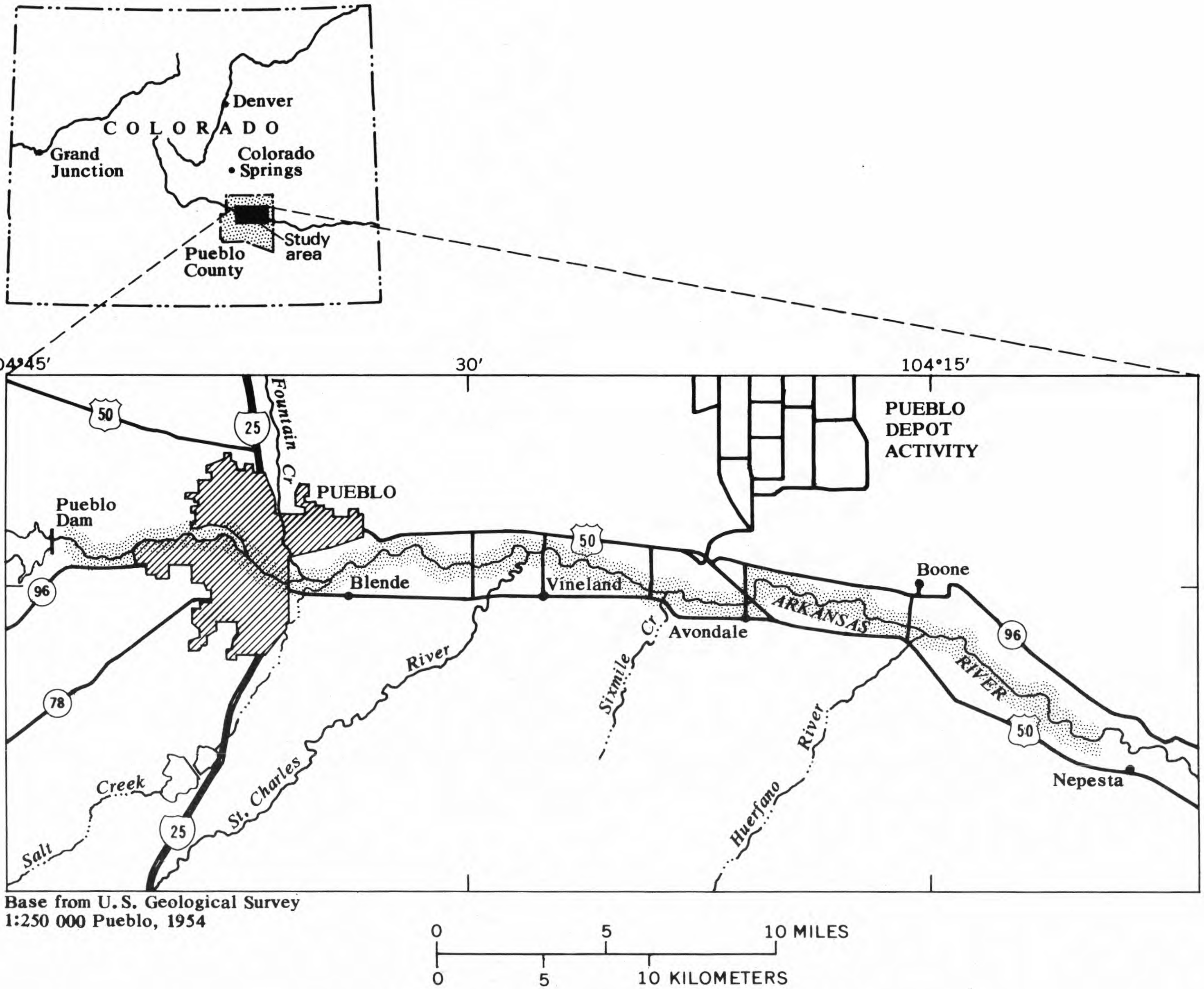

Figure 1.-- Location of study area (study reach shaded).

Objective and Approach

To comply with Section 208 of Public Law 92-500 and with regulations of the State of Colorado, the Pueblo Area Council of Governments requires the ability to predict the effects of various management alternatives on the water quality of the Arkansas River.

The objective of this investigation was to provide this capability through:

1. Calibration and verification of a one-dimensional steady-state water-quality model for a 42-mile reach of the Arkansas River between Pueblo Dam and the streamflow-gaging station near Nepesta.
2. Determination of the relationship between total and nonionized ammonia in the study reach.
3. Evaluation of the mixing zone downstream from the outfall of the Pueblo WWTP.
4. Model simulations for various water-quality and hydrologic-management alternatives.

Acknowledgments

The authors are grateful to those irrigators downstream from the city of Pueblo for their cooperation in allowing regulation of the riverflow at Pueblo Dam in September 1979 which permitted collection of data for model verification, and to Bob Jesse and Jim Kasic of the Pueblo Division State Engineers Office of the Colorado Department of Natural Resources for coordinating the regulation. The authors also thank the City of Pueblo, the CF&I Steel Corp., and the many residents and landowners of Pueblo County for permitting access to sampling sites on the Arkansas River and tributary streams.

Previous Investigations

A report by Goddard (1980) documents calibration and potential uses of a water-quality model for the Arkansas River in Pueblo County. That study, made in 1976, used hydraulic and water-quality data collected in April and October 1976 to calibrate the model. The streamflow in the Arkansas River below Pueblo Reservoir was 115 ft^3/s during the April survey and 400 ft^3/s during the October survey. Accurate simulation capability was developed by Goddard (1980) for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), total organic nitrogen, total nitrite, and total orthophosphate. The calibrated model gave less accurate simulation results for total ammonia, total nitrate, dissolved oxygen (DO), and coliform bacteria. Possible ways to improve the results for total ammonia and dissolved oxygen were suggested by Goddard (1980). The suggestions were based on changes made in the handling of nitrogen species and reaeration coefficients by the model as a result of studies of the Yampa River in Colorado (Bauer and others, 1978).

Other published studies related to this report include a summary of the hydrologic and water-quality data available for the Arkansas River in Pueblo County as of 1975 (Dumeyer, 1975). This report documents the mean low-flow value for the Arkansas River in Pueblo County that can be expected to occur for 7 consecutive days on the average of once in 10 years ($Q_{7,10}$). $Q_{7,10}$, as defined by Dumeyer (1975), occurs on the Arkansas River during late summer to early fall when the discharge on the Arkansas River below Pueblo Reservoir is 98 ft^3/s. The $Q_{7,10}$ is the critical flow designated by the Colorado Department of Health (1979a) for use by planners and managers in the design of wastewater-treatment plants. A more recent report by Dumeyer (1979) contains an updated analysis of low discharges on the Arkansas River and includes an analysis of the seasonal variation in discharge and selected water-quality constituents for the outfalls from the Pueblo WWTP and the CF&I Steel Corp. An assessment was also made of the possibilities for augmenting the riverflow during low-flow periods to provide for greater waste-assimilative capacity.

In addition to the above studies, water-quality data have been collected on a routine basis at several sites on the Arkansas River and its tributaries in Pueblo County by the Colorado Department of Health and the U.S. Geological Survey.

DESCRIPTION OF WATER-QUALITY MODEL USED IN ANALYSIS

The mathematical model used in this study was developed by the U.S. Geological Survey. Details of the model formulation and operation are documented by Bauer and others (1979). The model, which is based on the oxygen-sag equation of Streeter and Phelps (1925), assumes a one-dimensional transport scheme and steady-state conditions for streamflow, waste discharge, and stream quality. When analyzing water-quality management alternatives for periods of low flow, the assumption of steady-state conditions is generally acceptable (Bauer and others, 1979; McKenzie and others, 1979). Other assumptions of the model formulation include first-order decay kinetics for nitrogen species and $CBOD_5$ and complete mixing of wastewater and tributary inflows at the point they enter the river. Reaction coefficients used in the model are corrected for water temperatures other than 20°C using empirical relationships.

To apply the model, the river is divided into subreaches based on changes in hydraulic parameters such as discharge or channel geometry. In this study, discharge is held constant in each model subreach. The model computes a mass balance for each water-quality constituent at the point each waste or tributary inflow enters the river, then determines the total discharge, and computes concentrations of the water-quality constituents at selected downstream distances to the beginning of the next subreach. Nitrogen species are computed in the model using equations developed by Thomann and others (1971).

To use the model on a specific reach of river, comprehensive hydraulic and water-quality data are needed. The model has been used recently on similar studies of the Yampa River near Steamboat Springs, Colo. (Bauer and others, 1978) and the Chattahoochee River near Atlanta, Ga. (Miller and Jennings, 1978).

During this study the model was used to calculate concentrations of $CBOD_5$, total organic nitrogen, total ammonia, total nitrite, total nitrate, and DO. The model was not used to calculate concentrations of total orthophosphate or total- and fecal-coliform bacteria as done by Goddard (1980). Total orthophosphate was not considered because it is of little concern to water-quality planners in the study area. Coliform bacteria were not considered because of poor model results during the study by Goddard (1980). Model simulations were made using the Central Computer System of the Water and Power Resources Service located at the Denver Federal Center, Lakewood, Colo.

CALIBRATION AND VERIFICATION OF THE MODEL

To apply a general stream water-quality model to a given situation, the model first must be calibrated and then verified. Calibration consists of determining reaction rates so the model computes concentrations of various water-quality constituents that are in acceptable agreement with concentrations observed in the stream. A model is verified by running the calibrated model with one or more independent data sets. If the computed and observed concentrations match with an acceptable degree of accuracy, the model is considered to be verified. Once verified, the model can be used to simulate projected conditions.

Ideally, data to be used for model calibration and verification are collected when conditions are as close as possible to the conditions the model is expected to simulate (Bauer and others, 1979). The model will be used on the Arkansas River to simulate conditions of low flow which occur annually in the fall, between August 15 and October 15, and in the winter, from November 15 to March 15 (fig. 2).

The model calibration and verification results presented in this report are based primarily on data collected during low-flow periods in April 1976 and September 1979.

Data-Collection Program

Data used in model calibration and verification were collected in 1976 and 1979. Data collected in 1976 were tabulated by Goddard (1980) and data collected in 1979 were documented by Cain and Edelmann (1980).

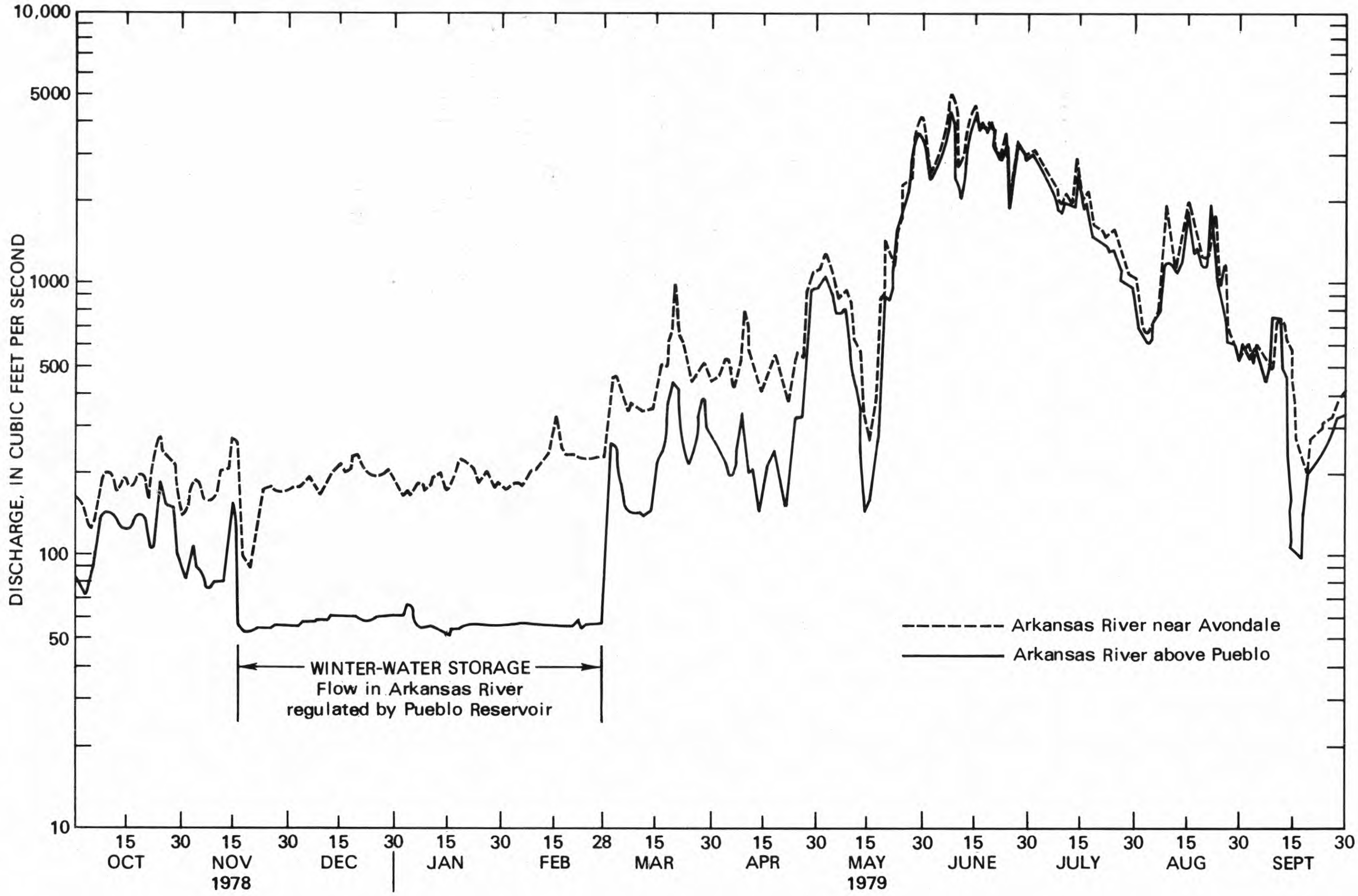

Figure 2. -- Daily mean discharges, Arkansas River above Pueblo, and Arkansas River near Avondale, 1979 water year.

Water-quality and discharge data were collected during two 24-hour periods: data used for model calibration were collected April 1 and 2, 1976, and data used for model verification were collected September 19 and 20, 1979. The river discharge below Pueblo Reservoir was 115 ft^3/s during the 1976 period, and 98 ft^3/s during the 1979 period. As noted earlier, the $Q_{7,10}$ below Pueblo Reservoir is 98 ft^3/s. The river discharge had been constant for 7 days before the 1976 period and for 3 days before the 1979 period. Water samples for analysis were collected at main-stem, drainage-ditch, tributary, and wastewater-discharge sites (table 1 and fig. 3). The frequency of sampling varied, depending on importance of data to the modeling effort and expected variations in concentrations of water-quality constituents. Sampling was conducted during a 24-hour period to obtain approximate diel variations of the constituents analyzed. Field determinations of pH, DO, temperature, and specific conductance were made when each sample was collected. Samples were analyzed for $CBOD_5$, total organic nitrogen, total Kjeldahl nitrogen, total ammonia nitrogen, total nitrite nitrogen, and total nitrate nitrogen. Samples for nitrogen species were chilled to 4°C immediately after collection and were delivered within 24 to 48 hours after collection to the U.S. Geological Survey Water Quality Laboratory in Arvada, Colo., for analysis. Methods used by the U.S. Geological Survey for the analysis of water samples are documented by Skougstad and others (1979). Samples for $CBOD_5$ were chilled immediately after collection and were analyzed for $CBOD_5$ using a procedure that inhibited nitrification (Hines and others, 1977). Discharge measurements were made during the two periods at selected main-stem, drainage-ditch, tributary, and wastewater-discharge sites (table 1). More than one discharge measurement was made at sites where the variation in discharge was expected to be greater than 25 percent. Techniques used by the U.S. Geological Survey for making discharge measurements are documented by Buchanan and Somers (1968; 1969) and Carter and Davidian (1968).

Traveltime data were collected September 17 to 20, 1979, in the critical model reach between sites 20 and 37 (table 1) because it is downstream from the two major wastewater discharges (sites 18 and 19). These data were collected during a low-discharge period to refine mean velocity curves prepared by Goddard (1980), using data collected during a period of higher discharge. Traveltime studies were made by injecting a fluorescent dye, rhodamine WT, into the river at selected sites and collecting samples for analysis of dye at downstream sites. Dye samples were analyzed using procedures described by Wilson (1968).

Measurements of channel geometry were made September 17 to 21, 1979, between sites 20 and 37. Data from the measurements were used to estimate mean depths used in calculation of reaeration coefficients. Channel geometry, measured at 72 sites, included stream width, depth, and cross-sectional area.

Model Inputs

Two types of data were submitted as input to the model for calibration and verification. Hydraulic data were needed to define the physical characteristics and water-quality data were needed to define the chemical characteristics of the study reach. The hydraulic and water-quality data submitted as input to the model for the calibration and verification phases of this study are given in tables 2 and 3.

Hydraulic Data

Discharge, traveltime, and reaeration are the hydraulic parameters needed by the model to define the physical characteristics of the study reach. The discharge for each subreach was computed by taking the discharge at the upstream end of the study reach; adding the inflow from tributaries, drainage ditches, and wastewater effluents; and subtracting the outflow due to diversions. A comparison of model-computed and measured discharges for the April 1976 and September 1979 sampling periods is shown in figure 4.

Traveltime is required by the model because wastes introduced into the river move downstream with the flow. Concomitantly, these wastes are affected by chemical and biological processes that change their concentrations. Traveltime was input to the model for each subreach. Traveltimes between sites 1 and 6 were estimated from the relationship between mean velocities and discharge at discharge-measurement sites (table 1) during the April 1976 and September 1979 sampling periods. Traveltimes between sites 6 and 20 were estimated from the relationship between mean velocities and discharge at discharge-measurement sites (table 1) during the April 1976 and September 1979 sampling periods and from limited traveltime data collected in October 1976 (Goddard, 1980). Traveltimes between sites 20 and 27 and between sites 33 and 37 were determined using mean velocity curves of Goddard (1980) and corrected using traveltime data collected in September 1979. Traveltimes between sites 20 and 27 and 33 and 37 measured in September 1979 were shorter than expected based on the mean velocity curves (table 4). Corrections applied to the mean velocity curves using the percent difference shown in table 4 should give more accurate traveltimes because the September 1979 data were collected at the approximate discharge during the calibration and verification data-collection periods. Traveltimes between sites 27 and 33 were determined using traveltime data collected in September 1979 coupled with an average slope of the mean velocity curves (Goddard, 1980) for the reaches immediately upstream and downstream.

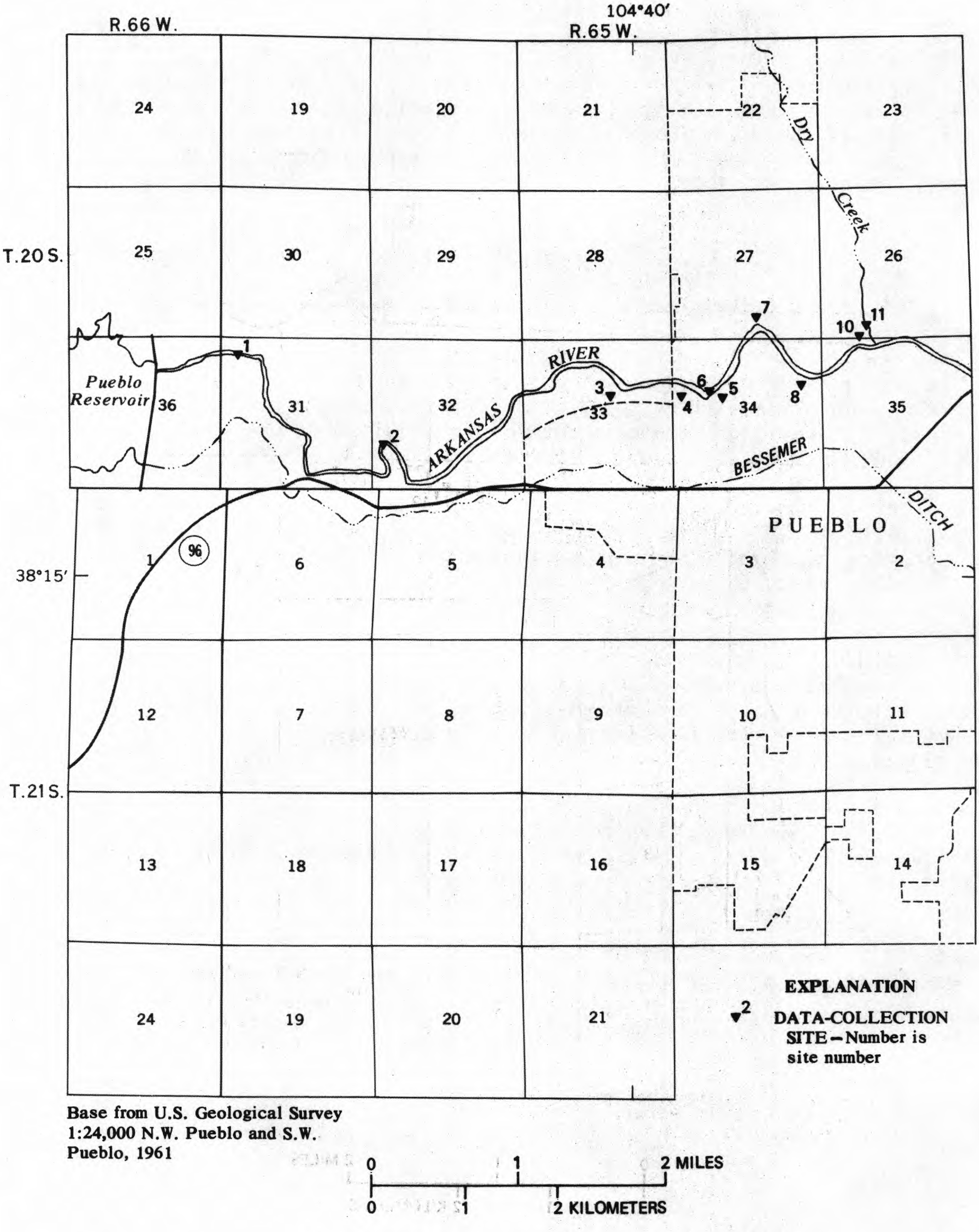

Figure 3. --Location of data-collection sites.

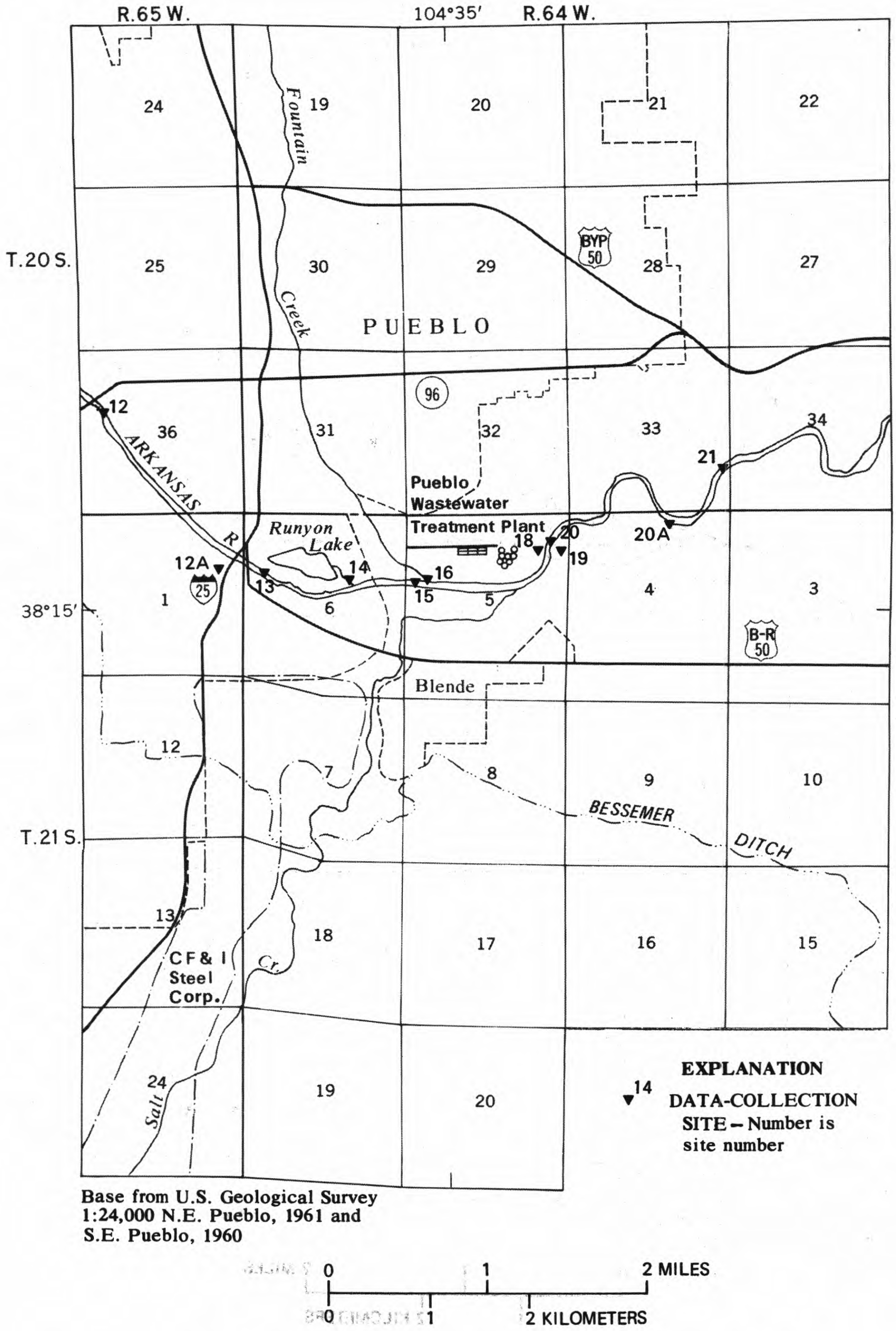

Figure 3. --Location of data-collection sites--Continued.

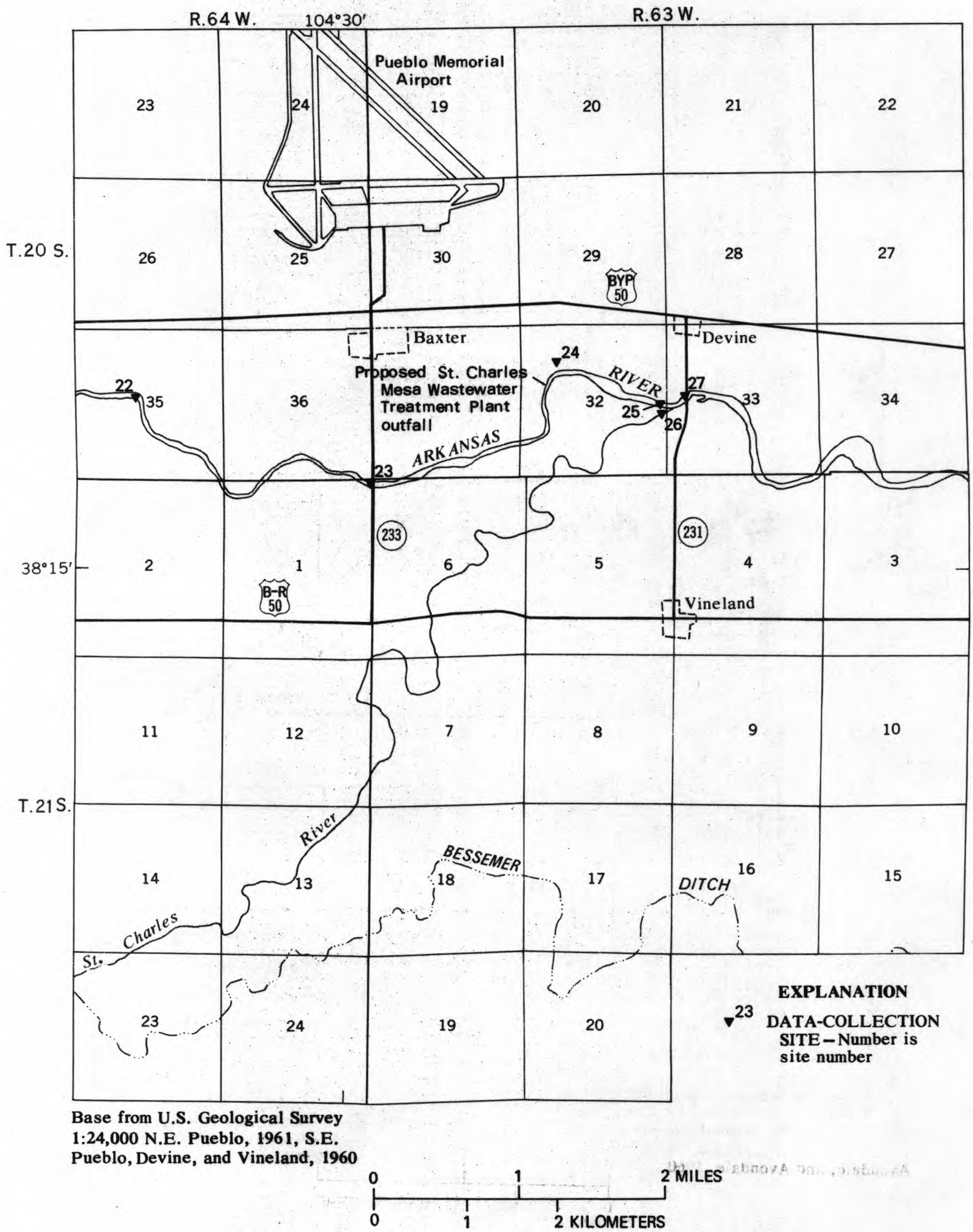

Figure 3. -- Location of data-collection sites -- Continued.

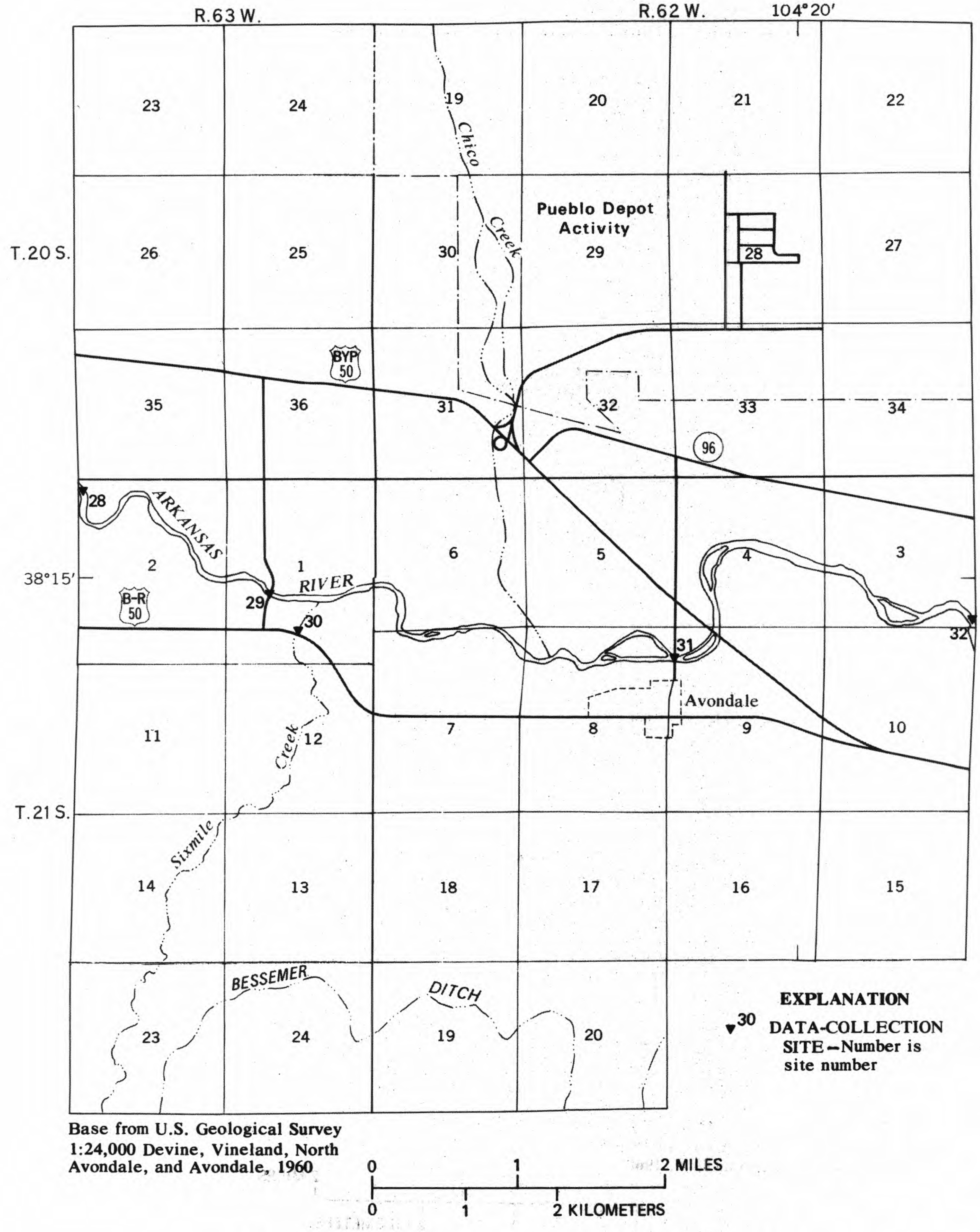

Figure 3.--Location of data-collection sites--Continued.

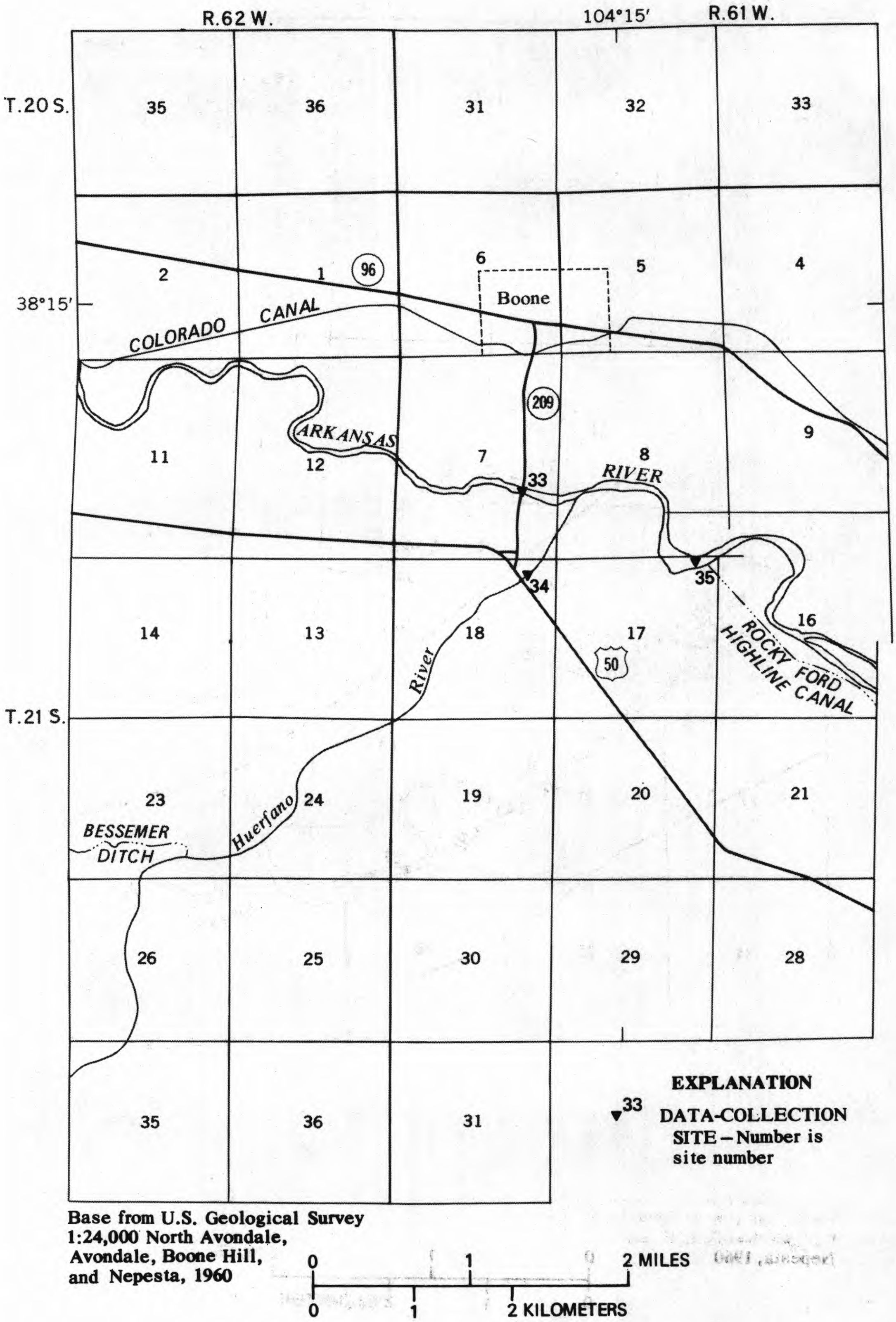

Figure 3.--Location of data-collection sites--Continued.

