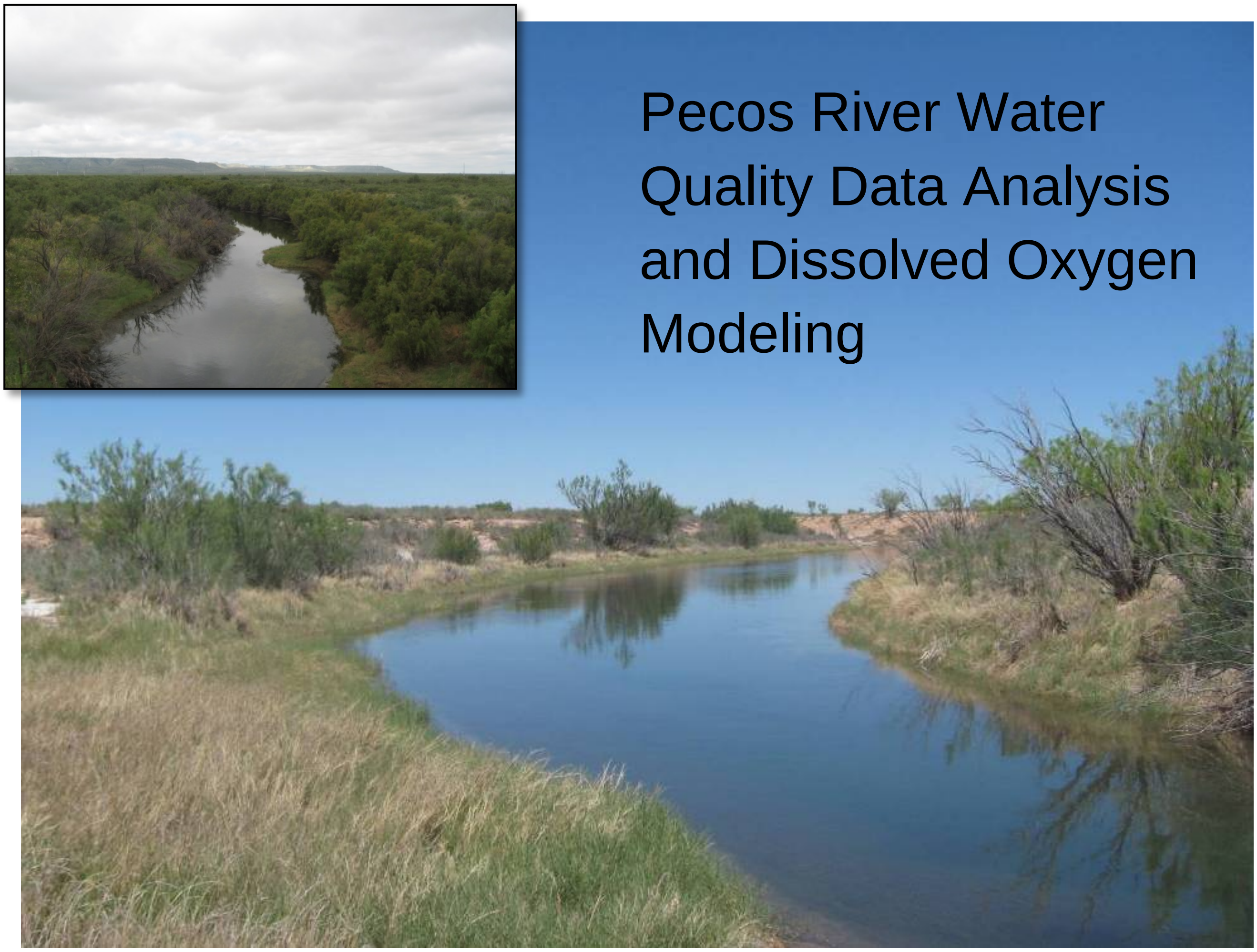


Pecos River Water Quality Data Analysis and Dissolved Oxygen Modeling

Prepared by:

Nabin Basnet

Larry M. Hauck

David Pendergrass

Texas Institute for Applied Environmental Research (TIAER)
Tarleton State University

Stephenville, Texas

December 2013

PECOS RIVER WATER QUALITY DATA ANALYSIS AND DISSOLVED OXYGEN MODELING

Prepared for:

Texas State Soil and Water Conservation Board

Temple, Texas

Prepared by:

Nabin Basnet
Larry Hauck
David Pendergrass

Texas Institute for Applied Environmental Research
Tarleton State University
Stephenville, Texas

TR1301

December 2013

Acknowledgements

Funding for this project was provided through Clean Water Act Section 319(h) funds of the U.S. Environmental Protection Agency. The Texas State Soil and Water Conservation Board (TSSWCB) administered the contract to the Texas Water Resources Institute (TWRI) of Texas A&M AgriLife Research. A subaward between AgriLife Research and the Texas Institute for Applied Environmental Research at Tarleton State University provided the source of federal funds for this project. State of Texas funds provided the matching requirements.

Thanks to the direction and assistance of Mr. Chuck Dvorsky, Texas Commission on Environmental Quality (TCEQ) Continuous Water Quality Monitoring Network Coordinator, the authors gained access to the huge data resources from the network stations operated on the Pecos River providing valuable dissolved oxygen data at several locations. Thanks also to Ms. Christine Kolbe and Mr. Greg Larson of TCEQ who greatly assisted this study through providing data from studies of the Pecos River and sharing their knowledge of the Pecos River. The study benefitted greatly from the knowledge and data provided by these individuals.

The authors are greatly appreciative of the review comments by Mr. Lucas Gregory, TWRI Project Manager, and Mr. Mitch Conine, TSSWCB Project Management Coordinator.

TABLE OF CONTENTS

List of Figures

List of Tables

List of Abbreviations and Acronyms

AU	Assessment Unit
BMP	Best Management Practice
CBOD	Carbonaceous Biochemical Oxygen Demand
cfs	Cubic feet per second
cms	Cubic meters per second
CWQMN	Continuous Water Quality Monitoring Network
CHLA	Chlorophyll-α
°C	Degrees Centigrade
DO	Dissolved Oxygen
FDC	Flow Duration Curve
IBWC	International Boundary and Water Commission
kg	Kilogram
km	Kilometer
LDC	Load Duration Curve
µg/L	Micrograms/liter
mg/L	Milligrams/liter
m^3	Cubic Meter
mL	Milliliter
NCDC	National Climatic Data Center
NH_3-N	Ammonia as Nitrogen
NO_3-N	Nitrate as Nitrogen
NO_{23}-N	Nitrite-Nitrate as Nitrogen
NOAA	National Oceanic and Atmospheric Administration
OP	Orthophosphate as Phosphorus
QUAL2E	EPA sponsored one-dimensional water quality model
QUALTX	TCEQ one-dimensional water quality model
RKM	River Kilometer
RR	Ranch Road
SOD	Sediment Oxygen Demand
SWQM	Surface Water Quality Monitoring
SWQMIS	Surface Water Quality Monitoring Information System
SWQS	Surface Water Quality Standards
TCEQ	Texas Commission on Environmental Quality
TIAER	Texas Institute for Applied Environmental Research
TPDES	Texas Pollutant Discharge Elimination System
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	U.S. Environmental Protection Agency
USGS	United States Geological Survey
WWTF	Wastewater Treatment Facility

CHAPTER 1

INTRODUCTION

Background

The Pecos River is a greatly depleted western river flowing 418 winding miles through hot, dry, semi-arid landscapes in Texas. It is the largest river sub-basin flowing into the Rio Grande from the United States. The Pecos River itself is also the lifeblood of many communities within its reaches, mainly as an irrigation source, recreational uses, and as recharge for underlying aquifers. As such, its importance historically, biologically and hydrologically to the future of the Rio Grande Basin is critical. The flows of the once great Pecos River have dwindled to a mere trickle due to many causes — some natural and some man-induced. Its upper reaches in Texas now resemble a small creek rather than a river.

Due to the lowered water quality and streamflows in the upper portion of the river, the aquatic community of the Pecos River has been drastically altered, according to reports from biologists and local users of the river. No longer does the river support as many diverse communities of aquatic plants, invertebrates, microorganisms, fish and amphibians as are described in the *Watershed Protection Plan for the Pecos River in Texas* (Gregory and Halter, 2008). The greatly reduced aquatic diversity has been negatively affected by changes in river hydrology, riparian community destruction, oil and gas activities, irrigation demands, long and short-term droughts, damming of the river and the desertification of the upland watershed due to several factors. These factors, both natural and man-made, have allowed introduced plant species, such as saltcedar, to infiltrate the riparian corridor and other nuisance brush species to become established on upland areas. Most of the above enumerated factors have likely contributed to water quality declines, such as dissolved oxygen (DO) impairment in the upper reaches of the river between U.S. Highway 80 (Business IH 20) and U.S. Highway 67.

According to data from the U.S. Section of the International Boundary and Water Commission (IBWC), the Pecos River contributes 274 million m^3 of streamflow to the Rio Grande, which accounts for approximately 11% of the total annual inflow to Amistad International Reservoir. However, it also contributes to the total dissolved solids (salt) loading into the reservoir at an annual rate of 0.54 million tons or 29.5% of the total annual salt load. The concentration of total dissolved solids (TDS) of the Amistad International Reservoir exceeded 1,000 ppm for a month in 1988, and has fluctuated since. It is important to control salt loading from the Pecos River to Rio Grande if TDS of the reservoir are to be kept in compliance with the Texas Surface Water Quality Standards. Several key areas where dissolved solids enter the river have been identified and quantified.

Study Purpose

The *Watershed Protection Plan for the Pecos River in Texas*, as well as the letter received from Environmental Protection Agency (EPA) Region 6 following their consistency review of the WPP, indicate the need for further assessment and the development of recommended management measures to address the DO impairment in the upper portions of the river. This report provides the results of historical data analysis and computer modeling efforts that investigated the depressed DO issue in the upper Pecos River.

The report provides details on three areas of investigation. First, analyses of historical streamflow, irrigation withdrawal, and water quality data of the Pecos River in Texas were performed. These analyses were directed to understanding the hydrology of the Pecos River system and to determine the specifics of the spatial and temporal aspects of the depressed DO. This analysis was not intended to be a comprehensive study of Pecos River water quality. Rather the intent was to provide only sufficient detail to inform the DO modeling, which was the major focus of this study. Second, an appropriate computer model was selected to predict DO in the Pecos River, especially for that portion with occurrences of depressed DO, and the model was calibrated and validated against measured water quality resulting in a Pecos River model with capabilities of reasonably predicting DO. Third, the Pecos River model was operated to evaluate various control practices and best management practices (such as, salinity control measures, enhanced streamflow, artificial riffles [small instream dams] and measures to reduce algal biomass), and these measures were evaluated separately and collectively to estimate the improvement in DO that can be obtained. The model selected for development and application to the DO issues of the Pecos River is called QUAL2K and this model will be described in more detail in later chapters of the report.

CHAPTER 2

HISTORICAL DATA REVIEW

Purpose of Historical Data Review

The purpose of this chapter is to provide an overview of hydrology and water quality in both the Upper Pecos River and Lower Pecos River, though the emphasis will be on the Upper Pecos where depressed DO is experienced. This overview is not intended to be comprehensive, but rather to provide sufficient detail to allow the reader to obtain an impression of characteristics of the Pecos River that will be considered in the DO modeling effort presented in later chapters and to obtain information on the nature of the depressed DO issues in the impaired portion of the Upper Pecos River.

Description of the Project Area and Water Quality Issues

The Pecos River is the largest U.S. tributary of the Rio Grande River. It begins in Mora County, New Mexico and flows approximately 1,490 km (926 miles) to its confluence with the Rio Grande River upstream of Amistad Reservoir in Val Verde County, Texas. Roughly 680 km (418 miles) of the river are below Red Bluff Reservoir in Texas, which predominately regulates streamflow through controlled releases from the dam, thus imposing a strong influence on the hydrology of the Pecos River in Texas.

The Texas Commission on Environmental Quality (TCEQ) divides the Pecos River in Texas into lower and upper segments and these are further subdivided into assessment units (AUs) by TCEQ to aid water quality assessments and management (Figures 2-1 and 2-2).

- The Lower Pecos River (Segment 2310) is defined from a point 0.7 km (0.4 miles) downstream of Painted Canyon in Val Verde County to a point immediately upstream of the confluence of Independence Creek in Crockett/Terrell Counties.
- The Upper Pecos River (Segment 2311) is defined from a point immediately upstream of the confluence of Independence Creek in Crockett/Terrell Counties to Red Bluff Dam in Loving/Reeves Counties.

The DO criteria for the Upper and Lower Pecos River are defined through the Texas Surface Water Quality Standards (TCEQ, 2011):

- Segments 2310 and 2311 have been assigned a high aquatic life use.
- One water quality constituent considered to protect the high aquatic life use is DO resulting in the following two criteria:
  - 24-hour average DO of at least 5.0 mg/L
  - 24-hour minimum DO of at least 3.0 mg/L

The Lower Pecos River contains two AUs and the Upper Pecos River contains eight (Table 2-1). Based upon TCEQ’s 2008 and 2010 biennial assessments (the Texas Integrated Report) of the Upper and Lower Pecos River segments, impairments due to depressed DO occur from U.S. Highway 67 upstream to U.S.

Highway 80 (AUs 2311_05 and 06 under TCEQ's 2008 definition of AUs and AUs 2311_03 and 04 under the 2010 definition of AUs; TCEQ 2008 and 2010a).

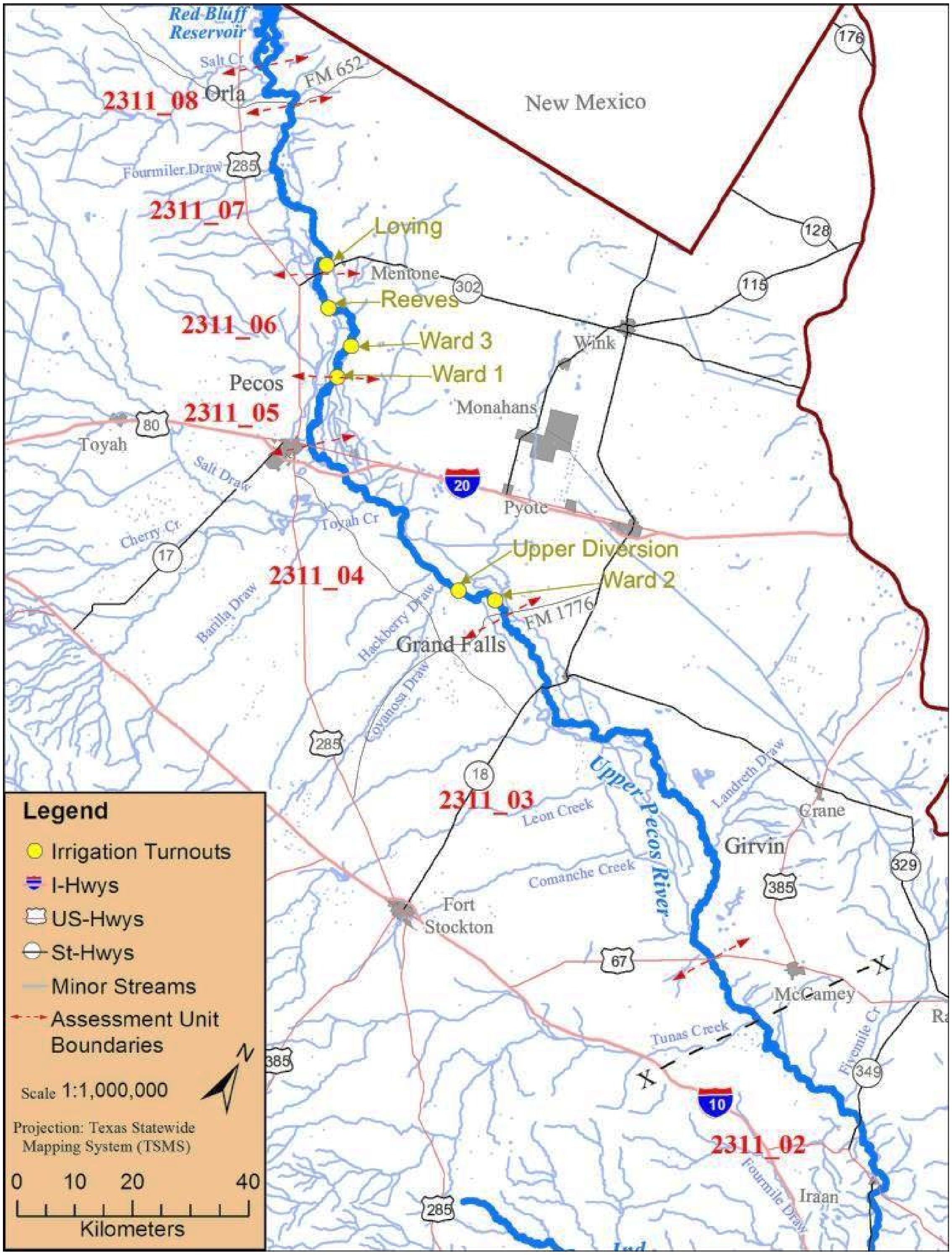


Figure 2-1. Pecos River from Red Bluff Reservoir near Orla, TX, downstream to U.S. Highway 67. (2010 Texas Integrated Report definitions of AUs shown on map.)

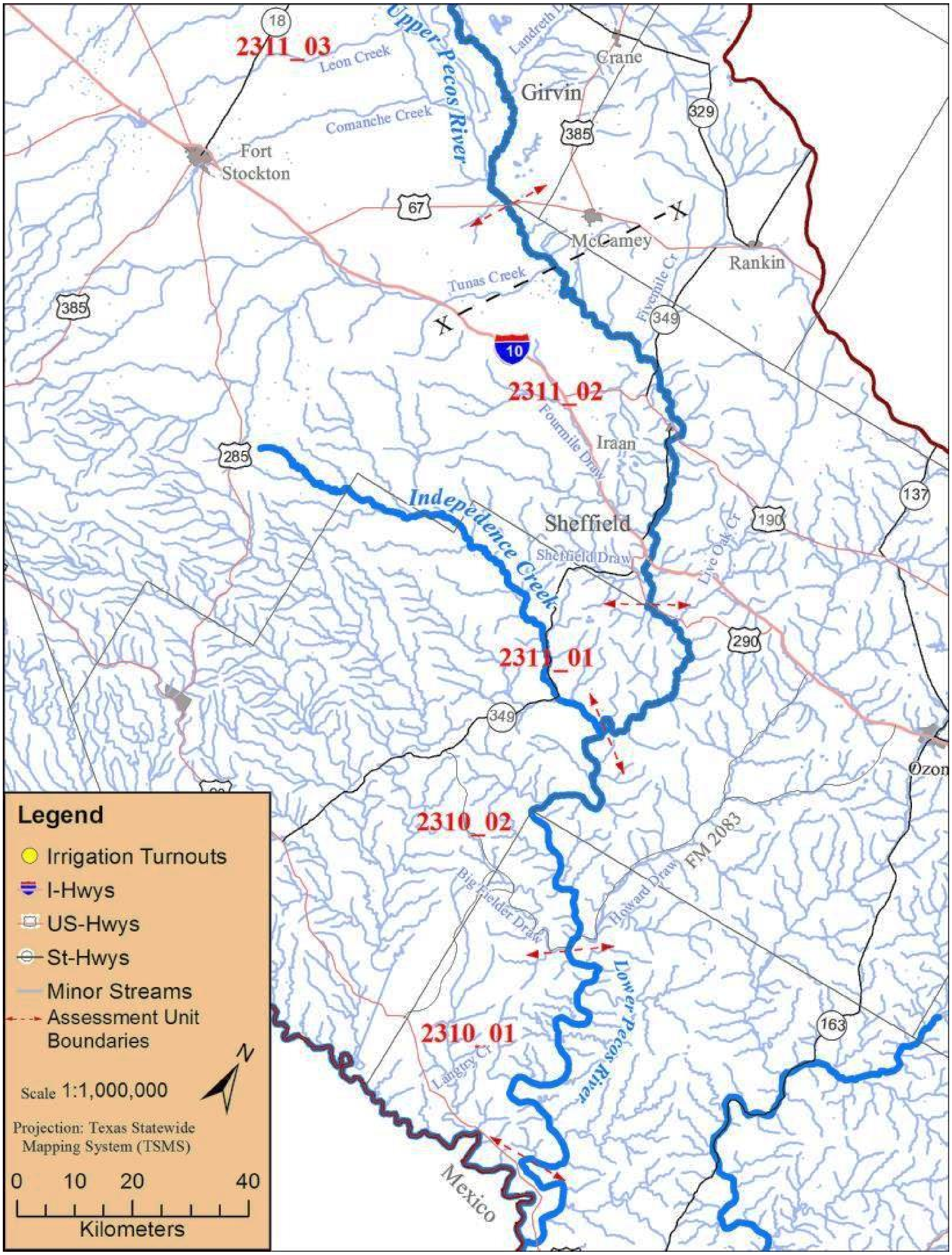


Figure 2-2. Pecos River from U.S. Highway 67 downstream to confluence with Rio Grande. (2010 Texas Integrated Report definitions of AUs shown on map.)

Further, the 2012 Texas Integrated Report (TCEQ, 2013) moves the boundary between TCEQ's 2010 definition of AUs 2311_03 and 04 upstream of FM 1776 to the Ward 2 Irrigation Turnout, but more significantly describes the area of depressed DO as being limited to AU 2311_03. The 2012 redefinition of AUs 2311_03 and 2311_04, while relatively insignificant in spatial distance, accomplished two things. First, from a hydrologic perspective, the Ward 2 Irrigation Turnout is the last irrigation turnout on the Pecos River and under normal streamflow conditions, little if any of the releases from Red Bluff Reservoir continue below this turnout. Second, the redefinition places all the TCEQ monitoring stations that have indicated significant occurrences of depressed DO in the same AU (2311_03) instead of occurring in two AUs.

Thus under the 2012 Texas Integrated Report, the geographic region of the Upper Pecos River indicated by monitoring data to be experiencing depressed DO is refined and limited to the length of the river from U.S. Highway 67 upstream to the Ward 2 Irrigation Turnout.

Table 2-1. Description of assessment units (AUs) for the Lower Pecos River (Segment 2310) and the Upper Pecos River (Segment 2311); TCEQ 2008 and 2010a.

2008 AUs	2010 AUs	AU Description
2310_02 *	2310_01	From the Devils River Arm of Amistad Reservoir confluence upstream to FM 2083 near Pan Dale
2310_01 *	2310_02	From FM 2083 near Pan Dale to just upstream of Independence Creek confluence
2311_08	2311_01	From just upstream of the Independence Creek confluence upstream to US Hwy 90
2311_07	2311_02	From US Hwy 290 upstream to US Hwy 67
2311_06	2311_03	From US Hwy 67 to FM 1776
2311_05	2311_04	From FM 1776 upstream to US Hwy 80 (Bus. IH 20)
2311_04	2311_05	From US Hwy 80 (Bus IH 20) upstream to the Barstow Dam
2311_03	2311_06	From the Barstow Dam upstream to State Hwy 302
2311_02	2311_07	From State Hwy 302 upstream to FM 652
2311_01	2311_08	From FM 652 upstream to the Red Bluff Dam

* The boundary between 2310_01 and 2310_02 is Big Hackberry Canyon in the 2008 Texas Integrated Report.

Red Bluff Reservoir, at the upstream terminus of Segment 2311, is the source of the majority of the flow in the more upstream reaches of the Upper Pecos River and the majority of the releases from the reservoir are to meet downstream needs for irrigation water. A series of irrigation turnouts along the Upper Pecos down to Ward 2 Irrigation Turnout reduce streamflow during the growing season (spring – fall) such that Red Bluff Reservoir releases are dissipated almost entirely by withdrawals before reaching the lower third of the segment. Independence Creek marks the boundary between the Upper and Lower portions of the Pecos River. Its spring-fed discharge improves the Pecos River hydrology and water chemistry, adding significantly to the streamflow and diluting the salty water of the Upper Pecos with fresher water.

This report is focused on the water quality issues of the Upper Pecos River, specifically depressed DO. Therefore, the reader is encouraged to explore other sources of information regarding the significance of Independence Creek on improving conditions of the Pecos River in Texas. (For example, the WPP for the Pecos River [Gregory and Hatler, 2008] is a good starting point on this subject.)

The AU subdivisions of the Pecos River used by TCEQ, though not arbitrary, do not lend themselves to the variety of analyses presented in this report and so an original set of subdivision boundaries were delineated based on USGS flow records, water quality data and the geography of tributaries and turnouts. These data suggest the Pecos River can be reasonably analyzed according to five distinct hydrologic sections based largely on streamflow and streamflow variability (Figure 2-3).

Section A — From the terminus of the Pecos River at Lake Amistad to Independence Creek (this section is equivalent to Segment 2310). The hydrology and chemistry of the lowermost section of the Pecos River is determined largely by the consistent fresh flows of Independence Creek.

Section B — From Independence Creek to the crossing of SH 349 roughly 8 km upstream of Iraan. Warm-season increases in discharge from Red Bluff Reservoir have little direct impact on this lowermost section of Segment 2311 because of the removal of reservoir releases by turnouts in upstream sections of the segment. Section B is upstream of Independence Creek but has considerable hydrological and limnological resemblance to reaches below Independence Creek because of a higher density of spring and tributary inputs and a stronger response to the local climate than the seasonal fluctuations in flow for irrigation purposes.

Section C — From SH 349 to Ward 2 Irrigation Turnout, near the junction of Reeves and Pecos counties. This middle portion of the Upper Pecos is a transitional section wherein the relative balance of influences on hydrology shifts from regulated to natural, i.e., factors such as precipitation and the water demands of vegetation have an increasingly dominant role in the quantity and quality of water in the stream channel.

Section D — From Ward 2 Irrigation Turnout to FM 3398 north of Pecos. Due to its proximity to Red Bluff Reservoir, Section D experiences strong variations in growing-season flows but under conditions of overall-lower discharge than Section E because it lies below the highest density of irrigation turnouts in the watershed.

Section E — FM 3398 north of Pecos to Red Bluff Reservoir. Large swings in growing-season discharge are common in the uppermost section where seasonally managed releases from the reservoir as well as irrigation turnouts make the reach susceptible to flow variability.

Some of the analyses that follow join Sections A-B and D-E and thus treat the Pecos River in an upper (D-E), middle (C) and lower context (A-B). Other analyses keep with the 5-section scheme where finer dissection is needed to highlight characteristics of smaller reaches of the river. The decision to use a 5-section or 3-section system was based on statistical differences for the parameters used in each analysis.

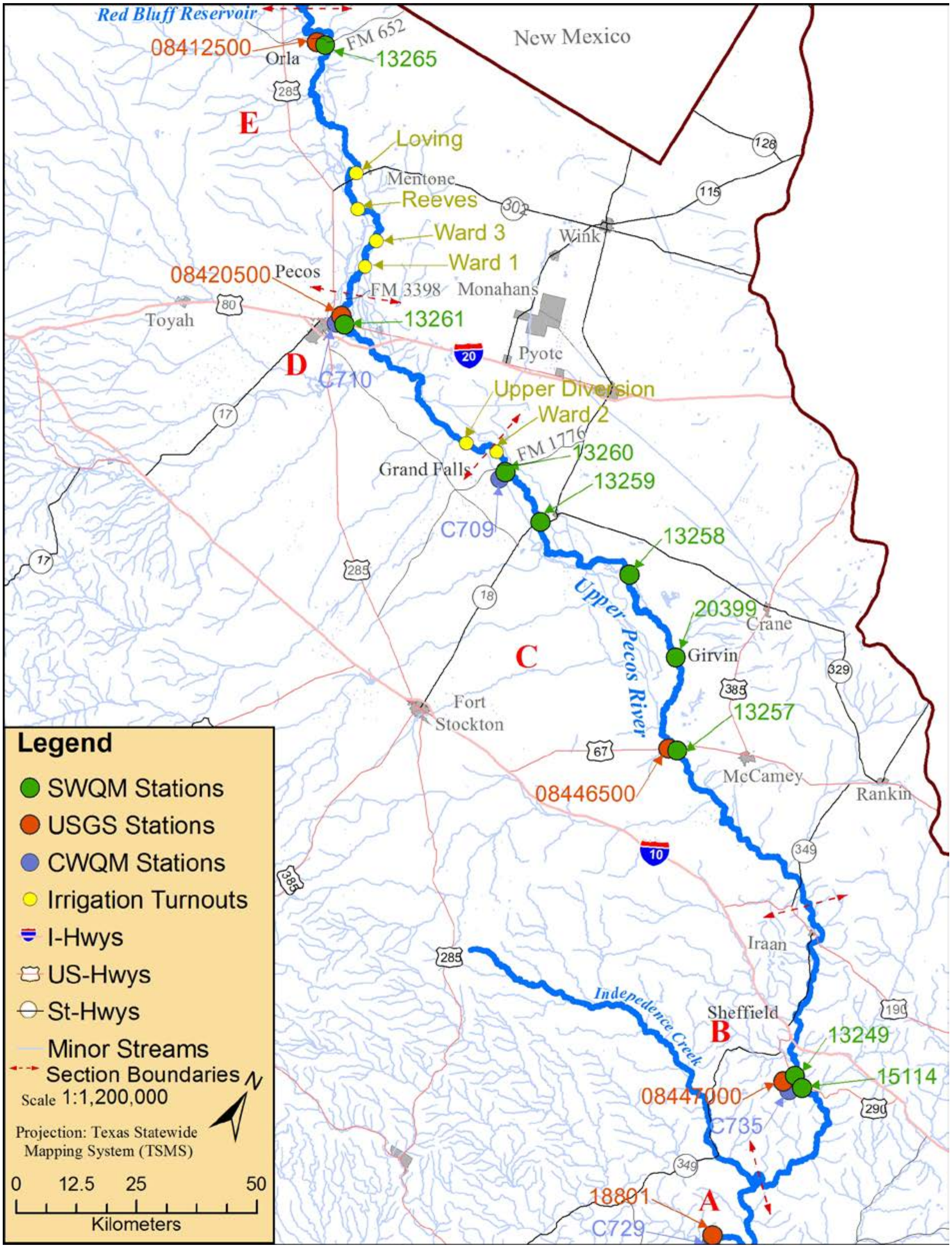


Figure 2-3. Pecos River with hydrologic sections indicated as used in this analysis.

General Description of Watershed

Climate and Geography

The Pecos River watershed in Texas is semi-arid and lies in the northeastern portion of the Chihuahuan Desert. Annual rainfall ranges from 280 mm (11 inches) in the Upper Pecos region to 430 mm (17 inches) in the Lower Pecos with much of the precipitation occurring in early summer and fall as brief and torrential storms (NCDC, 2011). Summers are hot and wetter than the cool, dry winters (Fig 2-4). October experiences the highest monthly average precipitation although Octobers were particularly wet in 2002 – 2005, skewing the 11-year average. The elevation of the Pecos River gradually and steadily descends from 853 m (2,800 feet) at Red Bluff Dam to 350 m (1,150 feet) at the terminus of the Lower Pecos River below Painted Canyon. The terrain surrounding the Lower Pecos is much more rugged and hilly than the generally flat Upper Pecos.

Land Use/Land Cover

Vegetation throughout the Pecos River watershed is primarily shrubs and low-profile trees adapted to the arid to semi-arid climate of the Chihuahuan Desert such as creosote bush (*Larrea tridentata*), tarbush (*Flourensia cernua*) and the nuisance saltcedar (*Tamarix spp.*). Water bodies are scarcer in the Upper Pecos than the Lower Pecos where many small springs, springbrooks, and intermittent streams dot the landscape. The invasive saltcedar, brought to Texas in the 1800s as an ornamental and for erosion control, is a major concern to water conservation in the Pecos River because it produces extremely dense riparian stands and removes groundwater through evapotranspiration (Gregory and Hatler, 2008; Hatler and Hart, 2009).

[Remainder of page intentionally left blank.]

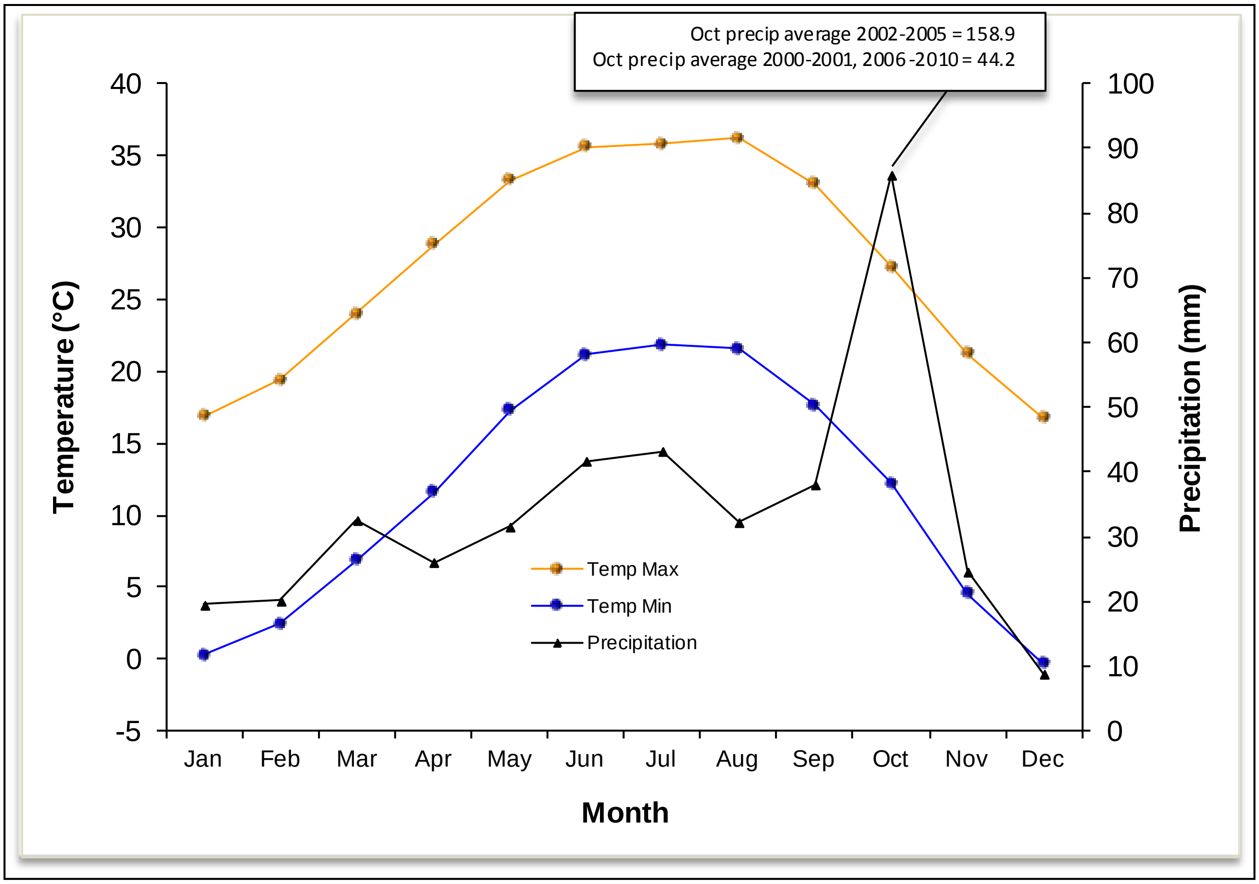


Figure 2-4. Temperature and precipitation normals for Sheffield, Texas (1 January 2000 – 31 December 2010) (NCDC, 2011).

Surface Water Irrigation

As mentioned in the introductory text, the flows in the upstream reaches of the Upper Pecos River below Red Bluff Reservoir are predominately dictated by the water release schedule from the reservoir. Because of the low rainfall in the watershed, the majority of streamflows in the Upper Pecos River above the Ward 2 Turnout are dictated by these releases from Red Bluff Reservoir and the withdrawals at the various irrigation district turnouts. For 2004–2010, irrigation turnouts along the Upper Pecos River withdrew on average 14,800 ac/ft of water annually from the stream channel, with most withdrawals occurring from April through October (Figure 2-5). In response to these irrigation needs, Red Bluff Reservoir releases extra water during the growing season to compensate, commonly starting in late March to April. Rainfall runoff entering the Pecos River between Red Bluff Reservoir and the irrigation turnouts constitute a portion of the total surface water used for irrigation purposes, but in most years this runoff amount is small compared to reservoir releases. Without additional flow releases, the riverbed of the Upper Pecos River would occasionally go dry according to landowners cited in Hatler and Hart (2009). In contrast, flows in Sections B and A are largely supported by spring flows, including Independence Creek, and are thus rarely interrupted and essentially perennial even during drought.

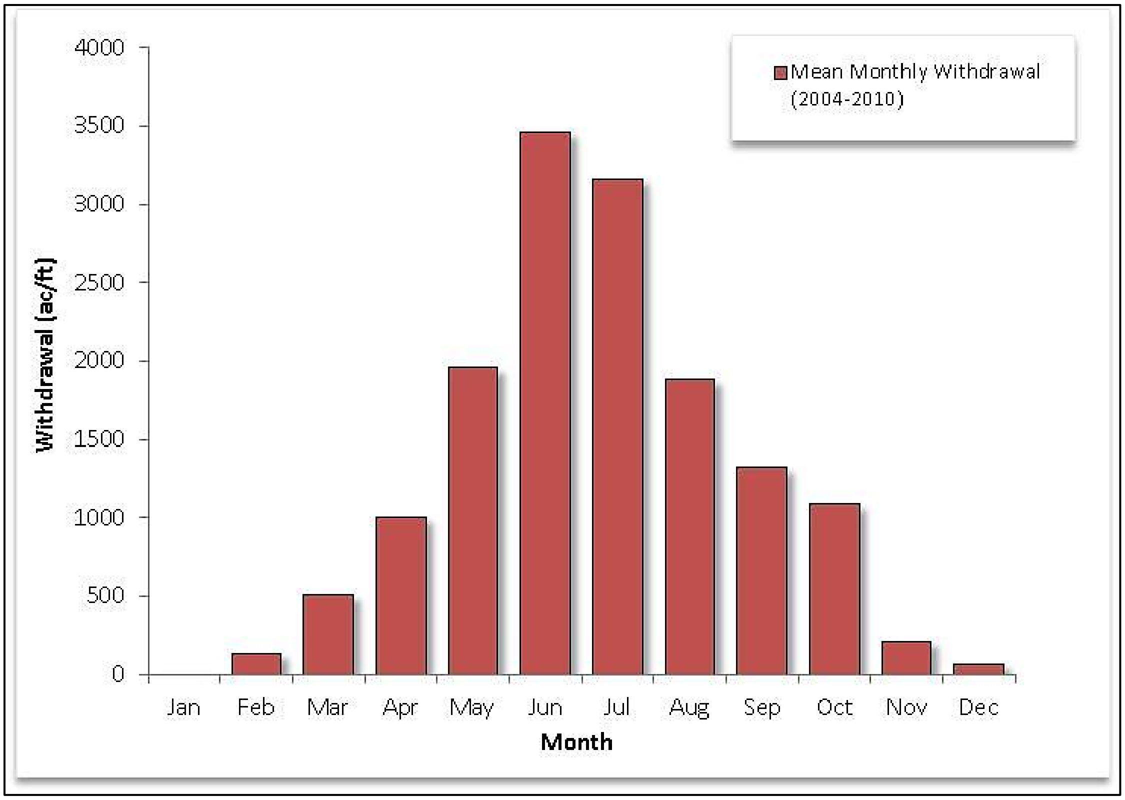


Figure 2-5. Monthly average withdrawals from all turnouts in the Pecos River 2004–2010.

Streamflow and Water Quality Data

SWQMIS and CWQMN Data

The water quality data for the Pecos River are available from two primary TCEQ sources: the Surface Water Quality Monitoring Information System (SWQMIS) and the Continuous Water Quality Monitoring Network (CWQMN). A query was conducted on 7 January 2011 of SWQMIS for all of the water quality data available from all sites and dates in Segments 2310, 2311, Red Bluff Reservoir and Independence Creek. This large dataset was reduced to a more manageable size by selecting for parameters of interest, culling stations with minimal data and removing records containing obvious errors. The resulting SWQMIS dataset contained 43 stations and 3,596 records, with a date range of 4 September 1968–25 August 2010.

