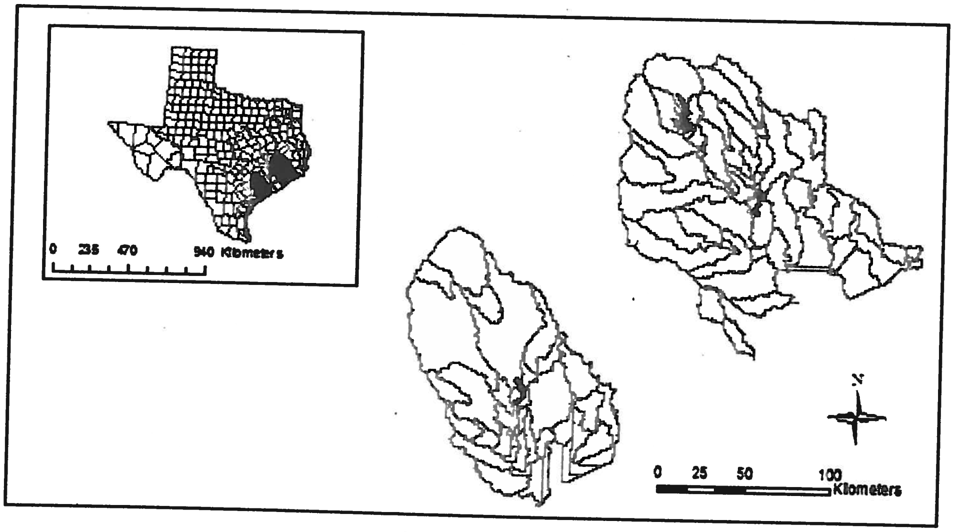
Estimating Sediment and Nutrient loads of Texas Coastal Watersheds with SWAT

A case study of Galveston Bay and Matagorda Bay

Final Report for the Texas Water Development Board

Project #1004831012



August, 2012

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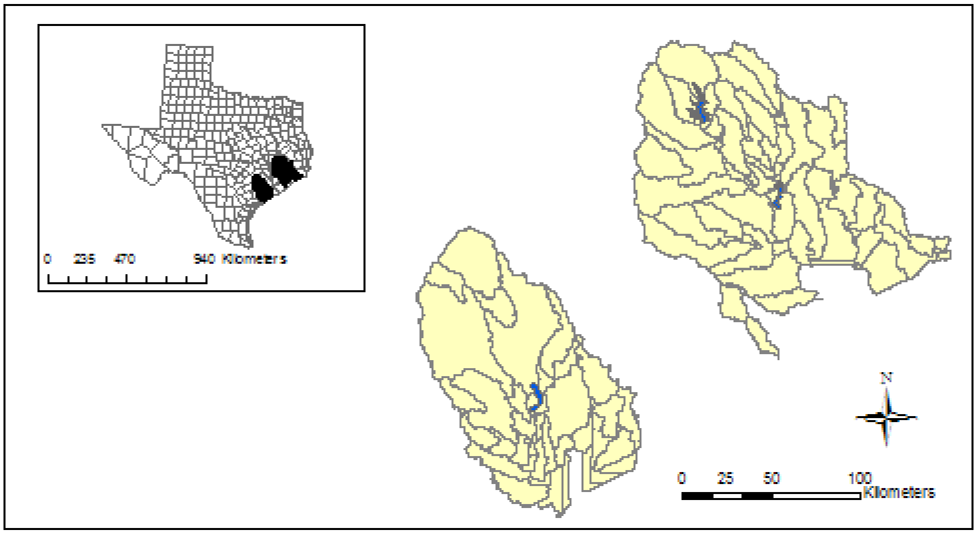

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Summary

The SWAT (Soil and Water Assessment Tool) model was used to estimate terrestrial sediment and nutrients loads to the Galveston and Matagorda bays from their contributing watersheds. In this report, the term "terrestrial loads" represents the sum of gauged loads from gauged subbasins and model-generated loads from ungauged subbasins. Because we did not have access to the point sources data, the municipal wastewater treatment plants (WWTPs) and industrial point source discharges are not included in this calculation of water quality variables. This information, however, would be required to calculate the total nutrient load actually reaching a bay. The predicted total N and P were compared to the estimated mean annual nutrient loads from fresh water by the previous studies.

SWAT is a spatially distributed, continuous model that can be used to estimate flow, sediment, and nutrients at a variety of scales ranging from a small hill slope to a large watershed. SWAT benefits can be summarized into three categories. First, SWAT offers finer spatial and temporal scales, allowing users to observe an output from a particular subbasin within a particular time frame. Secondly, it considers comprehensive hydrological processes at the subbasin level and within the entire watershed, estimating not only surface runoff with associated sediment and nutrients but also subsurface flow, groundwater flow and channel processes. And third, the calibrated model can be developed to analyze scenarios such as BMP (Best Management Practice) usage, land use changes, climate change and more.

In this study, two watersheds, the Galveston Bay and Matagorda Bay, were selected for a pilot study because one represents an urbanized watershed (Galveston Bay) and the other a rural watershed (Matagorda Bay).

