SWAT Modeling of the Arroyo Colorado Watershed

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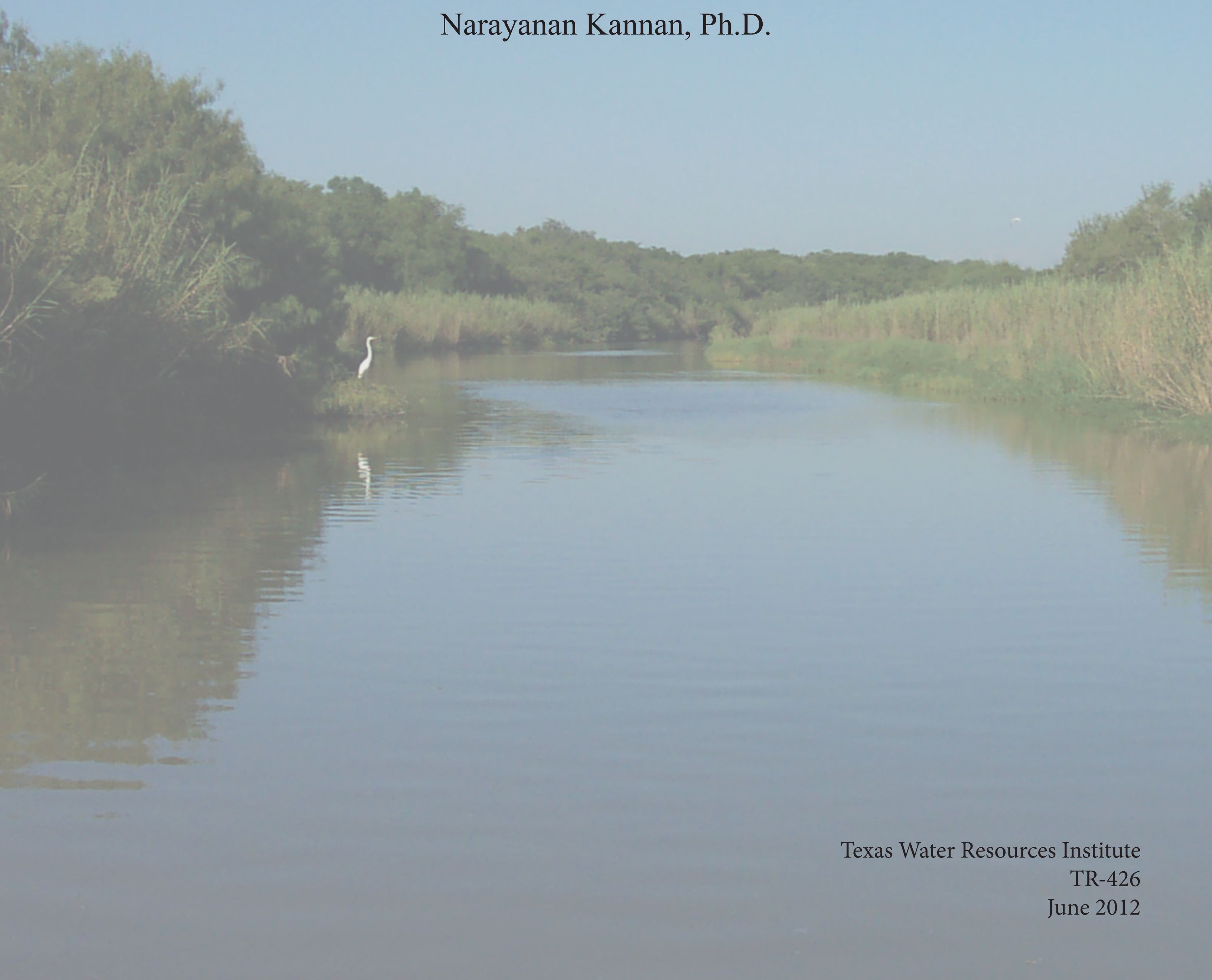

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THE ARROYO COLORADO WATERSHED

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Arroyo Colorado Agricultural Nonpoint Source Assessment
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Summary

A model setup of the Soil and Water Assessment Tool (SWAT) watershed model was developed to simulate flow and selected water quality parameters for the Arroyo Colorado watershed in South Texas. The model simulates flow, transport of sediment and nutrients, water temperature, dissolved oxygen, and biochemical oxygen demand. The model can also be used to estimate a total maximum daily load for the selected water quality parameters in the Arroyo Colorado. The model was calibrated and tested for flow with data measured during 2000–2009 at two streamflow-gaging stations. The flow was calibrated satisfactorily at monthly and daily intervals. In addition, the model was calibrated and tested sequentially for suspended sediment, orthophosphate, total phosphorus, nitrate nitrogen, ammonia nitrogen, total nitrogen, and dissolved oxygen, using data from 2000–2009. The simulated loads or concentrations of the selected water quality constituents generally matched the measured counterparts available for the calibration and validation periods. Two watershed scenarios were simulated for the years 2015 and 2025 after estimation of land cover maps for those years. The scenarios were intended to identify a suite of best management practices (BMPs) to address the depressed dissolved oxygen problem in the watershed.

Purpose and Scope

This report describes the setup, calibration, validation, and scenario analysis using the SWAT model to simulate the flow and water quality of the Arroyo Colorado watershed. The basin was subdivided into 17 subbasins—six in Segment 2201 and eleven in Segment 2202. The basin was characterized by a set of 475 hydrologic response units (HRUs) that are unique combinations of land cover, soil, and slope. For flow, 8 hydrologic process-related parameters were calibrated. A total of 26 process-related parameters were calibrated for water quality. Eleven years (1999–2009) of precipitation, air temperature, streamflow, and water-quality data were used for model calibration and validation. We used precipitation data from three stations; air temperature data from two stations; and streamflow data from two stations. Most of the water quality data used for model calibration and testing came from the station near Harlingen, Texas. Some water quality data available near Mercedes, Texas were also used in the study. Status of water quality in the river at present and for years 2015 and 2025 were projected using estimated land cover maps. Suggested solutions to bring dissolved oxygen in compliance for the stream were also discussed.

Introduction

The Arroyo Colorado watershed, a subwatershed of the Nueces-Rio Grande Coastal Basin, is located in the Lower Rio Grande Valley of South Texas and extends from near Mission, Texas, eastward to the Laguna Madre (fig. 1). Streamflow in the Arroyo Colorado primarily is sustained by municipal and industrial effluents. Additional streamflow results from irrigation return flow, rainfall runoff, and other point-source discharges. The Arroyo Colorado is used as a floodway, an inland waterway, and a recreational area for swimming, boating, and fishing, and is an important nursery and foraging area for shrimp, crab, and several types of marine fish.

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 of contact recreation and high aquatic life. The nontidal segment of the Arroyo Colorado, Segment

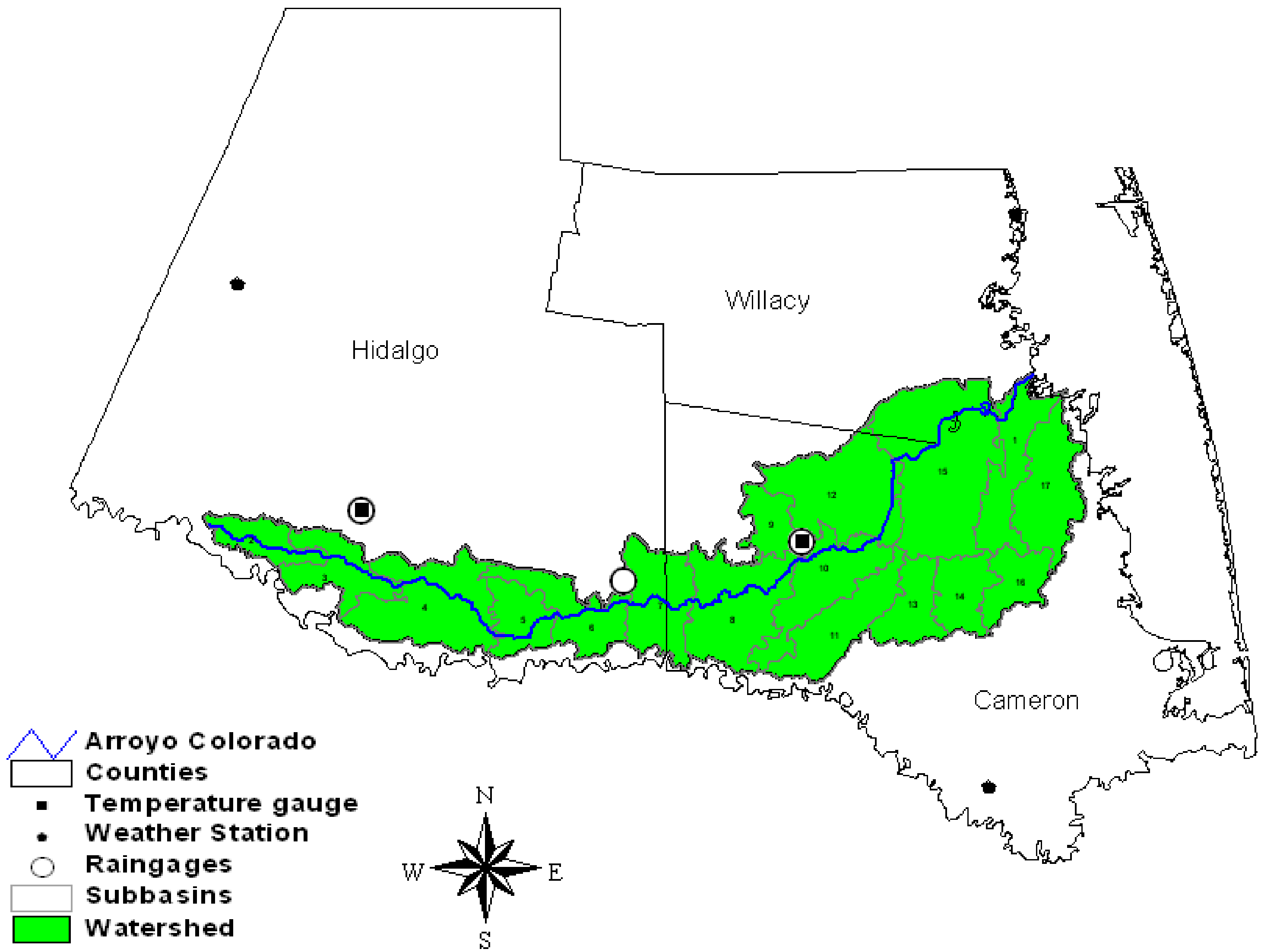

Figure 1. Location of Arroyo Colorado watershed

2202, has designated uses of contact recreation and intermediate aquatic life. The tidal segment of the Arroyo Colorado, Segment 2201, has failed to meet the water quality criteria required for its designated uses and is included on the State 303(d) list of impaired water bodies for dissolved oxygen (DO) levels below the criteria specified in the Texas Surface Water Quality Standards (Texas Natural Resource Conservation Commission, 1997).

Simulation models typically are used to estimate load reductions because the models are developed to represent the cause-and-effect relations between natural inputs to an aquatic ecosystem and the resulting water quality. Several BMP alternatives can be evaluated objectively using simulation models to determine what changes will be needed to meet the water quality standards.

Texas AgriLife Research, in cooperation with Texas State Soil and Water Conservation Board (TSSWCB) and TCEQ, began a study in 2008 to simulate the flow and the water quality of selected constituents in the Arroyo Colorado. The specific objectives of the study were to (1) develop a computer-based watershed model setup of the Arroyo Colorado that would allow representation of different BMPs adopted by growers in the watershed; (2) calibrate and validate a set of process-related model parameters with available streamflow and water quality data for the watershed; and (3) develop a suite of BMPs for changing land cover conditions predicted for 2015 and 2025, which, when progressively implemented in the watershed, would bring the water quality to compliance with current standards.

Study Area

The study area, the Arroyo Colorado watershed, is located in the Lower Rio Grande Valley of South Texas in parts of Hidalgo, Cameron, and Willacy counties (Fig. 1). It is a subwatershed of the Nueces-Rio Grande Coastal Basin, also known as the South (Lower) Laguna Madre Watershed (Hydrologic Unit Code 12110208). It is a 1,692 km^2 agricultural watershed with intensive cultivation. Most of the cultivated area receives irrigation from Rio Grande River through a network of canals, ditches, and pipes under a system of irrigation districts (Fig. 2). Irrigation practices consist of flooding fields with a specified depth of water during periods of insufficient precipitation to produce desired crop yields. Perennial stream flow in the Arroyo Colorado is primarily sustained by effluent from municipal wastewater treatment plants.