Data from all CWQMN stations in the Pecos River watershed was provided by TCEQ to Texas Institute for Applied Environmental Research (TIAER) in early 2011. This large dataset was reduced to include only the data sufficient for data analysis and for model verification. The multiprobes at each CWQMN station were retrieved and replaced by TCEQ staff every two weeks with a few exceptions, and the retrieved multiprobes were downloaded for stored data and made ready for redeployment on this two-week schedule of deployment and retrieval. Operator logs were maintained by TCEQ staff to document the viability of the data and the nature of any equipment failure and operator errors that might have compromised the data. The first step by TIAER in grooming CWQMN data was to review operator logs to determine what periods of data collection were corrupted by instrument or operator failure. Since logs were written every two weeks for several years at five stations and with variable syntax to describe data problems, several passes had to be made through the logs using keyword searches and reading fully through numerous logs to verify suspect data ranges and whether only some or all of the data collected was corrupted at suspect sites on suspect dates. Once questionable date ranges were removed, TIAER further culled the data based on TCEQ recommendations to include only the first full day after deployment (i.e., data beginning at the first midnight after deployment and continuing up to the second midnight after deployment). TCEQ experiences indicated that biofouling and sedimentation issues tended to cause the multiprobe data to become less reliable as time progressed after the initial time of the two-week instrument deployment. Hence, the TCEQ recommendation to restrict the amount of data considered accurate during each two-week deployment period to the first full day of deployment. Most multiprobes recorded water quality data every 15 minutes resulting in 96 records per deployment per station. During some collection periods, data were collected even more frequently (e.g., every 5 minutes) resulting in several hundred records per deployment. The final CWQMN dataset covered five stations, 41,794 records, and a date range of 12 July 2005–26 January 2011. For most analyses it was necessary to create daily summary records for each station and date of means, maximums, and minimums. Once 24-hour means, minimums, and maximums were calculated for key parameters (e.g., DO and water temperature) for each deployment at each station, the CWQMN dataset was reduced to 424 records.

After all records from SWQMIS and CWQMN were compiled new parameters were created by merging effectively equivalent parameters (e.g., chlorophyll-a (CHLA) determined by fluorometric and spectrophotometric methods) and arithmetic calculations (e.g., DO percent saturation). In some instances data fell below the limit of detection and was qualified with “<”. In such cases, in an effort to apply a consistent estimation procedure, those data were assumed to be half of the value presented as suggested in TCEQ (2010b). A summary of the water quality stations and dates compiled for this study is presented in Table 2-2 and the key stations used in data presentation and model calibration and verification are provided in Figure 2-3.

Streamflow Data

Streamflow data was obtained from five U.S. Geological Survey (USGS) streamflow gaging stations in the watershed, but only two stations had complete and lengthy records (Table 2-2). For each of the five sections of the main stem Pecos River (see section descriptions provided above and in Figure 2-3) and Independence Creek, a USGS station was selected to represent streamflow in this section. Sections C (station 08446500) and E (station 08412500) had periods of record from 1970–2010. All other stations had date ranges of summer 2007–2010.

Table 2-2. Data by section and source including available periods of record and station locations

Section	SWQM	SWQM Date Range		CWQMN	CWQMN Date Range		USGS	USGS Date Range		Location
		Start	End		Start	End		Start	End	
A	18801 & 13246*	4-Nov-08	6-Jul-10	729	11-Mar-06	25-Jan-11	08447300	15-Jul-07	31-Dec-10	LOWER PECOS RIVER CWQMN 0729
B	13249	27-Jun-69	7-Jul-10	735	5-Aug-06	25-Jan-11	08447000	13-Jul-07	31-Dec-10	UPPER PECOS RIVER AT SH 290
C	13257	5-Sep-68	13-Jul-10	—	—	—	08446500	1-Jan-70	31-Dec-10	PECOS RIVER AT US 67
C	13260	13-Oct-87	16-Jun-10	709	12-Jul-05	12-Aug-10	08437710	13-Jul-07	31-Dec-10	PECOS RIVER AT FM 1776
D	13261	13-Oct-87	16-Mar-10	710	10-Mar-06	26-Jan-11	08420500	2-Aug-07	31-Oct-10	PECOS RIVER AT US 80 CWQMN 710
E	13265	4-Sep-68	3-Aug-10	—	—	—	08412500	1-Jan-70	31-Dec-10	PECOS RIVER AT FM 652

* Stations 18801 and 13246 are not collocated but are in close enough proximity that their data are combined for any analyses herein.

Data Analysis

Seasonal Trends

Based on statistical analyses, streamflow (log_{10}-transformed), DO (24-hour average and minimum), and water temperature (24-hour average) of the Pecos River in Texas can be grouped into two seasonal categories - cool months of November–March and warm months of April–October (Table 2-3, Figure 2-6). There are differences, however, in the expression of seasonality between the Upper and Lower Pecos River. The hydrology of the Upper Pecos River, especially that portion above the Ward 2 Turnout, is largely defined by managed releases from Red Bluff Reservoir and withdrawals at the irrigation turnouts that have occurred predominately from April through October (Figure 2-5). Late summer and fall rains account for the bulk of annual precipitation in the Pecos River watershed and presumably are responsible for some of the flow variability seen in the boxplots of flow by month (Figure 2-6). However, the magnitude of summer flow variability below the reservoir (USGS gage 08412500) compared to the summer variability of the middle portion of the Upper Pecos (USGS gage 08446500) and Lower Pecos (USGS gage 08447300) suggests that releases from the reservoir overshadow precipitation-generated flow variation patterns in the Upper Pecos.

It is important to also note that the Pecos River does not receive discharges from municipal wastewater treatment facilities (WWTFs). Therefore water quantity and quality influences from these types of discharge facilities, which are very common in less arid and more populated areas of Texas, do not exist along the Pecos River.

Table 2-3. Results of t-tests by season (warm versus cool) for DO, water temperature, and flow (log-transformed).

Parameter	Season	n	Min	Max	Mean	St. Dev.	t	*p*
24-hr DO Average (mg/L)	cool	160	7.0	11.3	9.0	0.86	19.02	<0.0001
	warm	230	4.6	14.0	7.1	1.10		
24-hr DO Min (mg/L)	cool	160	5.0	10.3	8.1	1.05	19.43	<0.0001
	warm	212	2.2	12.4	5.5	1.5		
24-hr DO Range (mg/L)	cool	160	0.1	7.6	2.1	1.22	-8.88	<0.0001
	warm	230	0.4	23.9	4.4	3.68		
24-hr Water Temp Average (°C)	cool	160	4.0	21.1	12.9	3.98	-31.93	<0.0001
	warm	230	10.5	31.9	25.5	3.7		
$Flow_{Log-08447300}$ (cms) (Section A)	cool	515	0.5	0.8	0.6	0.05	11.97	<0.0001
	warm	703	0.3	0.9	0.6	0.14		
$Flow_{Log-08447000}$ (cms) (Section B)	cool	515	0.2	0.5	0.4	0.04	14.4	<0.0001
	warm	745	0.1	0.8	0.3	0.13		
$Flow_{Log-08446500}$ (cms) (Section C)	cool	3025	0.1	1.7	0.3	0.08	22.92	<0.0001
	warm	4280	0.1	1.4	0.2	0.12		
$Flow_{Log-08420500}$ (cms) (Section D)	cool	454	0.1	0.9	0.2	0.12	-21.41	<0.0001
	warm	681	0.0	1.0	0.4	0.23		
$Flow_{ln-08412500}$ (cms) (Section E)	cool	3025	0.00	1.1	0.2	0.15	-63.72	<0.0001
	warm	4280	0.0	1.7	0.5	0.3		

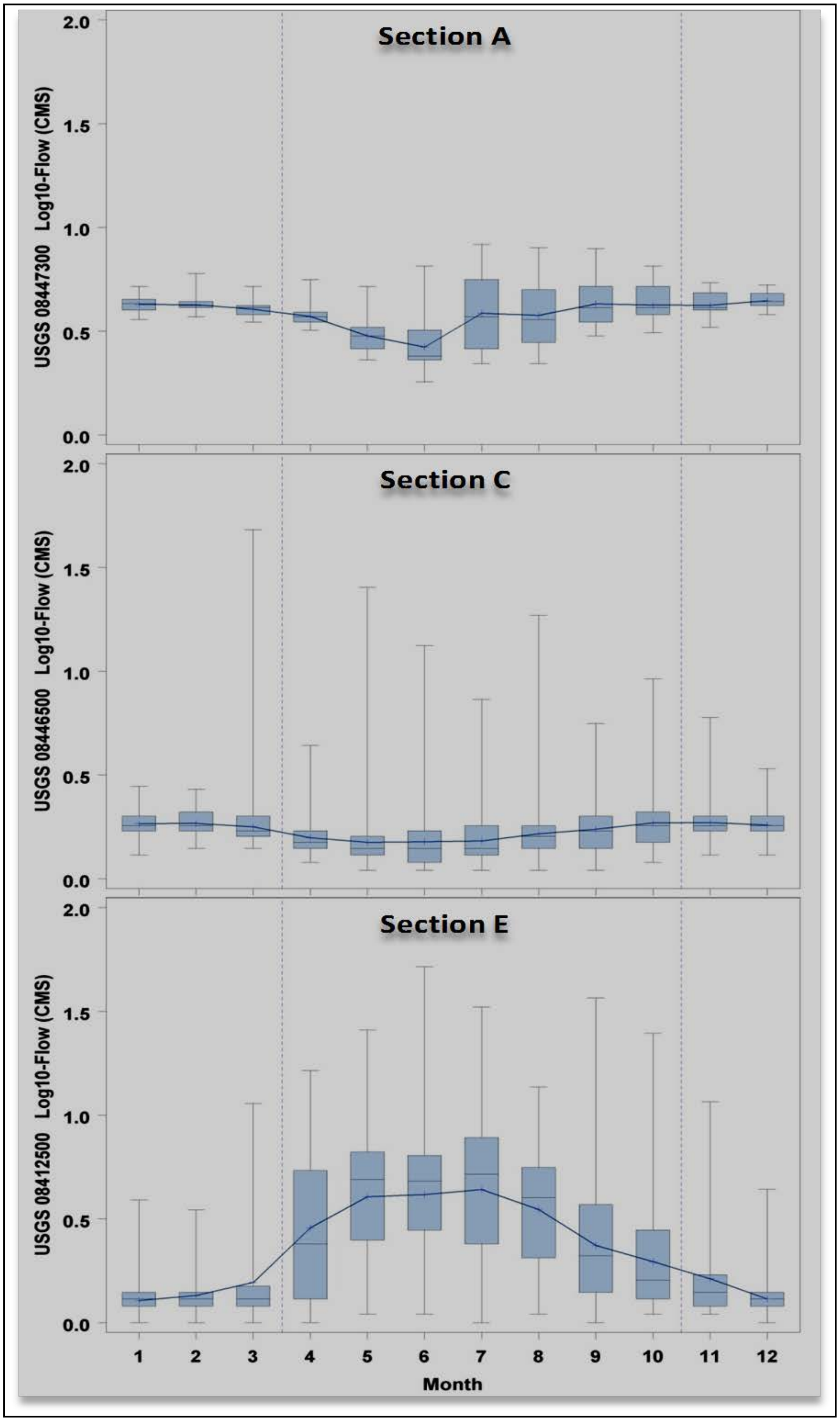


Figure 2-6. Boxplots of flow by month for Sections A, C and E of the Pecos River.

Hatler and Hart (2009) provide anecdotal evidence of the impact of the irrigation-driven flow regime in the Upper Pecos, citing landowner testimonies that the riverbed in the Upper Pecos has gone dry at times between reservoir releases (Section E in Figure 2-6). Because of spring flows, the Lower Pecos flow regime is more stable during the summer with mild dips and rises in mean discharge that follow closely the growing season and precipitation patterns of the region (see Figure 2-4), namely, uptake by riparian vegetation in the spring and early summer that reduces streamflow followed by late summer and early fall rains that replenish flow (Section A in Figure 2-6). Discharge from Independence Creek contributes nearly 50% (0.25 cms) of flow year-round to the Lower Pecos and this has a buffering effect on early summer losses and dampens flow variability. The more downstream portions of the Upper Pecos River (Section C) represent a transition from artificial flow alterations to more natural processes such as evapotranspiration and groundwater contributions to streamflow. This is evident in the flow-by-month boxplot of Section C (USGS 08446500; Figure 2-6) where summer flow resembles upstream sections in variability yet the average discharge parallels the Lower Pecos with modest spring drops followed by mild flow increases in the fall.

T-tests of flow data by season (cool versus warm) also show opposing trends in the Upper and Lower Pecos River (Table 2-3). The Upper Pecos River (Sections C, D and E) experiences higher flow in the warm season than in the cool season whereas the Lower Pecos has lower flows during the warm season. This corroborates the evidence of the flow boxplots and the precipitation graph that the hydrology patterns of the Upper Pecos are driven largely by releases from Red Bluff Reservoir and the Lower Pecos hydrology is primarily a function of tributary and spring inputs in tandem with climate and vegetation (evapotranspiration) processes.

DO also exhibited bi-modal seasonality. Twenty-four-hour average DO during warm months was nearly 2 mg/L lower than in cool months and variability (i.e., 24-hour DO range) was higher in the summer as well (Table 2-3). Cool and warm seasons were also significantly different for 24-hour minimum DO (Table 2-3). The boxplot of 24-hour average water temperature (Figure 2-7) shows clearly the distinctions between hot summers and cool winters, although longer transition periods make the seasonal boundaries appear less abrupt.

Bi-modal seasonality, specifically April–October as the warm season and November–March as the cool season, is also supported by the cluster analysis in Figure 2-8. The cluster shows the relative distances (normalized root mean squared distance) of 24-hour average DO and water temperature grouped by month. The two primary clusters group warm and cool season months just as the boxplots and t-tests of flow and 24-hour DO would suggest. The cluster also parses transitional months (4-5 and 10-11) from hot "deep summer" and cold "deep winter" months (7-8 and 12-1, respectively) demonstrating its effectiveness as a tool for understanding seasonality, at least within the Pecos River system.

In summary, patterns in flow regime, DO, and water temperature along with anecdotal evidence regarding the impact of reservoir releases on the flow regime all indicate that conditions in the Pecos River can be considered broadly as occurring in two seasons—a warm season from April–October and a cool season from November–March.

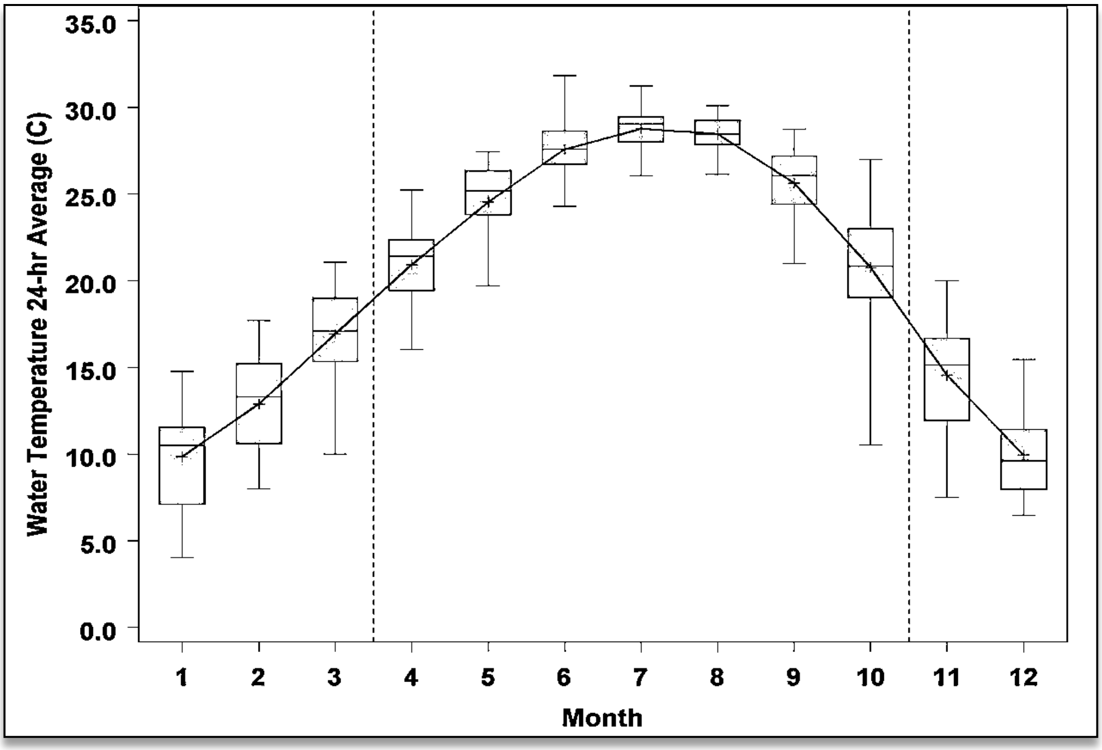


Figure 2-7. 24-hour average water temperature by month in the Pecos River. Vertical bars distinguish warm and cool seasons.

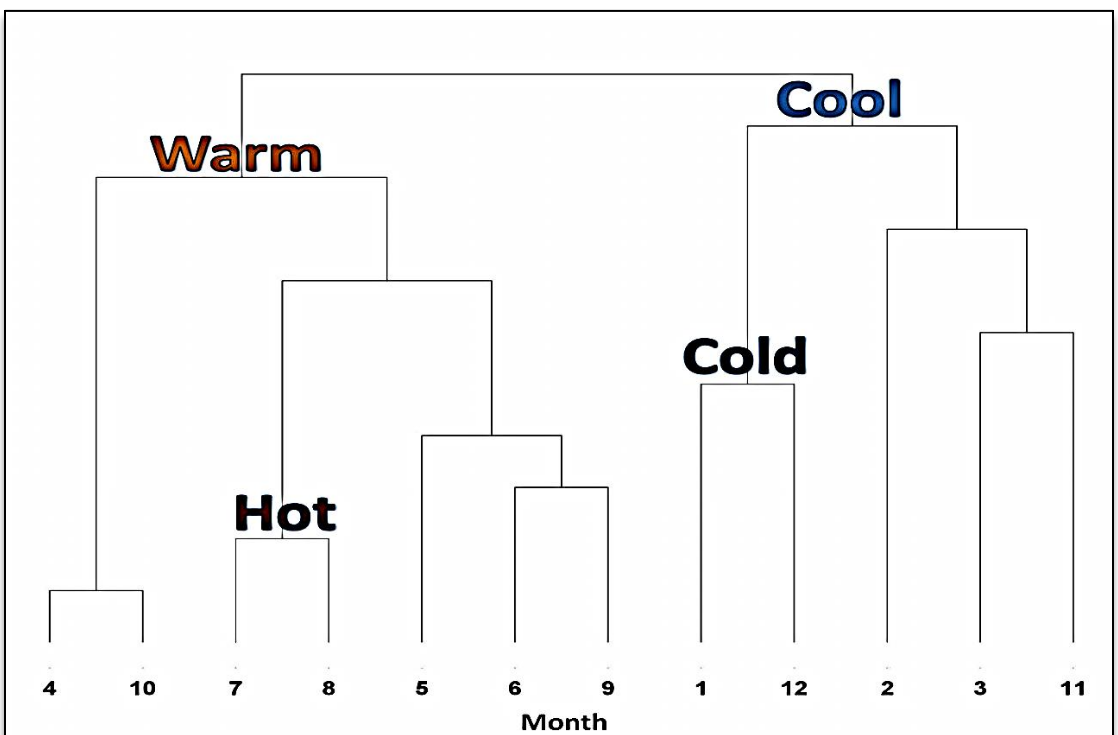


Figure 2-8. Cluster analysis showing relative distance of samples grouped by month according to 24-hour averages of DO and water temperature from diel SWQMIS and CWQMN data, June 2003–January 2011.

Diel Trends

The time of day when DO minimums and maximums occur in the Pecos River suggests that DO fluctuations are tied to photosynthesis and respiration processes (Figure 2-9). CWQMN data were used in the time plots which show that DO maximums at all stations occurred during the mid-afternoon and minimums occurred shortly after sunrise. This pattern is typical of streams containing large amounts of algae and macrophytes. A photographic example of the abundance of periphyton (also referred to as periphytic algae) in portions of the Upper Pecos River is provided in Figure 2-10.

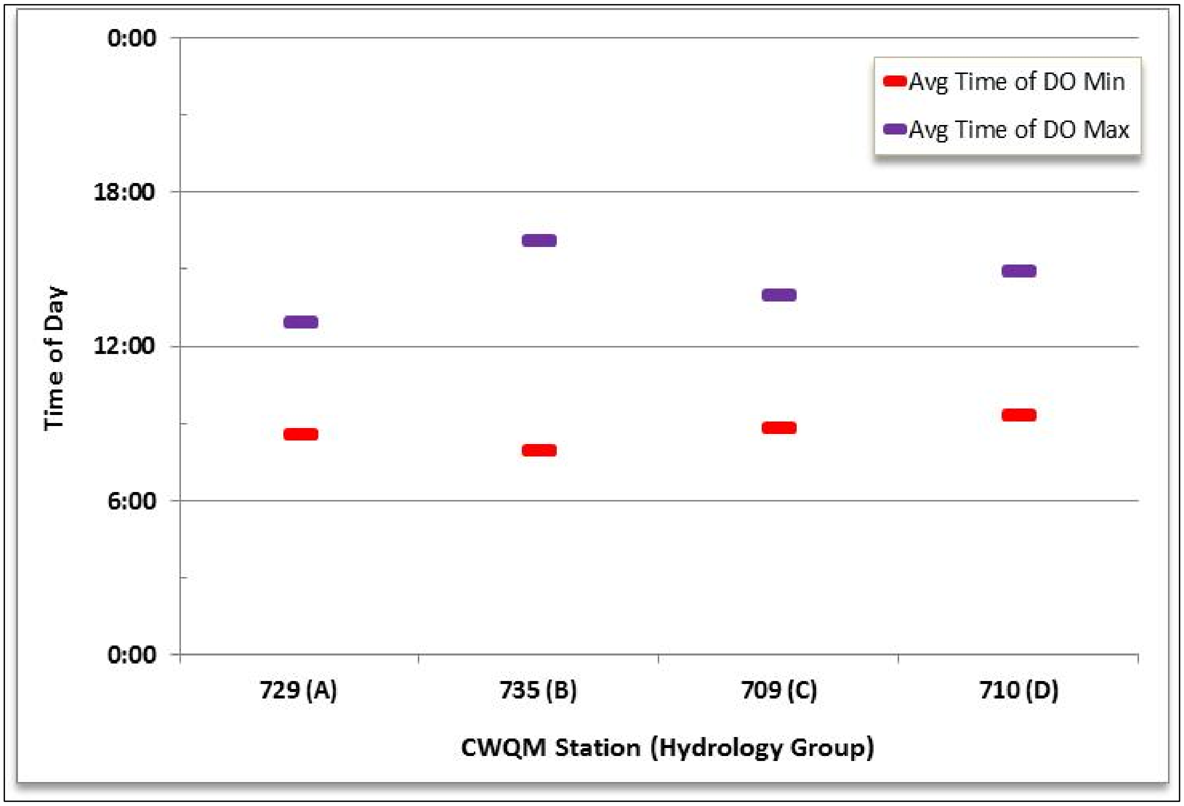


Figure 2-9. Daily average of time of occurrence of maximum and minimum DO at representative CWQMN stations.

Figure 2-10. Photograph of periphyton in Upper Pecos River at US Highway 67 bridge crossing (TCEQ station 13257). *Photograph taken May 4, 2010*.

Spatial and Flow Components to Depressed DO

Load duration curves (LDCs) were developed for each hydrologic section from 24-hour DO average and minimum data for the purpose of examining the relationship between streamflow and DO. LDCs are similar in appearance to flow duration curves (FDCs) but the y-axis is expressed in terms of a DO load in kg/day. The curve represents the relevant DO criterion, expressed in terms of a load through multiplication by the flows historically observed at the USGS station used in the LDC. Because the streamflow data used in generating the FDCs and LDCs are ordered from highest daily value to smallest, the left side of the graph indicates higher flow conditions and the right side indicates the lower flows. Loadings of DO plotted above the curve indicate that the DO criterion is being met, and conversely values falling below the curve indicate depressed DO not meeting the DO criterion.

Using the relevant criterion (average of 5.0 mg/L or minimum of 3.0 mg/L) to generate the LDC is necessary to display the minimum required load in relation to the existing loads represented by actual water quality samples. The stations and periods of record used in the LDC analysis are presented in Table 2-4. The LDCs reveal that depressed DO below the relevant criterion occur primarily in Section C and are primarily a low-flow phenomenon with some occurring during mid-range flows in Section C (Figures 2-11 through 2-15). Also, the overwhelming majority of occurrences of depressed DO are associated with the 24-hour minimum DO rather than the 24-hour average DO. Section E immediately below Red Bluff Reservoir has too few data points to come to any conclusions (Figure 2-15).

Table 2-4. Data used in the development of LDCs of DO average and minimum in Sections A-E of the Pecos River.

	Stations		Periods of Record			
Group	USGS	SWQM and CWQMN	Flow		DO	
			Start	End	Start	End
A	08447300	729	15-Jul-07	31-Dec-10	26-Jul-07	30-Dec-10
B	08447000	735	13-Jul-07	31-Dec-10	15-Feb-08	30-Dec-10
C	08446500	13257	1-Jan-01	31-Dec-10	24-Jun-03	13-Jul-10
		13260			26-Jun-03	23-Jul-08
		709			12-Jul-05	30-Jul-10
D	08420500	710	2-Aug-07	6-Oct-10	2-Apr-08	6-Oct-10
E	08412500	13265	1-Jan-01	31-Dec-10	11-Jun-09	21-Jul-10

[Remainder of page intentional left blank.]

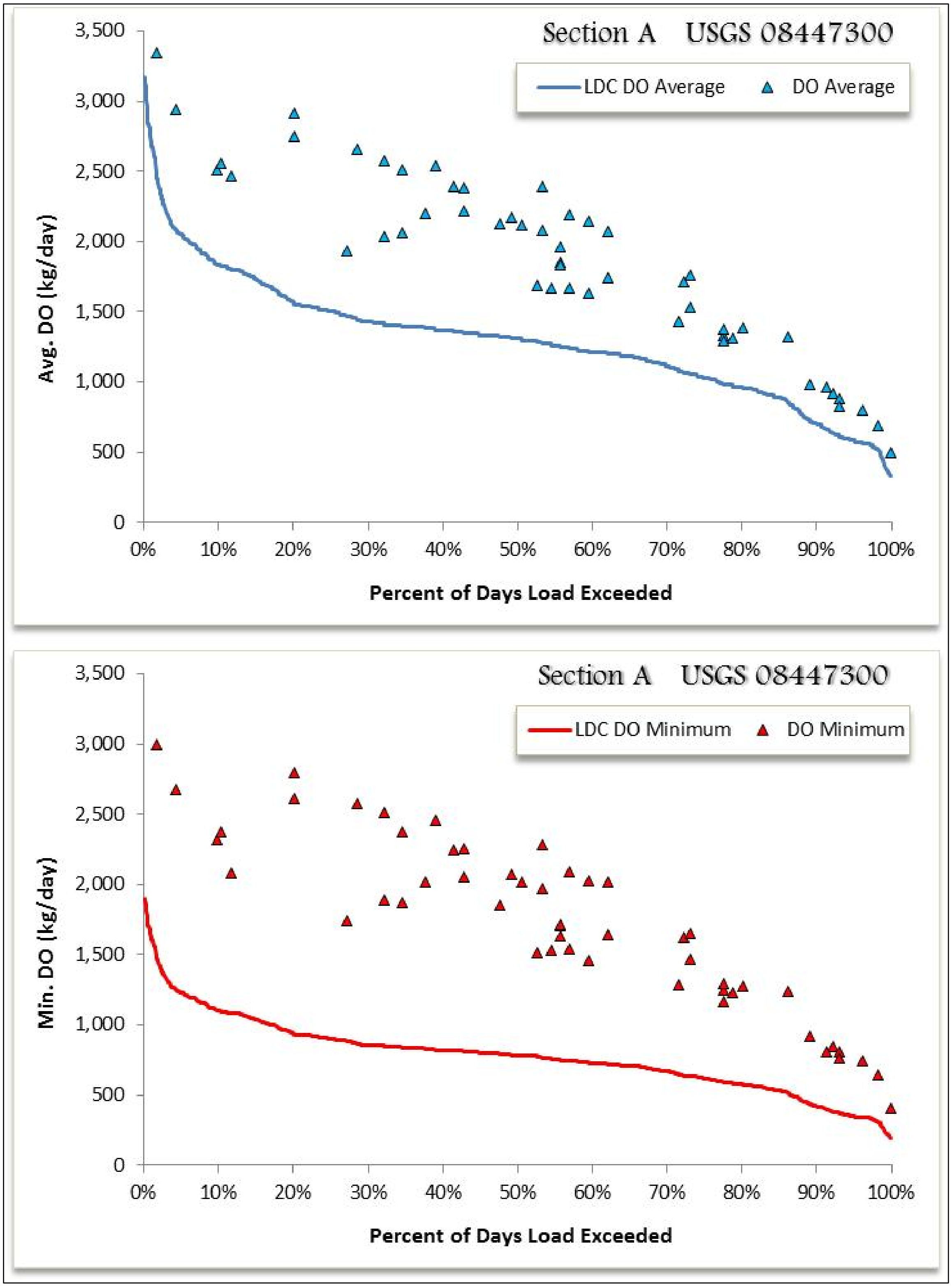


Figure 2-11. Load duration curves and loadings of 24-hour DO averages and minimums for Section A. Flow data from USGS gage 08447300; DO data from CWQMN station 729.

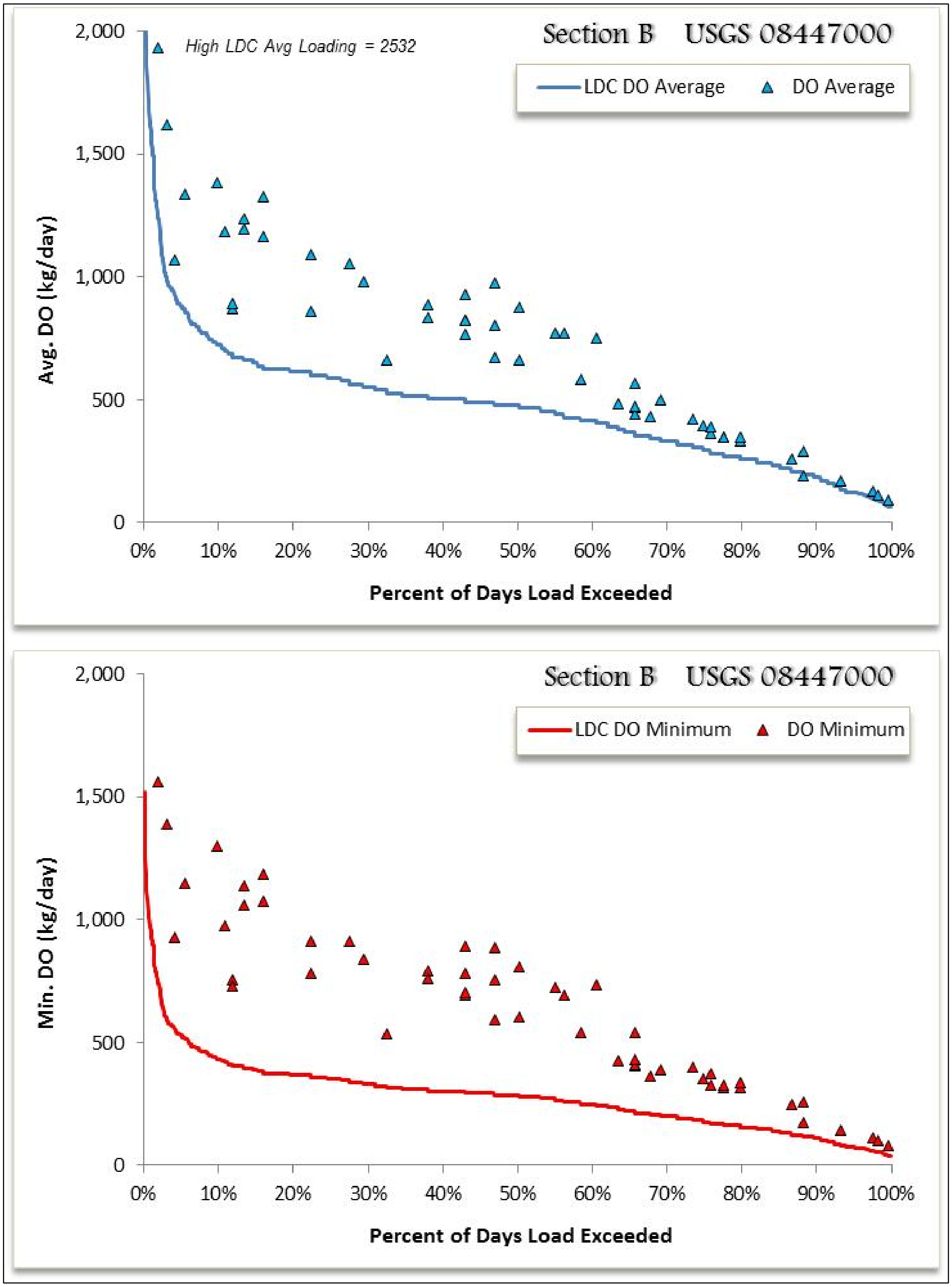


Figure 2-12. Load duration curves and loadings of 24-hour DO averages and minimums for Section B. Flow data from USGS gage 08447000, DO data from CWQMN station 735.

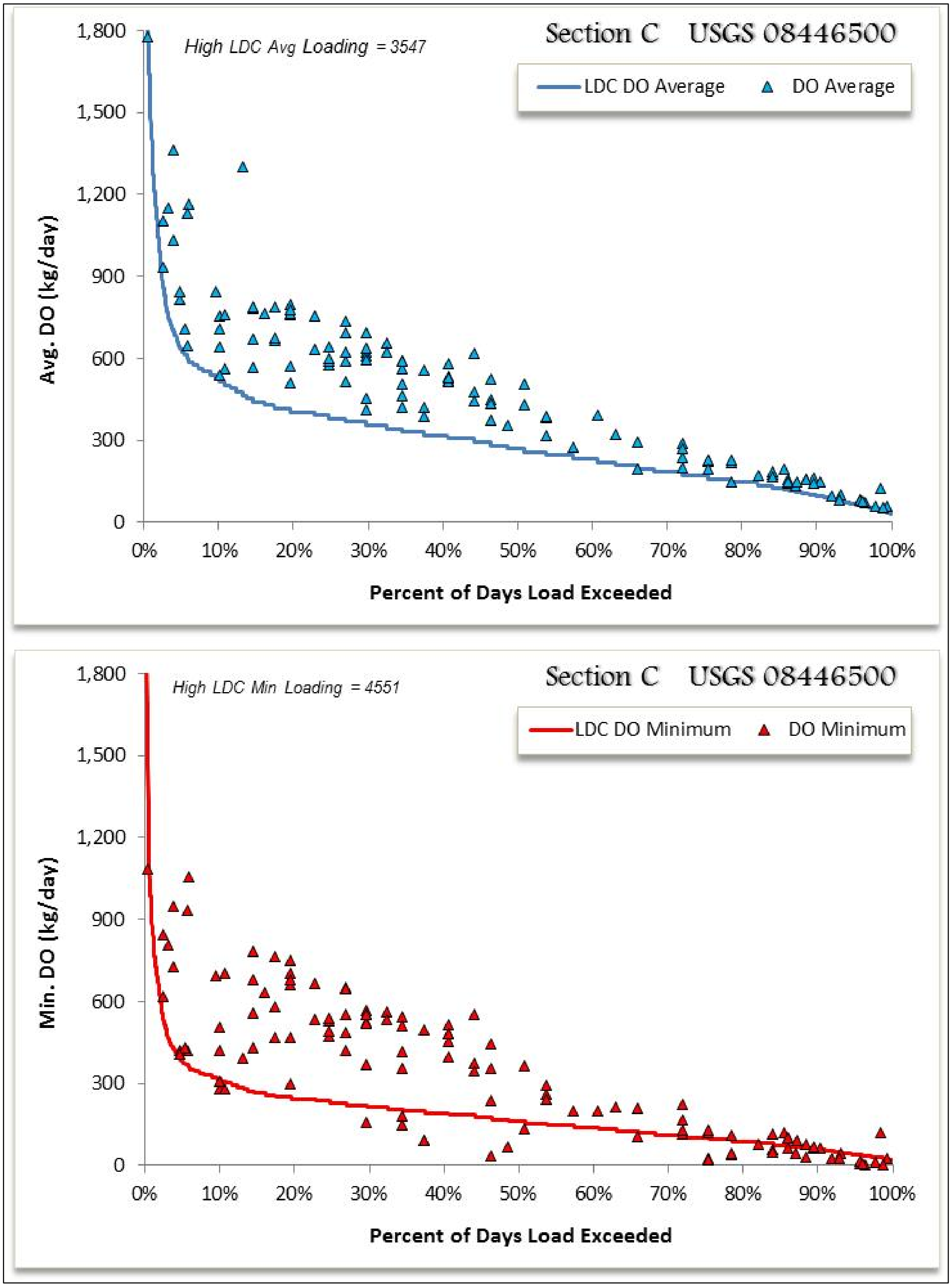


Figure 2-13. Load duration curves and loadings of 24-hour DO averages and minimums for Section C. Flow data from USGS gage 08446500; DO data from SWQM stations 13257 and 13260 and CWQMN station 709.

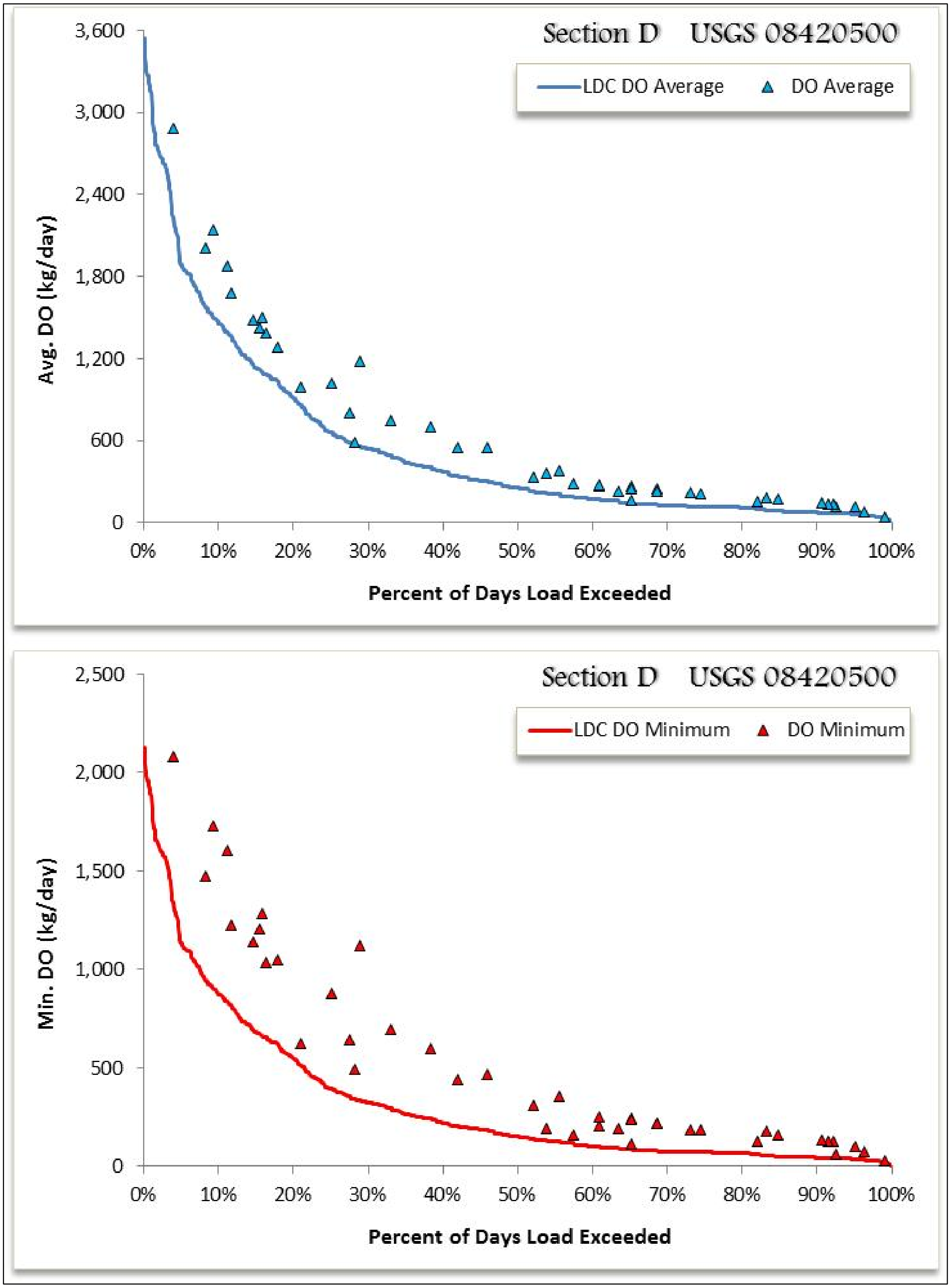


Figure 2-14. Load duration curves and loadings of 24-hour DO averages and minimums for Section D. Flow data from USGS gage 08420500; DO data from CWQMN station 710.