Geographic Information System (GIS) data and other parameters were obtained from several sources: the Digital Elevation Model (DEM) from the Natural Resource Conservation Service (NRCS) provided topography, land cover and soil data; the National Climate Data Center (NCDC) provided weather data; and U.S. Geological Survey stream gauge stations provided flow data series as well as sediment and nutrient samples.

The project consists of two parts. Hydrologic simulation was performed in the first phase, and the second phase focuses on the estimation of sediment and nutrient loads. Two separate SWAT models were developed; one for each watershed. SWAT's automatic processes delineated the watersheds, river channels, subbasins, and Hydrologic Response Units (HRUs). Weather station data were enhanced and adjusted using NEXRAD (Next Generation Radar) precipitation data. Two lakes, Lake Conroe and Lake Houston, were added to the model as reservoirs, and point sources were set up in each subbasin for future use. Modeled monthly sediment showed good agreement when compared with observed TSS with R^2 ranging from 0.67 to 0.86 and NSE ranging from 0.61 to 0.84. Estimated monthly total nitrogen and total phosphorus showed good to acceptable correlation with observed values, with R^2 ranging from 0.63 to 0.85 and NSE ranging from 0.46 to 0.80. However, predicted monthly nitrate from all gauging subbasins and predicted nutrient load from urbanized subbasins in the Galveston watershed were not satisfactory.

1. Introduction

The TWDB recently requested that the Soil and Water Assessment Tool (SWAT) be used to estimate surface inflows and sediment and nutrient loads to the bays with up-to-date technology and data. Accordingly, this project was initiated to develop and apply the SWAT model to two Texas estuaries in order to estimate sediment and nutrient loads and to evaluate model performance when compared to the TWDB reports. Freshwater inflow from ungauged and gaugd watersheds to coastal bays was predicted using SWAT in the first phase of this project. The purpose of the second phase of this project was to predict sediment, total nitrogen and total phosphorus on an annual basis for both gauged and ungauged subbasins using a calibrated model setting for gauged subbasins.

Although not considered, municipal WWTPs and industrial point source discharges from the subbasins would be required to calculate the total nutrient loads actually reaching a bay. The objectives of this study were to: 1) apply the SWAT model using up-to-date technology such as Geographic Information System (GIS) data, satellite imagery, and NEXt generation RADar (NEXRAD) weather data for two watersheds, 2) estimate sediment and nutrient loads to the estuary by including gauged and ungauged subbasins, and 3) develop methodologies and procedures for estimating terrestrial sediment and nutrient loads to the estuaries as required by the TWDB.

2. Methodology

2.1. Study Area

The Galveston Bay and Matagorda Bay watersheds are located in the southeastern coastal area of Texas (Figure 1). Both watersheds drain into their respective estuaries, which are connected to the Gulf of Mexico. The Galveston Bay watershed has a total drainage area of approximately 6,220 square miles (16,100 km^2) while the Matagorda Bay watershed's area is 4,480 square miles (11,600 km^2), as delineated by SWAT. In this study, the Galveston Bay watershed was delineated mainly by the San Jacinto River with some Trinity River subbasins included. Delineation guidance provided by TWDB provided the basis for this decision. The Galveston Bay watershed is considered an urbanized watershed and includes the city of Houston and its surrounding metro area. Guided by TWDB, the Matagorda Bay watershed was delineated mainly by the Tres Palacios River; although some Colorado River subbasins were included on the right side of the watershed. The Matagorda Bay watershed is considered a rural watershed.

