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Pollutant Loading and Dissolved Oxygen Dynamics in the Tidal Segment of the Arroyo Colorado

Segment 2201

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Introduction

Section 303(d) of the Clean Water Act requires all states to identify waters that do not meet, or are not expected to meet, applicable water quality standards. For each listed water body that does not meet a standard, states must develop a total maximum daily load (TMDL) for each pollutant that has been identified as contributing to the impairment of water quality in that water body. This document summarizes the results of a four-year study designed to establish a TMDL for constituents associated with low dissolved oxygen in the tidal segment of the Arroyo Colorado (Segment 2201).

In simple terms, a TMDL is a quantitative analysis that determines the amount of a particular pollutant that a water body can receive and still meet its applicable water quality standards. In other words, TMDLs are the best possible estimates of the assimilative capacity of a water body for a particular pollutant under consideration. When practicable, a TMDL is expressed as a load having units of mass per unit time, but a TMDL may also be expressed in other ways. TMDLs typically estimate how much a pollutant load needs to be reduced from current levels in order to achieve water quality standards.

The Total Maximum Daily Load Program, a major component of Texas' statewide watershed management approach, addresses impaired or threatened streams, reservoirs, lakes, bays, and estuaries (water bodies) in or bordering the state of Texas. The primary objective of the TMDL Program is to restore and maintain the beneficial uses (such as drinking water, recreation, support of aquatic life, or fishing) of impaired or threatened water bodies.

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (EPA) implementing regulations (40 Code of Federal Regulations, Section 130) describe the statutory and regulatory requirements for acceptable TMDLs. The TCEQ guidance document, *Developing Total Maximum Daily Load Projects in Texas* (GI-250, 1999), further refines the process for Texas. This report has been prepared in accordance with the guidelines specified in the two documents described above and is composed of the following six elements:

- Problem Definition
- Endpoint Identification
- Source Analysis
- Linkage Between Sources and Receiving Waters
- Margin of Safety

- Loading Allocation

Because of the uncertainty associated with the appropriateness of the water quality criteria currently used to assess the Arroyo Colorado and because the perceived dissolved oxygen impairment in the Arroyo Colorado is believed to be caused in part by physical modifications to the stream, the TMDL analysis presented in this report does not support do not support a quantitative, water quality target-based allocation of loadings of constituents associated with dissolved oxygen dynamics in the tidal segment of the Arroyo Colorado.

This report was prepared by the TMDL Team in the Strategic Assessment Division of the Office of Environmental Policy, Analysis, and Assessment of the Texas Commission on Environmental Quality. Contributors to the loading and dissolved oxygen dynamics investigation in the Arroyo Colorado include:

- Texas Institute for Applied Environmental Research
- Texas State Soil and Water Conservation Board
- Texas A&M University System
- United States Geological Survey
- Nueces River Authority

Background Information

The observed impairment addressed by this document is low dissolved oxygen in the upper reaches of the tidal segment of the Arroyo Colorado in south Texas (Segment 2201).

Dissolved oxygen is an essential biochemical attribute of all natural water bodies. The type(s) of aquatic ecosystem(s) a water body is capable of supporting depends in part on the amount of dissolved oxygen contained in the water body. Some aquatic ecosystems, such as mountain streams, support aquatic life that typically thrives in water containing consistently high levels of dissolved oxygen. Other natural water bodies, such as wetlands, tidal streams and estuaries, experience periodic episodes of depressed dissolved oxygen under natural conditions, but are also capable of supporting rich and diverse ecosystems. As a general rule, most estuarine animals can tolerate short exposures to reduced dissolved oxygen concentrations without apparent adverse effects. Prolonged exposures to moderate hypoxia, defined as DO levels below 5 mg/l, may result in altered behavior, reduced growth, adverse reproductive effects and possible mortality to sensitive species and juveniles (EPA 2002).

The Texas Surface Water Quality Standards (30 TAC §§307.1-307.10) specify the dissolved oxygen criteria that must be met for limited, intermediate, high, and exceptional aquatic life uses in water bodies of the state of Texas under minimal stress. The Arroyo Colorado, a tidal stream located on the Gulf coast of south Texas near the Rio Grande river, has been designated a high aquatic life use by the state of Texas and has an associated 24-hour average dissolved oxygen (DO) criterion of 4.0 mg/l and a 24-hour

DO minimum criterion of 3.0 mg/l. The Texas Surface Water Quality Standards also state that in tidal streams, such as the Arroyo Colorado, under conditions of density stratification, the DO criteria must be met in the mixed surface layer of the water column which is defined by the TCEQ as the vertical portion of the water column between the surface and the depth at which the conductivity of the water is 6,000 umhos higher than the conductivity at the surface.

The tidal segment of the Arroyo Colorado is currently included in the 2000 Texas Clean Water Act Section 303(d) List because dissolved oxygen concentrations in the upper 7.1 miles of the segment are sometimes lower than the criteria established to assure optimum conditions for aquatic life.

Current EPA guidance (*Draft Guidance for Water Quality-based Decisions: The TMDL Process, Second Edition, EPA 841-D-99-001, 1999a*) on the development of TMDLs offers flexibility in addressing particular situations and unusual circumstances, allowing states the discretion to adopt different approaches where appropriate. The guidance states that the allowable pollutant load "must be expressed in a manner ... that represents attainment and maintenance of water quality standards." The guidance allows for the use of alternative targets for situations where "no .... quantifiable pollutant load can be used to .... express the TMDL."

In preparing this report, the TCEQ has taken a pragmatic approach in determining the appropriate allocation of loadings of constituents associated with dissolved oxygen dynamics in the Arroyo Colorado.

As stated earlier, because of the complex interaction of physical and biochemical mechanisms involved in the dissolved oxygen dynamics of the Arroyo Colorado (i.e., natural tidal stream geomorphology, high degree of physical anthropogenic modification, dissolved and particulate organic and inorganic loadings, subtropical climatic setting, complexity and uncertainty associated with the cause-and-effect relationships associated with the observed impairment, and questions surrounding the appropriateness of the DO criteria currently applied to this and other tidal streams along the Texas Gulf Coast), the conclusions of this report do not support a quantitative, water quality target-based allocation of loadings of constituents associated with dissolved oxygen dynamics in the tidal segment of the Arroyo Colorado.

A factor of particular importance in this TMDL is the effect of physical, anthropogenic modification on DO dynamics in Segment 2201. In combination, physical modifications such as channel deepening and widening, placement of dredge spoils, and loss of riparian habitat have the effect of exacerbating low dissolved oxygen concentrations in the tidal portion of the Arroyo Colorado by reducing circulation, lowering reaeration rates and increasing sediment oxygen demand. The effect that this physical modification has on DO dynamics in the Arroyo is discussed in more detail in other sections of this document.

The ultimate goal of the analysis contained in this report is to provide the basis for developing a viable strategy to define, attain, and maintain DO criteria that are protective of the appropriate beneficial aquatic life use in the tidal segment of the Arroyo Colorado.

Problem Definition

The classified segments that comprise the Arroyo Colorado have consistently failed to meet the numeric criteria defined to support the designated uses established by the TCEQ as reported in the *Texas Water Quality Inventory* (305b report) and the *List of Impaired Waters* (303d list).

Since initial ecological surveys were conducted in 1966, there have been numerous documented manifestations of environmental stress in the Arroyo Colorado. Documented major fish kills occurred in 1971 (500,000 fish), 1981 (500,000 fish), and 1982 (120,000 fish). Fish kills of smaller magnitudes occurred in April and May of 1989, September 1990, June 1991, and June 1992 . More recently, massive fish kills (1,000,000 fish and above) have occurred in the Arroyo Colorado in 1997, 1998, and 1999 (TPWD 2002). A more detailed discussion of fish kill events in the Arroyo Colorado is provided in the section titled "Endpoint Identification."

Water Body and Watershed Description

The Arroyo Colorado extends 138 kilometers from the city of Mission, Texas, northeastward to the Laguna Madre; the entire watershed lies in the neotropical Southern Coastal Plain physiographic region and the Western Gulf Coastal ecoregion. Surface geology, in this area of south Texas, is dominated by Quaternary alluvial deposits. The flat terrain is extensively cultivated for agricultural purposes and considerable oil and gas activity also occurs in the area. Urbanization is extensive in the areas directly adjacent to the main stem of the Arroyo, particularly in the western and central portions of the watershed (including the cities of Mission, Mc Allen, Pharr, San Juan, Alamo, Donna, Weslaco, Mercedes, La Feria, Harlingen, San Benito, and Rio Hondo).

Originally a distributary channel of the Rio Grande River, the Arroyo Colorado has been extensively modified to carry flood water overflows to the Laguna Madre. The lower (tidal) portion of the Arroyo is also dredged to accommodate barge traffic to the Port of Harlingen.

Perennial flow in the Arroyo is sustained mainly by municipal discharges, with irrigation return flows and urban runoff supplementing the flow on a seasonal basis. The Arroyo serves primarily as a floodway, an inland waterway, and a recreational area for boating and fishing. The tidal reach also serves as an important nursery and foraging area for numerous marine fishes, shrimp, and crabs.

The Texas Commission on Environmental Quality (TCEQ) has classified two reaches of the Arroyo Colorado based on the physical characteristics of the stream. Segment 2201, from the port of Harlingen to the confluence with the Laguna Madre, is tidally influenced and has designated uses which include Contact Recreation and High Aquatic Life. The above-tidal segment of the Arroyo Colorado is classified as segment number 2202 and has designated uses which include Contact Recreation and Intermediate Aquatic Life. The Arroyo Colorado lies within Hidalgo, Cameron, and Willacy Counties, in the Nueces-Rio Grande Coastal Basin, which is located on the coastal plain between the Nueces River and the Rio Grande in the Lower Rio Grande Valley of south Texas (Figure 1):

- Segment 2202 (Arroyo Colorado above Tidal) extends from a point 100 meters downstream of Cemetery Road south of the Port of Harlingen in east-central Cameron County, upstream to Farm-to-Market (FM) Road 2062 near the City of Mission in south-central Hidalgo County. The segment includes the Main Floodway and Llano Grande Lake, but does not include the North Floodway.
- Segment 2201 (Arroyo Colorado Tidal) extends from the confluence with the Laguna Madre in Cameron/Willacy County to a point 100 meters south of the Port of Harlingen in Cameron. The segment includes the Port of Harlingen turning basin.

Figure 1. Arroyo Colorado Watershed

The Arroyo Colorado system is the major drainage for Cameron and Hidalgo Counties. The Arroyo consists of two major channels that drain a 2,344 square mile watershed (TWC 1990). The Main Floodway extends from the headwaters near the City of Mission in southwest Hidalgo County, to Llano Grande Lake southwest of the City of Mercedes in southeast Hidalgo County. Llano Grande Lake is a long, shallow depression that acts as a large settling basin, collecting much of the upstream sediment load.

The main channel of the Arroyo Colorado continues downstream from Llano Grande Lake, across southern and central Cameron County to the Port of Harlingen (UT PanAm 1995). The tidal portion of the Arroyo Colorado (Segment 2201) flows northeast from the Port of Harlingen, and discharges into the Laguna Madre. The main floodway and channel portion of the Arroyo Colorado, from the headwaters to the Laguna Madre, drain a 675 square mile watershed (TNRCC 2000).

The North Floodway splits from the Main Floodway of the Arroyo Colorado at the upper end of Llano Grande Lake. The vast majority of Willacy County drains to the North Floodway, as does a significant portion of northern and eastern Hidalgo County and a small portion of northwestern Cameron County. During flood conditions (flow >1,400 cubic feet per second), approximately 60 percent of the flow in the Arroyo is diverted into the North Floodway (TWC 1990).

The Arroyo Colorado lies in an extensive agricultural belt, where numerous crops are grown year-round, and where fertilizer and pesticide use is frequent. More than 90 percent of Hidalgo County and more than 80 percent of Cameron County are farm and ranch land (Garza 1999; Garza and Long 1999). The Arroyo Colorado watershed contains approximately 290,000 acres of irrigated cropland in these two counties. Primary agricultural crops include cotton, corn, grain, sorghum, sugar cane, citrus, and a variety of vegetables (TAES 2000).

Significant urbanization began in areas adjacent to the Arroyo Colorado in the late 1980s, particularly in the western and central portions of the watershed. The population in Hidalgo County more than doubled, while that of Cameron County nearly doubled, between 1970 and 1990 (Chapman et al., 1998). This urbanization trend has continued in the decade between 1990 and 2000 and is currently the principle trend in land use change in the Arroyo Colorado watershed. Perennial flow in the Arroyo begins at the City of Mission wastewater treatment plant (WWTP) discharge and is sustained primarily by municipal WWTP discharges with the seasonal addition of irrigation return flows and urban runoff (TWC 1989; Chapman et al., 1998). On rare occasions, flood water over-flows from the Rio Grande are diverted into the Main Floodway south of the City of Pharr. These infrequent diversion occur only during extreme flood events. Additionally, several industrial facilities discharge effluent into the Arroyo Colorado via municipal waste water treatment plants operated by several cities.

The Arroyo Colorado watershed is located in an economically distressed area of the state of Texas. Many communities within or adjacent to the Arroyo Colorado watershed lack basic water and wastewater infrastructure facilities. These communities, commonly known as “colonias,” are frequently found in many of the population centers located along the Texas-Mexico Border. Of the 1,200 colonias located along the US-Mexico border about 75 % are located in Lower Rio Grande Valley (TWDB 1996). It is widely believed that the lack of sanitary sewage, storm water discharge, and solid waste disposal facilities common to most colonias contributes significantly to the water quality problems in the Arroyo Colorado.

Review of Historical Water Quality

Over the last 20 years, the Arroyo Colorado has been a major focus of local concern regarding the quality of surface water in the Rio Grande Valley of south Texas. In a summary of testimony from hearings held jointly by the Lower Rio Grande Valley Development Council and the Southwest Center for Environmental Research and Policy in 1992 in Brownsville, Texas, water quality in the Arroyo Colorado featured prominently among the concerns of local residents along with concern over the ecological health of fish and shrimp nurseries in the Laguna Madre (SWCERP 1993).

In 1975, water quality modeling was performed on the Arroyo Colorado to evaluate the point source and nonpoint source effluent quality necessary to meet water quality goals (STRAAM Engineers 1975). Model simulations predicted depressed dissolved oxygen levels in the estuarine portion of the Arroyo (Segment 2201). Annual nonpoint source (NPS) loadings for biochemical oxygen demand (BOD) exceeded point source loadings. The report recommended non-structural NPS control measures be considered rather than expensive structural controls.

In 1977, the STORM (Storage, Treatment and Overflow) model was used to evaluate NPS load generation rates for water bodies in the Rio Grande Valley (LRGVDC, 1977). Both urban and agricultural waste loads were simulated. Although fairly high pollutant concentrations were noted during initial wash-off periods in some cases in the simulation, the report recommended that the relative magnitudes of NPS loads from specific sources be assessed further to accurately project water quality conditions.

Nitrogen, phosphorous, and suspended solids loads entering the Gulf of Mexico and the Laguna Madre from the Lower Rio Grande Valley area were sampled under a Clean Water Act (section 208) grant project completed by Black and Veatch in 1981. The results of the study indicate that concentrations of total Kjeldahl nitrogen, ammonia nitrogen, and nitrate nitrogen were greatest in the Arroyo Colorado. The study also reported that sufficient quantities of ammonia nitrogen existed to potentially yield toxic conditions. However, total phosphorous concentrations were reported to be uniformly low. The report went on to state that potential ammonia toxicity problems would be reduced by several mechanisms including conservative use of agricultural chemicals.

The TCEQ and predecessor agencies conducted intensive surveys in the Arroyo Colorado in 1976, 1982, 1983, 1987, 1994, 1995, 1996, 1998, and 1999.

The results of the initial intensive surveys conducted in the Arroyo Colorado in 1976 and 1982 indicated the following:

1. The Arroyo Colorado was unable to assimilate the waste load that it received without development of dissolved oxygen problems.
2. Oxygen depletion occurred below the City of McAllen sewage treatment plant (near Alamo, Texas) due to the presence of excessive oxygen demanding substances (a secondary, less intense oxygen sag also occurred below the City of Harlingen sewage treatment plant).
3. High primary productivity rates were observed in the Arroyo estuary. This seasonal eutrophic condition was attributed mainly to nutrient contributions from municipal discharges.
4. High algal metabolism resulted in wide diel oxygen fluctuations, periodic oxygen depletion, and occasional fish kills in portions of the tidal segment of Arroyo.

Other significant findings from the intensive surveys conducted in 1976 and 1982 included elevated “background” levels of nutrients (thought to be caused by agricultural runoff). However, the main contributor of nutrients as well as oxygen demanding compounds was identified as municipal wastewater discharges (TDWR 1978 and 1983).

Despite a 28% reduction in cumulative BOD_5 loading from the ten major dischargers, the results of the intensive survey conducted on the Arroyo Colorado in 1983 showed lower dissolved oxygen and poorer overall water quality than in previously conducted surveys. The report cited poor assimilative capacity resulting from low stream discharge and concomitant reductions in dilution of nutrients and oxygen demanding substances in addition to low atmospheric reaeration rates (TDWR 1985). Spatial data trends were, again, similar to previously conducted surveys.

Permit non-compliance is cited as one of the major components of the perceived waste loading problems in the Arroyo Colorado. Following 1983, many of the primary dischargers still routinely exceeded their BOD_5 and TSS limitations. More current data contained in from the Federal Permit Compliance System Database (PCS)shows strong evidence that this problem persists today. A Use Attainability Analysis (UAA) completed for the Arroyo Colorado in 1984 identified the major municipal dischargers in the watershed as the primary factor impacting water quality in the Arroyo Colorado (TDWR, 1984). Other findings of the UAA conducted in the Arroyo in 1984 include the following:

1. The Arroyo Colorado estuary is a naturally sensitive body of water with low assimilative capacity due to sluggish flow, low atmospheric reaeration rates, low volume of freshwater inflow, and saltwater intrusion/ salinity stratification.
2. Habitat complexity has been reduced in the tidal reach of the Arroyo Colorado by channel straightening.

3. Benthic conditions in the tidal reach of the Arroyo Colorado are less suitable for aquatic life due to stresses imposed by salinity stratification and periodic dredging of the navigation channel.

4. Turbidity is reduced in the tidal reach of the Arroyo Colorado due to the settling of suspended solids at the head of the estuary.
5. Although heavily influenced by human activity, the tidal reach of the Arroyo Colorado provides a fairly favorable habitat for estuarine life, particularly nekton.

In addition to conventional water quality parameters, the intensive survey conducted by the Texas Water Commission (now the TCEQ) on the Arroyo Colorado in 1987 included analysis of toxic substances in water, soil, and fish tissue, as well as toxicity testing on selected water samples (TWC 1989). The 1987 study concluded that the high aquatic life use designated for Segment 2201 was not being attained at the time the survey was conducted, but that toxic chemicals did not appear to be an important causative factor for non-attainment. Instead, the report cited periodic maintenance dredging, salinity stratification, and high primary productivity as potential stress-inducing factors which occasionally resulted in a disturbed benthic environment and depressed dissolved oxygen in bottom waters. Also mentioned in this 1987 report was the fact that the fine-particled substrate in Segment 2201 is very homogenous and is not conducive to colonization by diverse macrobenthic assemblages (TWC 1989). Surface DO concentrations measured during the 1987 intensive survey appeared adequate for maintaining the high aquatic life use designated for the tidal segment of the Arroyo Colorado (Segment 2201), but very low DO concentrations at the bottom of the water column, primarily due to natural conditions of periodic salinity stratification, acted to limit the kinds of benthic organisms that could exist at depth (TWC 1989). The report also concluded that toxic chemicals were contributing to a slight overall impairment of the intermediate aquatic life use designated for Segment 2202.

Another study conducted in 1989 by the National Oceanic and Atmospheric Administration (NOAA) identified the Lower Laguna Madre as being at the highest level of risk, or susceptibility, for eutrophication among all other bays and estuaries in the Gulf of Mexico (NOAA, 1992). The high inflow of nutrients from the mainland was cited as a potential cause. The report states that the Lower Rio Grande Valley watershed (which ends at the southwest boundary of the Lower Laguna Madre) is one of the most intensely farmed watersheds in Texas, with approximately 28% of the land area classified as cropland and approximately 72% of available cropland in active cultivation.

In an effort to define wastewater treatment levels and effluent limitations for the Arroyo Colorado, the Texas Water Commission (TWC) completed a waste load evaluation for the stream in 1990. The report classified both segments (2201 and 2202) of the Arroyo Colorado as “Water Quality Limited”, meaning that performance-based effluent limits alone would be sufficient to attain and maintain the DO criteria associated with the designated use specified in the Texas Water Quality Standards (TWC 1990). In addition to the conclusions listed above, the 1990 TWC waste load evaluation report recommended modification of the wastewater discharge permit held by the City of McAllen to reflect the implementation of “advanced treatment with nitrification.”

Among the conclusions of the waste load evaluation report were the following:

1. High-end fecal coliform values measured in the Arroyo Colorado suggested the possibility that discharges of essentially untreated sanitary wastewater were occurring.
2. The impact of irrigation return flows on overall water quality in the Arroyo Colorado was qualitatively determined to be significant.
3. Photosynthesis and associated eutrophication appeared to contribute significantly to the BOD and dissolved oxygen concentrations found in the stream.

The overall objective of the intensive surveys conducted in the Arroyo Colorado in 1994, 1995, and 1996 was to predict the long-term effects of aquaculture facilities which applied for permits to discharge directly into the Arroyo Colorado near the confluence with the Laguna Madre (at Arroyo City). Consequently, the studies were designed primarily to assess water quality in the lower portions of the tidal segment (2201) at Spring and Summer low (freshwater) inflow conditions. However, as part of the study, mid-channel water quality profile measurements were conducted at 2-km intervals throughout the entire tidal segment up to the port of Harlingen.

During the three intensive surveys conducted between 1994 and 1996, a high degree of salinity stratification was noted throughout the entire tidal segment with the largest conductivity gradients occurring in the upper portion of tidal segment. Twenty-four hour dissolved oxygen(DO) measurements conducted near Arroyo City during the August 1996 intensive survey did not meet the established criterion for tidal streams (24- hour DO average was below the 4.0 m/l criteria) and, on all three surveys (1994-96), instantaneous DO values, measured in the mixed surface layer during the collection mid-channel profile data, also exceeded the 24hr criterion. Low instantaneous DO readings in the mixed surface layer were, again, most frequently observed in the upper portion of the tidal segment above and below Rio Hondo.

In addition to low DO values and high degree of salinity stratification, the results of the surveys conducted in 1994, 1995, and 1996 also showed elevated levels of ammonia nitrogen and chlorophyll *a* throughout the entire tidal segment. Nitrate plus nitrite, orthophosphate and total phosphorus concentrations were found to be at or only slightly above background levels.

Early state-wide water quality assessments and water body inventories conducted by the state of Texas (i.e 1986 Segment Rankings) classified both segments of the Arroyo Colorado (Segment 2201 Arroyo Tidal and Segment 2202 Arroyo Above Tidal) as Water Quality Limited. Although the assessment methodologies used to create these early lists placed less emphasis on observed water quality than the assessment methodologies used in more recent years, a review of water quality data prior to 1986 showed low DO values were a common occurrence in the lower portion of Segment 2202 and upper portion of Segment 2201. Subsequent segment water quality inventory and rankings conducted in by the Texas Water Commission in 1992 and 1994 (1992 and1994 State of Texas §303(d) List) included only the above tidal segment of the Arroyo Colorado (Segment 2202) as impaired. However, among the pollutant or stressors cited for Segment 2202 were low DO and excessive levels of nutrients (Table 1).

In a 1994 TNRCC Clean Rivers Program report titled “Regional Assessment of Water Quality in the Rio Grande Basin,” a “concern” for nutrients was identified for the Arroyo Colorado and the North Floodway. A “concern” and a “possible concern” were also identified for dissolved oxygen for Segments 2201 and 2202 respectively. In addition, “possible concerns” were identified for fecal coliform in Segment 2202 (determined under low flow conditions) and for ammonia nitrogen for the Lower Laguna Madre (TNRCC 1994). The follow-up 1996 TNRCC Clean Rivers Program report on Regional Water Quality in the Rio Grande Basin again identified a “concern” for nutrients for Segment 2201 (TNRCC 1996).

The TNRCC included both segments of the Arroyo Colorado (Segments 2201 and 2202) in the State of Texas 1996 Clean Water Act (CWA)303(d) List. In this (1996) list of impaired water bodies, only Segment 2201 (the upper 8.5 miles) was listed for non-support of aquatic life use due to depressed dissolved oxygen concentrations.

In 1998, Segment 2201 was again listed for depressed dissolved oxygen concentrations in the State of Texas 1998 CWA Section 303(d) List. The 1998 303(d) listing of Segment 2201 was essentially a “carry-over” from the 303(d) listing in 1996 since the 305(b) assessment conducted by the TNRCC in 1998 did not include reassessment of water bodies in the Nueces-Rio Grande Coastal Basin (Table 1).