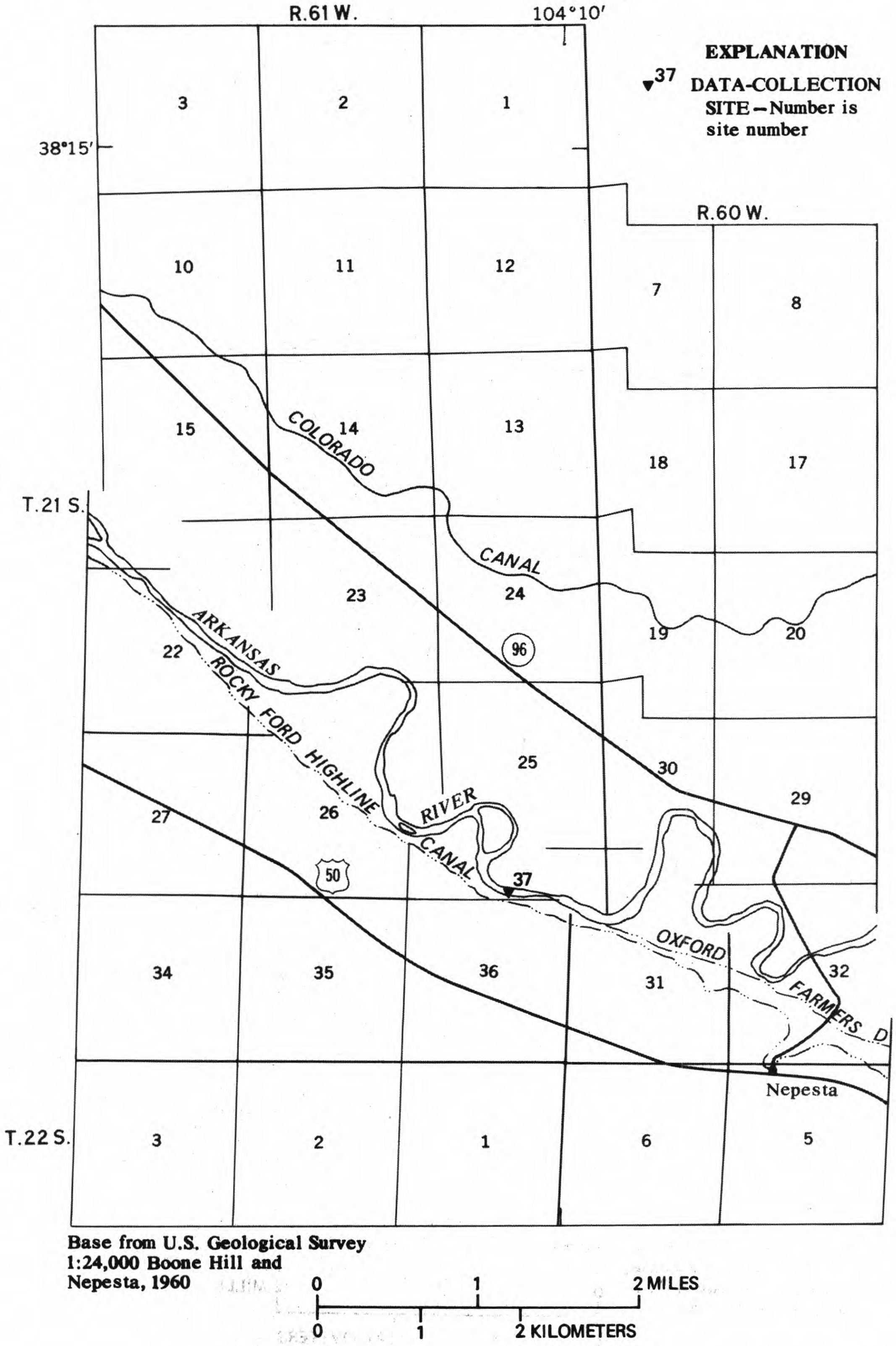

Figure 3.--Location of data-collection sites--Continued.

Table 1.--*Description of data-collection sites, data types, and collection periods*

Site number[1]	Site identifier[2]	Site type[3]	River mile[4]	Name	Data type[5]	Collection period
1	381617104430600	M----	42	Arkansas River above Pueblo	Q,CG,QW	April 1976
	(07099400)				Q,CG,QW	Sept. 1979
2	381544104414400	M----	40.1	Arkansas River near Goodnight	Q,CG,QW	April 1976
3	381604104400500	D----	38	Goodnight drain at mouth, near Pueblo	Q,QW	Oct. 1976
					Q,QW	Sept. 1979
4	381604104394200	D----	37.5	Pueblo Boulevard storm drain at mouth, near Pueblo	Q,QW	Oct. 1976
					Q,QW	Sept. 1979
5	381603104392200	D----	37.3	City Park Drain No. 1 at mouth, near Pueblo	Q,QW	Oct. 1976
					Q,QW	Sept. 1979
6	381602104392600	M----	37.2	Arkansas River near Pueblo	Q,CG,QW	April 1976
	(07099500)				Q,CG,QW	Sept. 1979
7	381623104390500	D----	36.7	North Side Waterworks sluice at mouth, near Pueblo	Q,QW	April 1976
					Q,QW	Sept. 1979
8	381608104383800	D----	36.2	City Park Drain No. 2 at mouth, near Pueblo	Q,QW	Oct. 1976
					Q,QW	Sept. 1979
10	381621104382000	D----	35.9	North Side Waterworks drain at mouth, near Pueblo	Q,QW	April 1976
					Q,QW	Sept. 1979
11	381628104381700	T----	35.7	Dry Creek at mouth, near Pueblo	Q,QW	April 1976
					Q,QW	Sept. 1979
12	381607104372500	M----	34.9	Arkansas River at 4th Street Bridge	Q,CG,QW	April 1976
					Q,CG	Sept. 1979
12A	381515104363100	T----	33.6	I-25 tributary at mouth, at Pueblo	Q,QW	Sept. 1979
13	381607104362200	M----	33.5	Arkansas River at Santa Fe Ave.	Q,CG,QW	April 1976
					QW	Sept. 1979
14	381508104354400	W----	32.8	Southern Colorado Power outfall at mouth, at Pueblo[6]	Q,QW	April 1976
					Q,QW	Sept. 1979
15	381510104350900	M----	32.5	Arkansas River near Colorado Highway 227, near Pueblo	Q,CG,QW	April 1976
					Q,CG,QW	Sept. 1979
16	381515104351900	T----	32.3	Fountain Creek at mouth, near Pueblo	Q,QW	April 1976
					Q,QW	Sept. 1979
18	381522104342100	W----	31.3	Pueblo Wastewater Treatment Plant outfall	Q,QW	April 1976
					Q,QW	Sept. 1979
19	381522104341800	W----	31.2	CF&I Steel Corp. outfall (before February 1980)	Q,QW	April 1976
					Q,QW	Sept. 1979

20	381523104341600	M----	31.2	Arkansas River at CF&I Steel Corp. outfall (before February 1980).	DI-----------	Sept. 1979
20A	381530104333200	W----	30.2	CF&I Steel Corp. outfall (after February 1980)[7]------------	-------------	---------
21	381547104330800	M----	29.8	Arkansas River near 23d Lane, near Pueblo-----------------	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979
22	381601104313000	M----	27.9	Arkansas River at 28th Lane, near Pueblo------------------	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979
23	381530104294600	M----	25.8	Arkansas River at Colorado Highway 233, at Baxter----------	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979
24	381609104282600	W----	24.2	Meadowbrook Wastewater Treatment Plant outfall------------	Q,QW----------	April 1976
					Q,QW----------	Sept. 1979
25	381600104272600	M----	23.3	Arkansas River above St. Charles River, near Vineland------	Q,CG,QW-------	April 1976
					QW------------	Sept. 1979
26	381556104273300	T----	23.2	St. Charles River at mouth, near Vineland-----------------	Q,QW----------	April 1976
					Q,QW----------	Sept. 1979
27	381613104272600	M----	23.1	Arkansas River at Colorado Highway 231--------------------	Q,CG,DC-------	Sept. 1979
28	381532104252100	M----	20.5	Arkansas River at 40th Lane, near Vineland----------------	Q,CG,QW-------	April 1976
					QW,DC---------	Sept. 1979
29	381453104235500 (07109500)	M----	18.5	Arkansas River near Avondale------------------------------	Q,CG,QW-------	April 1976
					Q,CG,QW,DI,DC-	Sept. 1979
30	381440104234200	T----	18.1	Six Mile Creek at mouth, near Avondale--------------------	Q,QW----------	April 1976
					Q,QW----------	Sept. 1979
31	381432104205500	M----	15.3	Arkansas River at Avondale--------------------------------	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979
32	381443104184200	M----	12.4	Arkansas River at Colorado Canal headgate, near Avondale---	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979
33	381401104153700	M----	7.8	Arkansas River at Boone-----------------------------------	Q,CG,DC-------	Sept. 1979
34	07116500	T----	7.4	Huerfano River near Nepesta-------------------------------	Q,QW----------	April 1976
					Q,QW----------	Sept. 1979
35	381338104142400	M----	6.7	Arkansas River at Rocky Ford Highline Canal headgate-------	Q,CG,QW-------	April 1976
					Q,CG,QW,DI,DC-	Sept. 1979
37	381103104102200 (07117000)	M----	0	Arkansas River near Nepesta-------------------------------	Q,CG,QW-------	April 1976
					Q,CG,QW,DC----	Sept. 1979

[1]Site number refers to number on figure 3 and in all tables.

[2]Latitude (first six digits), longitude (next seven digits), and sequence code (last two digits); U.S. Geological Survey station number given in parenthesis for established gaging stations.

[3]M=main stem of Arkansas River; D=drainage ditch or pipe; T=natural tributary; W=wastewater discharge.

[4]River miles upstream from the streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[5]Q=discharge; CG=channel cross sections; QW=water quality; DI=dye injection; DC=dye concentration.

[6]Discharge of cooling water from Southern Colorado Power's electrical-generating facility at Pueblo. Flows through Runyon Lake upstream from site.

[7]Data collected at this site used only for mixing-zone evaluation (March 1980).

Table 2.--*Water-quality data used for model calibration and verification*

[mg/L=milligram per liter]

Site number[1]	River mile[2]	Inflow type[3]	Model run[4]	Number of samples	Carbonaceous biochemical oxygen demand (5-day) (mg/L)	Total organic nitrogen (N) (mg/L)	Total ammonia nitrogen (N) (mg/L)	Total nitrite nitrogen (N) (mg/L)	Total nitrate nitrogen (N) (mg/L)	Dissolved oxygen deficit[5] (mg/L)
1	42.0	I	CAL	9	2.0	0.44	0.06	0.02	0.55	[6]10.0
			VER	4	1.0	.28	.04	.07	.24	[6]7.6
3	38.0	D	CAL	2	5.0	1.4	.04	.04	12	-.8
			VER	2	.8	1.1	.13	.13	1.7	1.5
4	37.5	D	CAL	2	5.0	.7	.02	.02	19	-.8
			VER	2	1.4	1.4	.06	.11	1.9	.1
5	37.3	D	CAL	2	.4	.26	.00	.01	4.4	-1.4
			VER	2	.8	.71	.06	.04	4.9	.4
7	36.7	D	CAL	[7]0	2.8	.44	.04	.01	.53	-1.5
			VER	2	1.5	.41	.03	.04	.19	.4
8	36.2	D	CAL	2	1.1	.22	.02	.02	.88	-1.2
			VER	2	1.0	.34	.27	.11	1.8	.7
10	35.9	D	CAL	3	.7	1.6	.47	.01	.60	0
			VER	2	1.0	.40	.18	.06	.15	1.1
11	35.7	T	CAL	3	1.2	.83	.03	.03	11	-.6
			VER	2	1.6	.53	.09	.53	3.7	.4
[8]12A	33.6	T	CAL	0	-----	----	-----	----	-----	-----
			VER	2	.7	.68	.11	.04	9.3	.2
14	32.8	W	CAL	3	2.0	.50	.04	.01	.74	-.2
			VER	4	1.5	.92	.06	.06	.36	-1.0
16	32.3	T	CAL	5	1.8	.72	.05	.03	2.5	-1.7
			VER	6	1.3	1.0	.05	.08	4.2	.4
18	31.3	W	CAL	9	89	9.3	15	.01	.02	2.2
			VER	12	47	3.9	19	.20	.05	1.0
19	31.2	W	CAL	4	9.9	1.0	3.4	.28	.68	.4
			VER	12	2.3	.45	.38	.23	1.0	1.3
24	24.2	W	CAL	5	30	4.3	9.2	.66	.97	.8
			VER	5	10	1.0	.40	.25	12	.6
26	23.2	T	CAL	5	2.2	1.1	.03	.02	.65	-.4
			VER	6	1.6	.72	.12	.20	11	-.3
30	18.1	T	CAL	3	1.1	.82	.03	.04	7.2	.9
			VER	4	1.2	.12	.05	.05	3.9	-.2
34	7.4	T	CAL	3	1.1	.54	.03	.00	.08	.5
			VER	0	0	0	0	0	0	0

[1]Refer to table 1 and figure 3.

[2]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]I=initial Arkansas River; D=drainage ditch or pipe; T=natural tributary; and W=wastewater effluent.

[4]CAL=calibration-model run; VER=verification-model run.

[5]Dissolved oxygen deficit is defined as the difference between observed and saturation.

[6]Dissolved oxygen concentration is input to model at initial Arkansas River site.

[7]Water-quality data estimated from Arkansas River samples.

[8]No information available on water quality at this site during 1976.

Reaeration, the process by which a stream absorbs oxygen from the atmosphere, is characterized by the reaeration rate, K_2. Reaeration rates are necessary to calculate DO concentrations which are critical to many biochemical reactions. Goddard (1980) used reaeration rates calculated from an equation of Bennett and Rathbun (1972). The model has recently been changed to allow reaeration rates based on other equations. The reaeration rates used in this study are calculated from an equation developed by Padden and Gloyna (1971):

$$K_2=2.98(\bar{U}/H^{1.5})^{0.703}, \tag{1}$$

where:

K_2 = reaeration rate, base 10 units, 20°C, in days^{-1};
$\bar{U}$ = mean reach velocity, in feet per second; and
H = mean reach stream depth, in feet.

This is one of two equations recommended by Goddard (1980) as being most applicable to the Arkansas River. This equation was preferable to the Langbein and Durum equation (1967) because of a better fit of calculated to observed DO concentrations during model calibration. Mean velocities used in the equation were the same as those used for determining traveltimes. Mean depths used in the equation between sites 1 and 20 were estimated from mean depths at discharge-measurement sites during the April 1976 and September 1979 sampling periods (table 1). Mean depths between sites 20 and 37 were estimated from the channel-geometry measurements made in September 1979.

Water-Quality Data

Water-quality data required by the model are water temperature and concentrations of DO, $CBOD_5$, and nitrogen species. Water temperature is used to determine DO-saturation values and to make adjustments to reaction rates. The concentrations of DO, $CBOD_5$, and total nitrogen species are required at the upstream end of the study reach, at each inflow, and at selected sites on the main stem of the Arkansas River. The values input to the model are simple averages for inflows with approximately constant discharge and weighted averages for inflows with discharge that varied appreciably during the data-collection period. Data from main-stem sites are used during calibration and verification in comparing model-computed and observed concentrations.

Table 3.--*Hydraulic data used for model calibration and verification*

Model sub-reach	River mile at upstream end of subreach[1]	River mile at down-stream end of subreach[1]	Model run[2]	Discharge change at beginning of subreach (cubic feet per second)	Mean temperature of subreach (degrees Celsius)	Reaeration rate in subreach (days^{-1})[3]	Traveltime in subreach (hours)
1	42.0	41.0	CAL	115	7.0	6.0	1.0
			VER	98	19.5	8.2	1.1
2	41.0	39.8	CAL	-10	8.0	6.1	1.3
			VER	-10.7	19.5	7.7	1.5
3	39.8	38.0	CAL	-29	9.0	6.5	2.4
			VER	-46	19.5	9.1	3.8
4	38.0	37.5	CAL	.1	9.0	6.5	.7
			VER	.2	20.0	9.2	1.0
5	37.5	37.4	CAL	.5	9.0	6.5	.1
			VER	.7	20.0	9.2	.2
6	37.4	37.3	CAL	-18	10.0	6.6	.2
			VER	0	20.0	9.2	.2
7	37.3	36.7	CAL	.6	10.0	6.6	1.0
			VER	1.0	20.0	7.8	1.3
8	36.7	36.2	CAL	10	10.0	6.2	.7
			VER	1.2	20.0	8.5	.9
9	36.2	35.9	CAL	1.0	10.0	6.2	.4
			VER	.7	20.0	8.5	.6
10	35.9	35.7	CAL	1.8	10.0	6.2	.3
			VER	.8	20.0	8.5	.4
11	35.7	34.7	CAL	.1	11.0	6.4	1.5
			VER	.1	19.5	8.5	1.8
12	34.7	33.6	CAL	-40	12.0	8.4	2.7
			VER	-21	19.5	11.0	3.2

13	33.6	32.8	CAL	0	12.0	8.4	2.0
			VER	1.3	19.5	11.0	2.4
14	32.8	32.3	CAL	39	13.0	6.6	.7
			VER	20	20.5	8.6	.9
15	32.3	31.3	CAL	6.5	14.0	7.2	1.3
			VER	14.3	20.5	8.1	1.6
16	31.3	31.2	CAL	24.7	15.0	9.3	.1
			VER	21.2	20.5	9.4	.1
17	31.2	30.2	CAL	103	15.0	7.7	.8
			VER	102	22.0	8.0	.9
18	30.2	29.0	CAL	0	15.0	7.7	1.0
			VER	0	21.5	10.2	1.1
19	29.0	27.0	CAL	0	15.0	8.5	1.9
			VER	0	21.0	9.7	1.9
20	27.0	24.3	CAL	0	15.0	8.6	2.7
			VER	0	22.5	10.2	2.8
21	24.3	24.2	CAL	0	15.0	8.1	.1
			VER	0	22.5	9.5	.1
22	24.2	23.2	CAL	.4	15.0	8.6	.9
			VER	.1	22.0	10.0	1.0
23	23.2	18.1	CAL	4.8	16.0	8.6	3.7
			VER	7.4	22.0	9.8	3.8
24	18.1	12.4	CAL	2.9	16.0	11.0	4.2
			VER	6.7	21.5	12.5	4.3
25	12.4	7.4	CAL	0	16.0	13.9	3.6
			VER	0	20.5	15.3	3.6
26	7.4	6.7	CAL	.9	16.0	11.7	1.0
			VER	0	20.0	13.0	1.1
27	6.7	.0	CAL	-110	16.0	14.9	6.3
			VER	-89	20.0	16.5	6.4

[1]River mile upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.
[2]CAL=calibration-model run; VER=verification-model run.
[3]The mean temperature of subreach, in degrees Celsius, used in calculating reaeration rate.

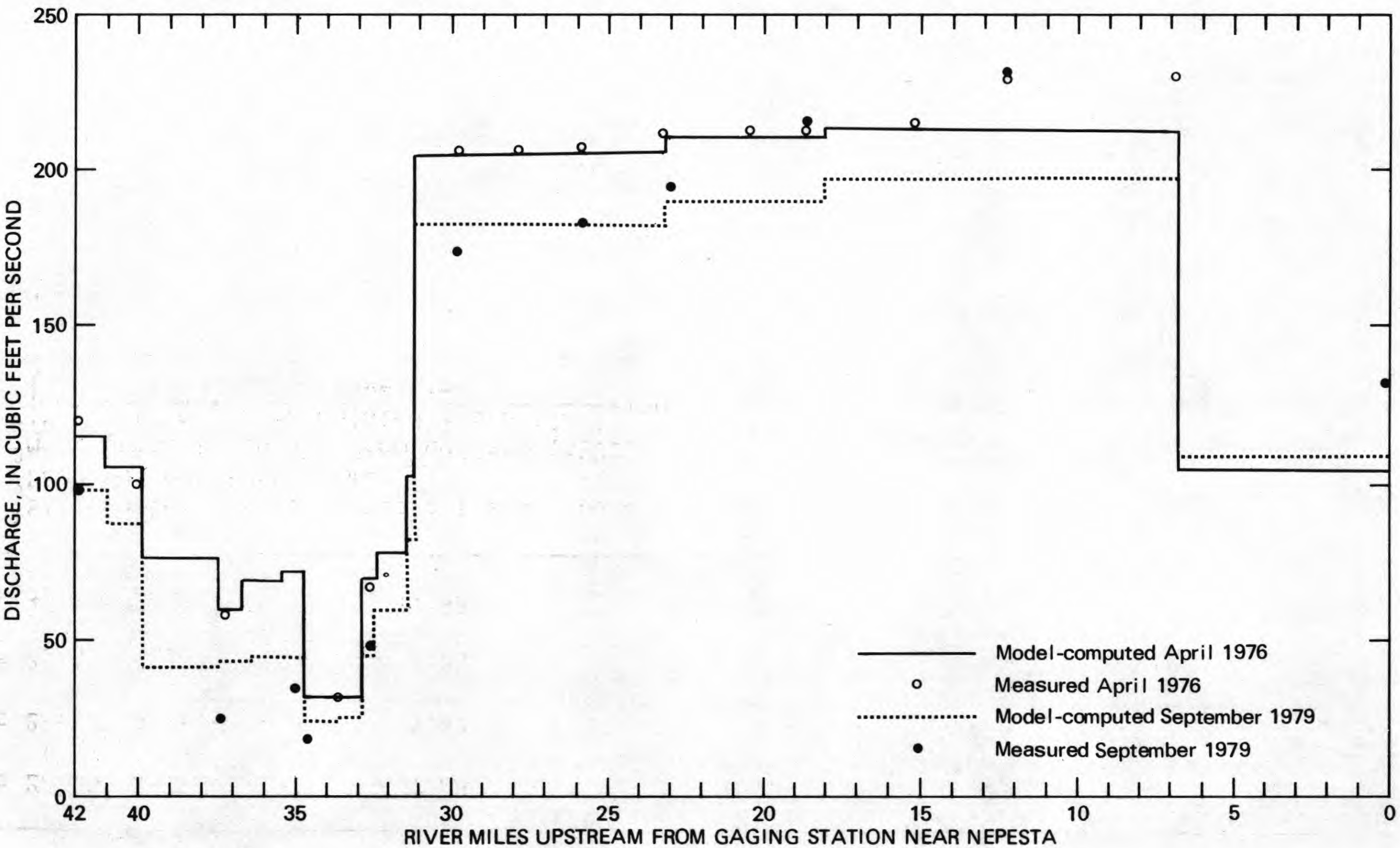

Figure 4.--Model-computed and measured discharges, April 1976 and September 1979.

Table 4.--*Comparison between traveltimes calculated from mean-velocity curves and measured during September 1979*

River reach[1]	Traveltime measured during September 1979, in hours[2]	Traveltime calculated from mean-velocity curves, in hours[3]	Percent difference[4]
Sites 20 to 21--------	1.08	1.11	2.7
Sites 21 to 23--------	3.42	3.96	13.6
Sites 23 to 27--------	2.25	2.62	14.1
Sites 33 to 37--------	7.88	9.42	16.3

[1]Site number refers to table 1 and figure 3.
[2]Peak to peak traveltime.
[3]Mean-velocity curves from Goddard (1980).
[4]$\left(\frac{\text{Measured minus calculated traveltime}}{\text{calculated traveltime}}\right) \times 100.$

Calibration Results

Model calibration consisted of determining the following first-order reaction rates: Decay rates for $CBOD_5$, total organic nitrogen, total ammonia nitrogen, total nitrite nitrogen, and total nitrate nitrogen; and forward-reaction rates for total organic nitrogen, total ammonia nitrogen, and total nitrite nitrogen. A procedure of fitting model-computed concentration curves to observed concentrations was used to determine the reaction rates. Details of the procedure are described by Bauer and others (1979). The reaction rates were determined using water-quality and discharge data collected during a 24-hour period on April 1 and 2, 1976. Data collected in October 1976 were used at inflow sites 3, 4, 5, and 8 because no data were collected at these sites in April 1976. The quantity and quality of inflow at these sites were assumed to be approximately the same in April as in October because the flows result primarily from ground-water discharge.

The following criteria for an acceptable calibration was used. First, trends of observed and model-computed concentrations should be similar. Second, the average percent difference between the mean of the observed values and the model-computed values should be less than 20 percent in the critical model reach downstream from the outfall of the Pueblo WWTP (river mile 31.3).

An acceptable calibration of $CBOD_5$ was achieved (fig. 5 and table 5) even though data-collection problems resulted in a lack of observed $CBOD_5$ concentrations between river miles 24 and 31. The reaction rate used (table 6) was higher than the value of 1.0 $days^{-1}$ at 20°C determined by Goddard (1980). The higher rate is due primarily to a refinement in traveltimes used by the model. The large increase in $CBOD_5$ at river mile 31.3 is caused by the input of $CBOD_5$ at the Pueblo WWTP. The decrease in $CBOD_5$ at river mile 31.2 results from dilution by the effluent from the CF&I Steel Corp.

The calibration of nitrogen species is a complex process involving determination of two rates for each nitrogen species except total nitrate. The forward-reaction rates describe the process of sequential reaction of nitrogen species called nitrification. In the sequence of nitrification, organic nitrogen is converted to form ammonia which oxidizes to form nitrite and then nitrate. Nitrification is generally the most significant process of the nitrogen cycle in a river but other reactions may occur. These include utilization of ammonia and nitrate by algae and attached plants (Kittrell, 1969) and escape to the atmosphere of nonionized ammonia as a gas (Willingham, 1976). The decay rates describe the total rate of change of each nitrogen species and include changes caused by nitrification and by other reactions. The decay rate is equal to the forward-reaction rate when other reactions are not occurring. If direct removal of a nitrogen species is occurring by processes such as utilization by plants, the decay rate is greater than the forward-reaction rate. This situation is recognized during model calibration by a downstream decrease in total nitrogen. During the model calibration described by Goddard (1980), only a decay rate was used for each nitrogen species, resulting in a poor calibration for some nitrogen species.

Model-calibration results were acceptable for all nitrogen species except total organic nitrogen (figs. 6-9 and table 5). The difference between model-computed and observed concentrations of total organic nitrogen may have resulted from inaccuracies in analyzing this constituent in the effluent from the Pueblo WWTP, as suggested by Goddard (1980). Another possible reason the model-computed concentrations were greater than the observed concentrations is that much of the organic nitrogen from the Pueblo WWTP is suspended and settles out in the river upstream from site 21.

The calibration for total ammonia was achieved by using a forward-reaction rate smaller than the decay rate in most of the study reach (table 6), resulting in a model-computed removal of ammonia from the river system. It was necessary to remove ammonia to obtain an acceptable calibration of total nitrate. The removal is caused primarily by attached plants rather than from loss of ammonia gas to the atmosphere because the average percentage of nonionized ammonia in the study reach is small (see section on Nonionized Ammonia). Because of smaller populations of attached plants in the downstream end of the study reach (Goddard, 1980), a decreased rate of ammonia removal is expected and decay rates and forward-reaction rates were set equal.

Nitrite is a relatively unstable nitrogen species in the nitrification-reaction sequence between ammonia and nitrate. The large reaction rates (7.5 $days^{-1}$ at 20°C) used in the calibration (table 6) reflect this instability. The forward-reaction rate and decay rate for total nitrite were set equal, indicating that all nitrite reacts to nitrate and is not removed in the river system.

Only a decay rate is used by the model to characterize the behavior of total nitrate. Nitrate, like ammonia, can be utilized by plants (Kittrell, 1969). Because of smaller populations of attached plants in the downstream end of the study reach, decreased removal of nitrate is expected, and decay rates were decreased (table 6).

Dissolved-oxygen concentrations are calculated by the model by balancing the rate at which DO is consumed with the rate at which it is replenished. Oxidation of organic matter and nitrification consume oxygen. During the nitrification process, 4.57 grams of DO are consumed for each gram of nitrogen which is oxidized from ammonia to nitrate (Thomann and others, 1971). Changes in the decay rate for $CBOD_5$ or forward-reaction rates for total ammonia and total nitrite will change the model-computed DO concentrations. Dissolved oxygen is replenished by reaeration at the stream surface. Reaeration rates were calculated during this study using an equation developed by Padden and Gloyna (1971). Other reactions which may affect DO but which were not considered during this study are: (1) production of DO by plants through photosynthesis, (2) consumption of DO by plants through respiration, and (3) streambed oxygen demand. These factors were not considered during the study because of constraints on time and personnel. A comparison of model-computed and observed DO concentrations (fig. 10 and table 5) shows close agreement, indicating an acceptable model calibration. The acceptable calibration suggests the reactions not considered by the model when computing DO concentrations had little net effect on observed concentrations during the April 1976 data-collection period.

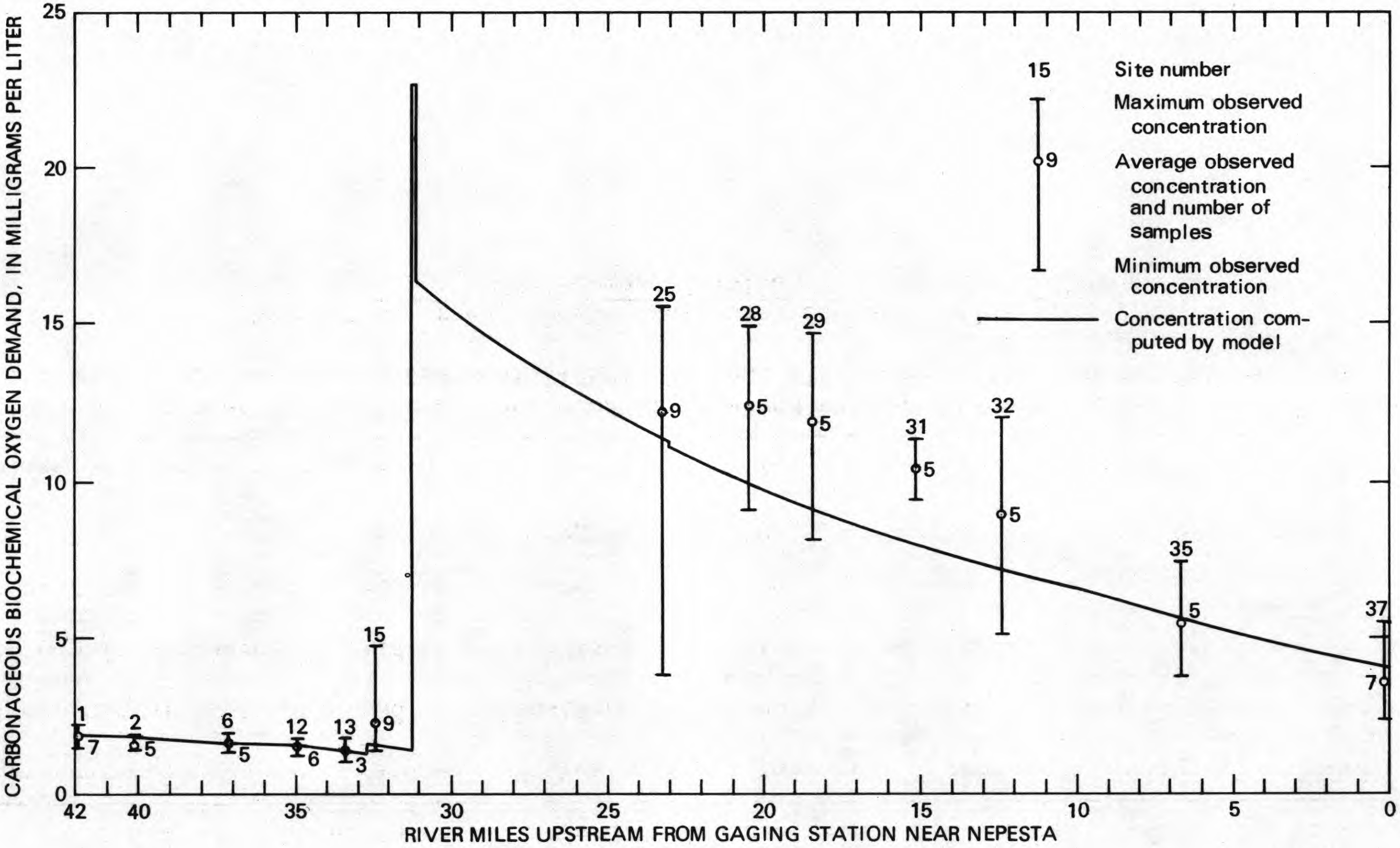

Figure 5.--Model-computed and observed concentrations of carbonaceous biochemical oxygen demand (5-day), April 1976.

Table 5.--*Calibration and verification results*

Water-quality constituent	Calibration			Verification		
	Percent difference[1]	Similar trend	Calibration acceptable	Percent difference[1]	Similar trend	Verification acceptable
$CBOD_5$	+15	Yes	Yes	-17	Yes	Yes
Total organic nitrogen	-38	Questionable	No	-34	Questionable	No
Total ammonia nitrogen	-18	Yes	Yes	+2.3	Yes	Yes
Total nitrite nitrogen	-19	Yes	Yes	+57	Yes	No
Total nitrate nitrogen	+6.4	Yes	Yes	+.2	Yes	Yes
Dissolved oxygen	+3.9	Yes	Yes	-20	Yes	Yes

[1]Average percent difference between mean of observed values and model-computed values downstream from Pueblo Wastewater Treatment Plant. Percent difference calculated as follows:

$$\left(\frac{\text{Mean of observed values minus model-computed value}}{\text{Model-computed value}}\right)\times 100$$

Table 6.--*Reaction rates determined during model calibration*

[All reaction rates expressed at 20° Celsius, in units of $days^{-1}$]

Model subreach	River mile at the upstream end of subreach[1]	River mile at the downstream end of subreach	Carbonaceous biochemical-oxygen demand (5-day) decay rate	Total organic nitrogen forward reaction rate	Total organic nitrogen decay rate	Total ammonia nitrogen forward reaction rate	Total ammonia nitrogen decay rate	Total nitrite nitrogen forward reaction rate	Total nitrite nitrogen decay rate	Total nitrate nitrogen decay rate
1	42.0	41.0	1.5	0.2	0.2	2.0	2.5	7.5	7.5	1.7
2	41.0	39.8	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
3	39.8	38.0	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
4	38.0	37.5	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
5	37.5	37.4	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
6	37.4	37.3	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
7	37.3	36.7	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
8	36.7	36.2	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
9	36.2	35.9	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
10	35.9	35.7	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
11	35.7	34.7	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
12	34.7	33.6	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
13	33.6	32.8	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
14	32.8	32.3	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
15	32.3	31.3	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
16	31.3	31.2	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
17	31.2	30.2	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
18	30.2	29.0	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
19	29.0	27.0	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
20	27.0	24.3	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
21	24.3	24.2	1.5	.2	.2	2.0	2.5	7.5	7.5	1.7
22	24.2	23.2	1.5	.2	.2	2.0	2.5	7.5	7.5	1.2
23	23.2	18.1	1.5	.2	.2	2.2	2.5	7.5	7.5	.8
24	18.1	12.4	1.5	.2	.2	2.5	2.5	7.5	7.5	.4
25	12.4	7.4	1.5	.2	.2	2.5	2.5	7.5	7.5	.4
26	7.4	6.7	1.5	.2	.2	2.5	2.5	7.5	7.5	.4
27	6.7	.0	1.5	.2	.2	2.5	2.5	7.5	7.5	.4

[1]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

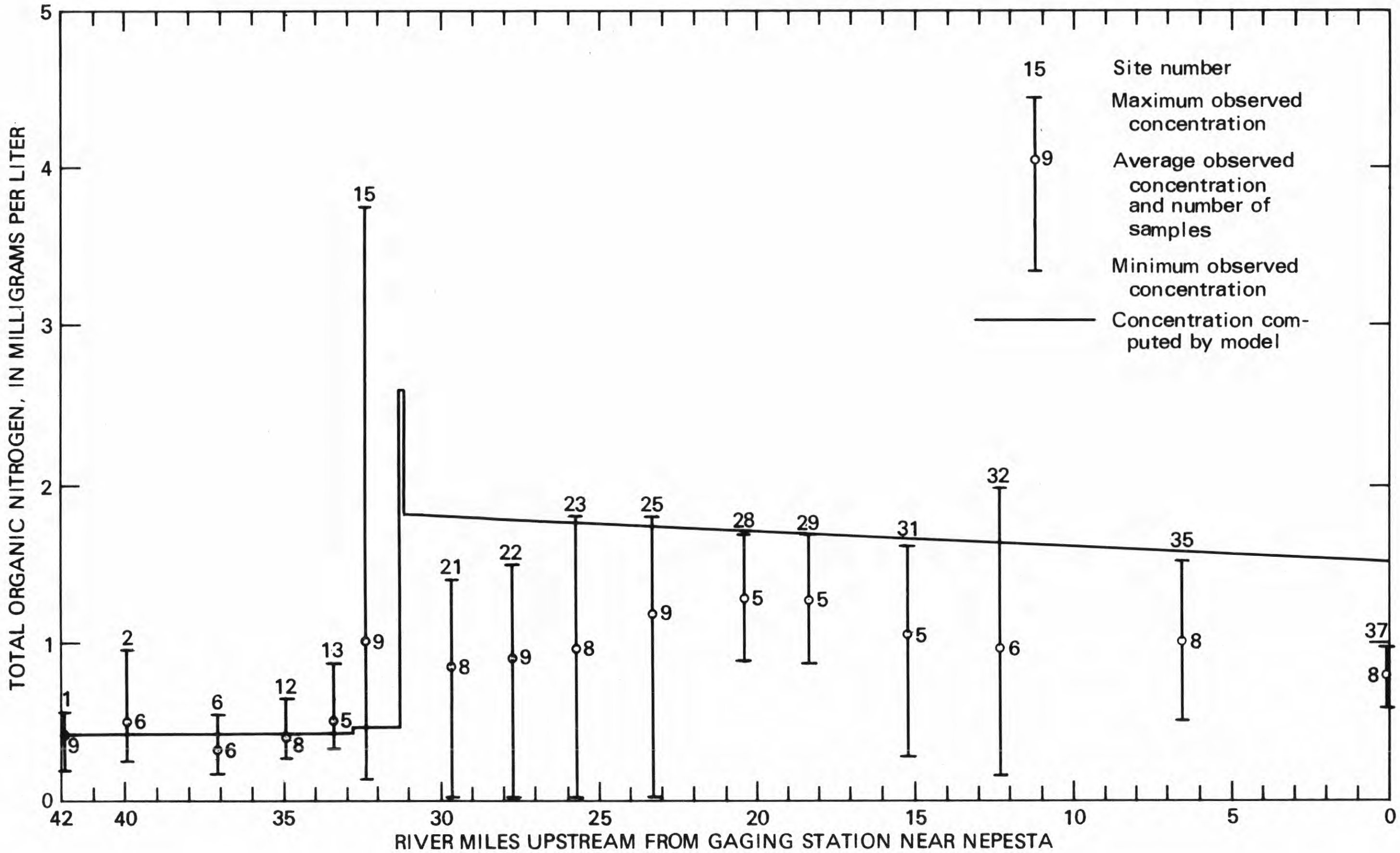

Figure 6.--Model-computed and observed concentrations of total organic nitrogen, April 1976.