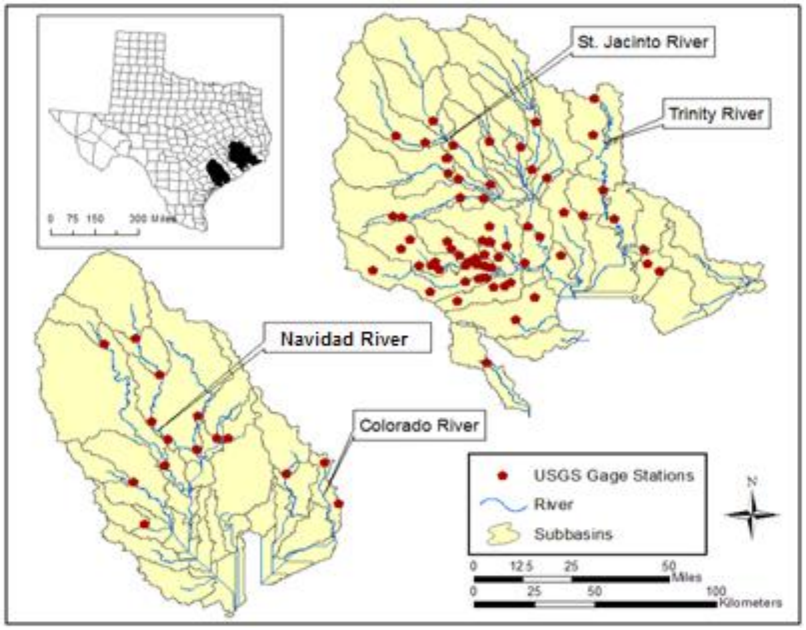


Figure 1. Matagorda (left) and Galveston (right) bay watersheds

2.2. SWAT

SWAT (Arnold et al., 1998) is a physically based, continuous simulation model developed to assess the short- and long-term impacts of management practices on large watersheds. The model requires extensive input data, which can be supplemented with GIS data and the model interface (Di Luzio et al., 2002). The model divides watersheds into a number of subbasins and adopts the concept of the hydrologic response unit (HRU), which represents the unique property of each parameter, such as land use, soil, and slope. SWAT is able to simulate rainfall-runoff based on separate HRUs, which are aggregated to generate output from each subbasin. SWAT is a combination of modules for water flow and balance, sediment transport, vegetation growth, nutrient cycling, and weather generation. SWAT can establish various scenarios detailed by different climate, soil, and land cover as well as the schedule of agricultural activities including crop planting, tillage, and BMPs (Best Management Practices; Flay, 2001).

In summary, the benefits of using SWAT for this project are that, first, it offers finer spatial and temporal scales, which allow the user to observe an output at a particular subbasin on a particular day. Second, it considers comprehensive hydrological processes, estimating not only surface runoff with associated sediment and nutrients but also groundwater flow and channel processes within each subbasin and at the watershed scale. However, sediment and nutrients were not modeled as part of this study. Third, upon completion of this study, the calibrated model can be developed to further analyze scenarios such as BMPs (Best Management Practices), land use changes, climate change, and more.

2.3. Data

1) Elevation (DEM)

On their Data Gateway Website, the Natural Resources Conservation Service (NRCS) provided a National Elevation Dataset (NED) with 30-meter resolution (http://datagateway.nrcs.usda.gov/). The digital elevation dataset was used to automatically delineate watershed boundaries and channel networks. Elevation in both the Galveston and Matagorda Bay watersheds ranges from -1 to 593 feet above sea level (Figure 2). Near the coast, the area is very flat; the average slopes of the Galveston Bay and Matagorda Bay watersheds are 0.99% and 0.61%, respectively.

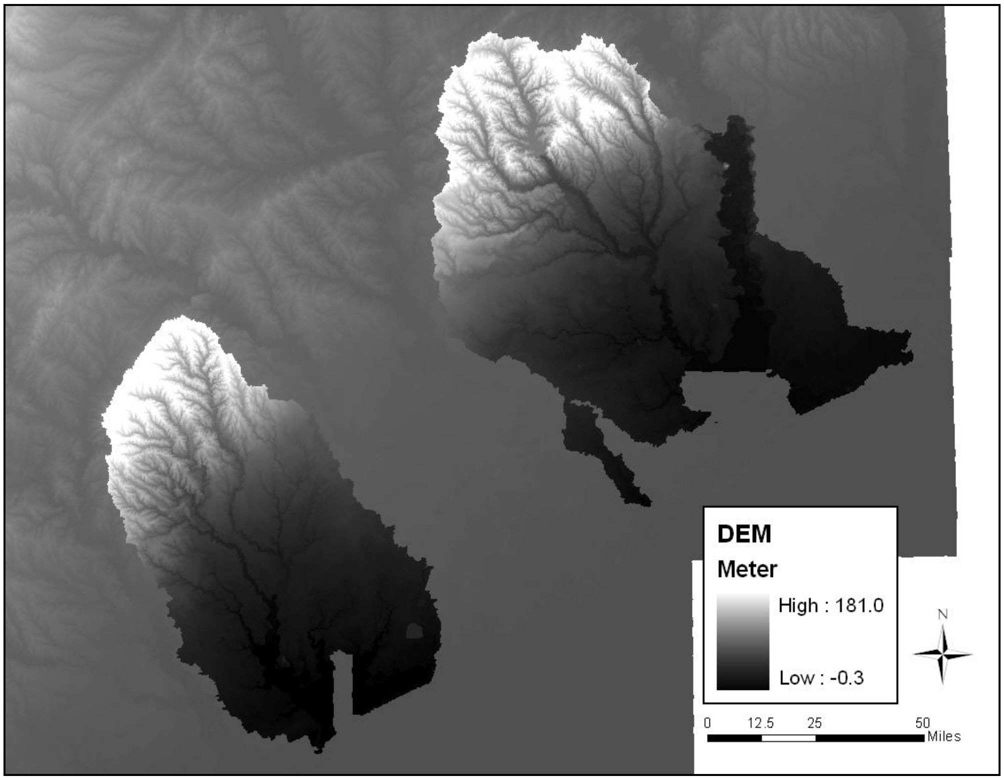


Figure 2. National elevation dataset (NED) of Matagorda (left) and Galveston (right) bay watersheds

2) Land use

The NRCS Data Gateway Website also provided the National Land Cover Dataset (NLCD) created in 2001 (Figure 3). Although a 2008 version of the Texas Cropland Data Layer (CDL) was available, 2001 land use data was considered more appropriate because this study simulated a historical period from 1975. Percentages of each land use are summarized in Table 1. Land use in the Galveston Bay watershed consists primarily of urban areas (23.8%) and pastureland (21.9%). In the Matagorda Bay watershed, on the other hand, pastureland accounts for the largest portion (43.9%), nearly half the area of the entire watershed.