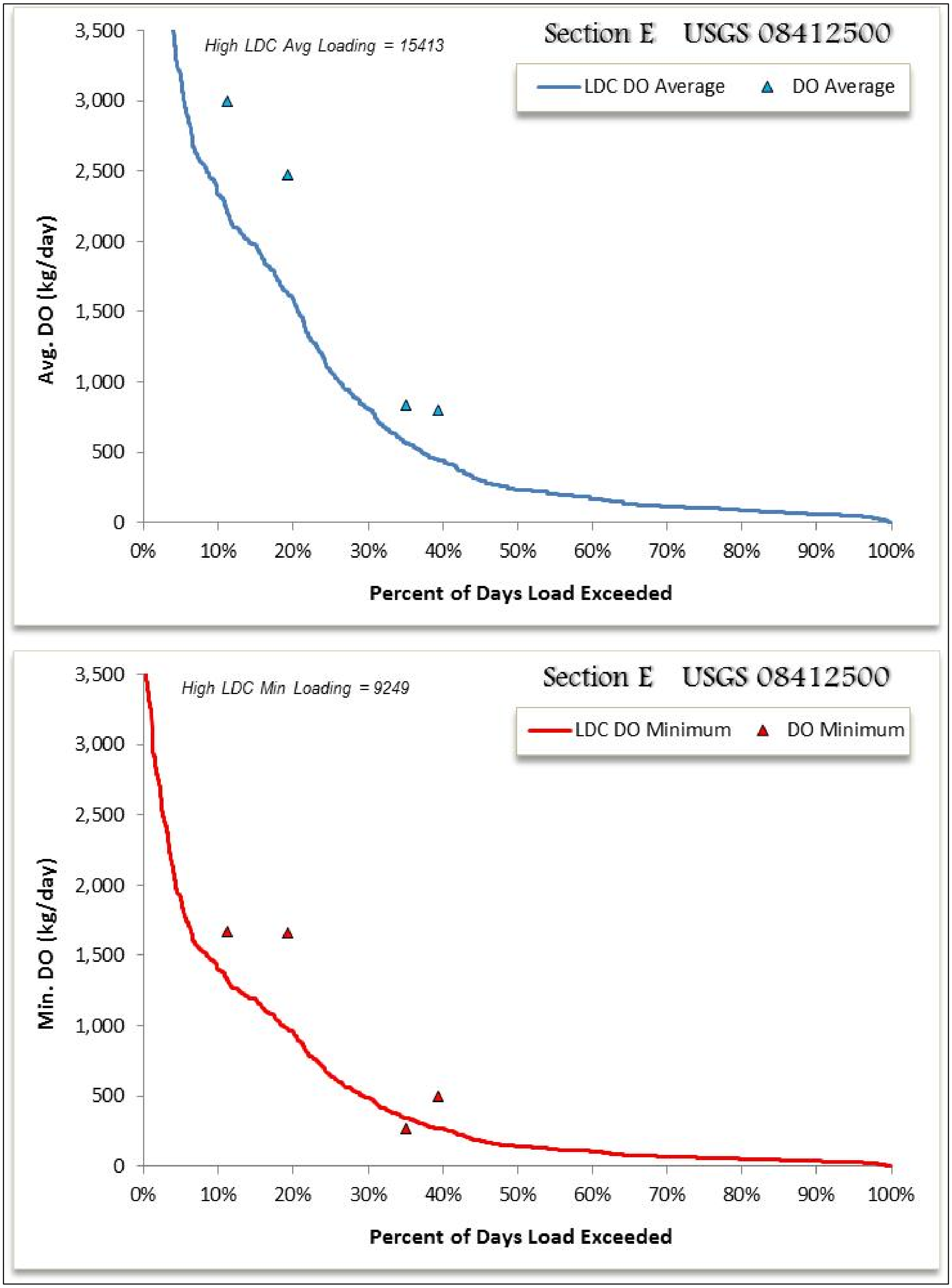


Figure 2-15. Load duration curves and loadings of 24-hour DO averages and minimums for Section E. Flow data from USGS 08412500; DO data from SWQM station 13265.

Spatial and Seasonal Components to Depressed DO

To provide additional insights into the spatial and seasonal occurrences of depressed DO along the Pecos River in Texas, 24-hour DO average and DO minimum for the period January 2005 to January 2011 were plotted for the CWQMN and SWQM stations (Figures 2-16 through 2-18). This series of graphs provides additional insights to the previous analysis (Figure 2-11 through 2-15) regarding the seasonality of the occurrences of depressed DO. The previous analysis indicated that hydrologic Section C was the reach of the Upper Pecos River where depressed DO was most likely to occur, that the depressed DO was predominately a 24-hour minimum issue and not a 24-hour average issue, and that the occurrences were often at the lower streamflows encountered in the system. This analysis adds to this information that the depressed minimum DO is largely a warm season phenomenon. The warm season occurrence is especially indicated in Figure 2-16 containing a combined dataset for Sections C, D and E. Section A and B, however, also show a strong seasonality in DO concentrations (Figures 2-17 and 2-18), though the cyclic pattern in these sections rarely results in warm season occurrence of DO below the relevant criteria.

Time Series of Salinity Data

Time series of salinity data for three stations were developed to provide a broad overview of conditions along the Pecos River (Figure 2-19). The three stations include 13265 on the Pecos River near Orla and below the Red Bluff Reservoir, 13257 on the Pecos River near Girvin, and 13246 immediately below the confluence with Independence Creek. Focusing on the most recent couple of decades of data, since station 13246 has a shorter period of measurements, the salinity data generally represent the patterns reported in more detail by others (e.g., Miyamoto et al., 2006). The data indicate that releases from Red Bluff Reservoir, as represented by station 13265, contain salinities between 6 to 12 ppt, with an average of around 8 ppt. In the lower portion of the Upper Pecos River above Independence Creek, represented here by station 13257, seepage of brackish groundwater results in increased salinities in the Pecos River of about 15 ppt, but below Independence Creek fresher spring flows decrease salinities at station 13246 to about 2 to 5 ppt.

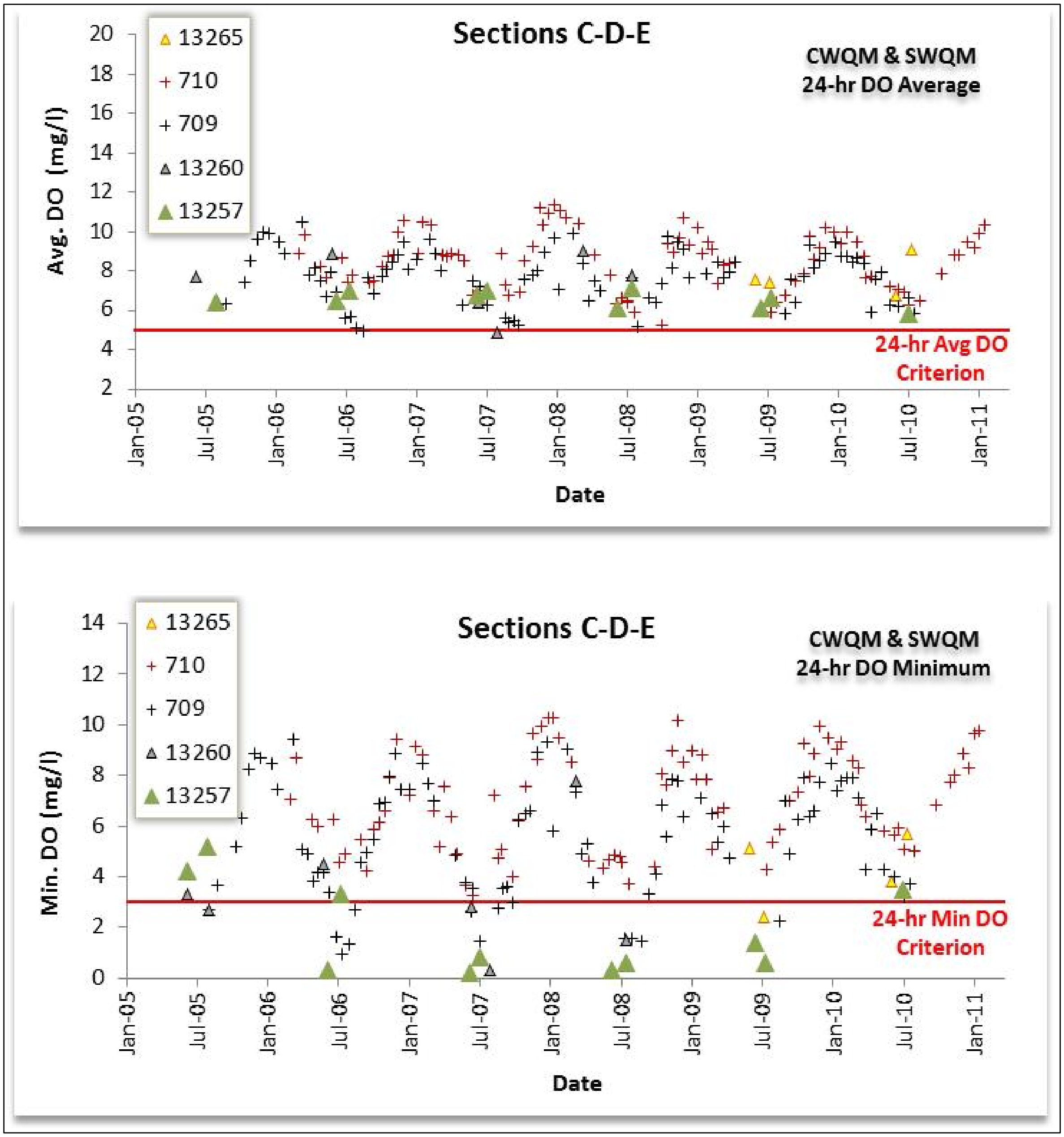


Figure 2-16. 24-hour DO average, and DO minimum for the Sections C, D and E of Upper Pecos River (uppermost and middle reaches).

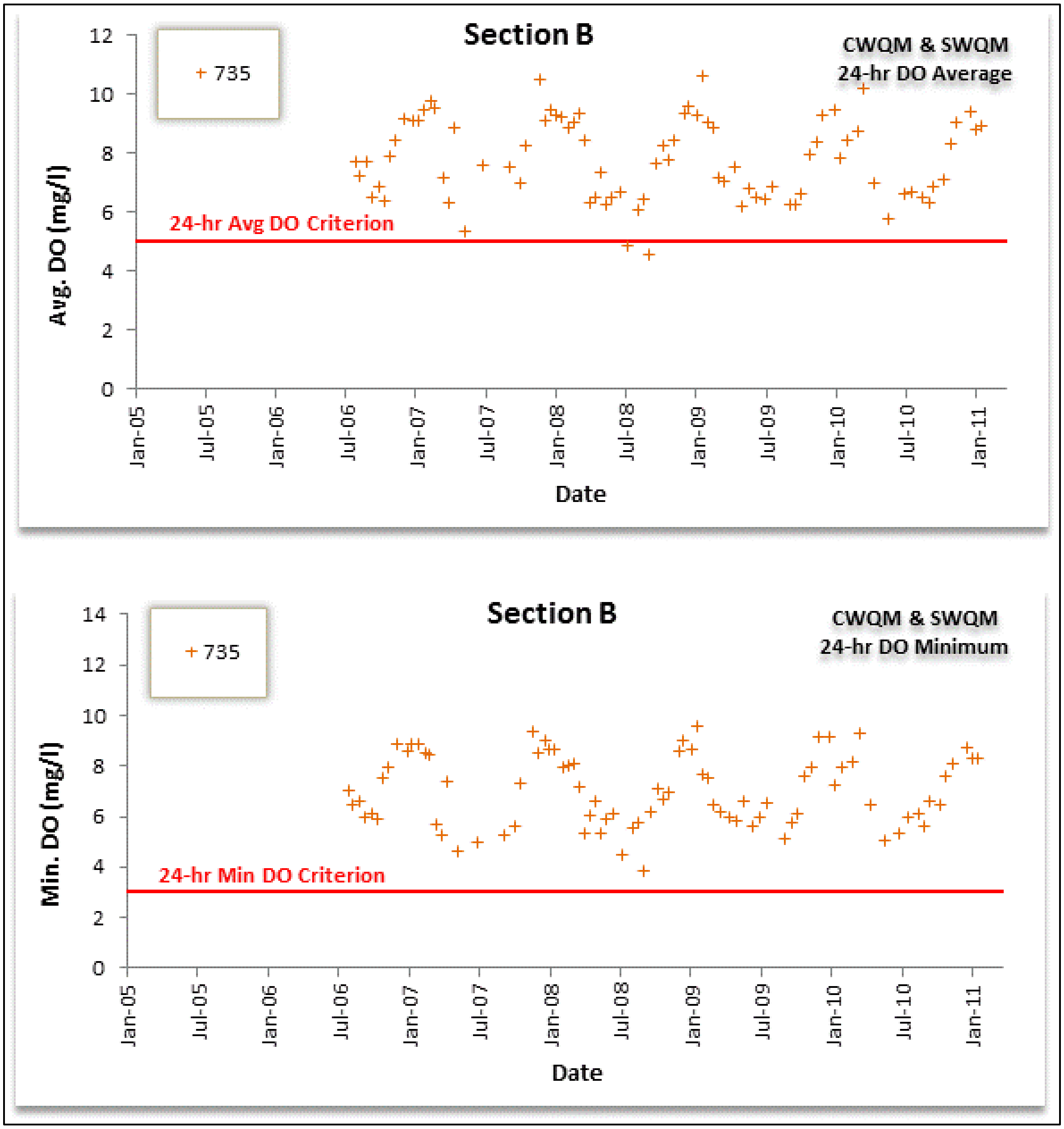


Figure 2-17. 24-hour DO average and DO minimum for the Section B, Upper Pecos River (lowermost reach).

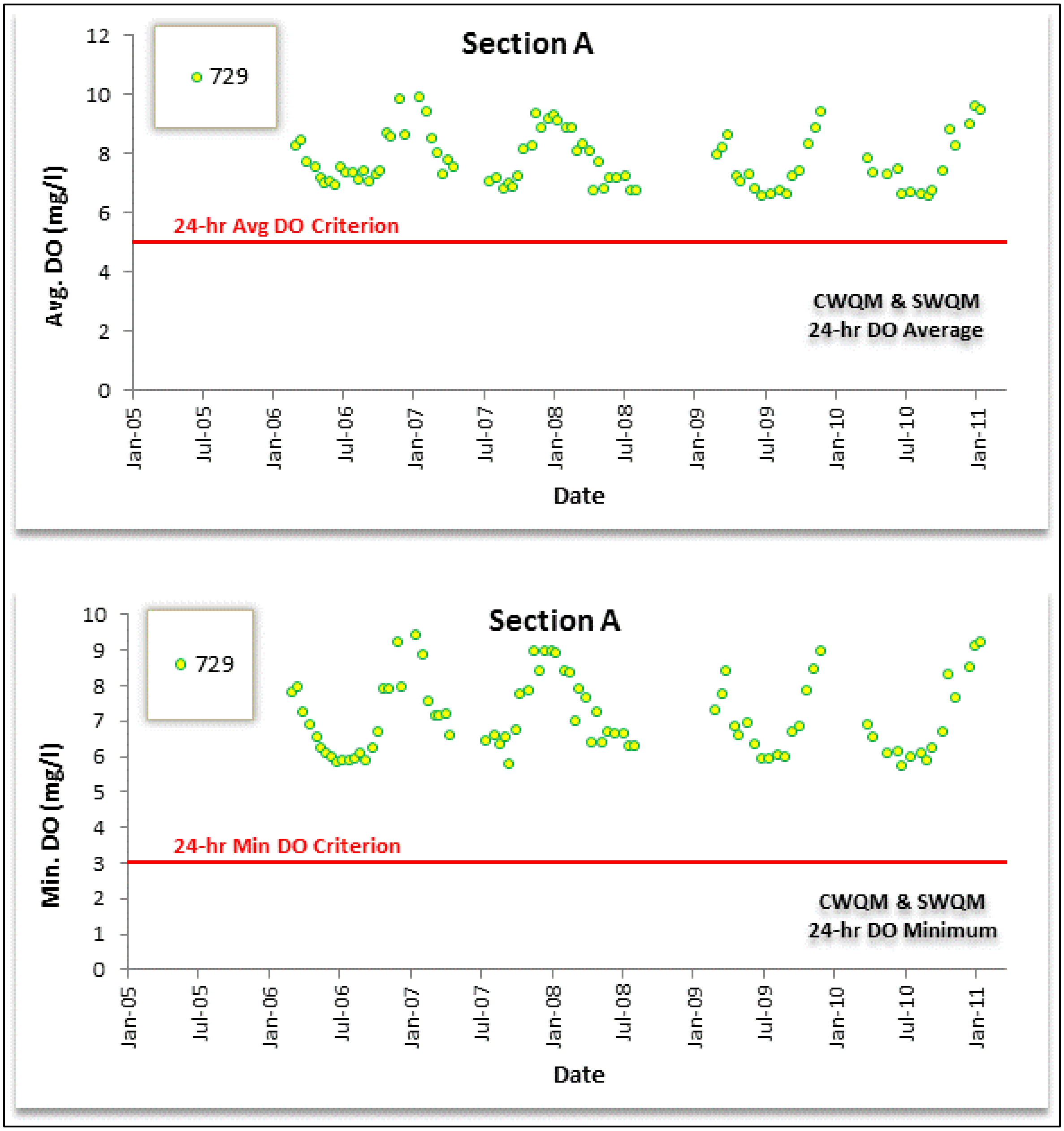


Figure 2-18. 24-hour DO average and DO minimum for the Section A, Lower Pecos River (uppermost reach).

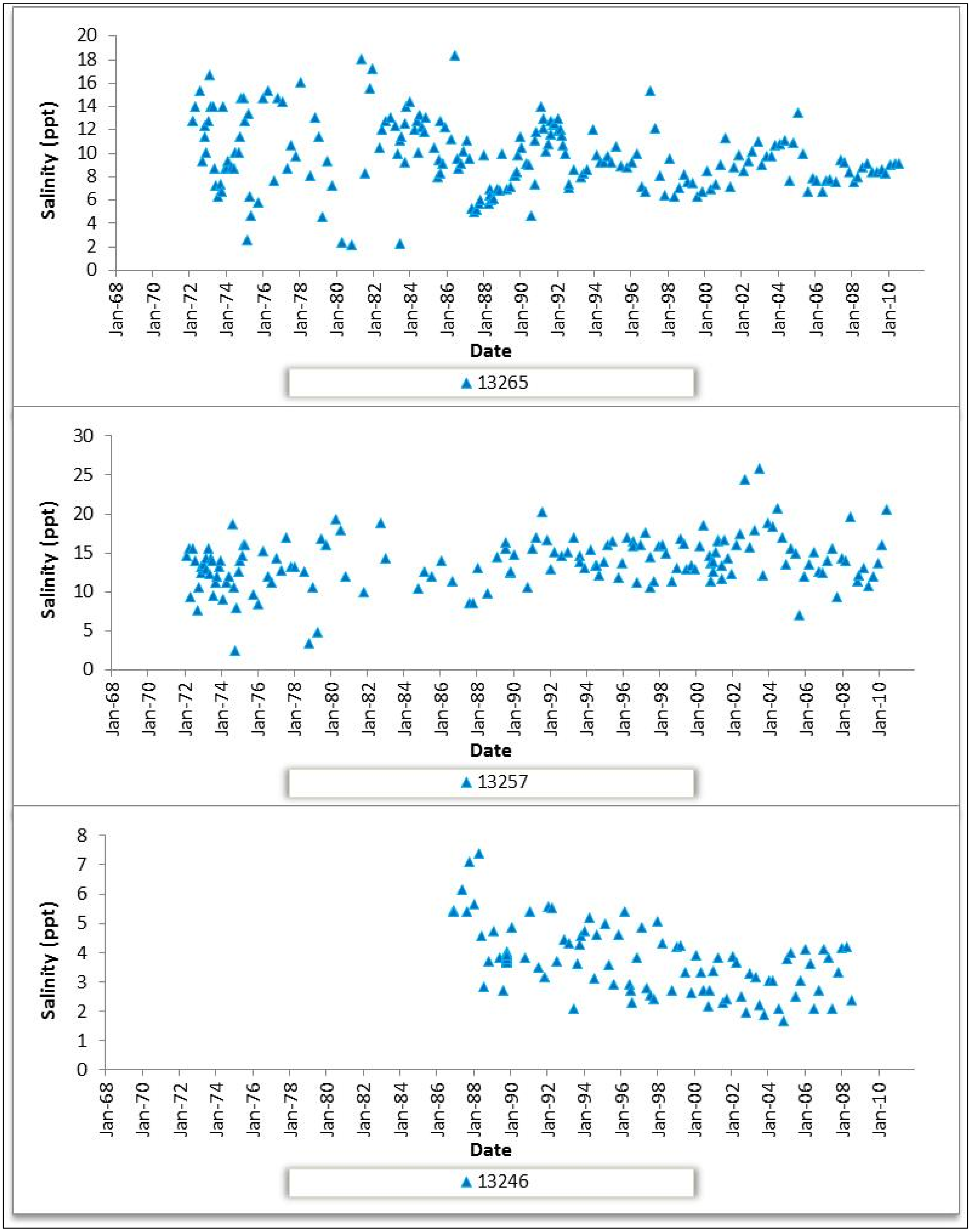


Figure 2-19. Time series of salinity concentrations by hydrologic section from SWQM data for 1972–2010

Time Series of Nutrients and Chlorophyll-a

The 2010 Texas Integrated Report (TCEQ, 2011), which assessed data from 1 December 2001–30 November 2008, revealed that chlorophyll-a (CHLA) values occasionally exceeded the screening level of 14.1 µg/L for freshwater streams in all Pecos River AUs, except 2311_01 and 2311_06, which were not assessed for CHLA. Figure 2-20 plots CHLA data from SWQMIS and confirms generally high values of CHLA have existed throughout the watershed since at least 2000.

The key nutrient species tracked by the TCEQ for eutrophication analyses, (ammonia as nitrogen [NH_3-N], nitrate as nitrogen [NO_3-N], orthophosphate as phosphorus [OP], and total phosphate [TP]) have only infrequently exceeded the screening levels set by TCEQ for freshwater streams (Figures 2-21 through 2-24). Recently, only NH_3-N has more frequently exceeded the 0.33 mg/L screening level but only in Section C. Orthophosphate briefly exceeded the screening level of 0.37 mg/L in 2003–2004 in Sections C and E during a period of slightly elevated OP readings and have since hovered near the lower limit of detection.

In general nutrient levels are not high along the entire length of the Pecos River, though there are some years when nutrients were indicated to be higher than in other years. Frequently the measured nutrient concentrations are at or below laboratory reporting or detection limits. If nutrient concentrations were consistently higher, that would indicate the water, itself, was the possible source of the nutrients supporting the high density of macrophytes along portions of the Upper Pecos River as well as the relatively high suspended algae as measured by CHLA. However, it cannot be as readily concluded that low nutrient concentrations, especially inorganic forms (NH_3-N, NO_3-N, OP) that are readily bioavailable, preclude the river's waters from supplying sufficient nutrients to support the abundant plant populations observed in portions of the Upper Pecos River. The bioavailable, inorganic nutrient forms could be kept at low levels by plant uptake. But given the hydrology of the system with generally low flows which are mostly withdrawn at irrigation turnouts prior to the zone of depressed DO in hydrologic Section C and the absence of point source discharges into the Pecos River, excessive nutrient loadings from inflows to the Pecos River appear unlikely.

Discussion

For the purposes of the DO modeling effort for which details are provided in the next two chapters, a few salient points were determined from this analysis. The DO issues in the Upper Pecos River concern the portion of the river from U.S. Highway 67 upstream to the Ward 2 Irrigation Turnout, and the DO issues manifest themselves seasonally during the warmer months through depressed 24-hour minimum DO concentrations. While there are no permitted discharges, which would otherwise potentially influence riverine water quantity and quality, irrigation does constitute a major hydrologic factor. During the warm growing season the Pecos River receives releases from the Red Bluff Reservoir, which drive the hydrology along the river down to the last irrigation turnout at Ward 2. None or very little of the releases make it past the series of irrigation turnouts, but below Ward 2 brackish groundwater does seep into the Pecos River providing a modicum of flow until the Independence Creek confluence where both water quantity and quality improve, albeit, below the area of study herein. Nutrients in the Upper Pecos River are at relatively low concentrations and are often below laboratory reporting limits. Nonetheless, the Upper Pecos River in various reaches supports an abundant periphytic algae community, which is only rarely disrupted by scouring events and is the apparent cause of the wide diel swings in DO that result in the 24-hour minimum concentrations being depressed during the warm season.

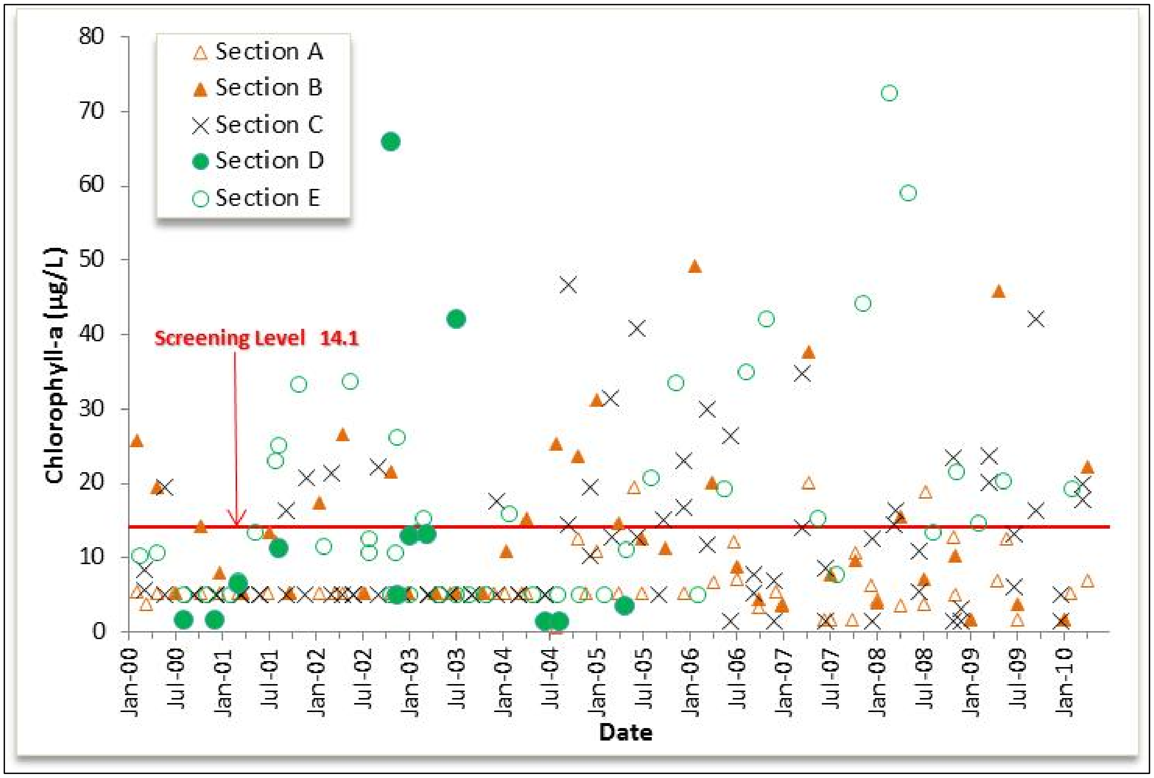


Figure 2-20. Time series of CHLA concentrations by hydrologic section from SWQM data for 2000–2010.

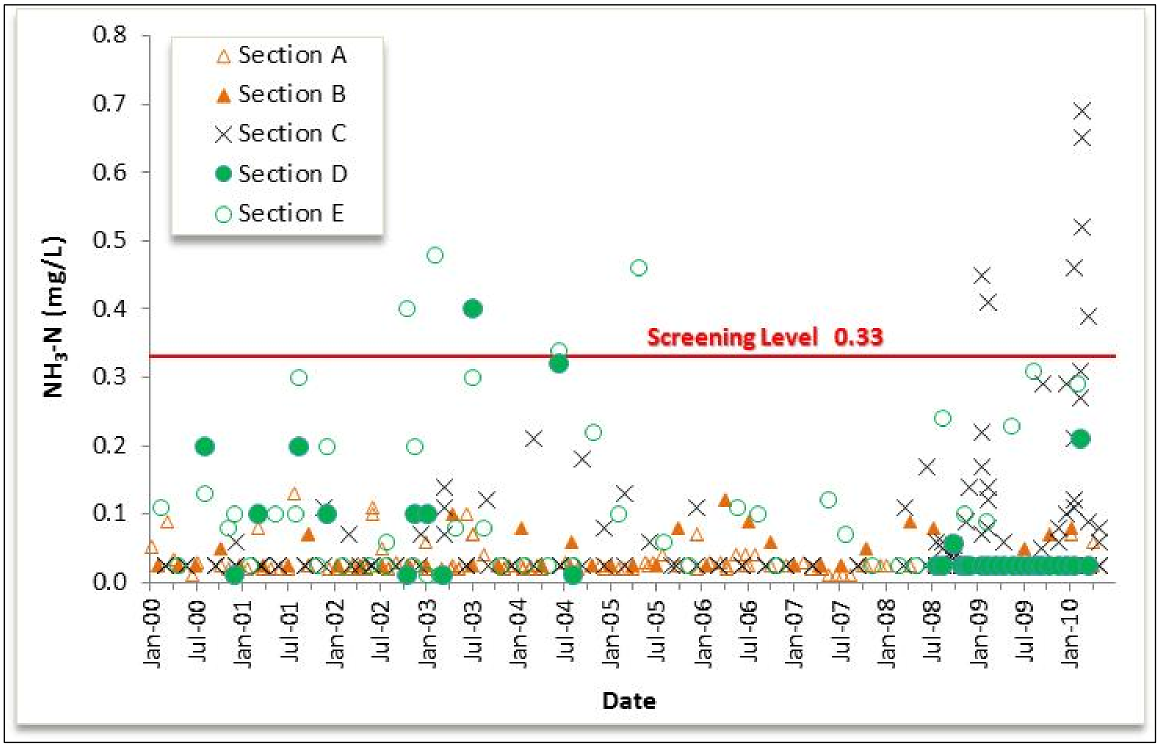


Figure 2-21. Time series of NH_3-N concentrations by hydrologic section from SWQM data for 2000–2010.

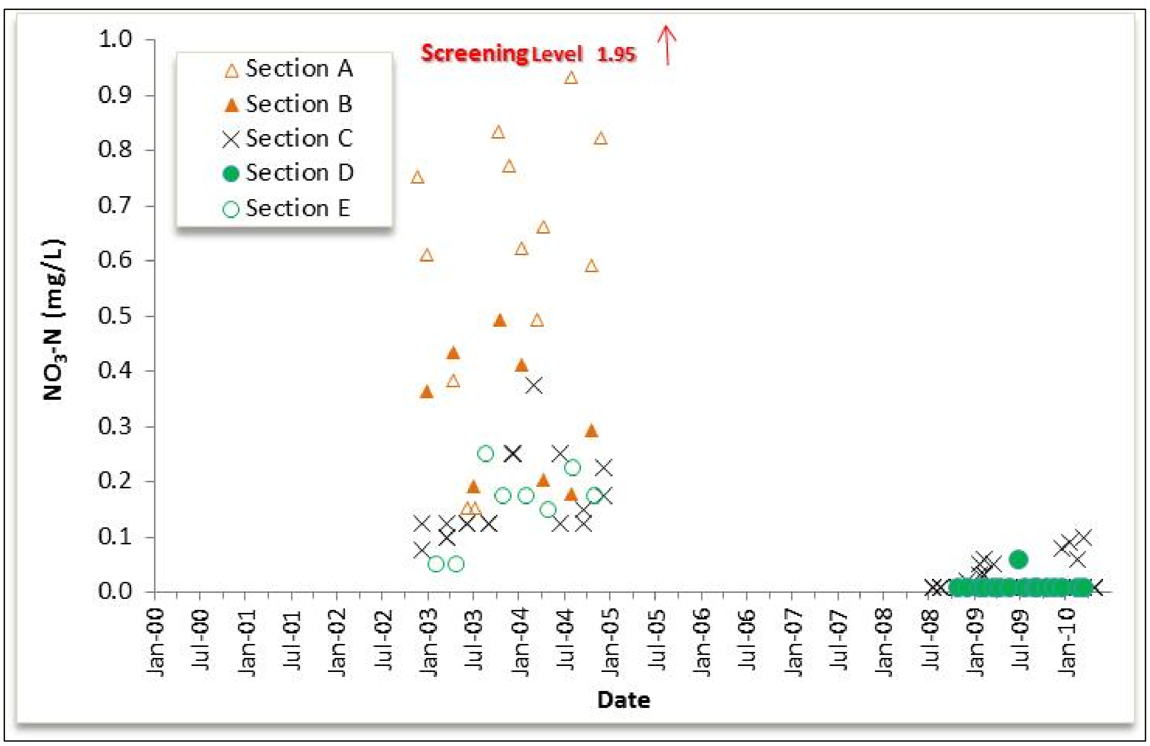


Figure 2-22. Time series of NO_3-N concentrations by hydrologic section from SWQM data for 2000–2010.

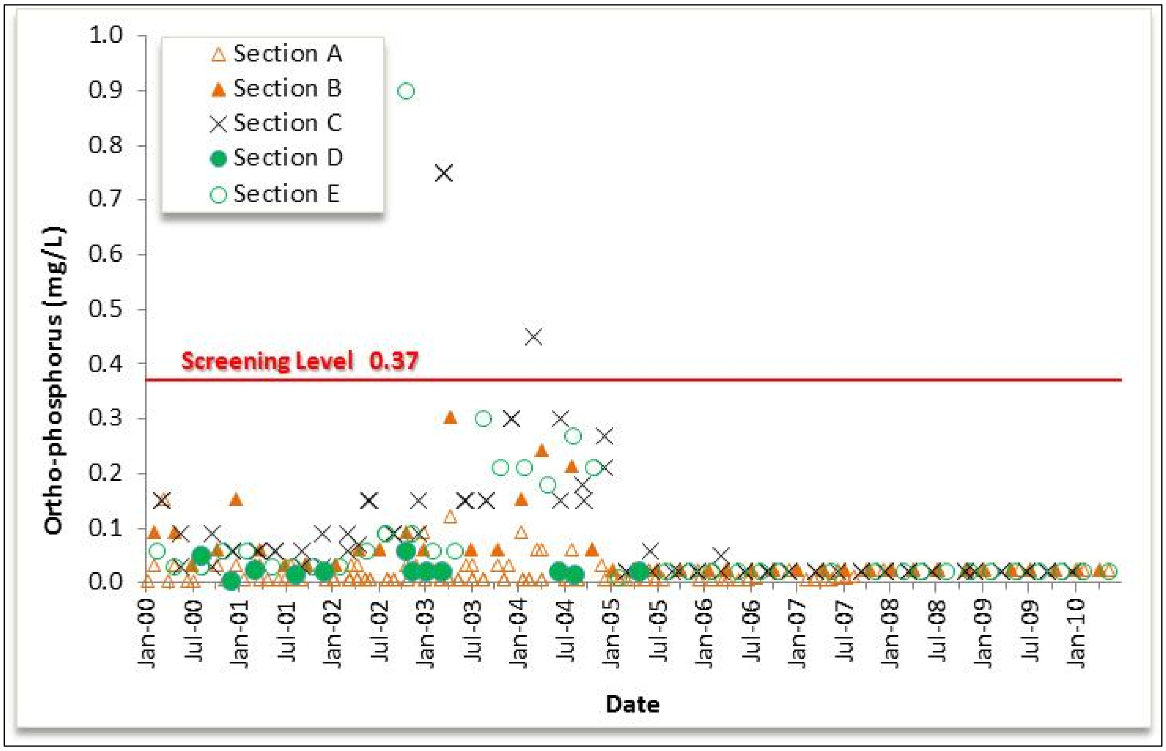


Figure 2-23. Time series of orthophosphate as phosphorus (OP) concentrations by hydrologic section from SWQM data for 2000–2010.

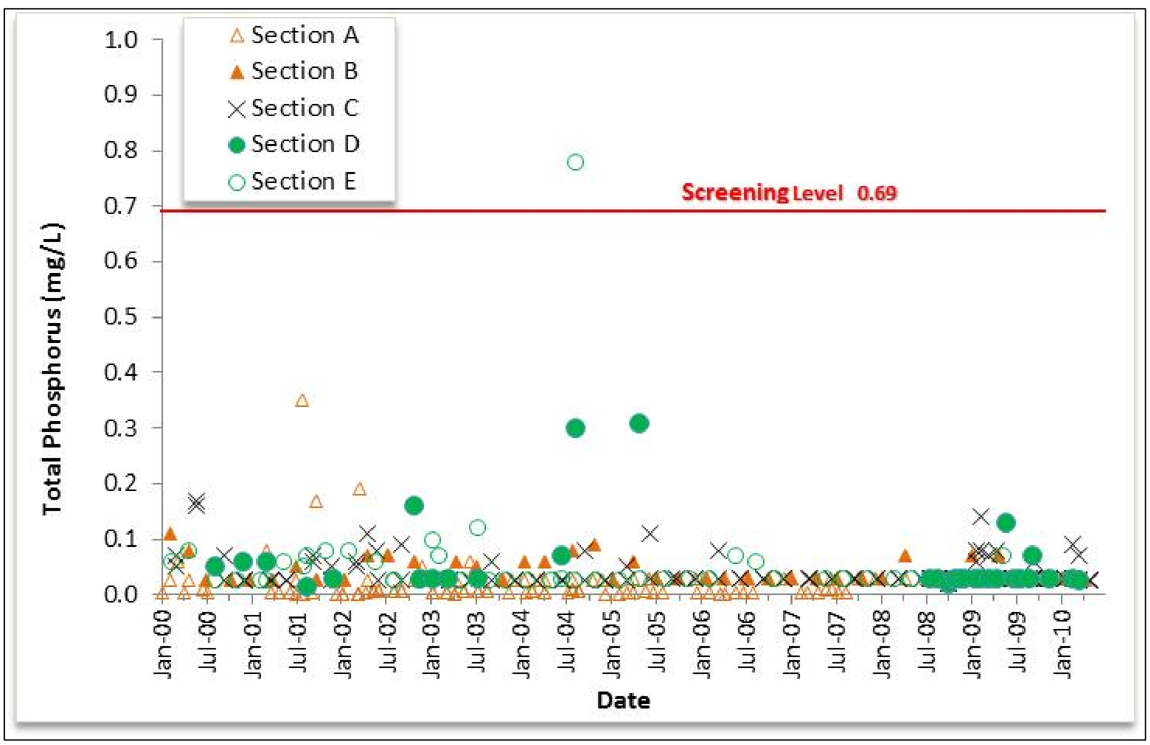


Figure 2-24. Time series of total phosphorus (TP) concentrations by hydrologic section from SWQM data for 2000–2010.

CHAPTER 3

SELECTION AND VERIFICATION OF THE DISSOLVED OXYGEN MODEL

This chapter includes selection of the dissolved oxygen model, verification of the selected model and sensitivity analysis of the verified model.

Model Selection

Mechanistic computer models can be used to study the impact of oxygen demanding substances (e.g., carbonaceous biochemical oxygen demand [CBOD] and NH_3-N), aquatic vegetation, and other factors (e.g., sediment oxygen demand or SOD) on DO and assist in evaluating alternative control measures for situations of unacceptably depressed DO concentrations. Models provide analytical abstractions (or simulations) of the real system, such as the Upper Pecos River for this study. Mechanistic models, also referred to as process models, are based on theoretical principles. The models can provide for representation of governing processes that determine the response of certain state variables (model outputs). For this project, DO is the primary output of interest, though other state variables (e.g., streamflow, water temperature, CBOD, NH_3-N, and periphytic algae) will also be discussed. Under circumstances where the governing processes are acceptably quantifiable, as is the case for DO, the mechanistic model provides understanding of important biological, chemical, and physical processes in the real system (that is, Upper Pecos River) and predictive capabilities to evaluate best management practices (BMPs).