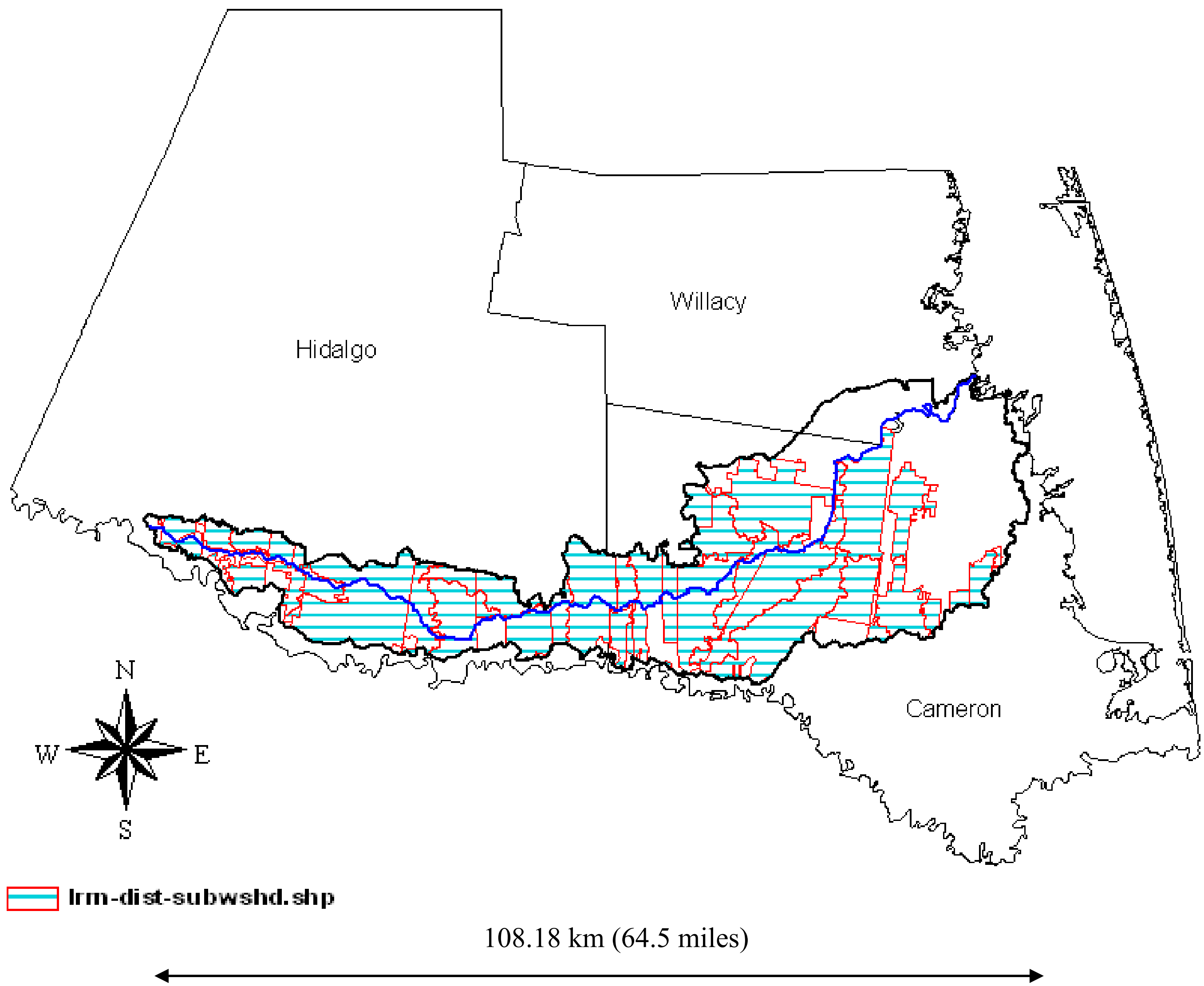

Figure 2. Irrigation districts in the watershed

Irrigation return flow and point source discharges supplement the flow on a seasonal basis. The Arroyo Colorado is used as a floodway, an inland waterway, and a recreational area for swimming, boating, and fishing, and is an important nursery and foraging area for numerous marine species. Urbanization is extensive in the areas directly adjacent to the main stem of the Arroyo Colorado, particularly in the western and central parts of the basin. Principal urban areas include the cities of Mission, McAllen, Pharr, Donna, Weslaco, Mercedes, Harlingen, and San Benito (Rains and Miranda, 2002; Rosenthal and Garza, 2007).

The most dominant land cover category in the watershed is agriculture (54 %) and the main crops cultivated are grain sorghum, cotton, sugar cane, and citrus, although some vegetable and fruit crops are also raised. Most of the cultivated area (including citrus and sugarcane) is irrigated. The watershed soils are clays, clay loams, and sandy loams. The major soil series comprise the Harlingen, Hidalgo, Mercedes, Raymondville, Rio Grande, and Willacy (U.S. Department of Agriculture, Soil Conservation Service, 1977, 1981–82). Most soil depths range from about 1,600 to 2,000 mm.

The mean annual temperature of the watershed is 22.7 degrees Celcius (°C) with mean monthly temperatures ranging from 14.5 °C in January to 28.9 °C in July. Mean annual precipitation ranges from about 530 to 680 mm, generally from west to east, in the basin (National Oceanic and Atmospheric Administration, 1996). Most of the annual precipitation results from frontal storms and tropical storms.

Observations used

Twelve years of weather data and flow, beginning in 1999 to 2010, were used for modeling. We used precipitation data from three and temperature data from two stations (Fig. 1). The weather data was obtained from Texas State Climatologist Office located at Texas A&M University in College Station. Stream flow data for two stations were obtained from International Boundary and Water Commission; one near Llano Grande at FM 1015 south of Weslaco (G1) and the other near US 77 in South West Harlingen (G2) (Table 1). There are 21 permitted dischargers in the Arroyo Colorado Basin, 16 are municipal, three are industrial, and two are shrimp farms. The discharge permit limits of the municipal plants range from 0.4 to 10 million gallons per day. The shrimp farms discharge infrequently (Rains and Miranda, 2002).

Water quality data from limited grab samples were obtained for suspended sediment (SS), nitrogen (ammonia nitrogen (amm N), nitrate-nitrogen (NO_3-N), and total nitrogen (TN)), phosphorus (orthophosphate (OP) and total phosphorus (TP)), water temperature (WT), and dissolved oxygen (DO). Data were available from three stations: the first near Weslaco, the second near Harlingen and the third near Port of Harlingen (Table 1). Out of the three stations, only the station near Harlingen had data for all the water quality variables. The gauge near Weslaco had flow, SS and, amm N only. However, the gauge near Port of Harlingen had very limited data (<10--20 observations) for SS, amm N, and WT, and therefore was not used for the analysis (Table 1).

The observations were available in the form of concentrations (except water temperature). The monitored observations (concentrations) were converted to time series of loads using a continuous time series of flow (typically daily stream flow). There are computer programs to accomplish this that convert flow and concentrations using regression and statistical techniques. They also estimate uncertainties of estimates. One such program is LOAD ESTimator (LOADEST) developed by United States Geological Survey (USGS) (Runkel et al. 2004). In LOADEST, data variables such as various functions of flow, time, and some other user-specified variables can be included. The program develops a regression model for estimation of load after calibration. Once formulated, the regression model is then used to estimate loads for a user-specified time frame. The LOADEST program estimates mean loads, standard errors, and 95 % confidence intervals developed on a monthly or seasonal basis. LOADEST output includes diagnostic tests and warnings to the user in determining correct estimation procedure and ways to interpret the information obtained. The time series of pollutants estimated this way using LOADEST based on grab sample pollutant concentrations and flow is referred to as "observations" throughout this report.

Description of simulation model

The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993) is a conceptual continuous simulation model developed to quantify the impact of land management practices on surface water quality in large watersheds (Gassman et al. 2007; Neitsch et al. 2004; http://www.brc.tamus.edu/swat).

Table 1. Selected physical and hydrological characteristics of Arroyo Colorado subbasins

SubBasin	Reach length (km)	Drainage area (Km^2)	Name of precipitation station	Streamflow gauging station number	Water quality sampling site number
(Segment 2202 non-tidal)					
2	11.5	50.3			
3	11.5	73.8	Mc Allen		
4	16.7	157.4			
5	9.0	57.7			
6	10.0	82.6	Mercedes	08-4703.00	13081
7	10.8	100.3			
8	19.6	143.3			
9	10.1	47.5	Harlingen		
10	12.7	104.9		08-4704.00	13074
11	20.3	96.9			
12	10.6	155.8			
(Segment 2201 tidal)					
13	10.0	59.4			
14	8.8	59.2			
15	53.4	249.0			
16	7.4	54.3			
17	25.6	110.2			
1	8.5	89.8			

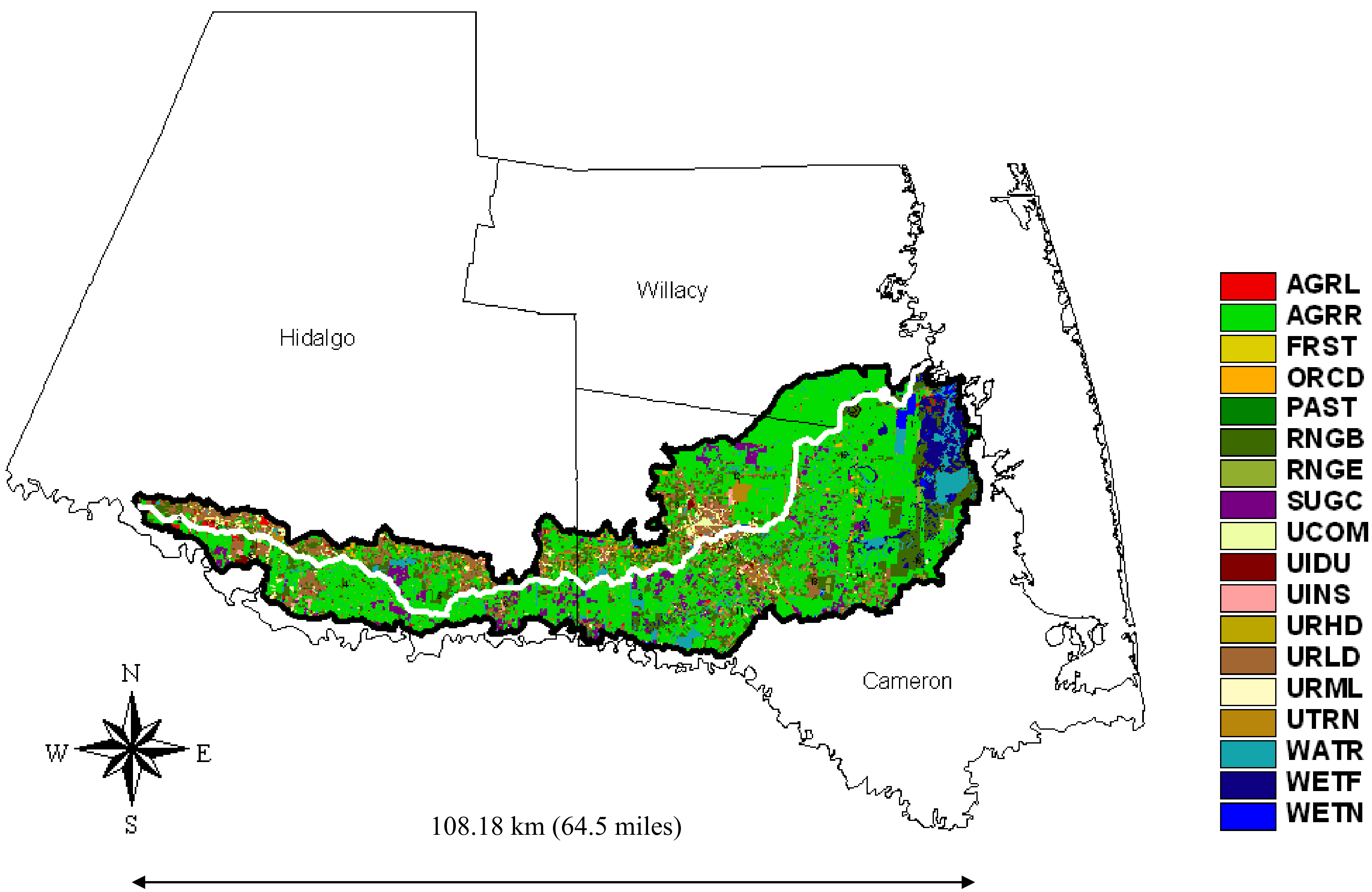

Figure 3. Land cover map of Arroyo Colorado

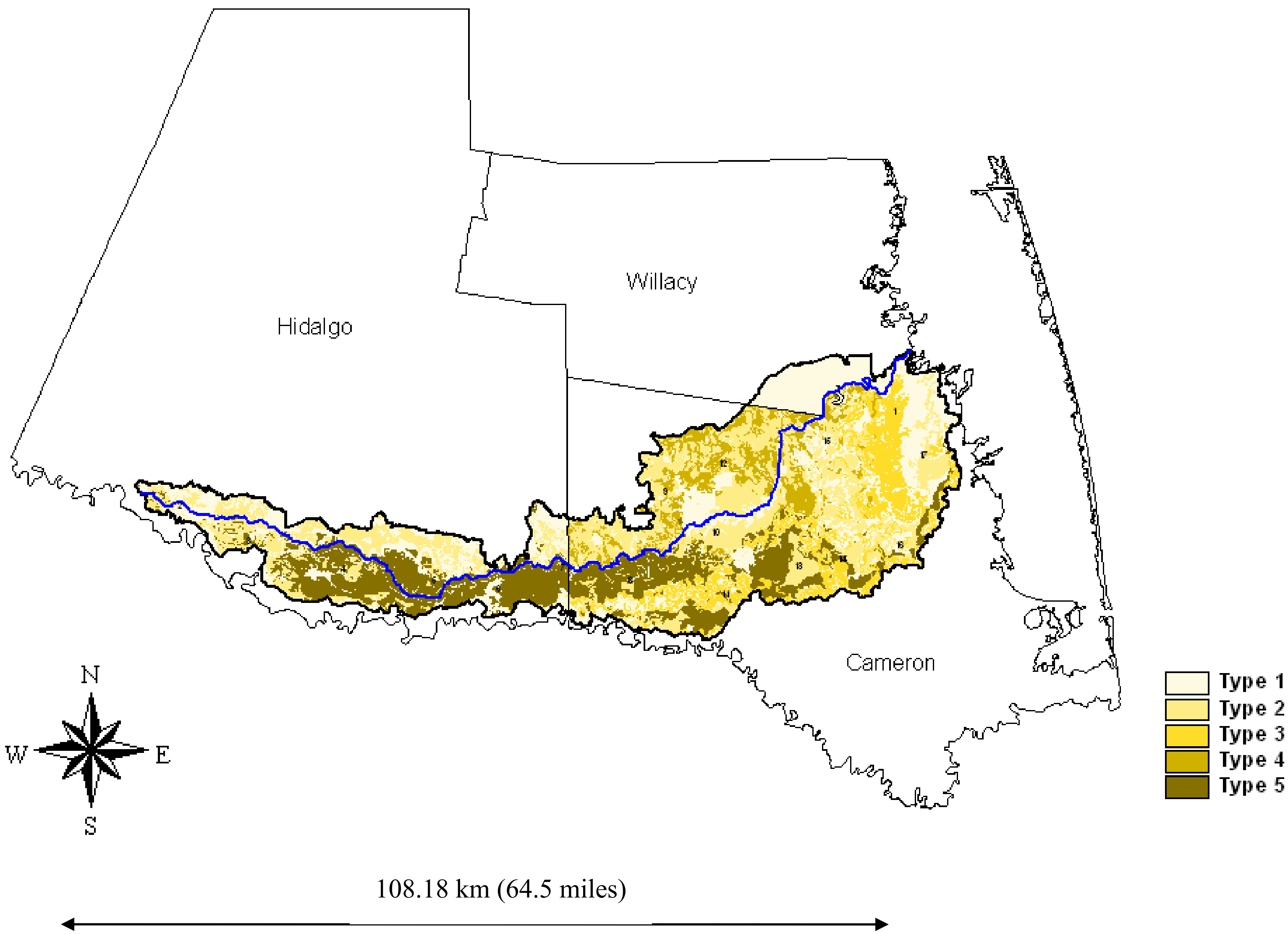

Figure 4. Soil map of the watershed

Table 2. Land cover map legend descriptions

Land Cover Code	Description
AGRL	Generic Agricultural Land
AGRR	Agricultural Land-Row Crops
FRST	Mixed Forest
ORCD	Orchard (Citrus for Arroyo Colorado watershed)
PAST	Pasture
RNGB	Range-Brush
RNGE	Range-Grasses
SUGC	Sugarcane
UCOM	Urban-Commercial facility
UIDU	Urban-Industry
UINS	Urban-Institution
URHD	Urban-High Density Residential
URLD	Urban-Low Density Residential
URML	Urban-Residential Medium/Low density
UTRN	Urban-Transportation
WATR	Water
WETF	Wetland-Forested
WETN	Wetland-Non-forested