Shortly after completion of the Texas 1998 Clean Water Act Section 303(d) List, the TNRCC began efforts to develop a TMDL for constituents associated with the DO impairment observed in Segment 2201. As part of this effort, two additional intensive surveys were conducted in the Arroyo Colorado to gain a clearer understanding of the physical and chemical factors associated with the dissolved oxygen dynamics in the zone of impairment and to provided additional data for calibration of a watershed loading model and an in-stream water quality model. The first of these two surveys was conducted under low flow conditions (≅100 cfs measured at Harlingen) in June of 1998. The second survey was conducted under moderate to high flow conditions (≅500 cfs measured at Harlingen) following a short rainfall event which occurred in March of 1999.

Although the results of the 1998 intensive survey of the Arroyo Colorado showed similarities to those of earlier intensive surveys (i.e., low DO and high salinity stratification), overall water quality in the stream was the worst ever measured in any synoptic study conducted in the Arroyo Colorado. Diel DO measurements conducted at the Port of Harlingen and at Rio Hondo met neither the 24-hour average DO criterion (4.0 m/l) nor the minimum DO criterion (3.0 m/l measured over a consecutive 8 hr period). Instanta-

Table 1. Historical listing of the Arroyo Colorado in the Texas §303(d) list and precursor state-wide Clean Water Act-mandated water quality and water body inventory lists.

Segment Number	Date of Listing	Portion of Segment listed	Description of Impairment	Parameter(s) Listed	Ranking (Number) or Priority
2201	1986	Entire Segment	Water Quality Limited	N/A	14
2201	1996	Upper 8.5 Miles	The aquatic life use is not supported in the upper 8.5 miles due to depressed dissolved oxygen concentrations	Dissolved Oxygen	Medium
2201	1998	Upper 16 Miles	Dissolved oxygen Concentrations are sometimes lower than the standard established to assure optimum habitat for aquatic life.	Dissolved Oxygen	TMDL Underway
2201	1999	Upper 7.1 Miles	In the upper 7.1 miles of the segment, dissolved oxygen concentrations are sometimes lower than the standard established to assure optimum conditions for aquatic life. Sediment toxicity occasionally exceeds the screening levels.	Dissolved Oxygen, Sediment Toxicity	TMDL Underway/ Medium
2201	2000	Upper 7.1 Miles	In the upper 7.1 miles of the segment, dissolved oxygen concentrations are sometimes lower than the criterion established to assure optimum conditions for aquatic life. Significant effects in ambient sediment toxicity tests sometimes occur.	Depressed Dissolved Oxygen, Toxicity in Ambient Sediment	High
2202	1986	Entire Segment	Water Quality Limited	N/A	21
2202	1992	Entire Segment	High Point Sources, Eutrophication, Toxics	Toxics, High Algae, Nutrients, Fecal Coliform, Chlorides	Not Assigned
2202	1994	Entire Segment	Ambient Toxicity; High Algae, Fish Fills	Dissolved Oxygen, Ammonia plus Nitrate Nitrogen, Phosphorus, Chlorides, Fecal Coliform	High

Segment Number	Date of Listing	Portion of Segment listed	Description of Impairment	Parameter(s) Listed	Ranking (Number) or Priority
2202	1996	Entire Segment	The Texas Department of Health (TDH) issued an all fish restricted consumption advisory for the general population in September 1980, due to elevated levels of chlordane, toxaphene, and DDE in fish tissue. The aquatic life use is only partially supported in the lower four miles due to elevated concentrations of nitrobenzene, isophorone, and bis (2-ethylhexyl) phthalate. The contact recreation use is not supported through the entire segment due to elevated fecal coliform bacteria levels.	Chlordane, Toxaphene, DDE, Nitrobenzene, isophorone, bis (2-ethylhexyl) phthalate, Fecal Coliform	Medium
2202	1998	Upper 7.1 Miles	The Texas Department of Health (TDH) issued a restricted consumption advisory for the general population in September 1980, due to elevated levels of chlordane, toxaphene, and DDE in fish tissue. Bacteria levels sometimes exceed the criterion established to assure the safety of contact recreation.	Chlordane, Toxaphene, DDE, Fecal Coliform	TMDL Underway
2202	1999	Entire Segment	Fish consumption is not supported, based on a non-consumption advisory issued by the Texas Department of Health in 1evels of chlordane, toxaphene, and DDE in fish tissue. In the lower 40 miles, bacteria levels sometimes exceed the criterion established to assure the safety of contact recreation.	Chlordane, Toxaphene, DDE, Fecal Coliform	Low/ TMDL Underway
2202	2000	Entire Segment	Fish consumption is not supported, based on a non-consumption advisory issued by the Texas Department of Health in 1evels of chlordane, toxaphene, and DDE in fish tissue. In the lower 40 miles, bacteria levels sometimes exceed the criterion established to assure the safety of contact recreation.	Chlordane, Toxaphene, DDE, Fecal Coliform	High

neous DO values measured in the mixed surface layer during the collection of profile data were below the 24hr standard at 4 of the 12 tidal stations. All low instantaneous DO readings measured during the survey were confined to the zone of impairment (above and below Rio Hondo). Additionally, low instantaneous DO measurements and high chlorophyll *a* concentrations observed in the above-tidal segment (2202) provided strong evidence of eutrophication in the middle and lower reaches of the above-tidal segment of the Arroyo Colorado (Segment 2202). Nutrient values were also uniformly high in Segment 2202 but decreased significantly near the confluence of tidal segment. Ammonia nitrogen, nitrate plus nitrite nitrogen, orthophosphorus, total phosphorus, and chlorophyll *a* remained elevated in the uppermost portion of Segment 2201 coinciding geographically with the zone of impairment.

The main objective of the high-flow intensive survey conducted in the arroyo Colorado in March of 1999 was to obtain information about the incremental loadings of nutrients, sediment, and oxygen demanding substances received by the Arroyo Colorado at distinct locations along the length of the Arroyo Colorado (Segments 2201 and 2202) before, during, and immediately after a measurable runoff event. The sampling locations were chosen to coincide with sub-basin boundaries defined by separate "pour points" within the watershed. Additionally, in-stream flow and water quality measurements made simultaneously at several stream locations at different points in the hydrograph provided a snapshot of the physical and chemical conditions associated with the moderate rainfall-runoff event of March 30, 1999 in the Arroyo Colorado watershed.

Typically, detailed high-flow loading studies involve the collection of data from several rainfall-runoff events using automated samplers. However, due to time and resource constraints, the intensive survey described above was the only detailed high-flow data collection event conducted in the Arroyo Colorado as part of the TMDL effort. Unlike most high flow studies, the March 1999 high flow intensive survey of the Arroyo Colorado included tidal flow and vertical profile measurements conducted simultaneously at different locations in the water body, at distinct times in the hydrograph. Although snapshots in time, the similarity in sampling methodology of the 1999 high-flow
intensive survey to that of the 1998 low-flow survey provides a direct and detailed comparison of physical and chemicals conditions in the stream during two very different flow conditions.

Lower average conductivities and higher DO values were observed during the 1999 high-flow intensive survey in both segments of the Arroyo Colorado due to increased freshwater inflows and greater degree of vertical mixing, especially in the tidal portion of the stream. Unlike previous surveys, sharp changes in conductivity with depth were only evident in the middle and lower portions of Segment 2201 as the mixed surface layer extended vertically to four meters in the upper portion of the tidal segment and approximately two meters in the middle portions of the tidal segment. Although all DO values measured during the 1999 high-flow event were above the established criterion and phosphorus and chlorophyll *a* concentrations were generally much lower, ammonia and nitrate plus nitrite nitrogen concentrations exceeded screening criteria and were significantly higher than those observed during the 1998 low-flow intensive survey. Average concentrations of five-day carbonaceous biochemical oxygen demand (CBOD5) in the zone of impairment (upper portion of Segment 2201) were approximately four times higher in the 1999 high-flow intensive survey than during the 1998 low-flow survey. As expected, average total suspended solids values in Segment 2202 were higher during the high-flow intensive survey than during the low-flow event of 1998. However, there was no significant difference in the concentration of total suspended solids between the high-flow and low-flow events in Segment 2201. Also of significance is the fact that although about 50% of the CBOD5 collected from the lower portion of Segment 2202 was in the form of particulate organic matter, only an average of 22% of the CBOD5 collected in the zone of impairment (Segment 2201) was found to be particulate organic matter.

In 1999, the TNRCC conducted a reassessment of water quality in the Arroyo Colorado as part of the state's effort to compile The State of Texas 1999 Clean Water Act Section 303(d) List. As a result of the reassessment, Segment 2201 was again included in the state's (1999) 303(d) list for aquatic life use impairment caused by occasional low DO concentrations in the upper 7.1 miles of the segment (Table 1). In addition to the DO impairment, Segment 2201 was also placed on the 1999 Surface Water Quality Concerns List for high levels of ammonia nitrogen (upper 11.5 miles), nitrate plus nitrite nitrogen (upper 6 miles), and chlorophyll *a*. Concerns for ammonia nitrogen, nitrate plus nitrite nitrogen, and chlorophyll *a* were also cited in the 1999 303(d) list for the lower 40 miles of Segment 2202.

Segment 2201 was again included in the 2000 Texas Clean Water Act Section 303(d) List for aquatic life use impairment caused by occasional low DO concentrations in the upper 7.1 miles of the segment (Table 1). Like the 1998 303(d) listing of Segment 2201 (which was based on the assessment conducted in1996), the appearance of Segment 2201 in the 2000 Texas 303(d) list was a "carry-over" from the 1999 303(d) list, since not enough new data was available in 2000 to meet the minimum data requirements for reassessment.

Within the last ten years, evidence of negative effects normally associated with excess nutrient loadings has begun to surface in the Lower Laguna Madre (which receives inflow from the Arroyo Colorado). A persistent algal bloom, known as the "brown tide", has been observed over large portions of the Laguna. In addition to creating stressful ecological environments typical of eutrophic conditions (i.e., sharp diurnal swings in dissolved oxygen), there is also evidence that reductions in light penetration caused by the density of high macroalgal biomass can harm the long-term productivity and viability of sea grasses along with the organisms which depend so heavily on the benthic environment these plants provide (Onuff, 1996). Recent studies conducted by the US Geological Survey in the Lower Laguna Madre appear to indicate that a correlation exists between high macroalgal biomass and inflows from the Arroyo Colorado (Onuff 1999). Although a sea grass species composition change has been observed recently in the Laguna Madre, factors affecting this change have not been definitively identified (TNRCC, 1994a and TGLO 1995) .

Endpoint Identification

In general terms, the endpoint of any TMDL effort is the restoration and/or protection of beneficial uses which have been determined to be impaired or threatened in a particular water body. In the case of the tidal segment of the Arroyo Colorado, the issue of beneficial use impairment is confounded by the difficulties associated with determining whether the appropriate aquatic life use has been defined and is being met in the segment.

Because of the absence of reliable biological indexes for estuarine and tidally-influenced water bodies located along the Texas Gulf Coast, studies designed to determine aquatic life use in these environments must rely on subjective professional judgement to determine use attainability. Additionally, the high degree of anthropogenic influence that characterizes the physical setting in Segment 2201 makes it difficult to determine the degree to which physical and chemical factors interact to limit aquatic life. Although the Texas Surface Water Quality Standards (30 TAC §§307.1-307.10) specify the dissolved oxygen criteria that must be met in tidal streams with high aquatic life use designations (such as the Arroyo Colorado), the standards do not currently specify numeric criteria for other constituents associated with dissolved oxygen dynamics (such as nutrients or chlorophyll *a*). Numeric endpoints for these constituents must be developed through site-specific association with the pertinent numeric DO criteria specified in the standards.

Dissolved Oxygen

The most current description of the DO impairment observed in the tidal segment of the Arroyo Colorado states that "In the upper 7.1 miles of the segment, dissolved oxygen concentrations are sometimes lower than the criterion established to assure optimum conditions for aquatic life."(TNRCC, 2000b). The water quality assessment that resulted in this impairment description was conducted by the TNRCC in 1999.

At the time of the 1999 assessment, most of the dissolved oxygen data collected at fixed stations were instantaneous measurements collected during daylight hours (0900 hours to 1400 hrs). As a result, proper comparison of assessment data to the 24-hour criterion (4.0 mg/l DO for the Segment 2201) was not possible. Due to these limitations, the 1999 assessment methodology used the 24-hour DO criterion as a single measurement minimum screening level to evaluate support of the appropriate aquatic life use. Support of the designated aquatic life use at each site for routinely collected instantaneous DO data was based on ranges for the percent of non-compliant samples when at least nine samples were available. A water body was found to be fully supporting the applicable aquatic life use if the calculated non-compliance rate was 10% or less; partially supporting if greater than 10% and less than 25%; and not supporting if greater than 25%. Water bodies were included in the 303(d) list if they were found to not support or only partially support the applicable aquatic life use.

Data from 48 stations were used to assess water quality in the tidal segment of the Arroyo Colorado in 1999 (Figure 2). Of the 13 monitoring stations representing the upper portion of the Arroyo Colorado tidal segment, 6 showed DO values below the criteria yielding a 36% non-compliance rate (8 non-compliant samples out of 22 measurements). In the lower portion of the tidal segment, only 1 of the 35 remaining downstream stations produced DO values below the assessment criteria yielding a 0.9% non-compliance rate (1 non-compliant sample out of 109 measurements). Figure 2 shows the location of all monitoring stations in Segment 2201 (DO violations occurred only in the stations that are labeled). Also shown in Figure 2 is the zone of impairment as defined in the 2000 Texas Clean Water Act Section 303(d) List.

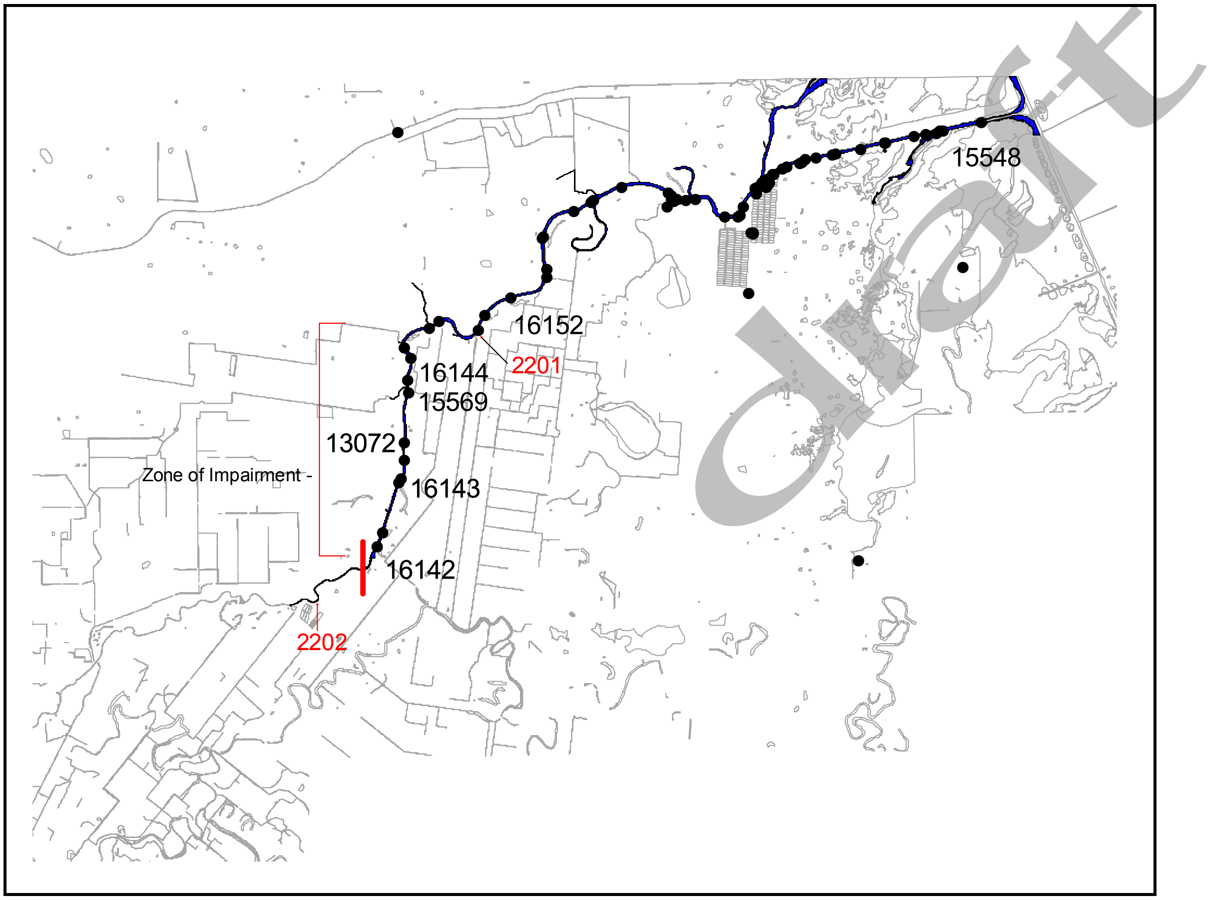


Figure 2. Monitoring stations in Segment 2201 (Arroyo Colorado Tidal). Non-compliance with DO criteria was observed in the labeled stations

After completion of the 2000 Texas CWA Section 303(d) list, the TNRCC modified the assessment methodology and listing policy regarding observed DO impairments. Beginning with the 2002 305(b) assessment of water quality in the state of Texas, water bodies are no longer listed on (or de-listed from) the state's list of impaired water bodies (303(d) list) for DO violations based on instantaneous DO measurements. Currently, compliance with the appropriate 24-hour DO criterion can only be determined through the collection and analysis of diel (24-hour) DO monitoring data. Additionally, in order to establish an acceptable probability of falsely listing water bodies as impaired (Type I error) or neglecting to include impaired water bodies on the 303(d) list (Type II error) the current 305(b) assessment methodology employs the *binomial method* to determine use support (TNRCC 2001). Although partial support and non support are still defined as non-compliance rates of more than 10 and 25 percent, respectively, under the *binomial method*, the number of non-compliant samples necessary to determine non-support and partial support varies with the number of samples available for assessment.

To determine use attainment for DO criteria under the current (2002) assessment methodology, at least ten (10) 24-hour monitoring events must be conducted at each site within a 5-year period to provide adequate data for assessment of aquatic life use. All 24-hour sampling events must occur within the index period (March 15- October 15).

However, at least one sample and between half and two thirds of each year's samples must be taken during the critical period of July 1, - September 30. No more than two thirds of the samples should be taken in the same year and the sampling events should be more than one month apart.

Assuming low DO concentrations are likely to occur within the critical portion of the index period, a numerical endpoint for DO (signifying full support of aquatic life use) may be expressed as a probability of less than 10% that the average 24-hour DO measured in the mixed surface layer during the index periods will be below 4.0 mg/l (i.e., 90% compliance rate). Similarly, an endpoint for the minimum DO may also be expressed as a probability of less than 10% that the 24-hour minimum DO concentration in the mixed surface layer of the segment will be below 3.0 mg/l over a consecutive 8-hour period.

Currently under the 2002 305 (b) assessment methodology, a determination of whether the designated aquatic life use is being fully supported in the tidal segment of the Arroyo Colorado can only be made after additional 24-hour DO monitoring is completed. Although historical data indicate the strong possibility that the DO criteria are not being met in the upper portion of Segment 2201, the data requirements of the current (2002) 305(b) assessment methodology and the lack of existing 24-hour DO data prevents full re-assessment of use attainment (for DO) in the segment until, at least, 2006.

In summary, the DO endpoints for this TMDL are a 90% compliance rate with the applicable 24-hour average DO concentration (4.0 mg/l) and also a 90% compliance rate with the applicable minimum DO criteria (3.0 mg/l).

Nutrients and Chlorophyll *a*

As mentioned previously, the Texas Surface Water Quality Standards (30 TAC §§307.1-307.10) do not specify numeric nutrient criteria for water bodies in the state of Texas. Consequently, water bodies are not listed for nutrient impairments in the state of Texas 303(d) list using numeric criteria. Instead, water bodies in the state are evaluated for nutrient concerns using screening criteria developed using the 85 percentile of nutrient data collected for similar water bodies in the state. A detailed description of the nutrient concerns identified in the 2000 Texas 303(d) list for Segment 2201 was discussed previously in the "Problem Definition" section of this document. It is interesting to note that under the 2002 305 (b) assessment methodology, no nutrient or chlorophyll *a* concerns were identified for Segment 2201.

Nutrient screening criteria are meant to represent an upper end of nutrient values which, if exceeded, may indicate over-enrichment of these constituents in the water body being assessed. However, criteria based on percentiles calculated from data collected in similar water bodies of the state cannot be considered viable numerical TMDL endpoint targets. In order to define a suitable endpoint target for these parameters, a cause-and-effect relationship must be established between the nutrient and chlorophyll *a* levels observed in Segment 2201 and the DO impairment in the upper portion of the segment.

In a study conducted between 1997 and 2000 in the upper portion of Segment 2201, Matlock found sampling sites in the zone of impairment showed no detectable increase in periphytic chlorophyll production with nutrient enrichment in the reaches measured (Matlock, et al., 2001). Also noted in the study was the fact that nutrients appeared saturated with respect to algal requirements and that little difference in primary productivity existed between the reaches analyzed. Based on these and other findings, Matlock concluded that nutrients were not limiting periphytic chlorophyll production in the upper portion of Segment 2201.

Failure to identify a limiting nutrient complicates the ability to associate a particular nutrient or nutrient type with the observed DO impairment in Segment 2201. Furthermore, although (relatively) elevated chlorophyll- a levels and DO supersaturation values indicative of hyper-eutrophication have been documented in the upper portion of Segment 2201, very low average 24-hour DO concentrations have also been measured in the upper portion of Segment 2201 during diel fluctuations that occurred below the theoretical DO saturation concentration; this includes the data collected during the 1998 intensive survey in which the most pronounced non-compliance with 24-hour DO criteria was recorded in Segment 2201 (Figure 3). In fact, a limited but credible amount of 24-hour DO data, suggests that some low average diel DO values measured in the tidal segment of the Arroyo can be attributed to factors other than eutrophication, such as temperature, salinity, and benthic oxygen demand (Matlock 2001).

While it is theoretically possible to define nutrient (and chlorophyll *a*) endpoints through the use of calibrated water quality model(s) designed to simulate dissolved oxygen and the complex interaction of these constituents in the processes associated with photosynthesis, primary productivity, and respiration, it is important to recognize that basing nutrient targets on a predetermined dissolved oxygen criteria will yield meaningful endpoint concentrations of these parameters only if realistic and appropriate DO criteria are first established and only after a significant association can be established between nutrient and chlorophyll *a* parameters and the DO impairment observed . Unfortunately, the results of the TMDL analysis conducted in Segment 2201 does not provide a quantitative, water quality target-based nutrient (or chlorophyll *a*) endpoint. Proposed nutrient endpoint concentrations are discussed in more detail in the “Loading Allocation” section of this document.

BOD and SOD

Like nutrients and chlorophyll *a*, TMDL target endpoints for Biochemical Oxygen Demand (BOD) are based on established cause-and-effect relationships between BOD levels and observed DO impairments. These relationships can also be quantitatively defined using calibrated water quality model(s) designed to simulate BOD loading, transport, and decay and dissolved oxygen dynamics. However, as with nutrients, establishing endpoints for BOD in the tidal segment of the Arroyo Colorado is dependent

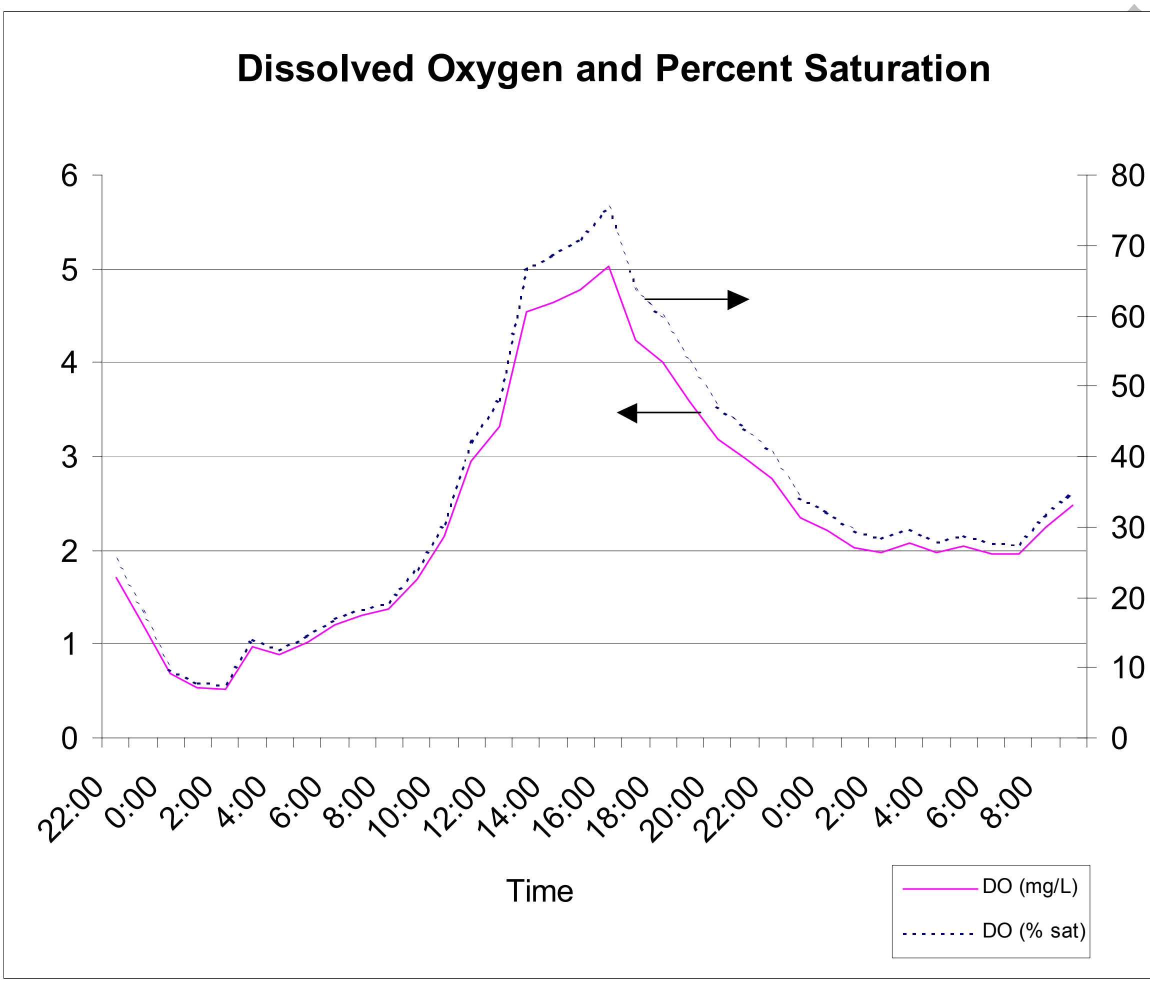


Figure 3. Graph of 24-hour DO measurement in Segment 2201 at Rio Hondo during August 16 and 17, 1998.

on the ability to establish a significant association between BOD parameters and the DO impairment observed in the upper portion of Segment 2201.