Table 1. Land use categories in each watershed as determined by the National Land Cover Dataset (2001).

Landuse type	Watershed	
	Galveston	Matagorda
Water (river & lake)	4.2%	9.2%
Urban	23.8%	0.0%
Forest	17.7%	9.3%
Agricultural	5.8%	26.2%
Pastureland	21.9%	43.9%
Rangeland	7.0%	8.5%
Wetland	19.5%	2.8%
Total	100.0%	100.0%

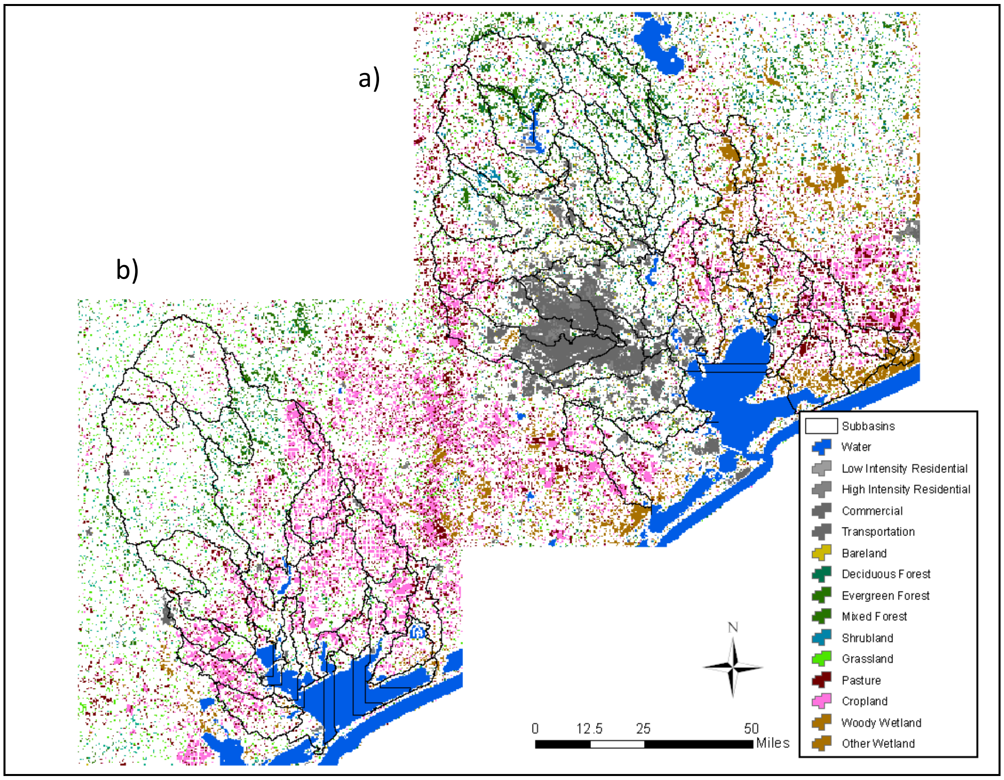


Figure 3. National Land Cover Dataset (30-m resolution) created in 2001 for a) Galveston Bay and b) Matagorda Bay watersheds

3) Soil

The NRCS Data Gateway also provided Soil Survey Geographic (SSURGO) data in shape file format and converted it to GRID format at 30-meter resolution. The SSURGO Data Processor processed the soil data for use in SWAT. The major soil types in the Galveston Bay watershed are Lake Cha and Bernard, covering 10.0% and 7.7%, respectively, of the total watershed area. In the Matagorda Bay watershed, Ligon (20.7%) and Dacosta (11.5%) are the major soil types.

4) Weather stations

The National Climate Data Center (NCDC) Website (http://www.ncdc.noaa.gov/oa/ncdc.html) provided weather data including precipitation and temperature (minimum and maximum) for weather stations within and near the watersheds from 1970 to 2008. A total of twenty weather stations were used in this study, eleven for the Galveston Bay watershed and nine for the Matagorda Bay watershed (Figure 4). When weather station data were missing at intervals ranging from a couple of days to months, data from the nearest weather station were used. In cases where only one or two days were missing temperature, temperatures were estimated using a linear calculation between the last available day and the next available day.