A consideration in the model selection process is the prevailing hydrology of the stream system under the water quality conditions of greatest concern. The Upper Pecos River is the domain or system to be modeled, because it includes the area where the depressed 24-hour minimum DO concentrations occur along the Pecos River in Texas. Because of the semi-arid to arid climatic conditions and the dominating influence of Red Bluff Reservoir on streamflows entering the Upper Pecos River, the river does not experience many stormwater pulses and from that perspective the hydrology does not fluctuate to the degree measured in many Texas streams and rivers located further east in the state. These factors allow the Upper Pecos River to be modeled using a steady-state model that assumes relatively constant flows over the period being simulated. Essentially, the flow can vary in the longitudinal direction increasing or decreasing with distance downstream, but at any location the flow should be relatively steady.

In the past QUALTX has been used as the standard water quality model in Texas for assessment of DO and it is the standard steady-state DO model employed by TCEQ for waste load allocations and other applications where steady-state hydraulic conditions may be assumed and 24-hour average DO is the primary state variable of concern. Because of the present limitation of QUALTX to simulate diel (24-hour) DO fluctuations and its inability to provide a 24-hour minimum DO, a different model must be considered to evaluate the DO impairment in the Upper Pecos River. The U.S. Environmental Protection Agency (USEPA) supported model, QUAL2K, was selected. QUAL2K has similar capabilities to those of QUALTX with the added dimension of simulating diel variations in water quality, which provides the model capabilities to simulate minimum DO for a 24-hour period. QUAL2K is a relatively recent model that was developed to provide a modernized version of QUAL2E, which was finding more limited applicability because it cannot be operated under present Operating Systems.

QUAL2K provides for the prediction of water quality in river and stream systems by representing the channel in a one-dimensional, longitudinal manner with the assumption of vertical and lateral complete mixing. The model allows branching tributaries, provides non-uniform, steady flow hydraulics, and water quality variables are simulated on a diel time scale. A Microsoft Excel workbook serves as the interface for QUAL2K. Model execution, input and output are all implemented from within Excel. Visual Basic for Applications (VBA) serves as Excel's macro language for implementing all interface functions, and numerical calculations are implemented in FORTRAN 90 (Chapra et al, 2008). QUAL2K version 2.11 was applied to develop the Upper Pecos River model.

Adjustment of Oxygen Saturation Equation in QUAL2K

An important part of the formulation of DO in any water quality model is the equation representing the dependency of oxygen saturation on factors that influence the saturating concentration. In QUAL2K oxygen saturation in water is represented as a function of water temperature and atmospheric pressure. The equations representing this functionality are provided in Chapra et al. (2008) where the atmospheric pressure is accounted for through the effect of elevation. Salinity is another factor of some importance in the Upper Pecos River that also influences oxygen saturation concentrations. As with water temperature and elevation, the higher the salinity, the lower the saturation concentration; i.e., there are inverse relationships of oxygen saturation to water temperature, elevation and salinity that can be represented by empirical equations.

The equation in QUAL2K does not include the effects of salinity. Because salinities are much higher in the Pecos River than the vast majority of streams and creeks in Texas and because various measures to reduce salinities have long been a consideration for the Upper Pecos River, it was important to this QUAL2K exercise that the impact of salinity on oxygen saturating concentrations be incorporated into the model application. Since QUAL2K is not an open code, the model formulation of oxygen saturation could not be readily incorporated into the coding of the model. Instead the formulation for elevation influences on oxygen saturation was used. Part of the model input is elevations along the Upper Pecos River. These elevations were incrementally increased based on the salinity regime along the Upper Pecos River for each model application. An Excel spreadsheet containing the necessary calculations was developed to determine the incremental increases in elevations along the Upper Pecos River that would result in the same decrease in saturating oxygen concentration as caused by the salinities in the river. In practice this necessitated as one of the first steps in operating the model to get the simulation to reasonably reproduce the measured salinities along the Upper Pecos River. These predicted salinities then became input to the Excel spreadsheet and were used in the calculations that determined the incremental increases in elevations needed to have the same effect on oxygen saturation as would the model predicted salinities. The incremental increases in elevation were then added to the actual model input elevations in the same Excel spreadsheet. These increased elevations, then, became the elevations used as input to QUAL2K for that application. While tedious in nature, this methodology was effective in allowing QUAL2K to be able to incorporate salinity effects.

Background to Model Verification Process

Model calibration and validation, which collectively are referred to as verification, are defined as follows:

- Calibration—the first stage testing and tuning of a model to a set of observational data, such that the tuning results in a consistent and rational set of theoretically defensible input parameters.

- Validation—Subsequent testing of a calibrated model to additional observational data to further examine model validity and preferably under different external conditions from those used during calibration (Thomann and Mueller, 1987).

Hence, calibration is a systematic procedure of selecting model input parameters to progressively improve the comparison of model predictions to observational data. For the present study, the adjustments of input parameters were constrained within literature-suggested ranges from such sources as TNRCC (1995) and Bowie et al. (1985). For any input parameters without direct measurements within the project area and literature values, expert judgment was used.

Within the separate validation step, the input parameters defining such things as kinetic rates remain at the values used in calibration step, and separate sets of observational data are used for comparison purposes. In the event model predictions for the validation step are unacceptable based upon visual inspection of graphical data comparisons, the model validation process requires recalibration to the measured validation data sets and then re-validation against the calibration data sets. In the application of QUAL2K to the Upper Pecos River the validation step provided fairly good results, but some minor additional fine tuning of a couple of input parameters was required, which necessitated the re-validation step.

The goal of validating the model in such a way is to obtain a robust model capable of making reliable predictions of DO concentrations under a variety of environmental conditions. Additional information on the subject is provided in the project's modeling QAPP (TWRI and TIAER, 2010).

Verification Data

The same SWQM and CWQMN water quality data and USGS streamflow data presented in Chapter 2 were used as the source of information for developing the datasets used in the verification process. The data grooming process, especially to limit the CWQMN data to only the first full day after multiprobe deployment, was also presented in Chapter 2. The datasets used in the QUAL2K verification process are defined herein as synoptic datasets. A synoptic dataset consisted of the following:

- Model Input: Hourly meteorological data (air temperature, dew point temperature, wind speed, and cloud cover) for Fort Stockton (source: NOAA NCDC).
- Model Input: Average daily streamflow for each active USGS gage in the Upper Pecos River used as input.
- Model Input: Average diversions at irrigation turnouts from data provided by the irrigation districts obtained for this project through the Texas A&M AgriLife Extension Service.

- Verification Data: CWQMN and SWQM 24-hour DO, water temperature, and specific conductance data.
- Verification Data and Headwater Water Quality: CWQM field parameters, TDS, nutrient forms, and CHLA data.

Temporally, the objective was to define a synoptic dataset as a condition with steady-state flow and CWQMN and SWQM water quality data at several stations within a period of time of roughly 2 weeks. Ideally, the synoptic datasets would have reflected water quality data collected over shorter than a 2-week period; however, the length of the Upper Pecos River apparently necessitated data collection by agencies to be spaced in time. Even more constraining to the desired shorter time frame, both the 24-hour data and the grab water quality were rarely collected at the same time at a station. The CWQMN deployments were the major source of 24-hour data, and routine water quality grab sampling did not occur at the time of instrument retrieval/deployment. Fortunately, relatively steady-state flow persists for fairly long periods in the Upper Pecos River due to the infrequent occurrence of stormwater runoff events. Because of the need for 24-hour DO data for the verification process, since the water quality issue is 24-hour minimum DO, and the fact that the vast majority of those types of data were collected recently, the synoptic dataset selection process was restricted to the time period of 2006 through 2009.

Each synoptic dataset was assigned to be either a calibration or validation scenario within the overall model verification process and that decision was based on having cool and warm season datasets for calibration and for validation. Typically, the most complete datasets are preferentially, though not exclusively, assigned to model calibration rather than validation, which allows the initial adjustment of input parameters to occur using the best described conditions. For the Upper Pecos River this resulted in many of the synoptic datasets in the latter half of the 2006–2009 period being assigned to calibration, because several USGS streamflow gages came online in a July–August 2007 time frame, providing data to allow better definition of actual streamflow conditions along the river as model input (Table 3-1).

Model Formulation and Input Data Requirements

QUAL2K solves a mass transport equation that describes the effects of advection, dispersion, sources, sinks, and kinetics for the water quality constituents being modeled. The model simulates non-uniform, steady flow, which does not allow flow to vary temporally, but does allow it to vary longitudinally due to discharges, tributary inflows, withdrawals (or abstractions), and incremental (or diffuse) flows (e.g., groundwater inflows). For this application the major water quality state variables (output) included in the QUAL2K applications were:

- Dissolved Oxygen (DO)
- Water Temperature
- Salinity
- Organic Nitrogen (Total Kjeldahl Nitrogen (TKN) – Ammonia (NH_3-N)
- NH_3-N
- Nitrite plus Nitrate Nitrogen (NO_2-N+NO_3-N)
- Total Nitrogen (TKN + NO_2-N+NO_3-N)
- Organic Phosphorus (TP – OP)
- Inorganic Phosphorus (OP)
- Total Phosphorus (TP)
- Suspended Algae or Phytoplankton (CHLA)

- Bottom Algae Biomass (or periphyton biomass)
- Total Suspended Solids (TSS)
- Carbonaceous Biochemical Oxygen Demand (CBOD)

The slow CBOD feature of QUAL2K was turned off by not entering values for any slow CBOD input data as per Chapra et al. (2008), and only fast CBOD was considered necessary for this application.

Table 3-1. QUAL2K calibration and validation synoptic datasets for Upper Pecos River.

Start Date	End Date	Stations		Comment
		SWQM	CWQMN	
13-Jun-06	17-Jun-06	13257, 13260	709, 710	Validation
7-Sep-06	16-Sep-06	13257, 13260	709, 710, 729, 735	Validation
4-Dec-06	9-Dec-06	13257, 13260, 16379	709, 710, 729, 735	Validation
13-Mar-07	22-Mar-07	13240, 13257, 13260	709, 710, 729, 735	Validation
2-May-08	9-May-08	13265, 13267, 13269	709, 729, 735	Calibration
12-Jun-08	18-Jun-08	13257, 13258, 13259, 13260, 13261, 20399	709, 710	Calibration
8-Jul-08	16-Jul-08	13109, 13246, 15114, 16379	709, 710, 729, 735	Validation
22-Jul-08	24-Jul-08	13257, 13258, 13259, 13260, 13261, 20399	709	Calibration, Sensitivity
2-Dec-08	6-Dec-08	13257, 13258, 13259, 13260, 13261, 20399	709, 710	Validation
20-Jan-09	24-Jan-09	13257, 13258, 13259, 13260, 13261, 20399	709, 710	Calibration
11-Nov-09	18-Nov-09	13257, 13258, 13259, 13260, 13261, 20399	709, 710	Validation
8-Dec-09	23-Dec-09	13109, 13257, 13258, 13259, 13260, 13261, 20399	709, 710, 729, 735	Calibration

Segmentation and Hydraulics Input: The Pecos River is relatively a long system. The TCEQ divides the Pecos River in Texas into Upper (2311) and Lower (2310) segments, and Independence Creek marks the boundary between the Upper and Lower Pecos. The spring-fed discharges into Independence Creek beneficially alters the Pecos River hydrology, chemistry, and water quality to the point that DO issues do not persistently occur in the Lower Pecos River. The Upper Pecos, therefore, is the singular focus of the QUAL2K modeling. Because the tributaries to the Upper Pecos River are for the most part highly ephemeral, the model representation became relatively simple; one main stem without tributaries (Figure 3-1). Further, the Upper Pecos River has no WWTF outfalls, but six irrigation turnouts are positioned along the upper half of the Upper Pecos River, which from upstream to downstream are Loving, Reeves, Ward 3, Ward 1, Upper Diversion and Ward 2. The irrigation turnouts were included in the model as point-source withdrawals.

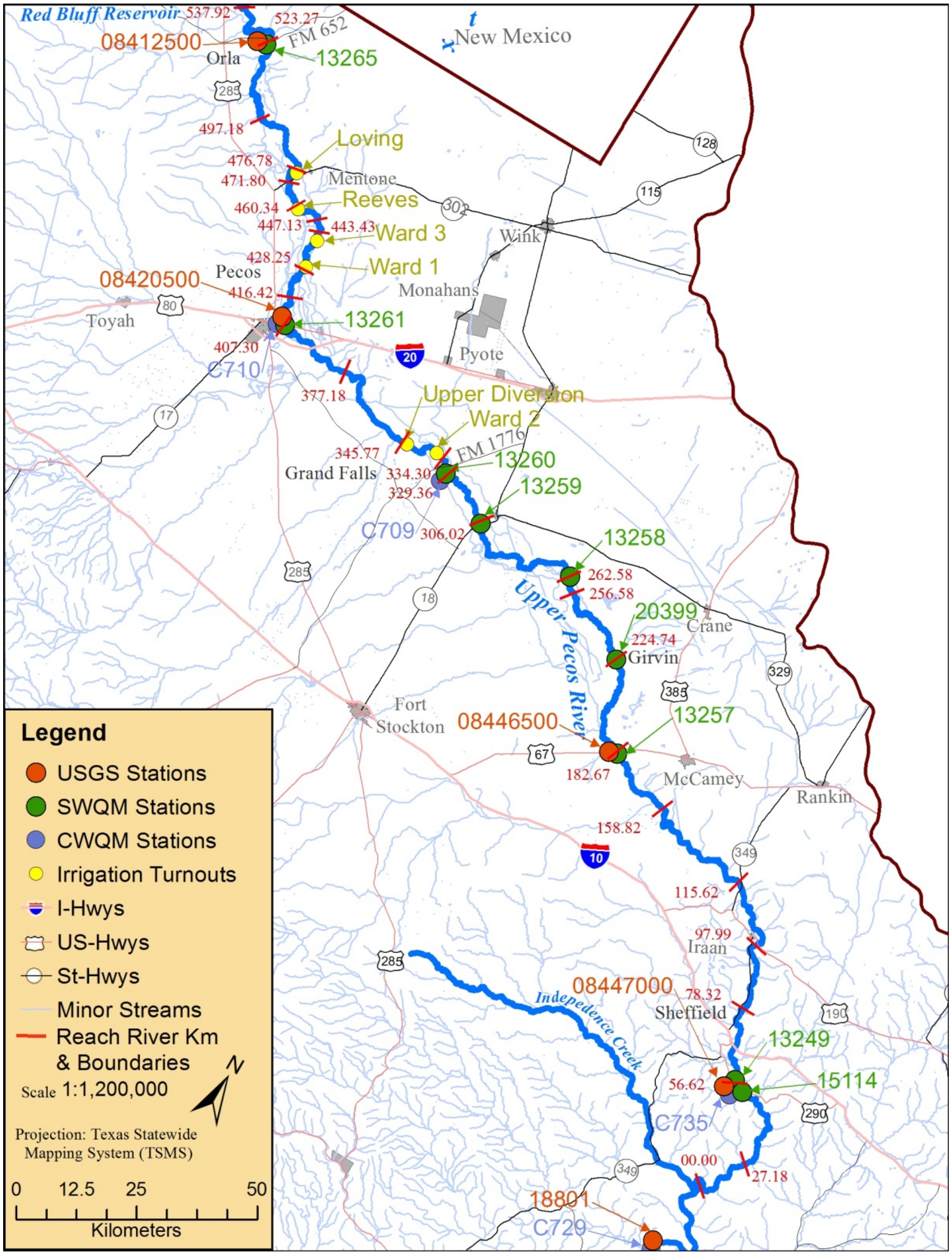


Figure 3-1. Map of Upper Pecos River showing QUAL2K segmentation, irrigation turnouts, and monitoring stations.

QUAL2K is structured to allow a representation of the Upper Pecos River by dividing the river longitudinally into reaches that can have unique hydraulic features (e.g., bottom width, rating curves for the two relationships of velocity and water depth to flow). A reach can be subdivided into a user specified number of equal-length elements. It is at the element level that the model provides its water quality and hydraulic predictions. The Upper Pecos River was divided into a total of 26 reaches and a total of 356 elements (Table 3-2, Figure 3-1). On average each element represented about 1.5 km (1 mile) of the Upper Pecos River.

Table 3-2. Segmentation information of Upper Pecos River.

Reach Name		Reach Number	Reach length	Location		Number of Elements
From	*To*		*(km)*	Begin *(km)*	End *(km)*	
Red Bluff Dam	FM 652	1	10	537.92	523.27	10
FM652	River Kilometer (RKM) 630	2	17	523.27	497.18	17
RKM630	Loving T.O.	3	13	497.18	476.76	13
Loving T.O.	SH302	4	3	476.76	471.8	3
SH 302 - Reeves T.O.	Reeves T.O.	5	7	471.8	460.34	7
Reeves T.O.	Station 13263	6	9	460.34	447.13	9
Station13263 - Ward 3 T.O.	Ward 3 T.O.	7	3	447.13	443.43	3
Ward 3 T.O.	Ward 1 T.O. (Barstow Dam)	8	10	443.43	428.25	10
Ward 1 T.O. (Barstow Dam)	Station 13262	9	8	428.25	416.42	8
Sta. 13262	US80 (Bus. IH 20)	10	6	416.42	407.3	6
US80 (Bus IH 20)	RKM 510	11	20	407.3	377.18	20
RKM 510	Upper Diversion	12	21	377.18	345.77	21
Upper Div. - Ward 2 T.O.	Ward 2 Turn Out	13	7	345.77	334.3	7
Ward 2 Turn Out	FM 1776	14	3	334.3	329.36	3
FM 1776	SH 18	15	15	329.36	306.02	15
SH 18	2 km above Hwy 1053	16	29	306.02	262.58	29
2 km above Hwy 1053	4 km below FM1053	17	4	262.58	256.58	4
4 km below Hwy 1053	Horse Head Rd	18	21	256.58	224.74	21
Horse Head Rd. - US 67	US Hwy 67	19	28	224.74	182.67	28
US Hwy 67	County Rd 1901	20	16	182.67	158.82	16
County Rd 1901	SH Hwy 349	21	29	158.82	115.62	29
SH Hwy 349	US Hwy 190	22	12	115.62	97.99	12
US Hwy 190	Olson Rd. off FM 349	23	13	97.99	78.32	13
Olson Rd. off FM 349	US 290 (Station 13249)	24	15	78.32	56.62	15
US 290 (Station 13249)	RKM 160	25	19	56.62	27.18	19
RKM 160	Independence Creek	26	18	27.18	0	18

The hydraulic rating curve information as power equations was developed from the field measurements collected at the Pecos River USGS streamflow gages and various field measurements collected at other locations by the USGS, TCEQ and Texas Parks and Wildlife Department (TPWD) staff during various biological surveys. Much of the data besides the readily available USGS gage data used to develop the hydraulic rating curves was provided by Ms. Kristine Kolbe of the TCEQ via email attachments to the authors of this report. Similar to QUALTX, power equations are used in QUAL2K to relate average velocity (U) and depth (H) to flow using the following two equations:

$$U=aQ^b \quad \text{and} \quad H=cQ^d$$

Where Q is flow, and a, b, c and d are constants. The various constants are provided in Table 3-3.

Reaeration Input: QUAL2K allows the user to specify computation of reaeration by one of several hydraulic-based formulations and then further allows prescribed input of a reaeration value at the reach level (not the element level) such that prescribed values will override the computation formula for any reach for which a prescribed value is provided. The reaeration rates along the Pecos River were determined using Texas reaeration equation (Cleveland, 1989) which was entered as input through one of the hydraulic-based formulations included as options within QUAL2K. It is calculated as follows:

$$k_\alpha = 1.923\frac{U^{0.273}}{H^{0.894}}$$

Where k_α is the reaeration rate at a temperature of 20°C, U is velocity (m/s), and *H* is depth (m).

The Texas reaeration equation was specified in the Rates sheet of QUAL2K input to provide the default reaeration rates.

Meteorological Input: QUAL2K does not provide the user an option to specify water temperatures as does QUALTX, but rather the model always simulates temperature. In order to simulate water temperature and available light for photosynthesis, QUAL2K requires hourly meteorological data over a 24-hour (one-day) period. Those data requirements include air temperature, dew-point temperature, wind speed, cloud cover and shade. Shade is considered here as non-traditional meteorological data and it represents the shading of the river provided by riparian vegetation. As with the other meteorological type data, shade is input as hourly values reflecting the changes in shading with position of the sun over time. The hourly meteorological data were downloaded from the National Weather Service for Ft. Stockton, TX. The approach taken with the meteorological data was to average the hourly conditions of each day within the time period comprising a synoptic dataset. The shade data were estimated from photographs and observations made of Pecos River riparian areas during reconnaissance trips of May 4 and 5, 2010 and September 21, 2010, and from investigations of recent aerial photographs and imagery. For the most part, shading is not important along the Pecos River due to the width of the river compared to the height of immediately adjacent vegetation.

Kinetics and Temperature Effects: Within QUAL2K, first-order kinetic rates can be specified globally for the entire modeled system and individually for specific reaches. Further the model contains a temperature effect correction for all first-order reactions that is defined as follows:

$$k_T = k_{20}\,\theta^{(T-20)}$$

Where k_T is the reaction rate, T is the water temperature, and θ is the temperature coefficient.

Several of the more important temperature-effect factors and the values θ used for model validation are as follows:

Reaction	θ
Atmospheric Reaeration	1.024
CBOD Decay	1.047
Organic Nitrogen Decay Rate	1.047
Ammonia Decay Rate	1.083
All Phytoplankton and Benthic Algae Rates (growth, respiration, death)	1.047

Specification of Headwater Conditions: QUAL2K requires specification of a non-zero headwater flow and hourly values for each water quality constituent. A value close to zero (0.0001 cms) would be input if there was no headwater flow due to the absence of observed surface flow in the reaches upstream of Orla station (USGS gage 08412500) during calibration and validation periods. Water quality of the headwater was determined from measured data, and in the cases where data were lacking, estimates were assigned by using default values applied by TCEQ in their waste load allocation modeling. The default values used by TCEQ for headwater constituents are DO = 80% of saturation value, CBOD = 3.0 mg/L, organic-N = 0.5 mg/L, CHLA = 2 µg/L, NH_3-N = 0.050 mg/L, NO_2+NO_3-N = 0.020 mg/L, TP = 0.020 mg/L with TP divided equally into organic-P = 0.010 mg/L and OP = 0.010 mg/L. In practice, headwater conditions were typically of little importance in the Upper Pecos River model application because the headwater flows are virtually removed by the six irrigation turnouts during the critical warm season when the depressed DO occur below the Ward 2 Irrigation Turnout. (As discussed in Chapter 2, it is that portion of the river downstream of Ward 2 Turnout where the depressed DO occurs.)

Point and Diffuse Sources: QUAL2K allows specification of discharge and water quality constituents for point and diffuse sources. Both point and diffuse sources may be entered as an inflow or a withdrawal. In the Pecos River segments there are not any point sources, while the six irrigation turnouts located at Upper Pecos segment are considered as point source withdrawals. The upper reaches of the Upper Pecos River are generally characterized as a losing stream while the lower reaches are generally characterized as a gaining stream. The Ward 2 Turnout area represents a rough demarcation between upstream losing and downstream gaining. USGS streamflow data and the diffuse source option in QUAL2K were used to quantify the streamflow along the Upper Pecos and the amount of losses and gains between USGS gage locations. That is, after considering the reported irrigation withdrawals, diffuse sources were used to prescribe the amount of streamflow gain or loss required for the model to match the USGS measured streamflow. Similar to the meteorological input data, the USGS gage data were averaged over the time

Table 3-3. Major input data in QUAL2K Reach sheet of 2-9 May 2008 Upper Pecos QUAL2K model.

Reach				Rating Curves				Bottom	Bottom	Prescribed	Prescribed	Prescribed	Prescribed
No.	begin	end	Element	Velocity		Depth		Algae	SOD	SOD	CH4 flux	NH4 flux	Inorg P flux
	km	*km*		*Coefficient*	*Exponent*	*Coefficient*	*Exponent*	*Cover*	*Cover*	*($gO_2/m^2/d$)*	*($mgN/m^2/d$)*	*($mgN/m^2/d$)*	*($mgP/m^2/d$)*
1	537.9	523.27	10	0.2374	0.508	0.3294	0.30	90%	100%	0.21	0.41	41.45	2.07
2	523.3	497.18	17	0.2374	0.508	0.3294	0.30	80%	100%	0.24	0.47	47.04	2.35
3	497.2	476.76	13	0.2374	0.508	0.3294	0.30	80%	100%	0.25	0.51	50.87	2.54
4	476.8	471.8	3	0.2374	0.508	0.3294	0.30	80%	100%	0.26	0.53	52.54	2.63
5	471.8	460.34	7	0.2374	0.508	0.3294	0.30	80%	100%	0.26	0.53	52.78	2.64
6	460.3	447.13	9	0.2374	0.508	0.3294	0.30	80%	100%	0.27	0.53	53.16	2.66
7	447.1	443.43	3	0.2374	0.508	0.3294	0.30	80%	100%	0.27	0.53	53.44	2.67
8	443.4	428.25	10	0.2688	0.483	0.5069	0.40	80%	100%	0.27	0.53	53.48	2.67
9	428.3	416.42	8	0.2688	0.483	0.5069	0.40	75%	100%	0.27	0.54	53.55	2.68
10	416.4	407.3	6	0.2688	0.483	0.5069	0.40	70%	100%	0.27	0.54	53.68	2.68
11	407.3	377.18	20	0.2688	0.483	0.5069	0.40	70%	100%	0.27	0.54	53.72	2.69
12	377.2	345.77	21	0.2997	0.533	0.3509	0.30	70%	100%	0.27	0.53	53.13	2.66
13	345.8	334.3	7	0.2997	0.533	0.3509	0.30	65%	100%	0.27	0.53	79.76	2.66
14	334.3	329.36	3	0.2997	0.533	0.3509	0.30	55%	100%	0.27	0.53	79.73	2.66
15	329.4	306.02	15	0.2997	0.533	0.3509	0.30	75%	100%	0.27	0.53	79.82	2.66
16	306	262.58	29	0.2997	0.533	0.3509	0.30	80%	100%	0.27	0.54	80.49	2.68
17	262.6	256.58	4	0.3333	0.533	0.2176	0.30	20%	70%	0.27	0.54	80.82	2.69
18	256.6	224.74	21	0.1212	0.55	0.6026	0.35	80%	100%	0.28	0.55	82.53	2.75
19	224.7	182.67	28	0.1212	0.55	0.6026	0.35	80%	100%	0.29	0.57	85.73	2.86
20	182.7	158.82	16	0.1212	0.55	0.6026	0.35	80%	100%	0.28	0.57	84.88	2.83
21	158.8	115.62	29	0.1212	0.55	0.6026	0.35	60%	80%	0.28	0.56	84.43	2.81
22	115.6	97.99	12	0.1212	0.55	0.6026	0.35	70%	90%	0.28	0.57	85.22	2.84
23	97.99	78.32	13	0.1212	0.55	0.6026	0.35	50%	80%	0.29	0.57	68.65	2.86
24	78.32	56.62	15	0.1212	0.55	0.6026	0.35	30%	70%	0.28	0.57	68.10	2.84
25	56.62	27.18	19	0.1212	0.55	0.6026	0.35	20%	70%	0.28	0.57	68.22	2.84
26	27.18	0	18	0.2014	0.562	0.4196	0.41	20%	70%	0.29	0.57	68.85	2.87

* Prescribed SOD, CH_4, NH_4, and Inorg Flux values at ambient temperature (not at 20°C) are required in QUAL2K for this input. The prescribed SOD is 0.25 $gO_2/m^2/d$, CH4 is 0.5 $gO_2/m^2/d$, NH4 is 50 $mgN/m^2/d$, and Inorg P is 2.5 $mgP/m^2/d$ at 20°C for all the reaches.

period of each synoptic dataset to arrive at an average streamflow at the gage location representative of conditions for each modeled scenario. The water quality assigned to diffuse sources were the TCEQ headwater default values described immediately above under section Specification of Headwater Conditions.

Sediment Oxygen Demand and Sediment Nutrient Release Rates: QUAL2K was operated during model verification with the sediment digenesis component turned on, which allowed the model to compute SOD and nutrient release and uptake rates from sediments longitudinally along the segmentation. During model calibration it became apparent that improved DO predictions were achieved by using the option to prescribe SOD rates and sediment release rates of NH_3-N and OP as listed for the 2–9 May 2008 calibration scenario in the right four columns of Table 3-3 and also explained in the footnote to the table. User prescribed SOD rates and nutrient release rates are added by the model to the values computed in the sediment diagenesis component.

Bottom Algae and SOD Coverage: QUAL2K allows for input regarding the percent of the streambed or bottom by reach that provides habitat for bottom algae (bottom or periphytic algae) and conditions for exertion of SOD. Based on field notes and observations from the May and September 2010 reconnaissance trips, the percent cover of the streambed by bottom algae was estimated and percent of area with fine-grained bed sediments were likewise estimated for SOD coverage. These input data are found on the Reach sheet (Table 3-3).

Model Verification

The Upper Pecos River QUAL2K model was calibrated and validated for different warm (April-Oct) and cool (Nov-Mar) season scenarios. Three summer and two winter scenarios between years 2006–2009 were chosen for calibration purpose and, similarly, three different summer and four different winter scenarios between the same years were chosen for validation purposes (Table 3-1).

For the calibration and validation periods, the model was operated for 30-days wherein the model considers the hourly meteorological input data set as being same for each day. By trial and error it was determined that it takes several days in the model for the relatively slow growing benthic algae to reach reasonable proximity to equilibrium conditions. To ensure equilibrium biomass conditions, the model was operated for 30-days. According to Dr. Steve Chapra, primary author of QUAL2K, a common error in applying QUAL2K is not simulating a sufficient number of days to allow benthic algae to approach equilibrium (Chapra, 2006).

To more accurately replicate measured streamflow, diffuse sources were added as inflows and withdrawals between streamflow measurement points. Addition of diffuse inflows to bring a closer flow balance is an often required process for applications of models such as QUAL2K due to the presence of unaccounted inflows from small tributaries, instream losses, and stream interactions with shallow groundwater. To improve DO prediction, prescribed SOD rates and sediment release rates of NH_3-N and OP were provided, which are added to the predictions from the sediment diagenesis component of the model of which an example is provided for the 2–9 May 2008 calibration scenario in Table 3-3.

Model Calibration

The QUAL2K model of the Upper Pecos River (Segment 2311) was calibrated for the most part by visually comparing model predictions to measured data using the graphical features associated with the model. Input parameters were adjusted to improve the comparison of predictions to measured data, and the range of adjustment was constrained within literature-suggested ranges from such sources as TNRCC (1995) and Bowie et al. (1985). For any input parameters without direct measurements within the project area and literature values, expert judgment was used in the calibration process.

The initial steps in calibration considered streamflow, water temperature, and salinity. First diffuse sources were adjusted such that the measured flow at each USGS gage was correctly replicated. Then measured salinities were replicated by adjusting the salinities associated with diffuse sources and/or adding various small sources of salinity. QUAL2K uses standard meteorological data and heat-balance functions to predict water temperature on a diel basis. In most cases water temperatures were initially under predicted by the model when compared to observed data in the Pecos River. A wind-sheltering coefficient less than 1.0 was multiplied by the wind speed to achieve acceptable water temperature predictions by providing a reduction of speed that decreased evaporation and increased water temperatures. Because of the presence of riparian vegetation adjacent to the river and the somewhat incised nature of the channel, the wind speed above the river surface would arguably be less than that of the input data from the National Weather Service station in Fort Stockton, where such obstructions to wind are purposely avoided.

The philosophy of the model calibration process was that streamflows, salinities, and water temperatures would be forced to match very closely, if not exactly, so that their influence on water quality would be as accurately reflected in the QUAL2K model as possible. The other water quality parameters besides temperature and salinity would then be calibrated separately. The process of adjusting the elevation input data to allow the model to replicate the influences of salinity of oxygen saturation have been previously addressed (the section on Adjustment of Oxygen Saturation Equation in QUAL2K).

Model Calibration Input Data

Global kinetic rates (Table 3-4), which apply to each reach in the segmentation, were used as the preferred model input whenever acceptable calibration could be obtained without necessitating specification of rates by reach. When spatial definition of kinetic rates by reach was required, this specification occurred within the Reach Rates sheet. Global kinetic rates were predominately used, and spatially varying rates were used very sparingly and only in the description of the maximum growth rate of benthic algae.

Table 3-4. QUAL2K Rates sheet of the Warm Season (April-Oct) for the Upper Pecos River.

Parameter	*Value* [a]	*Units*	*Symbol*
Stoichiometry:			
Carbon	40	gC	gC
Nitrogen	7.2	gN	gN
Phosphorus	1	gP	gP

Parameter	***Value*** [a]	***Units***	***Symbol***
Dry weight	100	gD	gD
Chlorophyll	1	gA	gA
Inorganic suspended solids:			
Settling velocity	0.01	m/d	v_i
Oxygen:			
Reaeration model	User specified		
User reaeration coefficient α	1.923		α
User reaeration coefficient β	0.273		β
User reaeration coefficient γ	0.894		γ
Temp correction	1.024		θ_a
Reaeration wind effect	None		
O2 for carbon oxidation	2.69	gO_2/gC	r_{oc}
O2 for NH4 nitrification	4.33	gO_2/gN	r_{on}
Oxygen inhib model CBOD oxidation	Half saturation		
Oxygen inhib parameter CBOD oxidation	0.60	mgO2/L	K_{socf}
Oxygen inhib model nitrification	Half saturation		
Oxygen inhib parameter nitrification	0.60	mgO2/L	K_{sona}
Oxygen enhance model denitrification	Half saturation		
Oxygen enhance parameter denitrification	0.60	mgO2/L	K_{sodn}
Oxygen inhib model phyto resp	Half saturation		
Oxygen inhib parameter phyto resp	0.60	mgO2/L	K_{sop}
Oxygen enhance model bot alg resp	Half saturation		
Oxygen enhance parameter bot alg resp	0.60	mgO2/L	K_{sob}
Slow CBOD:			
Hydrolysis rate	0.1	/d	k_{hc}
Temp correction	1.07		θ_{hc}
Oxidation rate	0	/d	k_{dcs}
Temp correction	1.047		θ_{dcs}
Fast CBOD:			
Oxidation rate	0.2	/d	k_{dc}
Temp correction	1.047		θ_{dc}
Organic N:			
Hydrolysis	0.2	/d	k_{hn}
Temp correction	1.047		θ_{hn}
Settling velocity	0.1	m/d	v_{on}
Ammonium:			
Nitrification	0.5	/d	k_{na}
Temp correction	1.083		θ_{na}
Nitrate:			

Parameter	***Value*** [a]	***Units***	***Symbol***
Denitrification	0.02	/d	k_{dn}
Temp correction	1.047		θ_{dn}
Sed denitrification transfer coeff	0.05	m/d	v_{di}
Temp correction	1.07		θ_{di}
Organic P:			
Hydrolysis	0.3	/d	k_{hp}
Temp correction	1.047		θ_{hp}
Settling velocity	0.1	m/d	v_{op}
Inorganic P:			
Settling velocity	0	m/d	v_{ip}
Inorganic P sorption coefficient	0	L/mgD	K_{dpi}
Sed P oxygen attenuation half sat constant	0.4	mgO_2/L	k_{spi}
Phytoplankton:			
Max Growth rate	0.6	/d	k_{gp}
Temp correction	1.047		θ_{gp}
Respiration rate	0.1	/d	k_{rp}
Temp correction	1.047		θ_{rp}
Excretion rate	0.05	/d	k_{ep}
Temp correction	1.047		θ_{dp}
Death rate	0.1	/d	k_{dp}
Temp correction	1.047		θ_{dp}
External Nitrogen half sat constant	25	ugN/L	k_{sPp}
External Phosphorus half sat constant	5	ugP/L	k_{sNp}
Inorganic carbon half sat constant	1.30E-04	moles/L	k_{sCp}
Light model	Half saturation		
Light constant	60	langleys/d	K_{Lp}
Ammonia preference	100	ugN/L	k_{hnxp}
Subsistence quota for nitrogen	0	mgN/mgA	q_{0Np}
Subsistence quota for phosphorus	0	mgP/mgA	q_{0Pp}
Maximum uptake rate for nitrogen	0	mgN/mgA/d	ρ_{mNp}
Maximum uptake rate for phosphorus	0	mgP/mgA/d	ρ_{mPp}
Internal nitrogen half sat constant	0	mgN/mgA	K_{qNp}
Internal phosphorus half sat constant	0	mgP/mgA	K_{qPp}
Settling velocity	0.025	m/d	v_a
Bottom Algae:			
Growth model	First-order		
Max Growth rate	1.1	$mgA/m^2/d$ or /d	C_{gb}

Parameter	***Value*** [a]	***Units***	***Symbol***
Temp correction	1.047		θ_{gb}
First-order model carrying capacity	800	mgA/m^2	$a_{b,max}$
Respiration rate	0.2	/d	k_{rb}
Temp correction	1.047		θ_{rb}
Excretion rate	0.05	/d	k_{eb}
Temp correction	1.047		θ_{db}
Death rate	0.05	/d	k_{db}
Temp correction	1.047		θ_{db}
External nitrogen half sat constant	50	ugN/L	k_{sPb}
External phosphorus half sat constant	10	ugP/L	k_{sNb}
Inorganic carbon half sat constant	1.30E-05	moles/L	k_{sCb}
Light model	Half saturation		
Light constant	60	langleys/d	K_{Lb}
Ammonia preference	100	ugN/L	k_{hnxb}
Subsistence quota for nitrogen	0.72	mgN/mgA	q_{0N}
Subsistence quota for phosphorus	0.1	mgP/mgA	q_{0P}
Maximum uptake rate for nitrogen	72	mgN/mgA/d	ρ_{mN}
Maximum uptake rate for phosphorus	10	mgP/mgA/d	ρ_{mP}
Internal nitrogen half sat constant	0.9	mgN/mgA	K_{qN}
Internal phosphorus half sat constant	0.13	mgP/mgA	K_{qP}
Detritus (POM):			
Dissolution rate	0.2	/d	k_{dt}
Temp correction	1.07		θ_{dt}
Fraction of dissolution to fast CBOD	1.00		F_f
Settling velocity	0.5	m/d	v_{dt}
Pathogens:			
Decay rate	0.8	/d	k_{dx}
Temp correction	1.07		θ_{dx}
Settling velocity	1	m/d	v_x
Light efficiency factor	1.00		α_{path}
pH:			
Partial pressure of carbon dioxide	347	ppm	p_{CO2}
Constituent i			
First-order reaction rate	0	/d	
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}
Constituent ii			
First-order reaction rate	0	/d	

Parameter	Value [a]	Units	Symbol
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}
Constituent iii			
First-order reaction rate	0	/d	
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}

* Cool season (Nov March) scenarios have the same rates as the warm seasons except the Phytoplankton Light constant is 30 langleys/d; Bottom Algae Light constant is 30 langleys/d. Also, through the Reach Rates input, a Maximum Bottom Algae growth rate of 1 mgA/m2/d is used for the last four reaches (while other reaches remained at 1.1 mgA/m2/d).

SOD rates and nutrient fluxes into the water from the sediment were predicted by the sediment diagenesis option in the model, which is controlled in the model input at the bottom of the Light and Heat sheet. The model also allows the user to prescribe SOD rates and nutrient fluxes which are added to the model predicted values when the sediment diagenesis algorithm is operative, as they were for all applications to the Upper Pecos River. In Chapra et al. (2008) it is mentioned that this prescription option is provided to account for situations where organic matter has been deposited during periods outside of the steady state period being studied (e.g., during spring runoff events, from fall and winter leaf fall, previous sedimentation). Unlike the kinetic rates on the Reach Rates sheet, which are specified at a value for 20° C and internally temperature adjusted in QUAL2K based on simulated temperatures, the prescribed SOD and nutrient fluxes must be input with the temperature adjustment externally applied on the Reach sheet.

The percent coverage by bottom algae and SOD were defined in Table 3-3 by model reach. The final percent covers used in the calibration were constrained by field observations, though some adjustments from the observed estimates were allowed.