Given the number of wastewater outfalls in the stream, the waste water treatment levels, and the permit compliance record of wastewater treatment plants in the Arroyo Colorado, historical BOD levels measured in Segment 2201 are low. Average and median $CBOD_5$ concentrations in Segment 2201 (derived from historical water quality monitoring data dating back to 1974) are 5.1 mg/l and 5.0 mg/l respectively. $CBOD_5$ values from more recent monthly monitoring conducted in 2000-2002 in the zone of impairment of Segment 2201 yield average and median values that are at and below detection limits ($\leq$3.0 mg/l) respectively.

As with nutrients and chlorophyll *a*, the results of the TMDL analysis conducted in Segment 2201 does not provide a quantitative, water quality target-based TMDL endpoint for BOD. Proposed BOD endpoint concentrations are discussed in more detail in the "Loading Allocation" section of this document.

One of the factors that emerges as an important component of DO dynamics in the Arroyo Colorado is sediment oxygen demand (SOD). SOD can be defined in a number of ways. However, for the purpose of this document, SOD is defined as the oxygen demand exerted on the water column by in-situ benthic biochemical processes such as diagenesis of sedimentary organic matter. SOD was investigated by Matlock et al., in a study conducted between 1998 and 2000 in the tidal and above-tidal segments of the Arroyo Colorado. As part of the study, SOD was measured in-situ using benthic chamber respirometers and ex-situ in the laboratory for 9 sites located mainly along the above-tidal portion of the Arroyo Colorado (Segment 2202). Although significant spatial and temporal variations in SOD were observed during the course of the study, high average and median values were reported throughout the segment (average of 44.4 mg/m^2-hr and median of 24.7 mg/m^2-hr) with values as high as 191.4 mg/m^2-hr reported for sites located in areas of high deposition (Matlock et al., 2001).

It is clear from the TMDL analysis conducted in the Arroyo Colorado that the combined effects of high SOD and poor mixing (referred to collectively as DO flux across the halocline) exert a powerful (seasonal) effect on dissolved oxygen dynamics in the mixed surface layer of Segment 2201. The TMDL analysis conducted in the Arroyo Colorado and similar studies conducted in other coastal water bodies also offer evidence that the physical channel dimensions, hydraulics, and geographic orientation of the water body probably have a high degree of influence on the DO flux in the Arroyo Colorado. Despite the TMDL analysis, there is still a general lack of information and understanding of the transport dynamics, and diagenesis of the particulate organic matter which is thought to play an important role in the formation of excessive SOD in Segment 2201. Moreover, other mechanisms associated with DO flux across the halocline are also poorly represented in the current TMDL analysis. The role of SOD/DO flux as it relates to DO dynamics in Segment 2201 are discussed in more detail in the “Linkage Between Sources and Receiving Waters” and “Load Allocation” sections of this document.

Fish Kills and Aquatic Life Use

As stated previously in this document, the ultimate goal of the TMDL analysis described herein is to provide the basis for developing a viable strategy to attain and maintain a DO criterion that is protective of the appropriate beneficial aquatic life use in the tidal segment of the Arroyo Colorado. In addition to monitoring and assessment results showing aquatic life use is not being supported in Segment 2201 (i.e., documented DO criteria violations), there is quantitative biological evidence of stress to aquatic life in the upper portion of Segment 2201. Since 1994, fish kills have been reported with increasing frequency in the tidal segment of the Arroyo Colorado (see Table 2.). While the suspected causes of the fish kills include disease and unknown factors, the majority of these events are attributed to low DO (TPWD 2002). Not surprisingly, the majority of the fish kills reported have also occurred in the zone of impairment defined in the 2000 Texas Clean Water Act Section 303(d) List.

Table 2. Historical fish kills in Segment 2201 (Arroyo Colorado Tidal)

Date	Location	Fish Killed	Suspected Cause
07/06/1994	Canal 5 miles north of US 83 on Bass Blvd. In Harlingen	100	Low Dissolved Oxygen
10/13/1994	Arroyo Colorado, intake canal at shrimp farm, back part of canal on private property	500	Low Dissolved Oxygen
09/16/1995	Arroyo Colorado turning basin east of Harlingen	2,000,000	Low Dissolved Oxygen
11/04/1996	Arroyo Colorado, from water tower in Arroyo City, upstream to Circle X	1,000	Disease
06/18/1997	Arroyo Colorado, Port of Harlingen to Camp Perry	1,000,000	Low Dissolved Oxygen
08/04/1997	Arroyo Colorado at Rio Hondo near port of Harlingen	1,000,000	Low Dissolved Oxygen
09/13/1997	Irrigation Canal off FM 803	300	Low Dissolved Oxygen
07/13/1998	On the west bank of the Arroyo Colorado from the port of Harlingen to the N of the Rio Hondo swing bridge	100,000	Low Dissolved Oxygen
07/30/1998	Arroyo Colorado at the Rio Hondo bridge	100,000	Low Dissolved Oxygen
08/17/1998	Arroyo Colorado approximately 0.5 miles N of Rio Hondo bridge	2,000,000	Low Dissolved Oxygen
07/26/1999	Arroyo Colorado T Pt of Harlingen	16,804	Low Dissolved Oxygen
08/03/1999	Arroyo Colorado Low water bridge to Pt of Harlingen	4,160	Low Dissolved Oxygen
08/06/1999	Arroyo Colorado Tidal	19,840,000	Low Dissolved Oxygen
09/08/1999	Pt of Harlingen downstream 1 mile	2,000	Low Dissolved Oxygen
01/06/2000	Arroyo Colorado near Arroyo City	unknown	unknown
09/19/2001	Cameron County Airport	6	unknown
09/24/2001	Arroyo Colorado	16,159	Low Dissolved Oxygen

Source of Data: Texas Parks and Wildlife Department – Fish Kill and Pollution Complaint Database

In 1993, Gorham-Test assessed aquatic life and habitat in the tidal segment of the Arroyo Colorado along with that of the Rio Grande Estuary (south Texas) and East Bay Bayou (southeast Texas). With the exception of sites located in the lowermost portion of Segment 2201, the study found stressed benthic community structures and lower species diversity, richness and abundance values in the Arroyo Colorado. The study concluded that, along with the Rio Grande Estuary and East Bay Bayou, the Arroyo Colorado was a significantly degraded estuary (EPA 1998).

Although difficult to quantify at present, the most important TMDL endpoint target for the upper portion of the Arroyo Colorado tidal segment is restoration and protection of the appropriate aquatic life use. Many of the biological surveys conducted in segment 2201 cite loss of habitat (from dredging and channel straightening) and the artificial creation of physical conditions not conducive to the development of a healthy benthic environment (accentuation of natural salinity stratification) as factors that contribute to the stress exerted on aquatic life in the Arroyo Colorado (TDWR, 1984 ; EPA, 1998).

The results of the TMDL analysis conducted in the Arroyo Colorado also indicate that anthropogenic modification of the Arroyo Colorado contributes significantly to the dissolved oxygen conditions observed in the upper portion of Segment 2201 and that reductions in loadings of chemical and biochemical constituents alone may not be sufficient to reduce environmental stresses to a level that will sustain a high aquatic life use in the segment. The physical factors (natural and anthropogenic) that contribute to the DO impairment observed in the upper portion of Segment 2201 are discussed further in the section of this document titled "Linkage Between Sources and Receiving Waters."

Source Analysis

In accordance with the TMDL target endpoint(s) identified above, the TMDL analysis conducted in the Arroyo Colorado focuses primarily on sources of constituents commonly associated with dissolved oxygen dynamics in surface waters. These constituents include the following parameters:

- BOD
- Ammonia Nitrogen
- Nitrate plus Nitrite Nitrogen
- Orthophosphate Phosphorus
- Organic Nitrogen
- Organic Phosphorus
- Sediment

An analysis of the sources of these constituents in the Arroyo Colorado watershed reveals a variety of point and nonpoint source contributors encompassing a number of social and economic sectors.

Point Sources

There are currently 39 active wastewater discharge permits associated with the Arroyo Colorado (33 municipal and domestic wastewater outfalls and 6 industrial outfalls), with a total permitted flow of approximately 56 million gallons per day. Thirty four of these discharge permits are for outfalls that discharge into Segment 2202 (Arroyo Colorado above tidal); 5 are for outfalls that discharge into Segment 2201 (see Table 3).

Figure 4 shows the location of wastewater outfalls relative to the various sub-basins that comprise the Arroyo Colorado watershed. Although officially classified by the TCEQ as discharging into the Arroyo Colorado, it should be noted that several of the wastewater outfalls listed Table 3 are located outside the Arroyo Colorado watershed and do not

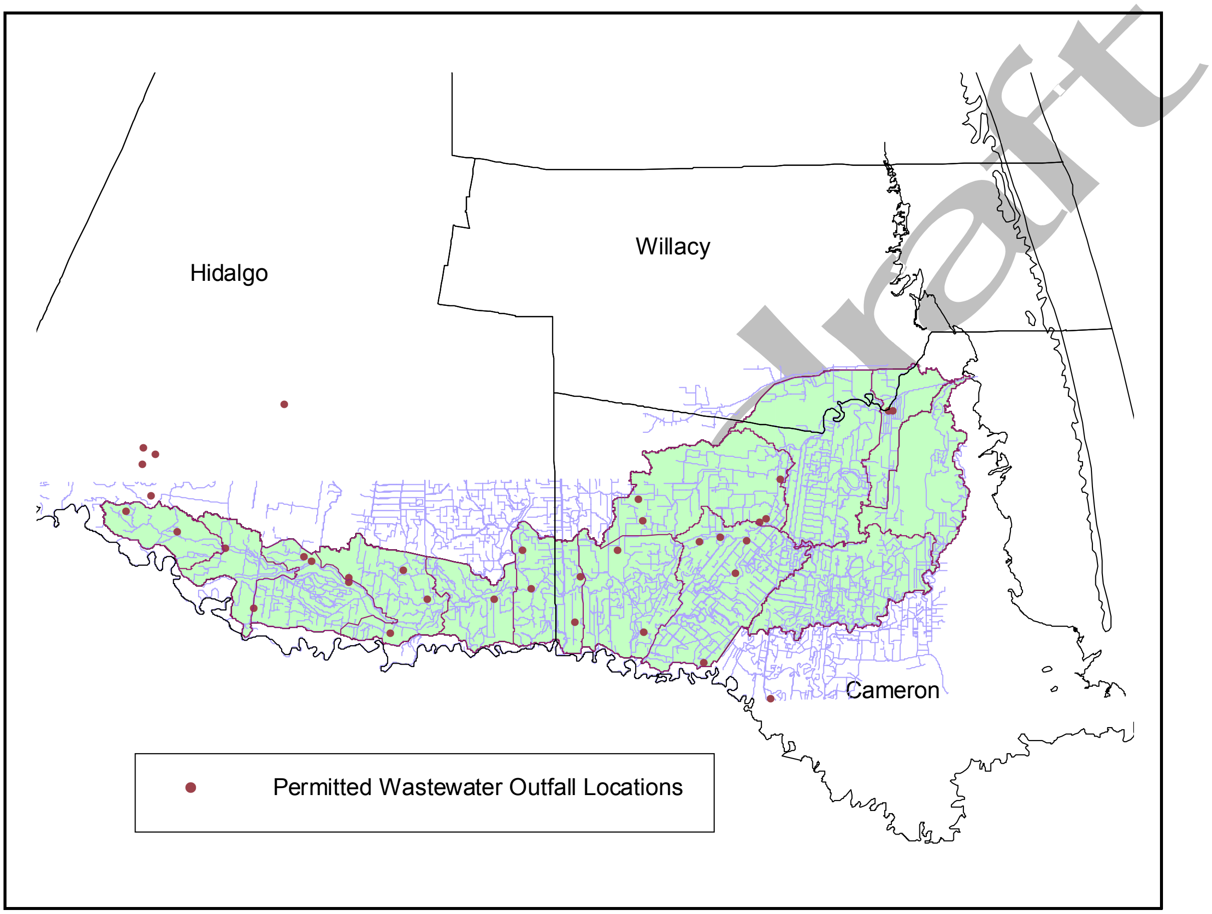


Figure 4. Wastewater outfall locations in the Arroyo Colorado watershed and watershed sub-basins.

contribute directly to the classified segments of the Arroyo Colorado. All of the permitted outfalls located outside of the Arroyo Colorado watershed are small domestic wastewater facilities with non-direct discharges such as subsurface drain fields or subsurface pressure injection.

Much of the information gathered during the TMDL analysis regarding actual flow and loading of BOD, suspended sediment and, in some cases, ammonia nitrogen for municipal point sources in the watershed was obtained from monthly effluent data submitted to the TCEQ as part of self-reporting requirements specified in individual TPDES permits. Information regarding municipal point source loadings of constituents such as nitrate plus nitrite, total kjeldahl nitrogen, total phosphorus, and orthophosphate was obtained from monitoring of wastewater effluents performed voluntarily by permitted wastewater treatment facilities in the watershed and from special effluent monitoring conducted by the TNRCC (now the TCEQ) as part of the TMDL effort in 2000 and 2001.

The information described above was assembled and entered into a Watershed Data Management File (WDM file) in the form of time series for input into a dynamic

Table 3. Active wastewater discharge permits in the Arroyo Colorado as of May 30, 2002.

Facility Name	Segment	TPDES Permit No.	Discharge Type	Permitted Flow (MGD)
Central Power & Light Bates Plant	2202	WQ0001254-000	Industrial	2
Central Power & Light La Palma Plant	2202	WQ0001256-000	Industrial	1.12
Frontera Generations Ltd.	2202	WQ0004051-000	Industrial	1.24
City of Mercedes	2202	WQ0010347-001	Municipal	2.3
City of San Benito	2202	WQ0010473-002	Municipal	2.16
City of Mission	2202	WQ0010484-001	Municipal	4.6
City of Harlingen Plant No. 1	2202	WQ0010490-002	Municipal	3.1
City of Harlingen Plant No. 2	2202	WQ0010490-003	Municipal	12.2
City of Donna	2202	WQ0010504-001	Municipal	2.7
City of Pharr	2202	WQ0010596-001	Municipal	5.0
City of Weslaco South Plant	2202	WQ0010619-005	Municipal	2.5
City of McAllen Plant No.2	2202	WQ0010633-003	Municipal	10.0
City of La Feria	2202	WQ0010697-001	Municipal	0.5
Palm Valley Estates	2202	WQ0010972-002	Domestic (irrigation)	0.28
City of Hidalgo	2202	WQ0011080-001	Municipal	0.407
City of San Juan	2202	WQ0011512-001	Municipal	5.2
Winter Garden Park Assoc.	2202	WQ0011628-001	Domestic	0.011
Harlingen Consolidated ISD Wilson Elementary	2202	WQ0011659-001	Domestic (Irrigation)	0.006
Military Hwy Water Supply Corporation Progreso Plant	2202	WQ0013462-001	Municipal	0.4
Military Hwy Water Supply Corporation La Paloma	2202	WQ0013462-002	Domestic (Irrigation)	0.21
Military Hwy Water Supply Corporation Santa Maria	2202	WQ0013462-003	Domestic (Irrigation)	0.23
Military Hwy Water Supply Corporation San Pedro	2202	WQ0013462-004	Domestic (Irrigation)	0.16
Military Hwy Water Supply Corporation Los Indios	2202	WQ0013462-005	Domestic (Irrigation)	0.135
Military Hwy Water Supply Corporation WWTP (S. Alamo)	2202	WQ0013462-006	Municipal	0.51

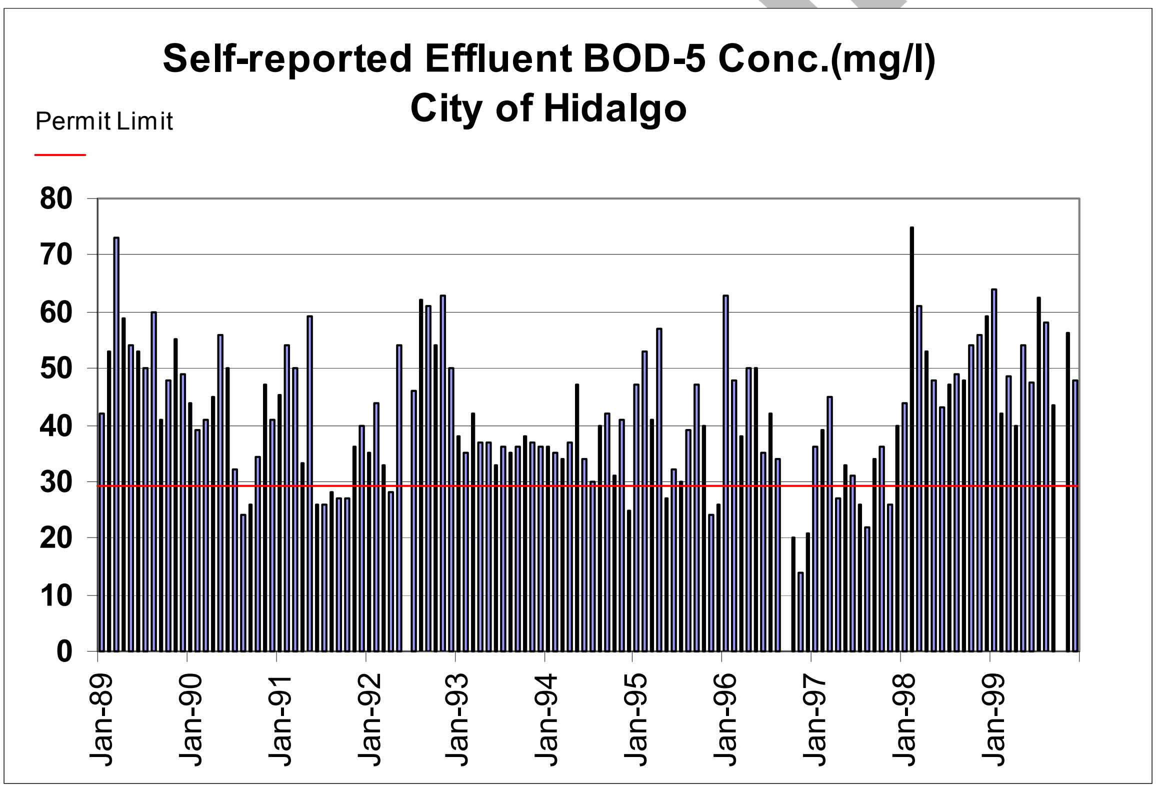
La Joya ISD La Joya Elementary	2202	WQ0013523-001	Domestic (Subsurface Pressure)	0.15
La Joya ISD Chapa Elementary	2202	WQ0013523-002	Domestic (Subsurface Drain Field)	0.15
La Joya ISD Kika De la Garza Elementary	2202	WQ0013523-003	Domestic (Subsurface Pressure)	0.15
La Joya ISD 11^{th} and 12^{th} Elementary	2202	WQ0013523-004	Domestic (Subsurface Pressure)	0.15
City of Alamo	2202	WQ0013633-001	Municipal	2.0
Donna ISD Runn Elementary	2202	WQ0013680-001	Municipal	0.017
Donna ISD Muñoz Elementary	2202	WQ0013680-002	Domestic (Subsurface Drain Field)	0.0125
Donna ISD Garza Elementary	2202	WQ0013680-003	Domestic (Subsurface Drain Field)	0.0125
Mission CISD Mission Elementary	2202	WQ0013887-001	Domestic (Subsurface Drain Field)	0.013
USDA Moore Field WWTP	2202	WQ0014155-001	Domestic (Subsurface Drain Field)	0.0033
Hartex Cattle Co. Feedlot	2201	WQ0001666-000	Industrial	N/A
Taiwan Shrimp Village Assoc. and Arroyo Aquaculture Inc.	2201	WQ0003596-000	Industrial	100
Southern Star Inc.	2201	WQ0004244-000	Industrial	50
City of Rio Hondo	2201	WQ0010475-002	Municipal	0.4
Military Hwy Water Supply Corporation Lago WWTP	2201	WQ0013462-008	Municipal	0.51

watershed and water quality model used to simulate water quality in the Arroyo Colorado.

The TMDL analysis conducted on the Arroyo Colorado indicates that municipal waste-water facilities in the Arroyo Colorado watershed are the most significant point source contributors of nutrients and BOD into the Arroyo Colorado (USGS, 2002).

Although marked improvements in permit compliance have been observed in the last 5-7 years, a comparison of permit limits of BOD and ammonia nitrogen to historical BOD and ammonia nitrogen effluent concentrations from self-reported data provides historical confirmation of permit non-compliance for several municipal wastewater facilities in the Arroyo Colorado watershed. Figures 5a-6b show historical BOD and ammonia nitrogen effluent concentrations plotted along with the applicable permit limits for several municipal wastewater facilities in the Arroyo Colorado watershed. The data shown in these figures highlights the fact that permit non-compliance has historically has been a problem in the Arroyo Colorado watershed.

Figure 5a. Historical effluent concentrations and permit limit for BOD-5 for the City of Hidalgo, Texas.



Nonpoint Sources

As in most watersheds, the contribution of constituents of concern in the Arroyo Colorado from nonpoint sources is closely related to the type of land use and land cover that is present in the watershed. Land use and land cover in the Arroyo Colorado watershed are composed of a complex mixture of agricultural, urban, and natural land which contributes large quantities of nutrients and BOD in the form of dissolved and particulate loadings during rainfall-runoff events and also as a result of irrigation return flows which occur mainly under low in-stream flow conditions.

Figure 7 shows land use in the Arroyo Colorado watershed during the period of 1995-1996. As part of the TMDL analysis conducted on the Arroyo Colorado, the TNRCC in

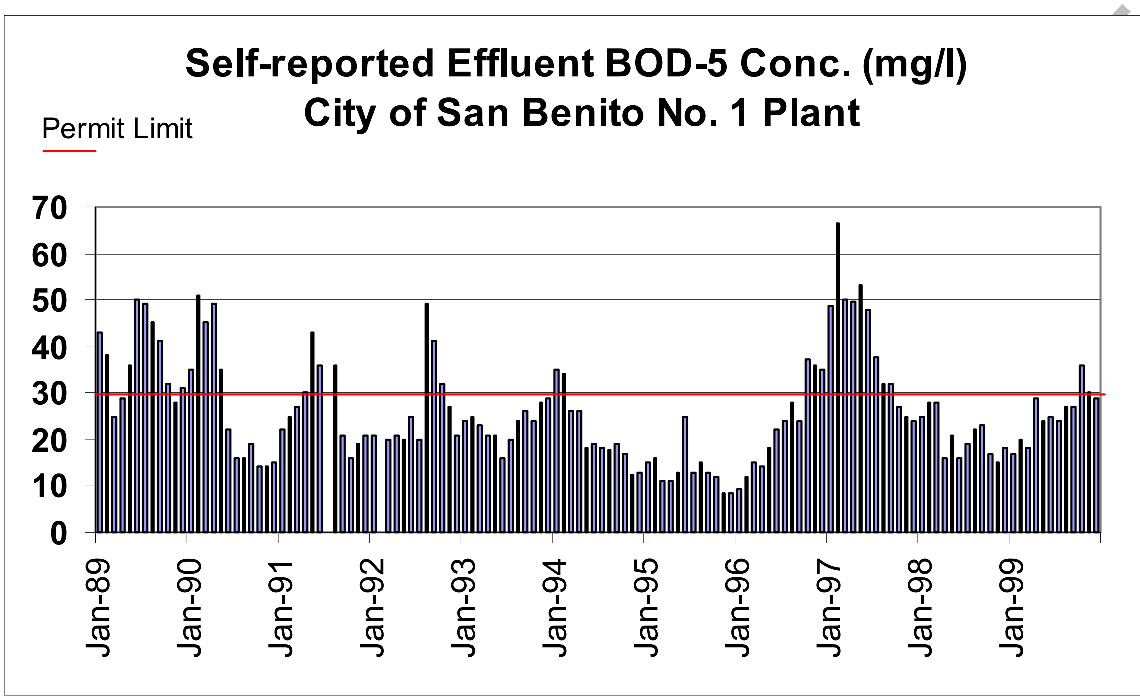


Figure 5b. Historical effluent concentrations and permit limit for BOD-5 for the City of San Benito, Texas.