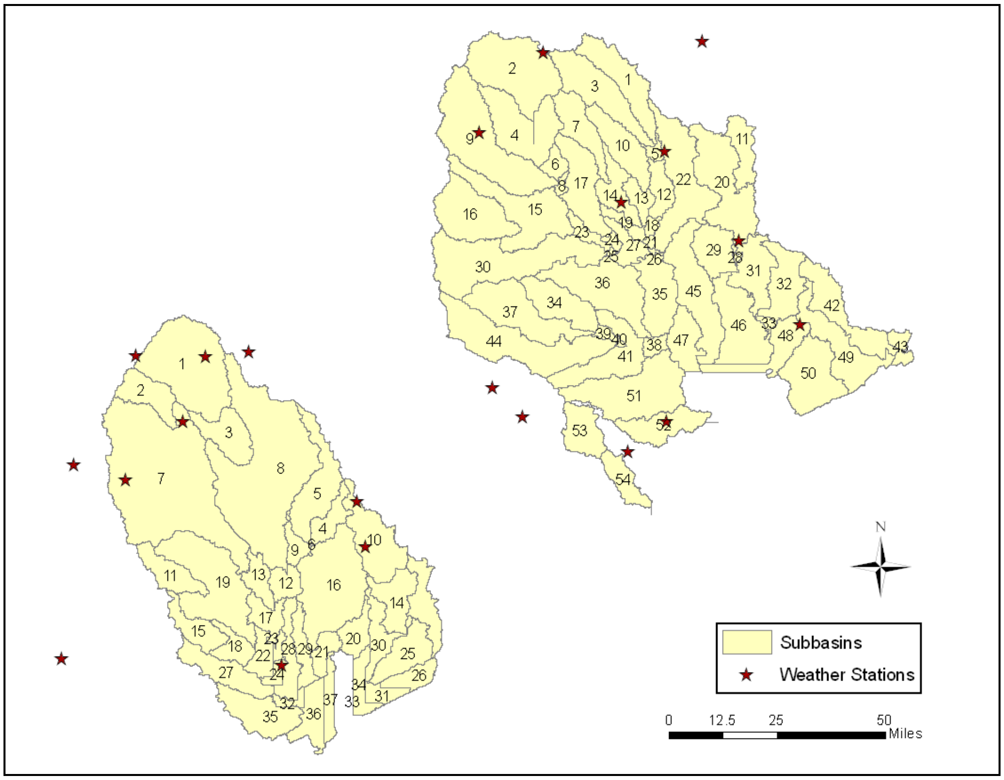


Figure 4. Weather stations used in this project; numbers indicate subbasin ID.

5) Stream flow data at USGS gauging stations

The USGS (U.S. Geological Survey) provided flow data at stream gauging stations, twenty-one of which were available in the watersheds (Figure 5). Of those stations, only eight in the Galveston Bay watershed and three in the Matagorda Bay watershed were used. All other stations were eliminated because they had either too much missing data or the gauging stations were located in a minor tributary and could not be analyzed. Table 2 summarizes the available gauging stations and explains why some were not used.

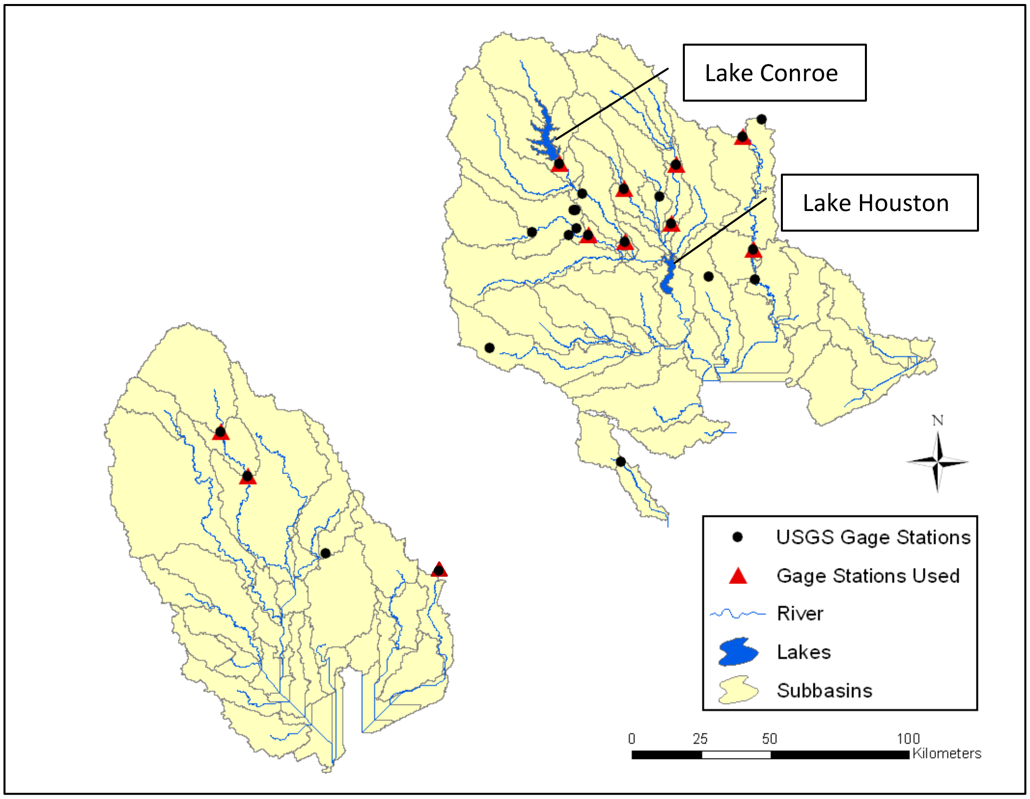


Figure 5. USGS gauging stations available in both watersheds

Gauging stations 08066500 and 08162500 were used as inlets for the Galveston Bay and Matagorda Bay watersheds, respectively. Station 08066500 was used as the control point for the Trinity River (Romayor, TX), which is located in the upper right corner of the Galveston Bay watershed. Station 08162500 was used as the control point for the Colorado River (Bay City, TX), which is located in the lower right corner of the Matagorda Bay watershed. Streamflow data from these two gauging stations served as model input because the upper watershed (above this gauging station) was not included in the model. Six gauging stations and one inlet were used for calibration in the Galveston Bay watershed, and two gauging stations and one inlet were used in the Matagorda Bay watershed.