Model Calibration Output

The calibrated model predictions are presented as graphical results with observational data provided on the same graphs. Based on visual inspection of graphs with measured and predicted DO data, the primary state variable, DO, was satisfactorily predicted during the calibration periods in both warm and cool seasons (Figures 3-2 and 3-3). To statistically evaluate model performance during the calibration process, the 24-hour average DO and 24-hour minimum DO measured and predicted data were compared. This evaluation was accomplished by taking pairs of measured and predicted DO concentrations at each station for each of the six calibration scenarios, graphing them as a scatterplot, and fitting a regression line through the data. Using this process 24-hour average and minimum DOs were evaluated separately (Figure 3-4). For this statistical analysis, the closer the regression line slope is to 1.0 the better model predictions and the closer the y-intercept value to 0.0 mg/L the better. The 24-hour average DO predictions were only satisfactory, though a closer inspection indicates that poor predictions for some of the higher concentrations were the cause of the less than optimal regression equation. These poorer predictions served as leverage data points "bending" the regression line to a slope less than 1.0. The 24-hour minimum DO analysis showed good fit by the model with a regression slope near 1.0, a y-intercept of less than 0.5 mg/L, and a R^2 value of almost 0.93. Based on the visual review of the individual scenarios and statistical evaluation through the regression line, the calibration process provided predictions of the critical parameter, 24-hour minimum DO, considered as acceptable.

The more important water quality parameters predicted by QUAL2K, besides DO, were difficult to evaluate other than visually. These more important parameters were the inorganic nutrients (i.e., NH_3-N, NO_2+NO_3-N, OP) that are readily available for suspended and periphytic algal growth but were often measured below reporting limits. An example of several of the numerous model output parameters are provided in Figures 3-5 through 3-7. Note that for the measured nutrient forms, when a maximum and minimum measured concentration is provided on the graph, this indicates a concentration reported in SWQM as less than the reporting limit. For example, a concentration of OP reported as < 40 µg/L was plotted as a maximum value of 40 µg/L and a minimum value of 0 µg/L, since the actual value could be anything between those two extremes (Figure 3-7).

[Remainder of page intentionally left blank.]

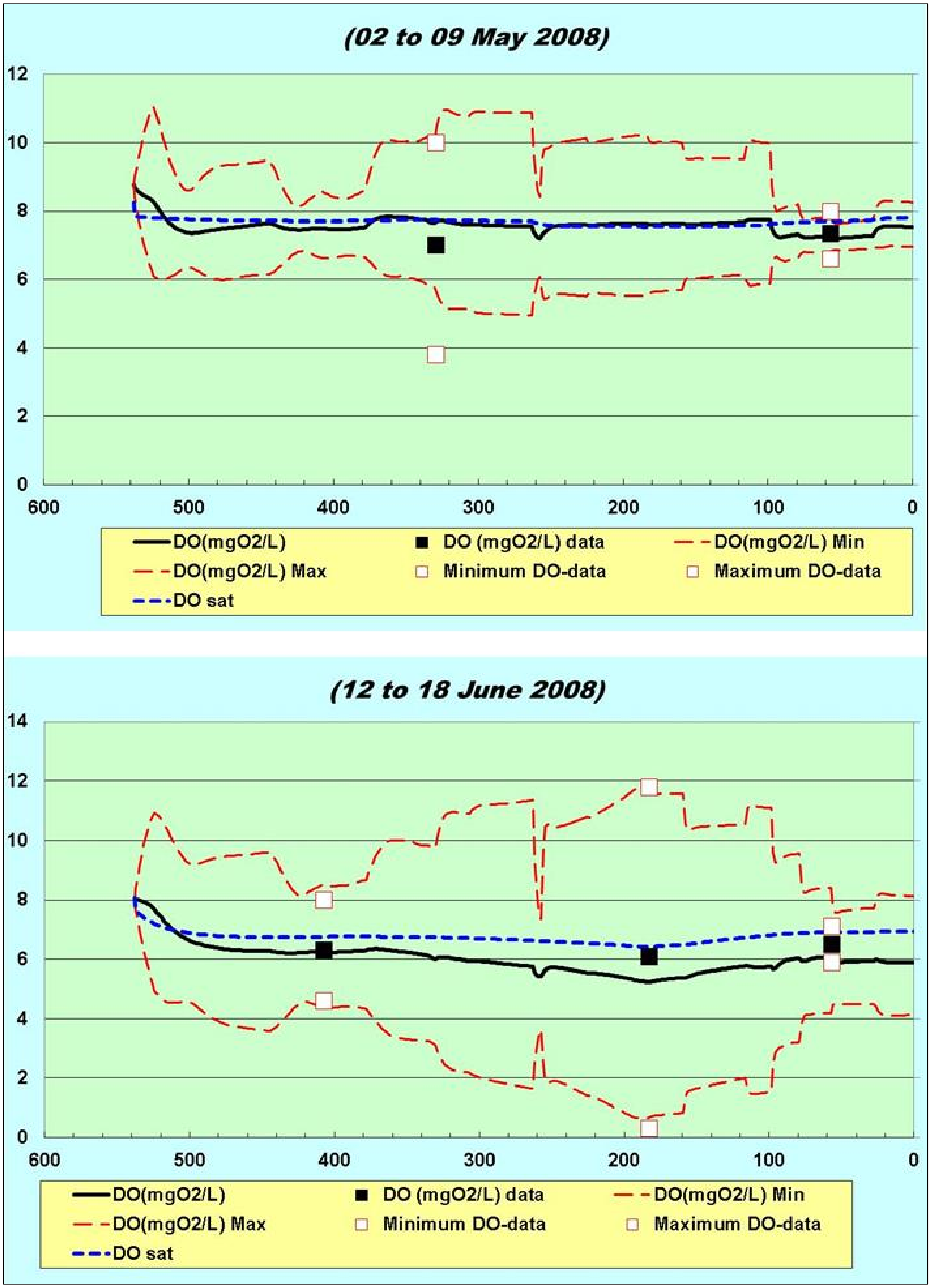


Figure 3-2. QUAL2K calibration simulations of warm season scenarios.

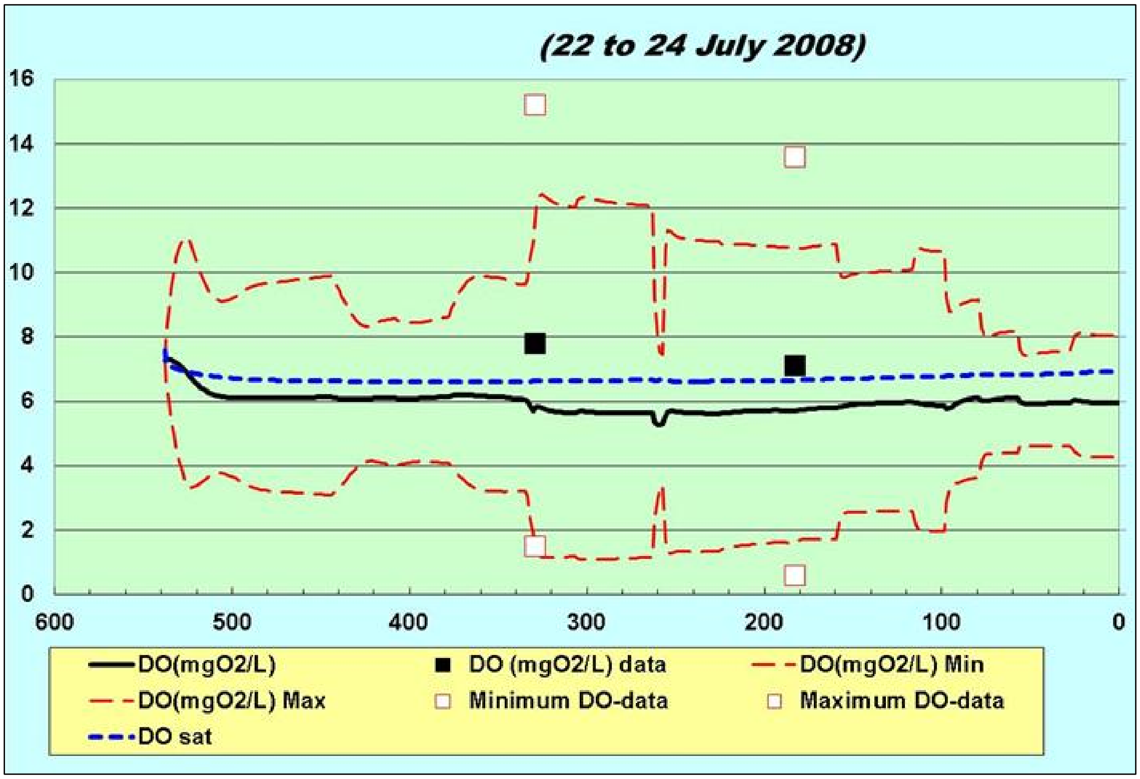


Figure 3-2 (cont'd). QUAL2K calibration simulations of warm season scenarios.

[Remainder of page intentionally left blank.]

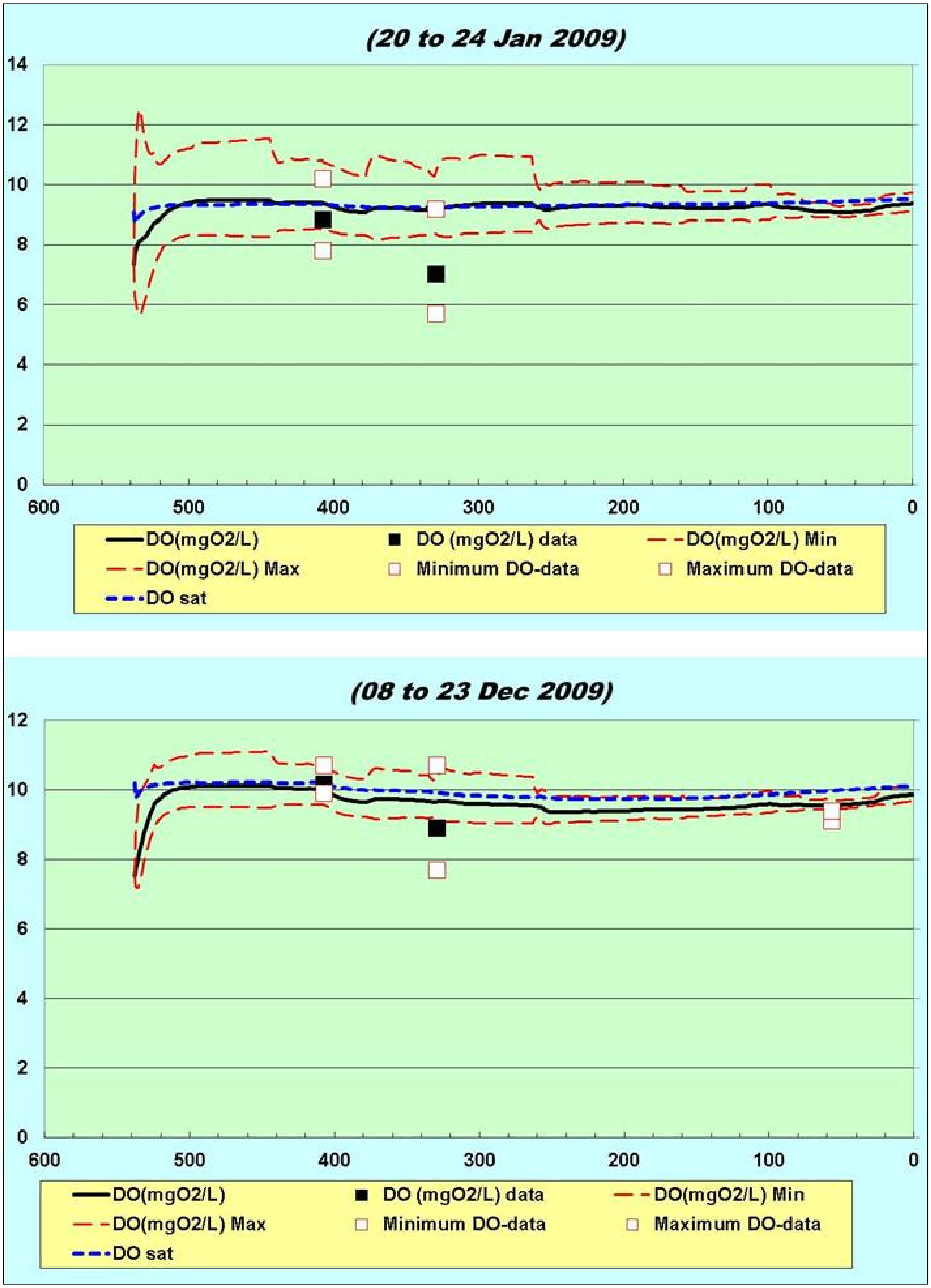
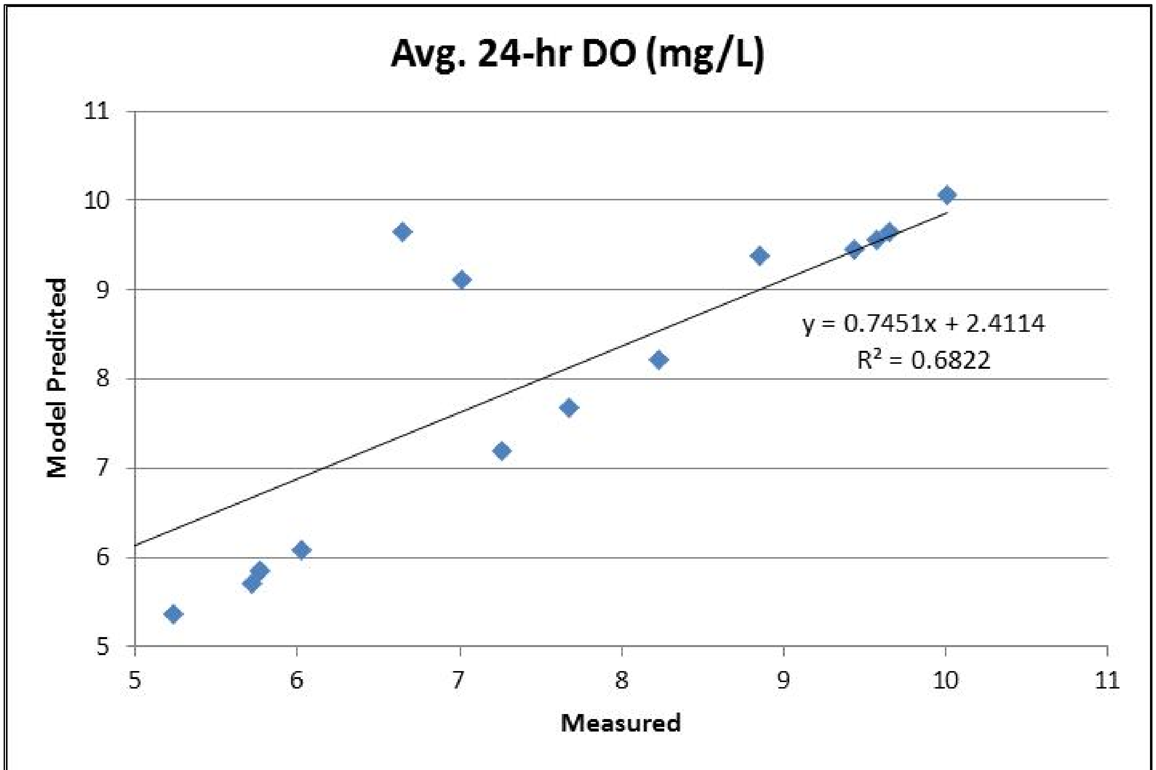


Figure 3-3. QUAL2K calibration simulations of cool season scenarios.



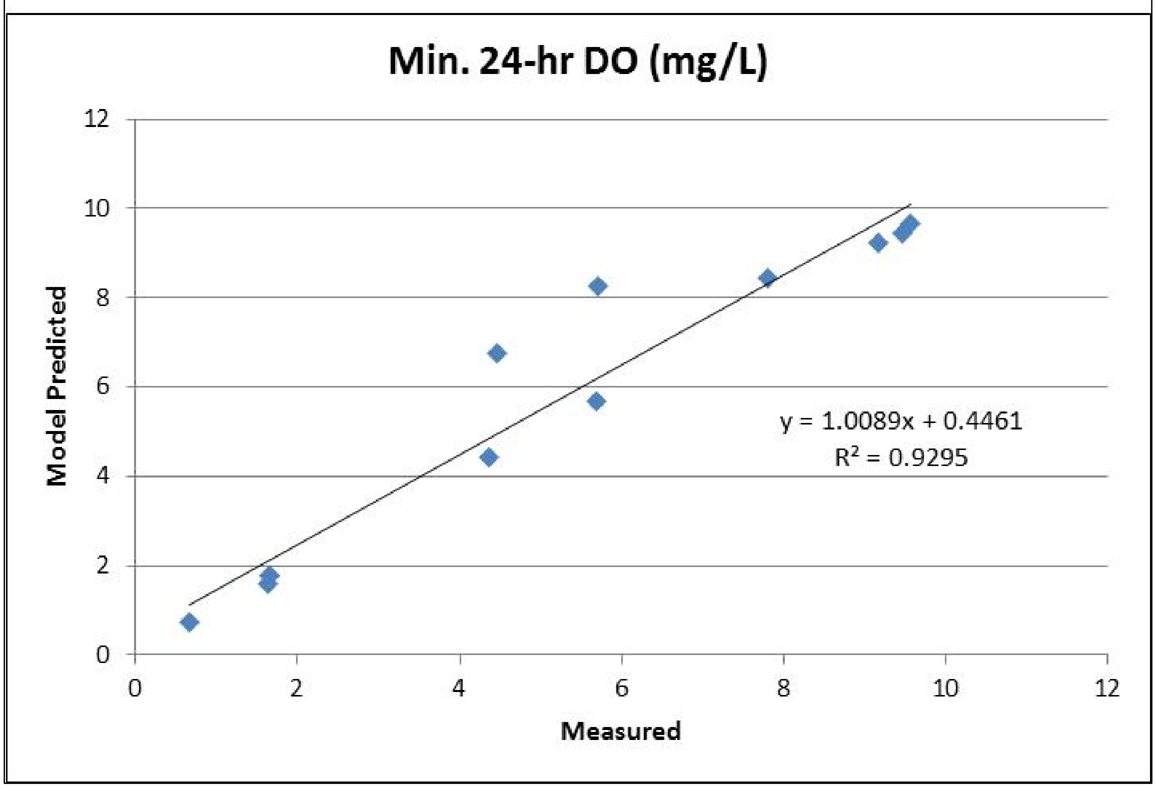


Figure 3-4. Comparison of model predicted vs. measured 24-hour average and minimum DOs for the calibration scenarios of the Upper Pecos River.

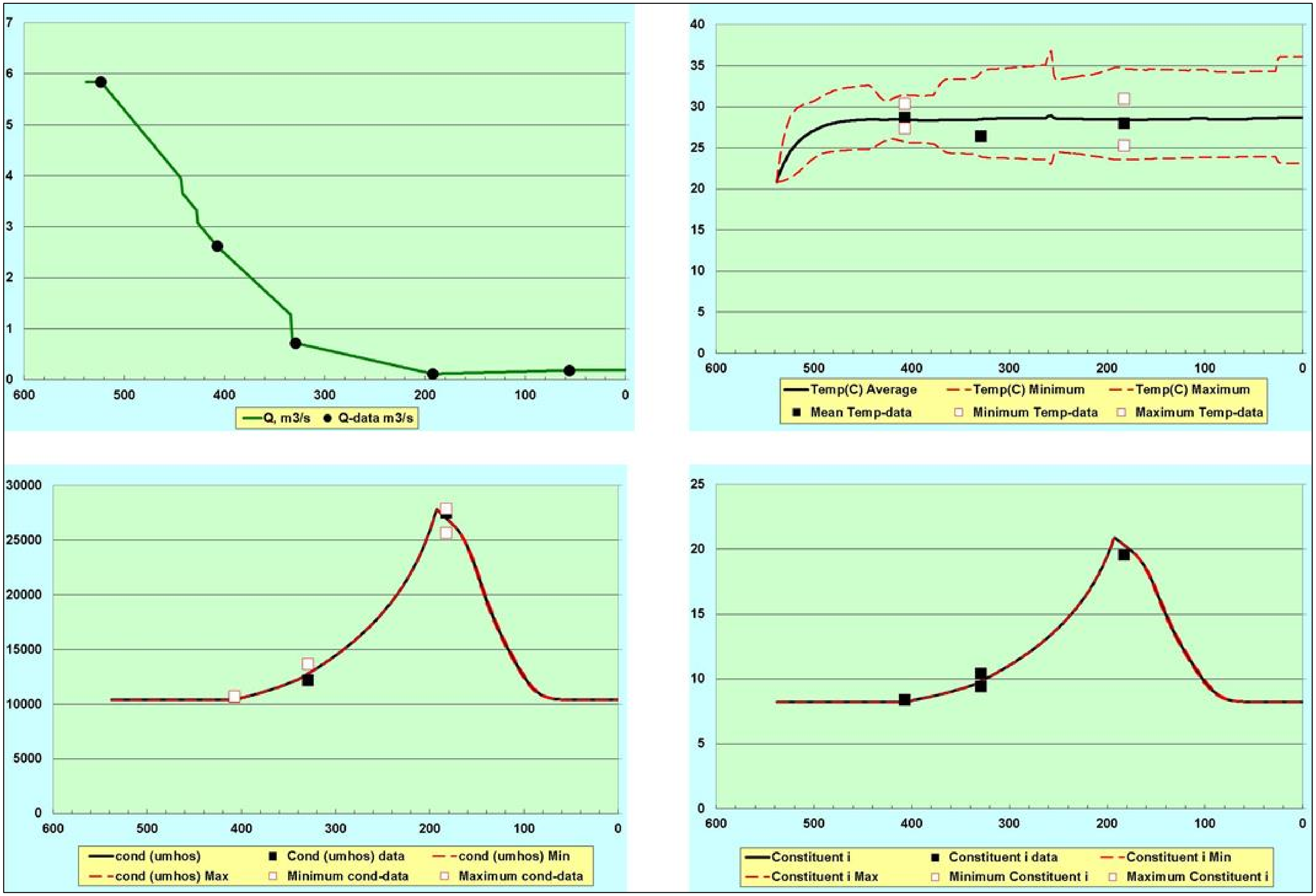


Figure 3-5. QUAL2K output showing measured vs. predicted flow, temperature, specific conductance and constitute-i (salinity) along the Upper Pecos River (12–18 June 2008).

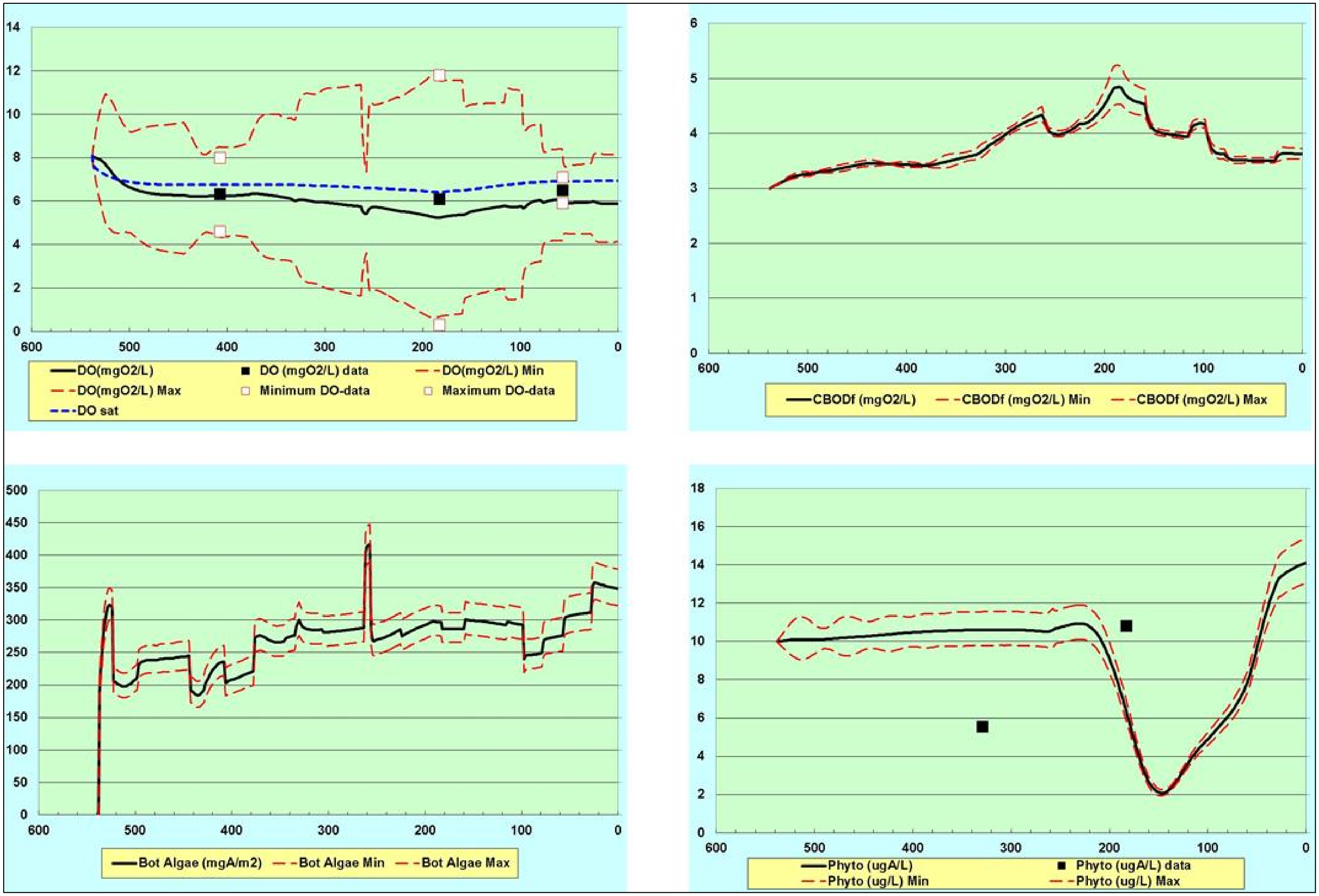


Figure 3-6. QUAL2K output showing measured vs. predicted dissolve oxygen, CBOD, bottom algae and phytoplankton (CHLA) along the Upper Pecos River (12–18 June 2008).

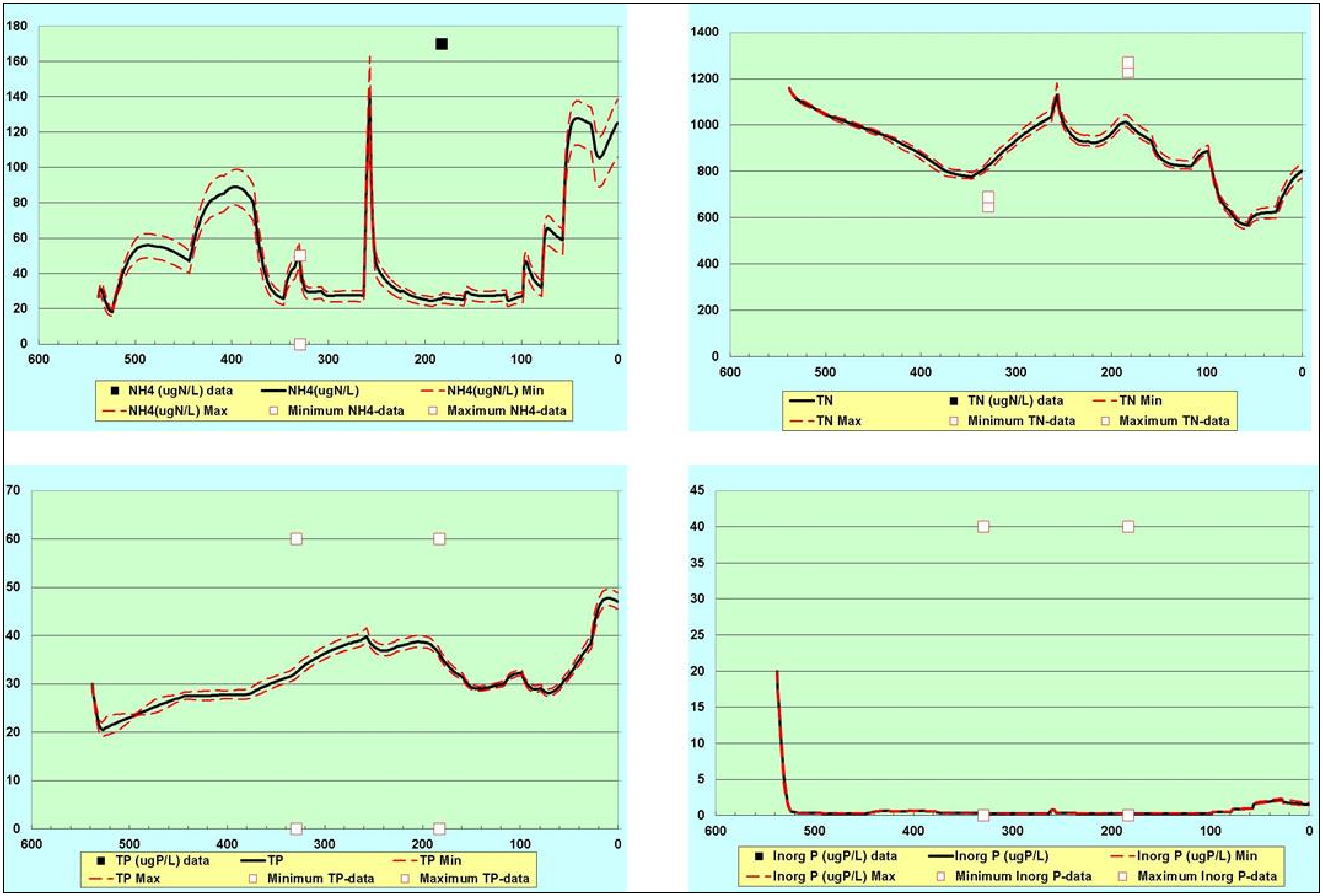


Figure 3-7. QUAL2K output showing measured vs. predicted ammonia, total nitrogen, total phosphorous and orthophosphate phosphorus along the Upper Pecos River (12–18 June 2008).

Model Validation

As for the model calibration, the validation predictions are presented as graphical results with observational data provided on the same graphs. In the validation step, the model was operated with the same input developed during the calibration step except for those parameters that were time dependent, such as meteorological data, streamflows, and withdrawals. Based on visual inspection, both average and minimum DOs were satisfactorily predicted for the three warm season validation scenarios and four cool season scenarios (Figures 3-10 and 3-11). The same statistical regression testing was applied to the validation scenarios as was used on the calibration scenarios. The results of the regression analysis showed that the QUAL2K validation results reasonably represented both 24-hour average and minimum DO conditions at monitoring stations with available data (Figure 3-12). For both average and minimum DO comparisons, the slope of the regression lines approach 1.0 and the y-intercept concentrations were not more than 0.3 mg/L from 0.0. These favorable statistical measures, as well as high R^2 values, support the conclusion that the QUAL2K Upper Pecos River model performed acceptably in the validation step.

As with the calibration step, the measured nutrient forms were often below reporting limits, which resulted in reliance on visual inspection of results as the means of evaluating goodness of model predictions.

[Remainder of page intentionally left blank.]

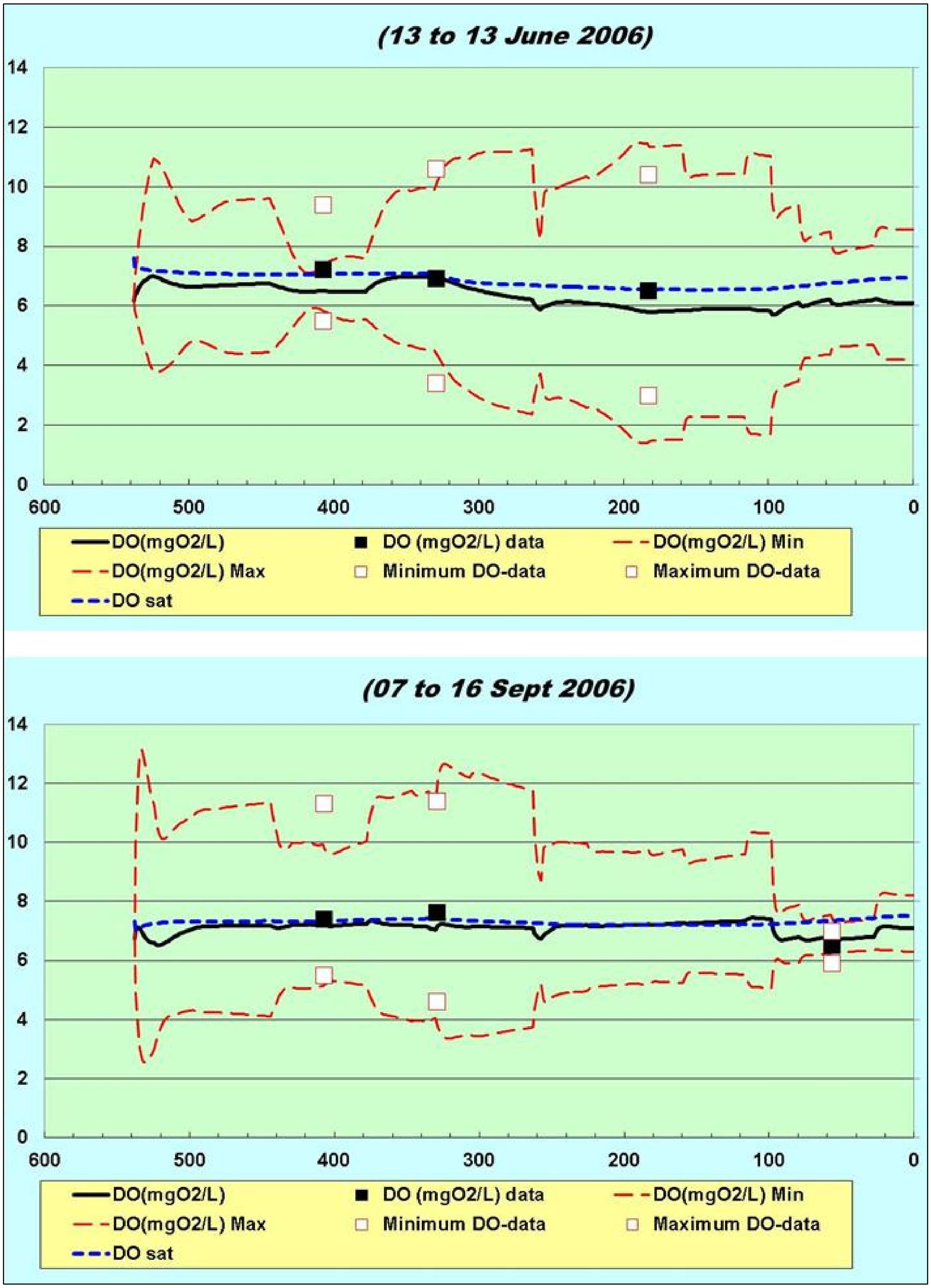


Figure 3-8. QUAL2K validation simulations of warm season scenarios.

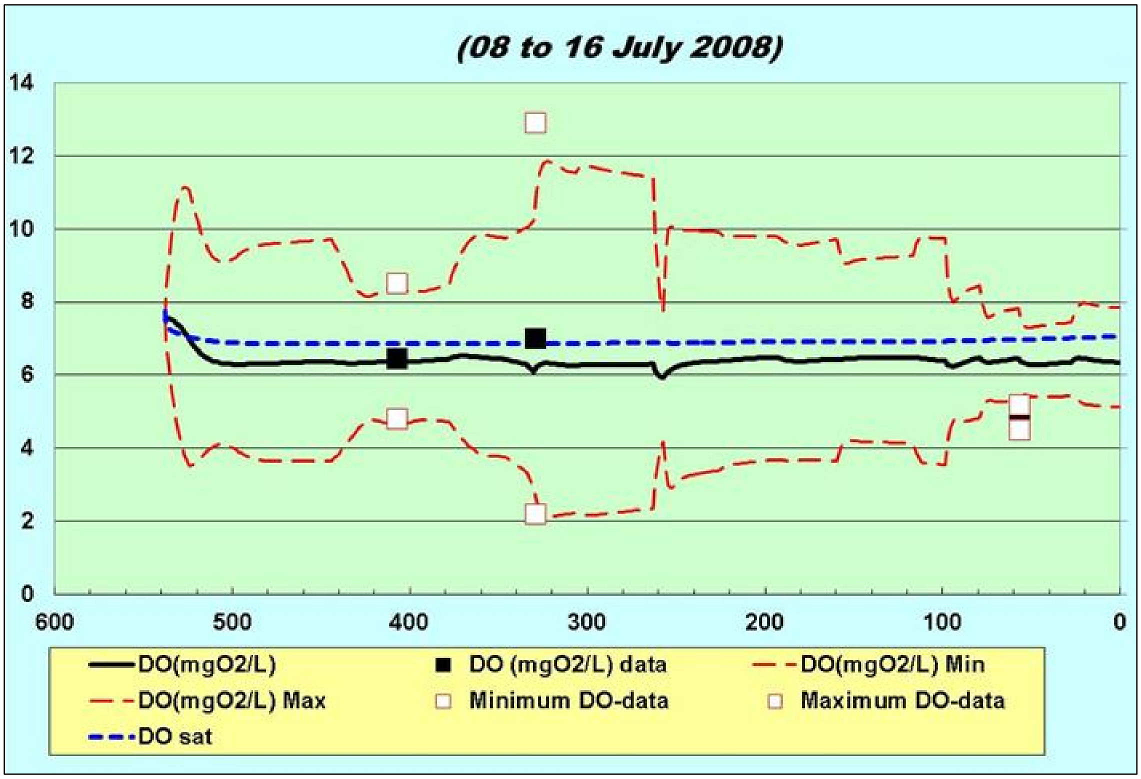


Figure 3-8 (cont'd). QUAL2K validation simulations of warm season scenarios.

[Remainder of page intentionally left blank.]

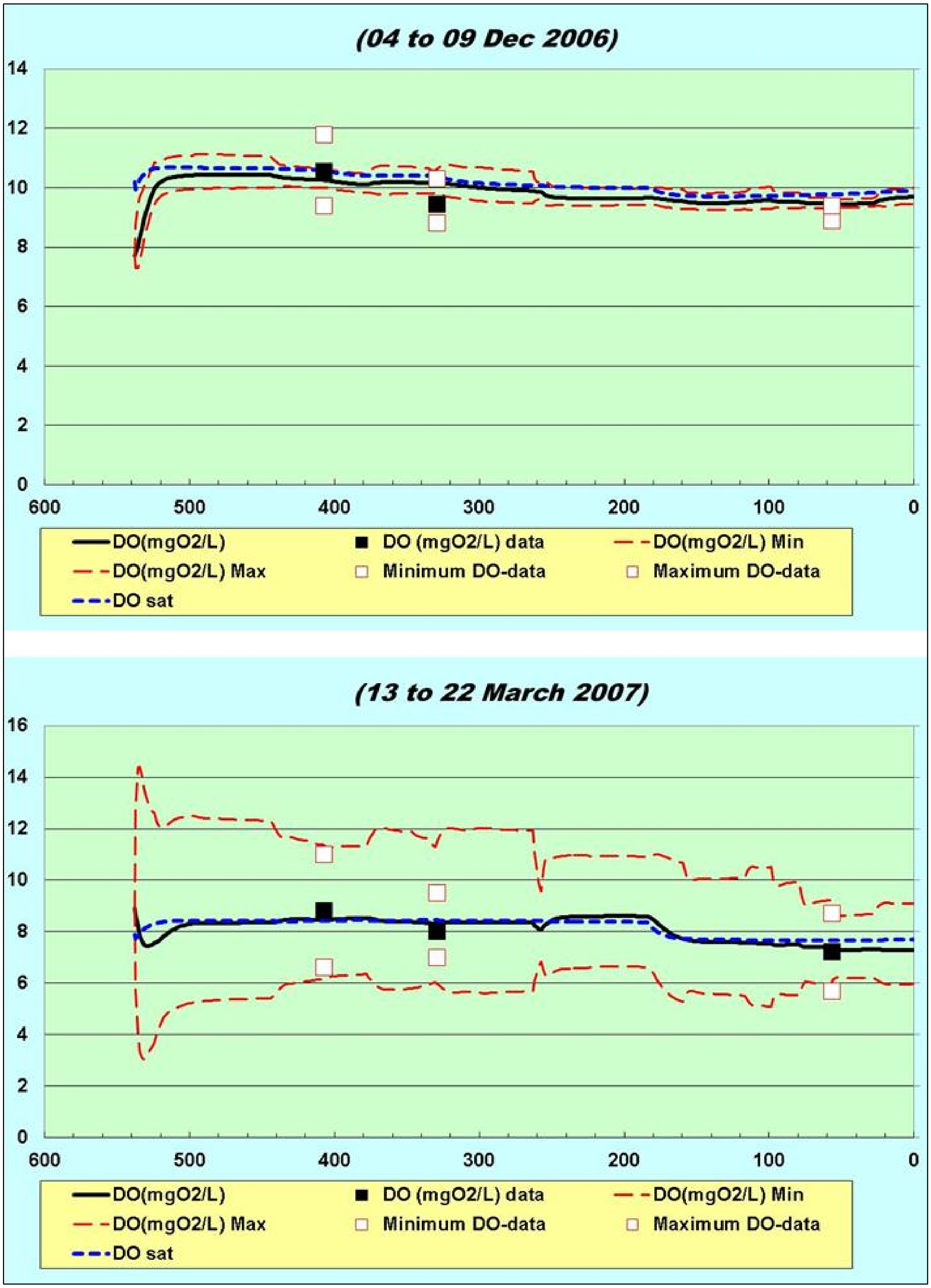


Figure 3-9. QUAL2K validation simulations of cool season scenarios.