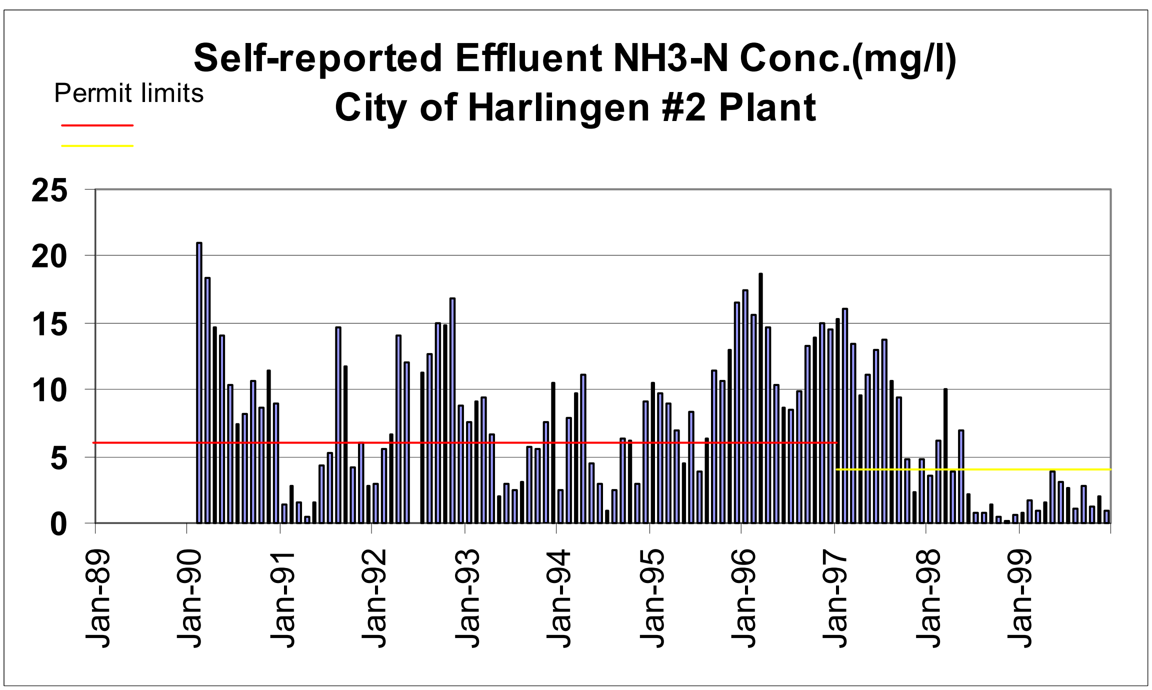


Figure 6a. Historical effluent concentrations and permit limit for ammonia for the City of Harlingen, Texas.

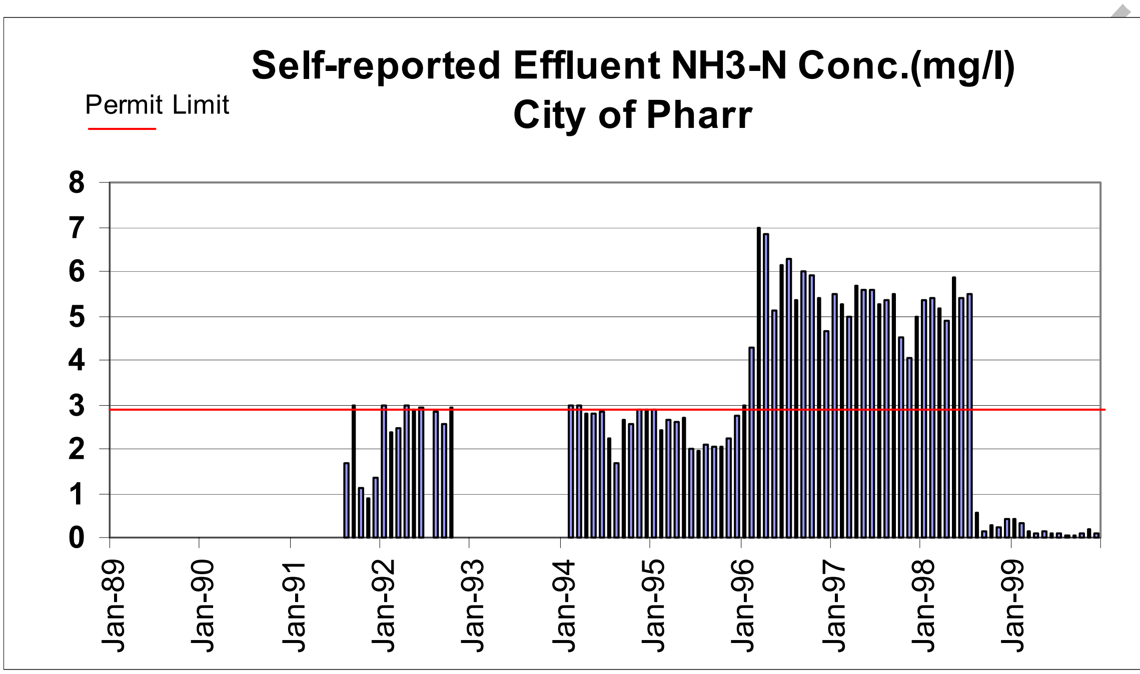


Figure 6b. Historical effluent concentrations and permit limit for ammonia for the City of Pharr, Texas.

cooperation with the USGS, developed a detailed coverage of land use and land cover for the Arroyo Colorado watershed based on the Multi-Resolution Land Characteristics Classification (MRLC) system. This system allows the customization of land use characteristics to a level commensurate with the unique needs of each particular land use analysis.

The date of the land use coverage shown in Figure 7 is considered to be an average condition for the entire period of record studied during the Arroyo Colorado TMDL analysis (1989-1999) because it represents the temporal center of the 11-year period encompassed by the study.

In order to analyze nutrient and BOD contributions from sub-sectors of agricultural production, agricultural land in the Arroyo Colorado watershed was characterized to the level of individual crop type (i.e., sugarcane, row crops, citrus, etc.). Detailed land use characterization was also conducted for urban and natural land uses.

Using the detailed land use information shown in Figure 7 and, in combination with information about soil types underlying the different permeable land uses, a series of permeable (PERLND) and impermeable (IMPLND) land groupings possessing unique hydraulic and constituent loading characteristics were developed for the Arroyo Colorado watershed (USGS 2002). The loading of sediment, nutrients and BOD for these land units into the Arroyo Colorado was then modeled using the Hydrologic Simulation Program - Fortran (HSPF).

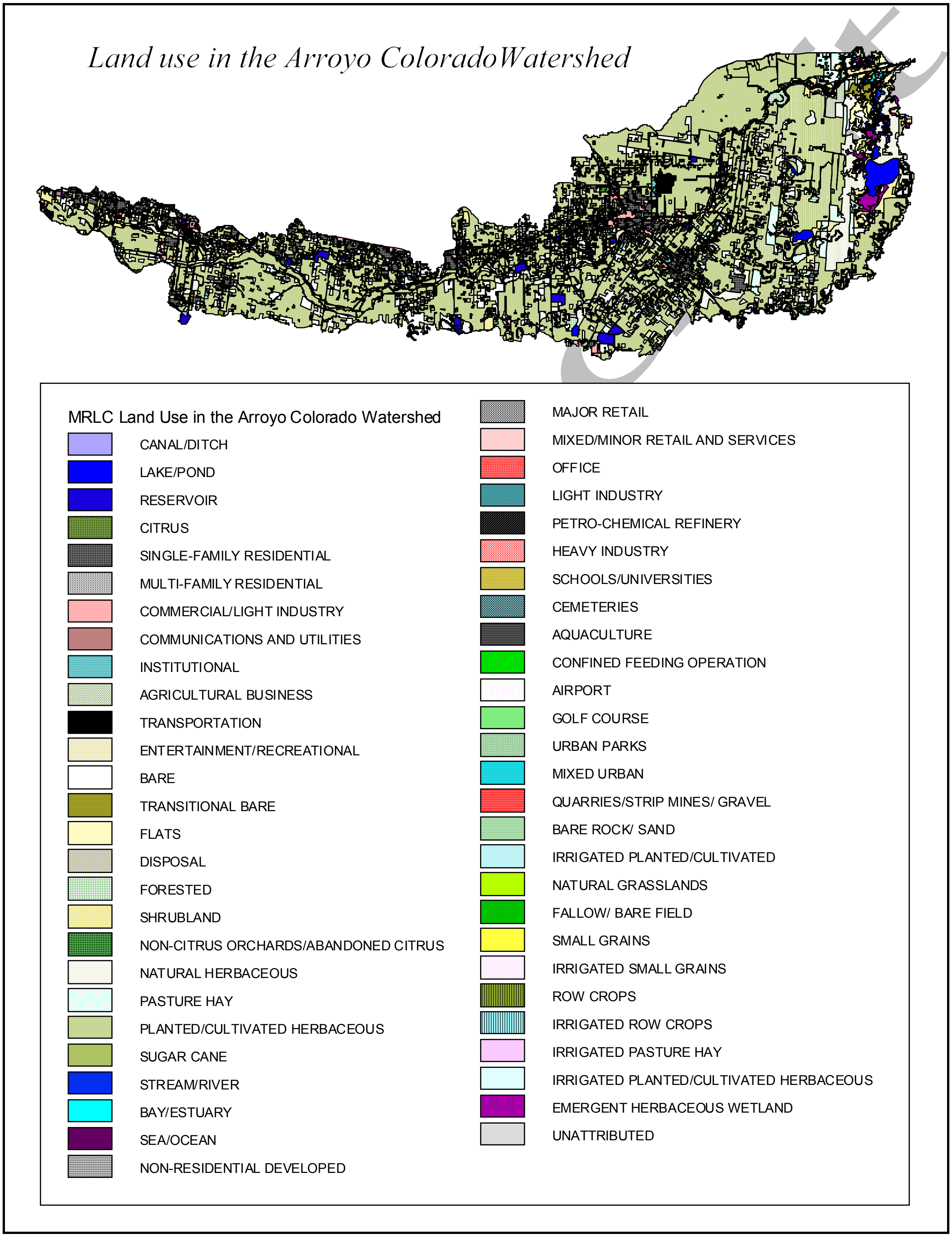


Figure 7. 1995 MRLC Land Use/Land Cover for the Arroyo Colorado Watershed

Calibration of the Arroyo Colorado HSPF watershed model was accomplished at differing geographic scales. Edge-of-field loadings of constituents for the different PERLND and IMPLND land units modeled in the TMDL analysis (including natural land) were determined using data from published and unpublished studies of flow and concentrations of constituents observed during run-off and irrigation events in similar land use types (USGS, 2002). Constituent buildup and wash-off factors for the different HSPF land units were adjusted to yield constituent edge-of-field concentrations similar to those observed in the published and unpublished data and using best professional judgement. Parameterization and calibration of the Arroyo Colorado HSPF watershed model at the sub-basin and reach scale was accomplished using the HSPF Parm library and software, observed flow and in-stream water quality data, and best professional judgement.

Domestic Wastewater Systems and Colonias

For the purpose of the TMDL analysis described herein, small domestic wastewater systems are defined as low capacity (< 0.15 MGD) wastewater systems with treatment mechanisms ranging from basic underground settling tanks with drain fields (i.e., on-site septic systems) to low-flow systems with more advanced primary treatment including aeration basins, clarifiers and aerobic digesters. In addition to the relatively low volume of wastewater produced, domestic wastewater systems are also typically characterized by indirect (or no) discharges to surface water bodies.

Small domestic wastewater systems in the Arroyo Colorado watershed were categorized, inventoried, assessed and modeled in accordance with the type of treatment and discharge mechanism associated with each system. Higher capacity systems, such as the (permitted) domestic wastewater systems included in table 3, were modeled according to the permitted flow and concentration of nutrients and BOD expected to be contained in the treated effluents. The indirect discharge mechanisms associated with these systems were also modeled according to permit specifications (i.e., size of subsurface drain or pressure field, acreage irrigated, etc). Smaller domestic systems, such as individual onsite septic systems, were modeled using population figures and GIS coverages provided by the local council of governments for areas served by these systems. The population (using septic systems) and GIS data was used along with assumptions regarding the average volume of wastewater produced per capita (according to the Texas Water Development Board), average size of most septic drain fields, and average concentrations of constituents found in wastewater from septic systems, to model loadings to the Arroyo Colorado.

The loading of nutrients and BOD into the Arroyo Colorado from colonias was modeled in a similar fashion to that of on-sight septic systems. Colonia population figures and GIS coverages obtained from the Texas Water Development board were used along with assumptions regarding per capita wastewater production, disposal areas, and effluent quality to model daily loading of nutrients and BOD to the Arroyo Colorado. However, wastewater application for colonias was assumed to be a surface process and the concentration of constituents was assumed to be that of essentially raw, untreated wastewater.

Linkage Between Sources and Receiving Waters

The relationship between the sources of the constituents described above and DO concentrations in the Arroyo Colorado was modeled using the Hydrologic Simulation Program - Fortran (HSPF) to simulate watershed loadings and in-stream flow and water quality in the tidal and above tidal segments of the Arroyo Colorado. Additionally, water quality in the mixed surface layer of the tidal segment of the Arroyo Colorado (Segment 2201) was simulated, in one dimension, for several critical steady-state flow conditions using QUAL2E to obtain a more detailed depiction of simulated nutrient and DO concentrations in Segment 2201. Watershed loadings simulated using the HSPF model where used to estimate loading boundary conditions each of the steady-state QUAL2E model simulations of Segment 2201.

Arroyo Colorado Watershed Model

The HSPF simulation program (EPA 1997) is a continuous-simulation model that uses a conceptual framework to represent infiltration, evaporation, interception storage, surface runoff, interflow, and baseflow on pervious land segments and retention storage and surface runoff on impervious land segments. Each user-defined land segment represents its own unique hydrologic response system based on land cover, soil type, watershed slope, or other basin characteristics. Runoff and constituent loadings from the various land segments and user-defined point sources are moved through a system of reaches using storage routing. Simulation of flow and water quality at the reach scale is accomplished through an in-stream flow and water quality simulation module contained in the program.

The Arroyo Colorado (HSPF) watershed model dynamically simulates point and nonpoint source flow and constituent contributions to Segments 2201 and 2202 from the 14 sub-basins that comprise the Arroyo Colorado watershed (see Figure 4). Watershed delineation for the Arroyo Colorado was performed using automated watershed delineation methods which define geographic drainage area through computer processing of digital elevation models (DEMs) edited to conform with updated hydrographic data (see USGS 2000). Sub-delineation of the total drainage area in the Arroyo Colorado watershed into the14 sub-basins defined in the study was accomplished by selecting pour points in the main stem of the stream chosen to coincide with historical flow and/or water quality monitoring stations. The pour points mark the beginning and end of adjacent sub-basins.

Time series of rainfall, irrigation, evaporation, air temperature, dewpoint, wind speed, cloud cover, solar radiation, streamflow, and concentrations for selected properties and constituents from 1989-1999 were used in the simulation. Twenty six different pervious land segments and three impervious land segments were defined based on land cover and soil groupings in the Arroyo Colorado watershed. In all, 18 process-related parameters were defined for each land segment for flow, 31 process-related parameters were defined for each land segment for water quality, and 75 process-related parameters for each stream reach for water quality (USGS 2002).

The Arroyo Colorado watershed model was calibrated and tested for flow and water quality with data collected between 1989 and 1999 from three flow and five water quality stations. Flow calibration was accomplished using data from 1989-1995 at two stations. Simulated flow was tested spatially with data from 1989-1995 at one station and tested temporally from 1996-1999 at two stations using the Expert System for Calibration of HSPF (HSPEXP). Water quality calibration was accomplished for seven properties and constituents from 1989-1995 using the two historical stations with the most data available. Water quality calibration was tested spatially at one station from 1989-1995 and temporally at three stations from 1996-1999. The simulated flow and water quality constituent concentrations generally fit the shape of the data available for the calibration and testing periods chosen for the study.

Figures 8-11 show examples of calibration plots generated as part of the Arroyo Colorado HSPF watershed model development effort. Additional details regarding the development, calibration, and testing of the Arroyo Colorado HSPF watershed model, including the full set of input parameters and calibration and verification plots, can be found in USGS Water Resources Investigation Report 02-4110 (USGS 2002).

A comparison, by source, of simulated loadings to Segment 2201 reveals that agricultural nonpoint sources were the principle source of sediment, nitrate nitrogen and ammonia nitrogen in the Arroyo Colorado watershed for the period 1989-1999. The distribution of orthophosphate and BOD loadings into Segment 2201 for the simulation period was more evenly divided between urban and agricultural sources and also between point and nonpoint sources (Figure 12).

Although widely used as a tool to simulate flow and water quality in many stream and river systems, HSPF is not particularly well suited for use in tidal streams due to an inherent inability of the HSPF software to simulate complex hydrodynamic regimes such as those found in tidal environments. For this reason, intensive calibration and testing of the Arroyo Colorado (HSPF) watershed model focused primarily on reaches and calibration points located in the non-tidal segment of the Arroyo (Segment 2202).

Because the DO endpoint defined for this TMDL effort is based primarily on a non-compliance probability (10^{th} percentile) for DO concentrations in the mixed surface layer of tidal segment of the Arroyo Colorado, there is a strong need for a continuous (daily time step), multi-year time series of simulated DO values in Segment 2201. In order to obtain this multi-year dynamic simulation of water quality in Segment 2201, the Arroyo Colorado (HSPF) watershed model was extended to include Segment 2201 using many of the assumptions and justifications used to develop the steady-state (QUAL2E) model of tidal segment of the Arroyo Colorado described below. Both models (the watershed HSPF model and the steady-state QUAL2E model) simulate only the mixed surface layer of the tidal segment. Flow in this uppermost layer of Segment 2201 is assumed to be unidirectional at all times and total water column depth in the simulations is assumed to be equal to the depth of the mixed surface layer. A detailed discussion of the assumptions and justifications associated with the modeling strategy used to simulate water quality in

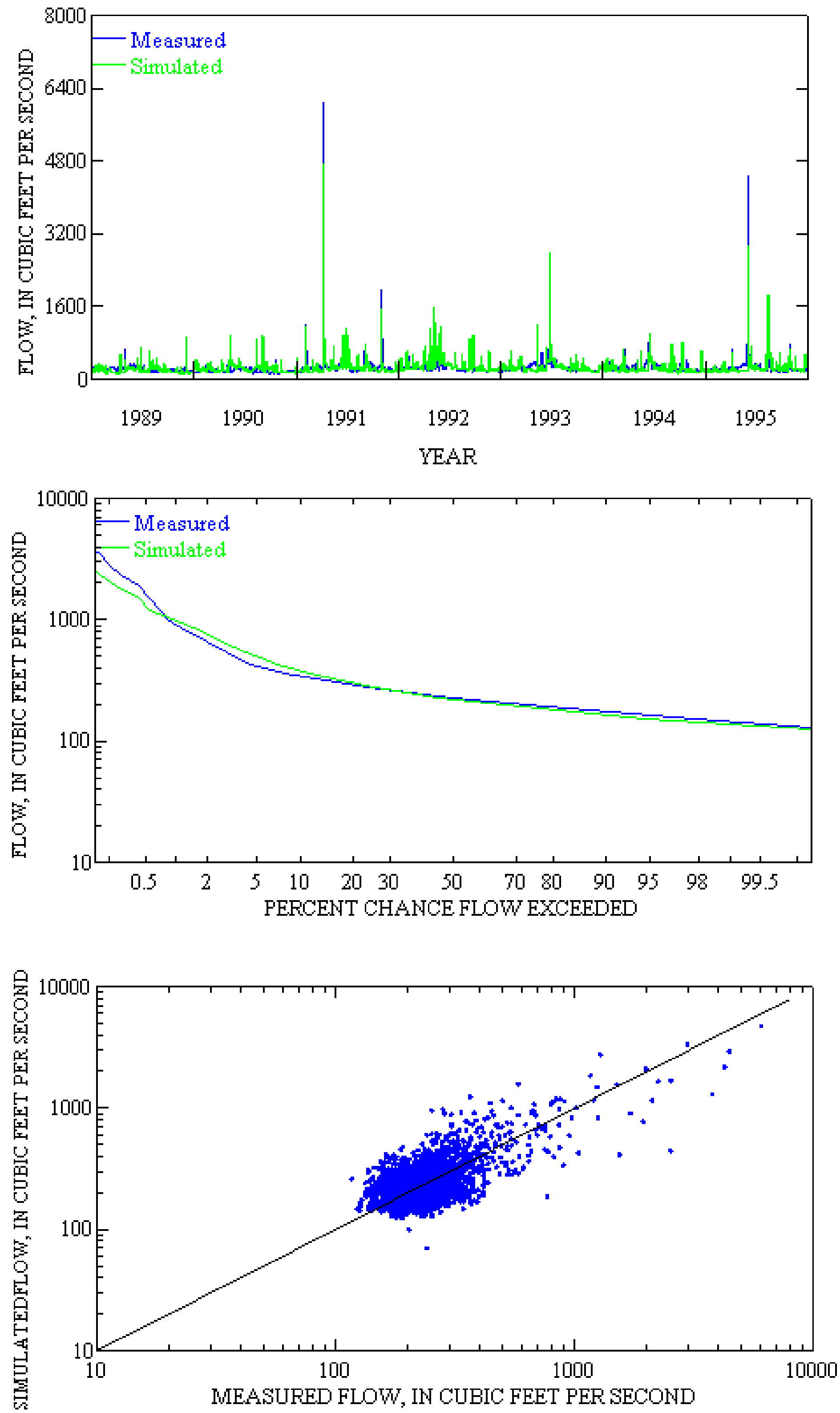


Figure 8. Measured and simulated stream flow in the Arroyo Colorado at Harlingen, 1989-95.

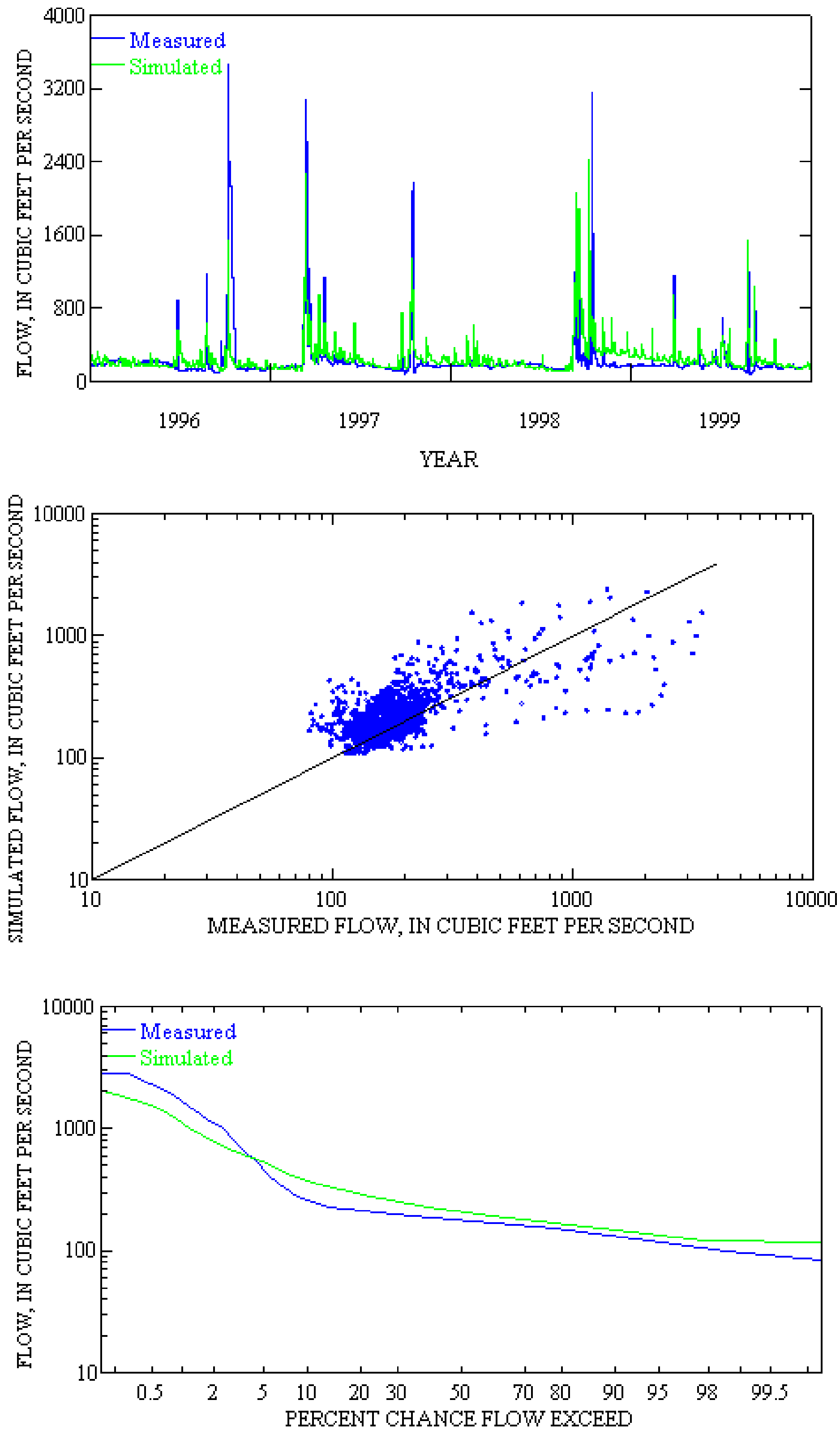


Figure 9. Measured and simulated stream flow in the Arroyo Colorado at Harlingen, 1996-99.