Table 2. List of available USGS gauging stations in the both watersheds, whether they were used (Y) or not (N) and the reason

Watershed	Station #	Used (Y/N)	Note
Galveston Bay watershed	08067650	Y	Subbasin 2, 4*
	08070000	Y	Subbasin 1, 3, 5
	08070500	Y	Subbasin 7
	08070200	Y	Subbasin 1, 3, 5, 12
	08068500	Y	Subbasin 15, 16
	08068090	Y	Subbasin 2, 4, 6, 8, 9, 17
	08066500	Y	Inlet for Galveston watershed
	08067000	Y and N	Available for peak flow only
	08066300	N	Tributary
	08067070	N	Missing data
	08067500	N	Tributary
	08068000	N	Tributary
	08068275	N	Missing data
	08068390	N	Tributary
	08068400	N	Tributary
	08068450	N	Tributary
	08071000	N	Missing data
	08071280	N	Tributary
	08072300	N	Tributary
	08078000	N	Tributary
Matagorda Bay watershed	08164300	Y	Subbasin 1
	08164350	Y	Subbasin 1, 3
	08162500	Y	Inlet for Matagorda watershed
	08164504	N	Tributary

* Subbasin numbers indicate the contributing subbasins for each gauging station.

6) Sediment and nutrient samples at USGS gauging stations

The USGS (U.S. Geological Survey) provided sediment sample data at stream gauging stations, eighty-five of which were available in the watersheds (Figure 6). Of those stations, only two in the Galveston Bay watershed and one in the Matagorda Bay watershed were used for sediment calibration. Nutrient samples were available at three gauging stations in the Galveston Bay watershed and two gauging stations in the Matagorda Bay watershed. All other stations were eliminated because they had either too much missing data or the gauging stations were located in a minor tributary and could not be analyzed. Details on station data and time periods are presented in Tables 4 and 5.

Loads were estimated for total P, total N, organic N, orthophosphate as inorganic P, and dissolved nitrate. There was no significant difference between filtered and unfiltered parameters and a combination of those samples was used to estimate water quality parameters. For all the gauged subbasins except for Subbasin 7 (08070500) in the Galveston Bay watershed, nitrate (NO_3) was considered to be the inorganic form of nitrogen because the concentration of ammonia (NH_4) and nitrite (NO_2) was negligible in comparison to the concentration of nitrate. Ammonia accounts for about 30% of inorganic nitrogen in Subbasin 7 (08070500) while it is less than 15% of total inorganic nitrogen of other gauged subbasins and does not significantly affect the total nitrogen prediction.

If more than three samples were collected on the same day that date was excluded from the samples. For less than four samples collected on same day, the first sample was used. Loads were estimated using the LOAD ESTimator (LOADEST) program (Runkel et al., 2004). Between nine regression models, the most accurate fitted model was used in this report. There are three options to select the form of the regression model. The user may select one of the predefined models, automated model selection option or develop a user-defined regression model. In this project the automated model selection option was selected to determine the best regression model from nine candidate regression models based on the Akaike Information Criteria. The regression model #9 was fitted to the most of the water quality samples dataset. Table 3 shows the summary of LOADEST regression models for sediment and water quality samples.

Gauging stations 08066500 and 08162500 are inlets for the Galveston Bay and Matagorda Bay watersheds, respectively. Due to the lack of sediment and nutrient data, delivered loads from the inlet to the Galveston watershed were ignored. However, that information would be required to calculate total sediment and nutrient loads actually reaching a bay. The monthly sediment, total N, and total P from the inlet to the Matagorda Bay watershed are estimated at Gauging Station 08162000, which is located upstream of the Matagorda inlet point (Gauge 08162500).