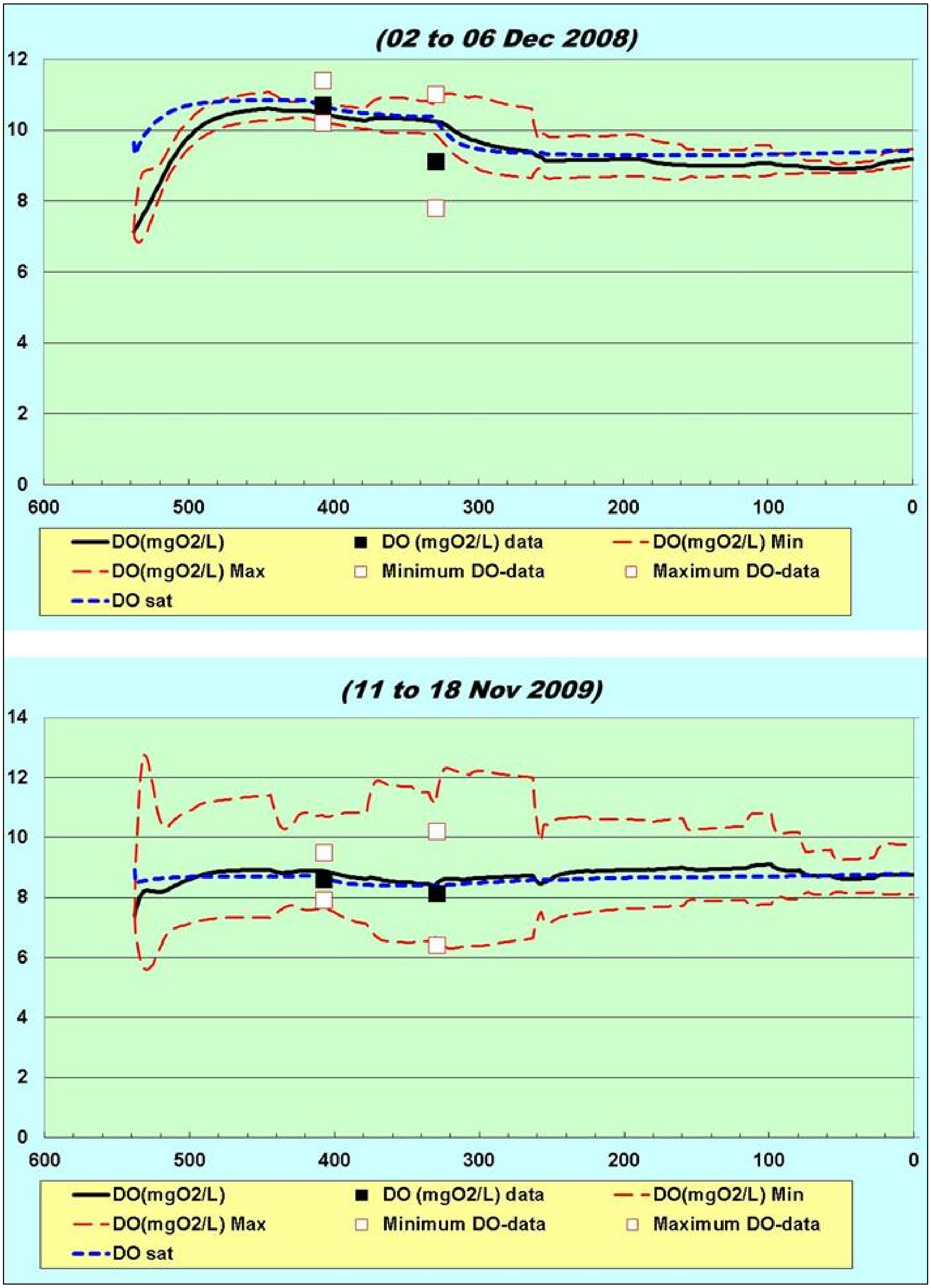


Figure 3-9 (cont'd). QUAL2K validation simulations of cool season scenarios.

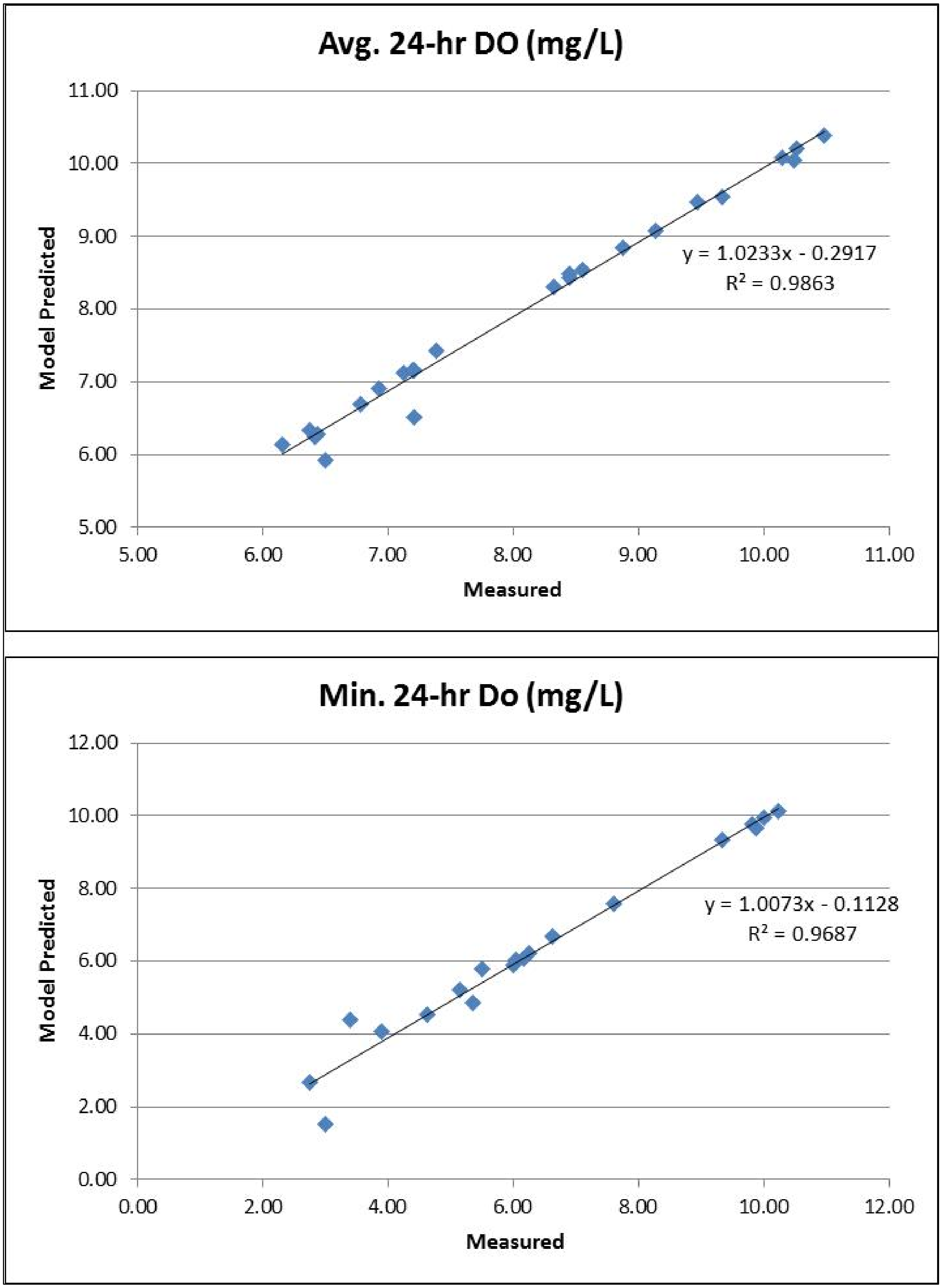


Figure 3-10. Comparison of predicted vs. measured 24-hour average and minimum DOs for the validation scenarios of the Upper Pecos River.

Model Sensitivity Analysis

A sensitivity analysis was performed to investigate the impact of several input parameters on daily average and minimum DO concentrations of the Pecos River. The parameters selected for sensitivity analysis were benthic algae maximum growth rate, headwater salinity, reaeration rate, headwater flow, percentage of SOD coverage, percentage of benthic algae coverage, velocity coefficient of hydraulic rating curves, depth coefficient of hydraulic rating curves, prescribed NH_3-N flux, prescribed OP flux, bottom algae death rate, and diffuse source salinity. The sensitivity analysis used the July 22–24, 2008 calibration scenario as a baseline and altered one parameter at a time. Alterations of +/- 25 percent were applied to all the selected parameters. The exceptions to these alterations were: 1) headwater flow, which could not be decreased at all without resulting in negative flows that could not be considered by the mode and 2) both percentage of SOD and bottom algae coverage, which could not be increased because the amount of riverbed considered as exerting SOD was already near 100 percent for most reaches (see Table 3-3).

The sensitivity analysis results are presented in Figures 3-11–3-16. Parameters to which predicted minimum and average DOs showed only small sensitivity included headwater salinity (Figure 3-11) velocity coefficient of the rating curves (Figure 3-14), prescribed NH_4-N and OP flux terms (Figure 3-15, bottom algae death rate (Figure 3-16), and diffuse source salinity (Figure 3-16). The 24-hour minimum predicted DO was particularly sensitive to decreasing the benthic algae maximum growth rate and increasing headwater flow (Figures 3-11 and 3-12). A moderate sensitivity of the minimum DO was indicated for changes of the reaeration rate (Figure 3-12), percentage of SOD coverage (Figure 3-13), percentage of benthic algae coverage (Figure 3-13), and depth coefficients in hydraulic rating curves (Figure 3-14).

Two conclusions from this sensitivity analysis will be made. First several parameters for which there were inadequate data for accurate characterization for the Upper Pecos River had significant impacts on the model predictions, especially of the critical 24-hour minimum DO output. These parameters included bottom algae growth rates, reaeration, SOD coverage, bottom algae coverage, and depth hydraulic coefficients. As with all complex mechanistic water quality models, QUAL2K is over parameterized indicating uncertainty exists that the correct input parameters were adjusted in the verification process. That limitation stated, it is most encouraging that the critical minimum DO model output was overall well simulated in both the calibration and validation steps, providing a level of confidence in the acceptability of the Upper Pecos River QUAL2K model and an indication of robustness in model performance.

Second, the sensitivity of the 24-hour minimum DO to flow (as represented by an increase in headwater flow) and bottom algae growth rate (an indication of biomass of bottom algae) supports the potential efficacy of certain BMPs to decrease the occurrences of depressed DO along the Upper Pecos River. However, this sensitivity analysis does not even attempt to address practical limits constraining how such BMPs that enhance flow and decrease bottom algae biomass can actually be implemented, which is left for discussion in the next chapter.

Conclusions on Model Verification Process

The QUAL2K representation of the Upper Pecos River was subjected to a verification process that included separate calibration and validation steps using data for the period of 2006 through 2009. This process involved 13 different scenarios representative of cool and warm season conditions of the Upper Pecos River. The primary parameter of concern was 24-hour minimum DO, because the existing depressed DO issues in the river are a result of not supporting the 3.0 mg/L 24-hour minimum DO criterion assigned through the Texas Surface Water Quality Standards to Segment 2311. Based on a combination of visual inspection and statistical evaluation through regression analysis of measured and predicted DO, the QUAL2K model was found to satisfactorily predict the primary parameter, 24-hour minimum DO, as well as 24-hour average DO. The 24-hour minimum DO predictions seemed to be particularly strong for the calibration and validation scenarios.

[Remainder of page intentionally left blank.]

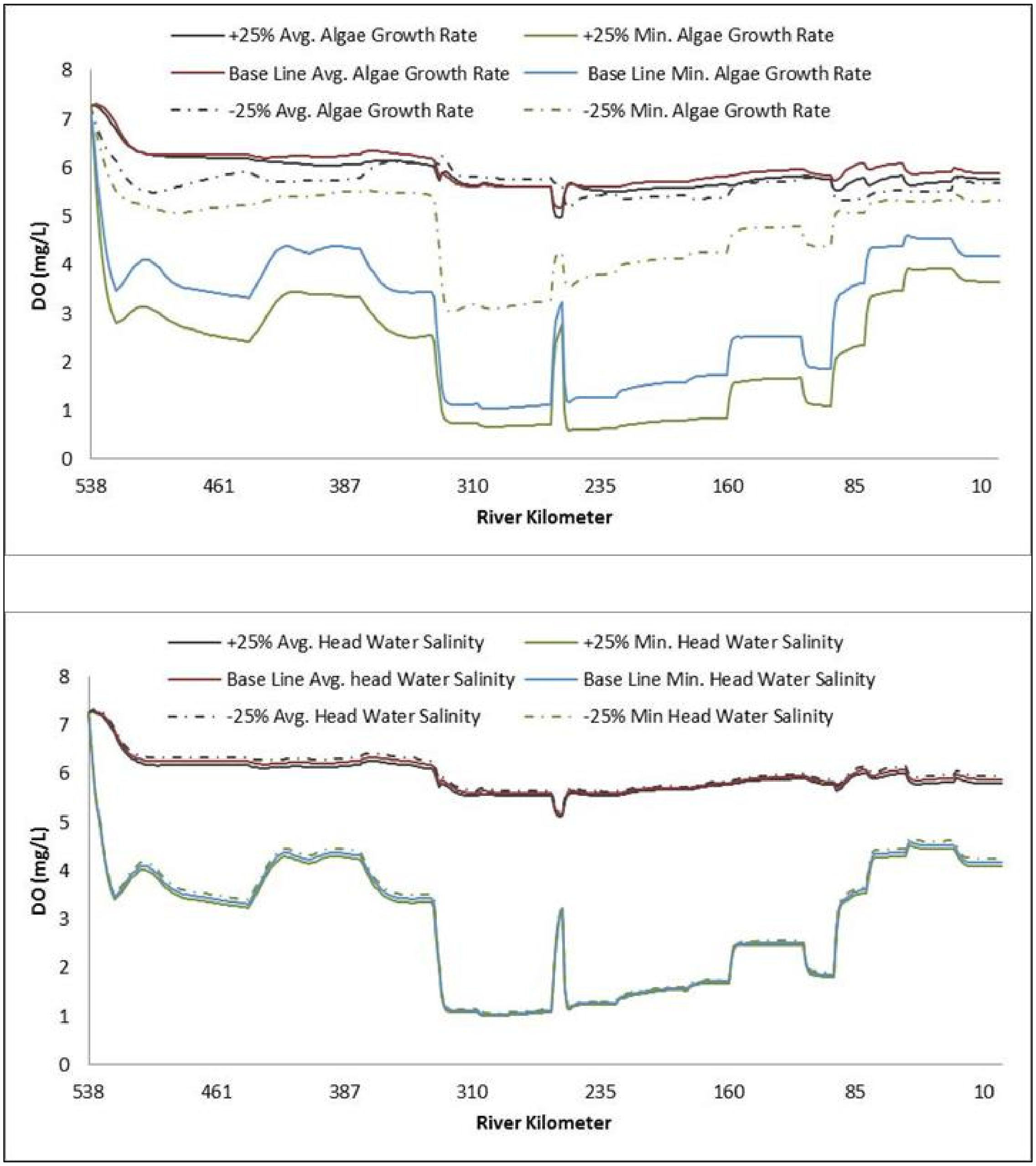


Figure 3-11. Sensitivity analysis of bottom algae growth rate, and headwater salinity, on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

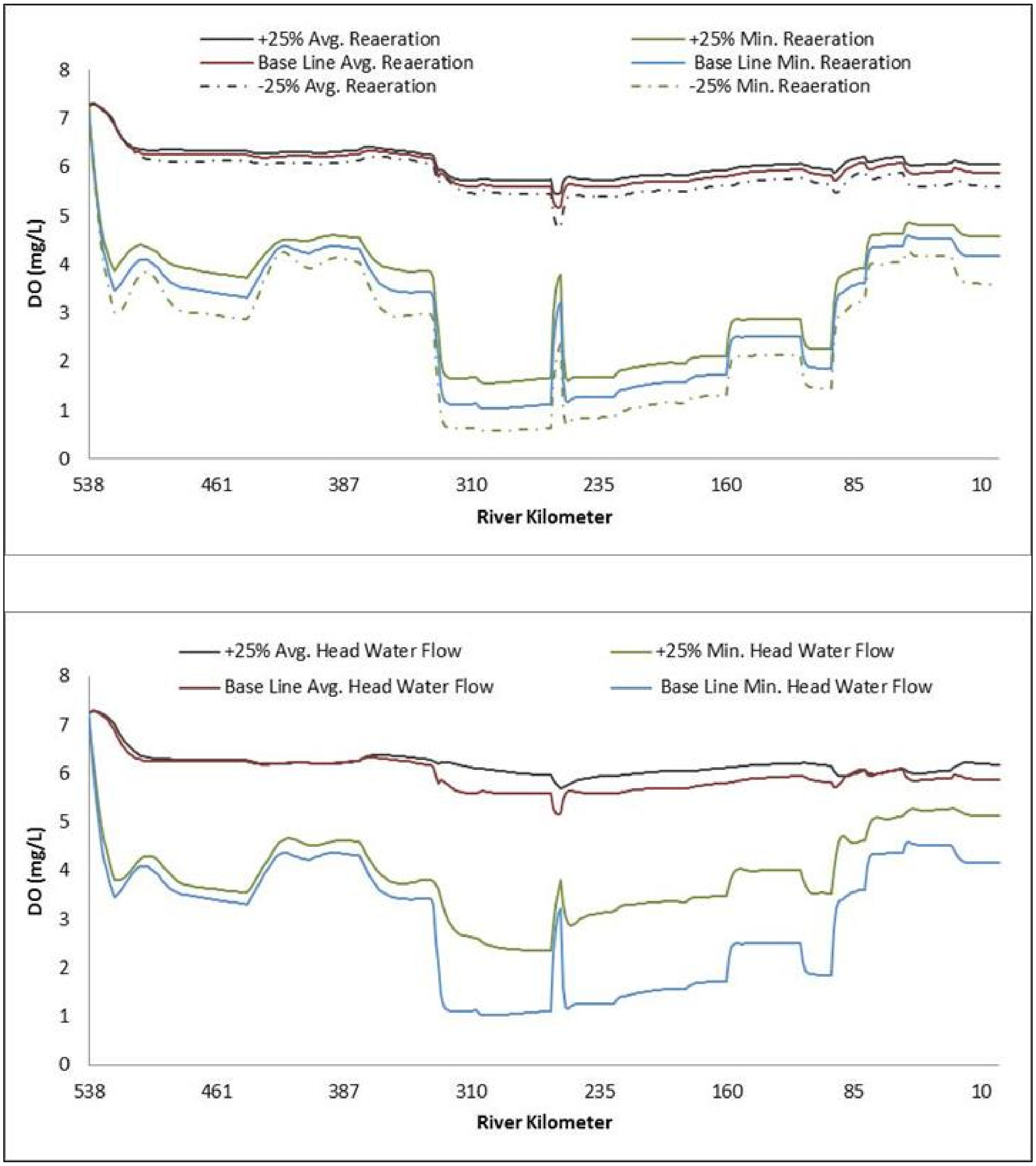


Figure 3-12. Sensitivity analysis of recreation, and headwater flow, on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

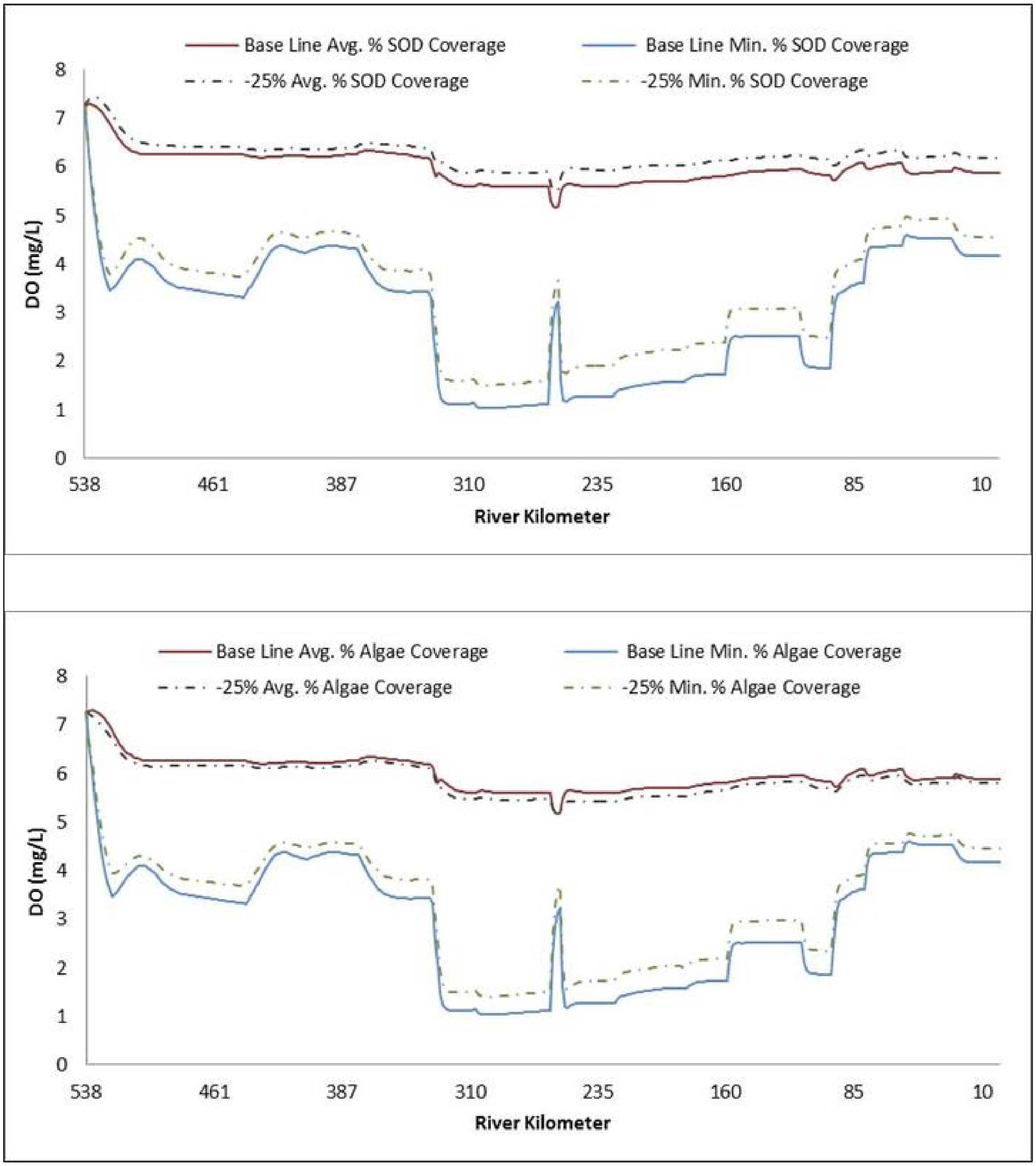


Figure 3-13. Sensitivity analysis of percent SOD coverage and percent bottom algae coverage on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

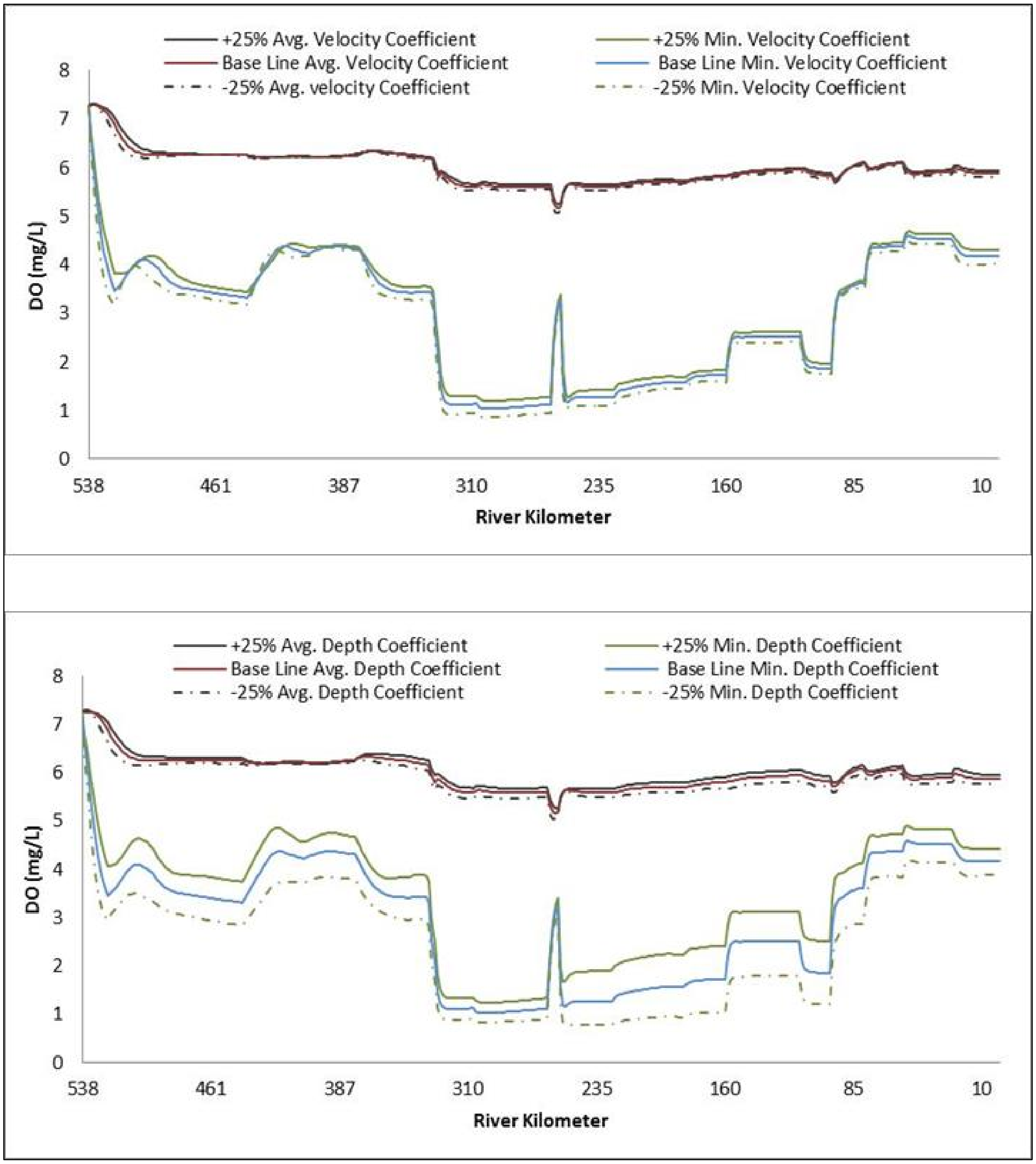


Figure 3-14. Sensitivity analysis of velocity coefficient, and depth coefficient, on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

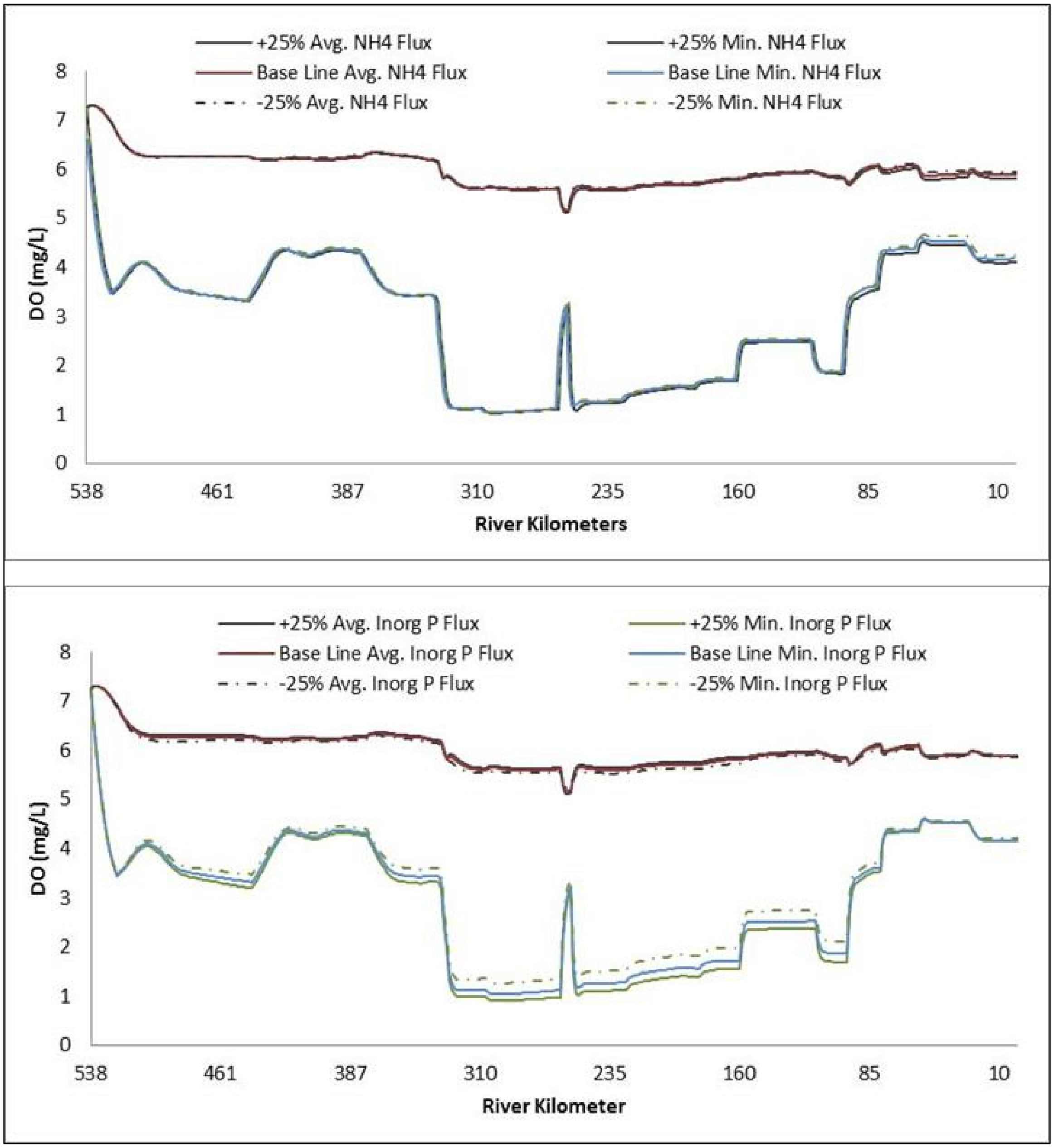


Figure 3-15. Sensitivity analysis of ammonia flux, and inorganic phosphorous flux, on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

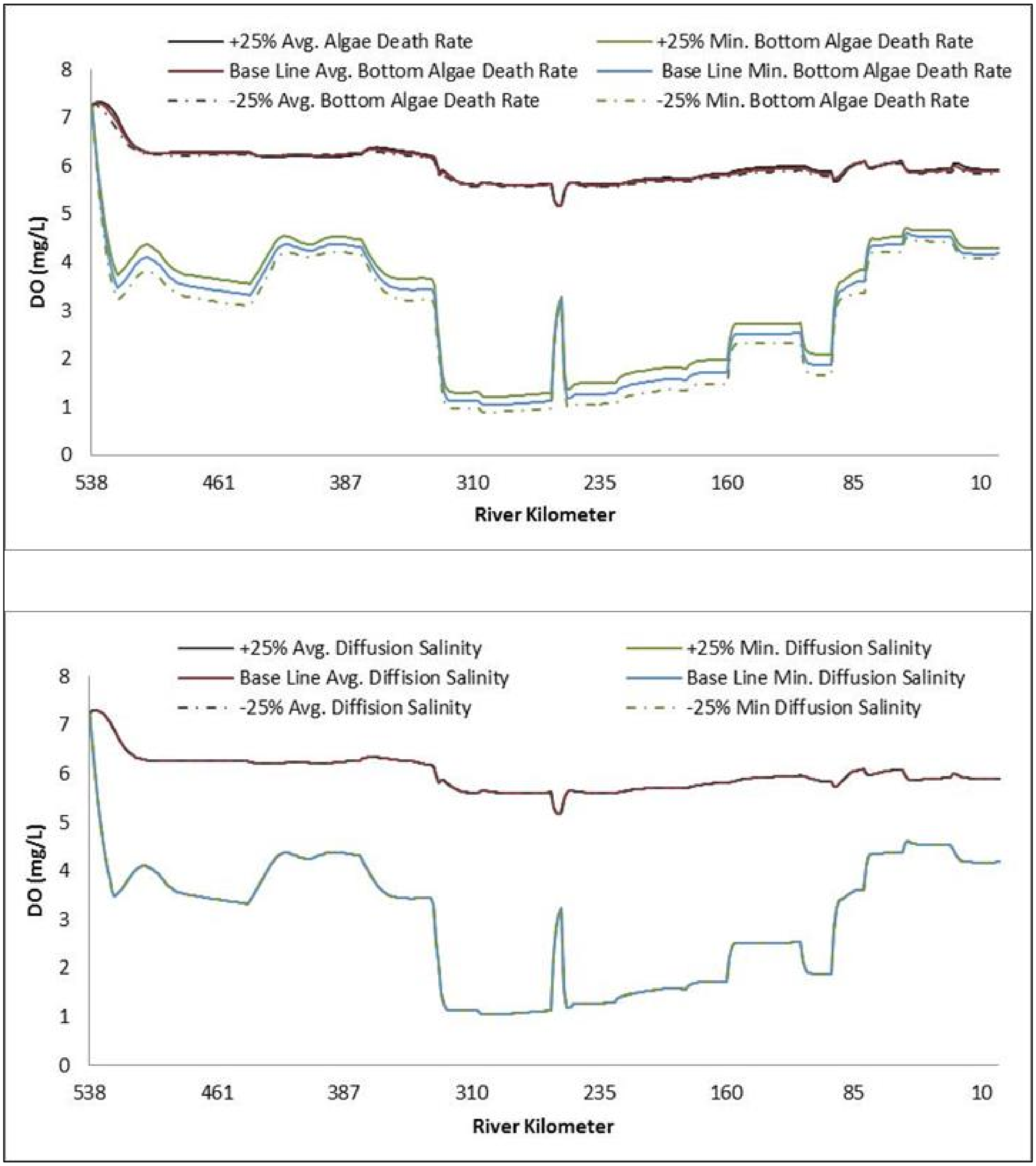


Figure 3-16. Sensitivity analysis of bottom algae death rate, and diffusion salinity, on 24-hour avg. and min. DOs for 22–24 July 2008 scenario.

CHAPTER 4

EVALUATION OF MANAGEMENT OPTIONS FOR UPPER PECOS RIVER

Integrated Modeling/Measured Data Approach to Evaluate Management Options

Because of TCEQ CWQMN stations and TCEQ's routine monitoring program of manual deployment and retrievals of multiprobes for 24-hour data collection, the Upper Pecos River segment contains a relatively high abundance of data useful for evaluating DO conditions. While CWQMN station data are not presently considered of sufficient quality to be included in the formal TCEQ biennial assessment, for this study the data used from these stations were restricted to only those values collected during the first full day (midnight to midnight) of the two-week deployment period and when the deployed multiprobe met post-calibration requirements. These two restrictions on the data selected obviate most of the concerns with CWQMN data reliability and of instrument drift resulting from biofouling and sediment build-up on the probes; both being processes that increase in severity with increasing time of deployment of the probes. Consequently, this data abundance from CWQMN and TCEQ manual deployments allowed the zone of impairment to be well defined, as developed in Chapter 2, confirming the TCEQ assessments.

An approach of integrating model predictions and measured data to evaluate management options will be detailed within this section, but first the environmental goals for DO need to be established for the Upper Pecos River and the zone of impairment defined. For the benefit of the reader, the environmental goals as defined through the Texas Surface Water Quality Standards and the TCEQ assessment methodology are repeated here from Chapter 2 with some additional elaboration:

- The Upper Pecos River (Segment 2311) has been assigned a high aquatic life use by TCEQ (TCEQ, 2010a).
- One water quality constituent considered to protect the high aquatic life use is DO resulting in the following two criteria:
    - 24-hour average DO of at least 5.0 mg/L
    - 24-hour minimum DO of at least 3.0 mg/L (TCEQ, 2010a)
- These criteria are not being supported when 10 percent or more of the data do not attain to each of these criteria (TCEQ, 2010b). (Recall that for the Upper Pecos River the depressed DO is a result of nonsupport of the 24-hour minimum DO criterion, which has simply been referred to as minimum DO in this report.)

The zone of impairment as determined in the 2008 and 2010 Texas Integrated Reports (TCEQ, 2008 & 2010b), further refined in the 2012 Texas Integrated Report (TCEQ, 2012), and confirmed through the analyses present in Chapter 2 is as follows:

- The Upper Pecos River from U.S. Highway 67 upstream to the Ward 2 Irrigation Turnout, which includes CWQMN Station 709, and SWQM Stations 13257 and 13260, of which Station 709 is collocated with Station 13260.

The calibrated and validated QUAL2K model of the Upper Pecos River (Segment 2011) was used to evaluate selected management practices and BMPs to determine their individual and collective efficacy in restoring DO levels in the Upper Pecos River. The evaluation approach used QUAL2K model runs for conditions with and without management options combined with historical 24-hour DO data collected in the zone of impairment in the Upper Pecos River from June 2003–January 2011. This approach uses the QUAL2K model to evaluate existing (base) conditions and management option conditions under a range of environmental factors (e.g., releases from Red Bluff, withdrawals of streamflow for irrigation, seasonal weather variation in sunlight and air temperature) preformed through separate runs of QUAL2K. Evaluations of model output was then conducted to determine the change in DO resulting from the management option as compared to the base condition at the key location in the zone of impairment with the most monitoring data (Pecos River at FM 1776 – locations of CWQMN Station 709 and SWQM Station 13260). The predicted changes in DO were then applied systematically to the observed DO data and those data analyzed to evaluate the improvement in DO resulting from a management option.

The approach of combining QUAL2K predictions with observed data was used to:

1) maximize use of the large set of observed 24-hour DO data available for the period of June 2003–January 2011 at a key location in the zone of depressed DO;
2) allow the evaluation period of management options to readily encompass the 8-½ year period of the observed 24-hour data, which would be very resource intensive to accomplish otherwise;
3) enhance confidence in predictions of management options by restricting model application largely to periods for which it was calibrated and validated; and
4) avoid uncertainties in model input of hydrologic conditions imposed by limitations in the location of streamflow records from USGS gages for the period prior to summer 2007 after which additional gages became operational.

Basically the approach employed the following seven steps of which steps 1-3 are preparatory and performed once while steps 4-6 are repeated sequentially to evaluate each management option:

1) Perform cluster analysis on observational DO data to determine seasonal patterns in DO,
2) Link QUAL2K and observational data by selecting QUAL2K scenarios to be used and establish the connection of model results to measured 24-hour DO data in the zone of impairment,
3) Operate QUAL2K for the selected scenarios to predict DO under baseline conditions and extract from model output the 24-hour average and minimum DO predictions,
4) Operate QUAL2K to predict DO for each management option and extract from model output the 24-hour average and minimum DO predictions,
5) Determine the differences in DO between baseline and management option scenarios and apply the differences in 24-hour DO concentrations to the observational 24-hour DO dataset, and
6) Develop DO duration curves based on the observational data and model predicted changes to the observational data, and then compare results to the relevant environmental goal of no more than 10 percent of the data being less than the relevant average and minimum DO criteria.