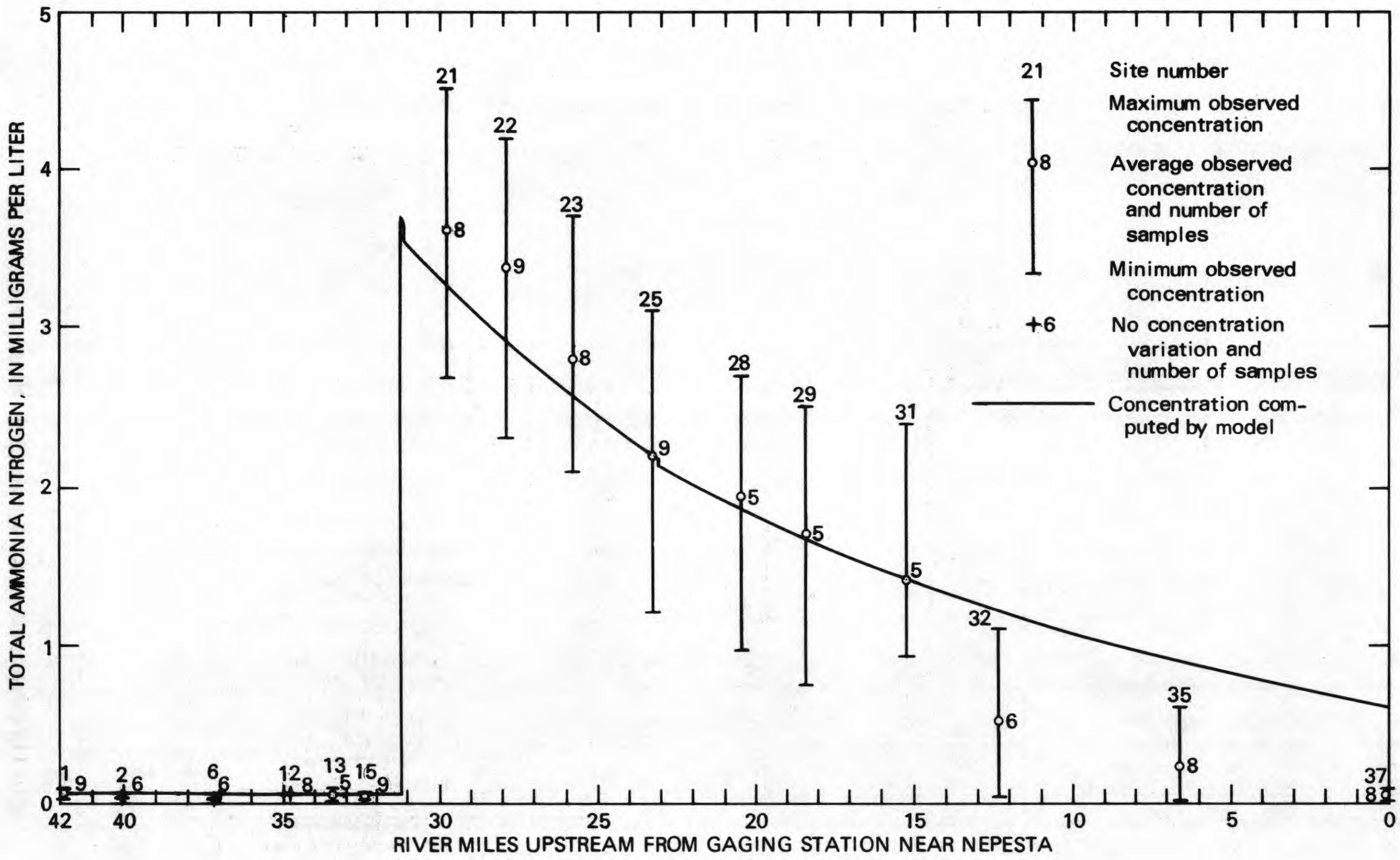

Figure 7.--Model-computed and observed concentrations of total ammonia nitrogen, April 1976.

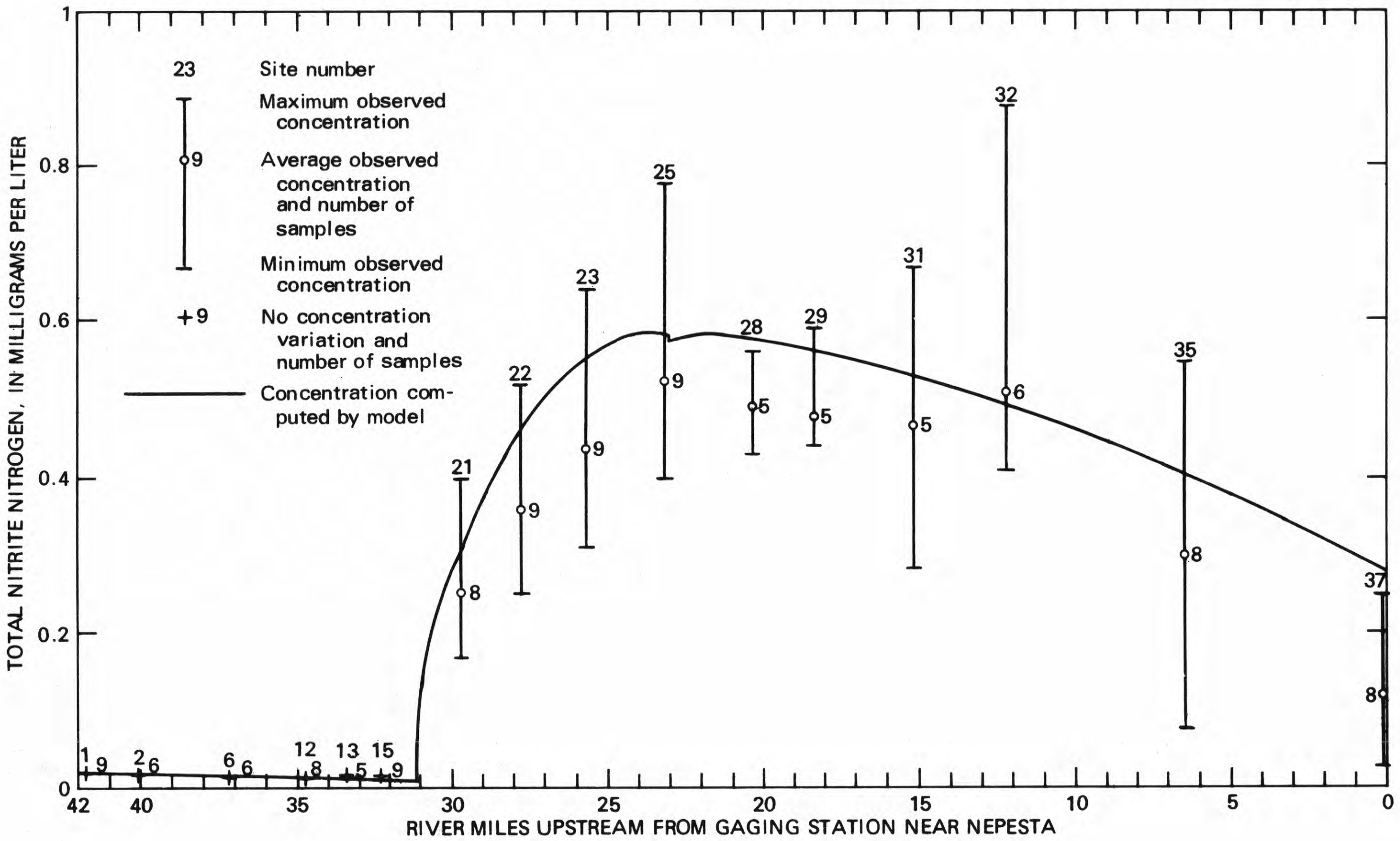

Figure 8.--Model-computed and observed concentrations of total nitrite nitrogen, April 1976.

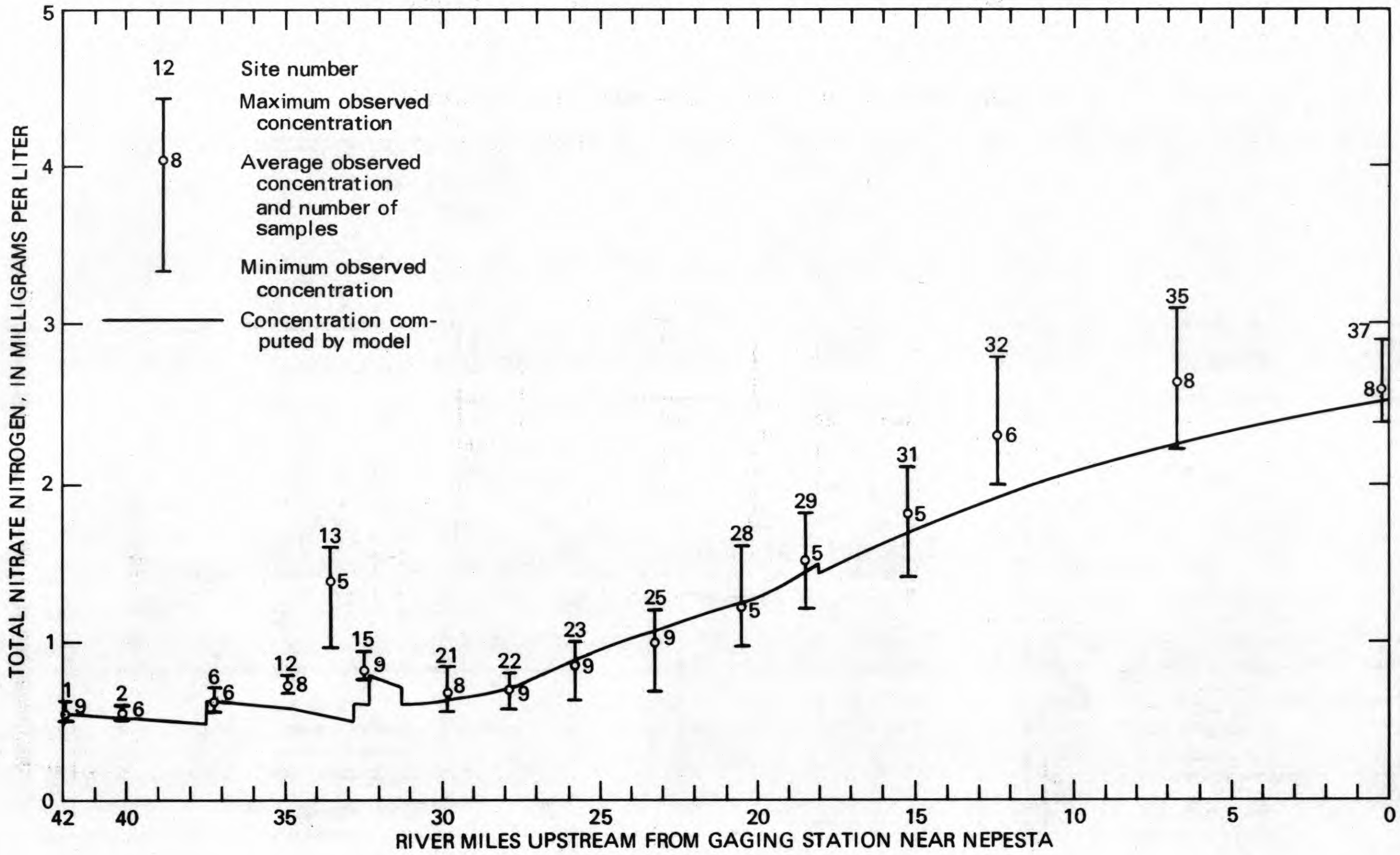

Figure 9.--Model-computed and observed concentrations of total nitrate nitrogen, April 1976.

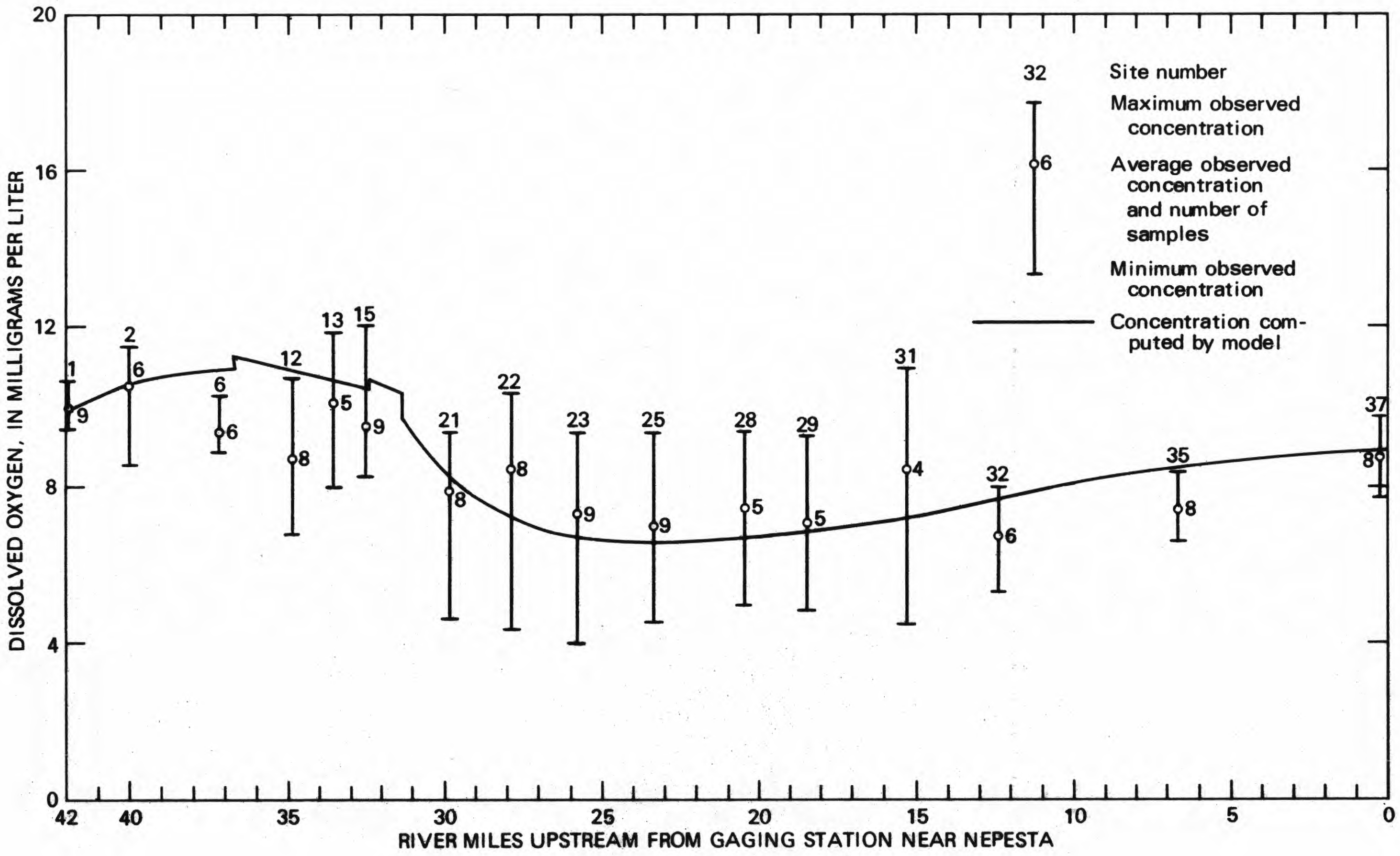

Figure 10.--Model-computed and observed concentrations of dissolved oxygen, April 1976.

Verification Results

Before a calibrated water-quality model can be confidently used to simulate projected conditions it must be verified. Verification consists of rerunning the calibrated model with one or more independent data sets. If model-computed concentrations match observed concentrations with a reasonable degree of accuracy, the model can be used to simulate projected conditions with a reasonable degree of confidence.

The model verification during this study was made using water-quality and discharge data collected during a 24-hour period on September 19 and 20, 1979. The river discharge and temperature during this period were very similar to the conditions expected during many of the model simulations described later in this report. This similarity suggests that river conditions, such as amount of bottom deposits and plant populations, also may be similar. This similarity should insure that the model is applicable to the simulation conitions (Bauer and others, 1979). A data set collected in October 1976 (Goddard, 1980) was not used during this study because river conditions differed from the conditions the model was expected to simulate. Upstream river discharge was four to eight times the discharge of most of the model simulations.

The results of the model verification are shown in figures 11 to 16 and in table 5. The criteria used for an acceptable verification are the same as for an acceptable calibration. An acceptable verification was achieved for $CBOD_5$, total ammonia, total nitrate, and DO.

Some differences between model-computed and observed concentrations of $CBOD_5$ and total nitrate occur upstream from river mile 33. The higher observed concentrations may result from nonpoint or unsampled sources of these two parameters. Because river discharge was low in this reach during the sampling period (fig. 4), small discharges of water with high concentrations of $CBOD_5$ and total nitrate could cause the higher observed concentrations in the river.

The verification for total organic nitrogen was not acceptable. The verification results were similar to the calibration results in that model-computed values were generally greater than observed values.

An acceptable verification of total nitrite was not achieved. Model-computed concentrations were generally 0.05 to 0.20 mg/L (milligrams per liter) lower than the mean of observed values downstream from the outfall of the Pueblo WWTP. The observed and model-computed values show a similar trend of decay. There are at least two possible reasons for the difference between observed and model-computed concentrations. Because nitrogen species, especially nitrite, are relatively unstable, changes in concentration may occur between sample collection and analysis. Another possible cause of the difference could be that the empirical relationship used by the model to adjust reaction rates may need adjustment for different temperatures. Model simulations presented later in this report use values for total nitrite. These values are included to provide some simulation capability for total nitrite and because they are considered to be the best presently (1980) available. However, these values should be used with some caution considering their apparent uncertainty.

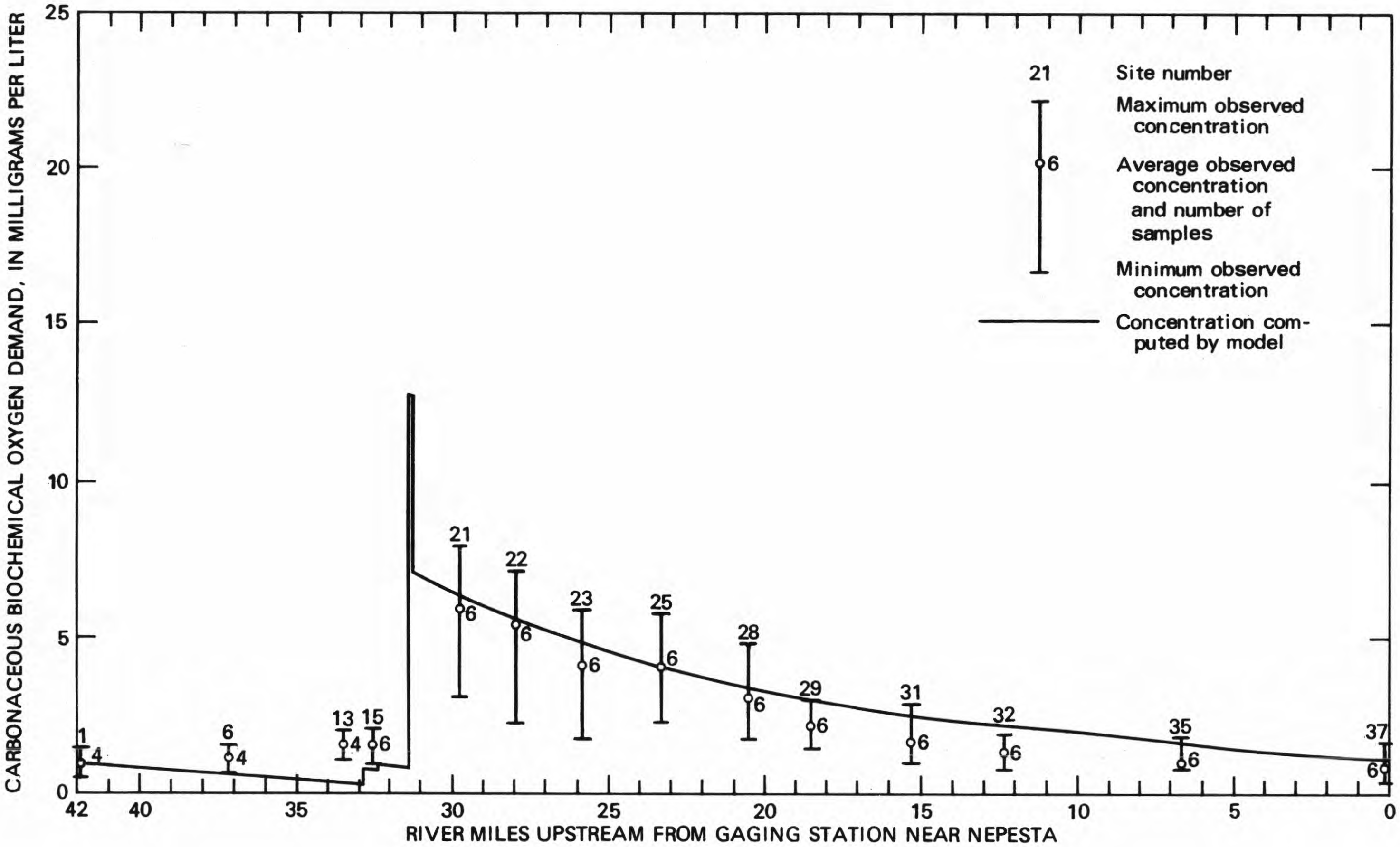

Figure 11.--Model-computed and observed concentrations of carbonaceous biochemical oxygen demand (5-day), September 1979.

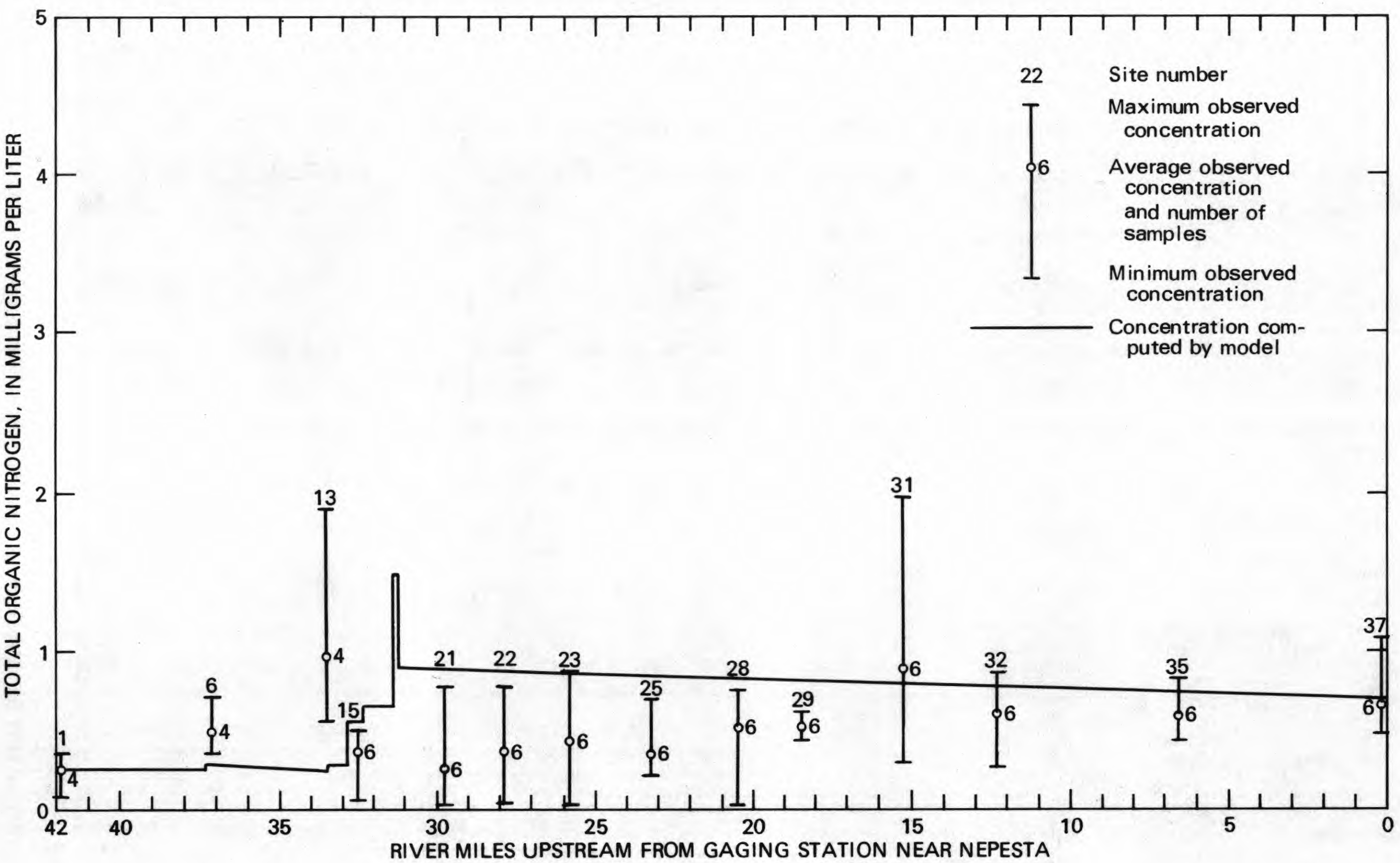

Figure 12.--Model-computed and observed concentrations of total organic nitrogen, September 1979.

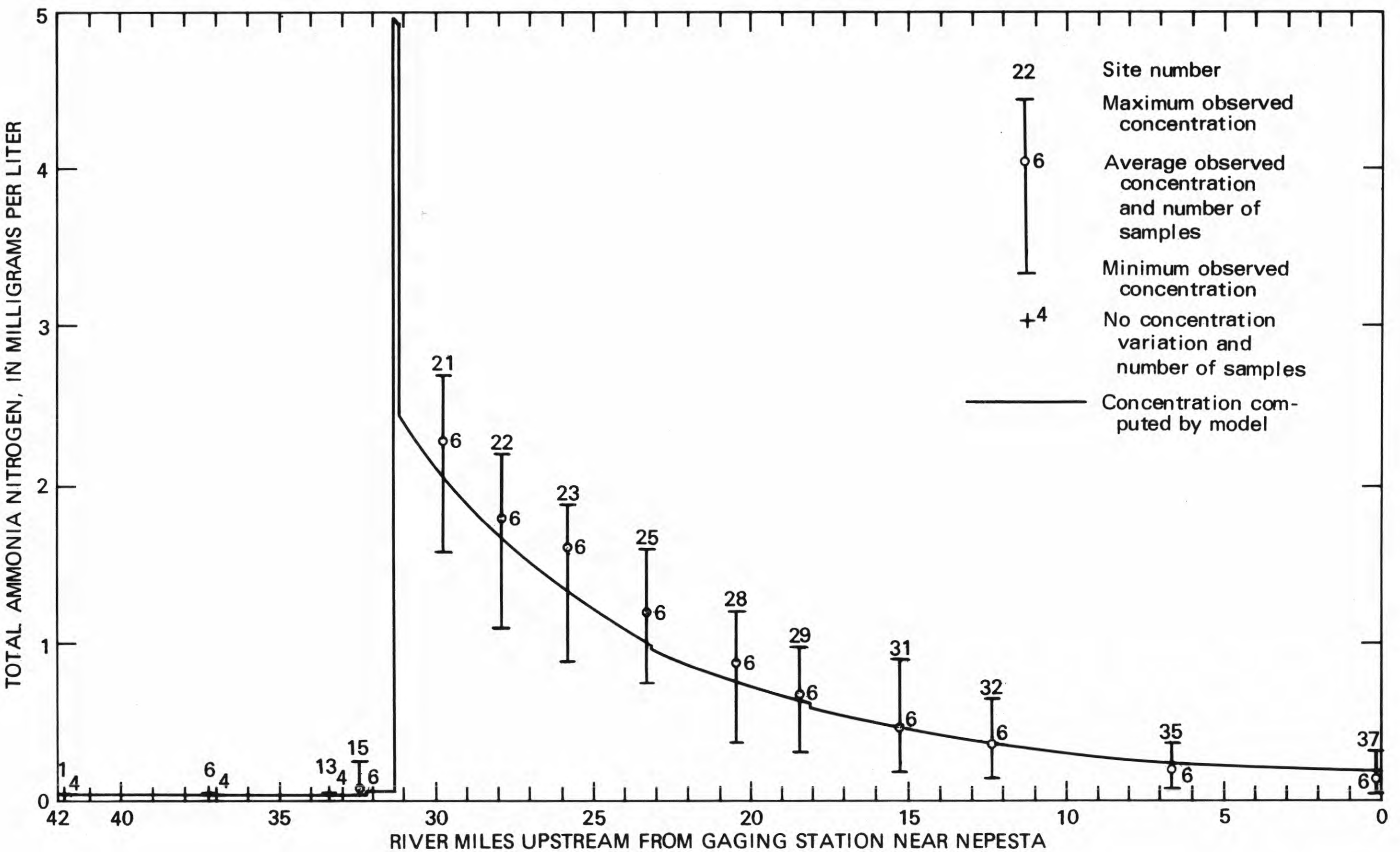

Figure 13.--Model-computed and observed concentrations of total ammonia nitrogen, September 1979.

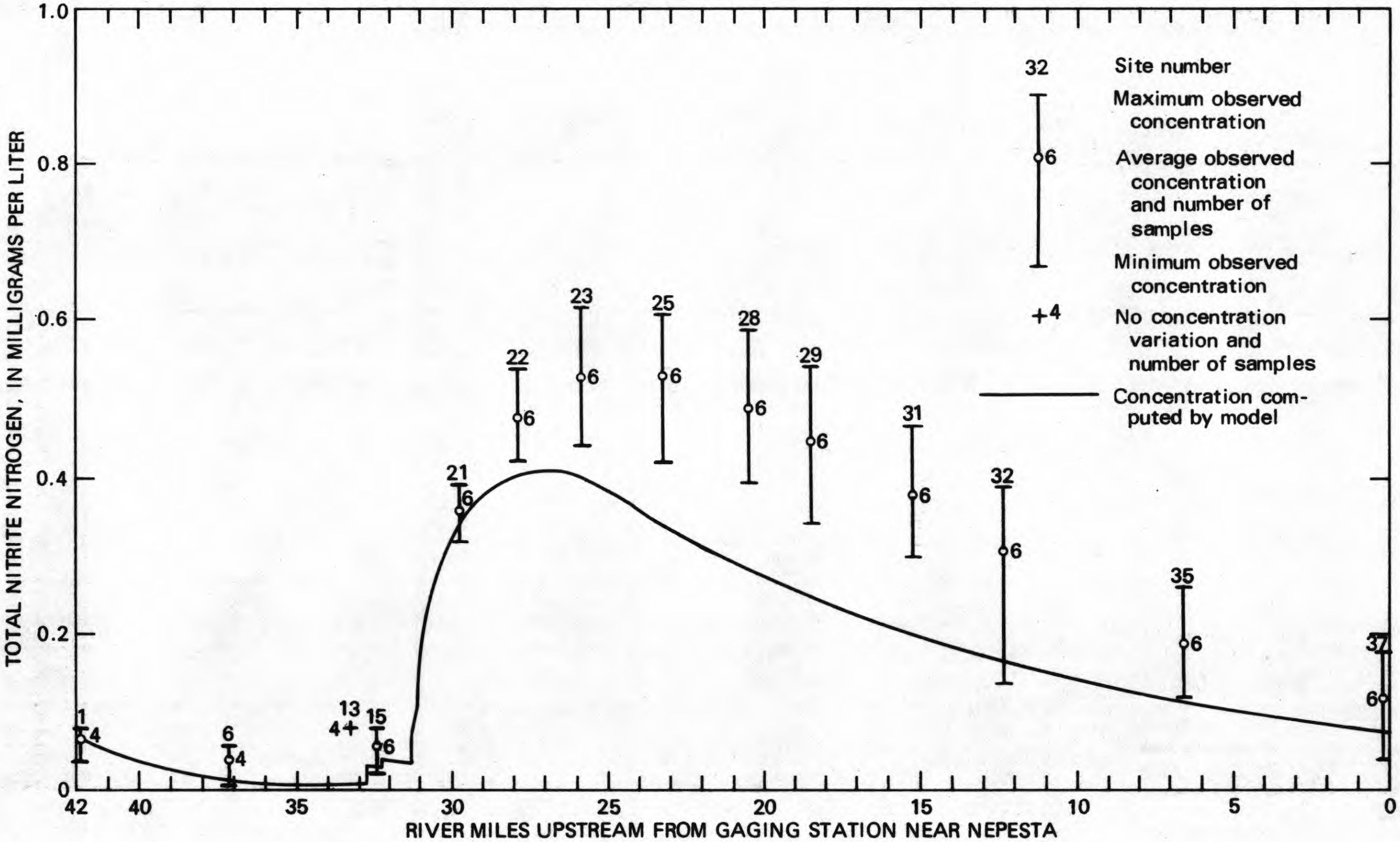

Figure 14.--Model-computed and observed concentrations of total nitrite nitrogen, September 1979.