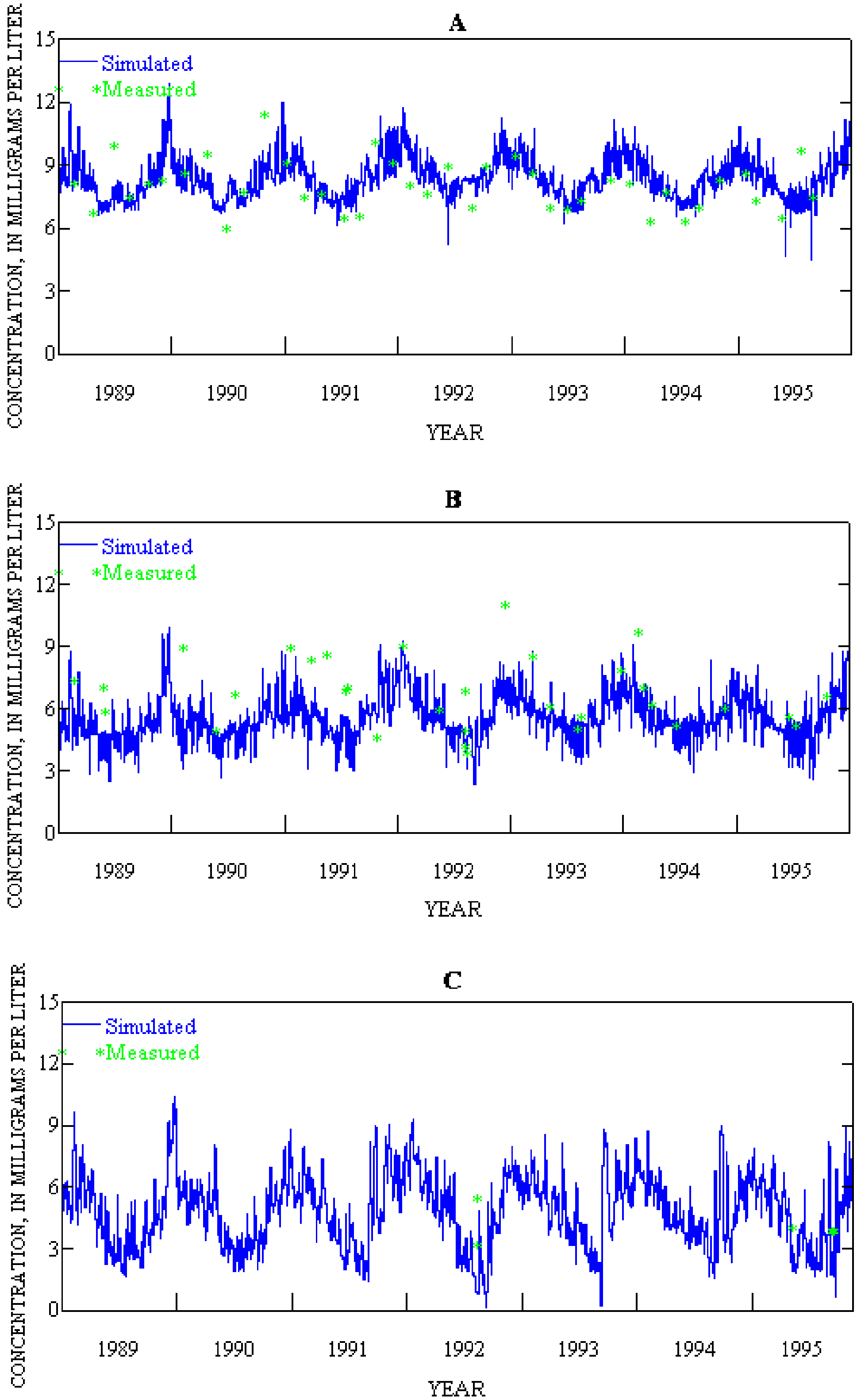


Figure 10. Measured and simulated dissolved oxygen in the Arroyo Colorado at: A. Harlingen, B. Lower boundary of Segment 2202, C. Segment 2201 at Rio Hondo, 1989-95

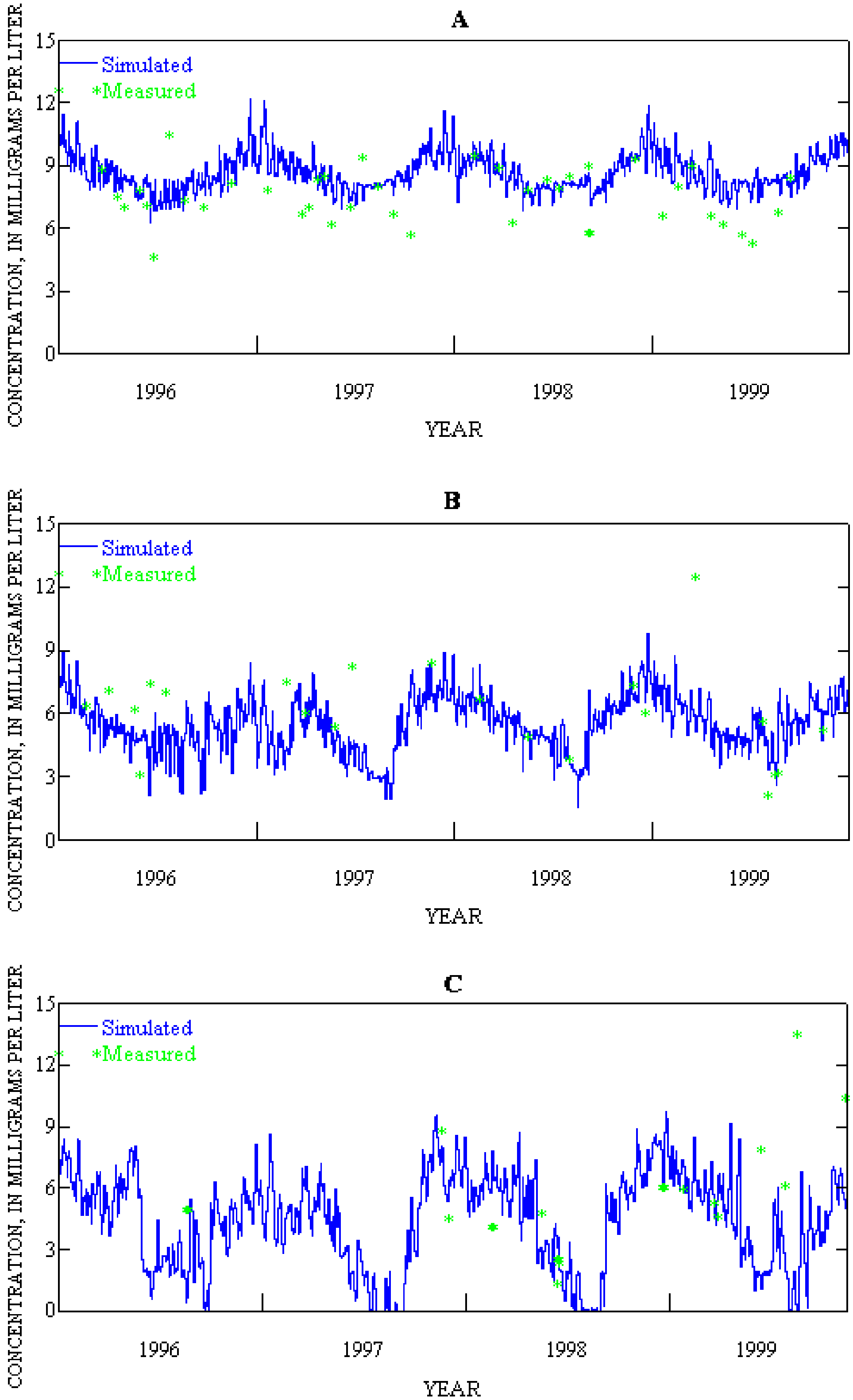


Figure 11. Measured and simulated dissolved oxygen in the Arroyo Colorado at: A. Harlingen, B. Lower boundary of Segment 2202, C. Segment 2201 at Rio Hondo,1996-99

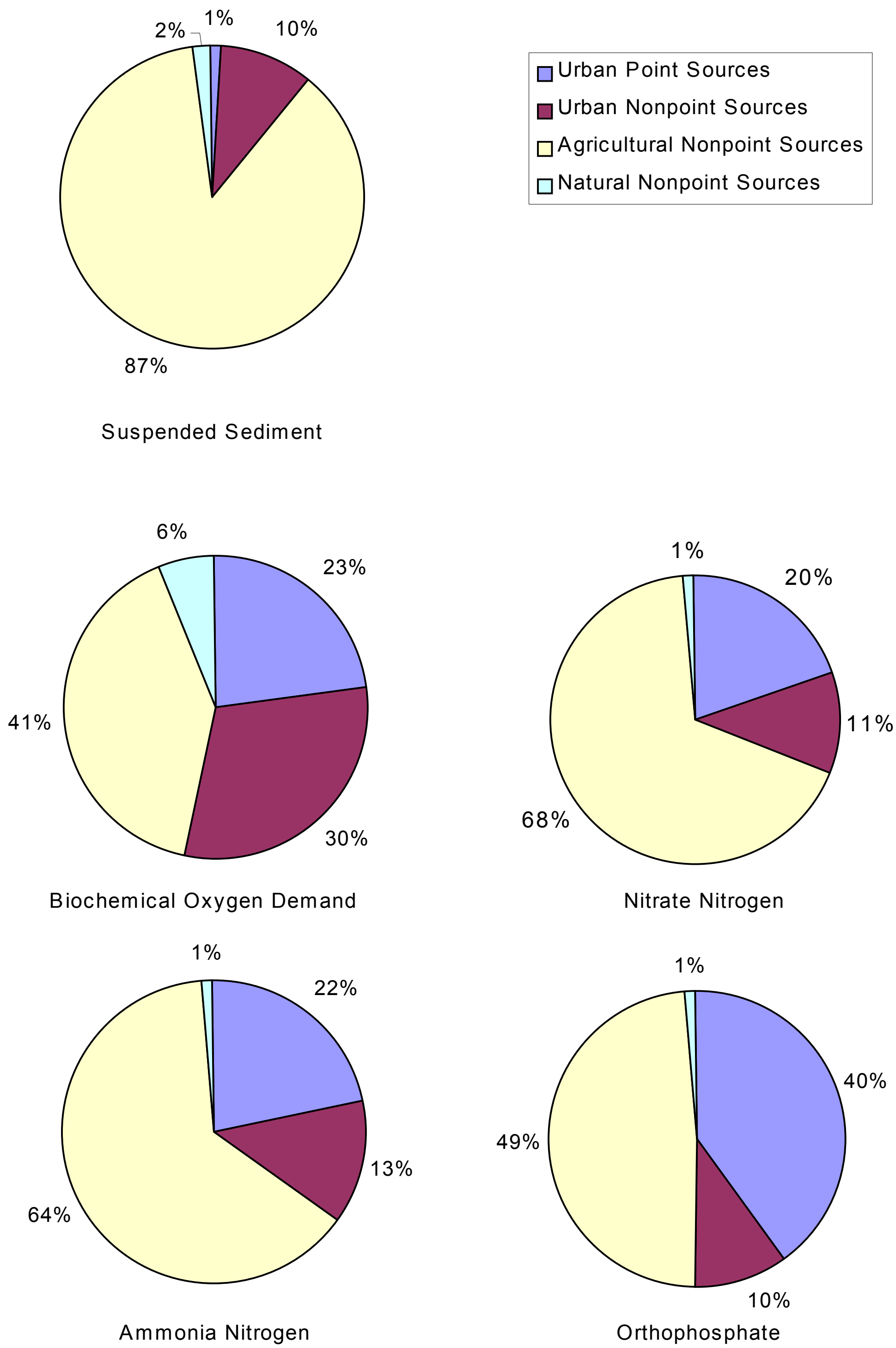


Figure 12. Percentage of loadings of selected constituents into the upper portion of Segment 2201 by source. Charts represent total loadings of each constituent between1989 and 1999 as estimated using Arroyo Colorado HSPF watershed model simulations.

the tidal segment of the Arroyo Colorado is included in the next section of this document titled "Steady-state Water Quality Model."

Using the time series of simulated daily average DO concentrations generated by the extension of Arroyo Colorado (HSPF) watershed model into Segment 2201, a frequency distribution can be established for the average DO values in each of the tidal reaches. Figure 13 shows the frequency distributions of simulated DO concentrations in the mixed surface layer in the uppermost reach of Segment 2201 (Rio Hondo). In general, there is good agreement between the non-compliance probability estimated from the frequency distribution of simulated DO concentrations (34.75%) and the percent non-compliance observed (36%) from the assessment data used to generate the State of Texas 1999 303(d) List.

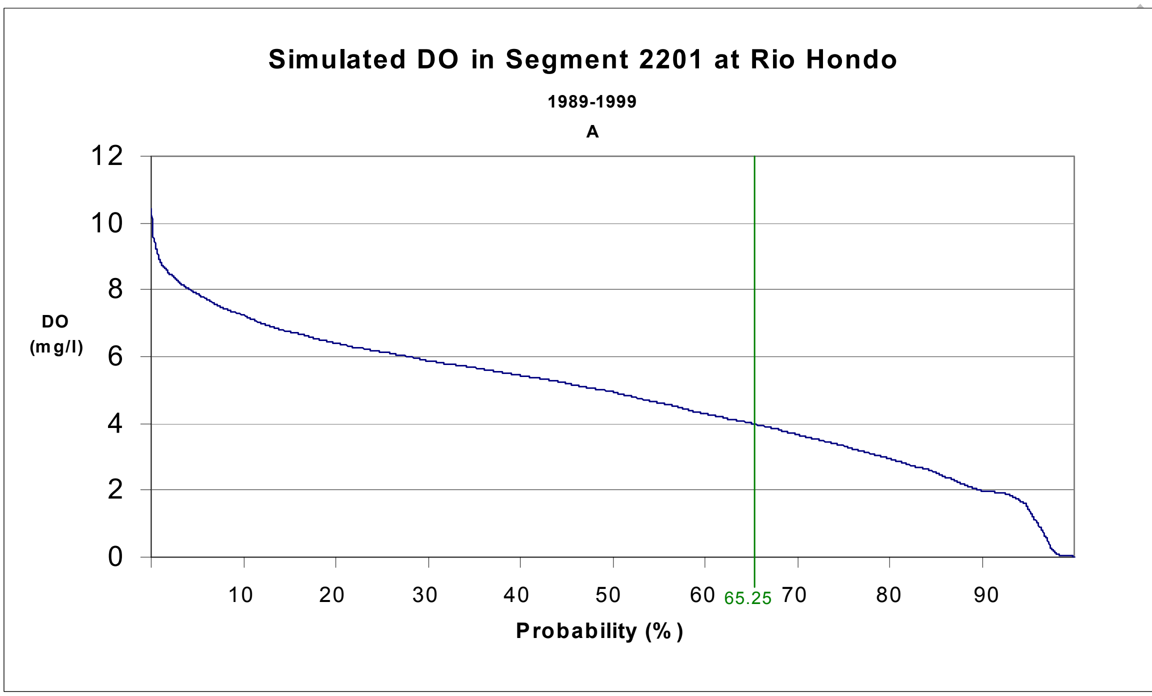
It is important to note, however, that under the current (2002) 305(b) assessment methodology for the State of Texas, only the probability distribution shown in chart "B" (Figure 13) would apply as a measure of use attainment for the segment, since only in-stream (24-hour) DO measurements collected in the months of March through October are used for assessment purposes.

Steady-state Water Quality Model

The Arroyo Colorado (HSPF) watershed model is an adequate tool for dynamic water quality simulation at the reach scale. The simulated DO concentrations generated in the HSPF model represent vertically and longitudinally averaged DO concentrations for each of the reaches simulated. Since individual land segments in each of the sub-basins modeled are associated with corresponding reaches, there is a practical limit to the number of reaches that can be defined in the model. This limitation forces reach lengths to be on the order of kilometers rather than meters for a watershed the size of the Arroyo Colorado's.

In order to characterize dissolved oxygen dynamics in greater detail, a separate modeling strategy, involving higher reach discretization, was developed to simulate water quality in the tidal segment of the Arroyo Colorado. The stream water quality simulation program QUAL2E was selected to simulate detailed water quality conditions in Segment 2201.

The QUAL2E water quality simulation program allows simulation of up to 15 water quality constituents in branching stream systems using an implicit backward finite-difference solution to the one-dimensional advective-dispersive equation. The stream is conceptually represented as a system of reaches of variable length, each of which is subdivided into computational elements that have the same length in all reaches. A mass and heat balance is applied for every element. Mass may be gained or lost from elements by transport processes and external sources and sinks. Although limited to the simulation of time periods during which stream flows, inflows, and loads are essentially constant, the model can also be run in a quasi-dynamic mode in which the effects of diurnal variations in meteorological data on water quality (primarily DO and temperature) can be examined.



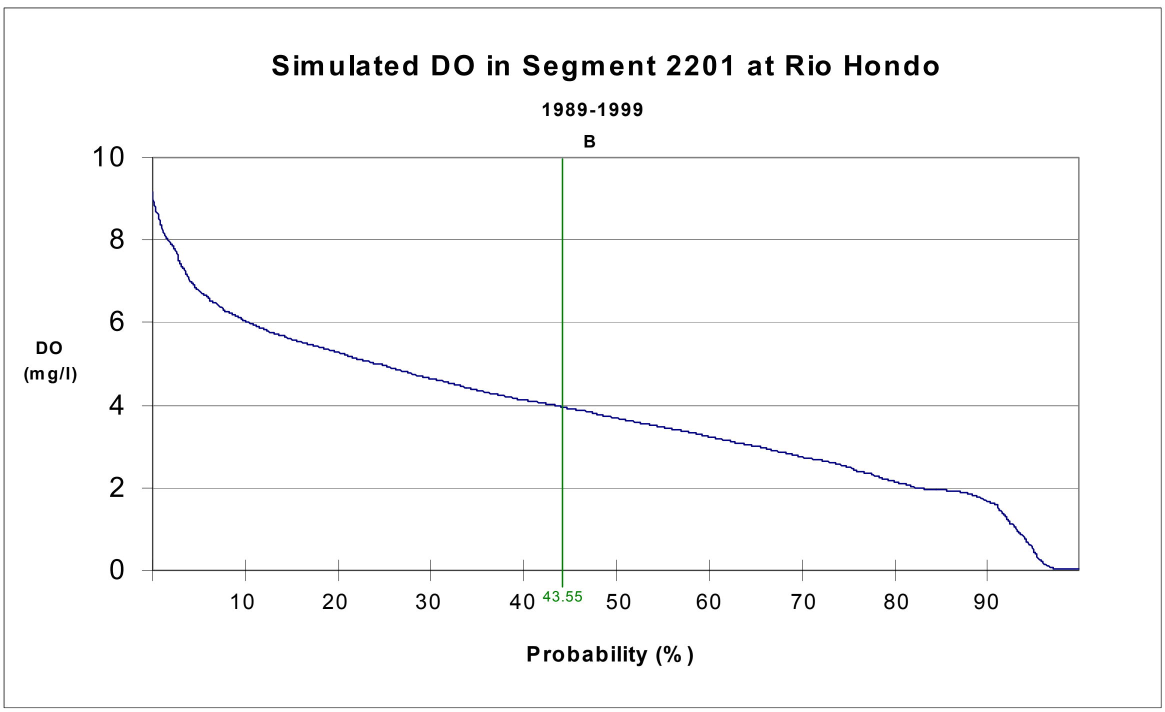


Figure 13. Probability distributions of simulated DO concentrations under current (base) conditions and probabilities of meeting the DO criteria for: A. Segment 2201 at Rio Hondo using entire simulated daily average time series, B. Segment 2201 at Rio Hondo using simulated daily average values for the periods between March 15 through October 15 of every year simulated.

The tidal segment of the Arroyo Colorado was discretized into 86 computational elements in 27 reaches for use in the Arroyo Colorado QUAL2E water quality model. Additionally, the 27 tidal QUAL2E reaches were grouped into three separate zones which are generally of the same length and geographic location as the (large) reaches used in the discretization of the Arroyo Colorado for the HSPF watershed model (Figure 14). Input to the QUAL2E model was derived from the Arroyo Colorado HSPF watershed model described in the previous section.

The principal assumptions used to develop the modeling strategy behind the use of QUAL2E to simulate water quality in the tidal segment of the Arroyo Colorado are the following:

1. Simulation of water quality at steady-state flow conditions is an adequate method to characterize and assess the cause-and-effect relationships that exist between loadings of constituents of concern and the DO impairment observed in the tidal segment of the Arroyo Colorado.
2. Using empirical relationships derived from observed data and an assumption of essentially unidirectional flow, the mixed surface layer of Segment 2201 can be modeled as a separate and distinct hydrologic unit which can be linked to the underlying water column through a mathematical term (DO flux) which describes the attenuation of DO in the mixed surface layer as a result of the physical interaction with the underlying layer(s).

The justifications for use of the QUAL2E program to simulate water quality in the tidal segment of the Arroyo Colorado are based largely on a detailed analysis of the historical flow, water quality, and biological data available for Segment 2201 (Flowers and Hauck 2001).

The data analysis focused on factors contributing to low dissolved oxygen and reported fish kills in Segment 2201 (best available indicator of DO problems in the segment), with particular emphasis on the upper 7.1 miles. The results of the analysis revealed longitudinal and vertical gradients in salinity characteristic of tidal systems.

Although seasonal in nature, a steep density gradient was generally apparent in the water column at two to three meters from the surface. Dissolved oxygen profiles exhibited a "classical" pattern in response to density stratification, with slight atmospheric reaeration affecting the surface layer and sediment oxygen demand impacting the lower layer resulting in higher DO in the near-surface waters and very low DO in bottom waters. This "classic" DO pattern was particularly evident in the summer months due to the effects of increased temperature and algal production (Flowers and Hauck, 2001).

Dissolved oxygen levels below the criteria also appear to coincide with periods of low, steady-state flow.

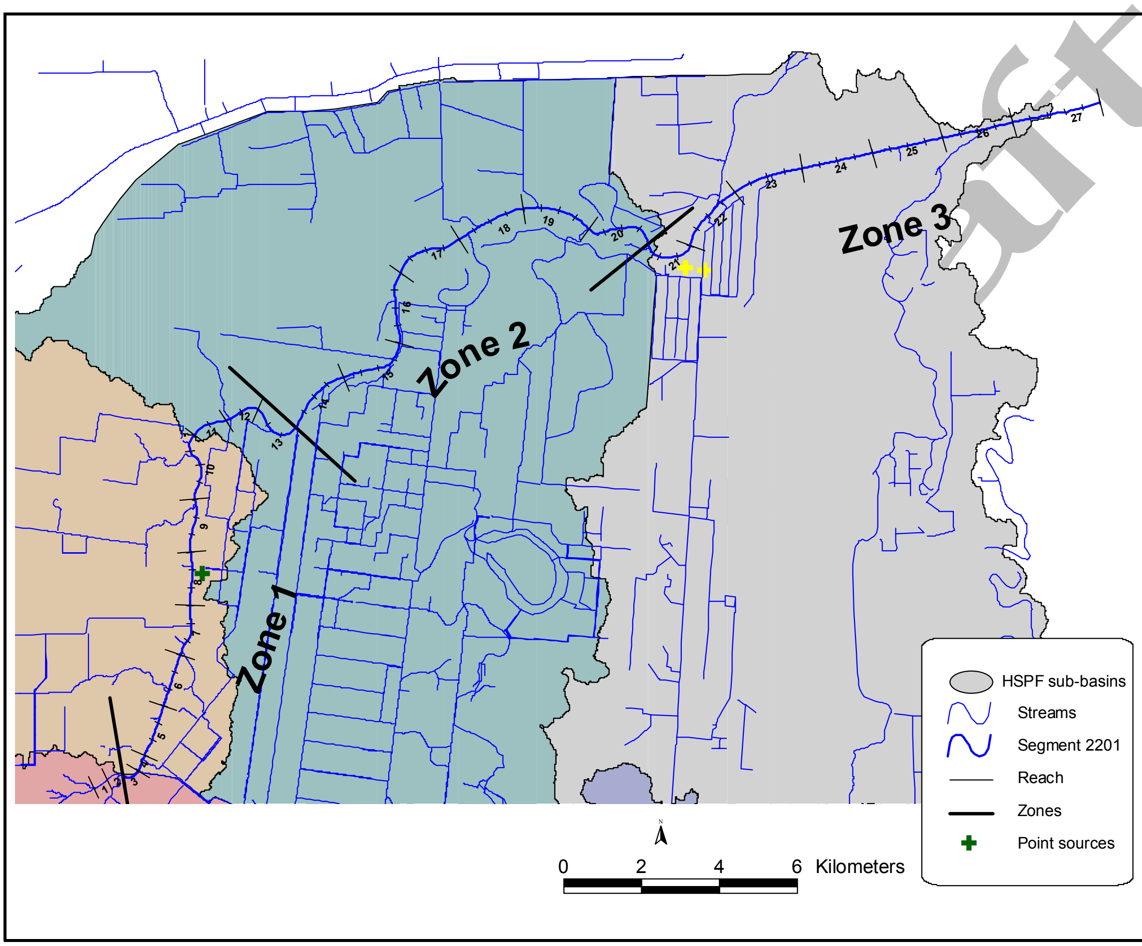


Figure 14. Stream segmentation and discretization used in the Arroyo Colorado QUAL2E water quality model.