Step 1 – Cluster Analysis

Under this approach that combines model operation with manipulation of observational data to evaluate effectiveness of management options, the initial step was to refine the information in Chapter 3 of this report on the seasonality of DO in the Pecos River in Texas. The 24-hour average and minimum DO data for CWQMN Stations 709 and 710 and SWQM Stations 13257 and 13260 were used in a cluster analysis. The number of 24-hour measurement events per station was 88 for CWQMN Station 709, 86 for CWQMN Station 710, 15 for SWQM Station 13257, and 11 for SWQM Station 13260, which included data collected over the period June 2003–January 2011. It is apparent from the number of 24-hour events that the data are weighted towards those collected at CWQMN stations. The cluster analysis focused on 24-hour minimum and average DOs in the zone of impairment and upstream of the impaired zone at CWQMN Station 710. While this analysis was similar to the analysis using water temperature and average DO for the entire Pecos River in Texas (Figure 2-8), by focusing exclusively on DO, thus excluding water temperature data from the cluster analysis and by limiting the data to that in the zone of impairment and immediately upstream, results were obtained informative of and specific to the seasonality of low DO (Figure 4-1). The three months of June–August were clustered as similar and based on knowledge of DO in the system; this cluster coincides with the period of lowest DOs. Further July and August are clustered together, forming the two-months when the low DOs are most likely to occur. The two months on either side of the June–August grouping (April and May in the spring and September and October in the fall) are months with the next greatest occurrences of low DO. Finally there is a cluster of the months of November–March with higher DOs, and December and January are closely clustered with the highest temporal grouping of DOs. Further, the cluster analysis information was instructive for determining which scenarios to include in QUAL2K runs as developed in the next step.

[Remainder of page intentionally left blank.]

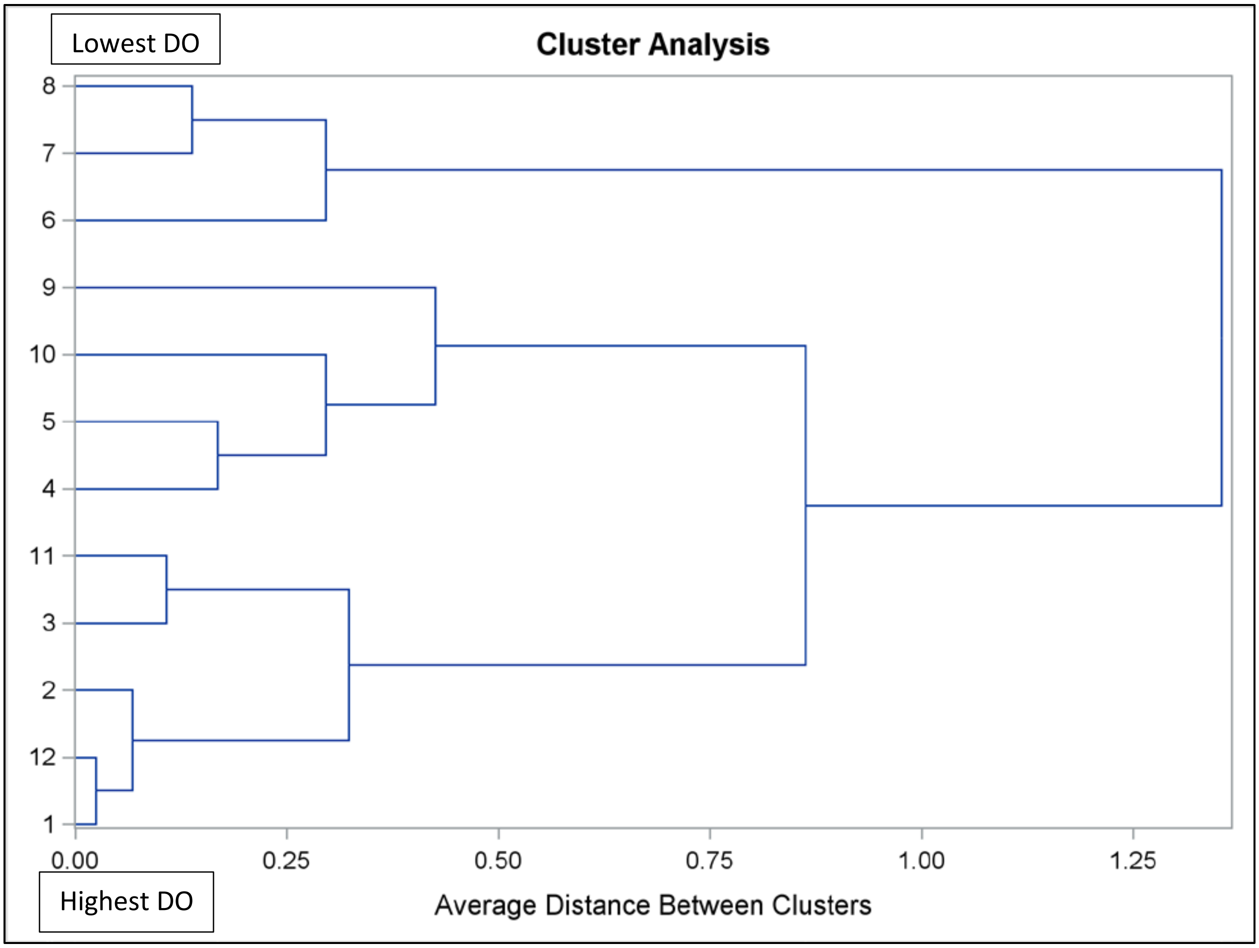


Figure 4-1. Cluster analysis results of 24-hour average and minimum DO data for CWQMN Stations 709 and 710 and SWQM Stations 13257 and 13260.

Step 2 – Link QUAL2K to Observational Data

Based on the cluster analysis (Step 1) and availability of input data required by QUAL2K, 12 scenarios were selected as representative of typical conditions in the Upper Pecos River and not influenced by stormwater runoff (i.e., can be approximated by steady state flows as required for QUAL2K). The 12 scenarios were predominately selected from the calibration and validation cases (Table 4-1), therefore largely representing situations known to be reasonable simulated by QUAL2K (see Chapter 3, especially Figures 3-4 and 3-10). The two exceptions are the 14–20 August 2008 period, which was initially a calibration case until it was determined that the observational 24-hour data for this period were suspect, and the 13–15 October 2009 period, which did not strictly meet the constraints imposed for cases to be considered steady state. The 12 scenarios reflect Pecos River conditions throughout the period of June 2006 through November 2009 with several of the scenarios during period of lowest DO during the summer of 2008 when hydrologic and water quality data were simultaneously most abundant.

Because the approach to evaluate management options entailed combining model predictions with observational data, the observational 24-hour dataset was assessed to ensure that these data were representative temporally of the Pecos River in the zone of impairment (i.e., did not contain significant biases of under or over representation of the months of the year). The key location for the analysis was selected to be the collocated CWQMN Station 709 and SQWM Station 13260 at the FM 1776 crossing of the Pecos River; the location with the most consistent occurrences of depressed DO and a dataset comprised of 99 distinct 24-hour measurements of average and minimum DO covering the period June 2003–January 2011. The 24-hour DO data for these stations are distributed reasonably across each of the 12 months of the year (Table 4-2) and provided some margin of safety to the analysis in that the distribution is slightly biased toward over representation of the periods with low DOs. June - August data points comprise 28 percent of the data whereas an even distribution would be at 25 percent and April–October data points comprise 61 percent whereas an even distribution would be 58 percent.

Table 4-1. QUAL2K scenarios employed in evaluation of management options.

Date	Comments
13–17 June 2006	Validation case
7–16 September 2006	Validation case
4–9 December 2006	Validation case
13–22 March 2007	Validation case
2–9 May 2008	Calibration case
12–18 June 2008	Calibration case
8–16 July 2008	Calibration case
22–24 July 2008	Calibration case
14–20 August 2008	Other (not used for testing because of suspected DO data errors)
2–6 December 2008	Validation case
13–15 October 2009	Other (measured flows more variable than optimal for testing)
11–18 November 2009	Validation case

Table 4.2. Distribution by month of the combined 24-hour DO data set for CWQMN Station 709 and TCEQ Station 13260.

Month	Count	Percentage of Data by Month (%)
January	6	6.06
February	6	6.06
March	9	9.09
April	8	8.08
May	6	6.06
June	11	11.11
July	8	8.08
August	9	9.09
September	9	9.09
October	9	9.09
November	10	10.10
December	8	8.08
Total	**99**	**100.00**

The linking or associating of the 12 QUAL2K scenarios to the observational dataset was based when possible on a one-to-one correspondence of the month of the QUAL2K scenario to the month of collection of the 24-hour data and on the DO cluster analysis (Figure 4-1) resulting in the associations in Table 4-3.

Table 4-3. Association of QUAL2K scenarios to periods of observed data (based on cluster analysis in Figure 4-1 and groupings listed from lowest to highest DO months).

QUAL2K Scenarios	**Cluster Analysis DO Groupings** (see Figure 4-1)
14–20 August 2008	August
8–16 July 2008; 22–24 July 2008	July
13–17 June 2006; 12–18 June 2008	June
7–16 September 2006	September
13–15 October 2009	October
2–9 May 2008	May and April
13–22 March 2007; 11–18 November 2009	November and March
4–9 December 2006; 2–6 December 2008	February, December and January

Step 3 – Operate QUAL2K for Baseline Scenarios

The QUAL2K model of each of the 12 scenarios listed in Table 4-1 was run to provide the baseline conditions of 24-hour average and minimum DO values for the Pecos River at FM 1776. From model output, the required pair of average and minimum DO predictions was extracted. The baseline scenarios only had to be run once, because these conditions do not change.

Step 4 – Operate QUAL2K for Management Options

To evaluate each selected management option each of the 12 QUAL2K scenarios was run with model input changed to reflect the change in environmental conditions imposed by the control measure(s) comprising the management option. Similar to Step 3, for each run the required pair of average and minimum DO predictions for the Pecos River at FM 1776 were extracted from the model output.

The control measures considered for evaluation were based on information in *A WPP for the Pecos River in Texas* (Gregory and Hatler, 2008) and the suggestions of the TSSWCB and TWRI, which reflected their collective knowledge and experience of the Pecos River and the landowner groups in the watershed. The control measures considered for evaluation and the associated management option number are as follows:

Option 1 – Malaga Bend Project

The Malaga Bend project involves control of brine intrusion in the Pecos River above Red Bluff Reservoir in New Mexico. From Miyamoto et al. (2007), if brine intrusion control is fully implemented at Malaga Bend (150,000 tons/year removal), salinity at Orla, TX can be decreased by 1.55 ppt to 1.68 ppt. Based on this information, evaluation of the Malaga Bend project entailed decreasing headwater salinity of each of the 12 QUAL2K scenarios by 1.6 ppt. Benefits are realized because of the lower salinity in waters released from Red Bluff Reservoir predominately to meet irrigation demands. Lower salinities slightly increase the saturation level of DO in water (e.g., Table 4-4) resulting in potential benefits to DO in the Pecos River.

Table 4-4. Saturation DO concentration as a function of temperature and salinity.

Dissolved Oxygen - Saturation Concentration (mg/L)					
Temp (°C)	Salinity (ppt)				
	0	5	10	15	20
0	14.6	14.1	13.6	13.2	12.7
5	12.8	12.3	11.9	11.6	11.2
10	11.3	10.9	10.6	10.3	9.9
15	10.1	9.8	9.5	9.2	8.9
20	9.1	8.8	8.6	8.3	8.1
25	8.2	8.0	7.8	7.6	7.4
30	7.5	7.3	7.1	6.9	6.8
35	6.9	6.8	6.6	6.4	6.2

Source: Metcalf & Eddy, Inc. 1991. Wastewater Engineering.

Option 2 – Increased streamflow in zone of impairment (BBEST 50th percentile flows)

For the period of lowest DOs in the zone of impairment (April–October) the local basin and bay expert science team (BBEST) recommended 50th percentile flows (BBEST, 2012a; BBEST 2012b) were imposed on the Upper Pecos River. The 50th percentile flows at Girvin provided in Table 4-5 were implemented in the model as the minimum flow in the reaches of the river below the Ward 2 Irrigation Turnout during the months of April through October.

The BBEST recommendations are an outcome of Senate Bill 3 (SB 3) passed by the Texas Legislature in 2007. SB 3 directed the development of environmental flow recommendations through a regulatory approach using local stakeholder process and the best available science. SB 3 directed the use of an environmental flow regime in developing flow standards to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats.

Notably the initial flow recommendations made by the BBEST are made without regard to the need for the water for other uses. Likewise, the use of the BBEST flows in this analysis does not take into account other uses for the water or even availability of the water. Rather, this management option, as well as Option 3, was included because it is generally recognized that the Upper Pecos River has a highly modified hydrologic regime and as such the benefits of increased flow in the zone of impairment were addressed through this study.

Table 4-5. BBEST recommended 50th percentile (BBEST 2012b) base flows in warm months (all flows in cfs; blue font values are the flows implemented in QUAL2K).

Location	April	May	June	July	August	September	October
Orla	15	15	15	33	33	33	33
Pecos	16	16	16	30	30	30	30
Girvin	**19**	**19**	**19**	**18**	**18**	**18**	**18**

Option 3 – Increased streamflow in zone of impairment (BBEST 50th & 75th percentile flows)

Same as Management Option 2 above, but used 75th percentile flow recommendations from BBEST for the period June–August keeping the 50th percentile flow recommendations for April, May, September and October (Table 4-6, BBEST 2012b). These flows were implemented by establishing them as the minimum flow in each QUAL2K scenario for the reaches downstream of the Ward 2 Irrigation Turnout for the months of April–October.

Table 4-6. Recommended 50th percentile base flows (cfs) (Blue Text) and 75th percentile base flows (cfs) (Red text) in warm months from BBEST (2012b).

Location	April	May	June	July	August	September	October
Orla	15	15	44	69	69	33	33
Pecos	16	16	78	104	104	30	30
Girvin	**19**	**19**	**25**	**27**	**27**	**18**	**18**

Option 4 - Decreased periphyton biomass by 25 percent

This option of decreasing periphyton biomass (or bottom algae biomass as represented in QUAL2K) was implemented in the model by increasing the input parameter controlling bottom algae die-off by 55 percent. This 55-percent increase in die-off was determined based on the average change in the die-off rate which yielded a 25-percent reduction in bottom-algae biomass in the Pecos River reach below the Ward 2 Irrigation Turnout running downstream to below Station 13257 in the Girvin area (in essence the zone of impairment) during the critical months (June, July and August).

The means of accomplishing the reduction in periphyton biomass (or bottom algae) were not taken into consideration for implementing this option into QUAL2K. Biological or chemical means could be used to accomplish the 25-percent reduction in biomass, though both means could be associated with unintentional environmental concerns and consequences. For example, introduction of a non-resident fish species to eat algae harbors unintended concerns in both the Pecos River as well as downstream water bodies from introducing a fish species that could disrupt biodiversity.

Option 5 - Decreased sediment-water fluxes by 25 percent

This management option considered in QUAL2K reduced the user prescribed flux of nutrients released from bottom sediments into the water column and sediment oxygen demand (SOD) by 25 percent using unspecified means. Land management practices and increased pulses of elevated flows could collectively or individually contribute to reducing sediment-water column exchanges.

Because of hydrologic modifications to the Pecos River, elevated flow events from stormwater runoff are rare and of reduced amplitude along the Upper Pecos River compared to conditions prior to development of storage reservoirs in New Mexico and Red Bluff Reservoir in Texas. Periodic elevated flows would serve to reduce sediment build-up in the bottom of the riverbed, which anecdotally has been indicated to be abundant by TCEQ staff familiar with the river. Also, various farm and range management measures have a potential to reduce sediment losses from the landscape into the Pecos River, though the arid conditions of the region make such measures of unknown efficacy.

Option 6 - Decreased headwater nutrients from Red Bluff Reservoir by 50 percent

Under this management option, the nutrient concentrations specified at the headwater in QUAL2K (i.e., the releases from Red Bluff Reservoir) were reduced by 50 percent. This management scenario was developed in response to the desire to improve the quality of water delivered to Texas from New Mexico.

Concerns have been raised by various parties in Texas regarding the lack of an agreement between Texas and New Mexico that specifies water quality targets. A mechanism similar to the Pecos River Compact, which was established in 1949 and allocates the waters of the Pecos River between Texas and New Mexico, has been discussed as a mechanism to improve water quality, but no action has taken place regarding the development of such a framework to date.

Option 7 - Added riffle above FM 1776 crossing of Pecos River

This management option was implemented in QUAL2K by changing input to the model to include a 1-meter high broad-crested weir located 1.5 km (approximately 1 mile) above FM 1776 crossing of Pecos

River. A series of riffles spaced every few kilometers would be required to bring improvement to the entire impaired stretch of the Pecos which may persist for about 150 km (almost 100 miles). Because implementing riffles through QUAL2K is manually very time consuming and requires reworking the segmentation of the Pecos River, a single riffle was evaluated located upstream of the point of evaluation for management options. Further the dam was inserted into the model using the instructions provided in Chapra et al. (2008) with input coefficients describing the re-oxygenation factors taken from Butts and Evans (1978).

Option 8 - Combination of management Options 3, 4 and 6

This option was represented by the combination of management measures of Option 3 (75th percentile BBEST recommended flow during the period June–August and 50th percentile flow for April, May, September and October), Option 4 (25-percent decrease in bottom algae biomass), and Option 6 (50-percent decrease in nutrients released from Red Bluff Reservoir).

Option 9 - Combination of Management Options 2, 4 and 5

This option was represented by the combination of management measures of Option 2 (50th percentile BBEST recommended flow during the period April–October), Option 4 (25-percent decrease in bottom algae biomass), and Option 5 (25-percent decrease in flux releases of nutrients into water from sediments).

Option 10 - Combination of Management Options 3, 4, 5 and 6

This option was represented by the combination of management measures of Option 3 (75th percentile BBEST recommended flow during the period June–August and 50th percentile flow for April, May, September and October), Option 4 (25-percent decrease in bottom algae biomass), Option 5 (25-percent decrease in flux releases of nutrients into water from sediments), and Option 6 (50-percent decrease in nutrients released from Red Bluff Reservoir).

Saltcedar Control

Those familiar with the Pecos River may wonder why the benefits of saltcedar control on the Pecos River and its tributaries are not considered as one of the management options. The reasons for omission of saltcedar control were the difficulties in scientifically quantifying increases in streamflow and decreases in salinity from eradication of saltcedar. As an invasive species that can dominate riparian zone vegetation, the control of saltcedar benefits biodiversity along the Pecos River. But the water quantity and quality benefits of its control have remained difficult to quantify. Some increases in streamflow immediately following saltcedar control have been indicated by research (Hart et al. 2005; Sheng et al. 2007). Scientists, however, also suggest that as native trees and vegetation replace the eradicated saltcedar and this vegetation matures in size, these immediate water quantity benefits from reduced evapotranspiration will be substantively reduced (Hatler and Hart, 2009). Consequentially, saltcedar control was not considered a quantifiable, long-term management option for improving DO along the Pecos River.

Step 5 – Determine differences in DO from Management Options and Adjust Observational Data

The QUAL2K runs from Steps 3 and 4 were next used to determine the changes in DO resulting from each management option. As stated in the descriptions of Steps 3 and 4, for all scenarios the 24-hour average and minimum DOs predicted were extracted from model output for the FM 1776 crossing of the Pecos River. Pairings of the extracted data for the baseline condition to each particular management option were created for both average and minimum DOs. The predicted DOs for the management option were subtracted from the predicted baseline condition. The difference obtained through the subtraction process gave a negative number whenever the management option improves DO and a positive number when the option actually decreased DO levels. The computations are described through this equation:

$$DIFF_{(i, j, k)} = DO\_BASE_{(i, j)} - DO\_OPT_{(i, j, k)}$$

Where,

$DIFF_{(i, j, k)}$ = Difference in 24-hour DO parameter i at FM 1776 for scenario j under management option k

$DO\_BASE_{(i, j)}$ = 24-hour DO parameter i at FM 1776 for baseline scenario j

$DO\_OPT_{(i, j, k)}$ = 24-hour DO parameter i at FM 1776 for baseline scenario j with management option k

i = 1 for computation of 24-hour average DO; i = 2 for computation of 24-hour minimum DO

j = represents each of the 12 baseline scenarios listed in Table 4-1

k = each of the 9 management options described in Step 4

The differences computed for both average and minimum DOs ($DIFF_{(i, j, k)}$) were then added to all observed data using the association depicted in Table 4-3 to determine which computed difference should be added to each observation in the 24-hour dataset (e.g., the difference for the 2–9 May 2008 scenario would be added to all observational data collected in the months of May and April). For associations with two QUAL2K scenarios, the differences were averaged before adding occurred to the observational data.

Step 6 – Develop DO Exceedance Curves

As the final step in the evaluation of management options DO exceedance curves were developed to indicate the percentage of the time that average and minimum DO concentrations support (exceed) the appropriate numeric criterion. Separate exceedance curves were developed by processing the actual observational dataset without any management options (i.e., the baseline condition) and each of the adjusted observational datasets that reflect management options. The processing also occurs separately for the 24-hour average and minimum datasets. The process entails the following:

1. Organize the adjusted observational data from Step 5 into two unique datasets, one each for the 24-hour minimum DO data and the 24-hour average DO data, for the baseline condition and each of the 10 management options.

2. Rank the extracted values in each dataset from highest DO value to lowest value for the 99 data points comprising the dataset giving each value a rank n that ranges from 1 (highest) to 99 (lowest).
3. Determine the percent of the time that each value is exceeded by dividing the rank n by the number of values plus one (99 + 1 = 100) and multiply by 100 to get into percent.
4. Plot the 99 pairs of DO values and exceedance values with the x-axis as exceedance and the y-axis as the DO value.
5. The DO criterion intersection of the exceedance line provides the percent of time the DO criterion is met. Use 5.0 mg/L as the criterion for 24-hour average DO and 3.0 mg/L for the minimum DO.

Results from Evaluation of Management Options

Following the approach outlined above, the baseline condition was run for each of the 12 QUAL2K cases and then each of the management options were run for the 12 cases changing the input to QUAL2K as needed to reflect the conditions of that management option. DO exceedance curves were developed for the baseline condition and for each management option, including separate curves for 24-hour average and minimum DO. For comparison purposes the baseline exceedance curves are included with the exceedance curves for each management option in a series of nine figures, each containing two graphs - (A) the 24-hour average DO, and (B) the 24-hour minimum DO.

Because the DO in the Pecos River is only depressed for the 24-hour minimum DO criterion and not for the 24-hour average DO, the benefits of each management option may be summarized in tabular form evaluating only the 24-hour minimum DO (Table 4-7). Note that under baseline or existing conditions, the 24-hour minimum DO is attained 79 percent at FM 1776 of the time; thus falling short of the request goal of at least 90 percent attainment, 11 percent of the time.

Each management option is discussed briefly and results of the DO exceedance curve results are presented in the remainder of this chapter.

[Remainder of page intentionally left blank.]

Table 4-7. Summary of 24-hour minimum DO exceedance graphs for baseline and management option conditions considering the percent time the minimum DO criterion is obtained at FM 1776.

Management Option	Brief Description	Percent time 24-hr minimum DO ≥ 3.0 mg/L on Pecos at FM 1776
None	Existing baseline conditions	79.0
1	Malaga Bend Project (decreased salinity in Red Bluff Reservoir releases)	79.0
2	BBEST 50th percentile environmental flows applied April–October	83.6
3	BBEST 50th and 75th percentile flow selectively applied April–October	84.4
4	Decrease algal biomass 25% in summer in zone of impairment	85.2
5	Decreased sediment-water fluxes by 25%	85.0
6	Decreased Red Bluff Reservoir nutrients 50%	79.0
7	Added riffle 1.5 km (1 mile) above FM 1776 crossing of Pecos River	87.7
8	Combination of Management Options 3, 4 and 6	87.2
9	Combination of Management Options 2, 4 and 5	93.0
10	Combination of Management Options 3, 4, 5 and 6	96.0

Management Option 1 (the Malaga Bend Project to decrease headwater salinity concentrations) did not change the occurrences of depressed minimum DOs in the zone of impairment (Figure 4-2B). Salinity is a secondary factor governing DO concentrations (see Table 4-4) and the benefits of salinity reductions are further reduced because under normal growing-season hydrology in the Upper Pecos River little to none of the flow released from Red Bluff Reservoir passes the final turnout (Ward 2 Irrigation Turnout). Despite the insignificant benefits of Management Option 1 on Pecos River DO, there are other environmental and water-use benefits of reducing salinity in the Pecos River.

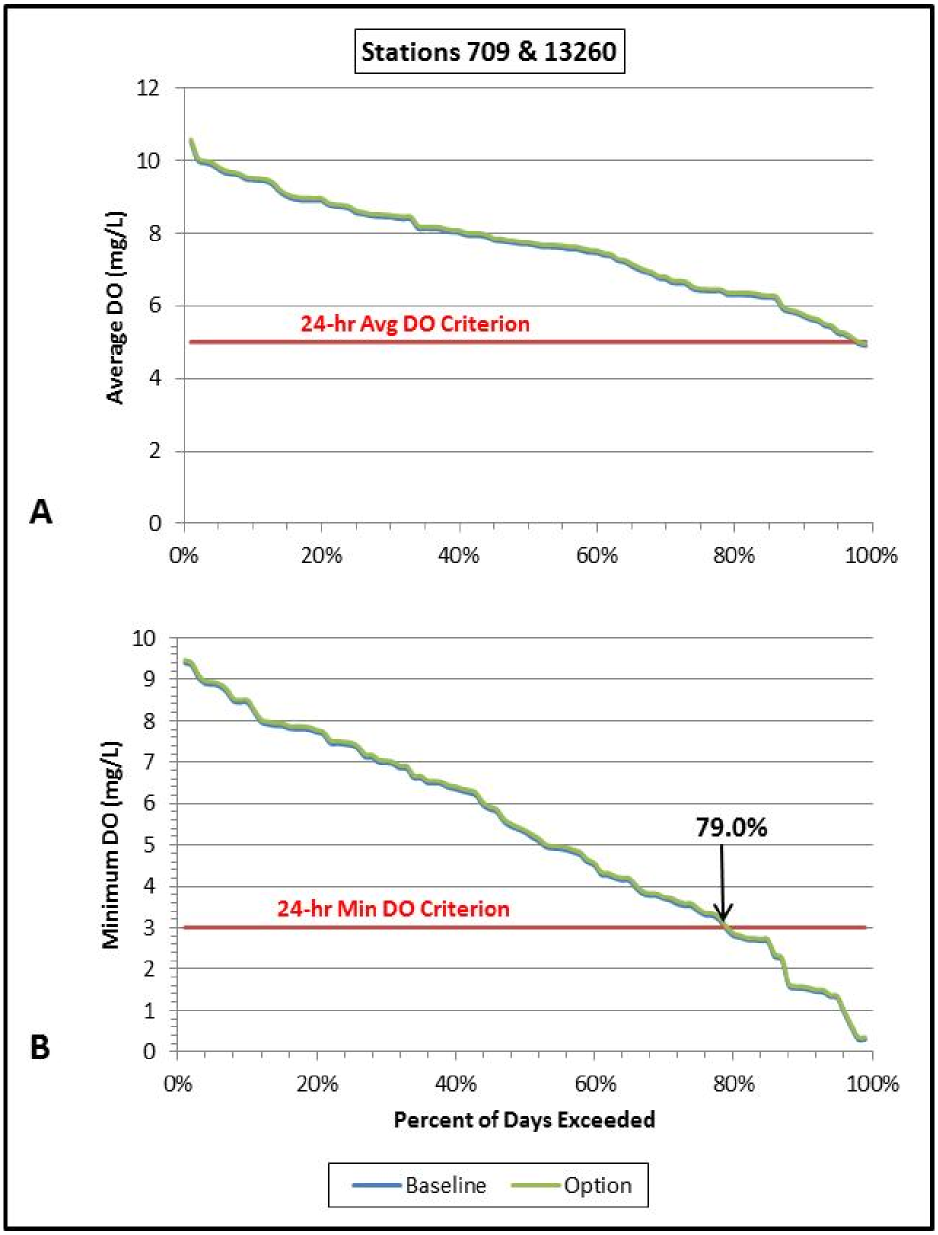


Figure 4-2. Management Option 1 (Malaga Bend Project) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 2 evaluated increasing streamflow in the zone of impairment to the 50th percentile values recommended by the BBEST during the months of April–October, when low DOs are most prevalent. This option did result in a predicted 83.6-percent attainment of the 24-hour minimum DO criterion, which still did not achieve the goal of 90-percent attainment (Figure 4-3B). Also note that this option has an insignificant impact on the average DO (Figure 4-3A).

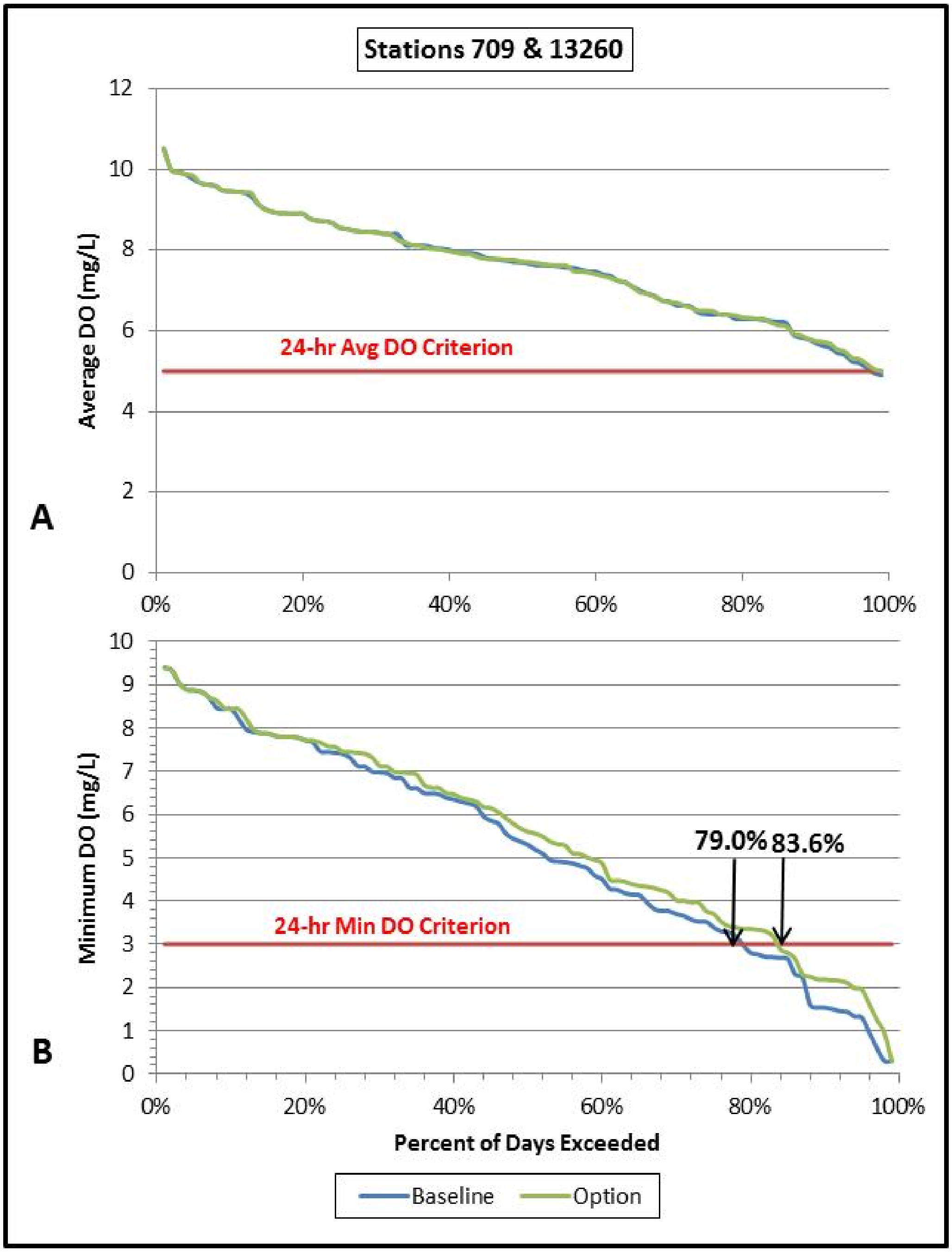


Figure 4-3. Management Option 2 (BBEST 50th percentile April –October) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 3 evaluated increasing streamflow in the zone of impairment to the 50th percentile values recommended by the BBEST during the months of April, May, September and October and to the higher 75th percentile recommendation for June–August. This option did result in predicting more than 84-percent attainment of the 24-hour minimum DO criterion, but the option still did not achieve the goal of 90-percent attainment (Figure 4-4B). As with Management Option 2, the average DO was insignificantly impacted by this option (Figure 4-4A).

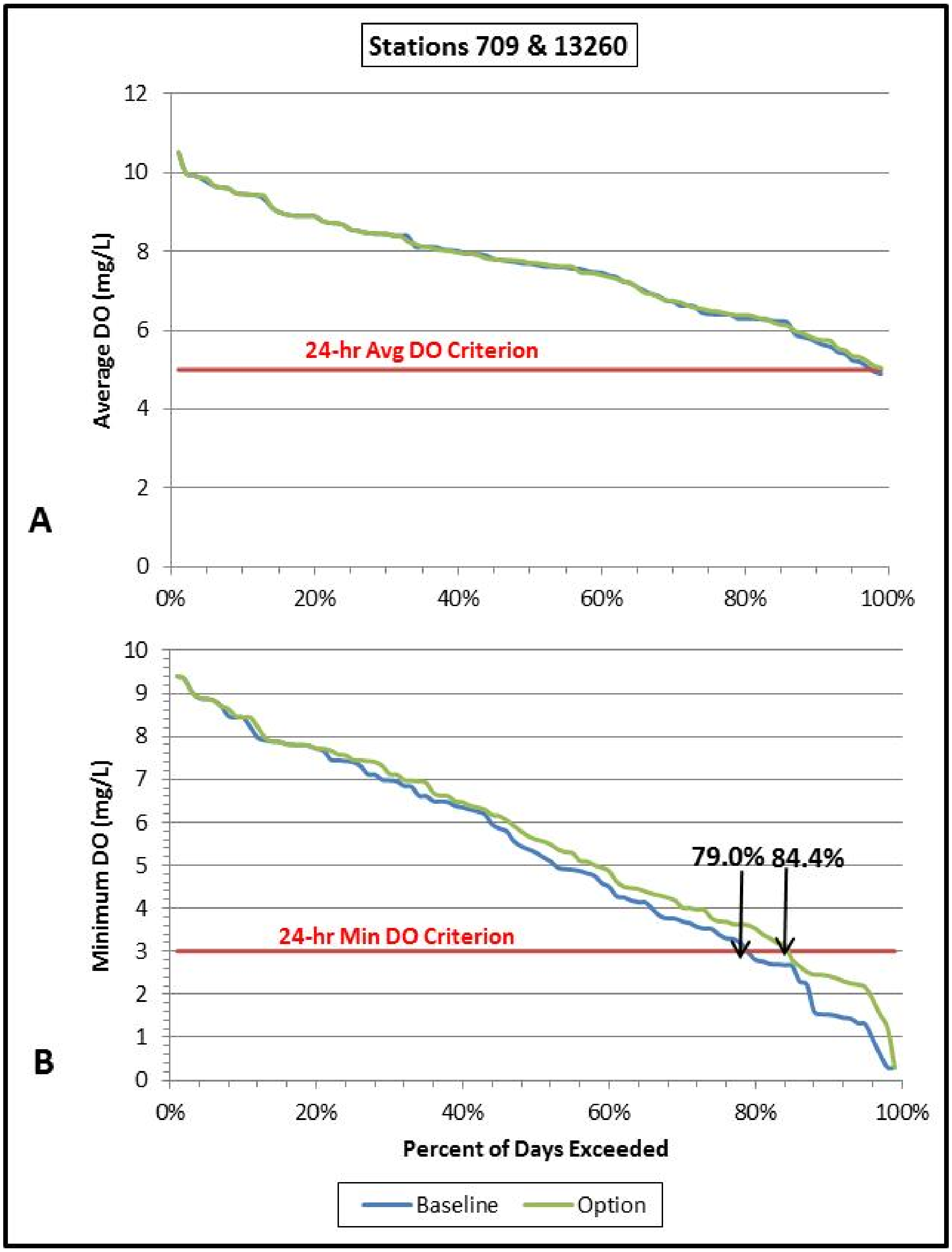


Figure 4-4. Management Option 3 (BBEST 50th & 75th percentile April–October) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Under Management Option 4 the effects on DO were evaluated for a 25-percent decrease in the periphyton biomass in the zone of impairment. Because the impairment is strongly associated with the abundance of attached algae (periphyton) in many reaches of the Upper Pecos River, this option resulted in attainment of the 24-hour minimum criterion over 85 percent of the time (Figure 4-5B). The reduction in algae biomass resulted in a decrease of daily DO range but kept the average 24-hour DO unchanged (Figure 4-5A).

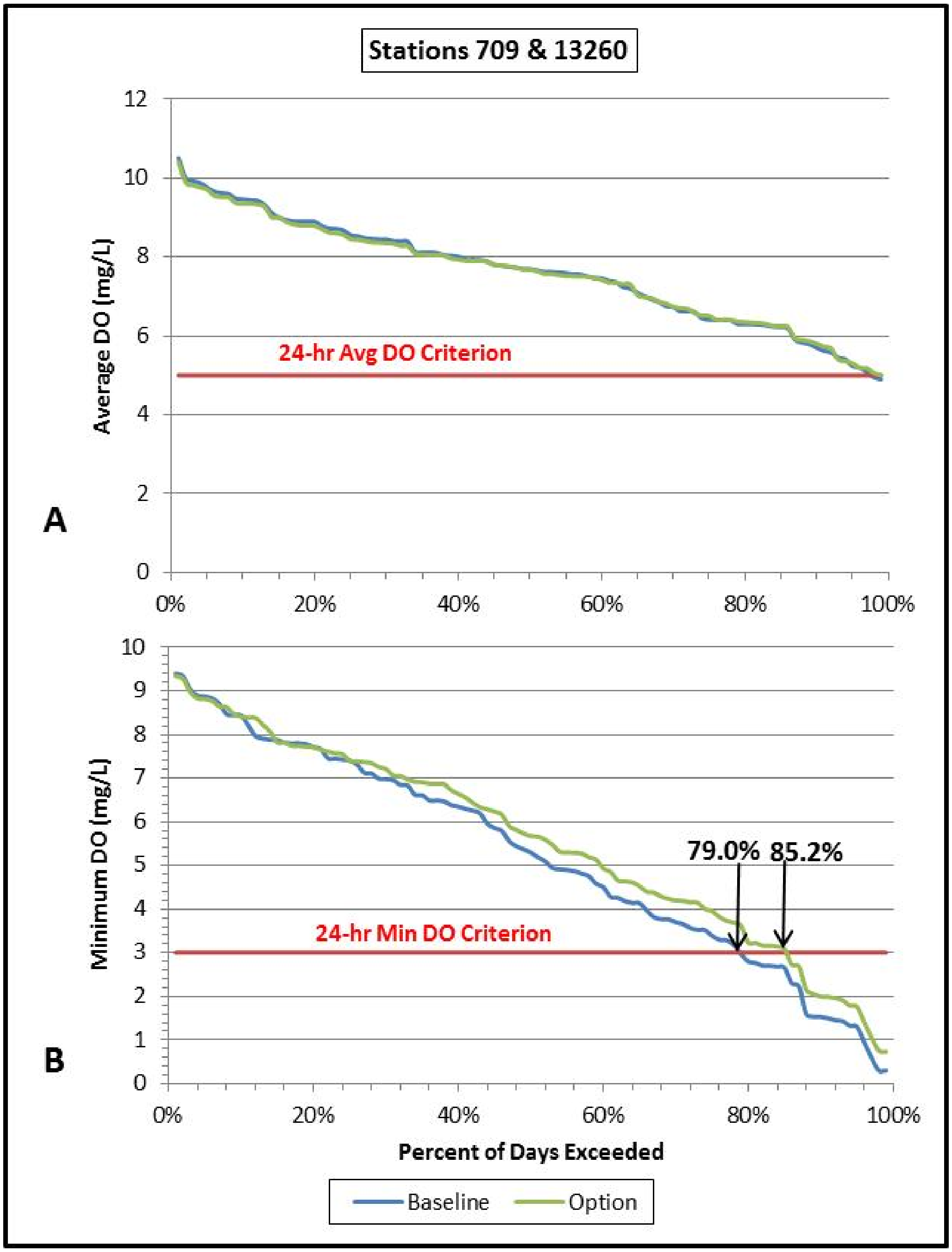


Figure 4-5. Management Option 4 (decrease periphyton biomass 25%) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 5 evaluated effects on DO by reducing SOD and nutrient releases (or fluxes) from the sediment by 25 percent. The predictions indicated an 85 percent attainment of the 24-hour minimum DO criterion at FM 1776 (Figure 4-6B). Similar to Management Option 4, this option resulted in a decrease in periphytic algae biomass, due to decreased nutrient availability from the sediment, and the reduction of SOD. Management Option 5 resulted in a slight increase in the average DO, which is only visible upon careful inspection of Figure 4-6A and comparison of it to its counterpart figures of average DO for the other management options. The reduction in SOD was the most likely causative factor in this slight increase in average DO.