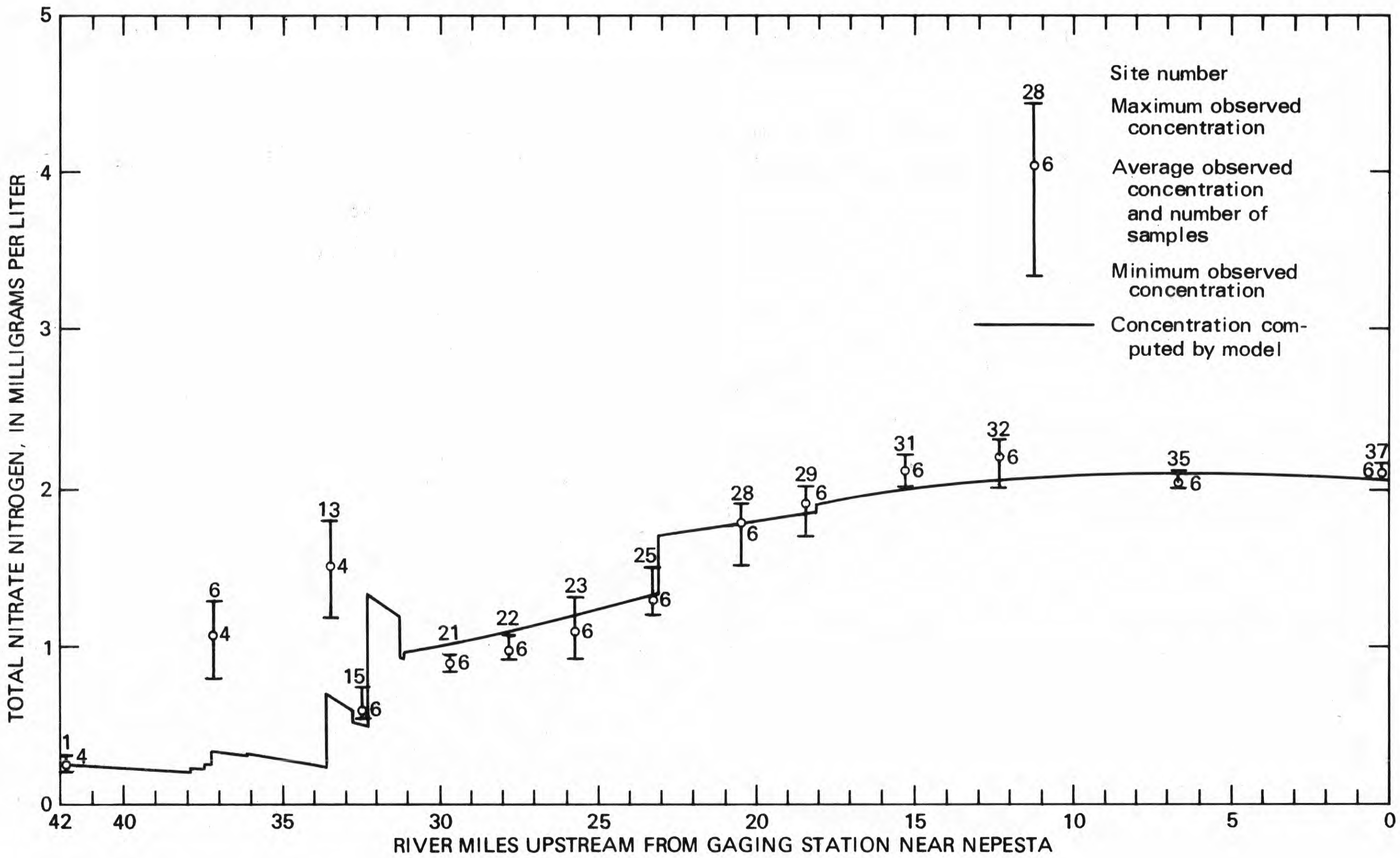

Figure 15.--Model-computed and observed concentrations of total nitrate nitrogen, September 1979.

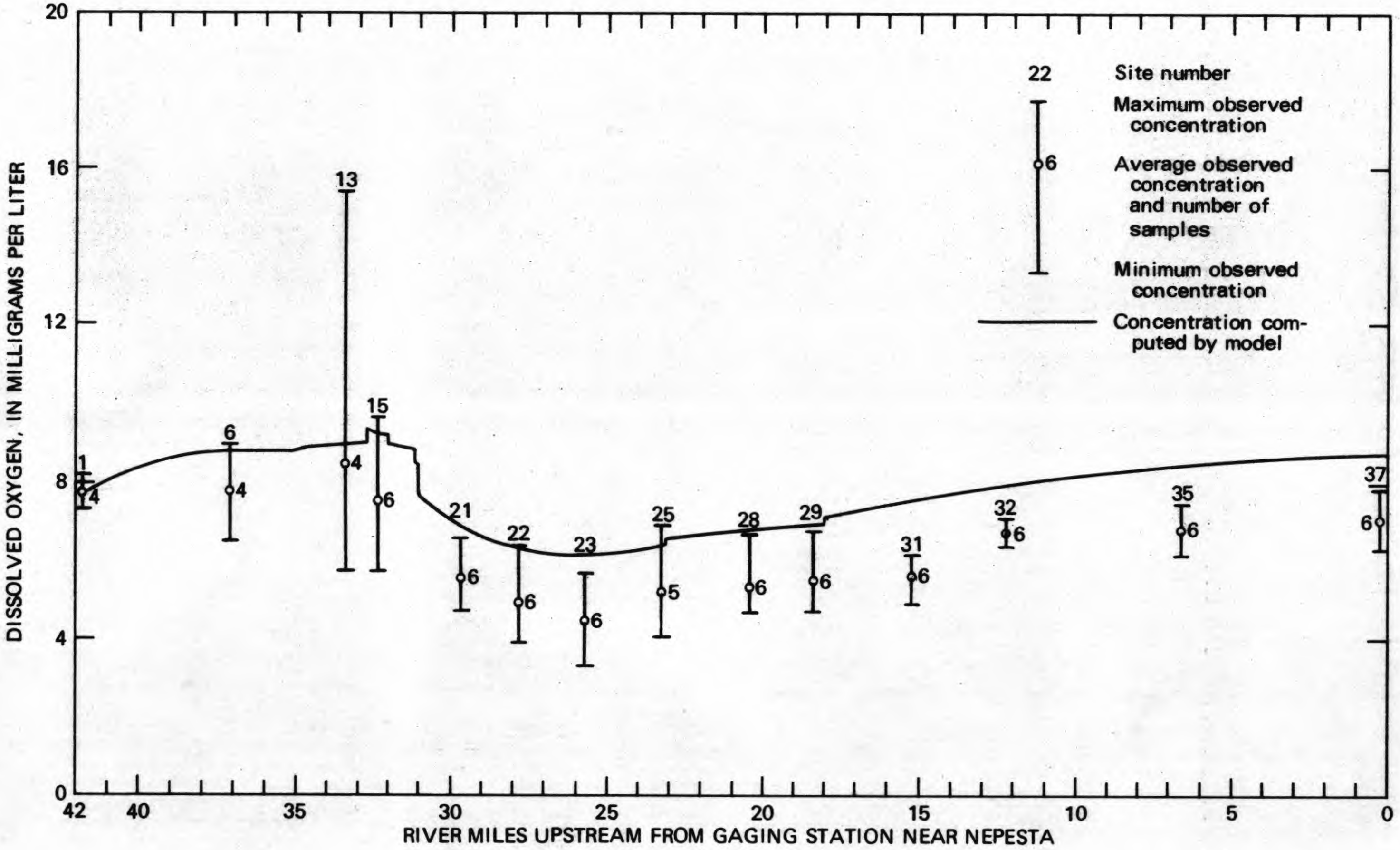

Figure 16.--Model-computed and observed concentrations of dissolved oxygen, September 1979.

An acceptable verification was obtained for DO (table 5). Model-computed concentrations were in the range of observed concentrations at most sites. Model-computed concentrations were generally greater than the mean of the observed concentrations by about 1.0 to 1.5 mg/L, suggesting that either reaeration coefficients used by the model were too large or an unmodeled consumption of oxygen was occurring in the river. Improvements in modeling of DO could possibly be made in future studies by including other processes which affect DO in the modeling effort. An analysis of photosynthesis, respiration, and streambed oxygen demand in the study reach should be included.

Diel Variation of Dissolved Oxygen

The calibrated and verified water-quality model can be used to predict the concentrations of various water-quality constituents. When using the model, it should be understood the values computed represent the average value that can be expected for a 24-hour period. For some water-quality constituents, such as DO, there is commonly a significant variation from the average value that occurs during any 24-hour period. Such a variation is known as a diel variation. The diel variation of DO concentrations is probably the most important of the water-quality constituents considered during this study.

The diel variation of DO concentrations on the Arkansas River at Colorado Highway 233 (site 23, river mile 25.8) is shown in figure 17 for two low-flow periods in 1979 and 1980. Some of the lowest model-computed and observed DO concentrations occurred near this site during model calibration and verification. Also shown is the water-quality guideline for DO of 5.0 mg/L for warm-water aquatic life (Colorado Department of Health, 1979a). The average DO concentration for each period was greater than the minimum observed value by approximately 1 mg/L.

Sensitivity of Model to Change in Location of Outfall from the CF&I Steel Corp.

In late February 1980, the location of the discharge from the CF&I Steel Corp. to the Arkansas River was changed. This discharge is one of the major wastewater effluents discharged to the Arkansas River in Pueblo County. The change was made to upgrade wastewater treatment by providing a longer holding time before discharging to the Arkansas River. The relocation involved a downstream change in the discharge point of 1.0 miles, from river mile 31.2 to river mile 30.2.

Data used for model calibration and verification were collected before the change in location. All model simulations were made using the new location. An analysis of the sensitivity of the model to the change in location was made to determine the validity of this approach.

Many of the changes in model inputs that resulted from the change in location of the discharge point can be handled directly by the model with little expected error. These include changes in river discharge, traveltimes, reaeration coefficients, temperature, and concentration or dilution of water-

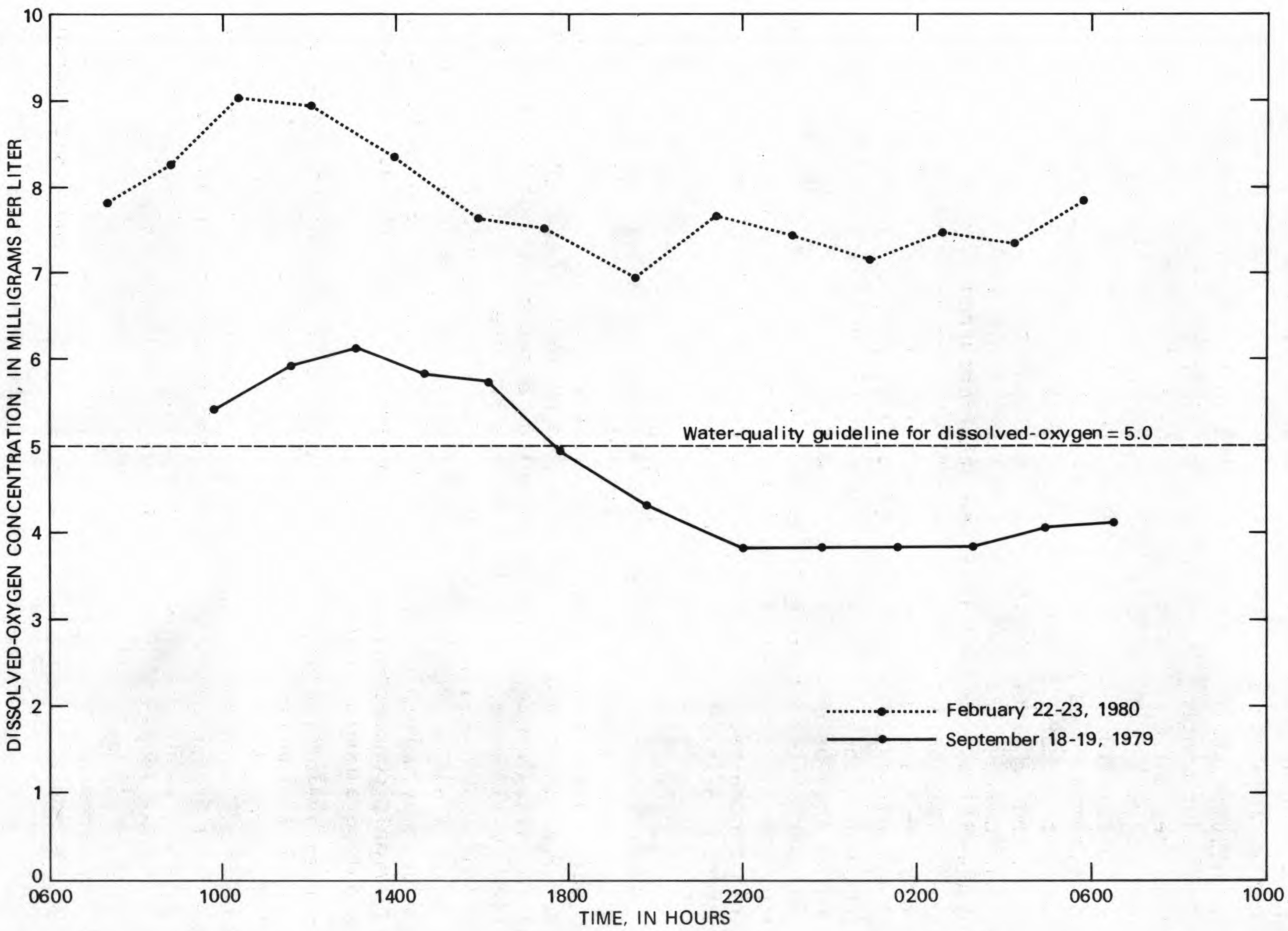

Figure 17. -- Diel variation of dissolved oxygen in the Arkansas River at Colorado Highway 233.

quality parameters. The one change in model input that cannot be handled directly is a change in reaction rates. The sensitivity analysis was made to evaluate the effect of changes in reaction rates that might occur as a result of the change in location of the discharge point.

The sensitivity analysis was made using total ammonia because this parameter is of major concern in water-quality planning on the Arkansas River. This analysis does not address changes in the effluent quality. It was assumed in the analysis that reaction rates would change from those determined during model calibration only in the river reach between the old and new outfall. This assumption is based on the idea that a large change in effluent quality would not occur as part of the relocation, and that where both the effluent from the CF&I Steel Corp. and the Pueblo WWTP are present in the river, the previously determined reaction rates would apply. The analysis was made using conditions similar to those that occurred during the September 1979 model-verification data-collection period. The forward-reaction and decay rates for ammonia were varied in the sensitivity analysis. The rates used in the calibrated model are 2.0 and 2.5 $days^{-1}$ at 20°C (table 6). Model-computed total ammonia concentrations and percent difference from concentrations computed using the original reaction rates at river miles 29.6, 28.6, and 25.8 using eight sets of reaction rates are shown in table 7. A large change in reaction rates results in a small percentage change in model-computed total ammonia concentrations, indicating the model is relatively insensitive to the change in location of the discharge point.

NONIONIZED AMMONIA

The water-quality model used during this study computes total ammonia. In aqueous solutions, ammonia exists in several chemical forms, including ionized NH_4^+ and nonionized NH_3. Nonionized ammonia is of greater concern than total ammonia in water-quality planning because nonionized ammonia is toxic to fish (Willingham, 1976). This fact has been recognized in the establishment of water-quality standards. The Colorado Department of Health (1979a) has set a guideline of 0.06 mg/L of nonionized ammonia as nitrogen in water to be used by warm-water aquatic life. To use model results to evaluate nonionized ammonia concentrations on the Arkansas River, it was necessary to relate nonionized ammonia to total ammonia.

The percentage of the total ammonia which is in the nonionized state can be approximated if the temperature, pH, and dissolved-solids concentration of the water is known (Skarheim, 1973). As pH and temperature increase, the percentage of nonionized ammonia increases. An increase in pH of 0.3 units or in temperature of 9°C approximately doubles the percentage of nonionized ammonia. In contrast, as dissolved-solids concentrations increase, the percentage of nonionized ammonia decreases. An increase of dissolved-solids concentration from 250 to 750 mg/L causes about a 5-percent decrease in the percentage of nonionized ammonia. Skarheim (1973) has prepared tables of the percentage of nonionized ammonia at various temperatures, pH's, and dissolved-solids concentrations.

To use the relationship between nonionized and total ammonia to evaluate nonionized ammonia concentrations for model simulations performed during this study, it was necessary to collect data to define the seasonal variation of

Table 7.--*Comparison of model-computed total ammonia concentrations using different reaction rates in the reach between the old and new outfall points for CF&I Steel Corp.*[1]

Total ammonia nitrogen forward reaction rate, in $days^{-1}$	Total ammonia nitrogen decay rate, in $days^{-1}$	Model-computed total ammonia concentrations, in milligrams per liter		
		River mile 29.6[2]	River mile 29.6[2]	River mile 29.6[2]
0.5	0.1	2.01	1.80	1.32
1.0	1.5	1.96	1.76	1.29
1.5	2.0	1.92	1.72	1.26
[3]2.0	[3]2.5	1.88	1.68	1.23
2.5	3.0	1.83	1.65	1.21
3.0	3.5	1.79	1.61	1.18
3.5	4.0	1.75	1.58	1.16
4.0	4.5	1.72	1.54	1.13

[1]CF&I Steel Corp. outfall point was relocated in February 1980.
[2]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.
[3]Reaction rate determined during model calibration and verified during model verification.

pH, temperature, and dissolved solids at selected points in the study reach. The data-collection program consisted of installation and operation of a continuous-recording water-quality monitor on the Arkansas River near Avondale (site 29, river mile 18.5) in July 1979. The water-quality monitor collects data hourly on water temperature, pH, DO, and specific conductance. To establish variation in these parameters at points on the Arkansas River between the water-quality monitor located near Avondale and the Pueblo WWTP (site 18, river mile 31.3), diel data were collected at two other sites on September 18 and 19, 1979, and February 22 and 23, 1980. The sites where diel data were collected are the Arkansas River at Colorado Highway 233 (site 23, river mile 25.8) and the Arkansas River near 23d Lane (site 21, river mile 29.8). The diel data collection was made during two 24-hour periods to evaluate seasonal variation.

During model simulations it was necessary to establish an expected average percentage of nonionized ammonia at river miles 29.6 and 28.6. The expected average percentage of nonionized ammonia was needed during two low-flow periods: (1) a late summer to early fall period and (2) a winter period. On the Arkansas River the late summer to early fall period generally occurs between August 15 and October 15. The winter low-flow period occurs during most years between November 15 and March 15 as a result of storage of water in Pueblo Reservoir.

The expected average percentage of nonionized ammonia used during model simulations of low flows occurring during each period was determined as follows.

The average temperature and median pH, determined using all data collected by the water-quality monitor during each period, are shown in table 8. The average temperature and median pH were used rather than the maximum values of these parameters because the toxicity of ammonia to fish at concentrations below 0.16 mg/L as nitrogen appears to result from prolonged rather than short-term exposure (European Inland Fisheries Advisory Commission, 1973). These values were then adjusted to account for somewhat higher pH and temperature at river miles 29.6 and 28.6 (see section on Mixing-Zone Evaluation). The adjustments (table 8) were based on diel measurements of these parameters made at site 21 (river mile 29.8) on September 18 and 19, 1979, for the August 15 to October 15 period, and February 22 and 23, 1980, for the November 15 to March 15 period. The adjustment for pH was the difference between the median pH at site 21 and at the water-quality monitor. The adjustment for temperature was the difference in average temperature between site 21 and the water-quality monitor. The data from site 21 were used to make the adjustments because this site was nearest river miles 29.6 and 28.6. The average temperature and median pH values used to determine the expected average percentage of nonionized ammonia are shown in table 8.

Before the percentage of nonionized ammonia could be determined it was necessary to know the concentration of dissolved solids. Specific-conductance data collected during this study were used to determine dissolved-solids concentrations used in defining the expected average percentage of nonionized ammonia. The specific-conductance values used are averages of data collected at site 21. The specific-conductance value used for the August 15 to October 15 period was 853 micromhos per centimeter (μmhos/cm) at 25°C and is based on

Table 8.--*Expected average percentage of nonionized ammonia used during model simulations*

Model-simulation period	Values from water-quality monitor on the Arkansas River near Avondale		Adjustments to values from water-quality monitor		Values used to determine average percentage of nonionized ammonia at river mile 28.6[1]			Average percentage of nonionized ammonia[2] (river mile 28.6)
	Median pH	Average temperature, in degrees Celsius	pH	Temperature, in degrees Celsius	pH	Temperature, in degrees Celsius	Dissolved solids, in milligrams per liter	
August 15 to October 15--	7.9	20.0	+0.2	+2.0	8.1	22.0	540	4.9
November 15 to March 15----	8.0	6.5	+0.2	+0.5	8.2	7.0	710	2.0

[1]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.
[2]Computed using tables from Skarheim (1973).

data collected during the low-flow period of September 18 to 20, 1979. The specific-conductance value used for the November 15 to March 15 period was 1,125 μmhos/cm at 25°C and is based on data collected during the low-flow period of December 13 and 14, 1979. The higher specific-conductance value noted during the winter period is a result of increased discharge of water with a relatively high specific conductance from Fountain Creek (site 16, river mile 32.3).

A relationship between dissolved solids and specific conductance was developed from 33 samples collected in 1976 and 1979 from the Arkansas River between river miles 0 and 29.8. The relationship, which was determined by the method of least squares, is:

$$DS=0.64SC-8.7, \qquad (2)$$

where DS=dissolved-solids concentration, in mg/L; and
SC=specific conductance, in μmhos/cm at 25°C.

The correlation coefficient is 0.98. Application of this equation to the specific-conductance values determined above resulted in the dissolved-solids concentrations shown in table 8.

Using the adjusted average temperature, adjusted median pH, and computed dissolved-solids concentrations, the expected average percentage of nonionized ammonia at river miles 29.6 and 28.6 was determined for each of the periods for which model simulations were performed (table 8), using the information in Skarheim (1973).

MIXING-ZONE EVALUATION

A zone of mixing occurs whenever a discharge enters a receiving water of different quality. The Colorado Department of Health (1979a) has provided for a mixing zone to serve as a zone of initial dilution in the immediate area of a discharge and defines the mixing zone as "that area of a water body . . . which is contiguous to a point source and in which standards may not apply." The standards referred to are those which are assigned to the receiving waters.

Several factors are considered in determining the configuration of the mixing zone. In addition to defining the downstream end of the mixing zone, those factors which were evaluated during this study include overlapping mixing zones and a zone of passage. According to the Colorado Department of Health (1979a, p. 14), "Mixing zones shall not overlap so as to cause harmful effects in adjacent waters or to interfere with zones of passage." Zones of passage are provided for, where necessary, to protect free-swimming or drifting aquatic life by allowing sufficient passage around the mixing zone (Colorado Department of Health, 1979a).

The mixing zone downstream from the Pueblo WWTP was evaluated during this study to help define the location where water-quality standards would be applied during the model simulations discussed in the "Evaluation of Water-Quality Management Alternatives" section of this report.

Description of Reach Evaluated

A $3\frac{1}{2}$-mile reach of the Arkansas River was studied to evaluate the mixing zone from the Pueblo WWTP outfall. The reach (fig. 18) began 0.03 mile upstream from the Pueblo WWTP outfall (site 18, river mile 31.3) and extended downstream to near site 22, Arkansas River near 28th Lane (river mile 27.9). The downstream end of the reach was chosen after reconnaissance sampling in September 1979. The only other major discharge in this reach is the outfall from the CF&I Steel Corp., which was located 0.12 miles downstream from the outfall of the Pueblo WWTP until relocated in late February 1980 to river mile 30.2.

That reach of the Arkansas River studied during the evaluation of the mixing zone is characterized by a meandering channel with a flow regime during low-flow periods that is transitional between pool and riffle and regular gradient shifting sand. The stream bottom varies in composition from cobble to sand and silt. The slope of the channel is about 10 feet per mile. An average velocity between 1.5 and 2.0 ft/s and an average depth between 1 and 2 feet occurred at the river discharges encountered during the mixing-zone evaluation (table 9). The angle is about 60 degrees between the flow directions of the effluent from the Pueblo WWTP and the Arkansas River at the outfall point. It was about 30 degrees at the CF&I Steel Corp. old outfall point and about 50 degrees at the new outfall point. The average velocity of the Pueblo WWTP effluent just upstream from the outfall point during the mixing-zone evaluation was 0.9 to 2.0 ft/s. The larger velocity occurred at the lower river stage. The average velocity of the CF&I Steel Corp. effluent, which was 2.5 to 3.0 ft/s just upstream from the outfall point at both the old and new outfall locations, was not affected by river stage.

Data Collection

The data-collection phase of the mixing-zone study consisted of injecting a fluorescent dye, rhodamine WT, at a constant rate in the effluents from the Pueblo WWTP and the CF&I Steel Corp. during three 2-day periods. A 20-percent solution of the dye was injected in one effluent on the first day and in the other effluent on the second day, using a small constant-discharge pump. After the dye had been injected, samples were collected for analysis of dye concentration at a control cross section on the river upstream from the point of outfall and at cross sections downstream from the point of outfall (fig. 18). Dye was injected continuously until all samples were collected. Each cross section was divided into six equal width intervals and water samples for analysis of dye concentration were collected approximately 0.25 foot below the water surface at the center of each interval. At selected sites, dye samples also were collected near the river bottom as a check on vertical mixing. In addition, water samples also were collected on one of the days at the centers of the six intervals for analysis of total organic nitrogen, total Kjeldahl nitrogen, total ammonia nitrogen, total nitrite nitrogen, and total nitrate nitrogen. Instream measurements of pH, temperature, and specific conductance were made when water samples were collected for analysis of

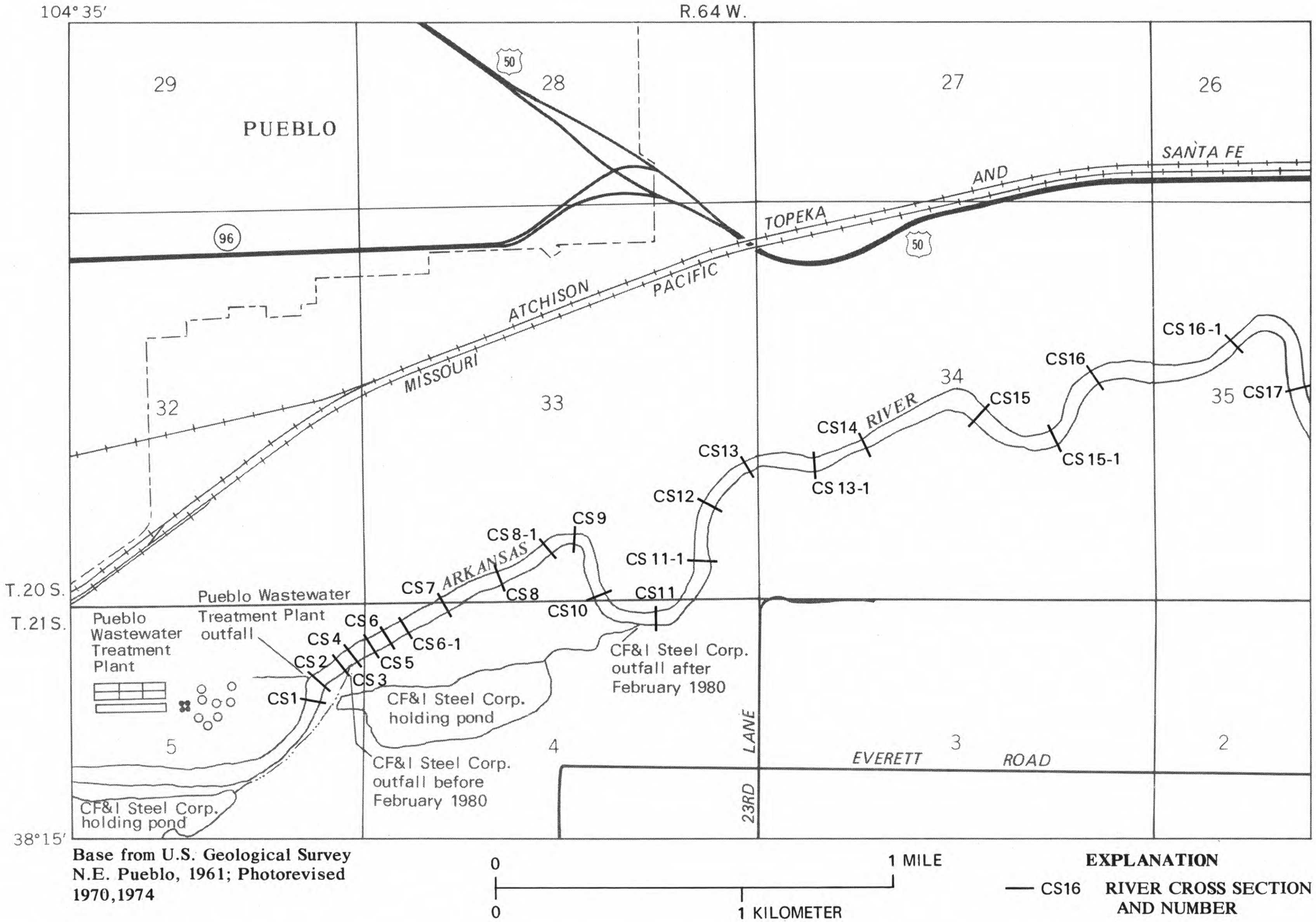

Figure 18. --Reach studied to evaluate mixing zone and river cross sections where mixing data were collected.

Table 9.--*Mean discharges during the mixing-zone data-collection periods*

Location[1]	Date	Mean discharge, in cubic feet per second
Arkansas River above the Pueblo Wastewater Treatment Plant outfall (river mile[2] 31.33).	November 15, 1979	369
	November 16, 1979	368
	December 13, 1979	75.2
	December 14, 1979	65.3
	March 10, 1980	170
	March 11, 1980	172
Pueblo Wastewater Treatment Plant outfall (river mile[2] 31.3)--	November 15, 1979	27.2
	November 16, 1979	24.5
	December 13, 1979	25.0
	December 14, 1979	25.2
	March 10, 1980	29.1
	March 11, 1980	24.8
CF&I Steel Corp. outfall (river mile[2] 31.18)-----------------	November 15, 1979	106
	November 16, 1979	113
	December 13, 1979	104
	December 14, 1979	104
CF&I Steel Corp. outfall (river-mile[2] 30.2)------------------	March 10, 1980	110
	March 11, 1980	114

[1]See figure 18.
[2]River miles upstream from streamflow-gaging station 07117000 Arkansas River near Nepesta.

total nitrogen species. The water depth at the center of each interval also was measured. Water samples for analysis of dye concendration and total nitrogen species were collected from the two effluents and field measurements also were made of pH, temperature, and specific conductance.

The first two data-collection periods were before the relocation of the CF&I Steel Corp. outfall point. The upstream river discharge was different during each of the data-collection periods (table 9). The locations of cross sections where samples were collected during each 2-day period are shown in figure 18 and in table 10. Data collected during the mixing-zone evaluation are given by Cain and Edelmann (1980).

Two assumptions were made during the mixing-zone evaluation which simplified both the process of data collection and data interpretation. The assumptions were: (1) The injected dye was completely mixed with each effluent at the point the effluent entered the river; and (2) vertical stratification in the river was negligible. Data were collected to verify both assumptions. To verify that the injected dye was well mixed with the effluents, water samples for analysis of dye were collected at six points across each outfall and at selected vertical sections in each outfall. The outfall from the Pueblo WWTP had an average width between 18 and 25 feet and an average depth between 0.6 and 1.3 feet during the three data-collection periods. The outfall from the CF&I Steel Corp. had an average width between 34 and 41 feet and an average depth between 0.9 and 1.3 feet during the three data-collection periods. The average width and depth of both the old and new outfalls were similar. The data indicate the dye was well mixed both vertically and horizontally in each outfall as it entered the Arkansas River (table 11). Negligible vertical stratification was expected in the study reach of the Arkansas River based on the concept that shallow depths (1 to 2 feet) and moderate velocities (1.5 to 2.0 ft/s) would combine to provide complete vertical mixing. At selected sites, water samples were collected both just below the water surface and near the river bottom as a check on the assumption of vertical mixing. The average difference in dye concentration between 61 sets of samples collected near the top and bottom of the water column was 4 percent, indicating minimal vertical stratification.

Results of Mixing-Zone Evaluation

Downstream End of the Mixing Zone

The mixing zone can be defined as that part of the Arkansas River where the effluent from the Pueblo WWTP is mixing with the river. Using this definition, that part of the Arkansas River where detectable dye concentrations were observed between the outfall from the Pueblo WWTP and the cross section of complete lateral mixing would comprise the mixing zone. Complete lateral mixing was based on measured concentrations of rhodamine-WT dye, using data collected on the days when dye was injected in the effluent from the Pueblo WWTP. Complete lateral mixing occurred when the difference in measured dye concentrations in a river cross section was less than 10 percent. This value was based on the precision and accuracy that dye samples can be collected and analyzed.

Table 10.--*Cross sections where samples were collected during each mixing-zone data-collection period*

Cross-section number[1]	River miles downstream from Pueblo Wastewater-Treatment Plant outfall[2]	River mile[3]	Data-collection periods[4] 1979 November	1979 December	1980 March
CS 1	-0.03	31.33	X	X	X
CS 2	.02	31.28	X	X	X
CS 3	.10	31.20	X	X	-
CS 4	.14	31.16	X	X	-
CS 5	.18	31.12	X	X	X
CS 6	.24	31.06	X	X	-
CS 6-1	.29	31.01	X	X	X
CS 7	.42	30.88	X	X	X
CS 8	.58	30.72	X	X	X
CS 8-1	.74	30.56	-	X	X
CS 9	.79	30.51	X	-	-
CS 10	.97	30.33	X	X	X
CS 11	1.2	30.10	X	X	X
CS 11-1	1.4	29.90	-	-	X
CS 12	1.5	29.80	X	X	X
CS 13	1.7	29.60	X	X	X
CS 13-1	1.9	29.40	-	-	X
CS 14	2.0	29.30	X	X	X
CS 15	2.3	29.00	X	X	X
CS 15-1	2.6	28.70	-	-	X
CS 16	2.8	28.50	X	X	X
CS 16-1	3.1	28.20	-	-	X
CS 17	3.5	27.80	X	X	X

[1]Cross-section number refers to number on figure 18.

[2]Negative number indicates cross section upstream from outfall of Pueblo Wastewater Treatment Plant.

[3]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[4]X indicates that data was collected at this cross section during the data-collection period.

Table 11.--*Concentrations of rhodamine-WT dye in the effluents from the Pueblo Wastewater Treatment Plant and CF&I Steel Corp. during the mixing-zone data-collection periods*

Effluent	Date	Mean concentration of rhodamine WT dye, in micrograms per liter	Mean percent lateral difference in dye concentration	Mean percent vertical difference in dye concentration
Pueblo Wastewater Treatment Plant outfall.	Nov. 15, 1979	0	-	-
	Nov. 16, 1979	178	3	-
	Dec. 13, 1979	0	-	-
	Dec. 14, 1979	121	9	3
	Mar. 10, 1980	0	-	-
	Mar. 11, 1980	134	2	0
CF&I Steel Corp. outfall----------	Nov. 15, 1979	48	3	-
	Nov. 16, 1979	0	-	-
	Dec. 13, 1979	32	0	0
	Dec. 14, 1979	0	-	-
	Mar. 10, 1980	32	2	0
	Mar. 11, 1980	0	-	-

The downstream end of the mixing zone was determined from dye data rather than concentrations of water-quality constituents such as total ammonia. Dye concentrations can be determined more precisely in all concentration ranges. Dye, unlike the water-quality constituents analyzed, was not present in either effluent or the river unless artificially introduced. The concentration of dye in the effluents can also be controlled at a nearly constant rate. These factors combine to more accurately define the downstream end of the mixing zone. The percent difference in dye concentrations within each sampled river cross section during the three data-collection periods is shown in figure 19.

Based on the previously defined criteria of complete lateral mixing, mixing occurred between 1.7 and 2.0 river miles downstream from the Pueblo WWTP outfall during the November 1979 sampling period, and between 2.6 and 2.8 river miles downstream from the Pueblo WWTP outfall during the March 1980 sampling period. The downstream end of the mixing zone was not well defined during the December 1979 sampling because of data-collection problems. An estimation of the downstream end of the mixing zone during the December 1979 period, based on the available data, indicates the end of the mixing zone occurred between 1.4 and 1.6 river miles downstream from the outfall of the Pueblo WWTP. The downstream end of the mixing zone for the effluent from the CF&I Steel Corp. occurred at approximately the same location as the effluent from the Pueblo WWTP during each data-collection period. Also shown in figure 19 is the percent difference in total ammonia concentrations within each sampled river cross section. The mixing of total ammonia is similar to that of dye.

Because the November and December 1979 data-collection periods occurred with the CF&I Steel Corp. outfall in the same location, the results can be directly compared to estimate the effect of different river discharges on the length required for complete lateral mixing. The upstream river discharge during the November 1979 sampling period was approximately five times the December 1979 sampling period. The length of river required to achieve complete lateral mixing was shorter by about 20 to 30 percent when the upstream discharge was smaller.

The much greater length required for complete lateral mixing during the March 1980 data-collection period is apparently related to two factors caused by the relocation of the CF&I Steel Corp. outfall point. First, slower mixing occurred in the first mile of the mixing zone, which appeared to be caused by a change in river hydraulics caused by the relocation. Second, the mixing zone was lengthened downstream from the new outfall point as the river, containing the partially mixed effluent from the Pueblo WWTP, required an additional 1.5 to 1.7 miles to mix with the effluent from the CF&I Steel Corp.

The downstream end of the mixing zone was defined as a point 2.7 miles downstream from the Pueblo WWTP during model simulations. This location is halfway between cross-sections CS15-1 and CS16 at river mile 28.6.