SWAT also provides a continuous simulation of processes such as evapotranspiration, surface runoff, percolation, return transport flow, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing, field drainage, crop growth, and material transfers (soil erosion, nutrient and organic chemical and fate). The model can be run with a daily time step, although subdaily model run is possible with Green and Ampt infiltration method. It incorporates the combined and interacting effects of weather and land management (e.g. irrigation, planting and harvesting operations, and the application of fertilizers, pesticides or other inputs). SWAT divides the watershed into subwatersheds using topography. Each subwatershed is divided into HRUs, which are unique combinations of soil, land cover and slope. Although individual HRU's are simulated independently from one another, predicted water and material flows are routed within the channel network, which allows for large watersheds with hundreds or even thousands of HRUs to be simulated.

SWAT model setup of Arroyo Colorado watershed

Input data used

We used ArcSWAT interface to prepare the SWAT model setup of Arroyo Colorado. For delineation of watershed boundary, we used 30-m USGS Digital Elevation Model (DEM). A digitized stream network and a watershed boundary from the previous HSPF modeling study (Rains and Miranda, 2002) were used as supporting information for the delineation of watershed and stream network for the present study. The watershed was eventually discretized into 17 subwatersheds.

Spatial Sciences Lab of Texas A&M University at College Station prepared the land cover map based on satellite data and a field survey. The map incorporates the present land cover conditions (2004–2007) in the watershed. Crop rotation, irrigation, and dates of planting are also available with the land use map on a farm/field basis. The dominant land cover categories in the watershed are agriculture (54 %), range (18.5 %), urban (12.5 %), water bodies (6 %) and sugarcane (4 %) although some vegetable and fruit crops are also raised (Fig. 3, Table 2). The soil survey geographic database (SSURGO) soil map was downloaded from USDA-NRCS for Cameron, Willacy and Hidalgo counties (Fig. 4). The soil properties associated with a particular soil type are derived using the SSURGO soil database tool. 475 HRUs were delineated based on a combination of land cover and soil. In the present delineation, areas as small as 9.1 ha (22.5 acres) are represented as HRUs.

Dates of planting were obtained from the land cover map. The durations of crops were obtained from crop fact sheets from Texas AgriLife Extension Service publications based on the tentative harvest dates as identified for each crop (Stichler and McFarland, 2001; Trostle and Porter, 2001; Stichler et al. 2008; Vegetable Team Production, 2008; Wiedenfeld and Enciso, 2008; Wiedenfeld and Sauls, 2008). Dates of harvest collected during our visits to the watershed were used along with the above information. Typically, there are two tillage operations (in conventional tillage) for each crop, one soon after the harvest of the previous crop and the other midway between the harvest of the previous crop and the planting of the present crop. In conservation tillage, one tillage operation (mostly soon after harvest of the previous crop) or no tillage operation is performed (Andy Garza, Texas State Soil and Water Conservation Board, Harlingen, personal communication).

Modeling Irrigation of crops

Tentative quantity, timing, and frequency of irrigation required for major crops (such as sorghum, cotton and sugar cane) were obtained from NRCS and TSSWCB staff in the watershed. Crop fact sheets published by Texas AgriLife Extension Service were also collected to estimate the irrigation information for the crops (Table 3; Stichler and McFarland, 2001; Trostle and Porter, 2001; Cruces, 2003; Fipps, 2005; Stichler et al. 2008; Vegetable Team Production, 2008; Wiedenfeld and Enciso, 2008; Wiedenfeld and Sauls, 2008). To model canal irrigation, the following procedure is used. We prepared a comprehensive map using the HRU information from the overlaid land cover map, soil map and subbasin map using GIS. An HRU under agriculture land cover can be either irrigated or not irrigated. If irrigated, the model will follow the canal irrigation procedure. Information on irrigation districts for the study area is available in the form of a map from the Irrigation Technology Center, Texas A&M University. In addition, the average water conveyance efficiency for each irrigation district is available separately. This information was combined and merged with the HRU map to identify the irrigation district that comes under each HRU. This has conveyance efficiency information for each HRU. For this study, conveyance efficiency includes all loses in the irrigation distribution system from water diversion river to field. Conveyance efficiency combined with depth of water application for each irrigation event for each crop allowed us to estimate the tentative quantity of water that could have been diverted from the source for irrigating the crop (Fig. A1). We consulted several publications/reports estimating depth, duration, and frequency of irrigation, and estimated the critical crop growth stages at which irrigation is essential. We also estimated the timings based on the probable days of irrigation (identified by looking at the daily water stress values reported by the model for the simulation that involves no irrigation event for any crop in any HRU) to schedule irrigation in the model set up, and the critical crop growth stages requiring irrigation were used as reported in the literature/field data.

Representing Best Management Practices (BMPs) in the model

Irrigation land leveling (NRCS practice code 464)

Irrigation land leveling represents the reshaping of the irrigated land to a planned grade to permit uniform and efficient application of water. It is typically used in mildly sloping land. Primarily it is carried out by agricultural producers who follow surface methods to irrigate their fields. Land leveling is generally designed within slope limits of water irrigation methods used, provide removal of excess surface water and control erosion caused by rainfall. This BMP is modeled in SWAT by reducing the HRU slope (by 8–12.5 % depending on the initial value) and slope length (one tenth of the default value) parameter. In reality, a leveled field infiltrates more water, reduces surface runoff, and therefore decreases soil erosion. When adjusted (reduced), slope and slope length parameters of the watershed model setup will bring similar effects in the predicted model results.

Irrigation Water Conveyance, Pipeline (NRCS practice code 430)

Irrigation water conveyance in pipeline form is installation of underground thermoplastic pipeline (and appurtenances) as a part of an irrigation system to replace canal lining. The decision to line a canal or replace the canal using a pipeline is often made based on how much water is conveyed in the canal. In practice, small district irrigation canals or lateral canals with capacity less than 100 cubic feet per second will be replaced with pipeline. This BMP reduces water conveyance losses and prevents soil erosion or loss of water quality. Some of the design and planning considerations include working pressure, friction losses, flow velocities, and flow capacity. On average, this BMP can save water up to 11 % (Texas Water Development Board, report 362). In a hydrologic modeling study involving a relatively large watershed, it is not possible to practically consider all the pipe network, irrigation appurtenances, and the associated pressure, friction losses, flow velocity, capacity etc. Therefore, irrigation water conveyance in pipeline form is modeled by increasing the conveyance efficiency of an HRU. In other words, the amount of water diverted to the field from the source is decreased.

Irrigation System-Surface Surge Valves

This BMP is often implemented to replace an on-farm ditch with a gated pipeline to distribute water to furrow irrigated fields. A surge irrigation system applies water intermittently to furrows to create a series of on-off periods of either constant or variable time intervals. The system includes butterfly valves or similar equipment that will provide equivalent alternating flows with adjustable time periods. Surge flow reduces runoff by increasing uniformity of infiltration and by reducing the duration of flow as the water reaches the end of the field. It also increases the amount of water delivered to each row and reduces deep percolation of irrigation water near the head of the field. The amount of water saved by switching to surge flow is estimated to be between 10 and 40 % (Texas Water Development Board, report 362) and is dependent upon soil type and timing of operations. Physical representation and modeling the operation of butterfly values for each field in a large watershed system was tedious. Also, methods do not exist to model them from a hydrologic perspective. Therefore, irrigation system-surface surge valves is simulated by increasing the conveyance efficiency while calculating the water diverted for irrigation.

Irrigation Water Management (NRCS practice code 449)

Under this BMP, the landowner will manage the volume, frequency, and application rate of irrigation in a planned, efficient manner as determined from the crop's water requirements complying with federal, state, and local laws and regulations. This BMP is modeled by varying several parameters. The volume of water required for irrigation is adjusted based on the seasonal total rainfall received (total rainfall from planting to harvest date).. If there is considerable rainfall around a scheduled irrigation period, that particular irrigation is skipped. This reduces the frequency of irrigation. Based on the quantity of rainfall and timing, the rate of water application is also adjusted, although this is less frequent.

Table 3. Frequency, timing and amount of irrigation for different crops in the watershed

Crop	Total water requirement, mm (inches)	Number of irrigations	Critical crop growth stages needing irrigation	Irrigation requirement (Days after planting)
Sorghum	458 (18)	3	One week before booting, two weeks past flowering	30, 60, 84
Cotton	508 (20)	3	Stand establishment, prebloom, shortly after boll set	25, 56, 94
Sugarcane	1270 (50)	7	Establishment, grand growth, ripening	75, 105, 145, 190, 235, 275, 305
Corn	508 (20)	3	Tasseling, silking, kernel fill	48, 70, 95
Citrus	1143 (45)	6	Pre-bloom, flower bud induction, fruit set, cell expansion, ripening	65, 100, 135, 195, 250, 320
Sunflower	304 (12)	2	20 days before flowering, 20 days after flowering	45, 85
Onion	635 (25)	5	stand establishment, bulb initiation, maturity	15, 60 (if dry), 90, 115, 135

Table 4. Water Diverted for Irrigation with and without BMPs

Subbasin	Year	Crop	Water diverted without BMPs mm (in.)	Water diverted with BMPs mm (in.)
3	2002	Sugarcane	1,524 (60)	1,160 (46)
3	2004	Sugarcane	1,052 (41)	801 (32)
8	2000	Cotton	677 (27)	552 (22)
8	2001	Corn	677 (27)	552 (22)
8	2002	Cotton	677 (27)	552 (22)

Conservation Crop Rotation (NRCS practice code 328)

This BMP implies growing high-residue-producing crops that produce a minimum of 2800 kg/ha/year (2500 lbs/ac/year) of residue for a minimum of 1 year within a given two year period. Corn and grain sorghum are examples for high-residue-producing crops. Sorghum is the dominant crop in cultivated areas of the watershed. Corn is also cultivated in some areas. The crop rotation in the watershed has sorghum, or corn as per the above-mentioned conditions prescribed for conservation crop rotation. Therefore, no changes were made in the watershed model set up to represent this BMP.

Nutrient Management (NRCS practice code 590)

Nutrient management means managing fertilizer quantity, placement, and timing based on realistic yield goals and moisture prospects. Under this BMP, fertilizer should be applied in split applications throughout the year (early March, late May, late August, and mid October) prior to irrigation or forecasted rain to maximize the use of the fertilizer and minimize the leaching potential. Nitrogen applications will not exceed 112 kg/ha (100 lb/ac) of total nitrogen per application. Specific nutrient recommendations will be given by NRCS when a soil analysis report is provided. A soil analysis is taken a minimum of once every third year by the land owner/renter beginning with the year that the plan or contract is signed. Nutrient management is mimicked in the model as given below.

The fertilizer applications for cultivated fields were already modeled in terms of two or three split applications. For the HRUs that come under this BMP, the split applications were strictly followed according to the guidelines suggested in the BMP practice code. In addition, the initial amount of N and P present in the soil were deducted from the recommended regular fertilizer application rates for different crops (to mimic soil-survey based N and P recommendations). Realistic initial N and P rates were obtained by using the final amount of N and P remaining in the soil (as reported by the model) after several years of model runs. With respect to recommended regular rates of N and P, under this management scenario, less proportion of P than N is applied .. This is because phosphorus is less likely to leach from the soil and more available. A comparison of N and P rates for different crops with and without nutrient management is given in Table 5.

Table 5. Fertilizer rates for different crops under nutrient management and non-nutrient management

Crop	Nitrogen (kg/ha)		Phosphorus (kg/ha)	
	Regular	Nutrient management	Regular	Nutrient management
Sorghum	160	152	69	55
Cotton	150	125	68	34
Sugarcane	224	216	0	0

Residue Management (NRCS practice code 329b)

Residue management-mulch-till is managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while growing crops. The entire field surface is tilled prior to the planting operation. Sometimes the residue is partially incorporated using chisels, sweeps, field cultivators, or similar implements. This BMP is practiced as part of a conservation management strategy to achieve some/all of the following: reduce sheet and rill erosion, reduce wind erosion, maintain or improve soil organic matter content, conserve soil moisture, and provide food and escape cover for wildlife (USDA-NRCS, 2001). This BMP was modeled by harvesting only the crop (no killing of crop; harvesting only the useful yield), and leaving the residue (non-yield portion of crop) until the planting of next crop.