Investigation of the occurrence of fish kills in Segment 2201 indicated that kills were much more prevalent during the summer months from May through September (Figure 15). Most fish kills were associated with steady-state, low flow conditions and the cause was frequently attributed to low DO (Flowers and Hauck, 2001).

Sufficient density of data was available in each of the three tidal zones shown in Figure 14 to develop statistically significant relationships predicting the depth of the mixed surface layer as a function of vertical mean conductivity. These statistical relationships form the basis for the estimates of depth of the surface layer used for each of the 3 tidal zones based on observed conductivity data.

Flow and salinity measurements conducted by the Texas Water Development Board (TWDB) in 1991 and 1994 in Segment 2201 also indicate the prevalence of a highly stratified body of water. A 1994 report summarizing the findings of the TWDB studies in the Arroyo Colorado observed that, at times, the lower layer of the water column is driven slowly upstream (probably in response to tidal influences and/or density differences) while the upper layer moves downstream (TWDB 1994).

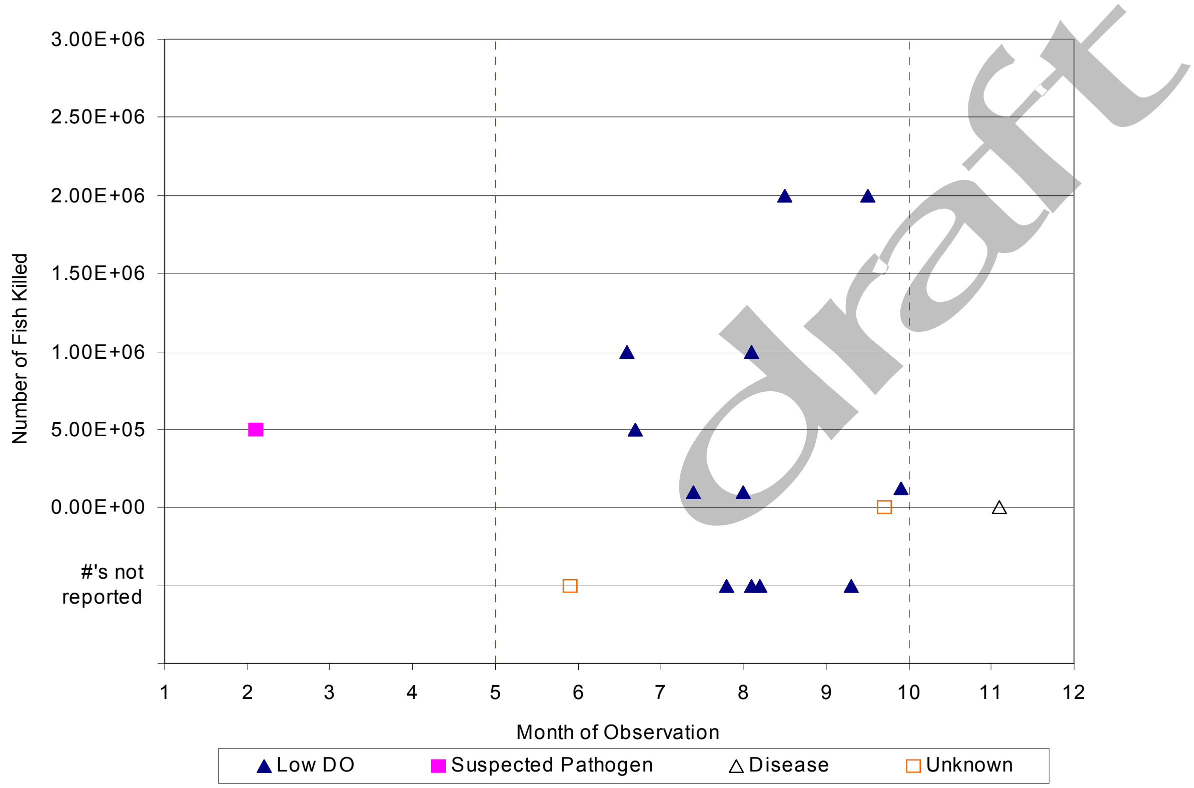


Figure 15. Graph of fish kills reported in the tidal segment of the Arroyo Colorado vs the month the kill events were observed.

Given the results of the data analysis described above, the need to evaluate water quality in the mixed surface layer of Segment 2201 (as defined in TCEQ guidance), and a desire to achieve realistic model results, the justification for applying the modeling strategy described above can be summarized with the following points (adapted from Flowers and Hauck 2001):

1. The modeling approach is the simplest approach that is feasible and technically sound.
2. The majority of DO-related fish kills and violations of the DO criteria (the focus of the TMDL modeling effort) occurred during steady-state flow conditions.
3. While not always defining the physical limits of vertical mixing, the mixed surface layer, as defined by the TCEQ, generally mimics the halocline/oxycline depth and provides a regulatory basis for endpoint determination.
4. Limited water quality data, other than DO, conductivity, and temperature exist below the mixed surface layer. This data limitation restricts the ability to calibrate and verify a model that vertically partitions the water body.
5. For modeling purposes, the mixed surface layer can be isolated from the remainder of the vertical water column and represented in a 1-D longitudinal

modeling approach. Restricting the model to the mixed surface layer avoids violating a major assumption of the 1-D longitudinal approach - that of complete vertical and lateral mixing. Consideration of the entire water column would violate this assumption due to extreme variations in the crucial water quality variable, DO, in the vertical axis. The preponderance of observational data indicate very low DO concentrations in the waters below the mixed surface layer and frequent supersaturating concentrations in near surface measurements. Vertically-averaging over the entire water column cannot resolve this DO signature. Complete vertical mixing would also diminish the magnitude of the diel DO fluctuations predicted by the model and would limit the model's ability to assess violations of the minimum DO criterion. Since diel DO fluctuations were determined to be an important factor in the impairment, modeling only the mixed surface layer addresses this aspect of the simulation more adequately.

6. Independent of the availability of vertical profile data needed to calibrate a model with vertical and longitudinal resolution, the ability of existing models, such as WASP6, EFDC and CE-QUAL-W2, to accurately predict the depth of the mixed surface layer must be questioned. Errors in the vertical and horizontal salinity gradients predicted by any model could greatly compromise the ability of the model to simulate DO concentrations in the mixed surface layer.
7. Sufficient observational data exists for the simulation period (1989-1999) to characterize the salinity and the mixed surface layer depth for each of the three tidal zones. Since salinity and depth of the mixed surface layer can be defined based on observed data, it is not necessary to model these variables; therefore, a one-dimensional modeling approach, restricted to the mixed surface layer, may be used to model DO in Segment 2201.

Under typical freshwater inflow conditions to Segment 2201, the hydraulic detention time is approximately 15 days. Twice the hydraulic detention time (30 days) was assumed to be a reasonable period for the tidal segment to reach steady-state conditions (more accurately defined as dynamic equilibrium). Therefore, inflow and constituent loadings over a 30-day period were used to define the input for the QUAL2E simulations.

Hourly predictions of flow and constituent loads from the (HSPF) watershed simulations were averaged over 30-day periods (i.e., the day simulated plus the preceding 29 days). Thirty-day mean flows and flow weighted mean concentrations were used as input to the QUAL2E model.

Having established, through the analysis of observational data, that violations of the DO criteria occur mainly in the late spring and summer months (May-October), and given the fact that most intensive data collection efforts yielding detailed spatial and temporal data sets were also performed during summer months, the following time periods were chosen for calibration and verification:

Calibration time periods	**Verification time periods**
June 16-17, 1998	August 16-19, 1999
August 5, 1998	May 19, 1998
August 12-13, 1992	August 19-20, 1996

Since the water quality data collected during these dates contained an abundance of DO values that were at or below the 4.0 mg/l criteria, these dates are also representative of critical conditions with respect to DO dynamics in Segment 2201.

A two-step process was used in performing QUAL2E simulation. The model was first run in steady-state mode and, using the models steady-state solution as initial conditions, the model was then run dynamically for a 84-hour period. Meteorological data were input at 3-hour intervals for the 84-hour dynamic simulation periods based on meteorological data processed for the HSPF watershed model.

Figure 16 shows example calibration plots for the three dates chosen for calibration of the QUAL2E model. The bars shown crossing the curve of the predicted mean DO concentrations represent the diel range in DO concentrations resulting from the dynamic simulation of the steady-state QUAL2E solution.

Figure 17 shows examples verification plots for the three dates chosen for verification.

Additional details regarding the development, calibration, and testing of the Arroyo Colorado QUAL2E water quality model, including the full set of input parameters, and calibration and verification plots, can be found in the report titled “Dissolved Oxygen Validation of QUAL2E for the Tidal Segment of the Arroyo Colorado - Segment 2201" (Flowers and Hauck 2001).

Margin of Safety

A qualitative (and when possible quantitative) discussion of the sources of uncertainty contained in the TMDL analysis presented in this document is necessary in order to describe the probable magnitude of error associated with estimates of pollutant loadings and their relationship to water quality in the Arroyo Colorado. The need for a discussion of uncertainty is also borne out of a requirement, specified in federal TMDL guidance, to include a margin of safety in the allocation of pollutant loadings as part of a TMDL. This margin of safety may be an explicit component that leaves a portion of the assimilative capacity of a water body unallocated, or an implicit component established through the use of conservative analytical assumptions (EPA 1999a).

Although the TMDL analysis presented in this document contains significant implicit safety margins built into many of the parameters and constants used in the simulations of flow and water quality, the discussion that follows focuses mainly on: 1) Qualitative descriptions of potential sources of error, 2) Quantitative and qualitative descriptions of

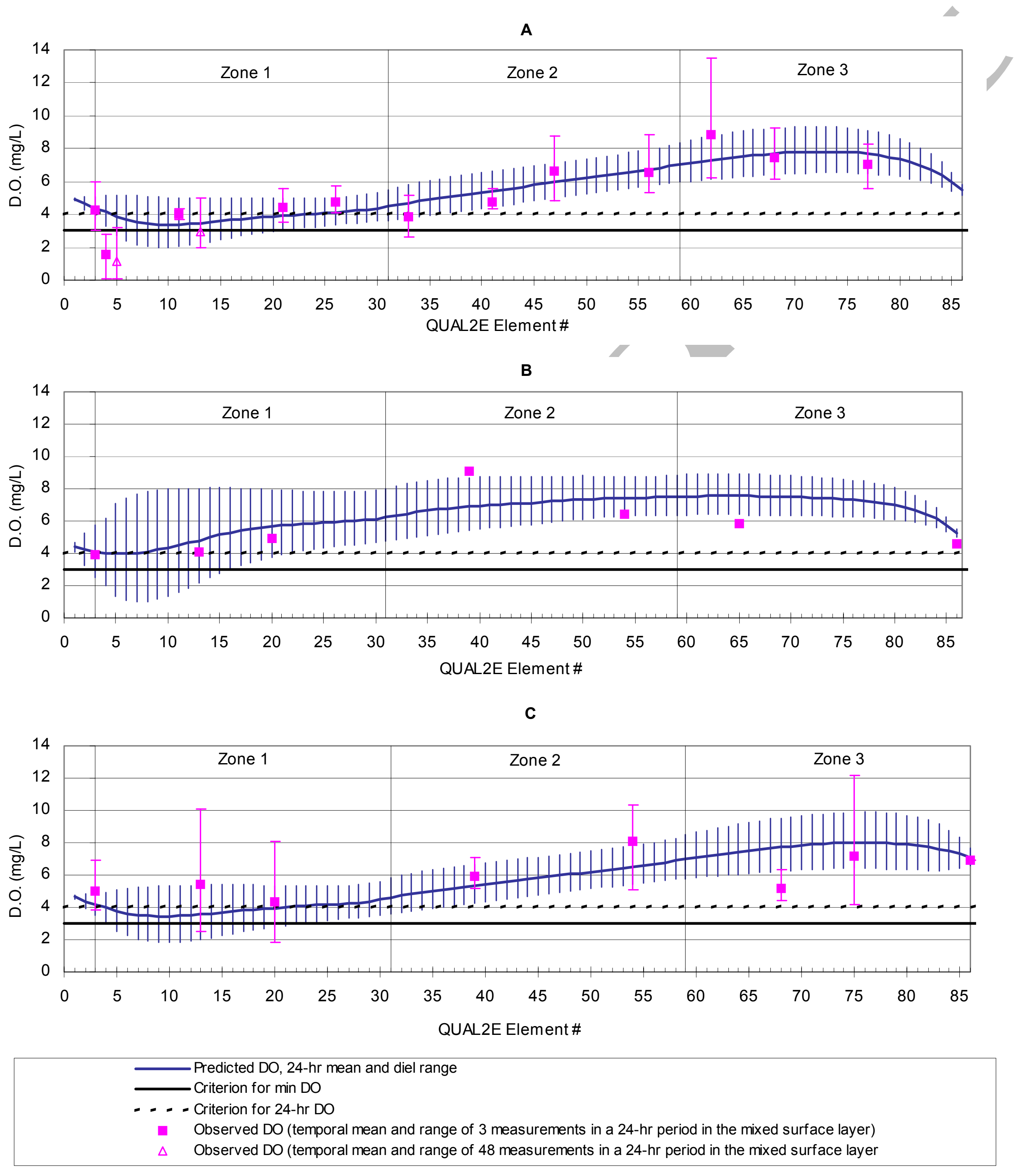


Figure 16. Observed and predicted dissolved oxygen in the tidal segment of the Arroyo Colorado for the following calibration dates: A. June 16-17, 1998, B. August 5, 1998, C. August 12-13, 1992.

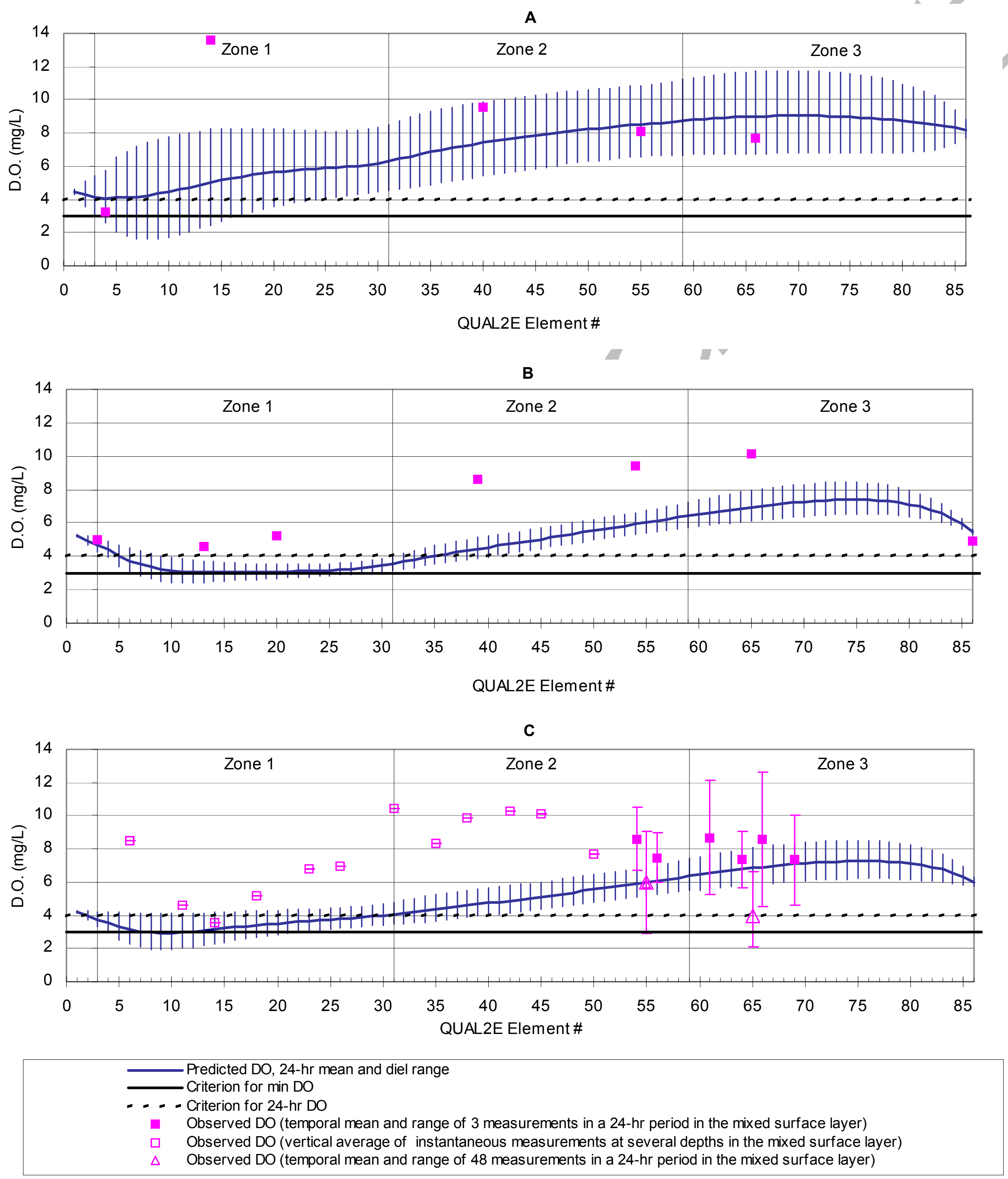


Figure 17. Observed and predicted dissolved oxygen in the tidal segment of the Arroyo Colorado for the following verification dates: A. August 16-19, 1999, B. May 19, 1998, C. August 19-20, 1996.

error in simulated values as compared to measured data (i.e., HSPEXP flow error analysis), 3) Quantitative and semi-quantitative descriptions of error associated with variation in input parameters (QUAL2E-UNCAS first-order error analysis), and 4) A discussion of the overall effect of these factors on total uncertainty associated with the study.

Sources of Uncertainty

A full accounting of the potential sources of error which contribute to the total measure of uncertainty in TMDL analysis is beyond the scope of this document. Sources of error can be found in literally every aspect of a TMDL analysis. The following are a few examples of the sources of error in most TMDL analyses:

- Measurement error in observational data
- Error associated with the inability of models to accurately represent complex natural processes mathematically (model equations and parameters)
- Error in parameter estimation (e.g., interception storage, roughness, reaeration, etc.).
- Computational limitations (e.g., time steps, number of elements, etc.)

Sources of error are not specific to any particular TMDL analysis and become reduced in time through refinement of methods and general advances in technology and research; most TMDL analyses simply compensate for the uncertainty introduced by sources of error by using conservative assumptions and model parameters.

In order to gain further understanding regarding the magnitude of uncertainty associated with a particular study, it is helpful to discuss the potential sources of error that are specific to this study. The following is a brief description of the potential sources of error specific to the Arroyo Colorado (DO) TMDL analysis:

1. Irrigation return volumes were estimated based on a combination of information which includes data on irrigation water use (i.e., monthly surface water diversions by local irrigation districts, geographic area of each irrigation district within the Arroyo Colorado watershed sub-basins, typical irrigation needs by crop type, and local irrigation practices), and flow analysis (in-stream water mass balance calculations of irrigation return inflows based on reconciliation of non-irrigation inflows to the Arroyo, evapotranspiration, and gaged in-stream flow). Because irrigation return flows were not (and currently cannot accurately) be measured directly, there is considerable uncertainty associated with the irrigation return flow volume used in the model. This is somewhat apparent in the results of the HSPF watershed model flow calibration/testing. A semi-quantitative accounting of the uncertainty associated with flow simulation at the watershed scale is presented later in this section.
2. Surface accumulation rates, surface storage limits and interflow concentrations of constituents of concern for the different permeable and impermeable land units represented in the model were estimated based on the results of published

studies (four of which were conducted in the Arroyo Colorado watershed) and also on limited, unpublished data.

3. Although data for average daily flow, suspended solids, BOD, and (in some cases) ammonia nitrogen concentrations from wastewater treatment facilities in the watershed was, for the most part, available through self-reported monthly effluent reports, data on nutrient parameters from these facilities was sparse or non-existent. This fact combined with some substantial data gaps in the self-reported effluent data and the use of average daily values for each month introduce a significant measure of uncertainty into the loading estimates from these point sources.
4. Sources of essentially untreated wastewater (i.e., colonias) in the Arroyo Colorado watershed are not well characterized. The potential error in loading estimates of constituents from these sources may be significant.
5. Background concentrations of constituents in soils, runoff, and irrigation return flows from sources such as atmospheric deposition and irrigation water are not well known. There is a potential error in loading estimates of constituents from these sources.
6. The TMDL analysis, as a whole, would benefit greatly from additional knowledge regarding several key physical and chemical input variables (i.e hydraulic parameters, reaeration rates, BOD decay rates, SOD, etc.). First order error analysis (QUAL2E-UNCAS) shows that a more detailed knowledge of the oxygen flux rate (transfer of DO the from the mixed surface layer to the lower hypoxic layer) and algal oxygen production and consumption rates in the upper portions of Segment 2201 would reduce the greatest source of uncertainty associated with the in-stream water quality modeling effort.

Comparisons of Simulated and Observed Data

To a large extent, the ability of a watershed model to accurately represent point and nonpoint source loadings into a receiving water depends on how well the model can simulate the complex hydrologic mechanisms associated with moisture storage, surface flow, interflow, and baseflow.

A measure of the accuracy of the Arroyo Colorado watershed model is revealed by the results of (HSPEXP) flow calibration and testing analysis. The Arroyo Colorado HSPF watershed model was calibrated for flow with data from 1989-95 at two flow gage stations, tested spatially with data from the same period at one flow gage station, and tested temporally with data from 1996-99 two flow gage stations using the expert system HSPEXP. The errors for total flow volume (storm flows plus base flows) ranged from -0.1 to 29.0 percent and the errors for total storm volume range from -15.6 to 8.4 percent. The errors for the total highest 10 percent flows range from -12.5 to 13.2 percent and the errors for lowest 50 percent flows range from -5.0 to 27.6 percent. The higher errors occurred in the temporal verification period 1996-1999 (USGS 2002).

The calibrated parameter set used to model water quality at the reach scale in the Arroyo Colorado HSPF watershed model adequately simulates water quality in the Arroyo

Colorado for the selected properties and constituents. Although water temperatures at the high range appear to be under-simulated, water temperature in general fits the annual cycle of measured water temperature at the three calibration sites chosen in the watershed model. Scatter in measured dissolved oxygen concentrations above and below the simulated values at upstream stations is within acceptable limits considering that simulated DO values match observed data near the zone of impairment. A lack of BOD data at the tidal boundary prevented testing of BOD simulation in the lower portions of the stream.

The QUAL2E water quality model of the Arroyo Colorado shows reasonable agreement between predicted and observed values for DO and chlorophyll *a* concentrations in the mixed surface layer of Segment 2201. Predicted mean DO values compared well with observations except for measurements taken just downstream of the Port of Harlingen turning basin in June, 1998 when the conductivity profile indicated a mixing depth extending to the bottom. Slight under-prediction of nitrate plus nitrite and over-prediction of ammonia nitrogen noted in the June 1998 critical period are probably the result of random error in parameter estimation. The largest discrepancy between the values predicted by the QUAL2E water quality model of the Arroyo Colorado and observed data occurs in the simulation of BOD, which is significantly under-predicted in all three zones of the tidal segment. It should be noted, however, that a general lack of historical BOD data prevented rigorous calibration of this parameter in both the watershed and water quality models (due to the expense associated with the analysis, this parameter the TCEQ and predecessor agencies dropped BOD from routine monitoring

Sensitivity and Error Analysis

Two techniques were used to quantify the sensitivity and uncertainty associated with QUAL2E model predictions for the tidal segment of the Arroyo Colorado, the sensitivity analysis and first order error analysis options. Since the TMDL analysis focuses on DO, the sensitivity and uncertainty analysis also focuses on DO as a response variable and further concentrates the interpretation on zone 1 near the region of maximum DO sag (element 6).

Inspection of the sensitivity analysis results for the six index periods simulated indicate the results are generally similar for all periods. The June 1998 index period (May 19, 1998 through June 17, 1998) was selected as a representative period for average headwater concentrations. The sensitivity and uncertainty analysis were performed on the steady-state solution for the June 1998 index period.