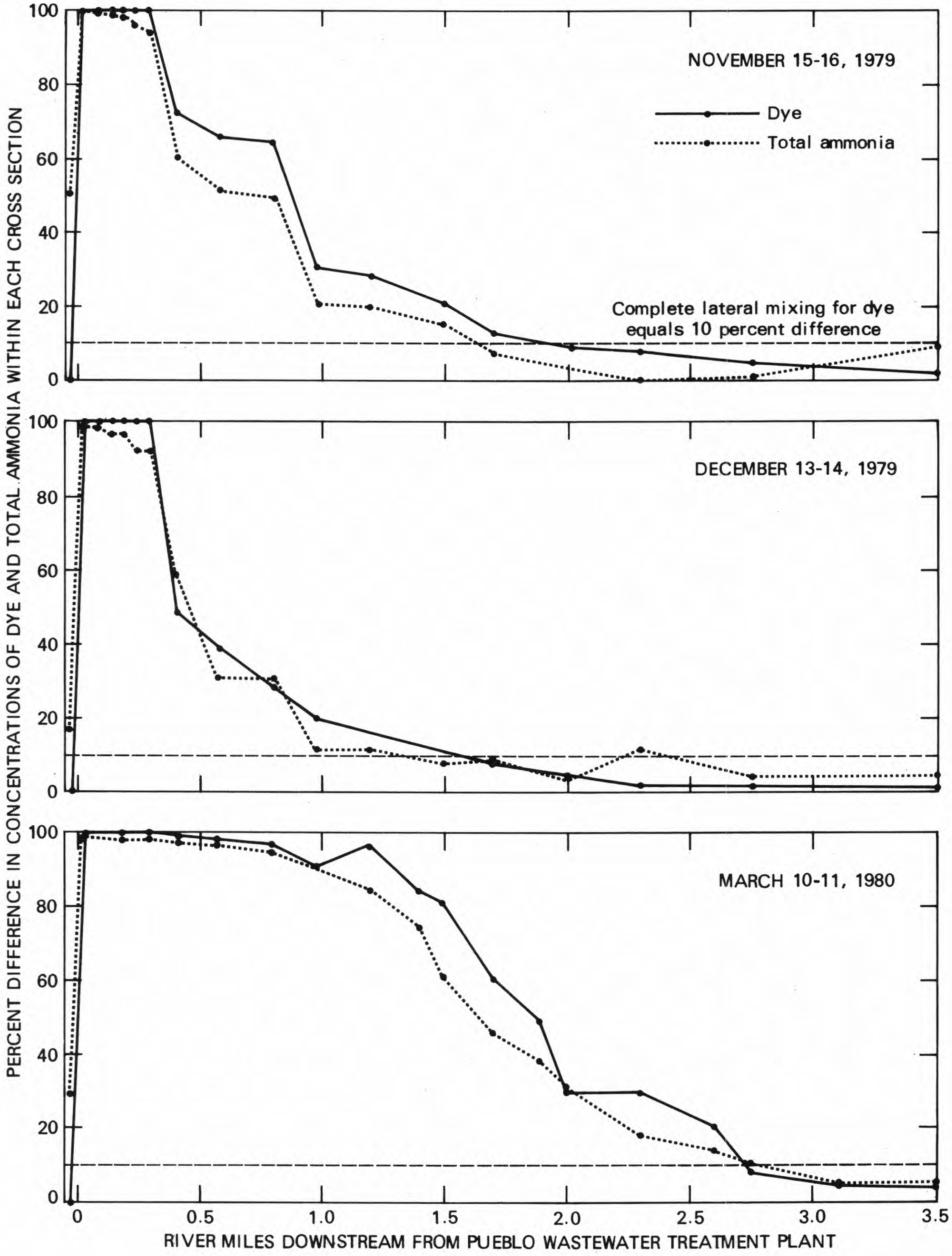

Figure 19.--Percent difference in concentrations of dye and total ammonia within each cross section during the three mixing-zone data-collection periods.

The river discharge upstream from the Pueblo WWTP during the March 1980 data-collection period (table 9) was greater than the $Q_{7,10}$ discharge. The downstream end of the mixing zone used during the model simulations, therefore, may be different from the downstream end of the mixing zone that would actually occur at the $Q_{7,10}$. Because it was not possible to collect additional data at a river discharge nearer the $Q_{7,10}$ discharge within the time frame of this study, the March 1980 data represents the best estimate of the downstream end of the mixing zone after the relocation of the CF&I Steel Corp. outfall.

Configuration of the Mixing Zone

The configuration of the mixing zone was considered only for the March 1980 data-collection period. The two data-collection periods in 1979 were not considered because the configuration of the mixing zone has been permanently changed by the relocation of the CF&I Steel Corp. outfall. A schematic diagram of dye concentrations in the mixing zone is shown in figure 20, based on data collected March 11, 1980, when dye was injected into the effluent from the Pueblo WWTP.

Dye concentrations shown in figure 20 are directly proportional to the percentage of effluent from the Pueblo WWTP which was present in the Arkansas River at any point. Where dye concentrations were highest, most of the water in the river was from the Pueblo WWTP. Where dye concentrations were lowest, little of the water at that point was from the Pueblo WWTP. Where dye concentrations were nearly equal in a cross section, mixing of the effluent from the Pueblo WWTP in the river was complete.

Lateral mixing in a river occurs as a two-stage process (Fischer and others, 1979). First, the initial momentum and buoyancy of the effluent determine the rate of mixing. As the effluent is diluted, the initial momentum and buoyancy are also diluted, leading to a second stage in which lateral mixing is primarily accomplished by turbulence and currents in the river. The second stage is noticeable in the Arkansas River. The effluent from the Pueblo WWTP tended to hug the left bank of the river and slowly mixed across the river width. This lateral mixing was reversed temporarily as dye-free water from the CF&I Steel Corp. outfall entered the river. Downstream from the CF&I Steel Corp. outfall, lateral mixing continued until complete mixing occurred between cross-sections CS15-1 and CS16.

Zone of Passage

Another purpose of the mixing-zone evaluation was to determine if a zone of passage was present in the mixing-zone reach. A zone of passage is an area of the river on the periphery of the mixing zone which can provide for safe passage of free-swimming and drifting aquatic life. The effect of the overlapping mixing zones from the outfalls of the Pueblo WWTP and the CF&I Steel Corp. on the zone of passage also required definition. The examination of the zone of passage was based on concentrations of nonionized ammonia during the March 1980 data-collection period. Other water-quality constituents determined during the mixing-zone evaluation were not considered in examining the zone of passage because they did not occur at levels that would violate water-quality guidelines (Colorado Department of Health, 1979a).

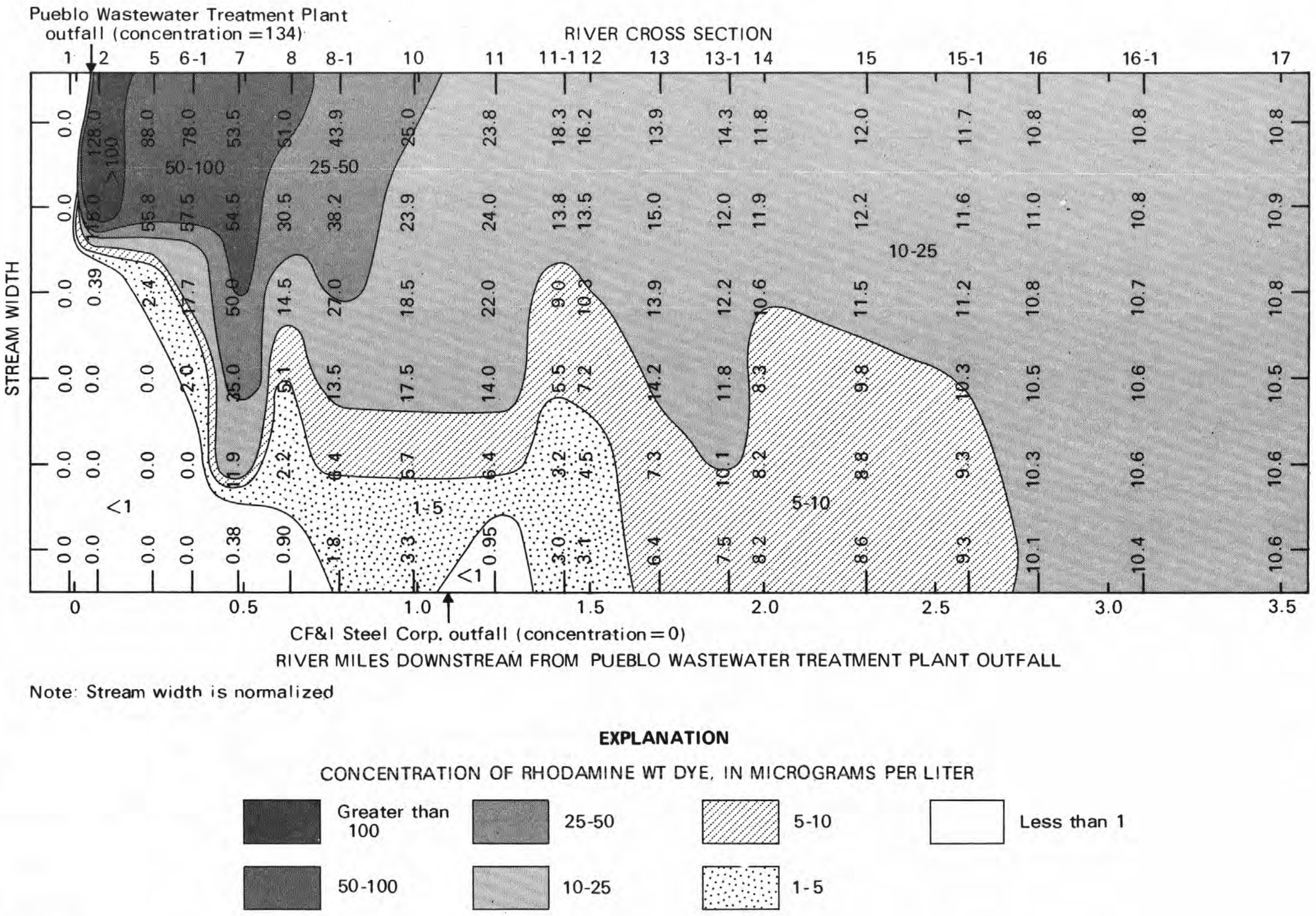

Figure 20. --Dye concentrations in mixing zone during injection of dye into the effluent from the Pueblo Wastewater Treatment Plant on March 11, 1980.

Schematic diagrams of total and nonionized ammonia concentrations in the mixing-zone reach are given in figures 21 and 22. The mixing of total ammonia was similar to that shown for dye in figure 20. Some differences occurred because of the presence of total ammonia in both the Arkansas River upstream from the Pueblo WWTP outfall and in the effluent from the CF&I Steel Corp. The schematic diagram of nonionized ammonia concentrations is somewhat different from that shown for total ammonia. The differences are primarily the result of variations in pH and temperature, and, to a lesser extent, specific conductance in the mixing-zone reach. These variations are caused by different pH, temperature, and specific conductance in the outfalls from the Pueblo WWTP and the CF&I Steel Corp. and in the Arkansas River as it flows into the mixing-zone study reach. Temperature, pH, and specific conductance also can be expected to vary both on a diurnal and seasonal basis, even with the same river discharge. For this reason, the schematic diagram of nonionized ammonia concentrations should be used as a representation of conditions during the data-collection period and as an indicator of the possible configuration of nonionized ammonia concentrations for other conditions.

Based on the water-quality guideline of 0.06-mg/L nonionized ammonia as nitrogen, a zone of passage for free-swimming and drifting aquatic life was present in the mixing-zone reach during the March 1980 data-collection period. The zone of passage would include that part of the river where nonionized ammonia concentrations were less than or equal to the water-quality guideline.

Although the mixing zones from the outfalls of the Pueblo WWTP and the CF&I Steel Corp. overlap in the mixing-zone reach, the overlap did not appear to have an adverse effect on the zone of passage during the March 1980 data-collection period based on calculated nonionized ammonia concentrations. It may be necessary to examine other water-quality constituents--especially in the effluent from the CF&I Steel Corp.--to determine if the zone of passage defined on the basis of nonionized ammonia is valid for other constituents.

EVALUATION OF WATER-QUALITY MANAGEMENT ALTERNATIVES

Various water-quality management alternatives for the Arkansas River in Pueblo County were evaluated during this study. The need to evaluate alternatives was brought about primarily by the requirement that the Pueblo WWTP comply with applicable regulations of the State of Colorado by July 1983 (Colorado Department of Health, 1979b). The regulations require that instream water-quality standards be met downstream from the outfall of the Pueblo WWTP. The water-quality standards are set as part of the process of stream classification and are based on guidelines of the Colorado Department of Health (1979a) and other available information.

Evaluation of water-quality management alternatives involved using the water-quality model to simulate effects on instream water quality of various combinations of wastewater treatment for the major point-source discharges to the Arkansas River. The effects were evaluated with respect to water-quality guidelines at the end of the mixing zone and at other downstream points on the Arkansas River.

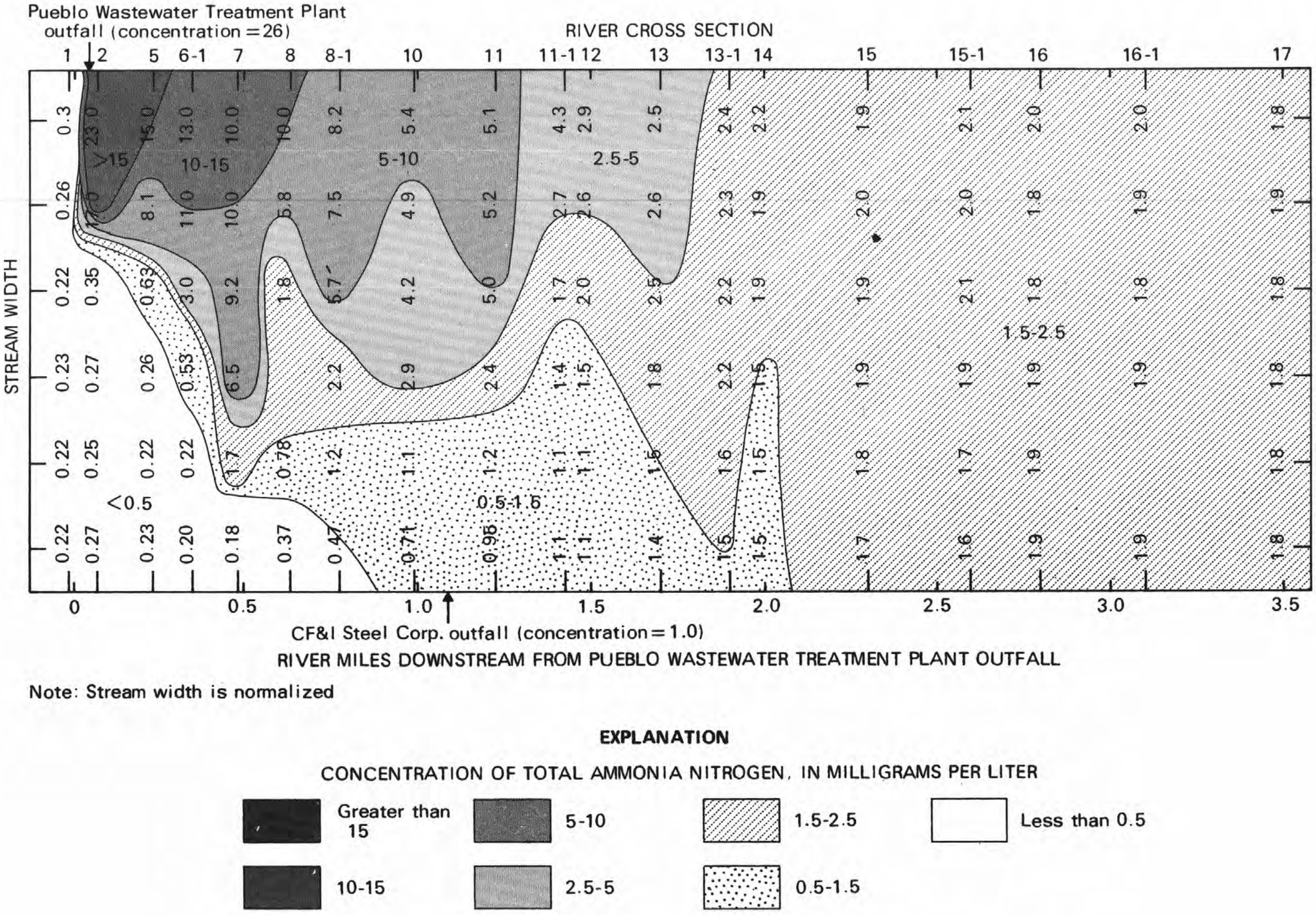

Figure 21. -- Concentrations of total ammonia in the mixing zone on March 11, 1980.

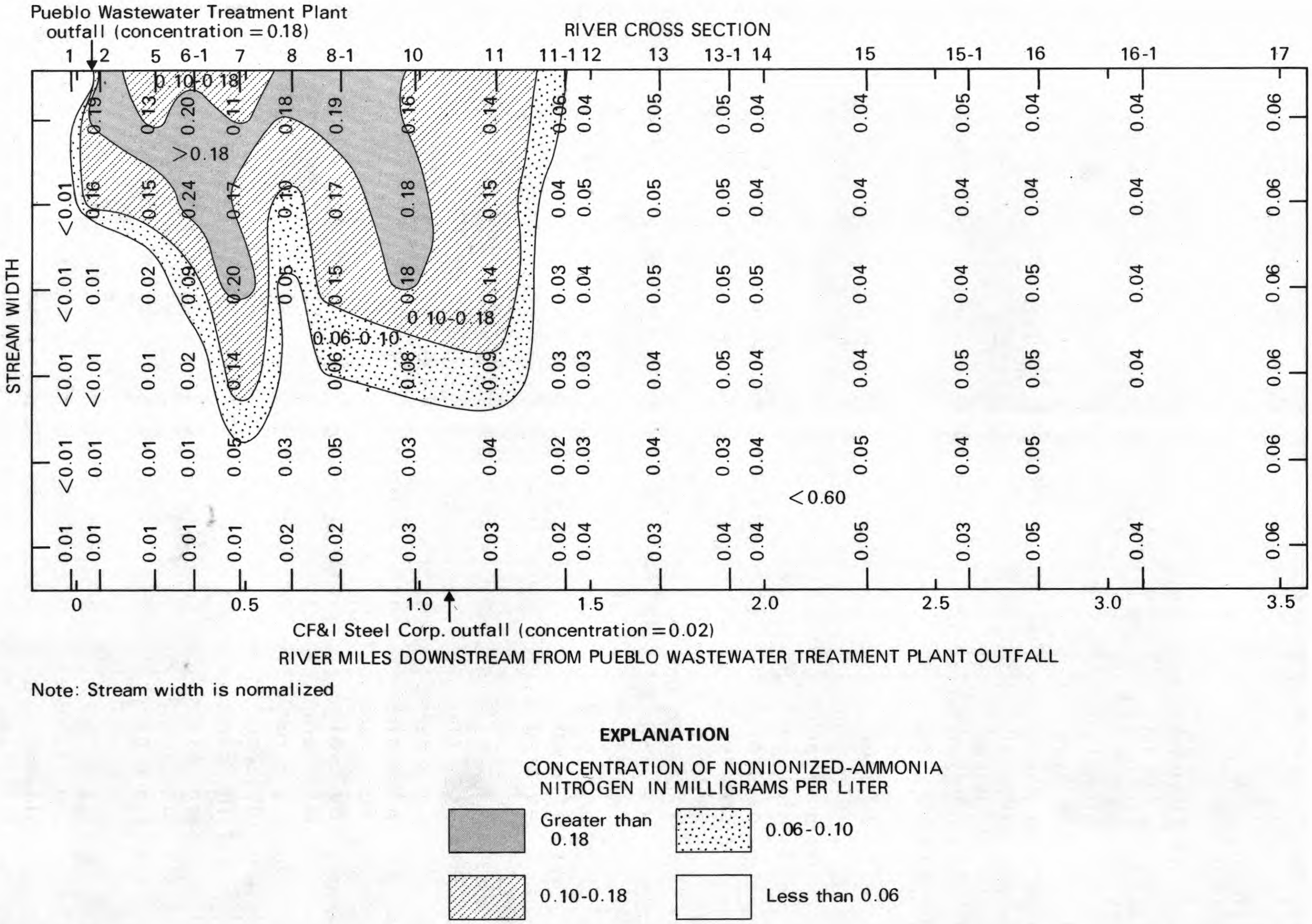

Figure 22. -- Concentrations of nonionized ammonia in the mixing zone on March 11, 1980.

River Low-Flow Periods

Three low-flow periods generally occur each year on the Arkansas River in Pueblo County. Natural low-flow periods occur in the spring, late March to early May, and in the fall, mid-August to mid-October (fig. 2). During recent years, an artificial low-flow period has occurred from mid-November to mid-March as a result of winter storage of water in Pueblo Reservoir. Of the two natural low-flow periods, the fall low-flow period was evaluated because stream temperatures will generally be higher than during the spring, resulting in lower DO concentrations and higher concentrations of nonionized ammonia. The winter low-flow period was evaluated to determine the water-quality effects of low flow resulting from storage of water in Pueblo Reservoir.

The fall low flow used for model simulations is the minimum average 7-consecutive-day flow expected to occur once in 10 years ($Q_{7,10}$). The $Q_{7,10}$ for the Arkansas River in Pueblo County determined by Dumeyer (1975) was used in this study with small modifications to account for some minor tributaries and changes in diversion practices. The $Q_{7,10}$ is based on discharge data collected before completion of the Pueblo Reservoir and the effect of reservoir operations on the $Q_{7,10}$ has not yet been evaluated. The discharge profile for $Q_{7,10}$ conditions in the study reach given in figure 23 assumes secondary treatment at the Pueblo WWTP for the year 2000 and results in a model-computed discharge of 57.2 ft^3/s just upstream from the outfall of the Pueblo WWTP. The discharge profile downstream from the Pueblo WWTP (river mile 31.3) will vary for different wastewater-treatment possibilities and years simulated. Discharges used during model simulations of $Q_{7,10}$ conditions are given in table 12.

The winter low flow used in this study was based on discharges that have occurred during the period from November 15 to March 15 as a result of storage of water in Pueblo Reservoir since it was completed in 1974. The discharge profile for winter low-flow conditions in the study reach (fig. 23) was determined by evaluating streamflow and diversion records for the Arkansas River and major tributaries in Pueblo County. The discharge profile assumes secondary treatment at the Pueblo WWTP outfall for the year 2000. The model-computed discharge is 76.2 ft^3/s just upstream from the outfall of the Pueblo WWTP. The discharge profile downstream from the Pueblo WWTP outfall (river mile 31.3) will vary for different wastewater-treatment possibilities and years simulated. Discharges used during model simulations of winter low-flow conditions are given in table 13.

The possibility of augmenting streamflows to provide for greater waste-assimilative capacity was also considered during this study. Augmentation would be accomplished by increased releases of water from Pueblo Reservoir and would result in an increase in discharge throughout the study reach.

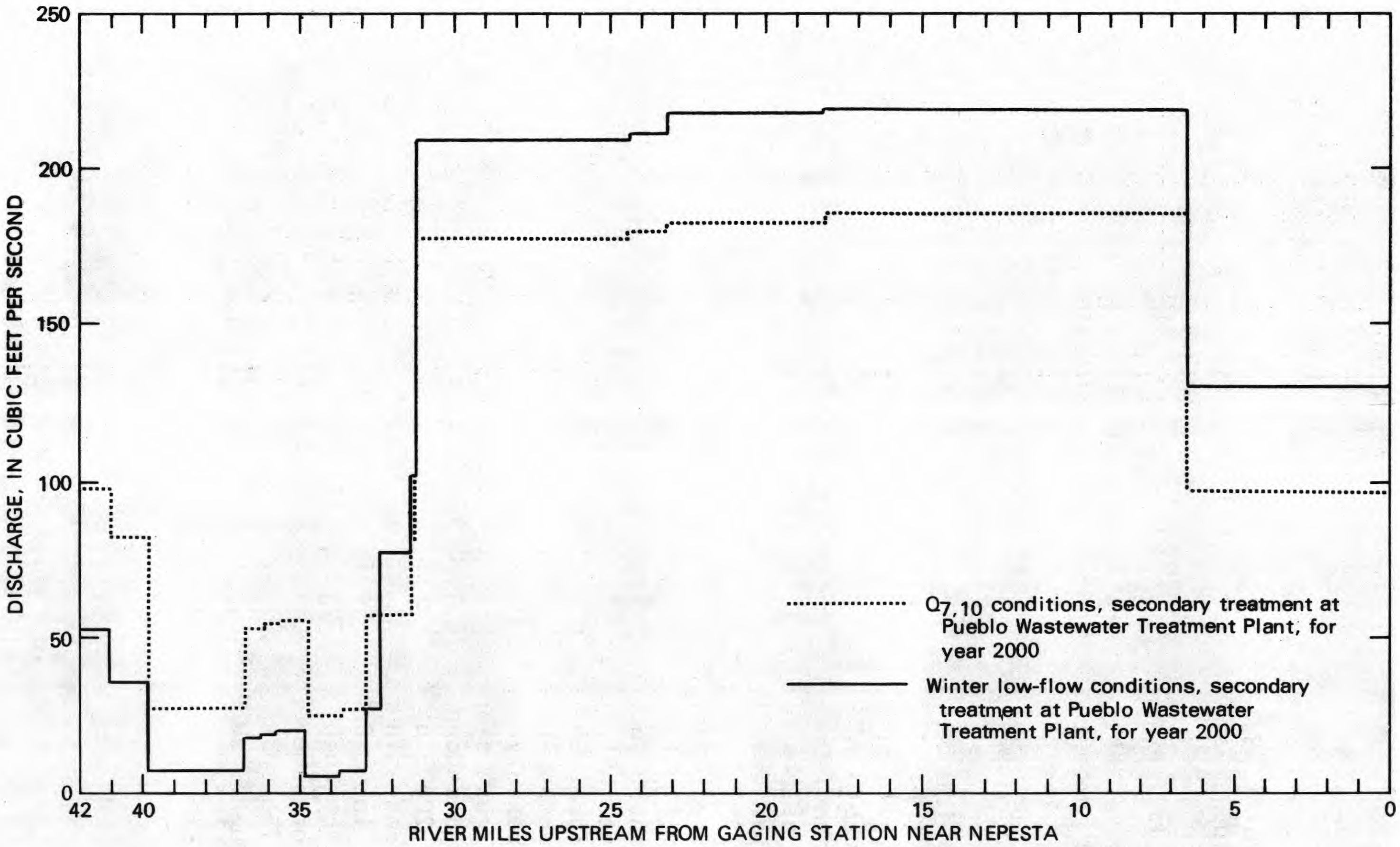

Figure 23.--Selected discharge profiles used during model simulations.

The different discharges used during model simulations require that different traveltimes and reaeration rates be input to the model. The traveltimes and reaeration rates for model simulations were calculated in the same way as during model calibration and verification. Because model simulations were made for low-flow periods which occur during different seasons, different stream temperatures were used. The required temperature data were collected in 1979 and 1980 by the water-quality monitor on the Arkansas River near Avondale (site 29, river mile 18.5). Additional diurnal temperature data were collected upstream and downstream from that site in April 1976, September 1979, and February 1980. The temperatures used during model simulations (tables 12 and 13) were based on estimates made from these data.

Wastewater-Treatment Possibilities

Different wastewater-treatment possibilities were considered for the Pueblo WWTP, for the CF&I Steel Corp., and for a small proposed wastewater-treatment plant for the St. Charles Mesa area east of Pueblo and south of the Arkansas River (fig. 3). The evaluation of water-quality management alternatives was primarily directed towards different wastewater-treatment possibilities at the Pueblo WWTP. Wastewater-treatment alternatives for the effluent from the CF&I Steel Corp. were considered only because it enters the river in the same reach as the effluent from the Pueblo WWTP, with consequent effects on instream water quality.

Four different wastewater-treatment possibilities were considered for the Pueblo WWTP: (1) existing (1980) conditions, (2) secondary treatment (ST), (3) advanced secondary treatment (AST), and (4) land application of treated effluent (LA). During this study, ST assumes 85-percent removal of BOD, or an effluent BOD concentration of 30 mg/L, whichever is more stringent (U.S. Environmental Protection Agency, 1979). AST refers to treatment modes higher than secondary and includes conversion of ammonia to nitrate. LA would result in no direct discharge of effluent to the Arkansas River. For secondary and advanced secondary treatment, model-simulation runs were made for the years 1985 and 2000, using increased discharge from the Pueblo WWTP based on projected increases in population and industrial discharges (D. Lederle, Sellards & Grigg, Inc., Consulting Engineers, written commun., 1980). Seasonal variations in the Pueblo WWTP effluent are reflected in differences in model-input values for some parameters between the $Q_{7,10}$ and winter low-flow model simulations. The model inputs for each of the wastewater-treatment possibilities at the Pueblo WWTP are compiled in tables 14 and 15.

Table 12.--*Hydraulic data used during model simulations of* $Q_{7,10}$ *conditions*

Model sub-reach	River mile at upstream end of subreach[1]	River mile at down-stream end of subreach[1]	Condition modeled[2]	Discharge change at beginning of subreach (cubic feet per second)	Mean temperature of subreach (degrees Celsius)	Reaeration rate in subreach ($days^{-1}$)[3]	Traveltime in subreach (hours)
1	42.0	41.0	DIS	98	20.0	8.3	1.1
			LA	98	20.0	8.3	1.1
2	41.0	39.8	DIS	-16	20.0	7.8	1.5
			LA	-16	20.0	7.8	1.5
3	39.8	38.0	DIS	-55	20.0	8.8	5.3
			LA	-55	20.0	8.8	5.3
4	38.0	37.5	DIS	.2	20.5	8.8	1.5
			LA	.2	20.5	8.8	1.5
5	37.5	37.4	DIS	.6	20.5	8.8	.3
			LA	.6	20.5	8.8	.3
6	37.4	37.3	DIS	0	20.5	8.8	.3
			LA	0	20.5	8.8	.3
7	37.3	36.7	DIS	.8	20.5	8.8	1.8
			LA	.8	20.5	8.8	1.8
8	36.7	36.2	DIS	25	20.5	8.1	.8
			LA	25	20.5	8.1	.8
9	36.2	35.9	DIS	.9	20.5	8.1	.5
			LA	.9	20.5	8.1	.5
10	35.9	35.7	DIS	1.3	20.5	8.1	.3
			LA	1.3	20.5	8.1	.3
11	35.7	34.7	DIS	.1	20.0	8.1	1.6
			LA	.1	20.0	8.1	1.6
12	34.7	33.6	DIS	-30	20.0	11.1	3.2
			LA	-30	20.0	11.1	3.2
13	33.6	32.8	DIS	1.3	20.0	8.8	2.4
			LA	1.3	20.0	8.8	2.4
14	32.8	32.3	DIS	30	21.0	8.2	.8
			LA	30	21.0	8.2	.8
15	32.3	31.3	DIS	0	21.0	8.2	1.6
			LA	0	21.0	8.2	1.6

16	31.3	31.2	DIS	[4]----	21.0	9.5	.1
			LA	0	21.0	8.9	.2
17	31.2	30.2	DIS	0	21.0	8.1	1.2
			LA	0	21.0	8.5	1.3
18	30.2	29.0	DIS	[5]----	22.0	8.8	1.1
			LA	[5]----	22.0	9.0	1.1
19	29.0	27.0	DIS	0	21.5	8.9	2.0
			LA	0	21.5	9.2	2.0
20	27.0	24.3	DIS	0	21.5	8.0	2.8
			LA	0	21.5	8.3	2.9
21	24.3	24.2	DIS	[6]----	21.0	8.4	.1
			LA	[6]----	21.0	8.6	.1
22	24.2	23.2	DIS	.1	21.0	9.2	1.0
			LA	.1	21.0	9.4	1.0
23	23.2	18.1	DIS	3	20.5	10.2	3.9
			LA	3	20.5	10.3	4.0
24	18.1	12.4	DIS	3	20.0	13.6	4.4
			LA	3	20.0	13.9	4.5
25	12.4	7.4	DIS	0	20.0	19.3	3.7
			LA	0	20.0	19.7	3.9
26	7.4	6.7	DIS	0	19.5	12.7	1.1
			LA	0	19.5	12.9	1.2
27	6.7	.0	DIS	-89	19.5	19.3	6.8
			LA	-89	19.5	19.3	7.6

[1]River mile upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[2]DIS=discharge of effluent from Pueblo Wastewater Treatment Plant to Arkansas River; LA=land application of effluent from Pueblo Wastewater Treatment Plant.

[3]The mean temperature of subreach, in degrees Celsius, used in calculating reaeration rate, using equation of Padden and Gloyna (1971).

[4]Discharge varies for different years; inputs compiled in table 9.

[5]Discharge varies for different seasons and years; inputs compiled in table 11.

[6]Discharge varies for different years; inputs compiled in table 11.

Table 13.--*Hydraulic data used during model simulations of winter low-flow conditions*

Model sub-reach	River mile at upstream end of subreach[1]	River mile at down-stream end of subreach[1]	Condition modeled[2]	Discharge change at beginning of subreach (cubic feet per second)	Mean temperature of subreach (degrees Celsius)	Reaeration rate in subreach ($days^{-1}$)[3]	Traveltime in subreach (hours)
1	42.0	41.0	DIS	52	4.0	6.1	1.8
			LA	52	4.0	6.1	1.8
2	41.0	39.8	DIS	-16	4.0	5.9	2.9
			LA	-16	4.0	5.9	2.9
3	39.8	38.0	DIS	-30	4.0	18.0	13.2
			LA	-30	4.0	18.0	13.2
4	38.0	37.5	DIS	.2	4.0	18.0	3.7
			LA	.2	4.0	18.0	3.7
5	37.5	37.4	DIS	.6	4.0	18.0	.7
			LA	.6	4.0	18.0	.7
6	37.4	37.3	DIS	0	4.0	18.0	.7
			LA	0	4.0	18.0	.7
7	37.3	36.7	DIS	.8	4.0	23.9	2.9
			LA	.8	4.0	23.9	2.9
8	36.7	36.2	DIS	10	4.0	9.2	1.8
			LA	10	4.0	9.2	1.8
9	36.2	35.9	DIS	.9	4.0	9.2	1.1
			LA	.9	4.0	9.2	1.1
10	35.9	35.7	DIS	1.3	4.0	6.8	.7
			LA	1.3	4.0	6.8	.7
11	35.7	34.7	DIS	.1	4.0	6.8	3.7
			LA	.1	4.0	6.8	3.7
12	34.7	33.6	DIS	-15	4.0	18.0	8.1
			LA	-15	4.0	18.0	8.1
13	33.6	32.8	DIS	1.3	4.0	18.0	5.9
			LA	1.3	4.0	18.0	5.9
14	32.8	32.3	DIS	15	5.0	6.9	1.8
			LA	15	5.0	6.9	1.8
15	32.3	31.3	DIS	55	5.5	6.1	1.3
			LA	55	5.5	6.1	1.3

16	31.3	31.2	DIS	[4]----	6.0	7.3	.1
			LA	0	5.5	7.0	.1
17	31.2	30.2	DIS	0	6.0	5.8	1.1
			LA	0	5.5	5.9	1.2
18	30.2	29.0	DIS	[5]----	7.0	6.4	1.0
			LA	[5]----	6.5	6.3	1.1
19	29.0	27.0	DIS	0	7.0	6.5	1.9
			LA	0	6.5	6.5	1.9
20	27.0	24.3	DIS	0	7.0	4.5	2.6
			LA	0	6.5	5.8	2.8
21	24.3	24.2	DIS	[6]----	7.0	6.2	.1
			LA	[6]----	6.5	6.2	.1
22	24.2	23.2	DIS	.1	6.5	6.7	.9
			LA	.1	6.0	6.6	1.0
23	23.2	18.1	DIS	7	6.5	7.4	3.6
			LA	7	6.0	7.4	3.8
24	18.1	12.4	DIS	1	6.5	9.9	4.2
			LA	1	6.0	9.9	4.3
25	12.4	7.4	DIS	0	6.5	14.3	3.2
			LA	0	6.0	14.3	3.7
26	7.4	6.7	DIS	0	6.0	9.4	1.0
			LA	0	5.5	9.4	1.1
27	6.7	.0	DIS	-89	6.0	14.0	6.2
			LA	-89	5.5	14.2	6.5

[1]River mile upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[2]DIS=discharge of effluent from Pueblo Wastewater Treatment Plant to Arkansas River; LA=land application of effluent from Pueblo Wastewater Treatment Plant.

[3]The mean temperature of subreach, in degrees Celsius, used in calculating reaeration rate, using equation of Padden and Gloyna (1971).

[4]Discharge varies for different years; inputs compiled in table 9.

[5]Discharge varies for different seasons and years; inputs compiled in table 11.

[6]Discharge varies for different years; inputs compiled in table 11.