Seasonal Residue Management (NRCS practice code 344)

Seasonal residue management is very similar to residue management. This BMP implies leaving protective amounts of crop residue (30 % ground cover/1,360 kg (3,000 lbs) minimum) on the soil surface through the critical eroding period (Dec. 15 to Jan. 1 or six weeks prior to planting) to reduce wind and water erosion during the raising of a high-residue crop. In the event that a low residue crop is being produced, the residue requirements are not met and soil begins to blow, emergency tillage operations will be performed. Similar to residue management, this BMP was modeled by harvesting only the crop (no killing of crop; harvesting only the useful yield) and leaving the residue (non-yield portion of crop). However, this can happen only during critical eroding period or six weeks prior to the planting of next crop.

Terrace (NRCS Practice Code 600)

Terraces are broad earthen embankments constructed across a slope to intercept runoff and control water erosion. They are intended for both erosion control and water management. Terraces decrease hill slope length, prevent formation of gullies, and intercept, retain, and conduct runoff to a safe outlet, and therefore reduce the concentration of sediment in water. Terraces increase the amount of water available for recharging the shallow aquifers by retaining runoff (Schwab et al., 1995). In this study, terraces are represented in the model by decreasing curve number (CN), reducing Universal Soil Loss Equation (USLE) conservation support practice factor (P factor) and decreasing slope length. Terraces are not one of the common BMPs in the watershed.

Constructed wetlands

Constructed wetlands are of two types: (1) free water surface systems (FWS) with shallow water depth and (2) subsurface flow systems with water flowing laterally through the sand or gravel. In general, constructed wetlands are very effective in removing suspended solids. Nitrogen removal occurs mostly in the form of NH_3 with dominating nitrification/denitrification process. Because of the shallow depth and access to soil, the phosphorus removal is relatively higher for constructed wetlands than natural wetlands. The bacteria attached to plant stems and humic deposits help in considerable removal of BOD_5. Typical pollutant-removal ability of wetlands is available in a report published by USEPA (USEPA, 1988 report EPA/625/1-88/022). For the study area, the probable pollutant removal efficiencies are obtained from the USEPA report based on wastewater inflow to the wetland. For representing the existing constructed wetlands in the watershed, the pollutants discharge from wastewater treatment plants (point source discharge data in the model setup) is discounted based on the typical pollutant removal efficiency estimated from the EPA report. The typical pollutant removal efficiencies used in the model setup to represent constructed wetlands are shown in Table 6. The constructed wetlands in the Arroyo Colorado watershed are assumed to be of FWS type. Effluent polishing ponds were aggregated at subbasin level, and pollutants from point source data were discounted using typical values shown in Arroyo Colorado Watershed Protection Plan report (2007). The total area of each BMP present in the watershed and that represented in the model are shown in Table 7.

Table 6. Typical pollutant removal efficiencies used for representing constructed wetlands

Location of wetland	Effluent inflow (m^3/day)	% removal of				
		SS	NH3 N	NO3 N	TDP	BOD
La Feria (Subbasin 8)	972.7	86	64.5	20	71	64
San Benito (Subbasin 10)	9,621.5	28	64.5	20	71	64

Table 7. Representation of different BMPs in the watershed model setup

Best Management Practice	Actual area (acres)	Represented in the model (acres)	% error (watershed level)
Conservation crop rotation	20,910.8	21,627.3	3.4
Irrigation land leveling	12,185.3	12,455.8	2.2
Irrigation System - Sprinkler - New	396.4	417.9	5.4
Irrigation System - Surge valves	22,931.6	22,636.2	-1.3
Irrigation Water Conveyance, Pipeline	10,470.3	10,750.6	2.7
Irrigation Water Management	23,724.3	24,132.3	1.7
Nutrient Management	12,053.8	11,838.9	-1.8
Pasture and Hay Planting	952.3	805.1	-15.5
Prescribed Grazing	961.0	955.2	-0.6
Residue Management	1,417.1	1,313.9	-7.3
Residue Management, Seasonal	19,357.2	20,654.0	6.7
Subsurface Drain	4,327.6	4,232.3	-2.2
Terrace	130.7	116.5	-10.8

Wastewater reuse

This BMP implies using wastewater for irrigation with the goal of reducing point source nutrient loads to the river. To represent wastewater reuse in the model, we needed to know the quantity of wastewater used and the location from which the wastewater is taken. This information is available for the Arroyo Colorado from the Arroyo Colorado Watershed Protection Plan. In the model, point source flow is discounted in proportion to the wastewater reuse intended from the effluent discharge facilities. The discounted water is then added to the irrigation water in the subbasin. The quantity of nutrients associated with the quantity of reuse is estimated and applied as fertilizer in the same HRU where the irrigation operation was defined. Any sediment associated with the wastewater was not accounted/discounted because the quantity was negligible.

Calibration and validation of model

Calibration of the chosen model and a subsequent validation are necessary to have confidence that the model gives reliable and useful results, and it is worthy to use it to do scenario trials. For the Arroyo Colorado watershed modeling study, the SWAT model was calibrated and validated for flow, sediment, nitrogen (nitrate, ammonia and total nitrogen), phosphorus (total phosphorus and orthophosphate), water temperature, and dissolved oxygen. The model was run at a daily time step from 1999–2010, and the results were aggregated at monthly time steps for the purpose of calibration. Flow calibration was carried out at both monthly and daily time steps. Data from 1999 is used for model warm-up to make state variables assume realistic initial values. Data from 2000–2003 is used for calibration and 2004–2006 for validation. However, the model was run until 2010. From this point onwards, this model setup will be referred to as baseline. The availability of water quality observations was not as good as flow. Therefore, a separate split sample calibration and validation was not carried out. Instead, the observations available (from 2000–2009) were used to verify whether the model gives reasonable results in terms of magnitude, pattern and timing.

Flow calibration and validation was carried out for two gauges: one near Weslaco/Mercedes and the other near Harlingen. The model is able to reproduce the flow observations very well in both gauges during calibration and validation periods (Tables A2 and A3). Similar results were obtained for flow at a daily time step. For sediment, the model-predicted values were good when compared to observations except for a couple of over-estimated peaks. Orthophosphate was predicted well by the model. However, total phosphorus was over-estimated. Also, for nitrogen, the model-predicted values were good enough to use for scenario trials. We did not carry out calibrations for water temperature and dissolved oxygen. SWAT estimates water temperature as an empirical function of air temperature and therefore, no parameter is available for calibration. For dissolved oxygen, the model gave better results without any requirement for calibration. All the calibration and validation results are provided in Figures A2-A14 and tables A1-A7 in Appendix A.

Watershed scenarios for 2015 and 2025

Estimation of future land cover maps

Data used

The data used includes city limits, census data, population projections, and land use/land cover maps from multiple years. City limit information was produced by the Texas Department of Transportation (TxDOT). The Census data was from the 1990 and 2000 census. The population projections were produced by the Texas Water Development Board based on the 2000 census. Projections from 2010, 2020, and 2030 were averaged to create projections for 2015 and 2025. Three different land use maps from 1992, 1998, and 2007 were used. The 1992 map was a subset of the National Land Cover Dataset (NLCD). The 1998 classification was produced by the Texas Commission on Environmental Quality (TCEQ) and the 2007 Classification was produced by the Spatial Sciences Lab at Texas A&M University in College Station (SSL).

Method

To quantify land cover change, the three available land cover maps (for years 1992, 1998 and 2007) needed to be in one format and reclassified into a common scheme. The two vector classifications were converted to raster using the extent and cell size of the 1998 classification, which had the same extent as the watershed boundary. After reclassification, pixel counts were exported and converted to acres. The results were observed in a table with both area and % of watershed values (% of watershed occupied by a certain land use).

The amount of residential land use areas within each city was extracted using the city limits and each of the reclassified maps. Cities with populations greater than 500 as of 2000 were identified and extracted. This was necessary because population projections were not available for cities with populations less than 500. Some did not have a population of 500 in 1990, but did in 2000, so they were included. The trend would simply include one less value. In some cases the population values did not steadily increase and there were some slight declines or no growth. This was because the values were extracted from different sources that were not consistent. If the population declined, it was averaged with the value before and after the decline to achieve steady growth. Each of the city limits was then given a unique identification number of 1000 through 21000. This ID number was then used to convert the city limits to raster. It was necessary to use values of 1000 or greater since the highest class values were three digits long, although the highest observed in the land use maps were two digits. Additional overlay was then used to extract the land uses within the city limits. The residential and nonresidential developed land uses were extracted and the total area of each was calculated individually. These values were then analyzed and used to compute future residential land use acreage.

In order to map probable locations of development or land use change, previous land use change was mapped using combination overlays of classifications with the classification from the previous time period. An overlay was also created using the oldest and most recent classifications. Using combinations makes it possible to identify areas that have changed from or to a specific land use. In this case, areas that changed to residential were extracted from combinations of 1992 and 1998, 1998 and 2007, and 1992 and 2007. Using each of the combinations accounted somewhat for the differences in extent between 1998 and 2007, although not entirely. The combinations identified what land uses were most frequently being developed into residential. Areas where the land use changed to residential as well as potential areas for residential development would both be used in the production of the final future land cover maps (Table 8).

The results show that rapid urban growth is likely to continue in the watershed through 2015 and 2025. Each city will experience growth in residential, infrastructure, and industrial land uses. This growth will require that other land uses decline to accommodate the increase. It also appears that many of the larger urban areas have little available land within their city limits for further development. To accommodate further growth, city limits will need to expand into the rural areas. Agricultural and industrial land uses provide work for the population living in the area so they will likely limit growth to some extent. However, residential expansion is currently occurring in agricultural lands as well as pastures.

Several assumptions were made about residential and urban expansion. Water and wetlands are unlikely to be developed although wetlands may expand in some areas due to the expansion of existing wetlands or the creation of wetlands to help improve water quality near wastewater treatment facilities. Transportation and infrastructure will expand as structures are built and neighborhoods expand, but this cannot be predicted with any confidence. Industry and agribusiness were expanded as part of the infrastructure.

Table 8. Present and estimated future land cover in the watershed

Land Cover	Area in acres		
	Present	2015	2025
Cultivated (CULT)	244,436.3	228,231.6	215,670.7
Range-Brush (RNGB)	67,090.0	63,067.4	58,040.6
Range-Grasses (RNGE)	11,104.9	10,439.1	9,615.5
Urban-Commercial (UCOM)	7,598.1	12,071.1	15,008.1
Urban-Industrial (UIDU)	2,219.4	4,781.6	10,567.4
Urban-High density residential (URHD)	0.0	707.5	1,061.2
Urban-Low density residential (URLD)	37,753.0	41,743.0	45,870.7
Urban-Transportation (UTRN)	5,269.5	12,576.8	17,681.6
Open water (WATR)	25,406.3	25,386.1	25,465.3
Wetland-Forested (WETF)	14,716.1	16,589.1	16,612.4
Wetland-Non-forested (WETN)	2,350.8	2,350.8	2,350.8

Development of model input files for future scenarios

In this study we attempted to predict land cover conditions of the Arroyo Colorado watershed for 2015 and 2025. Estimated land cover maps were the starting point for future scenario files. Soon after estimating future land cover, the input file generation for a future scenario goes as follows. The watershed and subwatershed boundaries are the same as base line. Soil map and slope information are also the same. However, the land cover map will be different (e.g. for scenario-2015 the land cover map to be used is the one that is estimated). The procedure used before for discretizing the subwatersheds to HRUs was also used here. The thresholds used for land cover, soil and slope are kept the same for scenarios as well to prevent any uncertainties arising from spatial discretization of subwatersheds in the scenarios, which might interfere the analysis of water quality results. Once the HRUs are delineated for each scenario, the required input files to run SWAT model are generated this way:

Soon after generating HRUs of scenarios, the procedure starts with base line HRUs that are calibrated for flow and selected water quality constituents. The HRUs of a scenario (say 2015) is compared with the HRUs of base line by matching the land cover, soil and slope. This will identify three sets of information. The HRUs of base line is to be a) kept b) removed and c) created new to represent the scenario conditions. For those HRUs to be kept, it involves changing the HRU area only. For those HRUs to be removed either we can fully delete them from the input files or make the HRU area zero. The later is followed for convenience and automation. The new HRUs to be created can be copied from existing baseline HRUs by carefully looking for land cover, soil and slope combinations. If a similar HRU does not exist in a subbasin, then HRUs can be copied from neighboring subbasins. By generating the model input files this way, we can avoid calibration of scenario files and proceed straight away to analysis of results.

Analysis of present and future water quality trends

Implementation of BMPs in the watershed, improvement in wastewater treatment, access of wastewater treatment to more colonia residents, strict effluent standards, treatment of effluent using polishing ponds and wetlands have improved the quality of water in the Arroyo Colorado over a period of few years. This is evident from the later part of dissolved oxygen trends (consistently close to 7) observed near Harlingen (Fig. A14). The improvements in water quality are also visible from the dissolved oxygen trends estimated from the model and analyzed using binomial method (Table 9). From the table we can see that most sections of tidal Arroyo Colorado are having DO compliance except at reach 13 and 14. These reaches are not on the main Arroyo Colorado, but they drain to reach 15 of the Arroyo Colorado. Nonpoint source transport of nutrients from cultivated fields can be attributed to the DO problem of reaches 13 and 14. The model estimates a threat to DO in some reaches of nontidal portion of the Arroyo Colorado (Table 9). Point source discharge (especially from subbasins 2 and 3) can be attributed to the problem in the nontidal portion of the Arroyo Colorado. It should be noted that any problem in DO due to point source is long lasting and spreads to other reaches downstream. On the other hand, DO problem from nonpoint source nutrient pollution is highly seasonal and mostly localized.