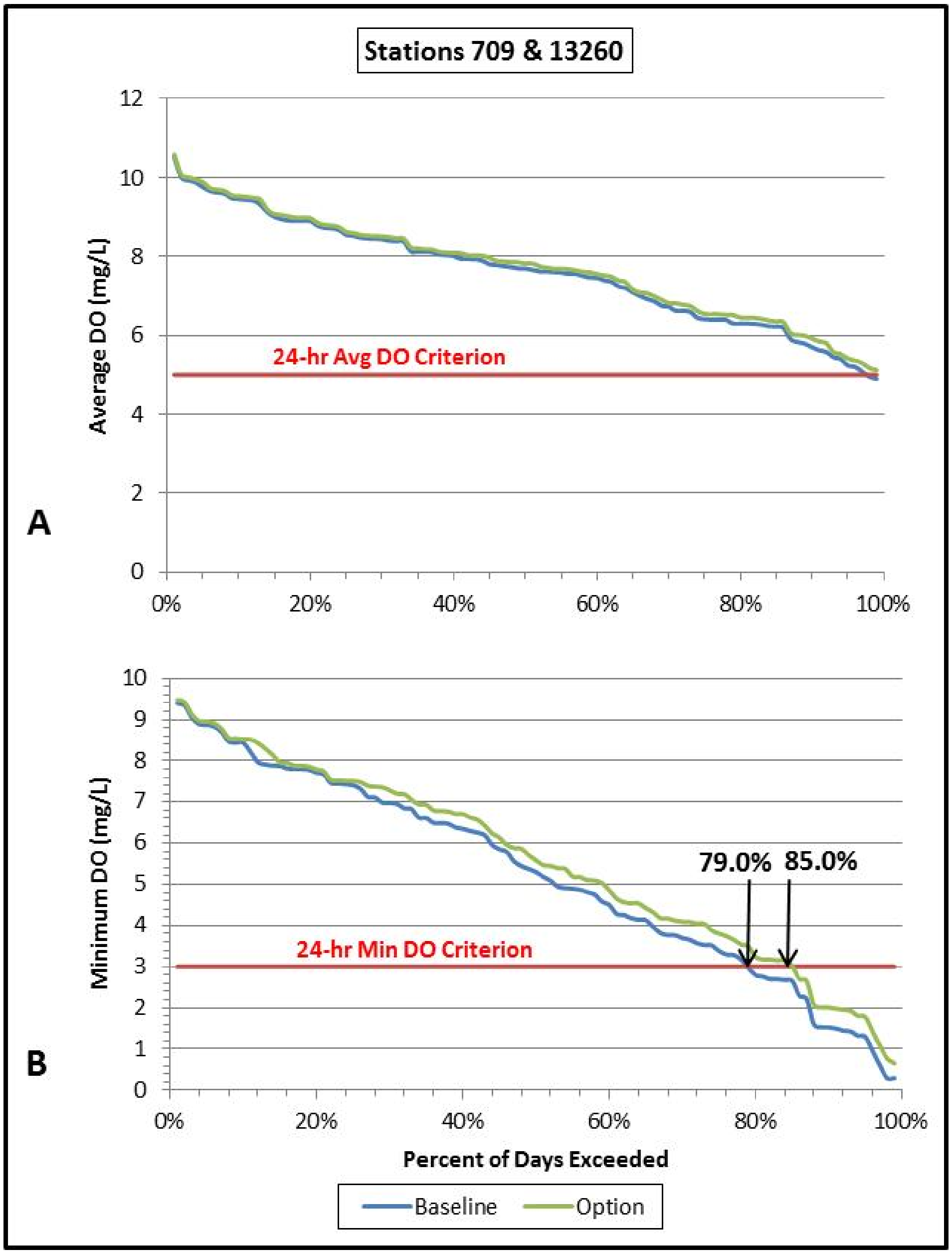


Figure 4-6. Management Option 5 (decreased SOD and sediment-flux of nutrients) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 6 evaluated changes in DO in the zone of impairment by reducing nutrient concentrations by 50 percent from Red Bluff Reservoir release. As already discussed in Option 1, under normal growing-season hydrology in the Upper Pecos River little to none of the flow released from Red Bluff Reservoir passes the final turnout (Ward 2 turnout). Despite the insignificant benefits to DO (Figure 4-7), this management option would most likely result in other environmental and water-use benefits to the reaches of the Pecos River close to the reservoir.

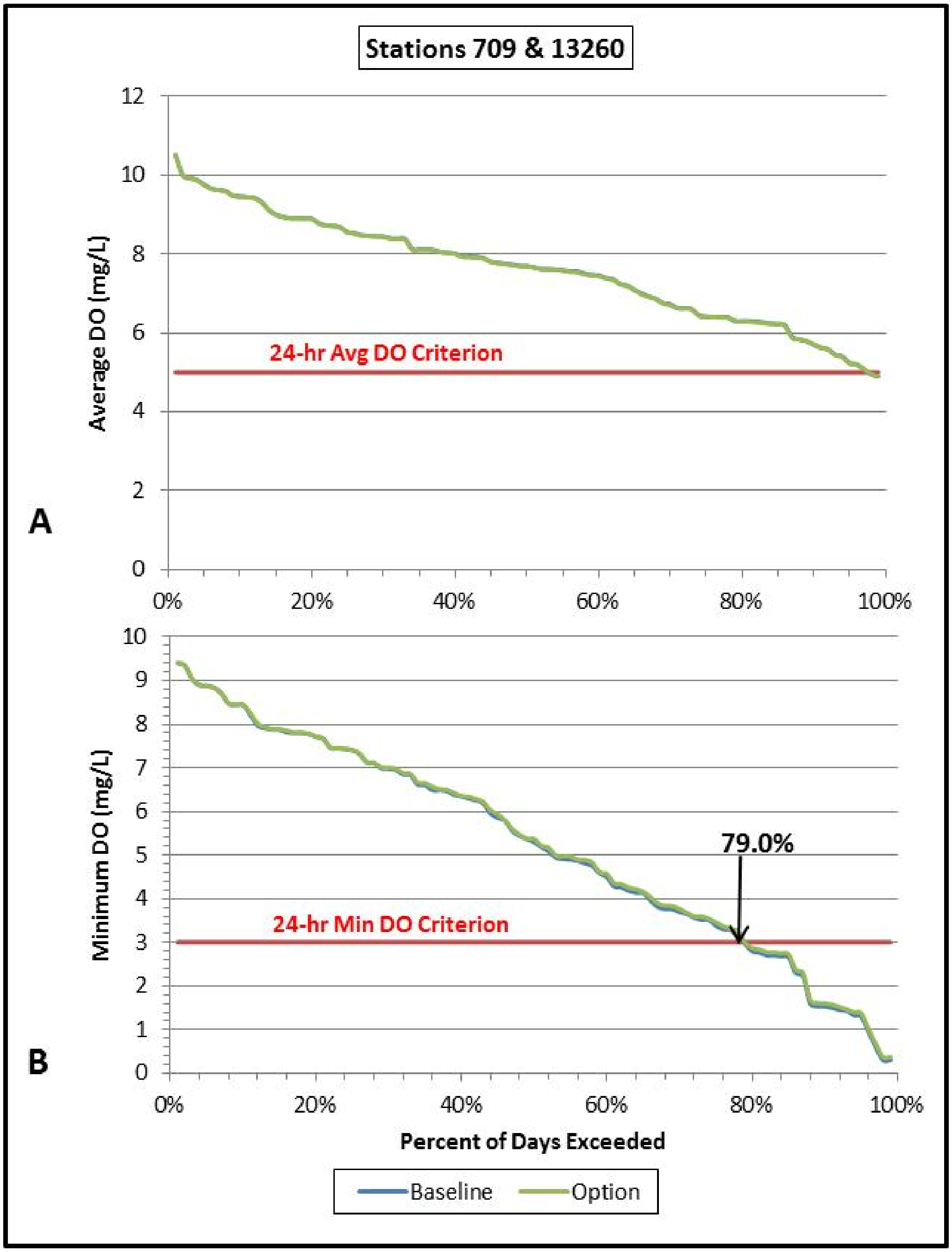


Figure 4-7. Management Option 6 (headwater nutrient reduction of 50%) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 7 evaluated a riffle structure placed 1.5 km (1 mile) above FM 1776. The riffle structure was considered to be a 1-meter (3-foot) high dam. The benefits from a riffle are much more pronounced for the minimum DO (Figure 4-8B) than the average DO (Figure 4-8A). The 24-hour minimum DO was improved to obtaining the criterion almost 88 percent of the time. To obtain DO improvement throughout the zone of impairment, multiple riffle structures would have to be installed along that entire reach. The low gradient of the bedslope of the Upper Pecos River can make placement of these artificial riffles difficult.

While perhaps somewhat counterintuitive, the greater benefit to the minimum DO over the average DO of Management Option 7 was driven by the mechanisms governing atmospheric reaeration; the process enhanced by a riffle structure. The actual flux of oxygen at the water-atmosphere interface is driven by several factors, and one of the primary factors is the difference between the saturation value of oxygen in the water and the actual DO concentration (DO_{sat} – DO_{water}). Therefore, the greater this difference, the greater is the flux of oxygen; all other factors remaining the same. In the zone of impairment for the warmer, biological most active months, during a single day the DO will range from low concentrations that are at times lower than the 24-hour minimum DO criterion to high concentrations greater than DO_{sat}. The 24-hour average DO is often relatively close to DO_{sat}. Since the flux of oxygen is greater the larger the difference between DO_{sat} and DO_{water}, the lowest DOs are increased, high DO concentrations above DO_{sat} will actually be decreased (oxygen will be released to the atmosphere), and the average will not be affected much.

For purposes of illustration, QUAL2K was run for the July 22–24, 2008 scenario with a series of 12 riffle structures, each represented by a 3-foot dam. Each structure was placed approximately 4.5 km (2.8 miles) apart in the model beginning just downstream of the Ward 2 Irrigation Turnout for the first structure and continuing downstream to the last structure. A comparison of the existing condition scenario (Figure 4-9A) and the condition with the series of riffle structures Figure 4-9B makes apparent some of the pros and cons of riffle structures. In Figure 4-9B, the coincident low values for maximum and average DOs with high values for minimum DO is the QUAL2K element with the dam. The structures are effective in increasing the 24-hour minimum DO appreciably; however, the benefits are restricted to a fairly short distance below the dam. The model simulation also depicted some decrease in the 24-hour average DO occurring in the deeper slower waters behind each dam.

[Remainder of Page Purposefully Left Blank]

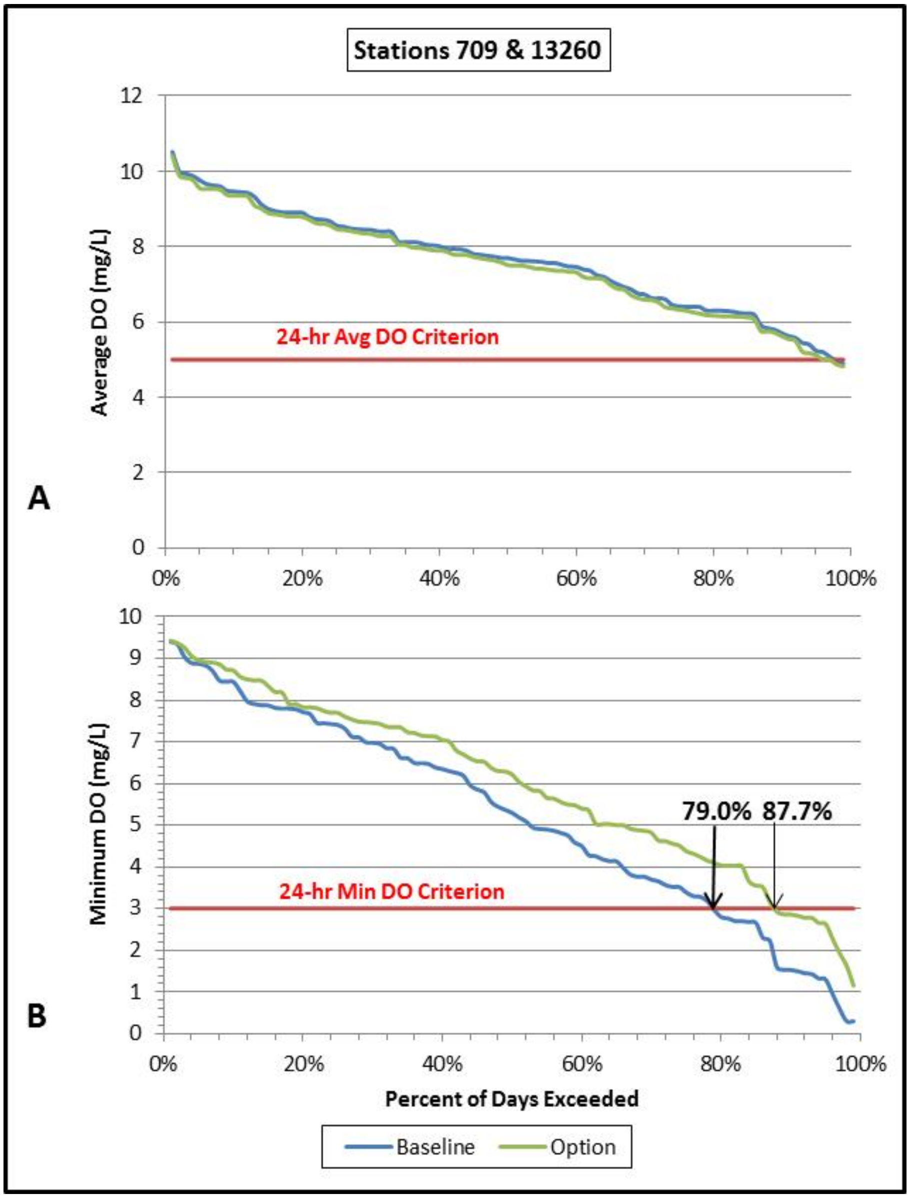


Figure 4-8. Management Option 7 (riffle structure added) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

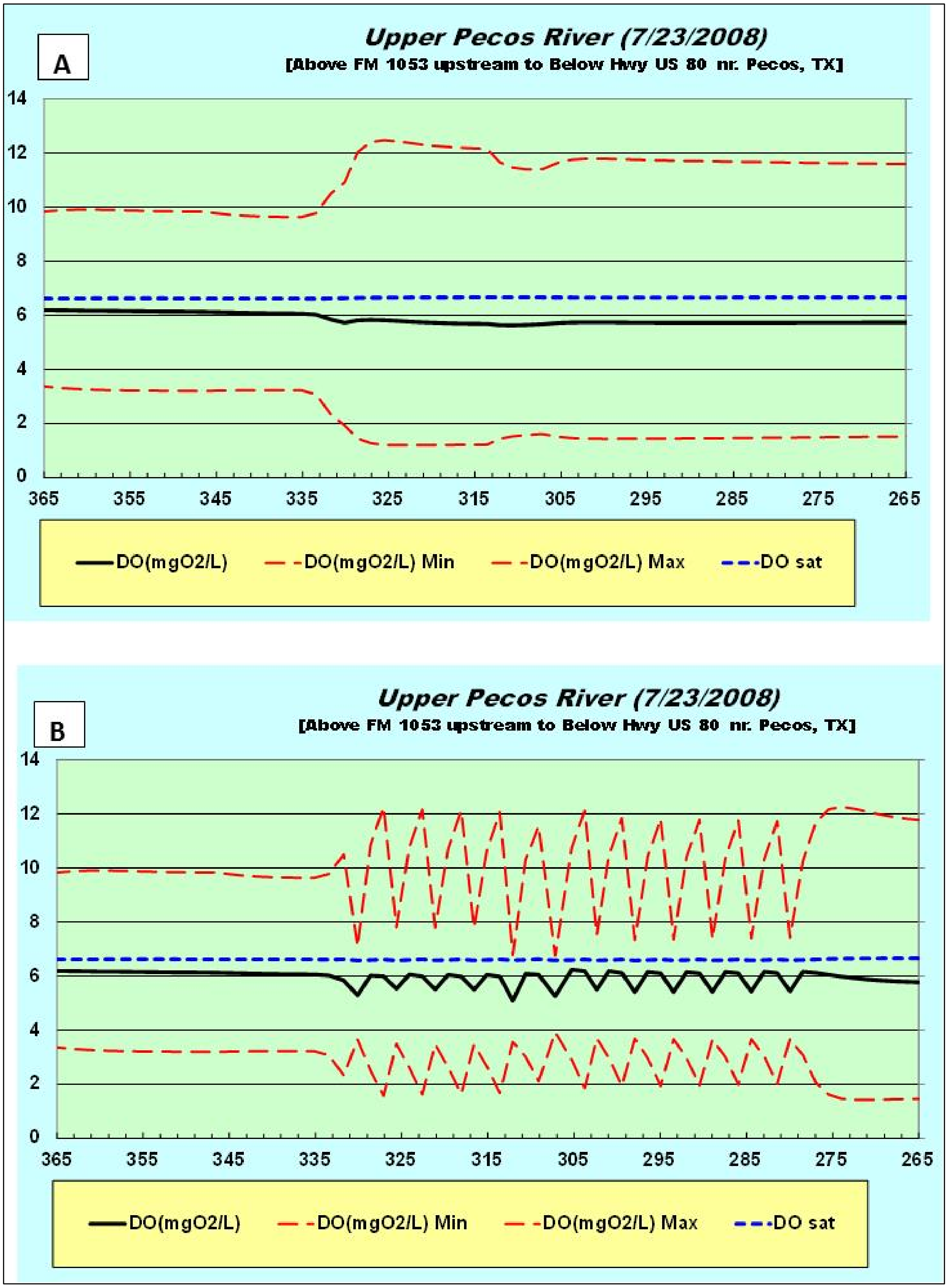


Figure 4-9. QUAL2K predictions of DO for the reach of the Upper Pecos River from Above FM 1053 (river kilometer 265) to Below Highway US 80 (river kilometer 365); (A) without riffle structures and (B) with riffle structures.

Management Option 8 combined Options 3, 4 and 6 resulting in little change to the average DO (Figure 4-10A), but increased the attainment of the minimum criterion to over 87 percent (Figure 4-10B). Management Option 8 included increasing streamflows in the zone of impairment to the 50th and 75th percentile recommendations of the BBEST, decreasing periphyton biomass by 25 percent, and as an additional part of the nutrient control program a 50-percent reduction in headwater nutrient concentration (releases from Red Bluff Reservoir). The reduction in nutrients in the releases from Red Bluff Reservoir are only a minor part of the success of this Management Option 8, which gets close to, but still falls short of, the 90-percent attainment requirement.

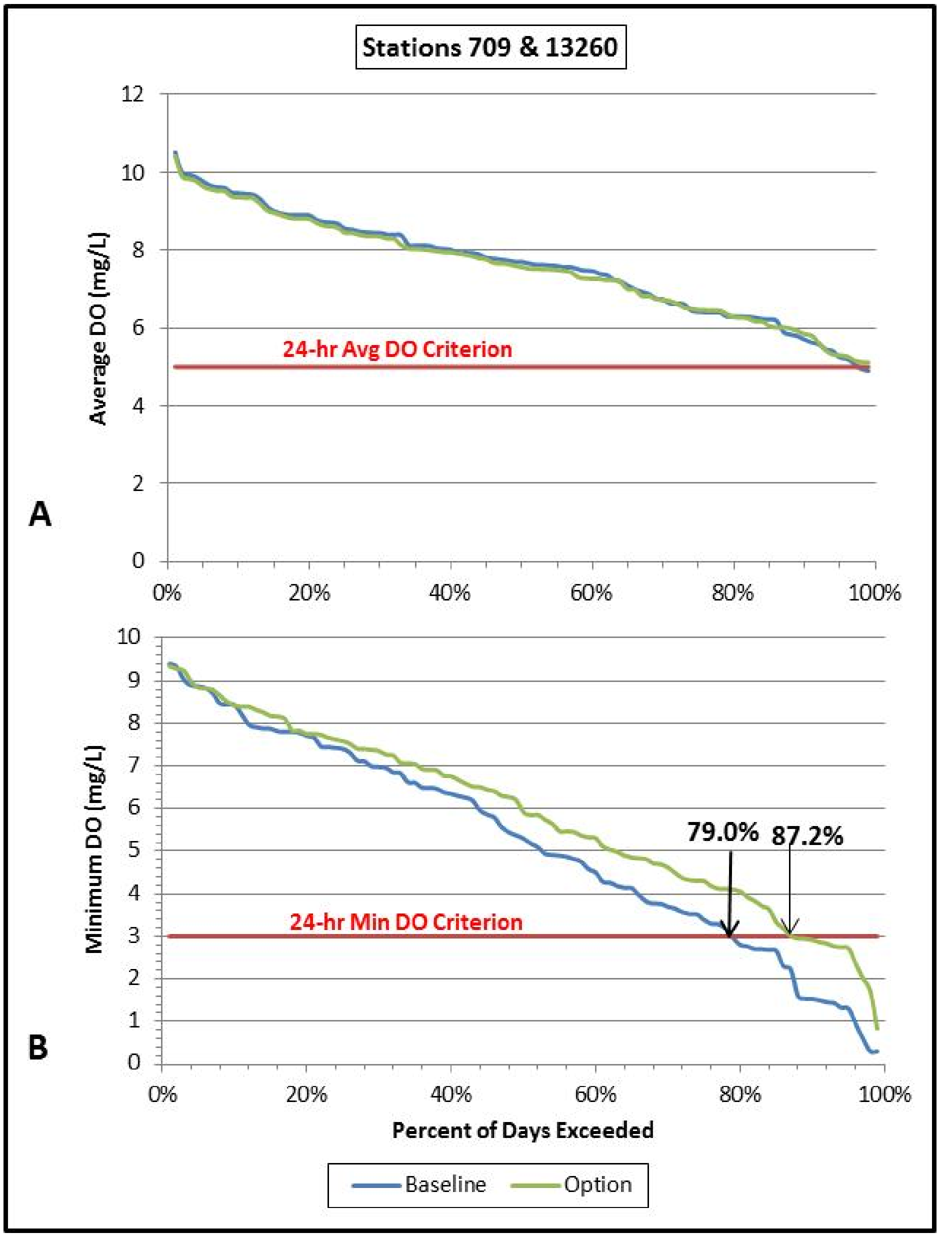


Figure 4-10. Management Option 8 (combine Options 3, 4 & 6) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 9 provided a combination of the various management options (combine Options 2, 4 and 5) achieving the requirement of at least 90-percent exceedance of the minimum DO requirement (Figure 4-11B). Management Option 9 included increasing streamflows in the zone of impairment to the 50th percentile recommendations of the BBEST, decreasing periphyton biomass by 25 percent, and reduction in sediment water fluxes by 25 percent.

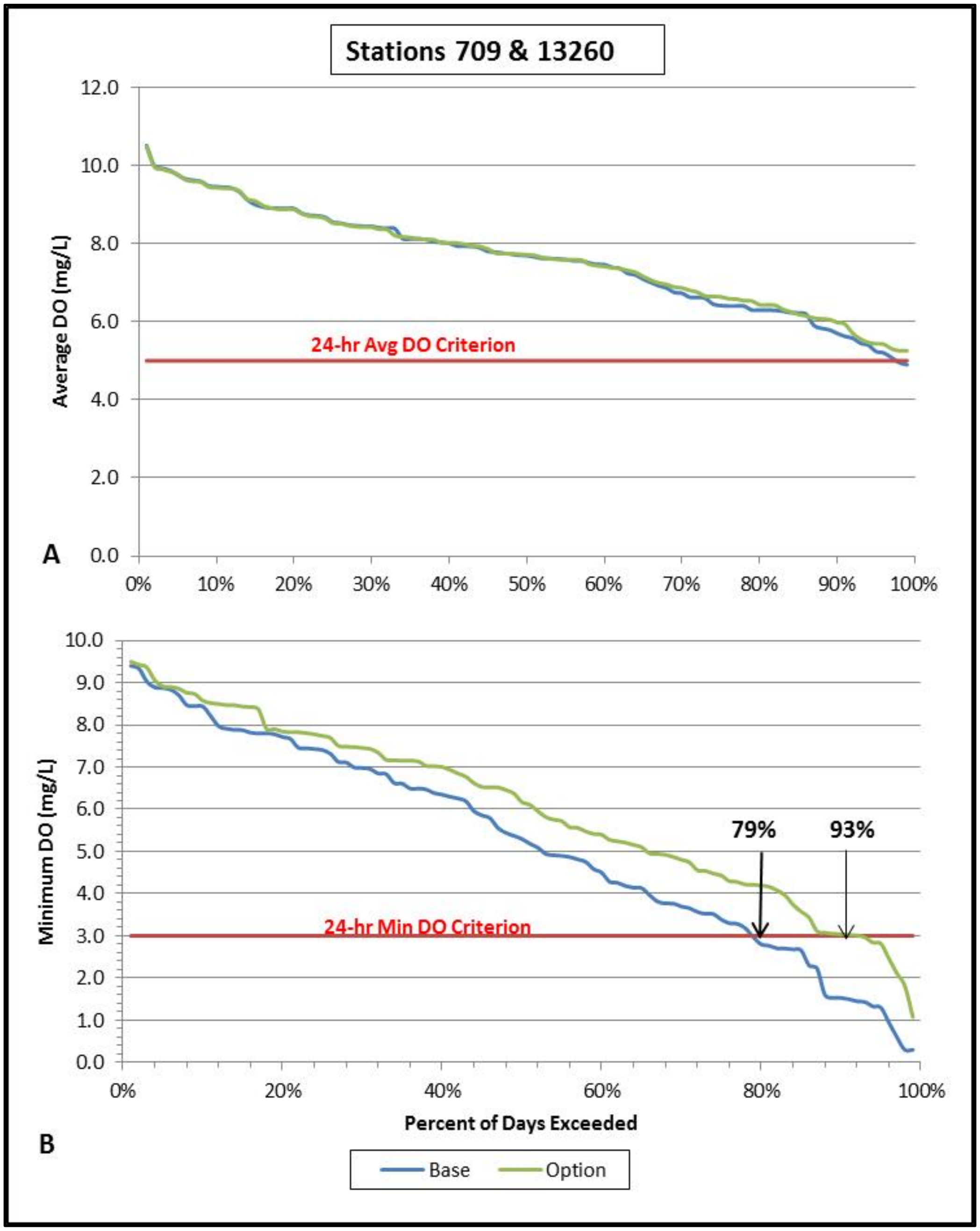


Figure 4-11. Management Option 9 (combine Options 2, 4, & 5) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Management Option 10 provided a combination of the various management options (combine Options 3, 4, 5 & 6) achieving the requirement of at least 90-percent exceedance of the minimum DO requirement. By adding a 25-percent reduction in SOD and nutrient releases to the suite of control measures in Management Option 8, this option is predicted to attain 96 percent of measurements above the requirement (Figure 4-12B).

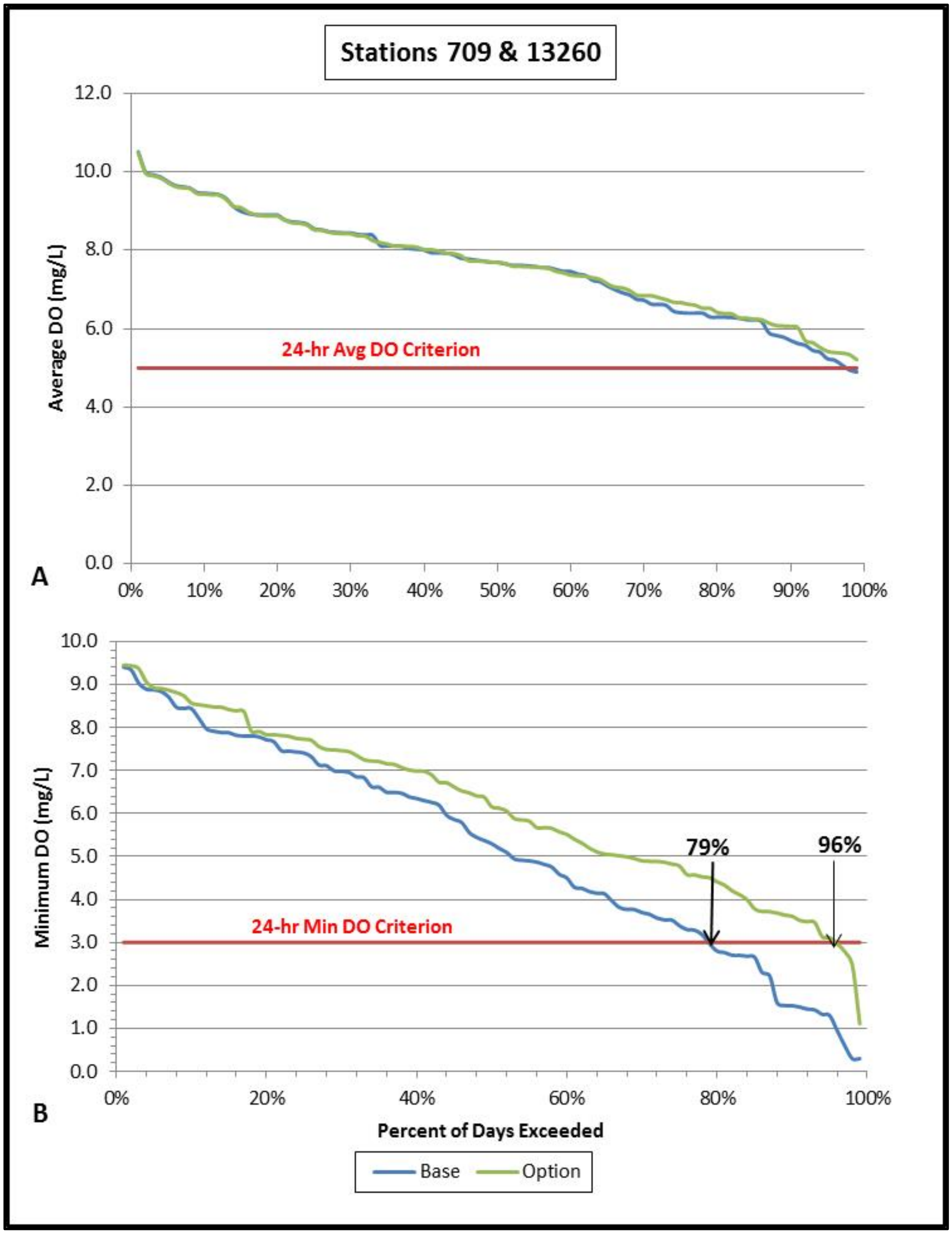


Figure 4-12. Management Option 10 (combine Options 3, 4, 5 & 6) exceedance curves at FM 1776 for (A) 24-hour average DO, and (B) 24-hour minimum DO.

Discussion of Management Options

This evaluation of various management options to restore DO in the Upper Pecos River has indicated that challenges will be faced to bring about restoration of the depressed levels in the zone of impairment. Impacts from decades of hydrologic modification of streamflows in the Upper Pecos River have resulted in portions of the river experiencing abundant sedimentation as well as prolific periphyton beds. The management options considered through application of QUAL2K are representative, though likely not exhaustive, of the various BMPs that could be considered to improve the depressed DO of the Upper Pecos River. While not exhaustive, the considered BMPs do encompass the predominate physical, chemical, and biological features of the Upper Pecos River that if improved would benefit the 24-hour minimum DOs experienced between the Ward 2 Irrigation Turnout and US Highway 67 (the zone of depressed DO). Measures to decrease salinities in the Pecos River represented here through Management Option 1 (Malaga Bend Project), while having positive benefits regarding water-use and various environmental benefits, do little to improve the DO. Only limited benefits will be realized through salinity reductions because salinity changes have only minor influences on oxygen saturation concentrations. Additionally, releases of the lowered salinity waters from Red Bluff Reservoir would not even reach the zone of depressed DO below the irrigation turnouts under normal flow conditions. Improving water quality in Red Bluff Reservoir by reducing nutrient concentrations, as considered in Management Option 6, also benefits water-use and the aquatic environment for those portions of the river influenced most directly and frequently by releases, but has no impact in the zone of depressed DO, which is again downstream of areas typically impacted by reservoir releases.

Streamflow increases during the warm season of April through October were considered under Management Options 2 and 3, with Option 3 defined to have the higher flows. These two options were based on the recommendations of the BBEST. While the BBEST recommendations may not be feasible, especially under the current drought influenced water shortage, these recommendations do represent a level of scientific inquiry into the streamflows needed to support the river's aquatic life community. Additionally, the BBEST results at least provide a basis for defining increased streamflow levels incorporated into the model. Both options indicated that increased streamflows during the warm season would increase concentrations in the zone of depressed DO but would not achieve the 90-percent attainment of the 24-hour minimum DO that is needed.

Adding some physical structures to provide additional riffles and enhanced reaeration was evaluated through Management Option 7. This BMP afforded potentially the greatest improvement of any single management option. However, this option suffers from at least two limitations. The first is that the DO improvement is localized to the areas immediately downstream of each structure and DO was not indicated to improve upstream of riffle structure or small dams consequentially leaving areas of depressed DO. Second, the gradient or bedslope of the Pecos River is slight in the zone of depressed DO meaning there may be physical limitations imposed that do not allow the needed close spacing of structures for the desired DO improvements.

Both the decrease in bottom algae biomass and reductions in SOD and nutrient fluxes from sediment to water as characterized in Management Options 4 and 5, respectively, afforded a little more improvement in DO concentrations than the options increasing streamflows. But neither Option 4 nor 5 was predicted to eliminate the depressed DO sufficiently to restore water quality. Both options also suffer from acceptable means of actually achieving the needed changes. Biological and chemical measures could be used to decrease algal biomass, but most likely at the expense of causing other environmental concerns. Decreased SOD and sediment-water fluxes of nutrients would seemingly require either much more frequent scouring high flow events than presently occur in the system or greater benefits from land management practices to reduce sedimentation than would likely occur to the degree needed in this area of low rainfall.

By combining various BMP options, the predicted results did indicate the possibility of reducing depressed 24-hour minimum DO occurrences to less than 10 percent of the time, which would restore DO to acceptable levels. The options considered in this study that achieved this goal are Options 9 and 10. Option 9 combined the increase in the streamflow (Option 2) with decrease in amount of bottom algae biomass and sediment water fluxes (Options 4 and 5). Option 10 was indicated to reduce the occurrences of depressed minimum DO even more than Option 9. Option 10 combined the higher streamflow increase (Option 3) with decreases in amount of bottom algae biomass and SOD (Options 4 and 5) and with decreases in reservoir nutrients (Option 6) included as a secondary factor. Therefore, these analyses indicated that a suite of combined BMPs will be needed to achieve desired improvements in DO.

The actual feasibility of each of these options was not considered when performing this analysis though inferences are made in these discussions as to the potential difficulties of actually implementing them.

CHAPTER 5

REFERENCES

BBESTs (Basin and Bay Expert Science Teams). 2012a. Environmental Flows Recommendations Reports by the Rio Grande, Rio Grande Estuary, and Lower Laguna Madre Basin and Bay Expert Science Teams. <http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/rgbbest_recs_combined.pdf>.

BBESTs (Basin and Bay Expert Science Teams). 2012b. Errata Sheet. <http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/urgbbest_errata.pdf>.

Bowie, G.L.,W.B. mills, D.B. Porcella, C.L. Campbell, J.R. Pagenhoff, G.L. Rupp, K.M. Johnson, P.W.H. Chan, S.A. Gherini, and C.E. Chamberlin. 1985. Rate, Constants, and Kinetics Formulations in Surface Water Quality Modeling (2nd Edition). EPA/600/3-85/040. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Athens, GA.

Butts, T.A. and R.L. Evans. 1978. Effects of Channel Dams on Dissolved Oxygen Concentrations in Northeastern Illinois Streams. (ISWS/CIR-132/78). Illinois State Water Survey, Urbans IL

Chapra. 2006. Personal communication with Dr. Steve Chapra, Tufts University, Medford, MA. May 10, 2006.

Chapra, S., G. Pelletier, and H. Tao. 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality (Version 2.11) Documentation. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Cleveland, K.D. 1989. Predicting Reaeration Rates in Texas Streams. Journal of Environmental Engineering. 115(3): 620-631.

Gregory, L. and W. Halter. 2008. A Watershed Protection Plan for the Pecos River in Texas. Investigating Agencies: Texas AgriLife Extension Service, Texas AgriLife Research, International Boundary and Water Commission (U.S. Section), and Texas Water Resources Institute. < http://pecosbasin.tamu.edu/media/5734/pecosriverwpp.pdf> accessed Feb. 4, 2013

Hart, C.R., L.D. White, A. McDonald, Z. Sheng. 2005. Saltcedar control and water salvage on the Pecos River, Texas, 1999-2003. *Journal of Environmental Management.* 75: 399-409.

Hatler, W.L. and C.R. Hart. 2009. Water Loss and Salvage in Saltcedar (*Tamarix* spp.) Stands on the Pecos River, Texas. *Invasive Plan Science and Management.* 2: 309-317.

Miyamoto, S., F. Yuan, and S. Anand. 2006. Reconnaissance Survey of Salt Sources and Loadings into the Pecos River. (TR 291), Texas Water Resources Institute, Texas A&M University System.

Miyamoto S., F. Yuan, and S. Anand. 2007. Water Balance, Salt Loading, Salinity Control Options of Red Bluff Reservoir, Texas (TR 298). Texas Water Resources Institute, Texas A&M University System.

NCDC (National Climatic Data Center). 2011. Sheffield COOP (ID 418252), <http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20024795> accessed October 3, 2011.

Sheng, Z., A.K. McDonald, C.R. Hart, W. Hatler, J. Villalobos. 2007. "Quantity and Fate of Water Salvage as a Result of Saltcedar Control on the Pecos River, Texas." Texas Water Resources Institute. TR-304.

TCEQ (Texas Commission on Environmental Quality). 2008. 2008 Water Quality Inventory and 303(d) List. < http://www.tceq.texas.gov/waterquality/assessment/08twqi/twqi08.html>. Accessed May 28, 2013.

TCEQ (Texas Commission on Environmental Quality). 2010a. Texas Surface Water Quality Standards, 2010 Rule Amendment, 30 TAC 307. Available online at: <www.tceq.texas.gov/assets/public/permitting/waterquality/standards/docs/TSWQS2010/TSWQS2010_rule.pdf > Accessed April 23, 2013.

TCEQ (Texas Commission on Environmental Quality). 2010b. 2010 Guidance for Assessing and Reporting Surface Water Quality in Texas. < http://www.tceq.texas.gov/assets/public/compliance/monops/water/10twqi/2010_guidance.pdf>. Accessed May 28, 2013.

TCEQ (Texas Commission on Environmental Quality). 2011. 2010 Texas Water Quality Integrated Report of Surface Water Quality for Clean Water Act Sections 305(b) and 303(d). <http://www.tceq.texas.gov/waterquality/assessment/10twqi/10twqi>. Accessed October 04, 2013.

TCEQ (Texas Commission on Environmental Quality). 2013. 2012 Texas Water Quality Integrated Report of Surface Water Quality for Clean Water Act Sections 305(b) and 303(d). < http://www.tceq.texas.gov/waterquality/assessment/waterquality/assessment/12twqi/twqi12>. Accessed October 04, 2013.

Thomann, R.V. and J.A. Mueller. 1987. Principles of Surface Water Quality Modeling and Control. Harper & Row Publishers, New York, NY

TNRCC (Texas Natural Resource Conservation Commission). 1995. QUAL-TX User's Manual. Version 3.4 Update December 1995. Austin, TX

TWRI (Texas Water Resources Institute) and TIAER (Texas Institute for Applied Environmental Research). 2010. Implementing the Pecos River Watershed Protection Plan through Continuous Water Quality Monitoring and Dissolve Oxygen Modeling. TSSWCB Project # 09-08, College Station, TX.