Table 14.--*Model inputs for different wastewater-treatment possibilities at the Pueblo Wastewater Treatment Plant for $Q_{7,10}$ model simulations*

[mg/L=milligram per liter]

Wastewater treatment[1]	Discharge (cubic feet per second)[2]	Carbonaceous biochemical oxygen demand (5-day) (mg/L)[3]	Total organic nitrogen (mg/L)[4]	Total ammonia nitrogen (mg/L)	Total nitrite nitrogen (mg/L)[4]	Total nitrate nitrogen (mg/L)	Dissolved oxygen deficit (mg/L)[5]
Existing conditions--	18.6	[6]29.9	4.1	[2]18.7	0.19	[4]0.06	1.4
ST-Year 1985--	21.0	30.0	4.1	[2]18.7	.19	[4].06	1.4
ST-Year 2000--	24.6	30	4.1	[2]18.2	.19	[4].06	1.4
			Year 1985[7]				
AST(.06)-DPL--	21.0	30	4.1	[8]4.30	.19	[9]14.1	1.4
AST(.06)-2BAT-	21.0	30	4.1	[8]10.4	.19	[9]8.34	1.4
AST(.06)-BAT--	21.0	30	4.1	[8]10.8	.19	[9]7.98	1.4
AST(.10)-DPL--	21.0	30	4.1	[8]12.9	.19	[9]5.89	1.4
AST(.10)-2BAT-	21.0	30.0	4.1	[8]18.6	.19	[9].14	1.4
AST(.10)-BAT--	21.0	30.0	4.1	[8,10]19.0	.19	[9]0	1.4
			Year 2000[7]				
AST(.06)-DPL--	24.6	30.0	4.1	[8]3.90	.19	[9]14.4	1.4
AST(.06)-2BAT-	24.6	30.0	4.1	[8]9.11	.19	[9]9.15	1.4
AST(.06)-BAT--	24.6	30.0	4.1	[8]9.42	.19	[9]8.84	1.4
AST(.10)-DPL--	24.6	30.0	4.1	[8]11.4	.19	[9]6.91	1.4
AST(.10)-2BAT-	24.6	30.0	4.1	[8]16.2	.19	[9]2.01	1.4
AST(.10)-BAT--	24.6	30.0	4.1	[8]16.8	.19	[9]1.45	1.4
			Year 2000[11]				
AST(.06)-DPL--	24.6	30.0	4.1	[8]5.35	.19	[9]12.9	1.4
AST(.06)-2BAT-	24.6	30.0	4.1	[8]10.2	.19	[9]8.02	1.4
AST(.06)-BAT--	24.6	30.0	4.1	[8]10.6	.19	[9]7.70	1.4
AST(.10)-DPL--	24.6	30.0	4.1	[8]13.2	.19	[9]5.02	1.4
AST(.10)-2BAT-	24.6	30.0	4.1	[8]18.1	.19	[9].12	1.4
AST(.10)-BAT--	24.6	30.0	4.1	[8,10]18.4	.19	[9]0	1.4
			Year 1985-2000				
LA------------	0	0	0	0	0	0	0

[1]When two groups of letters appear together, the first group refers to Pueblo Wastewater Treatment Plant and the second refers to CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology (R. Shankland, U.S. Environmental Protection Agency, written commun., 1979); and 2BAT=twice BAT limits.

Table 14.--*Model inputs for different wastewater-treatment possibilities at the Pueblo Wastewater Treatment Plant for $Q_{7,10}$ model simulations*--Continued

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[2]Values recommended by D. Lederle (Sellards and Grigg, Inc., Consulting Engineers, written commun., 1980).

[3]Definition of secondary treatment from the U.S. Environmental Protection Agency (1979), unless otherwise indicated.

[4]Average from samples collected by U.S. Geological Survey, September 1979.

[5]Average from measurements made by U.S. Geological Survey, September 1979 and data from NPDES monitoring reports.

[6]Seasonal average from NPDES monitoring reports.

[7]Inputs for total ammonia from Pueblo Wastewater Treatment Plant for model simulations were established based on stream limitations for nonionized ammonia nitrogen being met near 23d Lane (river mile 29.6).

[8]See text for explanation of process used to determine these values.

[9]Because advanced secondary treatment is defined (U.S. Environmental Protection Agency, 1979) to be conversion of ammonia to nitrate, any change from secondary treatment to advanced secondary treatment for total ammonia-nitrogen values was reflected in a corresponding change in total nitrate values.

[10]Total ammonia concentration for advanced secondary treatment is higher than for secondary treatment so would not realistically be considered as a treatment alternative.

[11]Input for total ammonia from Pueblo Wastewater Treatment Plant for model simulations were established based on stream limitations for nonionized ammonia nitrogen being met at the end of the mixing zone (river mile 28.6).

Table 15.--*Model inputs for different wastewater-treatment possibilities at the Pueblo Wastewater Treatment Plant for winter low-flow model simulations*

[mg/L=milligram per liter]

Wastewater treatment[1]	Discharge (cubic feet per second)[2]	Carbonaceous biochemical oxygen demand (5-day) (mg/L)[3]	Total organic nitrogen (mg/L)[4]	Total ammonia nitrogen (mg/L)	Total nitrite nitrogen (mg/L)[4]	Total nitrate nitrogen (mg/L)	Dissolved oxygen deficit (mg/L)[5]
Existing conditions--	18.6	[5]43.3	4.1	[2]20.8	0.19	[4]0.06	2.3
ST-Year 1985--	21.0	30.0	4.1	[2]20.5	.19	[4].06	2.3
ST-Year 2000--	24.6	30.0	4.1	[2]19.8	.19	[4].06	2.3
			Year 1985[6]				
AST(.06)-DPL--	21.0	30.0	4.1	[7]20.0	.19	[8].06	2.3
AST(.06)-2BAT-	21.0	30.0	4.1	[7,9]25.8	.19	[8]0	2.3
AST(.06)-BAT--	21.0	30.0	4.1	[7,9]26.1	.19	[8]0	2.3
AST(.10)-DPL--	21.0	30.0	4.1	[7,9]40.7	.19	[8]0	2.3
AST(.10)-2BAT-	21.0	30.0	4.1	[7,9]46.4	.19	[8]0	2.3
AST(.10)-BAT--	21.0	30.0	4.1	[7,9]46.8	.19	[8]0	2.3
			Year 2000[6]				
AST(.06)-DPL--	24.6	30.0	4.1	[7]17.6	.19	[8]2.31	2.3
AST(.06)-2BAT-	24.6	30.0	4.1	[7,9]22.5	.19	[8]0	2.3
AST(.06)-BAT--	24.6	30.0	4.1	[7,9]22.8	.19	[8]0	2.3
AST(.10)-DPL--	24.6	30.0	4.1	[7,9]35.5	.19	[8]0	2.3
AST(.10)-2BAT-	24.6	30.0	4.1	[7,9]40.4	.19	[8]0	2.3
AST(.10)-BAT--	24.6	30.0	4.1	[7,9]40.7	.19	[8]0	2.3
			Year 2000[10]				
AST(.06)-DPL--	24.6	30.0	4.1	[7]18.2	.19	[8]1.64	2.3
AST(.06)-2BAT-	24.6	30.0	4.1	[7,9]23.1	.19	[8]0	2.3
AST(.06)-BAT--	24.6	30.0	4.1	[7,9]23.4	.19	[8]0	2.3
AST(.10)-DPL--	24.6	30.0	4.1	[7,9]36.6	.19	[8]0	2.3
AST(.10)-2BAT-	24.6	30.0	4.1	[7,9]41.5	.19	[8]0	2.3
AST(.10)-BAT--	24.6	30.0	4.1	[7,9]41.8	.19	[8]0	2.3
			Year 1985-2000				
LA------------	0	0	0	0	0	0	0

[1]When two groups of letters appear together, the first group refers to Pueblo Wastewater Treatment Plant and the second refers to CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology (R. Shankland, U.S. Environmental Protection Agency, written commun., 1979); and 2BAT=twice BAT limits.

Table 15.--*Model inputs for different wastewater-treatment possibilities at the Pueblo Wastewater Treatment Plant for winter low-flow model simulations*--Continued

[2]Values recommended by D. Lederle (Sellards and Grigg, Inc., Consulting Engineers, written commun., 1980).

[3]Definition of secondary treatment from the U.S. Environmental Protection Agency (1979), unless otherwise indicated.

[4]Average from samples collected by U.S. Geological Survey, September 1979.

[5]Seasonal average from NPDES monitoring reports.

[6]Inputs for total ammonia from Pueblo Wastewater Treatment Plant for model simulations were established based on stream limitations for nonionized ammonia nitrogen being met near 23d Lane (river mile 29.6).

[7]See text for explanation of process used to determine these values.

[8]Because advanced secondary treatment is defined (U.S. Environmental Protection Agency, 1979) to be conversion of ammonia to nitrate, any change from secondary treatment to advanced secondary treatment for total ammonia-nitrogen values was reflected in a corresponding change in total nitrate values.

[9]Total ammonia concentration for advanced secondary treatment is higher than for secondary treatment so would not realistically be considered as a treatment alternative.

[10]Input for total ammonia from Pueblo Wastewater Treatment Plant for model simulations were established based on stream limitations for nonionized ammonia nitrogen being met at the end of the mixing zone (river mile 28.6).

Four different wastewater-treatment possibilities were considered for effluent from the CF&I Steel Corp. (site 20-A): (1) existing (1980) conditions, (2) current effluent water-quality limits set by the Colorado Department of Health (1979c) in the discharge permit (DPL) for the CF&I Steel Corp., (3) an estimation of effluent limits that will be required of the CF&I Steel Corp. as part of the best available technology (BAT) guidelines for the iron and steel industry (B. Shankland, U.S. Environmental Protection Agency, written commun., 1979), and (4) an alternative to the estimated BAT guidelines that would allow twice the amount of ammonia in that part of the effluent that results from the steelmaking process (2BAT). Different values for discharge and for some water-quality parameters were used for the $Q_{7,10}$ and winter low-flow model simulations based on seasonal variations. Different discharges were also used for the model simulations based on 1980 conditions as compared to the simulations for the years 1985 and 2000, which are based on discharge information from 1969 to 1978 (Dumeyer, 1979). The model inputs for each of the wastewater-treatment possibilities considered for the effluent are compiled in table 16.

Only secondary treatment was considered for the proposed St. Charles Mesa WWTP. For the model simulations it was assumed the outfall would be located at river mile 24.3 (Pueblo Regional Planning Commission, 1977). As noted in table 16, the probable discharge from this facility would be small and is not likely to have a significant water-quality effect on the Arkansas River. For this reason, only secondary treatment was considered (D. Baldridge, Pueblo Area Council of Governments, written commun., 1979).

Water-quality data input to the model for other wastewater discharges, drainage ditches, tributaries, and the Arkansas River at the upstream end of the study reach were based on an average of data collected during April 1976 and September 1979. These model inputs were not varied for the different low-flow periods unless available data indicated significant seasonal trends in the water-quality data used by the model. One instance where significant seasonal trends occur is on Fountain Creek. Concentrations of nitrogen species and BOD in Fountain Creek at the mouth (site 16) are generally different in the winter. The values used for these parameters during the winter low-flow period model simulations are based on an average of available data from November 15 to March 15 during the 1975 to 1979 period (table 17). The water-quality values used during model simulations for sites other than the Pueblo WWTP, the CF&I Steel Corp., and the proposed St. Charles Mesa Wastewater Treatment Plant are given in table 17.

Water-Quality Guidelines

The instream water-quality guidelines used in the evaluation of management alternatives are based on the stream-use classification. The Arkansas River in Pueblo County is currently classified as B2, indicating warm-water aquatic life and secondary body-contact recreation (Colorado Department of Health, 1974). This classification may be changed in the near future as the Colorado Department of Health (1979a) reclassifies the Arkansas River and other streams in the State using a new classification scheme. Several possible classifications in the new scheme are under consideration for the Arkansas River in Pueblo County (Pueblo Area Council of Governments, 1978; Pueblo Regional Planning Commission, 1977). The classifications that affected and provided direction to this study are those proposed for the Arkansas River from the Pueblo Southside Waterworks Intake (river mile 37.2) to the eastern Pueblo County line. The classifications being considered for this reach are Class 2 Domestic Water Supply, Class 2 Recreation, Agriculture, and Warm-Water Aquatic Life. The Warm-Water Aquatic Life classification results in the most stringent set of guidelines for the water-quality constituents evaluated during this study. The water-quality guidelines (Colorado Department of Health, 1979a) are: a minimum DO concentration of 5.0 mg/L, a maximum concentration of nonionized ammonia as nitrogen of 0.06 mg/L, and a maximum concentration of total nitrite as nitrogen of 0.5 mg/L. A maximum concentration of nonionized ammonia as nitrogen of 0.10 mg/L was considered as an alternative water-quality guideline (T. Looby, Pueblo Area Council of Governments, oral commun., 1979).

Model Simulations for Existing (1980) Conditions, Secondary Treatment, and Land Application at the Pueblo Wastewater Treatment Plant

Model simulations were made for 26 different combinations of wastewater treatment and river low-flow periods, which included existing conditions, secondary treatment, and land application of treated effluent at the Pueblo WWTP. A summary of the results of these simulations is included in tables 18 and 19. Nine of these model simulations were selected for graphical presentation and discussion.

Each model simulation was made for a wastewater-treatment possibility at the Pueblo WWTP and the CF&I Steel Corp. for a given year and during a specific low-flow period. For greater ease in discussing model simulations, a shorthand notation was used to describe the various simulations. For example, ST-DPL-1985-$Q_{7,10}$ indicates the model simulation was made for $Q_{7,10}$ conditions, wastewater discharges for 1985, secondary treatment at the Pueblo WWTP, and current discharge-permit limits for water-quality constituents at the CF&I Steel Corp. As another example, LA-BAT-2000-Winter indicates the model simulation was made for winter low-flow conditions, wastewater discharges for the year 2000, land application of treated effluent at the Pueblo WWTP, and best available technology effluent water-quality limits for the CF&I Steel Corp.

Table 16.--*Model inputs for different wastewater-treatment possibilities for CF&I Steel Corp. and the proposed St. Charles Mesa Wastewater Treatment Plant*

[mg/L=milligram per liter]

Wastewater treatment[1]	Discharge[2] (cubic feet per second)	Carbonaceous biochemical oxygen demand[3] (5-day) (mg/L)	Total organic nitrogen[4] (mg/L)	Total ammonia nitrogen[4] (mg/L)	Total nitrite nitrogen[4] (mg/L)	Total nitrate nitrogen[4] (mg/L)	Dissolved oxygen deficit (mg/L)[5]
CF&I Steel Corp. ($Q_{7,10}$ conditions)							
Existing conditions--	[2]88	[2]2.0	[6]1.4	[3]0.31	[6]0.20	[6]1.6	[7]1.3
DPL-----------	[8]95	[9]10	[10]1.4	[4]1.66	[6].20	[6]1.6	[7]1.3
2BAT----------	[8]95	[9]10	[10]1.4	[5].39	[6].20	[6]1.6	[7]1.3
BAT-----------	[8]95	[9]10	[10]1.4	[5].31	[6].20	[6]1.6	[7]1.3
CF&I Steel Corp. (winter low-flow conditions)							
Existing conditions--	[2]89	[2]4.6	[10]1.4	[2]1.05	[10].20	[10]1.6	[11]1.5
DPL-----------	[8]108	[9]10	[10]1.4	[4]1.48	[6].20	[6]1.6	[11]1.5
2BAT----------	[8]108	[9]10	[10]1.4	[5].36	[6].20	[6]1.6	[11]1.5
BAT-----------	[8]108	[9]10	[10]1.4	[5].29	[6].20	[6]1.6	[11]1.5
St. Charles Mesa Wastewater Treatment Plant[12] (all flow conditions)							
Existing conditions--	0	0	0	0	0	0	0
ST-Year 1985--	1.0	30	8.3	[13]20	.2	.1	3.1
ST-Year 2000--	1.5	30	8.3	[13]20	.2	.1	3.1

[1]DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limit suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); 2BAT=twice BAT limits; and ST=secondary treatment.

[2]Seasonal averages from NPDES monitoring reports.

[3]CF&I Steel Corp. reported total ammonia as a gross value until May 1979, when it began reporting an influent total-ammonia value and an effluent net total-ammonia value. A $Q_{7,10}$ seasonal average for influent total ammonia of 0.06 mg/L was added to the 0.25 seasonal net-ammonia value to yield the 0.31 mg/L total-ammonia value for model input.

[4]NPDES permit effluent limit of 820 lbs/d of total ammonia (Colorado Department of Health, 1979c). Concentrations were based on seasonal flows. Since NPDES-permit limit is for net concentration of total ammonia, a NPDES-permit report seasonal average for influent total ammonia was added to net value. For the $Q_{7,10}$ period, 0.06 mg/L was added to 1.60 mg/L to yield 1.66 mg/L (853 lbs/d). For the winter season, 0.07 mg/L was added to 1.41 mg/L to yield 1.48 mg/L (864.7 lbs/d).

Table 16.--*Model inputs for different wastewater-treatment possibilities for CF&I Steel Corp. and the proposed St. Charles Mesa Wastewater Treatment Plant*--Continued

[5]Allows for a flow of 1 million gallons per day (B. Zander, U.S. Environmental Protection Agency, oral commun., January 14, 1980) from CF&I Steel Corp. Wastewater Treatment Plant plus effluent limitations for discharge from the steelmaking process. Specific breakdown of ammonia contributions are as follows: (a) Sewage-treatment plant--84 lbs/d; (b) BAT--42.4 lbs/d (steelmaking); and (c) 2BAT--2(42.4 lbs/d)=84.8 lbs/d. Therefore, under BAT limitations, the total-ammonia load from the CF&I Steel Corp. outfall is 126.4 lbs/d (42.4+84). For 2BAT it is 168.8 lbs/d (84.8+84). Sanitary sewer, BAT, and 2BAT recommendations were from R. Shankland (U.S. Environmental Protection Agency, written communs., March 3, 1978, and June 14, 1979). BAT and 2BAT limitations were for net-effluent concentrations (R. Shankland, U.S. Environmental Protection Agency, written commun., March 27, 1980). Therefore, the ammonia concentrations for the $Q_{7,10}$ season were adjusted by 0.07 mg/L, yielding 210.3 lbs/d for 2BAT and 169.4 lbs/d for BAT.

[6]Average of samples collected by U.S. Geological Survey, September 1979, data from NPDES monitoring reports, and additional data from CF&I Steel Corp.

[7]Average of measurements made by U.S. Geological Survey, September 1979, and data from NPDES monitoring reports.

[8]Seasonal averages from 10 years of discharge data (Dumeyer, 1979).

[9]NPDES permit limits (Colorado Department of Health, 1979c).

[10]Data furnished by CF&I Steel Corp.

[11]Seasonal average from NPDES monitoring reports.

[12]Input parameter values recommended in the Pueblo 208 Water Quality Management Plan (Pueblo Regional Planning Commission, 1977).

[13]Recommended by B. Zander (U.S. Environmental Protection Agency, written commun., January 7, 1980).

Table 17.--*Water-quality data used during model simulations*

[mg/L=milligram per liter]

Site number[1]	River mile[2]	Inflow type[3]	Carbonaceous biochemical oxygen demand (5-day) (mg/L)	Total organic nitrogen (N) (mg/L)	Total ammonia nitrogen (N) (mg/L)	Total nitrite nitrogen (N) (mg/L)	Total nitrate nitrogen (N) (mg/L)	Dissolved oxygen deficit[4] (mg/L)
1	42.0	I	1.5	0.36	0.05	0.05	0.40	[5]7.6, 11.9
3	38.0	D	2.9	1.3	.09	.09	6.9	0.4
4	37.5	D	3.2	1.1	.04	.07	11	-.4
5	37.3	D	.6	.49	.03	.03	4.7	-.5
7	36.7	D	2.2	.43	.04	.03	.36	-.6
8	36.2	D	1.1	.28	.15	.07	1.3	-.3
10	35.9	D	.9	1.0	.33	.04	.38	.6
11	35.7	T	1.4	.68	.06	.28	7.4	-.1
[6]12A	33.6	T	.7	.68	.11	.04	9.3	.2
14	32.8	W	1.8	.71	.05	.04	.55	-.6
[7]16	32.3	T	5.3	1.4	1.3	.08	3.0	-.7
[8]18	31.3	W	----	----	----	----	-----	--------
[9]20A	30.2	W	----	----	----	----	-----	--------
([10])	35.4	W	----	----	----	----	-----	--------
[11]24	24.2	W	10	1.0	.40	.25	12	.7
26	23.2	T	1.9	.9	.08	.11	5.8	-.4
30	18.1	T	1.2	1.0	.04	.05	5.6	.4
[12]34	17.4	T	0	0	0	0	0	0

[1]Refer to table 1 and figure 3.

[2]River mile upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]I=initial Arkansas River; D=drainage ditch or pipe; T=natural tributary; and W=wastewater effluent.

[4]Dissolved oxygen deficit defined as the difference between observed and saturation. Negative deficit is supersaturation (concentration greater than saturation).

[5]Dissolved oxygen concentration is input to model at initial Arkansas River site; first value was used during model simulations for $Q_{7,10}$ conditions; second value was used during model simulations for winter low-flow conditions.

[6]Model inputs at this site are based on data collected only in September 1979.

[7]Model inputs at this site, Fountain Creek at mouth, are for winter low-flow conditions only, since modeled discharge during $Q_{7,10}$ conditions is zero. Values are an average of available data collected between November 15 and March 15 each year since 1975.

[8]Model inputs at this site, Pueblo Wastewater Treatment Plant outfall, vary for different seasons, years, and wastewater-treatment possibilities. The inputs used are compiled in tables 9 and 11.

[9]Model inputs at this site, CF&I Steel Corp. outfall, vary for different seasons, years, and wastewater-treatment possibilities. The inputs used are compiled in table 11.

[10]This site is the proposed St. Charles Mesa Wastewater Treatment Plant. Model inputs vary for different years and are compiled in table 11.

[11]Model inputs at this site are based only on data collected during September 1979, since this better represents current and expected conditions.

[12]Model inputs at this site, Huerfano River near the mouth, are all zero, since modeled discharge is zero at this site.

Table 18.--*Results of model simulations for existing conditions, secondary treatment, and land application at the Pueblo Wastewater Treatment Plant for* $Q_{7,10}$ *conditions*

[mg/L=milligram per liter; lbs/d=pounds per day; WWTP=Wastewater Treatment Plant]

Model simulations[1]	Total ammonia: From Pueblo Wastewater Treatment Plant		Total ammonia: From CF&I Steel Corp.		Nonionized ammonia in stream		Total maximum daily load (TMDL) (lbs/d)[3]	Highest simulated total nitrite below Pueblo WWTP outfall		Lowest simulated dissolved oxygen below Pueblo WWTP outfall	
	mg/L	lbs/d	mg/L	lbs/d	Near 23d Lane (river mile 29.6)[2]	End of mixing zone (river mile 28.6)[2]		mg/L	River mile[2]	mg/L	River mile[2]
Existing conditions---	18.7	1,880	0.31	148	0.09	0.08	2,040	0.40	28.2	6.2	26.2
					Year 1985						
ST-DPL---------	18.7	2,120	1.66	853	.13	.12	2,990	.53	27.4	5.1	25.8
ST-2BAT--------	18.7	2,120	.39	200	.10	.09	2,330	.49	30.2	5.5	25.9
ST-BAT---------	18.7	2,120	.31	159	.10	.09	2,290	.42	28.4	5.6	25.9
					Year 2000						
ST-DPL---------	18.2	2,420	1.66	853	.14	.13	3,280	.57	27.3	4.8	25.6
ST-2BAT--------	18.2	2,420	.39	200	.11	.10	2,630	.53	30.2	5.3	25.9
ST-BAT---------	18.2	2,420	.31	159	.11	.10	2,590	.46	28.2	5.3	25.9
					Year 1985						
LA-DPL---------	0	0	1.66	853	.05	.04	865	.20	27.8	6.9	26.0
LA-2BAT--------	0	0	.39	200	.01	.01	212	.13	30.2	7.4	26.6
LA-BAT---------	0	0	.31	159	.01	.01	171	.13	30.2	7.5	26.6
					Year 2000						
LA-DPL---------	0	0	1.66	853	.05	.04	865	.20	27.8	7.0	24.3
LA-2BAT--------	0	0	.39	200	.01	.01	212	.13	30.2	7.4	26.6
LA-BAT---------	0	0	.31	159	.01	.01	171	.13	30.2	7.5	28.0

[1]First group of letters refers to wastewater treatment at the Pueblo Wastewater Treatment Plant. Second group of letters refers to wastewater treatment at CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limits suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); and 2BAT=twice BAT limits.

[2]River miles upstream from the streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]TMDL=lbs/d of total ammonia from Pueblo Wastewater Treatment Plant and CF&I Steel Corp., plus 12 lbs/d total ammonia in the Arkansas River above the Pueblo Wastewater Treatment Plant outfall.

Table 19.--*Results of model simulations for existing conditions, secondary treatment, and land application at the Pueblo Wastewater Treatment Plant for winter low-flow conditions*

[mg/L=milligram per liter; lbs/d=pounds per day; WWTP=Wastewater Treatment Plant]

Model simulations[1]	Total ammonia: From Pueblo Wastewater Treatment Plant		Total ammonia: From CF&I Steel Corp.		Nonionized ammonia in stream		Total maximum daily load (TMDL) (lbs/d)[3]	Highest simulated total nitrite below Pueblo WWTP outfall		Lowest simulated dissolved oxygen below Pueblo WWTP outfall	
	mg/L	lbs/d	mg/L	lbs/d	Near 23d Lane (river mile 29.6)[2]	End of mixing zone (river mile 28.6)[2]		mg/L	River mile[2]	mg/L	River mile[2]
Existing conditions---	20.8	2,090	1.05	506	0.06	0.06	2,980	0.54	12.6	10.0	24.3
					Year 1985						
ST-DPL---------	20.5	2,330	1.48	865	.06	.06	3,570	.59	13.0	9.8	24.3
ST-2BAT--------	20.5	2,330	.36	210	.05	.05	2,920	.50	11.3	10.0	24.3
ST-BAT---------	20.5	2,330	.29	169	.05	.05	2,880	.49	12.6	10.0	24.3
					Year 2000						
ST-DPL---------	19.8	2,640	1.48	865	.07	.06	3,880	.64	11.4	9.7	24.3
ST-2BAT--------	19.8	2,640	.36	210	.05	.05	3,220	.54	12.4	9.8	24.3
ST-BAT---------	19.8	2,640	.29	169	.05	.05	3,180	.54	10.7	9.9	24.3
					Year 1985						
LA-DPL---------	0	0	1.48	865	.02	.02	1,240	.26	15.7	11.0	24.3
LA-2BAT--------	0	0	.36	210	.01	.01	589	.16	30.2	11.2	24.2
LA-BAT---------	0	0	.29	169	.01	.01	548	.16	30.2	11.2	24.2
					Year 2000						
LA-DPL---------	0	0	1.48	865	.02	.02	1,240	.27	14.6	11.0	24.3
LA-2BAT--------	0	0	.36	210	.01	.01	589	.16	30.2	11.2	24.2
LA-BAT---------	0	0	.29	169	.01	.01	548	.16	30.2	11.2	24.2

[1]First group of letters refers to wastewater treatment at the Pueblo Wastewater Treatment Plant. Second group of letters refers to wastewater treatment at CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limits suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); and 2BAT=twice BAT limits.

[2]River miles upstream from the streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]TMDL=lbs/d of total ammonia from Pueblo Wastewater Treatment Plant and CF&I Steel Corp., plus 380 lbs/d total ammonia in the Arkansas River above the Pueblo Wastewater Treatment Plant outfall.

The model simulation for existing (1980) conditions of wastewater treatment for both the Pueblo WWTP and the CF&I Steel Corp. for $Q_{7,10}$ conditions (fig. 24) indicated the presence of nonionized ammonia nitrogen at concentrations greater than the water-quality guideline of 0.06 mg/L at the end of the mixing zone (table 20). The model simulation for existing (1980) conditions of wastewater treatment for winter low-flow conditions (fig. 25) indicated nonionized ammonia nitrogen would not exceed the water-quality guidelines of 0.06 mg/L (table 20), even though total ammonia concentrations at the end of the mixing zone were higher during the winter period. The reason for the difference is the lower percentage of nonionized ammonia in the river in winter (table 8) which results primarily from lower stream temperatures. Simulated total nitrite concentrations exceeded the water-quality guideline of 0.5 mg/L for the winter period but not for the $Q_{7,10}$ period. Lower winter stream temperatures result in smaller reaction rates which cause the greater simulated nitrite concentrations. Simulated DO concentrations for existing conditions were above the water-quality guideline of 5.0 mg/L during both periods.

Model simulations for ST-DPL-2000-$Q_{7,10}$ (fig. 26), ST-2BAT-2000-$Q_{7,10}$ (fig. 27), and ST-BAT-2000-$Q_{7,10}$ (fig. 28) indicate that concentrations of nonionized ammonia would exceed the water-quality guideline of 0.06 mg/L at the end of the mixing zone for all three sets of conditions (table 20). However, an alternative nonionized ammonia nitrogen water-quality guideline of 0.10 mg/L could be met for both ST-2BAT-2000-$Q_{7,10}$ and ST-BAT-2000-$Q_{7,10}$. In addition, acceptable concentrations of both total nitrite and DO would be present based on the two model simulations. Concentrations of DO and total nitrite would not be acceptable in terms of the water-quality guidelines for the simulated conditions ST-DPL-2000-$Q_{7,10}$. Model-simulation results for ST-2BAT-2000-Winter (fig. 29 and table 20) indicate that only total nitrite would be present at concentrations greater than the water-quality guideline.

A comparison of model-simulation results for existing (1980) conditions and secondary treatment at the Pueblo WWTP for the year 2000 indicates better simulated instream water-quality conditions for 1980 than for the year 2000 (table 20). This situation is primarily the result of a projected increase in effluent discharge at the Pueblo WWTP for the year 2000 (tables 14 and 15).

Model simulations which included land application of treated effluent at the Pueblo WWTP (figs. 30-32) resulted in no instream concentrations of nonionized ammonia, total nitrite, or DO in violation of water-quality guidelines. However, land application of treated effluent would result in decreased streamflow downstream from the Pueblo WWTP outfall and may result in nonpoint-source discharges to the Arkansas River. These factors were not evaluated during this study.

Table 20.--*Summary of results of selected model simulations*

[mg/L=milligram per liter]

Model simulation[1]	Concentration of nonionized ammonia at end of mixing zone, river mile 28.6[2] (mg/L)[3]	Largest model-computed concentration of total nitrite below the outfall from the Pueblo Wastewater Treatment Plant (mg/L)[4]	Smallest model-computed concentration of dissolved oxygen below the outfall from the Pueblo Wastewater Treatment Plant (mg/L)[5]
		$Q_{7,10}$ conditions	
Existing conditions---	0.08*	0.40	6.24
		Year 2000	
ST-DPL---------	.13*	.57*	4.84*
ST-2BAT--------	.10*	.47	5.30
ST-BAT---------	.10*	.46	5.33
AST(.06)-DPL---	.06	.29	6.04
AST(.06)-2BAT--	.06	.32	6.04
AST(.06)-BAT---	.06	.30	6.04
AST(.10)-DPL---	.10*	.46	5.30
AST(.10)-2BAT--	.10*	.53*	5.30
LA-DPL---------	.04	.20	6.95
LA-2BAT--------	.01	.13	7.44
LA-BAT---------	.01	.13	7.48
		Winter low-flow conditions	
Existing conditions---	.06	.54*	10.03
		Year 2000	
ST-2BAT--------	.05	.54*	9.85

[1]First group of letters refers to wastewater treatment at Pueblo Wastewater Treatment Plant. Second group of letters refers to wastewater treatment at CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limits suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); and 2BAT=twice BAT limits.

[2]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]Asterisk indicates concentration exceeds water-quality guideline of 0.06 mg/L nonionized ammonia nitrogen.

[4]Asterisk indicates concentration exceeds water-quality guideline of 0.50 mg/L nitrite nitrogen.

[5]Asterisk indicates concentration is less than water-quality guideline of 5.0 mg/L dissolved oxygen.

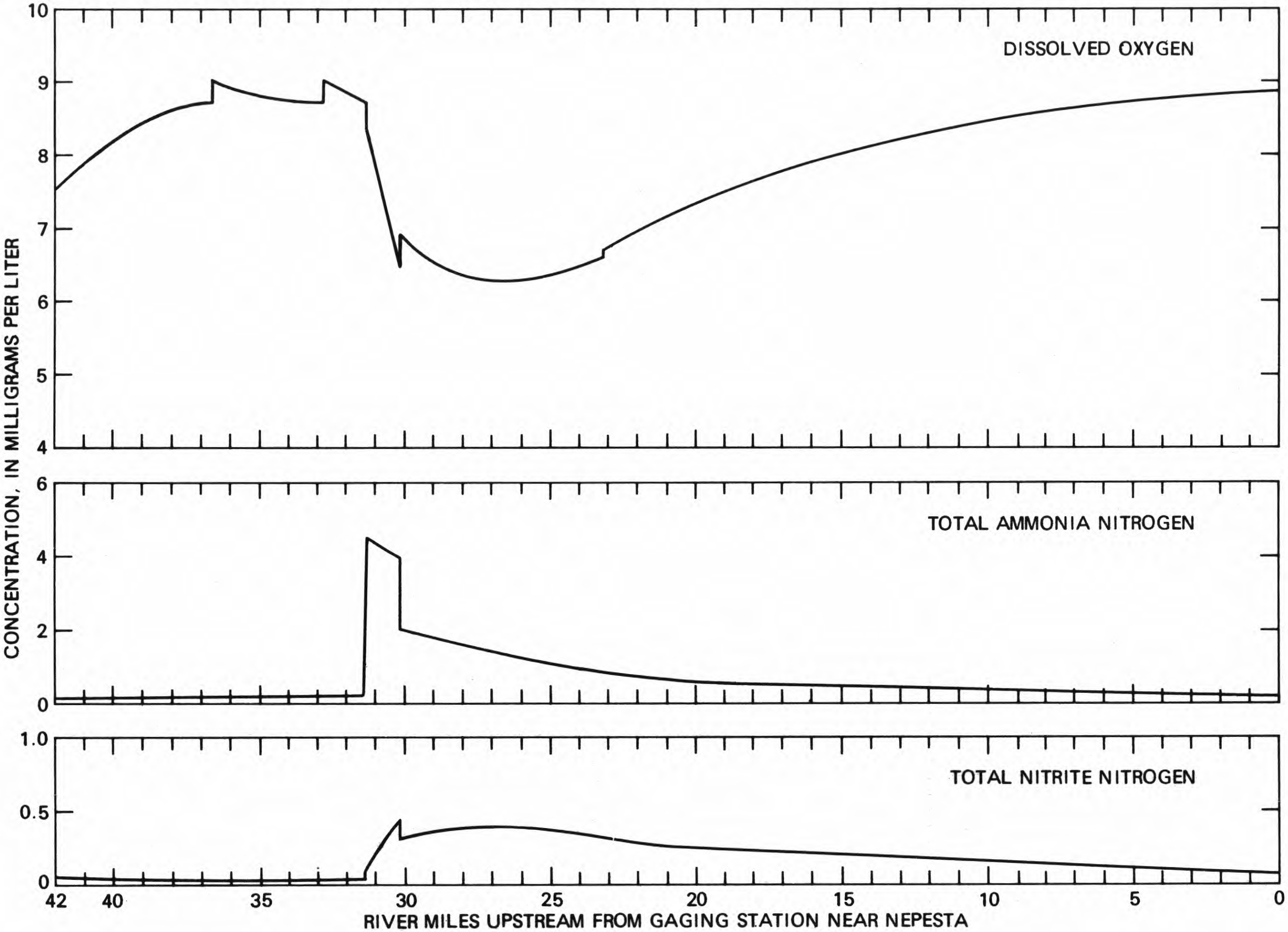

Figure 24.--Results of model simulation for existing (1980) wastewater-treatment conditions for $Q_{7,10}$ conditions.