Table 9. Modeled dissolved oxygen compliance in various reaches-Binomial Analysis results (with existing BMPs in the watershed model setup)

Reach	Location	Confidence of Dissolved Oxygen Compliance (%) [Average number of days/year when DO < 4 mg/L]		
		Baseline (present)	2015	2025
2	Non-tidal	0.0 [316]#	0.0 [342]#	0.0 [334]#
3	Non-tidal	0.0 [237]#	0.0 [273]#	0.0 [274]#
4	Non-tidal	0.0 [106]#	0.0 [145]#	0.0 [161]#
5	Non-tidal	100.0 [34]	0.0 [56]	0.0 [62]
6	Non-tidal	100.0 [34]	96.7 [34]	0.03 [40]
7	Non-tidal	100.0 [24]	100.0 [24]	100.0 [28]
8	Non-tidal	100.0 [27]	100.0 [27]	100.0 [29]
9	Non-tidal	0.0 [45]	0.0 [46]	0.0 [46]
10	Non-tidal	100.0 [27]	100.0 [29]	99.9 [33]
11	Non-tidal	0.0 [226]#	0.0 [250]#	0.0 [171]#
12	Non-tidal	100.0 [24]	100.0 [26]	100.0 [29]
we				
13	Tidal	93.0 [37]	19.0 [38]	0.0 [44]
14	Tidal	85.0 [38]	0.5 [40]	0.0 [43]
15	Tidal	100.0 [22]	100.0 [23]	100.0 [25]
16	Tidal	100.0 [31]	97.8 [34]	100.0 [32]
17	Tidal	100.0 [17]	100.0 [19]	100.0 [16]
1	Tidal	100.0 [16]	100.0 [14]	100.0 [15]

Model over reacted to point source loads. Therefore, care was taken while interpreting the results and translating to recommendations

In 2015, because of land cover change and population increase, the water quality is expected to be worse, which is correctly estimated by the model. Although the trends in DO for 2015 are similar to base line, the average number of days per year during which DO concentration is less than 4 mg/L is more for 2015 than base line for most reaches (Table 9). It should be noted that the proposed wastewater polishing ponds, regional wetlands and better emission standards for effluents to the Arroyo Colorado watershed as described by the watershed protection plan are going to be very helpful to protect the water quality of the Arroyo Colorado. As a part of this study, we carried out the suite of BMPs required to bring the DO in compliance . The subbasins of the Arroyo Colorado were prioritized for implementation of BMPs based on model-predicted average number of days when DO is less than 4 mg/L (Table 10) in the reach. The BMPs to be implemented in the cultivated area were also prioritized based on the extent of load reductions they can bring to the Arroyo Colorado (Table 11).

Table 10. Prioritized implementation of BMPs by subbasin in the watershed

Prioritization of BMPs based on		
Dissolved Oxygen	**Total Nitrogen**	**Total Phosphorus**
2	8	8
3	7	5
11	5	7
4	4	6
9	10	10
14	12	4
13	11	11
5	15	15
6	6	2
16	3	9
10	2	3
8	9	16
12	13	13
7	14	14
15	16	12
17	17	17
1	1	1

Table 11. Possible load reductions from different BMPs and their prioritization for implementation

Best Management Practice	% of load reductions obtained from BMPs in		
	Total Nitrogen	**Total Phosphorus**	**Sediment**
Residue management	22.05	45.1	20.2
Irrigation BMPs	11.85	4.25	3.00
Nutrient management	4.1	19.85	0.25
Seasonal residue management	3.25	24.15	4.75
Land leveling	34.75	*	42.4
Tile drains*	6.6	1.7	0.8

[*] Negative results (increase in nutrient loads) possible sometimes. Therefore, care should be taken while choosing these BMPs.

Not all BMPs are fully effective in controlling nutrient loads or dissolved oxygen in the Arroyo Colorado. For example, tile drains, when implemented for reducing water table, will transport more soluble nitrogen to the river than when there are no drains. Also, residue management is much more effective than seasonal residue management. Therefore, care should be taken while choosing BMPs for implementation in a subbasin.

Discussion of mitigation of dissolved oxygen problems

Table 12 shows the suite of BMPs required by 2015 to bring DO compliance for the Arroyo Colorado. The study identified a set of BMPs for different subbasins where they can work better. Irrigation BMPs in Table 12 is a collection of three different BMPs, namely irrigation water management, irrigation water conveyance (in the form of) pipeline, and irrigation system-surface surge valves.

Table 12. Suite of additional BMPs needed by 2015 to meet dissolved oxygen criteria

Subbasin	Scenario 2015-Area of different BMPs (acres)			
	Land leveling	**Residue management**	**Irrigation BMPs**	**Nutrient management**
2	1,902	1,902	----	----
3	682	----	----	1,460
4	16,119	----	16,715	----
5	8,107	9,238	----	9,315
9	1,757	509	----	633
11	1,632	7,463	----	6,099
13	489	4,374	489	4,373
14	7,003	2,452	51	1,667
Total	37,691	25,938	17,254	23,549

Implementation of additional BMPs can take care of the DO problem in the tidal portion of the Arroyo Colorado. However, for the nontidal portion of the Arroyo Colorado, implementation of BMPs alone is insufficient to address the DO problem. An integrated approach of reducing/reusing/better treating of point source discharge along with implementation of BMPs is needed to address the nontidal DO problem. This study recommends reducing/reusing/treating at least 40% of pollutants from point sources associated with subbasins 2, 3, 9, and 11. The same recommendations are suggested for scenario 2025 as well. However, it is recommended to implement additional BMPs (in addition to whatever suggested for 2015 (see Table 12) in the watershed to take care of nonpoint source transport of nutrients and sediments from cultivated areas (Table 13).

Table 13. BMPs needed by 2025 to meet DO criteria (in addition to those of 2015)

Subbasin	Scenario 2025-Area of different BMPs (acres)			
	Land leveling	**Residue management**	**Irrigation BMPs**	**Nutrient management**
2	1,415	1,415	----	----
3	1,282	----	----	105
4	5,289	16,729	1,593	----
5	1,098	----	----	81
6	9,464	7,462	----	----
7	11,101	----	----	11,029
8	3,019	16,849	----	14,750
11	24	----	----	1,484
13	3,772	----	----	----
Total	36,464	42,455	1,593	27,450

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References

Arnold, J.G., Allen, P.M., and Bernhardt, G. (1993). "A comprehensive surface-groundwater flow model". *Journal of Hydrology,* 142, 47–69.

Bean, B. and McFarland, M. 2008 Getting the most out of your nitrogen fertilization in Corn. Texas AgriLife Extension Service, Texas A&M University System, USA.

Bosch, D.D., Sheridan, J.M., Batten, H.L., and Arnold, J.G. (2004). "Evaluation of the SWAT model on a coastal plain agricultural watershed". *Transactions of the American Society of Agricultural Engineers*, 47 (5), 1493–1506.

Burt, C.M. (1993). "Irrigation canal simulation model usage". *Journal of Irrigation and Drainage Engineering*, 119 (4), 631–636.

Cruces L. (2003). "Drought strategies for Cotton". Co-operative Extension Service, *Circular 582*, College of Agriculture and Home Economics, New Mexico State University.

Fipps, G. (2005). "Potential Water Savings in Irrigated Agriculture for the Rio Grande Planning Region", Irrigation Technology Center, Department of Biological and Agricultural Engineering, Texas A&M University System

Fipps, G., and Pope, C. (1998). "Implementation of a district management system in the Lower Rio Grande Valley of Texas". In Proc. *14th Technical Conference on Contemporary Challenges in Irrigation and Drainage*, U.S. Committee on Irrigation and Drainage, Phoenix, (June 3–6, 1998).

Fipps, G., and Pope, C. (1999). "Irrigation district efficiencies and potential water savings in the Lower Rio Grande Valley of Texas", Texas A&M University

Fohrer, N., Haverkamp, S., Eckhardt, K., Frede, H.G. (2001). "Hydrologic response to land use changes on the catchment scale". *Physics and Chemistry of Earth* 26 (7–8), 577–582.

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G. (2007). "The soil and water assessment tool: historical development, applications and future research directions". *Transactions of the American Society of Agricultural and Biological Engineers* 50 (4), 1211–1250.

George, B.A., Raghuwanshi, N.S. and Singh. R. (2004). "Development and testing of a GIS integrated irrigation scheduling model", *Agricultural Water Management*, 66, 221–237.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, D., and Veith, R.D. (2007). "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations" *Transactions of the American Society of Agricultural and Biological Engineers*, 50 (3), 885–900.

Nash, J. E., and Suttcliffe, J.V. (1970). "River Flow Forecasting through Conceptual Models, Part I – A Discussion of Principles". *Journal of Hydrology* 10(3): 282–290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R. (2004). "Soil and Water Assessment Tool-Version 2000-User's Manual", Temple, TX, USA.

Nicolaisen, J.E., Gilley, J.E., Eghball, B. and Marx, D.B. Crop residue effects on runoff nutrient concentrations following manure application. Transactions of the ASABE, 50(3): 939–944.

Nunez, J., Hartz, T., Suslow, T., Mc Giffen, M.and Natwick, E. 2008. Carrot Production in California, Vegetable Production Series, University of California Vegetable Research and Information Center, University of California, USA.(publication 7226)

Obreza, T.A. and Morgan, K.T. 2008 Nutrition of Florida Citrus Trees, Institute of Food and Agricultural Sciences Extension, University of Florida, USA (SL 253).

Parcher, J. and Humberson, D.G. 2007. CHIPS: A New Way to Monitor Colonias Along the united States-Mexico Border, U.S. Geological Survey Reston, VA, USA (Open File Report 2007-1230).

Rains, T.H., and Miranda, R.M. (2002). "Simulation of Flow and Water Quality of the Arroyo Colorado, Texas, 1989-99". United States Geological Survey-Water Resources Investigations *Report, No: 02-4110*.

Rosenthal, W., and Garza, A. (2007). "SWAT Simulations of Nutrient Loadings in the Arroyo Colorado Watershed". In Proc. *2007 ASABE Annual International Meeting, Minneapolis, Minnesota* (paper No. 072031).

Santhi, C., and Pundarikanthan, N.V. (2000). "A new planning model for canal scheduling of rotational irrigation" *Agricultural Water Management*, 43, 327–343.

Santhi, C., Muttiah, R.S., Arnold, J.G., and Srinivasan, R. (2005). "A GIS based regional planning tool for irrigation demand assessment and savings using SWAT", *Transactions of the American Society of Agricultural Engineers*, 48(1): 137–147.

Sauls, J.W. 2010 Citrus – Watering, Fertilizing, Weed Control, Pruning and Cold Protection. Home Fruit Production - Citrus Texas Agricultural Extension Service, Texas Agricultural Extension Service, Texas A&M University System, Weslaco, Texas (B-1629).

SCS. (1956). "Hydrology. National Engineering Handbook, Supplement A, Section 4". Soil Conservation Service, US Department of Agriculture: Washington, DC; *Chapter 10*.

Stichler, C., and McFarland, M. (2001). "Crop Nutrient Needs in South and Southwest Texas", Texas Agricultural Extension Service, Texas A&M University System. (*B-6053, 04-01*)

Stichler, C., McFarland, M., and Coffman, C. (2008). "Irrigated and Dryland Grain Sorghum Production South and Southwest Texas", Texas Agricultural Extension Service, The Texas A&M University System (*5M—5-97, New AGR14*).

Surface Water Quality Monitoring Program. 2008. Guidance for Assessing and Reporting Surface Water Quality in Texas, Texas Commission on Environmental Quality, Austin, TX, USA.

Texas Water Development Board. 2005 Water Conservation Best Management Practices (BMP) Guide for Agriculture in Texas. Water Conservation Implementation Task Force (Report 362), Texas Water Development Board, USA.

Trostle, C., and Porter, P. (2001). "Common Concerns in West Texas Sunflower Production and Ways to Solve Them", Texas Agricultural Extension Service, The Texas A&M University System.

United States Environmental Protection Agency (USEPA). 1988. Design Manual-Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. Center for Environmental Research Information, Cincinati, OH, USA

Vegetable Team Production. (2008). "Onion Production Guide", Cooperative Extension Service, The University of Georgia/College of Agricultural and Environmental Sciences.

"Water Conservation Best Management Practices (BMP) Guide for Agriculture in Texas", Based on the Agricultural BMPs contained in: Texas Water Development Board, *Report 362*, Water Conservation Implementation Task Force.

Wiedenfeld, B., and Enciso, J. (2008). "Sugarcane Responses to Irrigation and Nitrogen in Semiarid South Texas", *Agronomy Journal*, 100, 665–671.

Wiedenfeld, B., Sauls, J. (2008). "Long term fertilization effects on 'Rio Red' grapefruit yield and shape on a heavy textured calcareous soil". *Scientia Horticulturae*, 118, 149–154.