Table 3. Summary of LOADEST regression models

Parameter	Station #	Regression model #	Estimation period	Sample size	Load R^2	Prob. Plot Corr. Coeff.	Serial Correlation of Residuals	Concentration R^2	95% Prediction intervals		Standard error prediction
Galveston									Lower	Upper	
TSS	30	9	1976-2008	75	95.32	0.99	0.05	77.05	307.76	620.19	78.11
	15	4	1965-2010	108	94.70	0.99	0.23	66.61	192.96	365.22	40.9
TN	7	9	1983-1999	85	95.25	0.95	0.00	27.21	0.18	0.26	0.02
	30	9	1983-1999	94	95.56	0.98	0.08	82.60	1.49	1.77	0.07
	12	9	1984-1999	82	96.88	0.97	-0.14	27.71	0.57	0.81	0.06
ON	7	5	1983-2004	94	93.89	0.95	0.11	51.08	0.17	0.28	0.03
	30	9	1983-2008	110	98.12	0.99	0.10	24.67	0.86	1.96	0.28
	12	9	1984-1999	82	96.30	0.97	-0.19	52.98	0.49	0.80	0.08
NO3	7	9	1983-1999	82	83.42	0.94	-0.10	65.40	0.03	0.04	0.00
	30	9	1983-1999	86	67.90	0.98	0.04	90.27	0.64	0.85	0.05
	12	6	1983-2011	146	81.12	0.95	0.22	36.96	0.07	0.09	0.01
NH4	7	9	1983-1999	84	92.89	0.99	0.13	50.64	0.01	0.02	0.00
TP	7	3	1983-1999	85	91.35	0.91	0.06	32.38	0.02	0.04	0.00
	30	9	1983-1999	87	64.16	0.80	-0.06	57.80	0.45	0.74	0.07
	12	9	1984-1999	83	91.53	0.92	0.08	36.18	0.06	0.10	0.01
MINP	7	3	1991-2004	39	88.67	0.96	-0.26	54.05	0.01	0.01	0.00
	30	9	1991-1999	31	88.90	0.97	0.12	88.44	0.08	3.36	0.99
	12	9	1991-2010	96	92.18	0.96	0.06	29.83	0.03	0.08	0.01
Matagorda											
TSS	7	1	1977-1993	97	90.17	0.98	-0.10	19.51	5.69	72.36	68.43
TN	7	9	1975-1993	134	96.82	0.99	0.29	78.37	0.83	1.87	0.26
	10	9	1976-1981	50	87.83	0.99	-0.25	28.20	0.50	1.34	0.21
ON	7	9	1979-1993	104	93.63	0.99	0.29	14.10	0.66	1.78	0.28
	10	2	1976-1981	50	89.91	0.97	-0.04	8.17	0.26	0.57	0.08
NO3	7	9	1969-1993	165	94.37	0.99	0.10	81.32	0.18	0.43	0.06
	10	9	1976-1981	47	57.90	0.93	-0.29	14.27	0.06	0.80	0.20
TP	7	9	1977-1993	121	94.74	0.98	-0.04	6.47	0.13	0.26	0.03
	10	9	1977-1981	41	82.42	0.98	0.15	28.90	0.06	0.27	0.05
MINP	7	9	1982-1993	54	96.76	0.99	-0.04	13.08	0.05	0.12	0.02