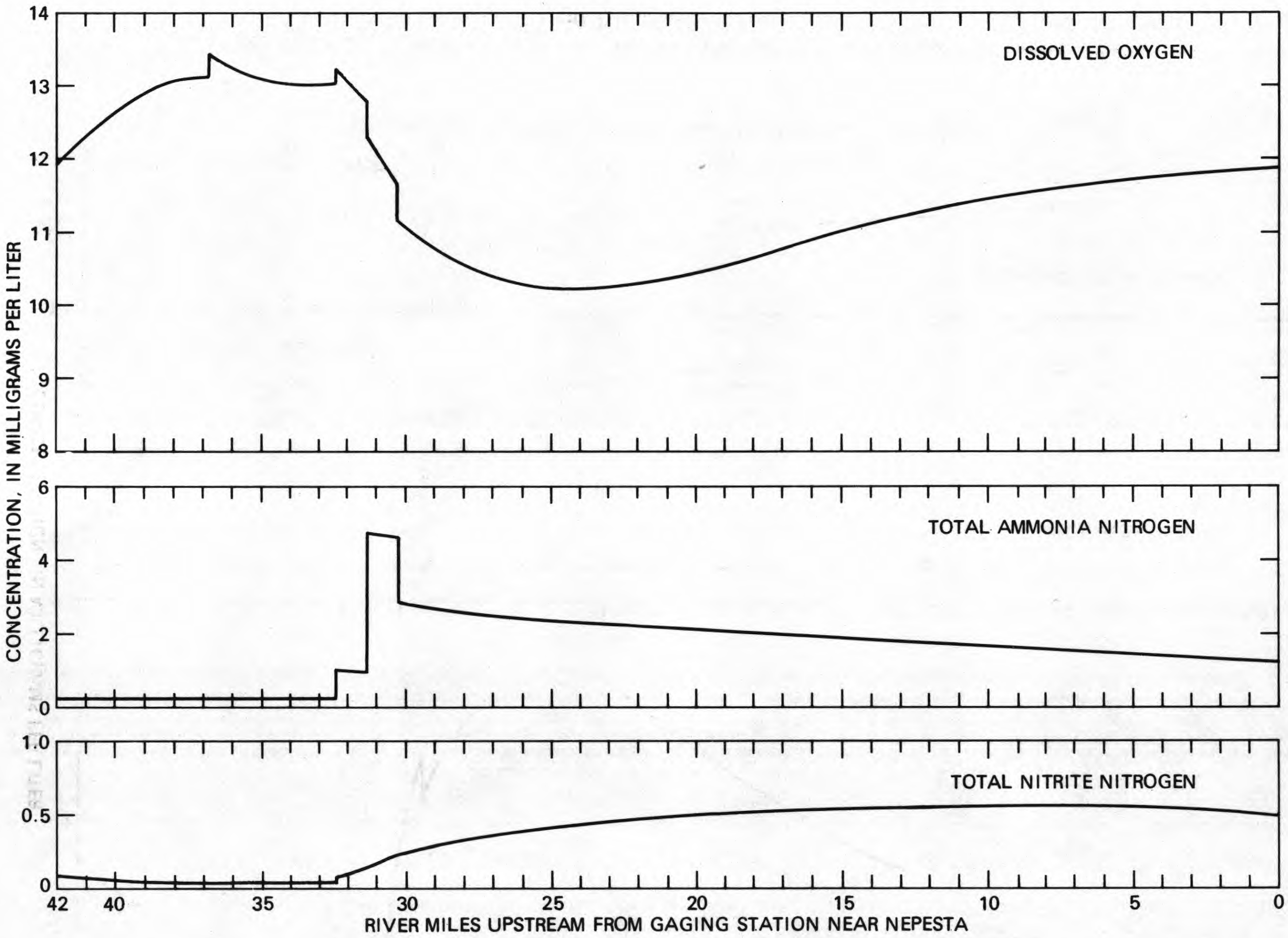

Figure 25.--Results of model simulation for existing (1980) wastewater-treatment conditions for winter low-flow conditions.

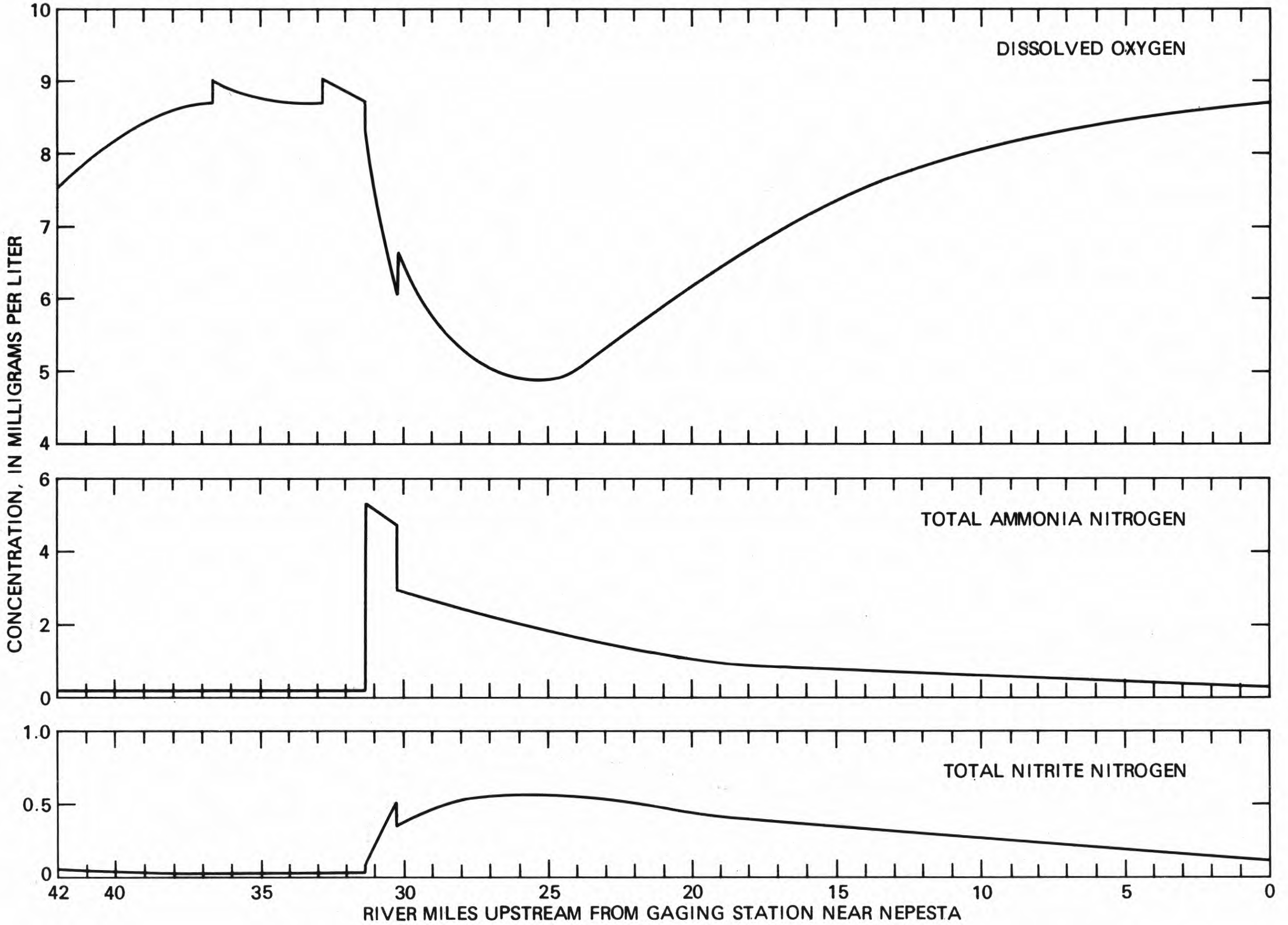

Figure 26.--Results of model simulation for secondary treatment at the Pueblo Wastewater Treatment Plant and current NPDES discharge permit effluent limits at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

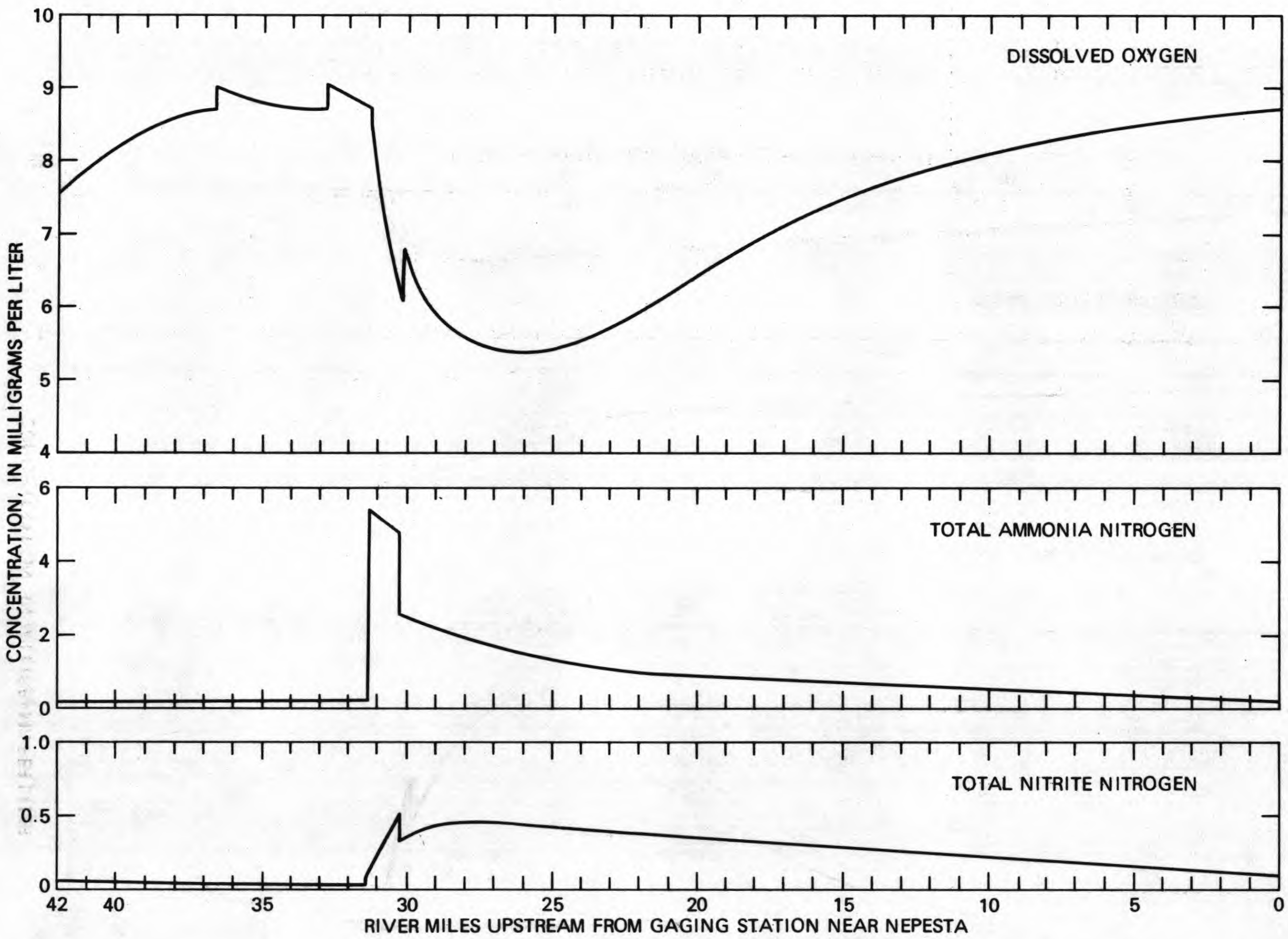

Figure 27.--Results of model simulation for secondary treatment at the Pueblo Wastewater Treatment Plant and twice-the-best available technology effluent concentration of ammonia at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

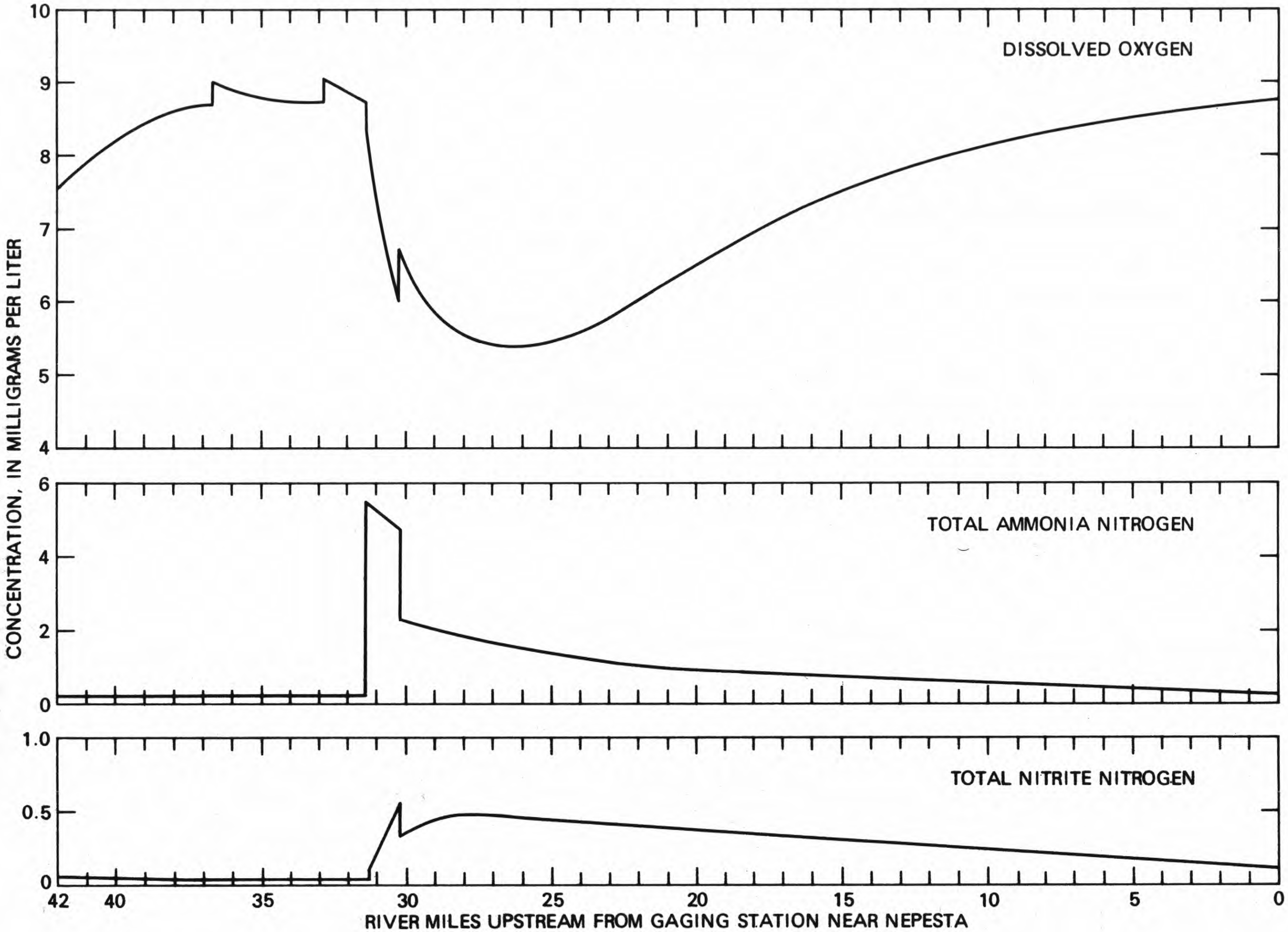

Figure 28.--Results of model simulation for secondary treatment at the Pueblo Wastewater Treatment Plant and best available technology wastewater treatment at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

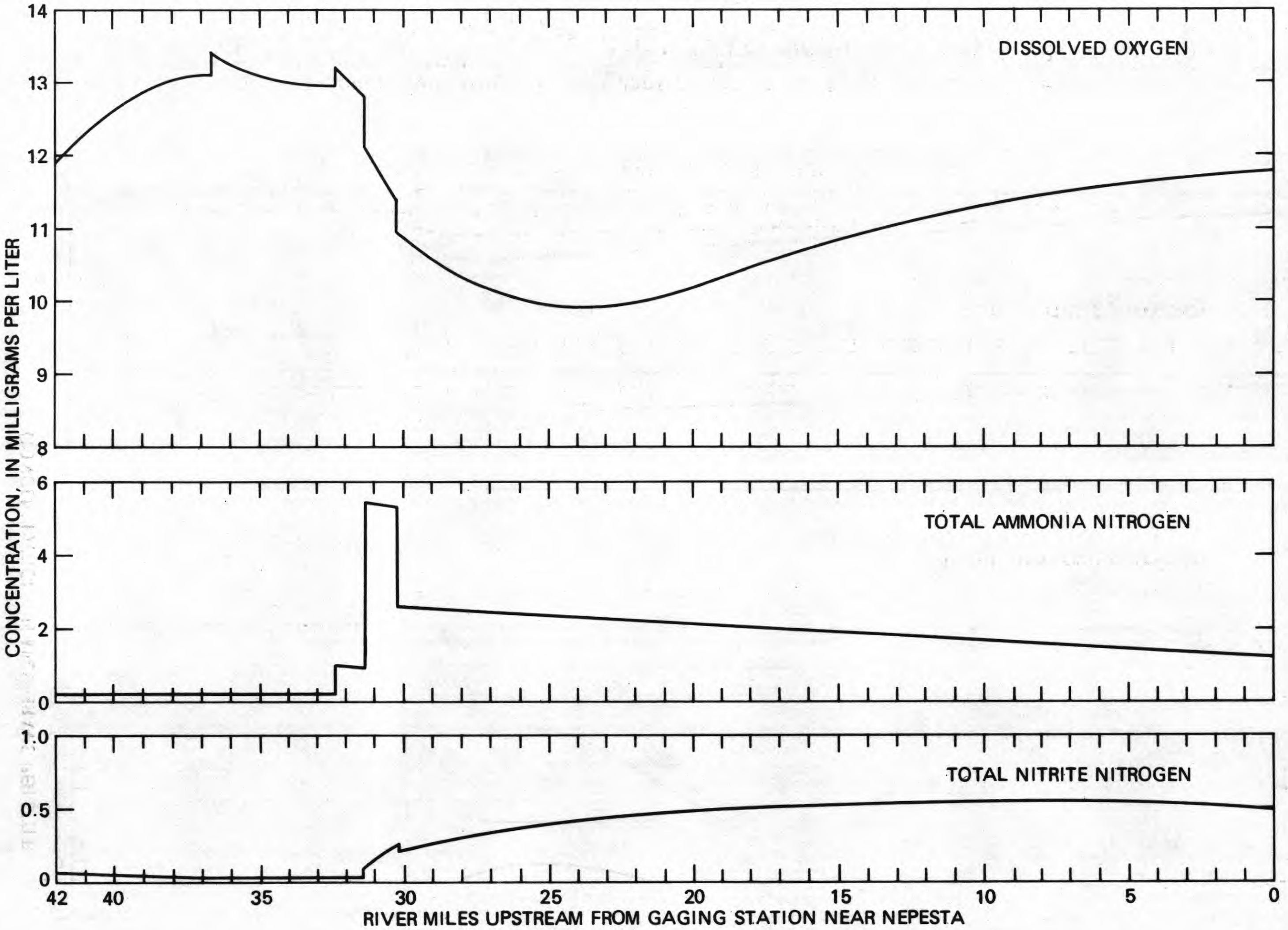

Figure 29.--Results of model simulation for secondary treatment at the Pueblo Wastewater Treatment Plant and best available technology wastewater treatment at CF&I Steel Corp. for winter low-flow conditions using projected wastewater discharges for the year 2000.

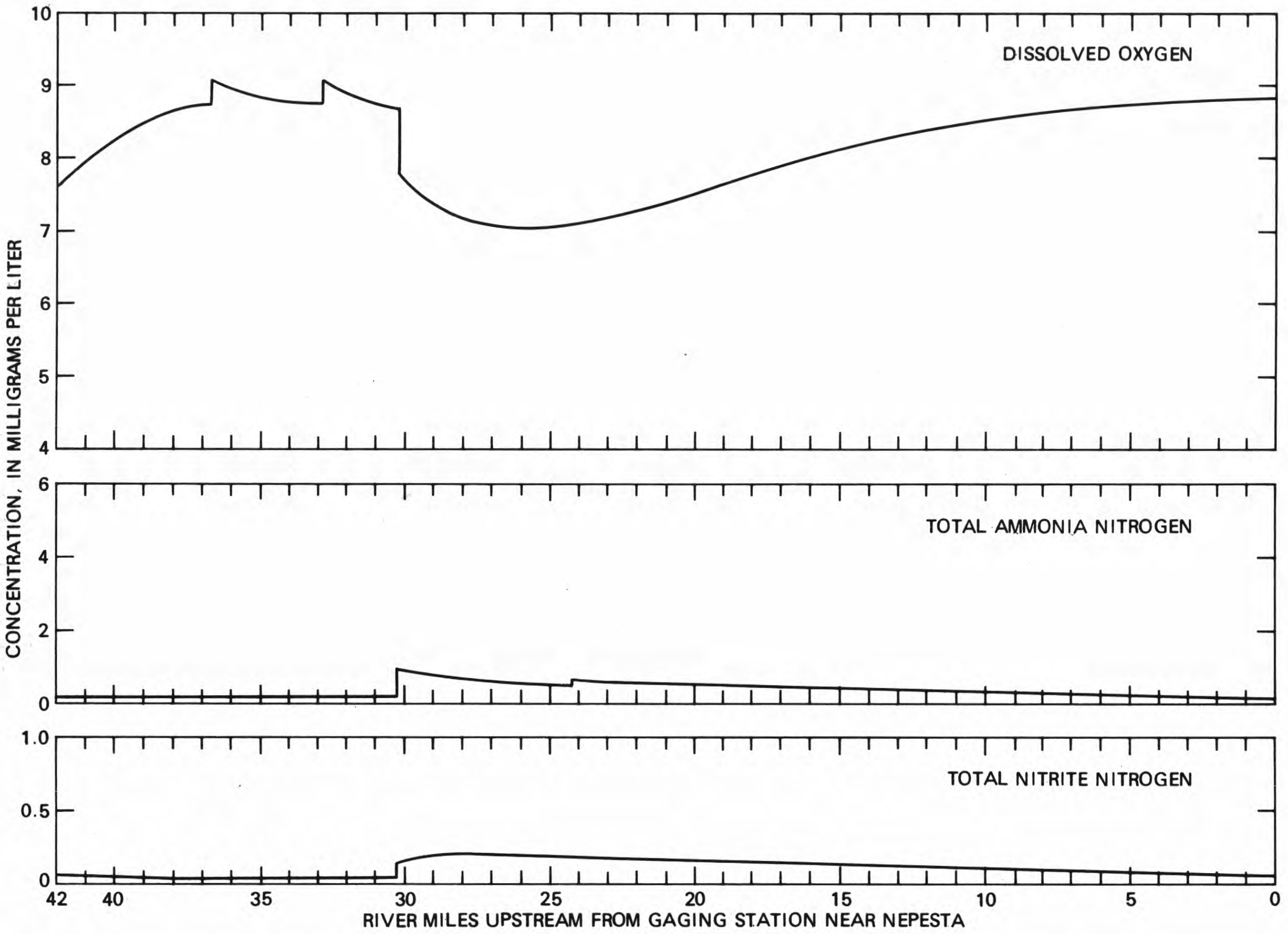

Figure 30.--Results of model simulation for land application of treated effluent at the Pueblo Wastewater Treatment Plant and current NPDES discharge permit effluent limits at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

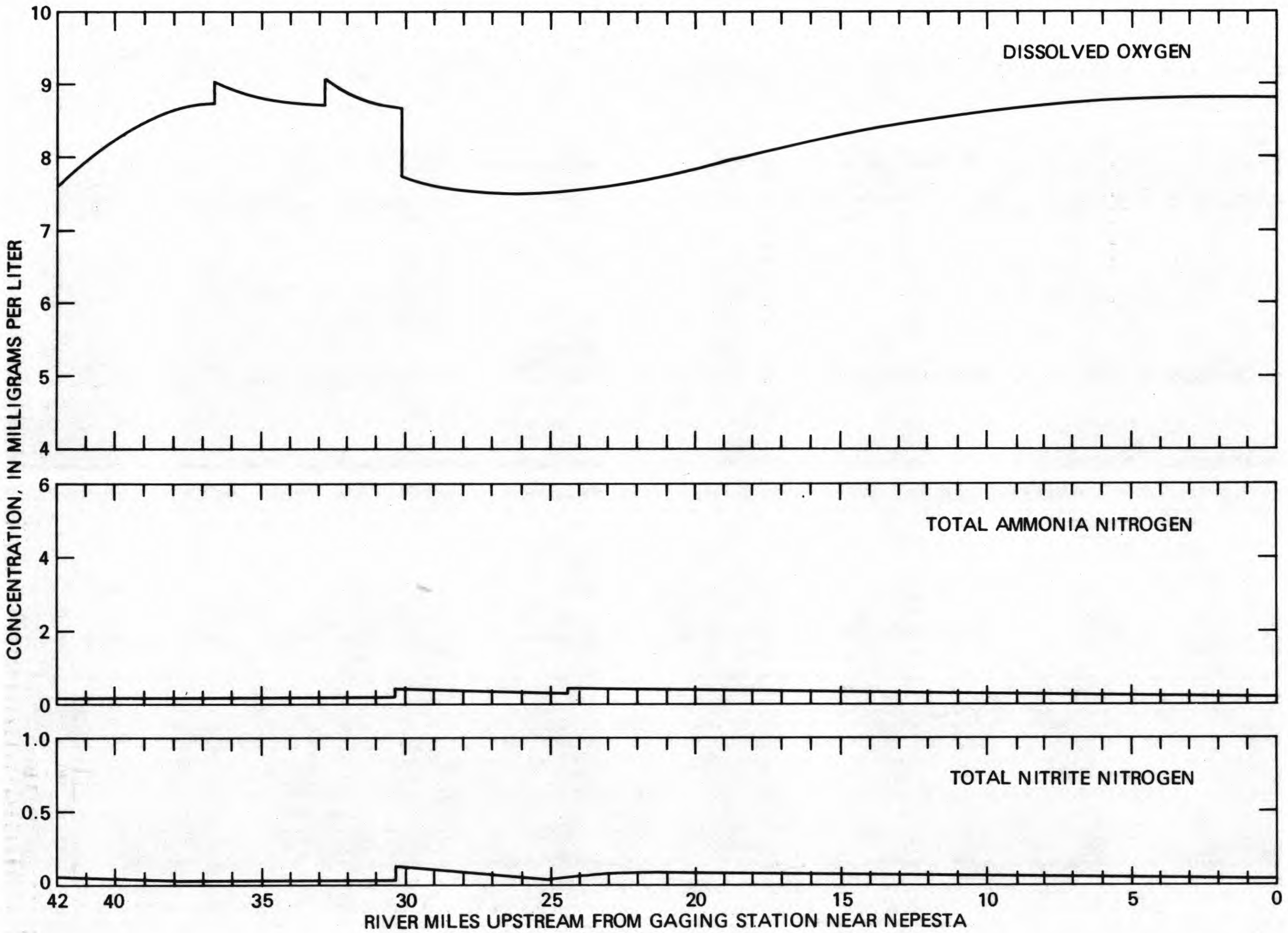

Figure 31.--Results of model simulation for land application of treated effluent at the Pueblo Wastewater Treatment Plant and twice-the-best available technology effluent concentration of ammonia at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

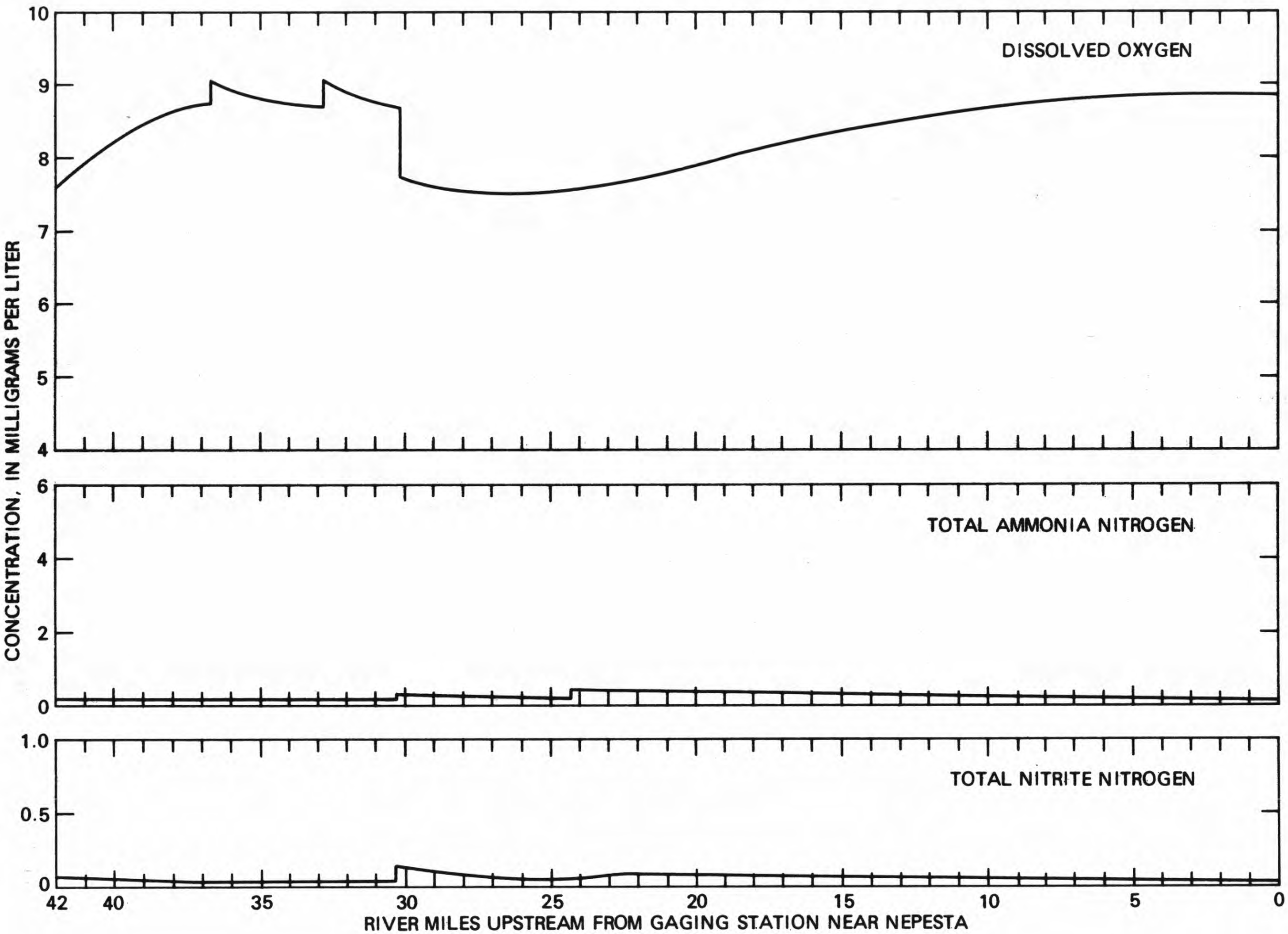

Figure 32.--Results of model simulation for land application of treated effluent at the Pueblo Wastewater Treatment Plant and best available technology wastewater treatment at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

Model Simulations for Advanced Secondary Treatment at the Pueblo Wastewater Treatment Plant

Model simulations for advanced secondary treatment at the Pueblo WWTP assume that advanced secondary treatment could be used to decrease total ammonia concentrations in the effluent from the Pueblo WWTP to levels necessary to meet an instream water-quality guideline for nonionized ammonia at the downstream end of the mixing zone (river mile 28.6) or at an alternative point (river mile 29.6). The total ammonia concentration in the effluent from the Pueblo WWTP input to the model was determined as follows. The total ammonia concentration at the end of the mixing zone, or at the alternative point, which would meet the water-quality guideline under consideration for nonionized ammonia, was calculated by dividing the water-quality guideline by the percentage of nonionized ammonia for the proper low-flow period (table 8) and multiplying the result by 100.

Using this total ammonia concentration, the total ammonia concentration just downstream from the CF&I Steel Corp. outfall was estimated using the decay rate for total ammonia in the river subreach (table 6). Because the simulated total ammonia concentrations and discharge at the CF&I Steel Corp. outfall were known for each wastewater-treatment possibility (table 16), a mass-balance calculation was made to determine the total ammonia concentration in the Arkansas River just upstream from the CF&I Steel Corp. outfall. Using the total ammonia concentration just upstream from the CF&I Steel Corp. outfall, the total ammonia concentration in the river just downstream from the Pueblo WWTP outfall was estimated based on the decay rate for total ammonia in the river subreach. The estimated concentration of total ammonia in the effluent from the Pueblo WWTP was then determined based on another mass-balance calculation. This value was input to the model for simulation purposes and checked to determine if the concentration of total ammonia at the end of the mixing zone was the same as the concentration calculated from the water-quality guideline for nonionized ammonia. In most cases, this value resulted in acceptable model-simulation results. If not, adjustments were made to the input total ammonia concentration until agreement was achieved. If the concentration of total ammonia in the effluent from the Pueblo WWTP determined in this way was greater than the concentration for secondary treatment under the same conditions, then advanced secondary treatment would not be necessary to meet the water-quality guideline (tables 14, 15, 21, and 22).

Table 21.--*Results of model simulations for advanced secondary treatment at the Pueblo Wastewater Treatment Plant for* $Q_{7,10}$ *conditions*

[mg/L=milligram per liter; lbs/d=pounds per day; WWTP=Wastewater Treatment Plant]

Model simulations[1]	Total ammonia: From Pueblo Wastewater Treatment Plant (mg/L)	Total ammonia: From Pueblo Wastewater Treatment Plant (lbs/d)	Total ammonia: From CF&I Steel Corp. (mg/L)	Total ammonia: From CF&I Steel Corp. (lbs/d)	Nonionized ammonia in stream at river mile 29.6 or 28.6[2] (mg/L)	Total maximum daily load (TMDL)[3] (lbs/d)	Highest simulated total nitrite below Pueblo WWTP outfall (mg/L)	Highest simulated total nitrite below Pueblo WWTP outfall (River mile[2])	Lowest simulated dissolved oxygen below Pueblo WWTP outfall (mg/L)	Lowest simulated dissolved oxygen below Pueblo WWTP outfall (River mile[2])
					Year 1985[4]					
AST(.06)-DPL---	4.30	531	1.66	853	0.06	1,400	0.26	27.9	6.2	25.4
AST(.06)-2BAT--	10.4	1,180	.39	200	.06	1,400	.28	28.6	6.2	25.8
AST(.06)-BAT---	10.8	1,220	.31	159	.06	1,400	.28	28.8	6.2	25.9
AST(.10)-DPL---	12.9	1,460	1.66	853	.10	2,330	.42	27.6	5.5	25.7
AST(.10)-2BAT--	18.6	2,120	.39	200	.10	2,330	.49	30.2	5.5	25.6
AST(.10)-BAT---	[5]19.0	2,160	.31	159	.10	2,330	.43	28.0	5.5	25.6
					Year 2000[4]					
AST(.06)-DPL---	3.90	519	1.66	853	.06	1,380	.26	28.0	6.2	25.7
AST(.06)-2BAT--	9.11	1,210	.39	200	.06	1,420	.28	28.6	6.2	26.0
AST(.06)-BAT---	9.42	1,250	.31	159	.06	1,420	.28	28.8	6.2	26.0
AST(.10)-DPL---	11.4	1,520	1.66	853	.10	2,360	.42	27.6	5.5	25.6
AST(.10)-2BAT--	16.2	2,160	.39	200	.10	2,380	.48	30.2	5.5	25.8
AST(.10)-BAT---	16.8	2,200	.31	159	.10	2,380	.49	30.2	5.5	26.0
					Year 2000[6]					
AST(.06)-DPL---	5.4	712	1.66	853	.06	1,580	.29	28.0	6.0	25.6
AST(.06)-2BAT--	10.2	1,360	.39	200	.06	1,580	.32	30.2	6.0	25.8
AST(.06)-BAT---	10.6	1,410	.31	159	.06	1,580	.30	28.9	6.0	25.9
AST(.10)-DPL---	13.2	1,760	1.66	853	.10	2,630	.46	27.6	5.3	25.4
AST(.10)-2BAT--	18.1	2,420	.39	200	.10	2,630	.53	30.2	5.3	25.7
AST(.10)-BAT---	[5]18.4	2,460	.31	159	.10	2,630	.54	30.2	5.3	25.7

[1]First group of letters refers to wastewater treatment at the Pueblo Wastewater Treatment Plant. Second group of letters refers to wastewater treatment at CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limits suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); and 2BAT= twice BAT limits.

[2]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]TMDL=lbs/d of total ammonia from Pueblo Wastewater Treatment Plant and CF&I Steel Corp., plus 12 lbs/d total ammonia in the Arkansas River above Pueblo Wastewater Treatment Plant outfall.

[4]Inputs from Pueblo Wastewater Treatment Plant for model simulations established based on stream limitations for NH_3 being met near 23d Lane (river mile 29.6).

[5]Total ammonia concentration for advanced secondary treatment is higher than for secondary treatment so would not realistically be considered as a treatment alternative.

[6]Inputs from Pueblo Wastewater Treatment Plant for model simulations established based on stream limitations for NH_3 being met at end of mixing zone (river mile 28.6).