Appendix A

Figure A1. Modeling canal irrigation

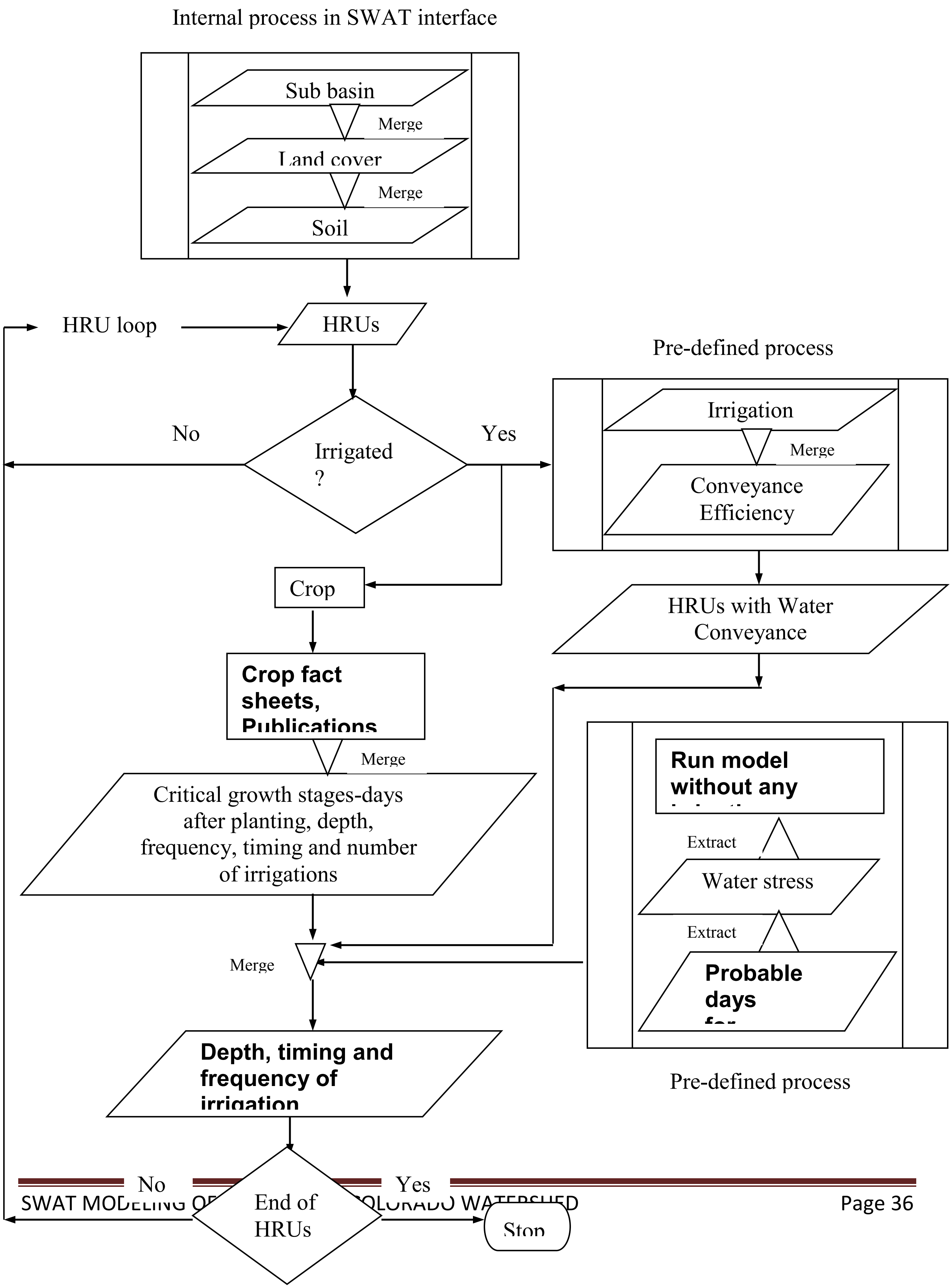

Figure A2. Monthly flow for Arroyo near Mercedes-Calibration period

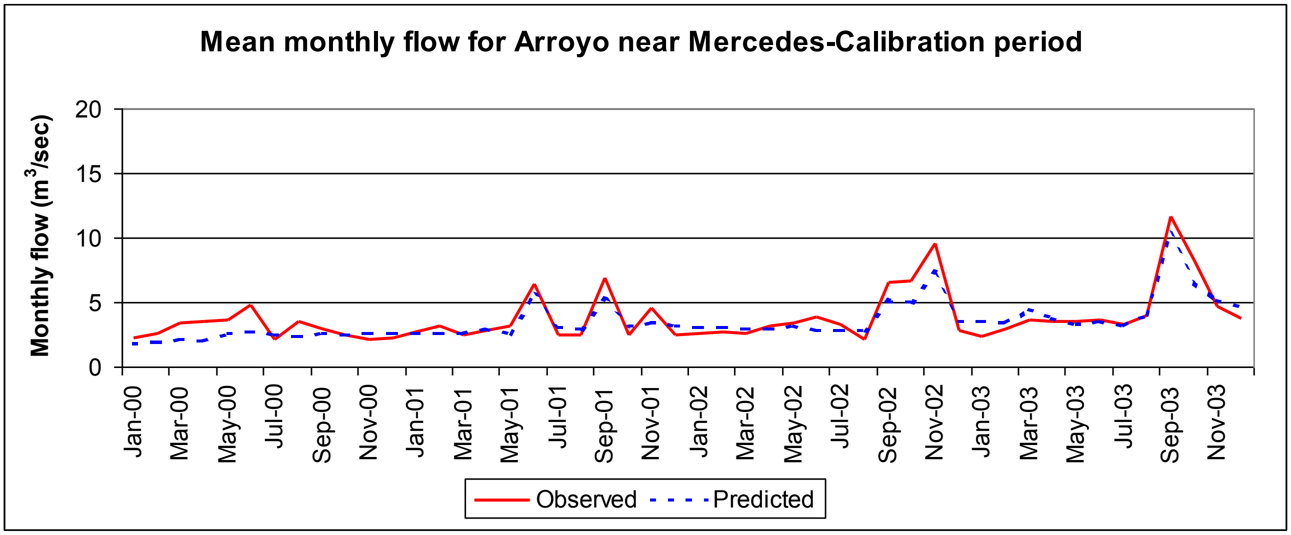

Figure A3. Monthly flow for Arroyo near Harlingen-Calibration period

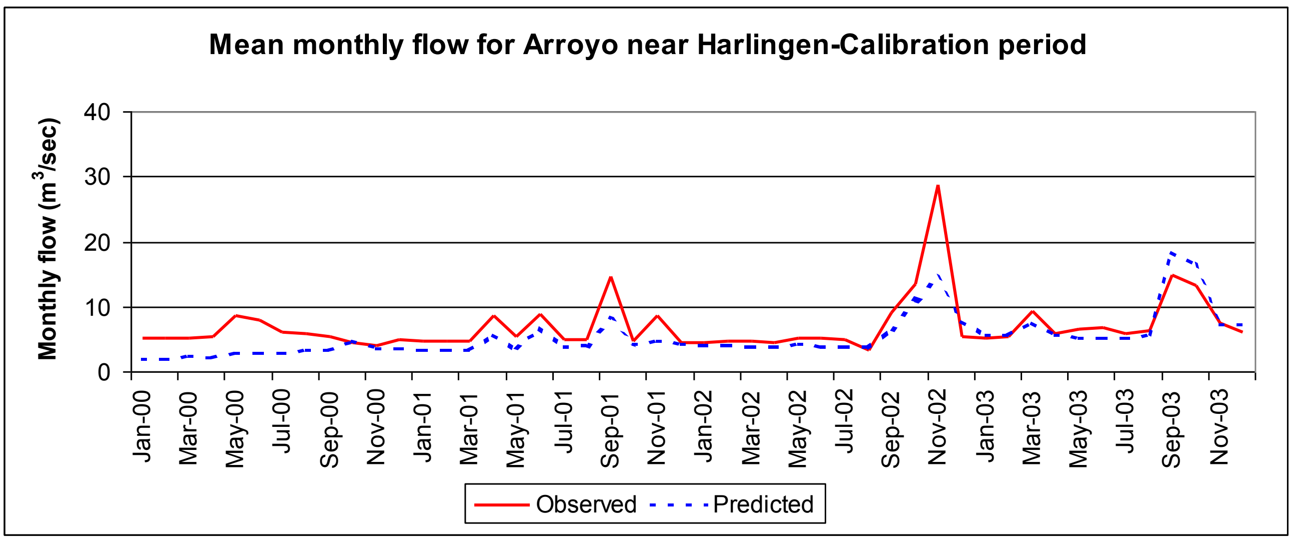

Figure A4. Monthly flow for Arroyo near Mercedes-Validation period

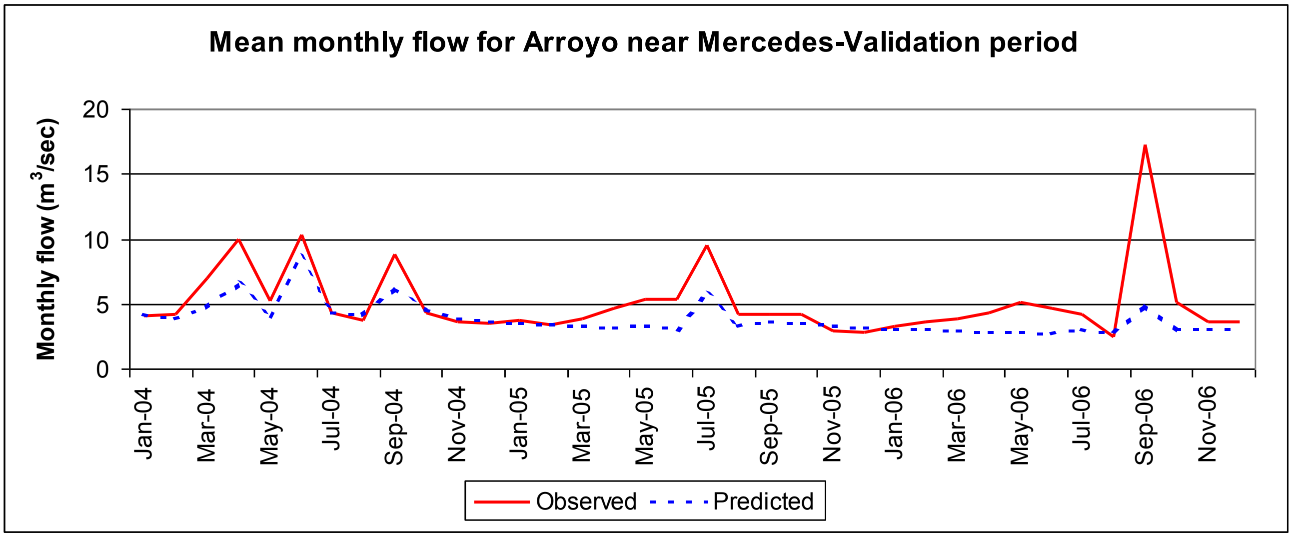

Figure A5. Monthly flow for Arroyo near Harlingen-Validation period

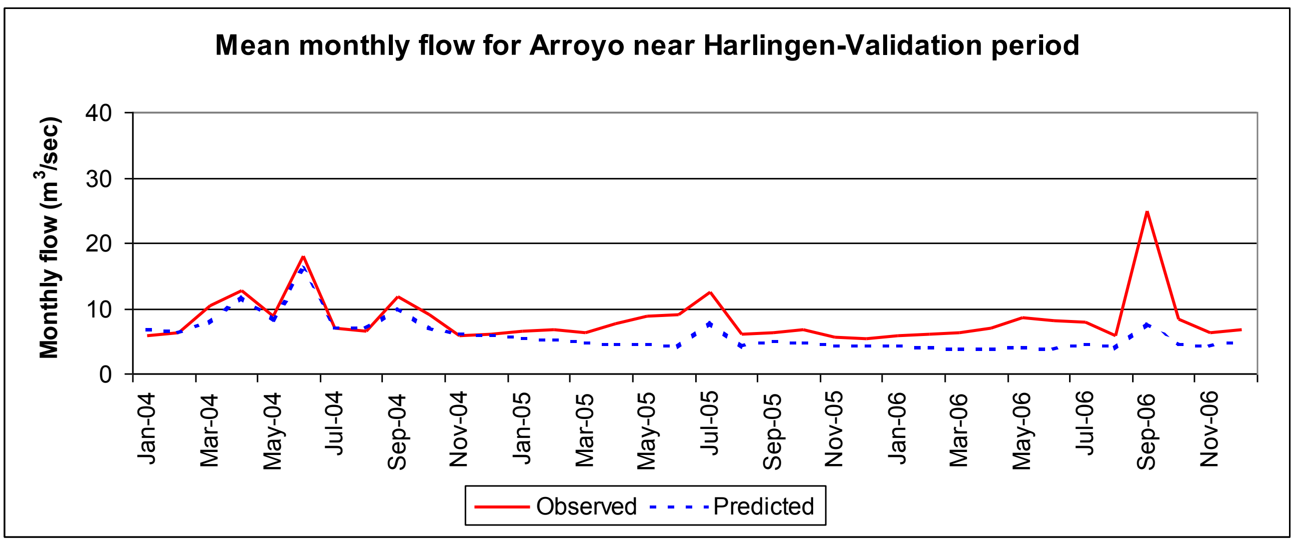

Figure A6. Monthly sediment load for Arroyo near Mercedes

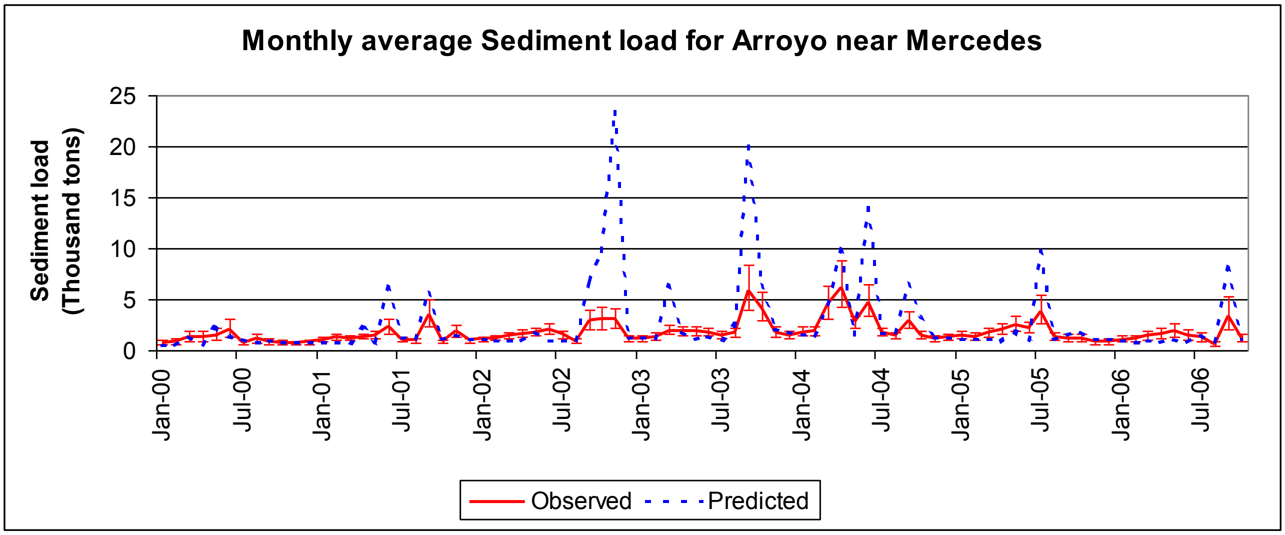

Figure A7. Monthly sediment load for Arroyo near Harlingen

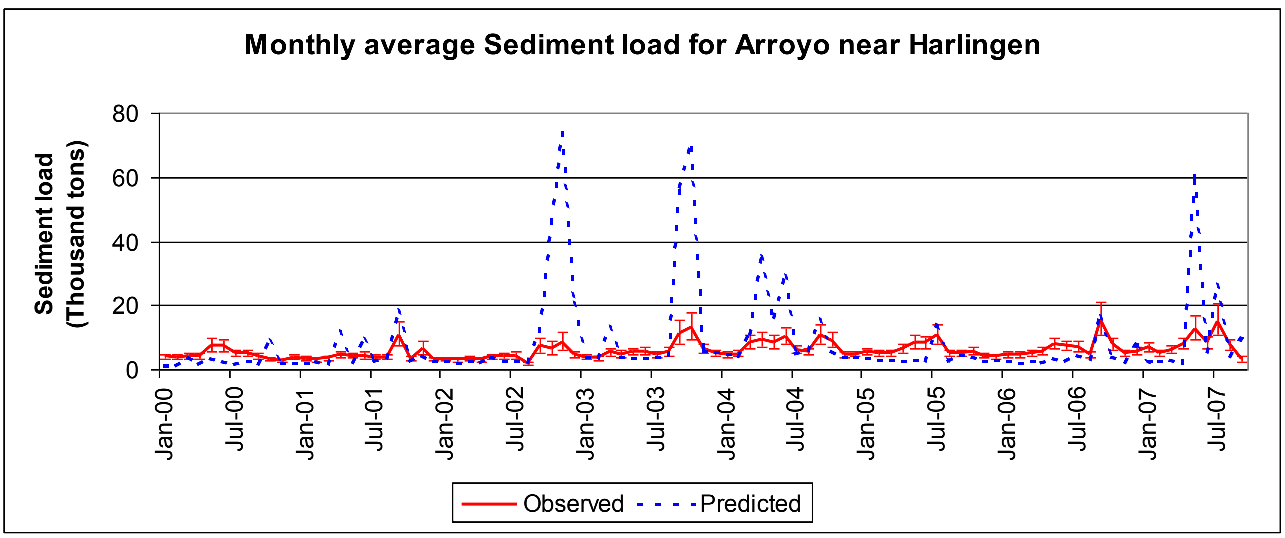

Figure A8. Monthly Orthophosphate load for Arroyo near Harlingen

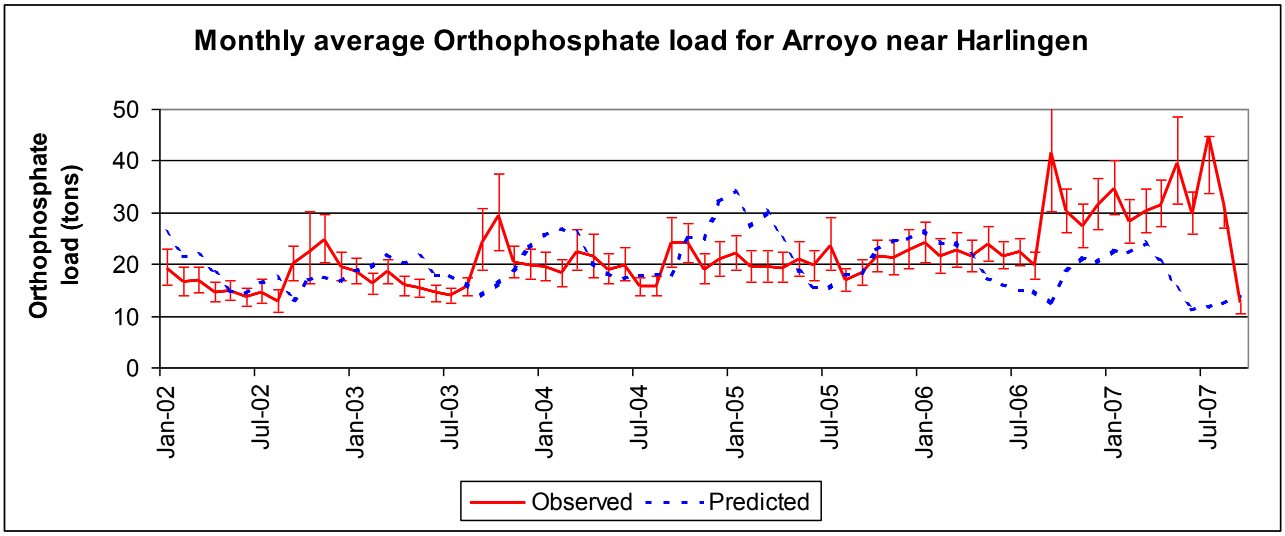

Figure A9. Monthly total phosphorus load for Arroyo near Harlingen

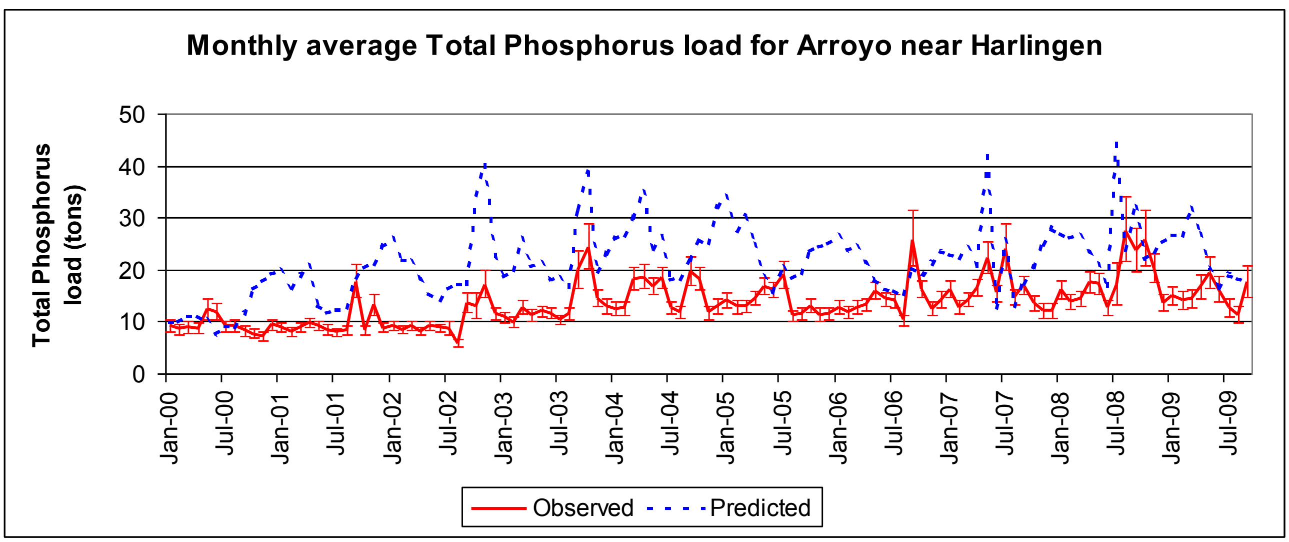

Figure A10. Monthly ammonia nitrogen load for Arroyo near Mercedes

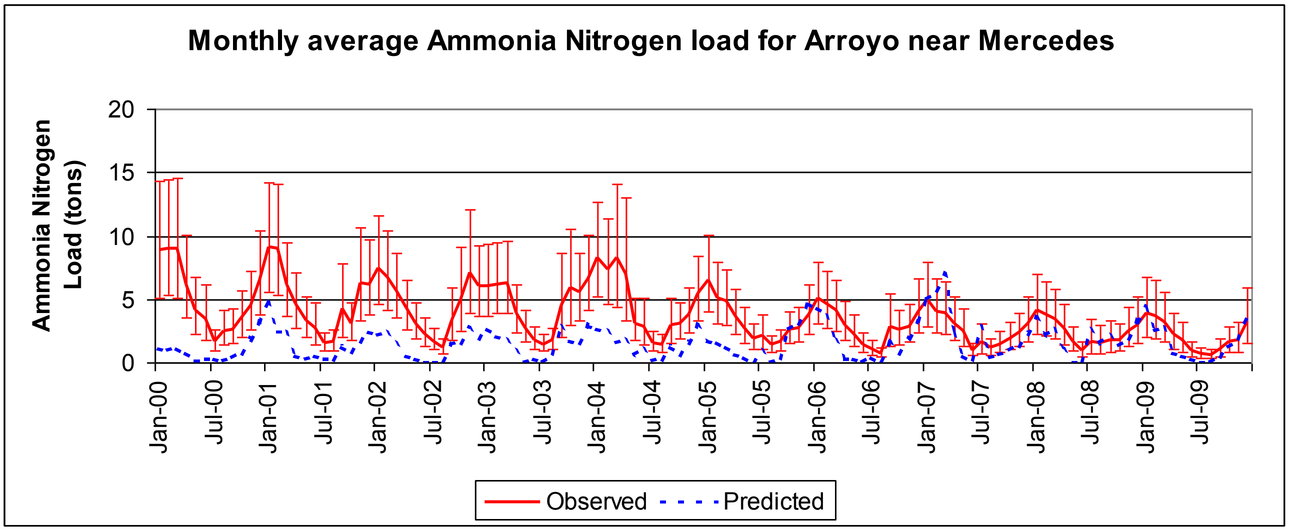

Figure A11. Monthly nitrate nitrogen load for Arroyo near Harlingen

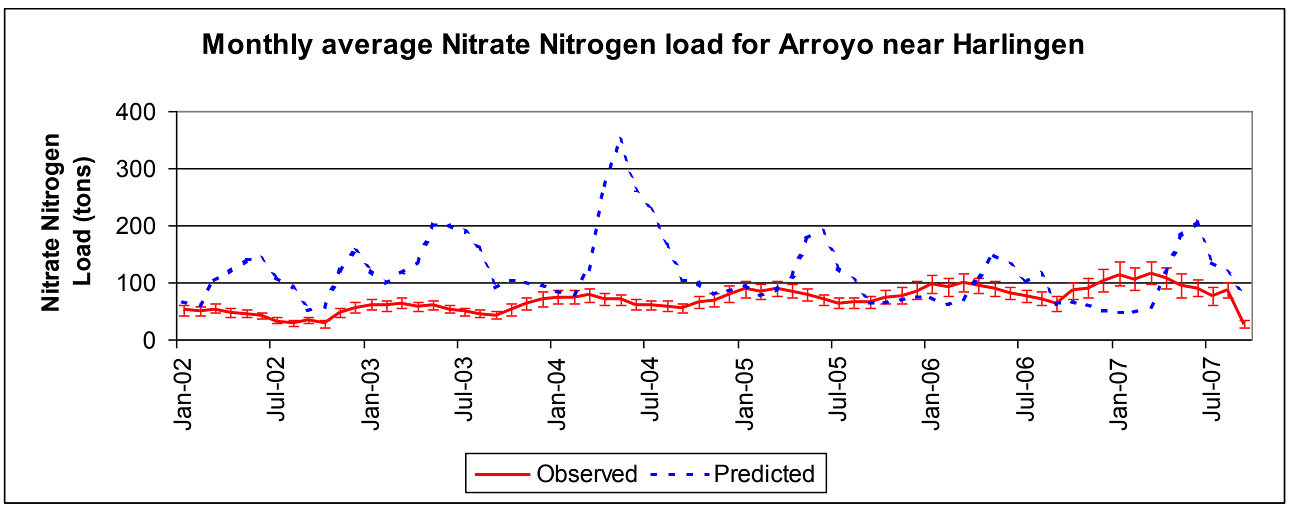

Figure A12. Monthly total nitrogen load for Arroyo near Harlingen

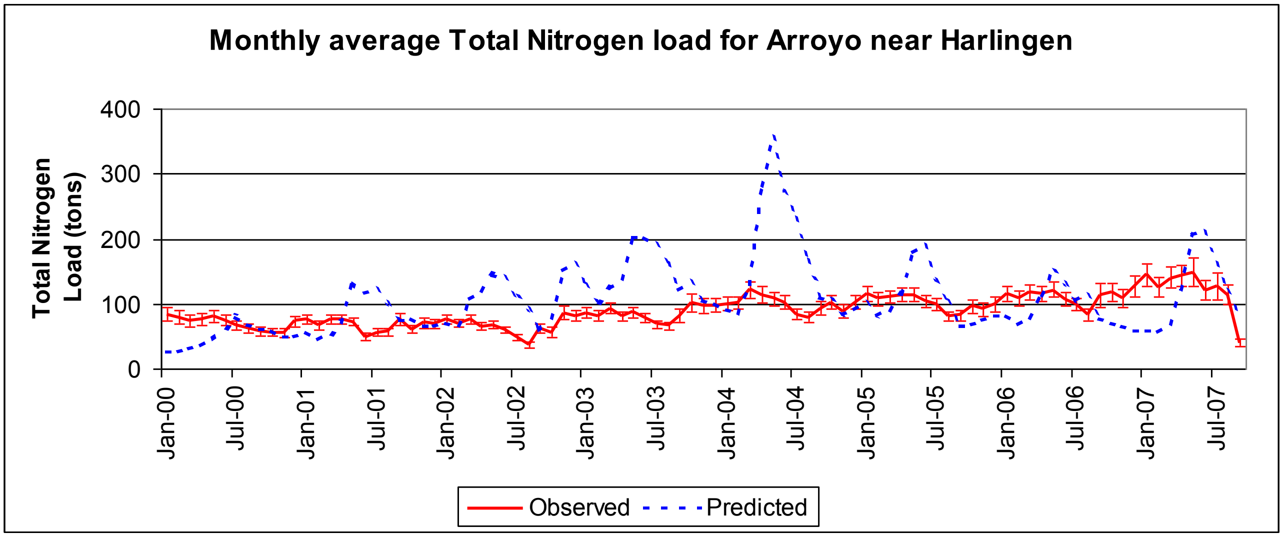

Figure A13. Mean Daily water temperature for Arroyo near Harlingen

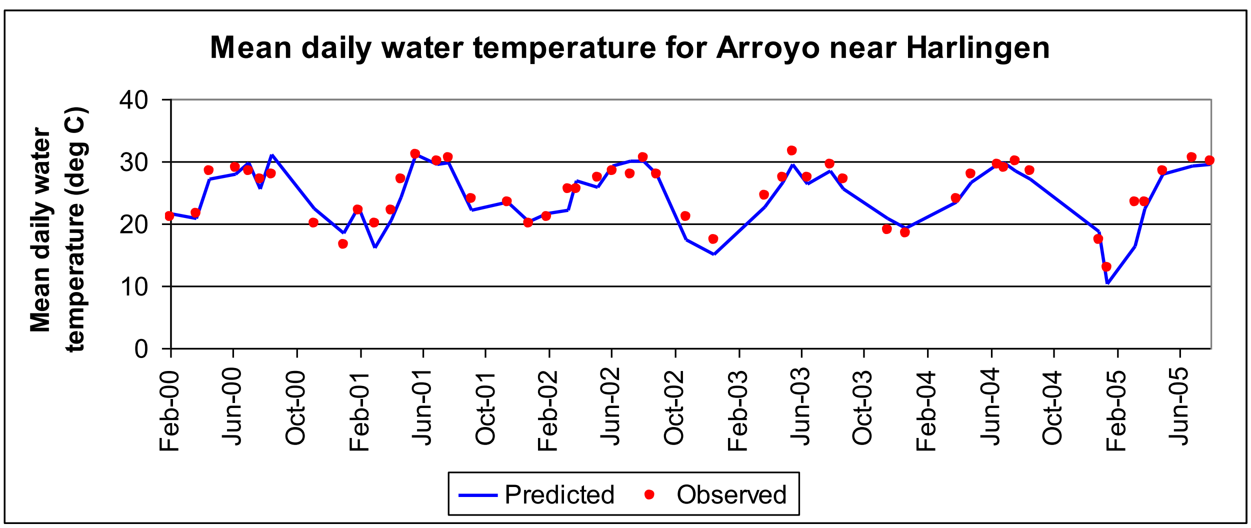

Figure A14. Mean daily dissolved oxygen for Arroyo near Harlingen

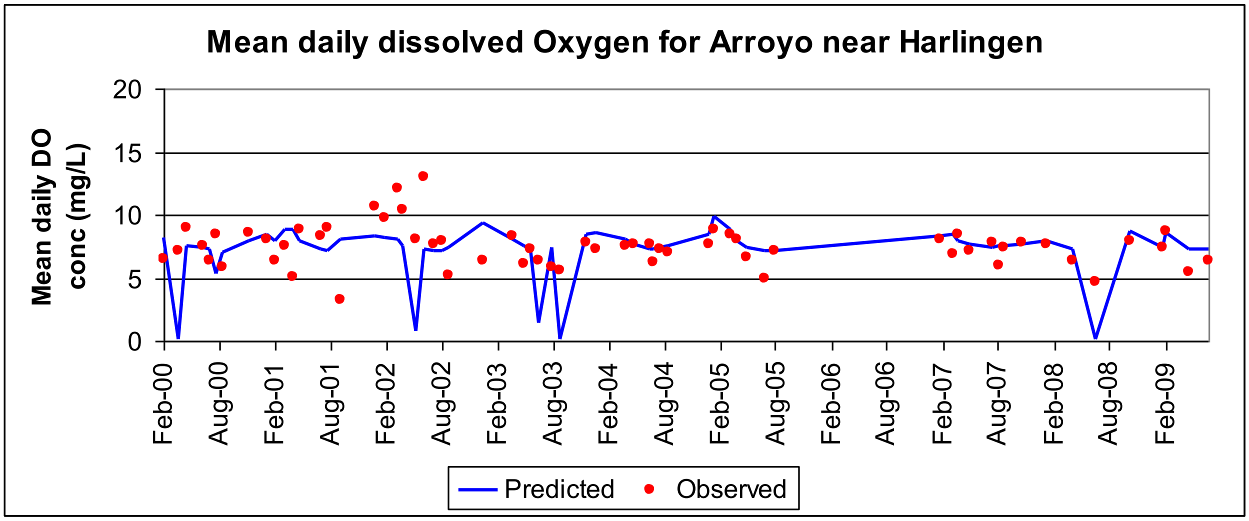

Figure A15. Pollutant load from different sources in the watershed model setup

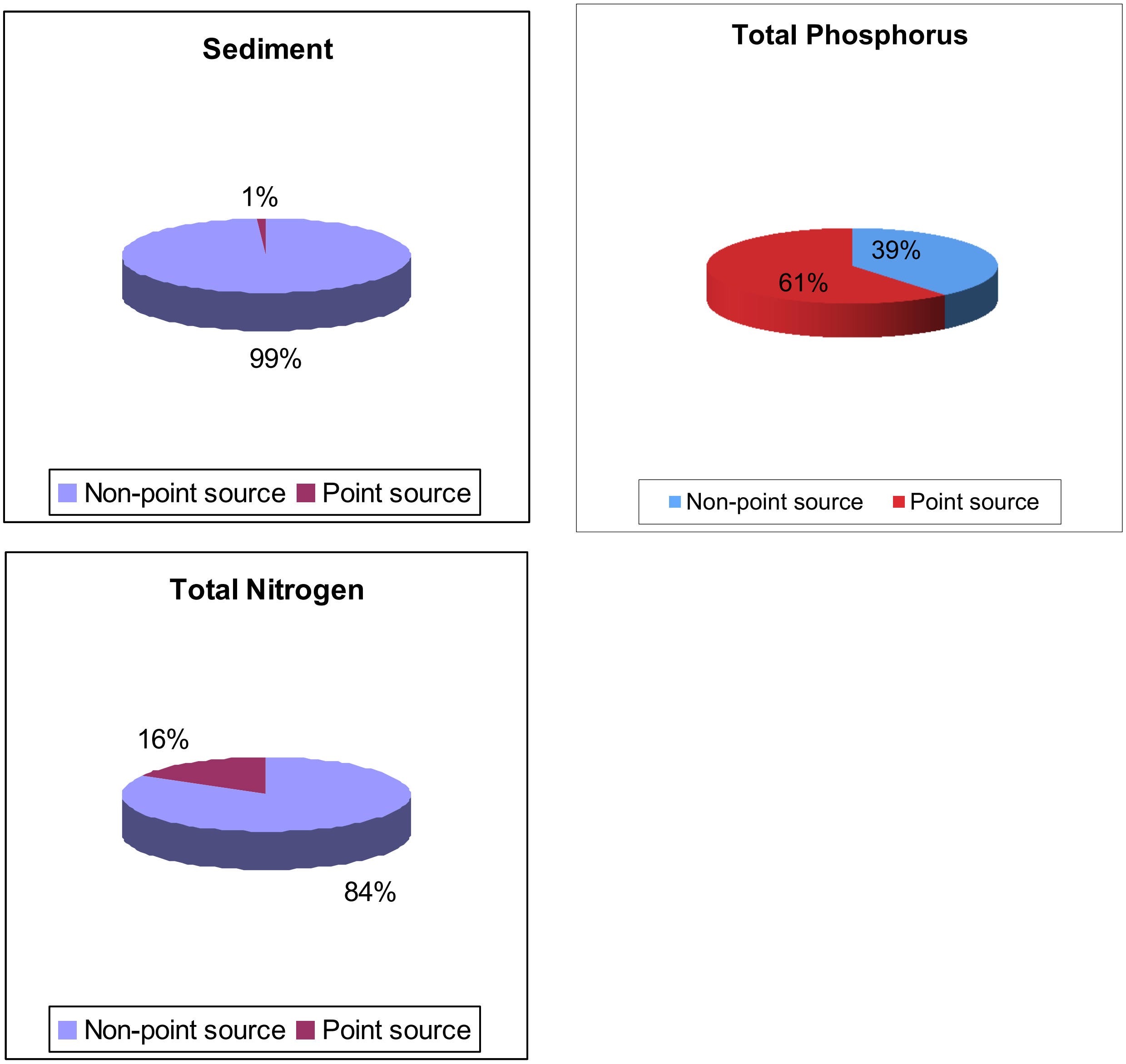

Table A1. Model parameters and their range considered for flow calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
SURLAG	Surface runoff lag coefficient	days	watershed	0.001	15
AWC	Available water capacity	--	HRU	-0.04	+0.04
CN2	SCS runoff curve number for moisture condition II	--	HRU	-4.0	+4.0
EPCO	Plant uptake compensation factor	--	HRU	0.001	1
ESCO	Soil evaporation compensation factor	--	HRU	0.001	1