Results of the sensitivity analysis indicate that predicted DO in the tidal segment in general, and in the zone of impairment in particular, displayed the highest sensitivities to input parameters defining algal photosynthesis and respiration. Four input parameters defining algal oxygen production and consumption in QUAL2E are:

- algal maximum species growth rate (AGYGROMX),
- oxygen production by algal growth (AGYOXYPR),
- algal respiration rate (AGYRESPR), and

- oxygen uptake by algal respiration (AGYOXYUP).

AGYGROMX and AGYOXYPR contributed 14 percent and 13 percent respectively to the total variance of DO in element 6. AGYRESPR and AGYOXYUP contributed about 9 percent each to DO variance in element 6 (Figures 18-19). Results of the sensitivity analysis for other input parameters such as SOD rate, reaeration rate (K2-OPT), initial temperature (INITTEMP), and headwater DO (HWTRDO), and chlorophyll *a* (HWTRCHLA) are shown in Figures 19 and 20.

The greatest single contributor (21 percent) to the DO variance at element 6 was the SOD rate, which, in the Arroyo Colorado model application, represents the oxygen flux values specified for the transfer of DO across the halocline. The high variance values for the SOD parameters underscore the need to gain a greater understanding of the physical processes associated with the transfer of DO across the halocline in the upper portion of Segment 2201. Additional details regarding the sensitivity and uncertainty analysis of the Arroyo Colorado QUAL2E Water Quality Model, including the full set of input variables, resulting coefficients of variance, and resulting percent variances, can be found in Flowers and Hauck 2002.

Uncertainty and Margin of Safety

The previous discussion on uncertainty describes the relative importance of the sources of uncertainty in the Arroyo Colorado TMDL analysis and also provides a quantitative (or semi-quantitative) description of several additional aspects of uncertainty found within the TMDL analysis. However, given the breadth and potential magnitude of the sources of uncertainty in the various areas discussed, it is difficult to quantify the overall effect of all factors of uncertainty on the study. The effects of some factors of uncertainty may be compounded or counteracted by the effects of others. For example, if errors in the loading estimates have the effect of over predicting loads, the effect of simultaneously over-predicting flow volumes would have a compensating effect on resulting concentrations. However, if watershed loads are overestimated, simultaneous underestimation of constituents sinks (from in-stream processes) may have the effect of severely under-predicting true assimilative capacity in the stream.

Below is a summary of the magnitude of error(s) estimated for the principle components of uncertainty described in the sections above:

Uncertainty Factor	Maximum Percent Error Range
Watershed Loading Estimates	unknown
Watershed Flow Simulation	-0.1 to +29.0
QUAL2E Water Quality Input variables	-20.4 to +20.7

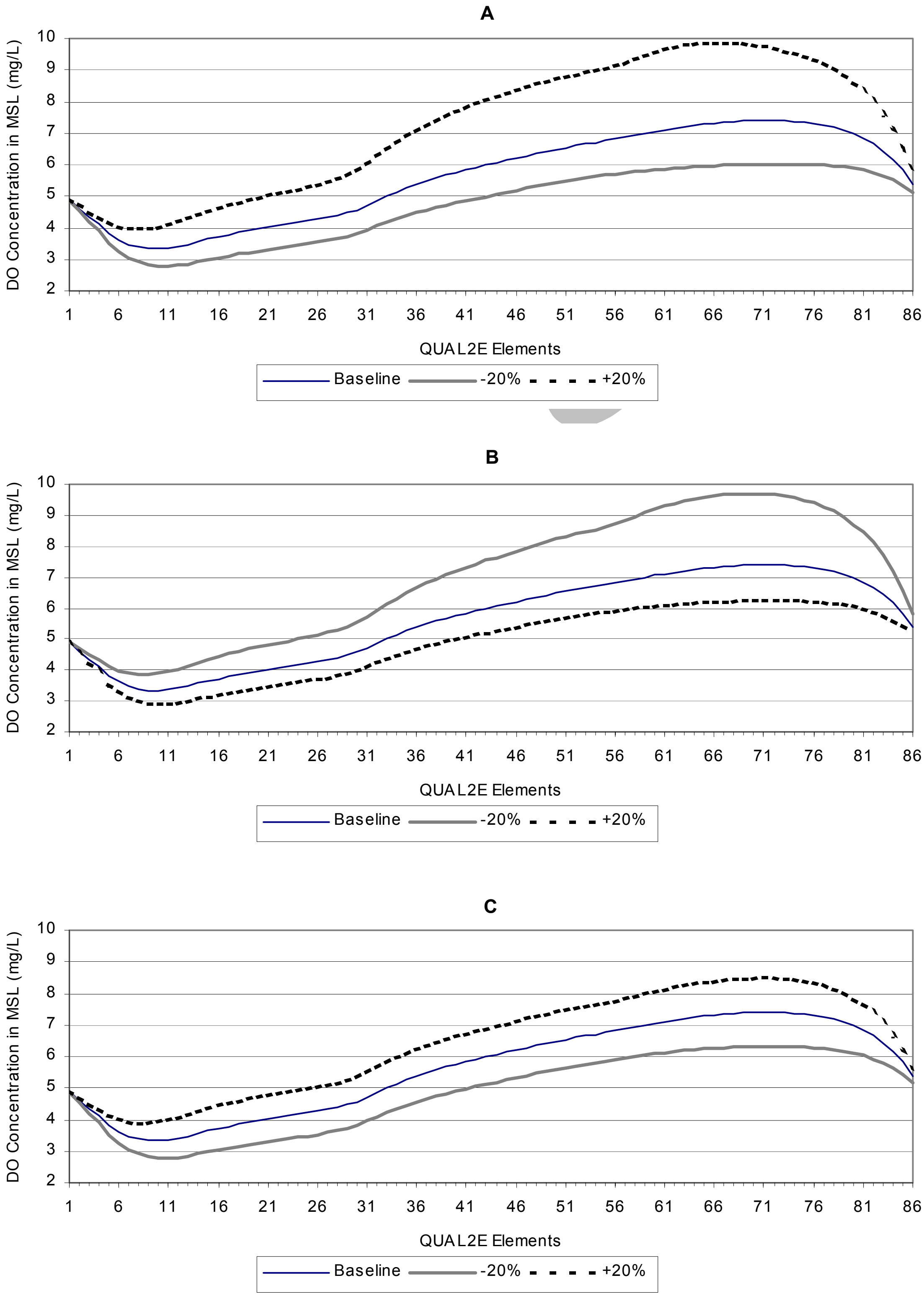


Figure 18. Sensitivity analysis for the response variable dissolved oxygen in the tidal segment of the Arroyo Colorado for the following input variables: A. AGYGROMX, B. AGYRESPR, and C. AGYOXYPR (from Flowers and Hauck, 2002).

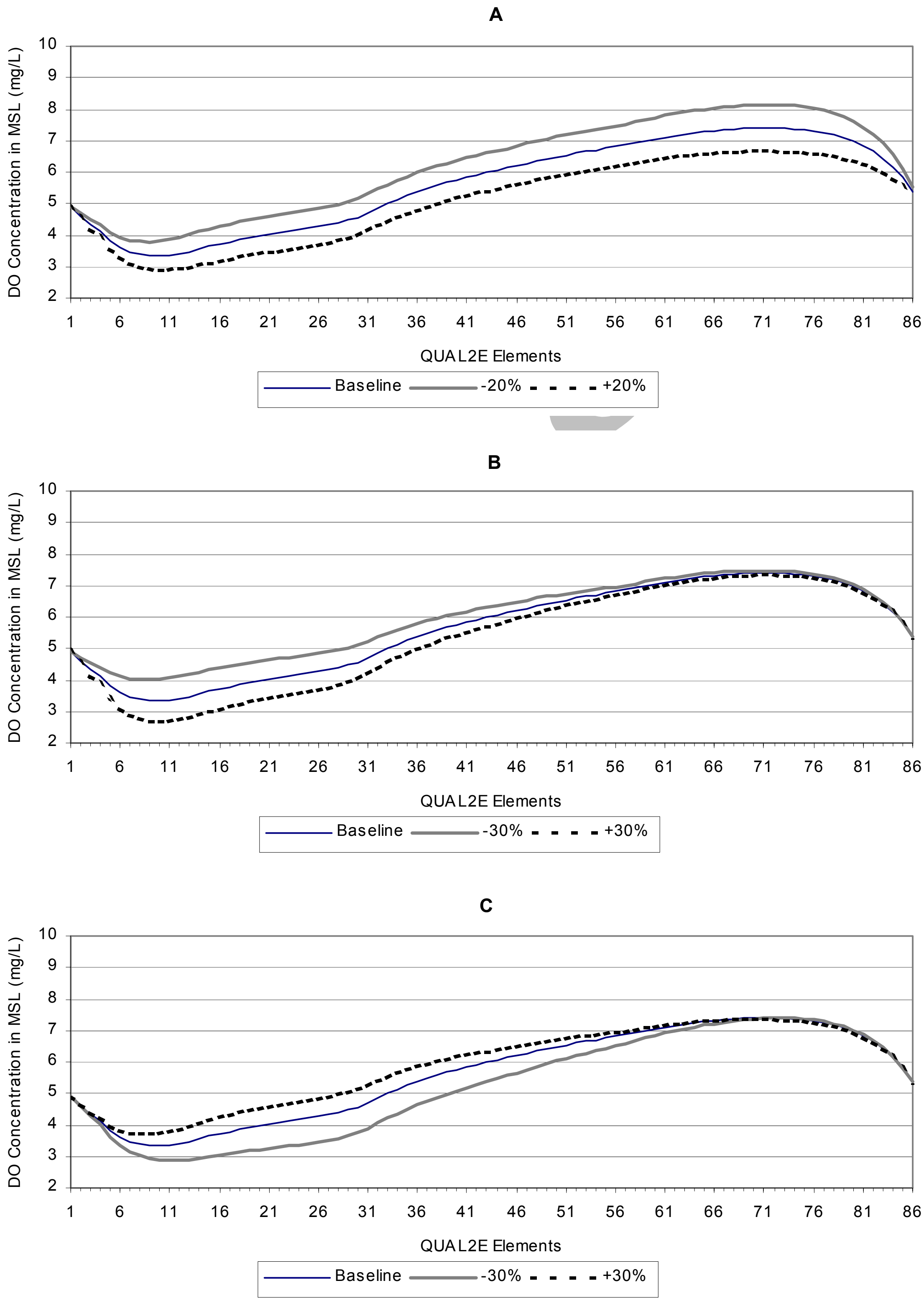


Figure 19. Sensitivity analysis for the response variable dissolved oxygen in the tidal segment of the Arroyo Colorado for the following input variables: A. AGYOXYUP, B SOD rate (DO flux), and C. K2-OPT1 (from Flowers and Hauck, 2002).

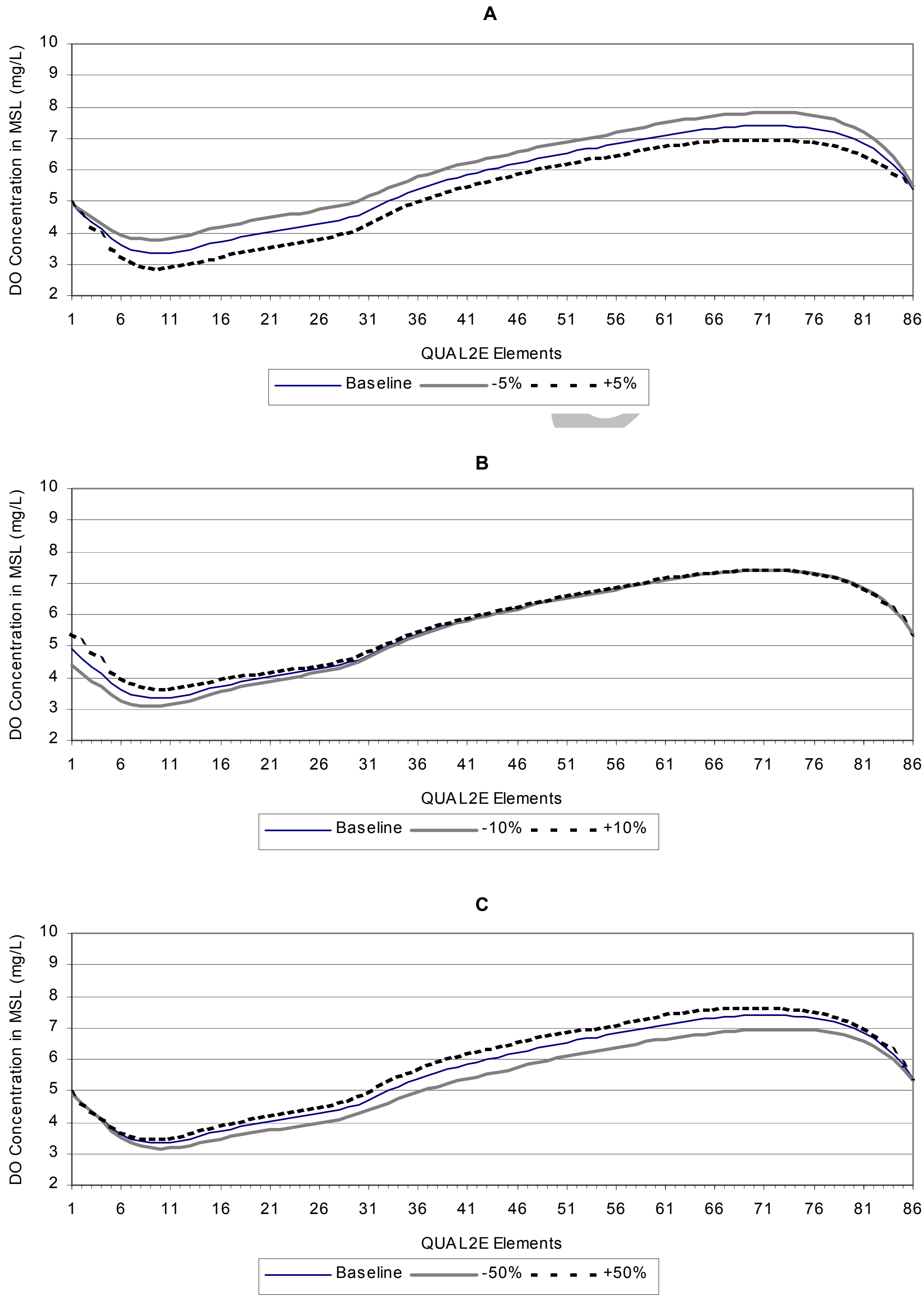


Figure 20. Sensitivity analysis for the response variable dissolved oxygen in the tidal segment of the Arroyo Colorado for the following input variables: A. INITTEMP, B HWTRDO, and C. HWTRCHLA (from Flowers and Hauck, 2002).

Uncertainty associated with one of the most important sources of error in the Arroyo Colorado TMDL analysis, watershed loading estimates, is one of the least quantifiable at this time. This is only one of the reasons why it is not possible to accurately estimate a viable margin of safety for the current Arroyo Colorado TMDL analysis based on available information. As will become apparent in the following section, an attempt to estimate a margin of safety (that leaves a portion of the assimilative capacity of the Arroyo Colorado unallocated) is actually not warranted in this study.

Loading Allocation

As stated in the introduction section of this document, the TMDL analysis presented herein does not support a quantitative, water quality target-based allocation of loadings of constituents associated with dissolved oxygen dynamics in the tidal segment of the Arroyo Colorado. This is due, in part, to the important role played by the physical modifications imposed on the Arroyo Colorado which have the effect of exacerbating the frequency and magnitude of episodes of anoxia in the mixed surface layer. A quantitative, water quality target-based allocation of loadings is also problematic due to a general inability of the DO criteria applied to the Arroyo to take into account episodes of low dissolved oxygen that are the result of naturally occurring conditions. However, the TMDL analysis does show that improvements in water quality and a potential reduction in the environmental stresses to aquatic life can be achieved through the reduction of nutrients, BOD, and sediment loadings into the Arroyo Colorado.

The effect(s) of reductions in loadings of constituents of concern on dissolved oxygen concentrations and other selected water quality parameters in the mixed surface layer of the tidal segment of the Arroyo Colorado were simulated under a number of load reduction scenarios. Detailed spatial analysis of the effects of loading reductions were conducted for the six index periods chosen for the QUAL2E simulations. Temporal analysis of the effects of loading reductions were conducted using the 11-year dynamic simulation output provided by the Arroyo Colorado (HSPF) watershed model.

Three load reduction scenarios were chosen for discussion in this document (20%, 50%, and 90%). Due to the absence of a limiting nutrient parameter and the low sensitivity of the water quality model to headwater BOD and chlorophyll *a* concentrations, the percent reductions in loadings shown in the different scenarios represent across-the-board reductions in loadings for all constituents of concern by the same percentage (e.g., the 20% load reduction scenario represents a 20% reduction in BOD loading, plus a 20% reduction in ammonia N loading, plus a 20% reduction in NO_3+NO_2 N loading, plus a 20% reduction in PO_4P loading, etc.). It should be noted, that flow volumes were not altered during the load reduction runs and remain the same in each scenario.

Figures 21 and 22 show QUAL2E simulations of dissolved oxygen concentrations in the tidal segment of the Arroyo Colorado resulting from the reduction of loadings of constituents of concern by 20%, 50%, and 90%. Although the simulation periods shown in these figures correspond only to the June 1998 and August 1992 index periods, similar results were observed for all other simulation index periods.

The load reduction scenario simulation results show that the measurable effects of constituent loading reductions on dissolved oxygen concentrations in zone 1 of Segment 2201 (the zone of impairment) are very small for the 20% and 50% reduction scenarios; the most visible effects being an apparent attenuation of diel ranges in dissolved oxygen concentrations. In some cases, the load reduction scenarios show a slight lowering of the mean DO in zones 2 and 3. The 24-hour average DO concentrations in zone 1 do not appear to change significantly in any of the load reduction scenarios except for the 90% load reduction scenario, which shows an appreciable increase in the 24-hour average and minimum DO concentrations, especially in Figure 22.

The results of the scenario simulations shown in Figures 21 and 22 can be considered reasonable if, as suspected, the DO dynamics in the upper portion of Segment 2201 are dominated by the potentially high DO sink represented by the DO flux variable in this portion of segment. The loss of oxygen from the mixed surface layer to bottom waters is most likely influenced by the concentration gradient between layers and the natural vertical mixing process (vertical velocity shear). Anecdotal evidence and some observational data suggests that much of the suspended solids load (some of it particulate organic matter) from the non-tidal segment is deposited in the region of the turning basin of the port of Harlingen (upper portion of Segment 2201) due to decreasing velocities as the channel widens. It is believed that this mechanism contributes to high SOD values in this portion of the stream. Oxygen flux values are, therefore, thought to be highest in the upstream portion of Segment 2201 and decrease progressively downstream along the length of the segment.

As is apparent from Figures 21 and 22, only one of the load reduction scenarios presented above resulted in compliance with the 24-hour DO criteria (the 90% load reduction scenario) and that slightly lower average DO values resulted in zones 2 and 3 under all load reduction scenarios. However, the attenuation of diel ranges in dissolved oxygen concentrations in the most of the scenario simulations may nevertheless constitute an improvement in overall conditions for aquatic life use in the segment by reducing diel stress to nectonic organisms.

Simulations of load reduction scenarios using the Arroyo Colorado QUAL2E Water Quality model are useful for identifying detailed spatial (and temporal) diel changes in dissolved oxygen concentrations in the mixed surface layer of the tidal segment of the Arroyo Colorado during time periods in which steady-state conditions predominate. However, to determine compliance with the TMDL endpoint target specified in the "Endpoint Identification" section of this document, a probability of compliance with the DO criteria must be established for each of the load reduction scenarios.

Figure 23 shows the frequency distributions (March 15 - October 15 for years 1989-1999) of simulated DO concentrations in the mixed surface layer in the uppermost reach of Segment 2201 (Rio Hondo) for two of the load reduction scenarios discussed above (20% and 50% reductions). These graphs were constructed using output from the Arroyo HSPF

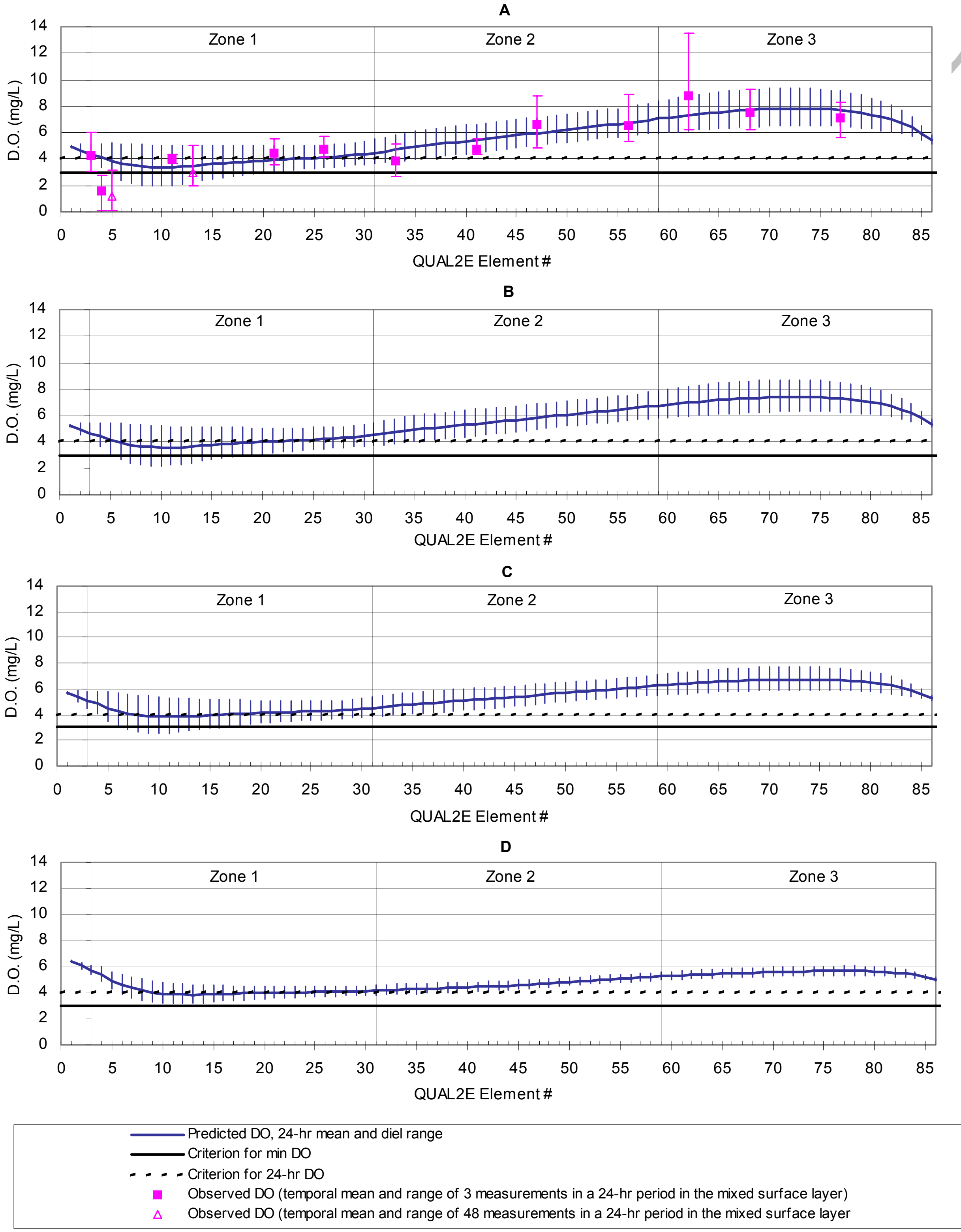


Figure 21. Predicted DO in the tidal segment of the Arroyo Colorado for the simulation index period of June 16-17, 1998. A. Base scenario, B. 20% load reduction scenario, C. 50% load reduction scenario, and D. 90% load reduction scenario.