Table 22.--*Results of model simulations for advanced secondary treatment at the Pueblo Wastewater Treatment Plant for winter low-flow conditions*

[mg/L=milligram per liter; lbs/d=pounds per day; WWTP=Wastewater Treatment Plant]

Model simulations[1]	Total ammonia: From Pueblo Wastewater Treatment Plant (mg/L)	Total ammonia: From Pueblo Wastewater Treatment Plant (lbs/d)	Total ammonia: From CF&I Steel Corp. (mg/L)	Total ammonia: From CF&I Steel Corp. (lbs/d)	Nonionized ammonia in stream at river mile 29.6 or 28.6[2] (mg/L)	Total maximum daily load (TMDL)[3] (lbs/d)	Highest simulated total nitrite below Pueblo WWTP outfall (mg/L)	Highest simulated total nitrite below Pueblo WWTP outfall (River mile[2])	Lowest simulated dissolved oxygen below Pueblo WWTP outfall (mg/L)	Lowest simulated dissolved oxygen below Pueblo WWTP outfall (River mile[2])
					Year 1985[4]					
AST(.06)-DPL---	20.0	2,270	1.48	865	0.06	3,520	0.59	11.3	9.8	24.3
AST(.06)-2BAT--	[5]25.8	2,930	.36	210	.06	3,520	.59	11.2	9.8	24.3
AST(.06)-BAT---	[5]26.1	2,970	.29	169	.06	3,520	.59	11.2	9.8	24.3
AST(.10)-DPL---	[5]40.7	4,620	1.48	865	.10	5,860	.95	9.4	9.1	24.3
AST(.10)-2BAT--	[5]46.4	5,280	.36	210	.10	5,860	.95	9.2	9.1	24.3
AST(.10)-BAT---	[5]46.8	5,320	.29	169	.10	5,860	.95	9.1	9.1	24.3
					Year 2000[4]					
AST(.06)-DPL---	17.6	2,340	1.48	865	.06	3,580	.60	10.2	9.8	24.3
AST(.06)-2BAT--	[5]22.5	2,990	.36	210	.06	3,580	.60	10.0	9.8	24.3
AST(.06)-BAT---	[5]22.8	3,030	.29	169	.06	3,580	.60	10.0	9.8	24.3
AST(.10)-DPL---	[5]35.5	4,720	1.48	865	.10	5,970	.95	10.9	9.1	24.3
AST(.10)-2BAT--	[5]40.4	5,380	.36	210	.10	5,970	.95	10.8	9.1	24.3
AST(.10)-BAT---	[5]40.7	5,420	.29	169	.10	5,970	.95	10.8	9.1	24.3
					Year 2000[6]					
AST(.06)-DPL---	18.2	2,420	1.48	865	.06	3,670	.61	11.2	9.7	24.3
AST(.06)-2BAT--	[5]23.1	3,080	.36	210	.06	3,670	.61	11.1	9.7	24.3
AST(.06)-BAT---	[5]23.4	3,120	.29	169	.06	3,670	.61	11.1	9.7	24.3
AST(.10)-DPL---	[5]36.6	4,870	1.48	865	.10	6,110	.98	8.8	9.0	24.3
AST(.10)-2BAT--	[5]41.5	5,520	.36	210	.10	6,110	.98	8.3	9.0	24.3
AST(.10)-BAT---	[5]41.8	5,570	.29	169	.10	6,110	.98	8.3	9.0	24.3

[1]First group of letters refers to wastewater treatment at the Pueblo Wastewater Treatment Plant. Second group of letters refers to wastewater treatment at CF&I Steel Corp. ST=secondary treatment; AST=advanced secondary treatment; LA=land application of treated effluent; DPL=National Pollutant Discharge Elimination System permit limit (Colorado Department of Health, 1979c); BAT=best available technology effluent limits suggested by R. Shankland (U.S. Environmental Protection Agency, written commun., 1979); and 2BAT= twice BAT limits.

[2]River miles upstream from streamflow-gaging station, 07117000 Arkansas River near Nepesta.

[3]TMDL=lbs/d of total ammonia from Pueblo Wastewater Treatment Plant and CF&I Steel Corp., plus 380 lbs/d total ammonia in the Arkansas River above Pueblo Wastewater Treatment Plant outfall.

[4]Inputs from Pueblo Wastewater Treatment Plant for model simulations established based on stream limitations for NH_3 being met near 23d Lane (river mile 29.6).

[5]Total ammonia concentration for advanced secondary treatment is higher than for secondary treatment so would not realistically be considered as a treatment alternative.

[6]Inputs from Pueblo Wastewater Treatment Plant for model simulations established based on stream limitations for NH_3 being met at end of mixing zone (river mile 28.6).

Model simulations were made for 36 different combinations of wastewater treatment and low-flow periods including advanced secondary treatment at the Pueblo WWTP. A summary of the results of these simulations is given in tables 21 and 22. Five of these model simulations were selected for graphical presentation and discussion.

Model simulations for advanced secondary treatment assume a 0.06-mg/L or a 0.10-mg/L nonionized ammonia nitrogen instream water-quality guideline at the downstream end of the mixing zone (river mile 28.6) or at an alternative point (river mile 29.6). All model simulations discussed here were made by applying the water-quality guideline at the downstream end of the mixing zone. The shorthand notation used to describe advanced secondary treatment model simulations is similar to that defined earlier. For example, AST(.06)-BAT-2000-$Q_{7,10}$ indicates the model simulation was made for $Q_{7,10}$ conditions, wastewater discharges projected to the year 2000, best available technology effluent water-quality limits for the CF&I Steel Corp., and model inputs at the Pueblo WWTP for advanced secondary treatment based on a total ammonia concentration necessary to meet a water-quality guideline of 0.06 mg/L for nonionized ammonia at the end of the mixing zone.

The results of model simulations for AST(.06)-DPL-2000-$Q_{7,10}$, AST(.06)-2BAT-2000-$Q_{7,10}$ and AST(.06)-BAT-2000-$Q_{7,10}$ are shown in figures 33-35 and in table 20. Instream water-quality conditions are similar for the three sets of conditions. The similarity is expected because similar loads of total ammonia (table 21) and $CBOD_5$ are present downstream from the outfall from the CF&I Steel Corp. for the three sets of conditions. In addition to meeting the water-quality guideline for nonionized ammonia, the simulated concentrations of both total nitrite and DO were acceptable based on water-quality guidelines for these parameters.

The total ammonia concentrations in the effluent from the Pueblo WWTP used in the advanced secondary-treatment model simulations (tables 14 and 15) depend largely on the concentration of total ammonia at the CF&I Steel Corp. outfall (table 16). When the effluent from the CF&I Steel Corp. contains higher concentrations of total ammonia, a lower concentration is required in the effluent from the Pueblo WWTP to meet the same instream water-quality guideline.

The results of model simulations for AST(.10)-DPL-2000-$Q_{7,10}$ and AST(.10)-2BAT-2000-$Q_{7,10}$ are shown in figures 36 and 37. Results show slightly poorer instream water quality than the model simulations for advanced secondary treatment with an instream water-quality guideline of 0.06 mg/L for nonionized ammonia (table 20). The water-quality guideline for total nitrite was exceeded for model-simulation AST(.10)-2BAT-2000-$Q_{7,10}$. The simulated DO concentrations for both sets of conditions were greater than the water-quality guideline of 5.0 mg/L.

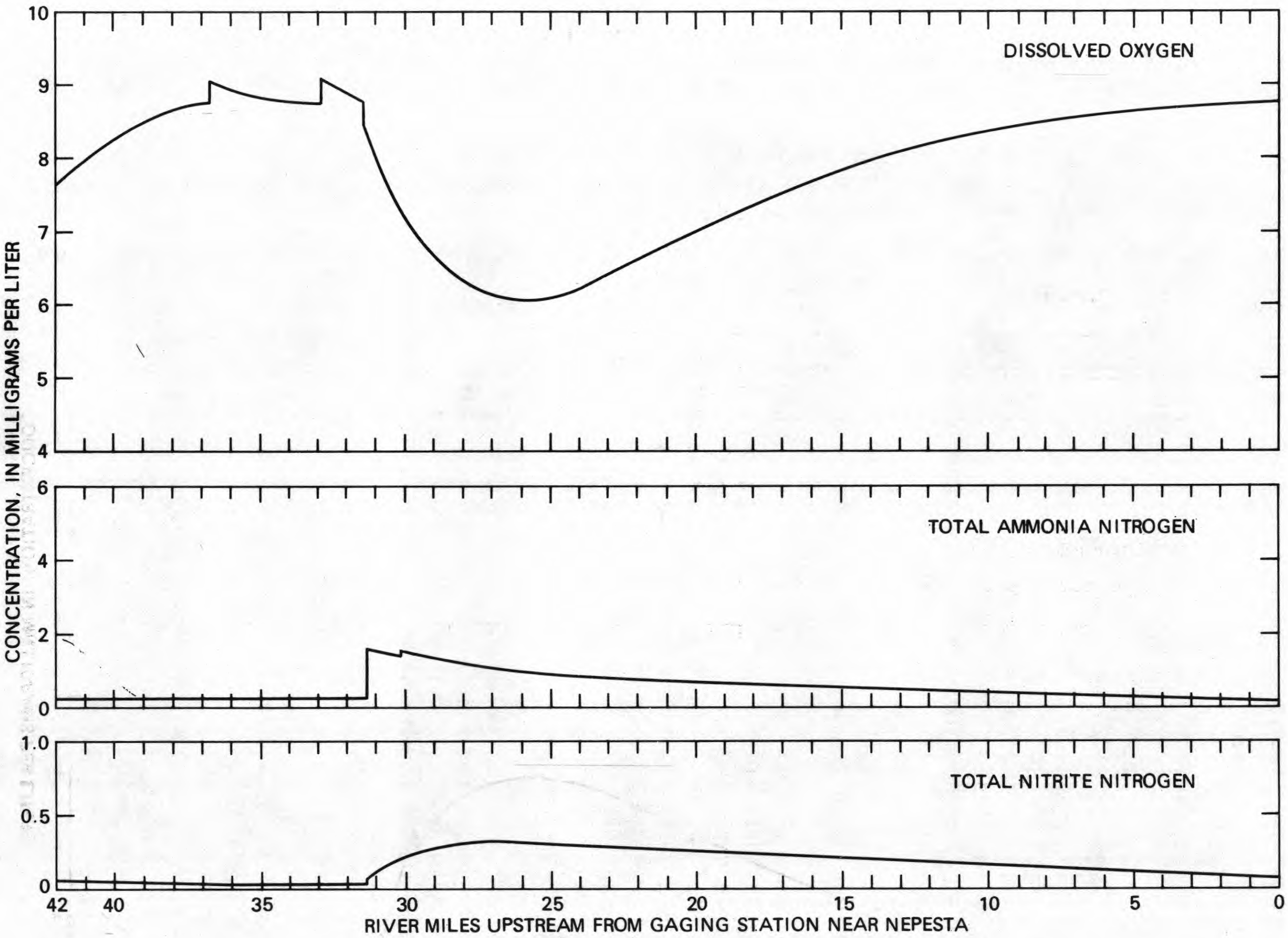

Figure 33.--Results of model simulation for advanced secondary treatment at the Pueblo Wastewater Treatment Plant to meet a water-quality guideline of 0.06-mg/L nonionized ammonia nitrogen at the end of the mixing zone and current NPDES discharge permit effluent limits at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

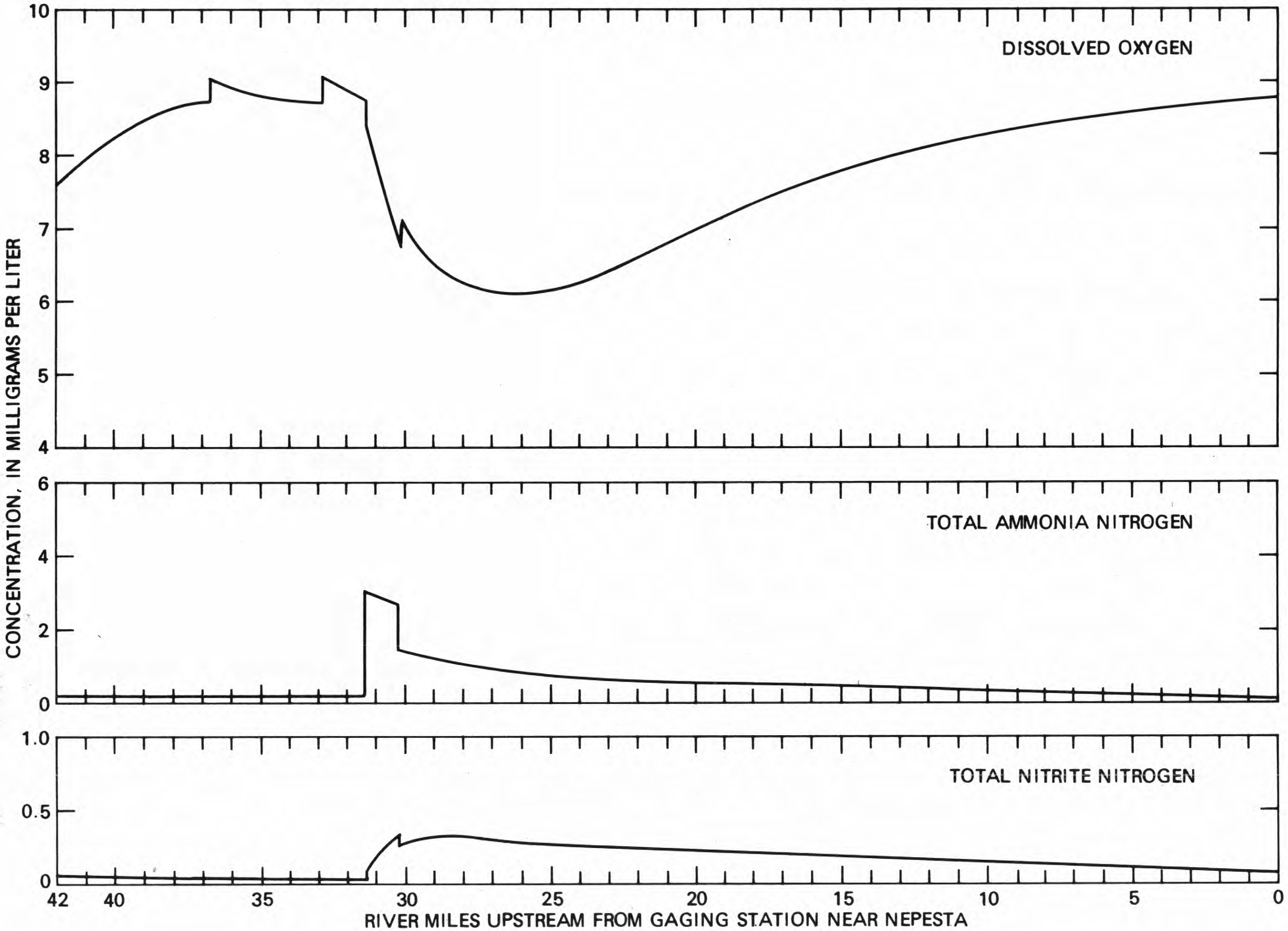

Figure 34.--Results of model simulation for advanced secondary treatment at the Pueblo Wastewater Treatment Plant to meet a water-quality guideline of 0.06-mg/L nonionized ammonia nitrogen at the end of the mixing zone and twice-the-best available technology effluent concentration of ammonia at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

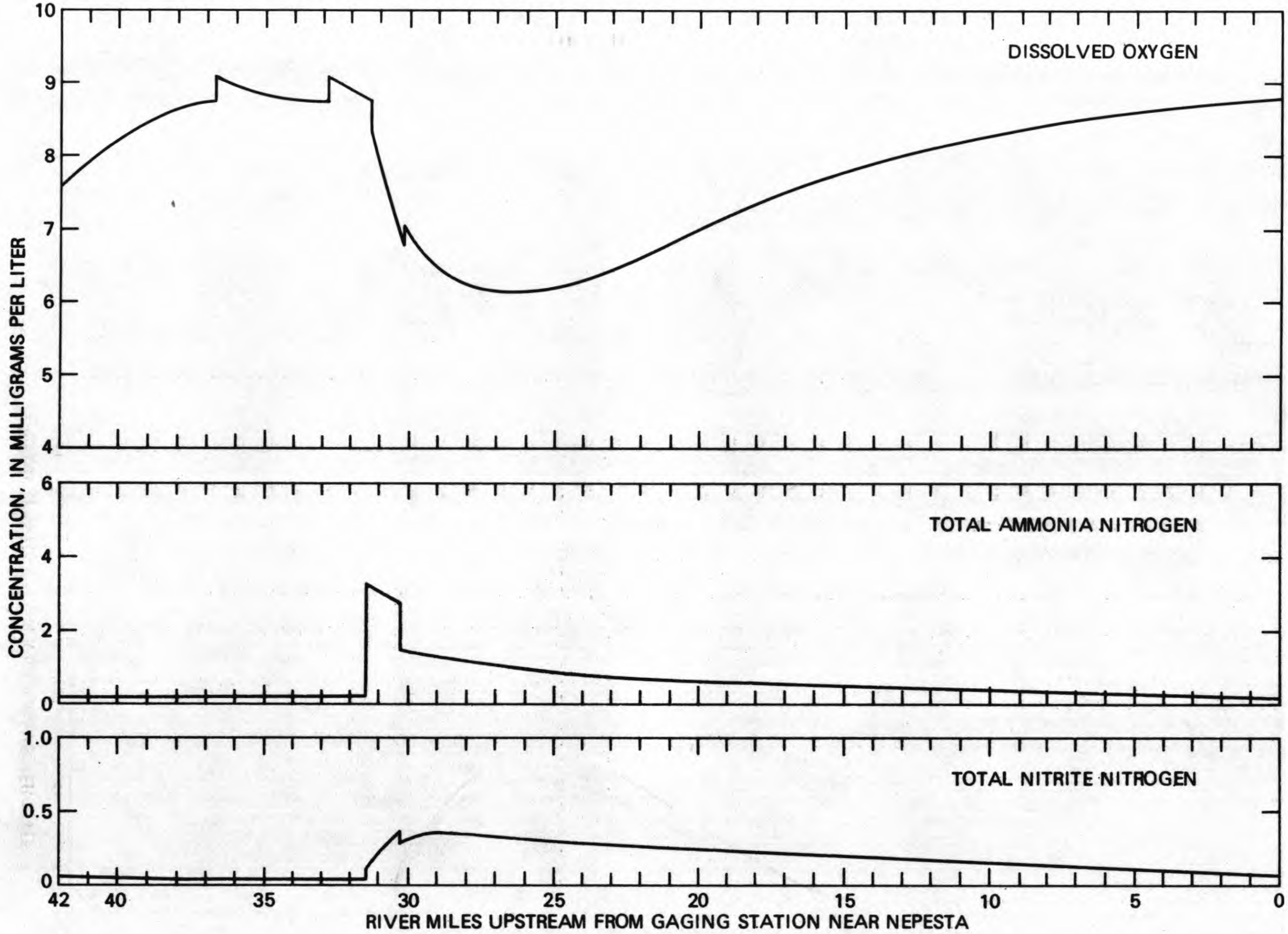

Figure 35.-- Results of model simulation for advanced secondary treatment at the Pueblo Wastewater Treatment Plant to meet a water-quality guideline of 0.06-mg/L nonionized ammonia nitrogen at the end of the mixing zone and best available technology wastewater treatment at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

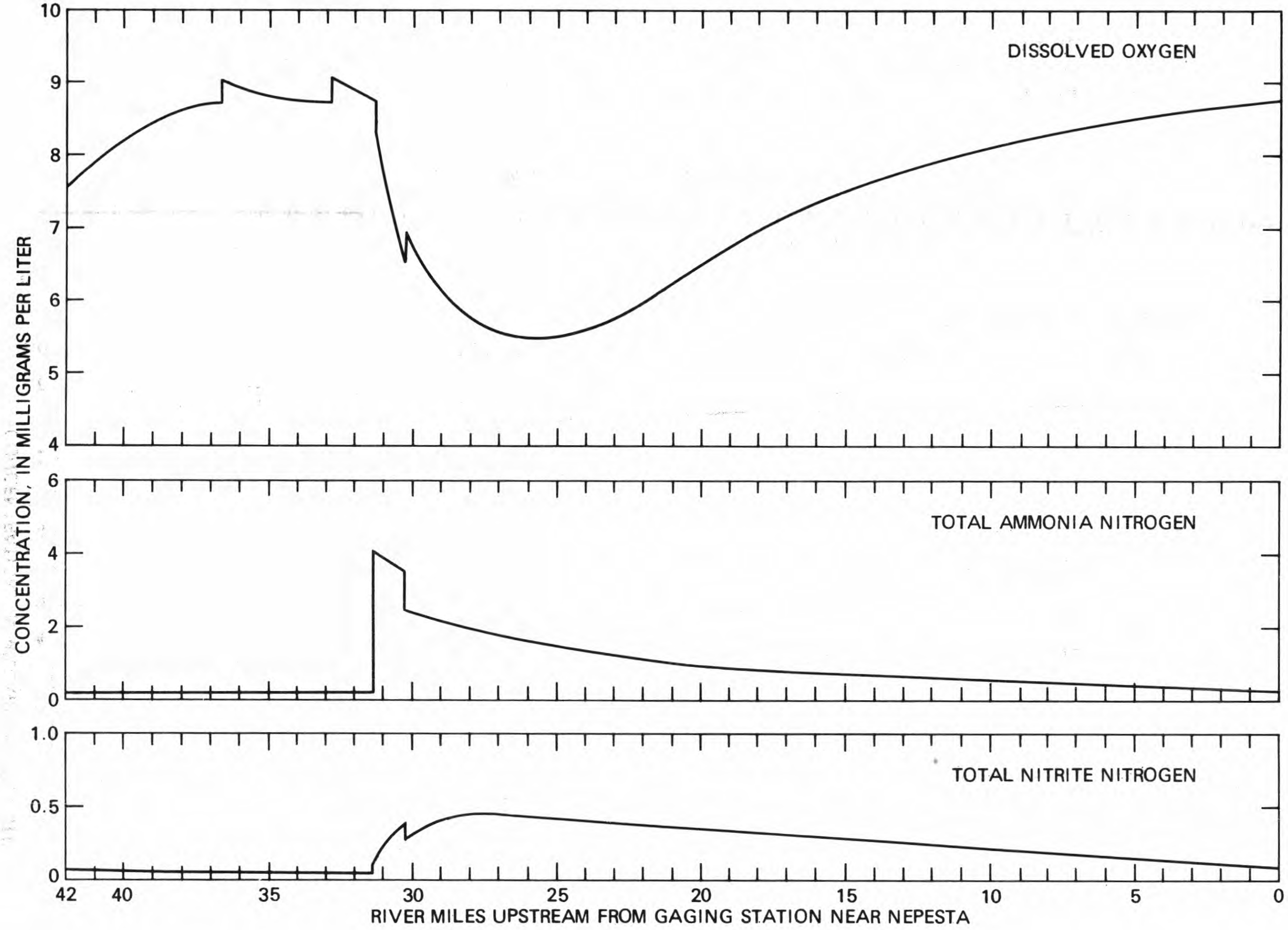

Figure 36.--Results of model simulation for advanced secondary treatment at the Pueblo Wastewater Treatment Plant to meet a water-quality guideline of 0.10-mg/L nonionized ammonia nitrogen at the end of the mixing zone and current NPDES discharge permit effluent limits at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

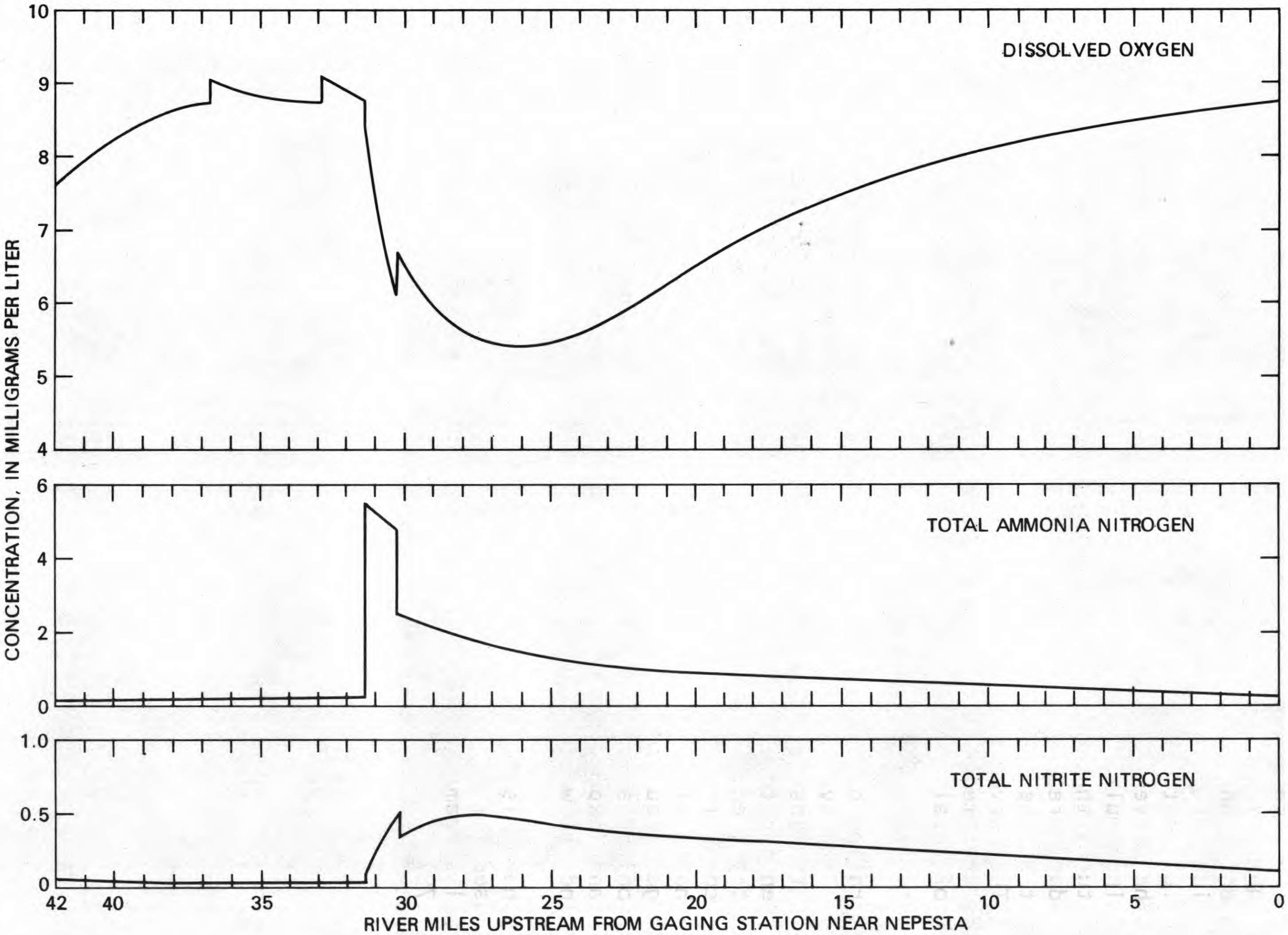

Figure 37.-- Results of model simulation for advanced secondary treatment at the Pueblo Wastewater Treatment Plant to meet a water-quality guideline of 0.10-mg/L nonionized ammonia nitrogen at the end of the mixing zone and twice-the-best available technology effluent concentration of ammonia at CF&I Steel Corp. for $Q_{7,10}$ conditions using projected wastewater discharges for the year 2000.

Model Simulations with Flow Augmentation in the Arkansas River

An alternative to advanced secondary treatment at the Pueblo WWTP is the possibility of augmenting streamflow during low-flow periods to meet an instream water-quality guideline for nonionized ammonia. To determine the amount of augmentation that would be necessary, curves were prepared relating the concentration of total ammonia at the downstream end of the mixing zone (river mile 28.6) to the discharge just upstream from the Pueblo WWTP outfall (fig. 38). The curves were prepared for both the $Q_{7,10}$ and winter low-flow periods by making multiple model simulations at several selected discharges and at temperatures that occur during each period. The curves were prepared based on secondary treatment at the Pueblo WWTP (tables 14 and 15) and wastewater treatment at the CF&I Steel Corp. to meet the estimated 2BAT guidelines (table 16). The curves will also closely approximate the correct results if the wastewater treatment at the CF&I Steel Corp. is BAT because a similar concentration of total ammonia is present at the end of the mixing zone in both instances.

An illustration of the use of the curves is shown in figure 38. For the $Q_{7,10}$ period, the average expected percentage of nonionized ammonia is 4.9 (table 8). If the instream water-quality guideline for nonionized ammonia is 0.06 mg/L, then the total ammonia concentration which could not be exceeded is 1.22 mg/L at the end of the mixing zone. The horizontal line of figure 38 drawn at this concentration intersects the curve for the $Q_{7,10}$ temperature of 21°C at a discharge of 195 ft^3/s upstream from the Pueblo WWTP outfall. This is the discharge required to meet an instream water-quality guideline of 0.06-mg/L nonionized ammonia at the end of the mixing zone for average $Q_{7,10}$ temperatures and expected average percentage of nonionized ammonia for the $Q_{7,10}$ period and the wastewater-treatment conditions defined above.

This discharge is approximately 140 ft^3/s greater than the model-computed discharge used for $Q_{7,10}$ discharge conditions. Possible ways of providing this additional streamflow were not evaluated in this study but are discussed by Dumeyer (1979).

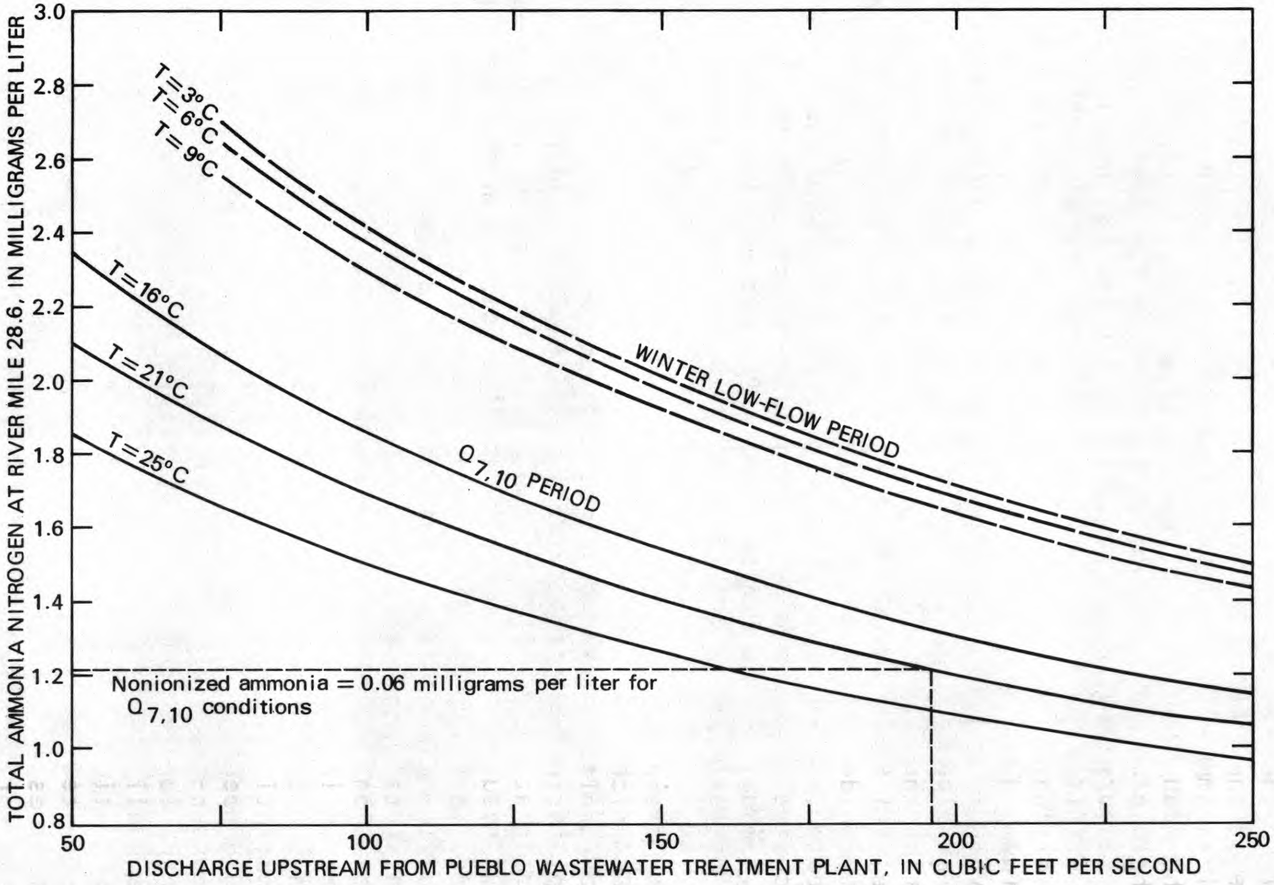

Figure 38.--Relationship between total ammonia concentration at the end of the mixing zone (river mile 28.6) and discharge of the Arkansas River just upstream from the outfall of the Pueblo Wastewater Treatment Plant.

SUMMARY

An analysis of the waste-assimilation capacity of the Arkansas River in Pueblo County indicated that concentrations of nonionized ammonia nitrogen and total nitrite nitrogen may exceed water-quality guidelines for warm-water aquatic life (Colorado Department of Health, 1979a) under conditions of secondary treatment at the Pueblo WWTP. The analysis was made based upon a projected discharge at the Pueblo WWTP for the year 2000. Simulated concentrations of nonionized ammonia nitrogen exceeded the water-quality guideline of 0.06 mg/L for the mean low flow which can be expected to occur for 7 consecutive days on the average of once in 10 years ($Q_{7,10}$). The $Q_{7,10}$ discharge (Dumeyer, 1975) occurs between August 15 and October 15 in the study area. Simulated total nitrite concentrations exceeded the water-quality guideline of 0.5 mg/L for discharge conditions based on low flows that have occurred in recent years between November 15 and March 15 as a result of storage of water in Pueblo Reservoir. Simulated nonionized ammonia nitrogen concentrations did not exceed an alternative water-quality guideline of 0.10 mg/L for secondary treatment at the Pueblo WWTP and estimated best available technology treatment at the CF&I Steel Corp. Simulated DO concentrations were less than the water-quality guideline of 5.0 mg/L for warm-water aquatic life (Colorado Department of Health, 1979a) for secondary treatment at the Pueblo WWTP with a projected discharge for the year 2000 and effluent water quality at the CF&I Steel Corp. equal to the limits set in the current NPDES permit (Colorado Department of Health, 1979c).

Based on simulated concentrations, wastewater-treatment possibilities for the year 2000 which would result in meeting water-quality guidelines for nonionized ammonia nitrogen, total nitrite nitrogen, and dissolved oxygen include land application of treated effluent at the Pueblo WWTP and advanced secondary treatment at the Pueblo WWTP. Land application of treated effluent would, however, result in decreased streamflow and may result in nonpoint-source discharges to the Arkansas River. These effects were not evaluated during this study. Advanced secondary treatment at the Pueblo WWTP could decrease effluent total ammonia concentrations by conversion to nitrate. The existing concentration of total ammonia nitrogen in the effluent is 18 to 21 mg/L. To meet an instream water-quality guideline of 0.06-mg/L nonionized ammonia nitrogen for $Q_{7,10}$ conditions and projected discharges for the year 2000, the concentration of total ammonia nitrogen in the effluent from the Pueblo WWTP would need to be 5.4 to 10.6 mg/L. The exact concentration depends on wastewater-treatment processes being used by the CF&I Steel Corp. The lower concentration would be required if the effluent from the CF&I Steel Corp. was of the quality indicated in their current waste-discharge permit. The higher concentration would be required if the effluent from the CF&I Steel Corp. was treated to comply with estimated best available technology guidelines. At these lower total ammonia concentrations, instream water-quality guidelines for total nitrite nitrogen and DO could also be met.

Also considered was augmentation of streamflow to provide dilution of nonionized ammonia nitrogen to levels required to meet the water-quality guideline of 0.06 mg/L. The evaluation was made for the $Q_{7,10}$ period, secondary treatment at the Pueblo WWTP with a projected discharge for the year 2000, and effluent water quality at the CF&I Steel Corp. which would contain twice the estimated ammonia concentration resulting from steel production allowable for best available technology treatment. The estimated flow augmentation necessary to meet the water-quality guideline, based on simulated concentrations of total ammonia, is 140 ft^3/s. Possible ways of providing this additional streamflow were not evaluated during this study.

The simulated concentrations of water-quality constituents are based on a one-dimensional steady-state water-quality model for a 42-mile reach of the Arkansas River from just downstream of Pueblo Reservoir to near Nepesta, about 6 miles west of the Pueblo County line. The model was calibrated and verified for 5-day carbonaceous biochemical oxygen demand, total organic nitrogen, total ammonia, total nitrite, total nitrate, and dissolved oxygen. The calibration was considered to be acceptable for all constituents except total organic nitrogen. Model verification was acceptable for all constituents except total organic nitrogen and total nitrite. Model-simulation results for total nitrite may be lower than what might occur in the river. The calibration and verification were based on hydraulic and water-quality data collected in April 1976 and September 1979.

Because the model does not compute concentrations of nonionized ammonia, it was necessary to define the relationship between total ammonia and nonionized ammonia to provide simulation capability for nonionized ammonia. The relationship was defined for the $Q_{7,10}$ and winter low-flow periods based on pH, temperature, and specific-conductance data collected during the study. The expected average percentage of total ammonia which is in the nonionized state was determined to be 4.9 percent for the $Q_{7,10}$ period, and 2.0 percent for the winter period.

The mixing zone downstream from the Pueblo WWTP was evaluated to determine the river cross section where water-quality guidelines were applied during the model simulations. The downstream end of the mixing zone was defined as the cross section in the Arkansas River where complete lateral mixing of the effluent from the Pueblo WWTP occurred. Based on data collected in March 1980, the mixing zone was 2.7 miles in length.

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