GW_DELAY	Delay time for aquifer recharge	days	HRU	0.001	100
GW_REVAP	Groundwater revap coefficient	--	HRU	0.02	0.2
GWQMN	Threshold water level in shallow aquifer for base flow	mm	HRU	0.01	100

Table A2. Mean monthly flow results for Arroyo Colorado

Monitoring station	Calibration period (2000-2003)		Validation Period (2004-2006)	
	Predicted (m^3/sec)	Observed (m^3/sec)	Predicted (m^3/sec)	Observed (m^3/sec)
Near Mercedes	3.47	3.76	3.79	5.08
Near Harlingen	5.24	6.89	5.81	8.20

Table A3. Model performance evaluation for flow calibration

Monitoring station	Calibration period (2000-2003)		Validation Period (2004-2006)	
	R^2	Nash and Sutcliffe Efficiency (%)	R^2	Nash and Sutcliffe Efficiency (%)
Near Mercedes	0.83	78.6	0.47	19.5
Near Harlingen	0.59	43.1	0.41	1.82

Table A4. Water quality data availability for Arroyo Colorado watershed

Parameter	Data Availability		
	Near Llano Grande at FM 1015 south of Weslaco	Near US 77 in South West Harlingen	Port of Harlingen
Stream flow	Available	Available	
Suspended Sediment	Available	Available	Available*
Total Nitrogen		Available	
Nitrate Nitrogen		Available	
Ammonia Nitrogen	Available	Available	Available*
Total Phosphorus		Available	
Ortho phosphate		Available	
Dissolved Oxygen		Available	
Water temperature		Available	Available*

* Very few samples; not considered for calibration

Table A5. Model parameters and their range considered for sediment calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
ADJ_PKR	Flow peak rate adjustment factor for sediment routing in tributaries	--	watershed	0.0	1.0
PRF	Flow peak rate adjustment factor for sediment routing in main channel	--	watershed	0.0	1.0
SPCON	Linear parameter controlling sediment re-entrained in channels	--	watershed	0.0001	0.01
SPEXP	An exponent controlling sediment re-entrained in channels	--	watershed	1.0	2.0
CH_N2	Manning's n value for the main channel	--	reach	0.016	0.15
CH_COV1	Channel erodibility factor	--	reach	0.0	1.0
CH_COV2	Channel cover factor	--	reach	0.0	1.0