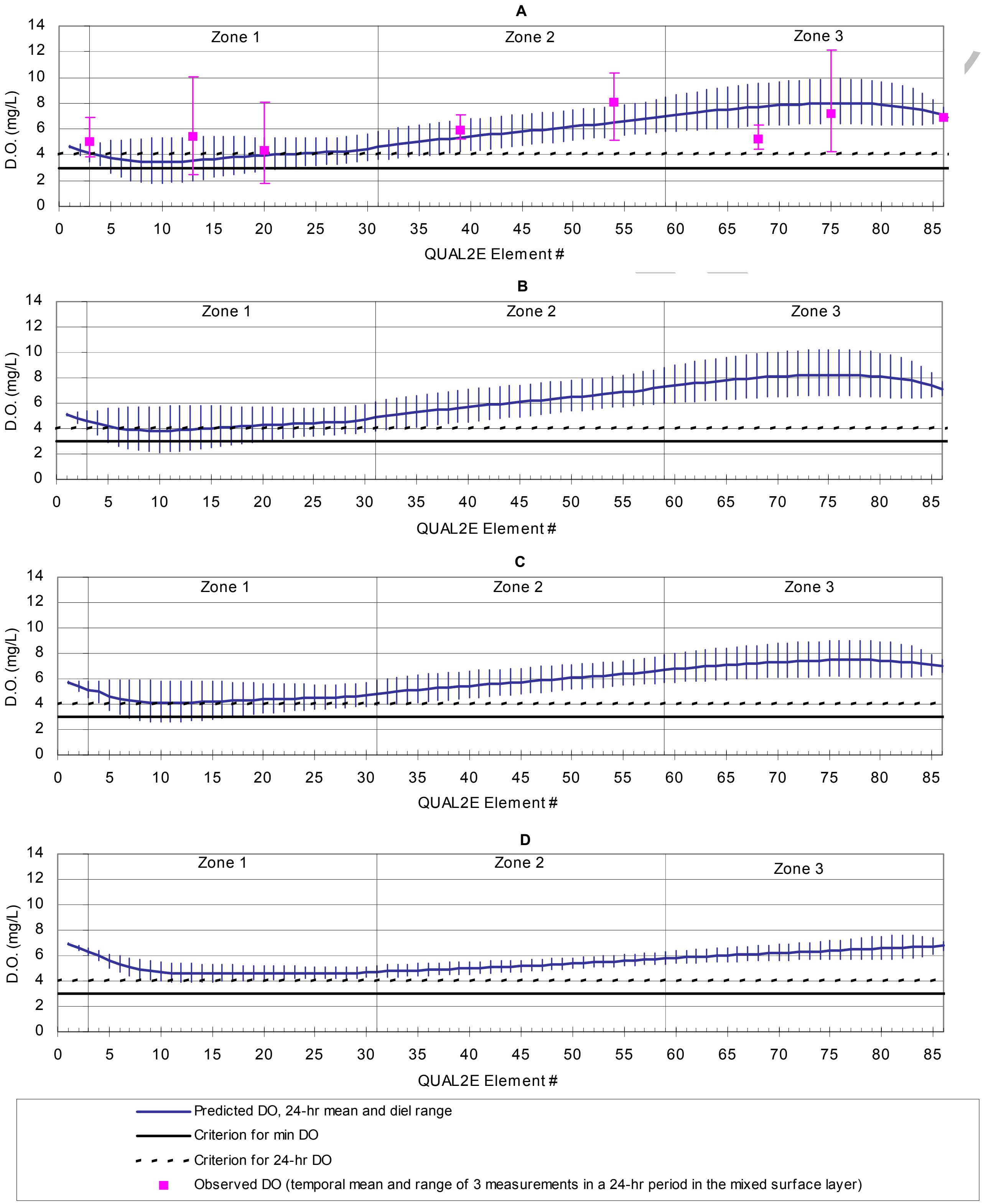


Figure 22. Predicted DO in the tidal segment of the Arroyo Colorado for the simulation index period of August12- 13, 1992. A. Base scenario, B. 20% load reduction scenario C. 50% load reduction scenario, D. 90% load reduction scenario.

model. The graphs show that, although the probability of compliance with the 24-hour DO criteria improves, the endpoint target of 90% probability of compliance is not met in either load reduction scenario. In fact, after numerous iterations and load reduction scenario simulations using HSPF, the endpoint target of 90% compliance was met only after a 90% reduction in loadings of constituents of concern was achieved (Figure 24).

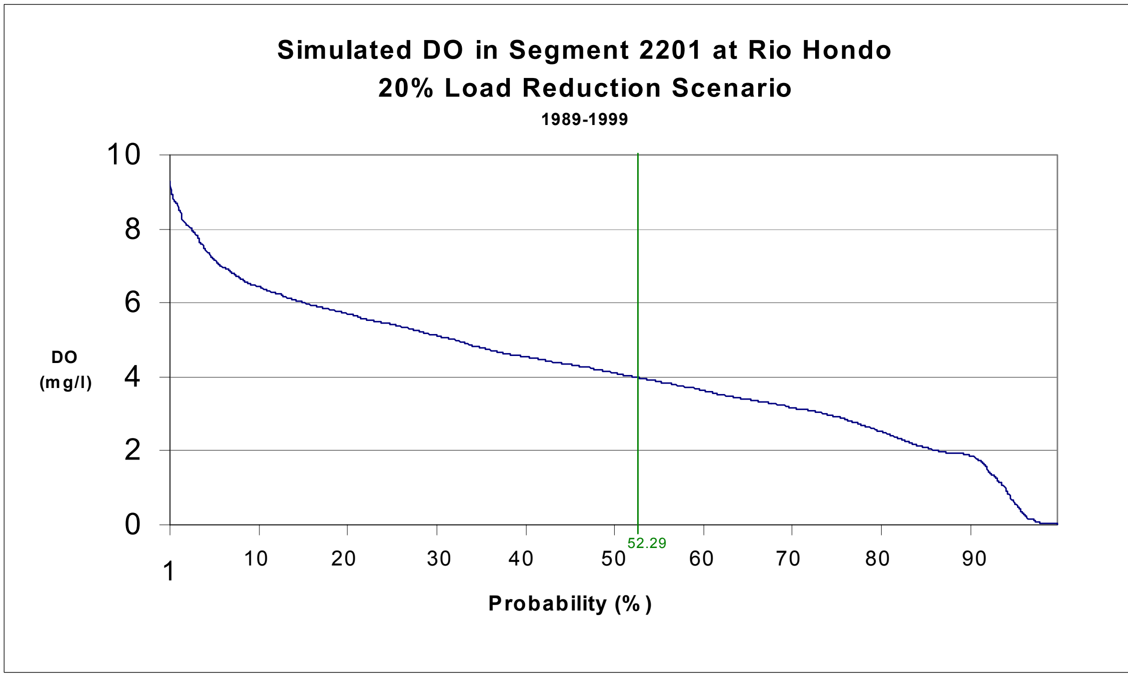
In order to appreciate the magnitude of change in loading that a 90% load reduction scenario in the Arroyo Colorado watershed would represent, one must put these loading reductions into context. To do this, it is helpful not only to calculate the total reduction in mass of constituents necessary to achieve the TMDL endpoint target (e.g. 5.6 tons/day of total nitrogen, 0.6 tons/day of total phosphorus, and 11.1 tons/day of BOD, as per average year of simulation), it is also helpful, for comparison purposes, to develop an estimate of the loadings of constituents of concern that would be expected in the Arroyo Colorado watershed under natural conditions. This estimate of natural loadings was accomplished by performing an HSPF simulation of the Arroyo Colorado watershed under natural conditions; that is, having removed all anthropogenic point and nonpoint sources from the input file and having converted all land use and land cover to natural land (i.e., natural herbaceous, trees and shrubs).

Figure 25 shows a graph of the frequency distribution of DO concentrations predicted for the natural loading scenario (March 15 - October 15 for years 1989-1999). It is interesting to note that the frequency of compliance with the 4.0 mg/l criteria shown in Figure 25 is similar to that of the base (current) condition (see Figure 13).

A detailed view of the spatial (and temporal diel) changes in dissolved oxygen concentrations that could be expected in the mixed surface layer of the tidal segment of the Arroyo Colorado under a natural loading scenario during critical periods is exemplified by some of the QUAL2E simulation index periods is presented in Figure 26.

The predicted DO concentrations shown in Figure 26, resulting from QUAL2E simulations under natural loading conditions, underscore the potential contributions of the physical setting to the DO dynamics observed in the tidal segment of the Arroyo Colorado. Unlike the load reduction scenarios presented in Figures 21 and 22, the predicted response in DO concentrations in the mixed surface layer to the reduction in loading and flow volume represented by the natural loading scenario is a notable decrease in average DO values in the upper portion of Segment 2201 and very small ranges in diel DO fluctuations for all simulation index periods.

The predicted low range in diel DO fluctuations shown in Figure 26 can be attributed to the decrease in nutrient concentrations associated with the natural loading scenario. The low DO ranges, along with the lower average DO values, are indicative of a decrease in primary productivity in Segment 2201 and reveal the relative importance of algal productivity as a source of dissolved oxygen and a counteracting factor to dissolved oxygen flux across the halocline and low reaeration rates in the zone of impairment.



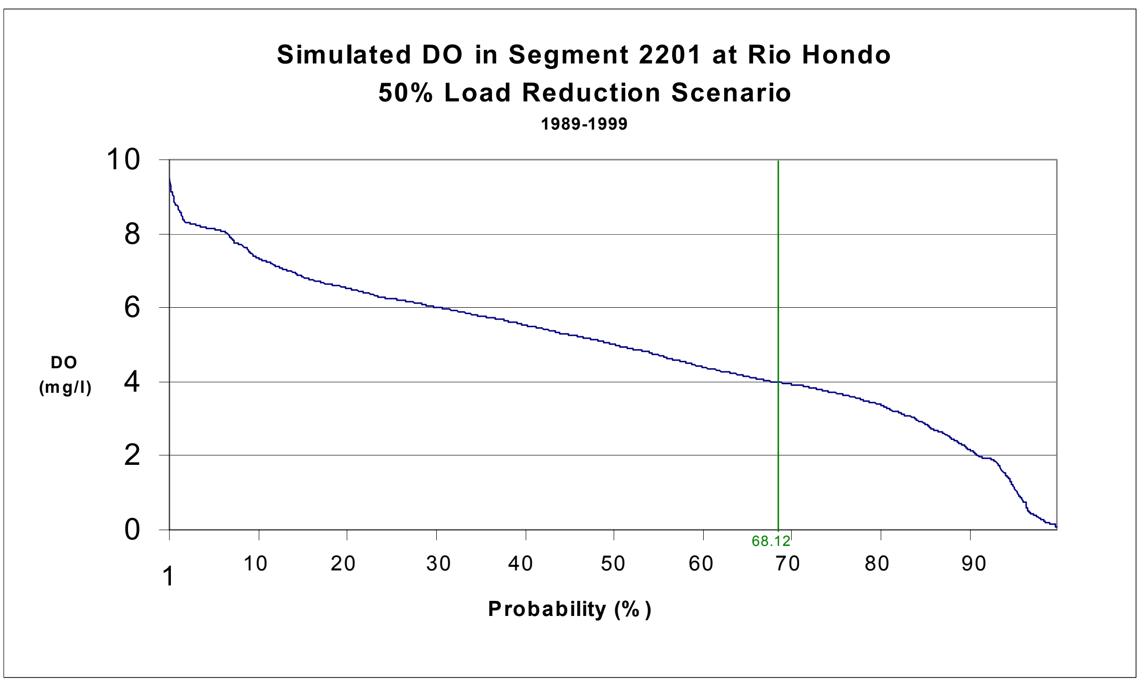


Figure 23. Probability distributions of predicted daily average DO concentrations and probabilities of meeting the DO criteria for scenarios of 20% and 50% reduction of constituents for the periods between March 15 through October 15 of every year simulated.

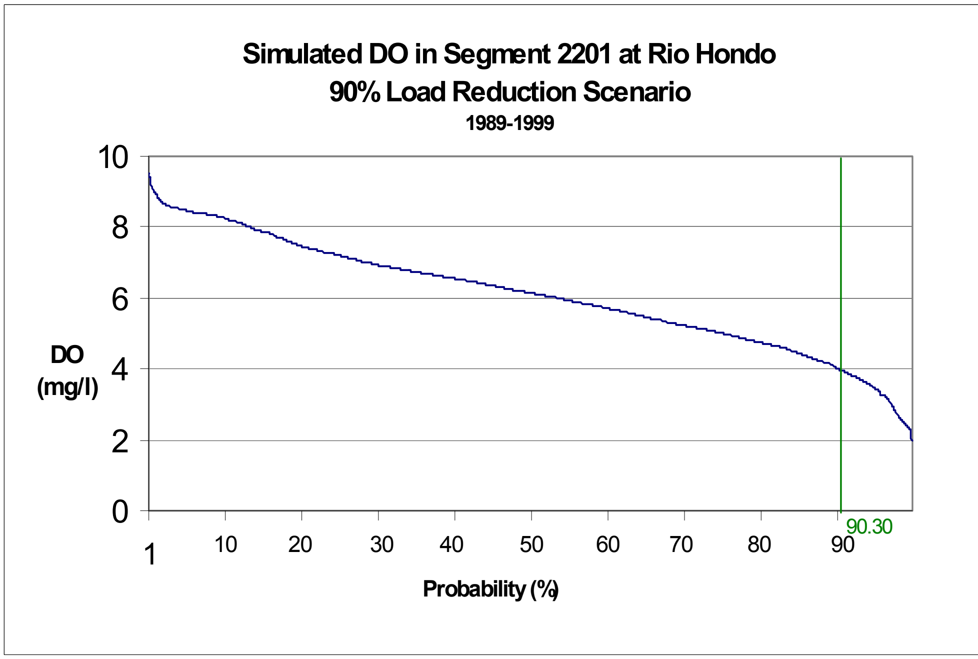


Figure 24. Probability distributions of predicted daily average DO concentrations and probabilities of meeting the DO criteria for a scenario of 90% reduction of constituents for the periods between March 15 through October 15 of every year simulated.

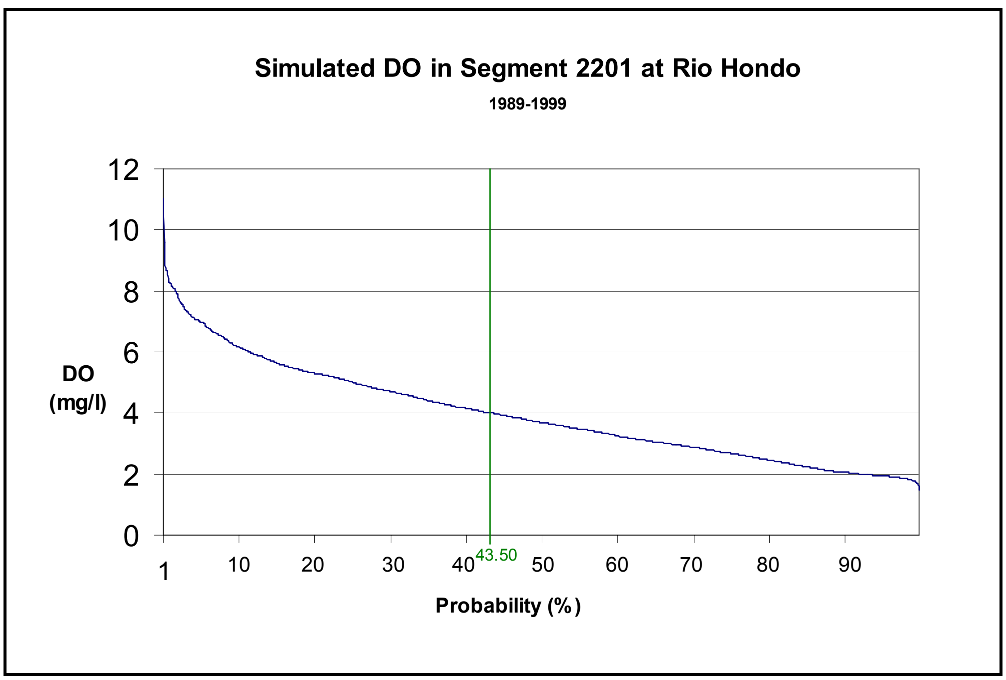


Figure 25. Predicted daily average DO concentrations in the mixed surface layer of the tidal segment of the Arroyo Colorado at Rio Hondo under a natural loading scenario and probability distribution (March 15 through October 15 of every year simulated) and probability of meeting the DO criteria under a natural loading scenario.

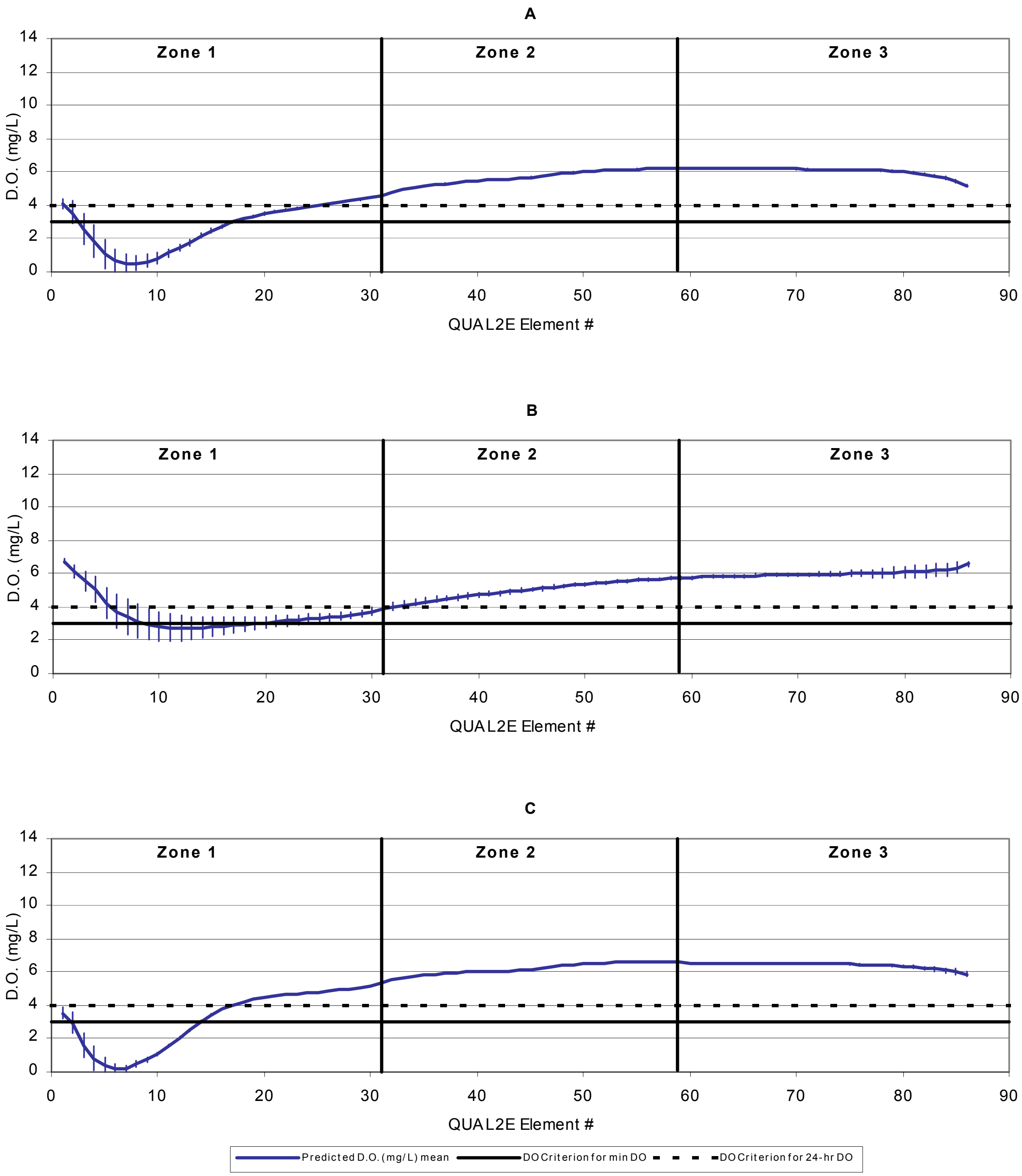


Figure 26. Predicted dissolved oxygen in the tidal segment of the Arroyo Colorado under a natural loading scenario for the simulation index periods of: A. June 16-17, 1998, B. August 12-13, 1992, and C. August 19-20, 1996.

Analysis of HSPF simulation output for the natural loading scenario and the 90% loading reduction scenario discussed previously (see Figure 24) reveals that loading of constituents of concern into zone 1 of Segment 2201 under a 90% loading reduction scenario are comparable to the loadings estimated under a natural loading scenario. The results of this analysis imply that even at much higher (anthropogenically augmented) flow volumes, the Arroyo Colorado is unable to assimilate loadings in excess of what would be expected under natural conditions. It should also be noted that, even under natural flow volumes and loadings, the Arroyo Colorado would meet the current DO criteria only 43.5% of the time, which is about as often as the DO criteria is currently met.

The analysis described above leads to the conclusion that the physical setting in the Arroyo Colorado (and in particular in zone 1 of Segment 2201) contributes significantly to the observed DO impairment in the tidal segment of the Arroyo Colorado and that even extreme reductions in the loading of constituents of concern into the Arroyo Colorado will not achieve the TMDL endpoint target described in the "Endpoint Identification" section of this document without mitigating the effects of some of the physical modifications imposed on the Arroyo Colorado (i.e., dredged channel, leveed and/or raised banks, lack of riparian habitat, etc.)

Given the conclusions stated above, the TMDL analysis presented herein does not support a quantitative, water quality target-based allocation of loadings of constituents associated with dissolved oxygen dynamics in the tidal segment of the Arroyo Colorado. However, the analysis does show improvements in water quality and a potential reduction in the environmental stresses to aquatic life can be achieved through the reduction of nutrients, BOD, and sediment loadings into the Arroyo Colorado. There is also evidence that reductions of constituent loadings into the Arroyo Colorado would also greatly benefit aquatic life in the Laguna Madre, an important downstream receiving water body which is also currently thought to suffer from nutrient over-enrichment. Efforts to improve water quality in the Laguna Madre should, therefore, include mechanisms for reduction of constituent loadings entering the Arroyo Colorado.

Discussion and Conclusions

The TMDL analysis presented in this document is a useful tool for designing a Watershed Action Plan to address the dissolved oxygen impairment observed in the upper portion of the tidal segment of the Arroyo Colorado. Although the analysis does not support an allocation of constituents of concern among sources in the watershed, the knowledge gained through the study of the water body can be used as a foundation for achieving the ultimate goal stated at the beginning of this document, which is to provide the basis for developing a viable strategy to develop, attain and maintain a DO criterion that is protective of the appropriate beneficial aquatic life use in the tidal segment of the Arroyo Colorado.

Recommendations for designing a Watershed Action Plan based on the knowledge gained through the Arroyo Colorado TMDL analysis can be summarized into the following points:

1. Loadings of total nitrogen, total phosphorus, BOD, and sediment into the Arroyo Colorado should be reduced to levels that are technically achievable with consideration given to economic viability issues. Better compliance with existing TPDES permit limits should be achieved through increased enforcement efforts and by upgrading existing treatment methods in several POTWs. Reductions in nonpoint source loadings should be achieved through increased emphasis of existing state and federal voluntary cost-share programs in the watershed.

2. Aquatic habitat in the Arroyo Colorado should be improved to mitigate the environmental stresses currently being experienced by indigenous aquatic life. The physical anthropogenic modifications which currently characterize the tidal segment of the Arroyo Colorado must be changed or compensated for through additional modifications in order to improve aquatic habitat. For example, low reaeration rates in the upper portion of the tidal segment of the Arroyo Colorado are thought to be influenced by the depth of entrenchment of the (dredged) channel and the placement of dredge spoils along the channel banks which may have the effect of blocking wind action. In addition to in-stream and riparian modifications such as the building of settling basins and reaeration structures (EPA 1996), management practices such as proper placement or alternative disposal of dredge spoils should also be considered. Among the factors that influence DO dynamics is DO and nutrient loading from Segment 2202. In addition to reductions in contaminant loadings, increasing the assimilative capacity as well as the dissolved oxygen content in the above-tidal segment would greatly improve water quality in Segment 2201. Therefore, improvements in physical habitat should not be limited to Segment 2201.

3. Given the questions surrounding the appropriateness of the DO criteria currently applied to this (and other) tidal stream(s) located along the Texas Gulf Coast, a review of the applicability of the current DO criteria to the Arroyo Colorado should be conducted. The review should include updated biological information and water quality monitoring data. The review should also consider the altered physical nature of the water body and it's relationship to use attainability.

4. Biological, flow, and water quality monitoring in the Arroyo Colorado should be continued and enhanced. In order to improve understanding of the cause-and-effect relationships associated with the DO impairment observed in Segment 2201 and also to provide a means to establish more detailed water quality trends. A monitoring program similar to that currently in existence should continue to monitor changes in constituent concentrations in (and loadings into) the Arroyo Colorado. Monitoring should also include long-term biological sampling and continuous profile monitoring in the upper reaches of Segment 2201 (specifically at the Port of Harlingen turning basin and at Rio Hondo). This monitoring is needed in order to establish trends and to gain a better understanding of the relationship between DO concentrations in the

mixed surface layer and hydrodynamics in the tidal segment of the Arroyo Colorado.

5. Characterization of watershed loadings, in-stream rates and constants, and DO dynamics in the Arroyo Colorado should be improved to enhance understanding of the cause-and-effect relationships between flow, loadings, biochemical interactions, and physical setting. Studies should include edge-of-field measurements of flow and constituent concentrations resulting from runoff and irrigation events, measurements of irrigation return flow volumes, direct monitoring of nutrient loading from municipal wastewater facilities, measurements of SOD in the upper portion of Segment 2201, measurements of nutrient cycling and algal productivity, measurements of particulate organic matter loadings from various sources in the watershed, and measurement of the deposition and accumulation rates of particulate organic matter in the upper portion of Segment 2201. The results of the data collection efforts described above would be used to enhance the sophistication of modeling efforts and to refine the overall TMDL analysis of the Arroyo Colorado.

6. More detailed hydrodynamic modeling should be conducted on the tidal segment of the Arroyo Colorado in order to better characterize the effects of the complex hydraulic environment which exists in Segment 2201. Additional data collection should be conducted to document kinetic rates, productivity parameters, and nutrient cycling parameters for use in the hydrodynamic model.

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