CH_N1	Manning's n value for the tributary channels	--	subbasin	0.025	0.15
Erosion K	Soil erodibility factor	--	HRU	0.0	1.0
LAT_SED	Sediment concentration in lateral flow	mg/L	HRU	0.0	--

Table A6. Model parameters and their range considered for nutrient calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
N_UPDIS	Nitrogen uptake distribution parameter	--	watershed	0.0	40
P_UPDIS	Phosphorus uptake distribution parameter	--	watershed	0.0	40
NPERCO	Nitrogen percolation coefficient	--	watershed	0.01	1.0
PPERCO	Phosphorus percolation coefficient	--	watershed	10.0	17.5
PHOSKD	Phosphorus soil partitioning coefficient	--	watershed	0.01	300
PSP	Phosphorous sorption coefficient	--	watershed	0.0	1.0
RS2	Benthic source rate for dissolved phosphorus	--	reach	0.001	0.1
RS3	Benthic source rate for ammonia nitrogen	--	reach	0.001	0.1
RS4	Rate coefficient for organic nitrogen settling	--	reach	0.001	0.1
RS5	Rate coefficient for organic phosphorus settling	--	reach	0.001	0.1
BC1	Rate constant for biological oxidation of ammonia to nitrite	--	reach	0.1	1.0
BC2	Rate constant for biological oxidation of nitrite to nitrate	--	reach	0.2	2.0
BC3	Rate constant for hydrolysis of organic nitrogen to ammonia	--	reach	0.2	0.4
BC4	Rate constant for mineralization of organic phosphorus	--	reach	0.01	0.7
GWSOLP	Concentration of soluble phosphorus in groundwater	mg/L	HRU	0.01	1.0
HLIFE_NGW	Half life of nitrate in the shallow aquifer	days	HRU	30.0	200

Table A7. Comparison of predicted and observed mean of various water quality parameters

Average parameter values	Near Llano Grande at FM 1015 south of Weslaco		Near US 77 in South West Harlingen	
	Predictions	**Observations**	**Predictions**	**Observations**
Suspended sediment load (tons/year)	2,634.1	1,795.0	8,434.0	5,956.0
Ammonia Nitrogen (tons/year)	1.3	4.2	--	--
Nitrate Nitrogen (kg/day)			116.0	69.0
Total Nitrogen (kg/day)			107.0	89.0
Ortho Phosphorus (kg/day)			19.8	21.8
Total Phosphorus (kg/day)			21.4	13.5
Water temperature (°C)			24.6	25.3
Dissolved Oxygen (mg/L)			7.2	7.5