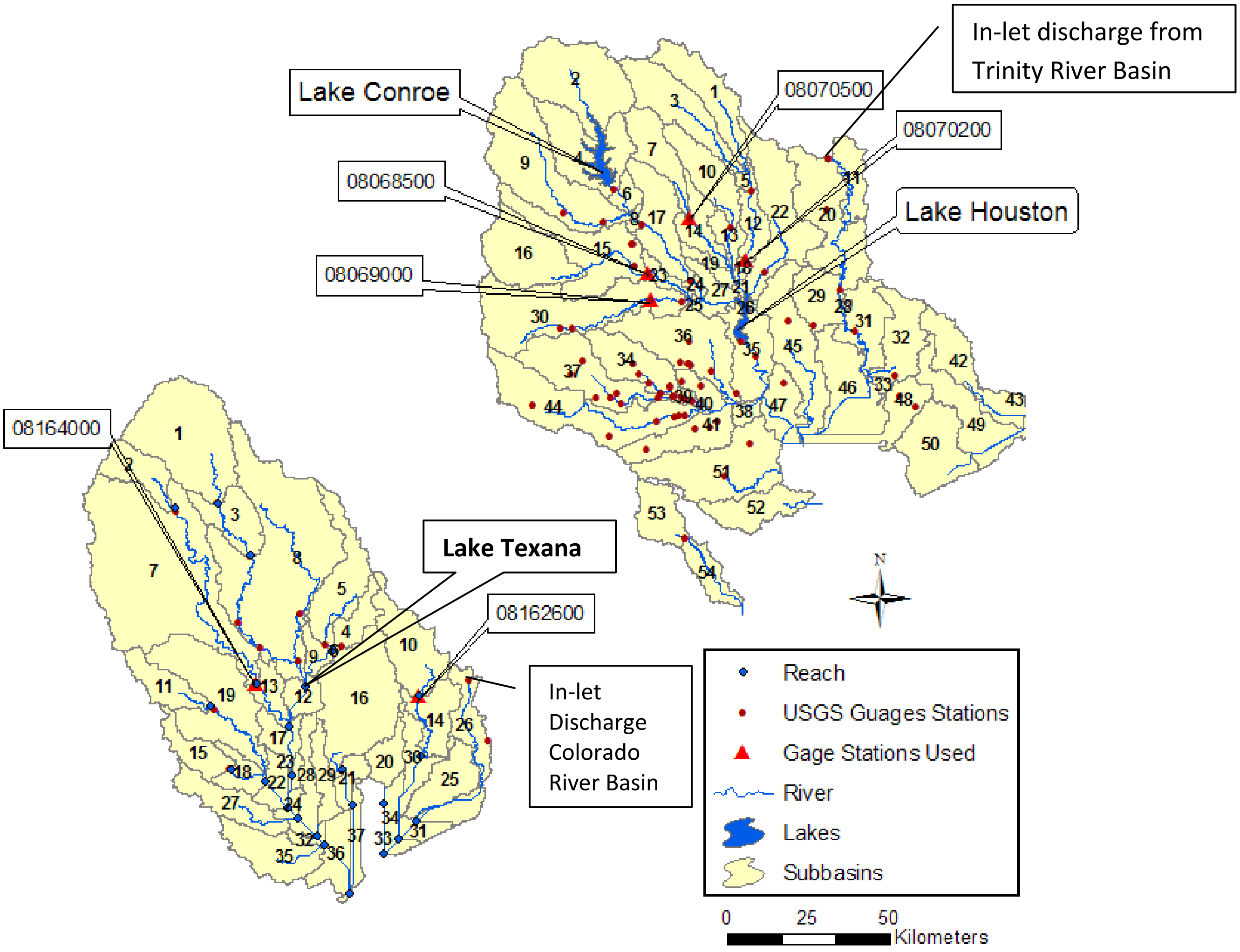


Figure 6. USGS gauging stations available in both watersheds

Table 4. List of USGS gauging stations used for sediment calibration in both watersheds

Watershed	Station #	Samples	Period	USGS parameter and code
Galveston Bay watershed	08069000 Subbasin 30	106	1965-1975, 2005-2010	Suspended sediment 80155
	08068500 Subbasin 16, 15*	109	1976-1990, 2004-2008	Total sediment 80156 Instantaneous discharge 00061
Matagorda Bay watershed	08164000 Subbasin 2, 7*	97	1977-1993	Average daily discharge 00060

* Subbasin numbers indicate the contributing subbasins for each gauging station.

Table 5. List of USGS gauging stations used for nutrients calibration in both watersheds

Watershed	Station #	Samples	Period	USGS parameter
Galveston Bay watershed	08070500 Subbasin 7	368	1983-2004	Total N 00600 Organic N 00605 Total P 00665 Total NO3 00620 Total NH4 00610 Dissolved NO3 00618 Total P 00665 Orthophosphate 00665
	08069000 Subbasin 30	431	1983-1999, 2008	
	08070200 Subbasin 1, 3, 5, 12*	432	1984-1999, 2005-2010	
Matagorda Bay watershed	08164000 Subbasin 2, 7*	578	1969-1993	
	08162600 Subbasin 10	190	1976-1981	

* Subbasin numbers indicate the contributing subbasins for each gauging station.

2.4. Project Setup

In SWAT, two separate projects were set up, one for each watershed. The modeled periods for sediment load at the Galveston and Matagorda Bay watersheds lasted from 1984 to 2000 (warm-up period: 1975 to 1983) and 1980 to 2000 (warm-up period: 1975 to 1979), respectively. All data used in the SWAT model were projected to Albers Equal Area with North America 1983 for datum. This section explains the setup and parameters of the two SWAT projects.

1) Watershed delineation

Each watershed and its subbasins were delineated using a DEM in SWAT. The maximum drainage area thresholds for the Galveston and Matagorda Bay watersheds were 15,000 hectares and 10,000 hectares, respectively. Iterations of the subbasin delineation were conducted to match subbasin maps provided by TWDB. When a USGS gauging station was available for calibration, an outlet was inserted manually, splitting the subbasin in two, with a gauged upper half and non-gauged lower half. Overall, subbasins matched well with TWDB subbasin maps; although part of the Galveston Bay watershed was not delineated (Figure 7) because SWAT was unable to delineate such a flat area using the 15,000-hectare threshold. In order to delineate the missing subbasins, a much lower threshold should be used. However, this would result in too many subbasins throughout the rest of the Galveston Bay watershed. Therefore, flow from undelineated subbasins was estimated and later added to the total bay inflow using the sum of average flow from Subbasins 51 and 52 (Figure 7). Those subbasins were selected because they are geographically adjacent, their area is similar, and thus precipitation was assumed to be similar.

2) Subbasins and HRUs

Automatic subbasin delineation, based on given threshold areas and manual input of subbasin outlets, generated 54 subbasins for the Galveston Bay watershed and 37 for the Matagorda Bay watershed (Figure 6). SWAT then divided each subbasin into more detailed HRUs. SWAT delineates HRUs with user-defined thresholds represented as percentages of each land use, soil type, and slope. In this project, land use and soil type thresholds were set at 5%, meaning that any land use covering more than 5% of a subbasin was considered an HRU, and from that portion of land use, any soil type covering more than 5% was considered to be an HRU. These thresholds were chosen to avoid creating too many HRUs, which would make analyses too complicated and time-consuming for the model process. Based on the thresholds selected, there were a total of 829 and 252 HRUs in the Galveston and Matagorda Bay watersheds, respectively. These HRUs can be used for analyses on a particular land use or soil type.

Figure 7. A map of Galveston Bay watershed showing subbasin delineation and the portion of the watershed (grey) that could not be delineated using the 15,000-hectare threshold.

3) Land use distribution in each gauged watershed

Table 6 shows the percentage of each land use category in each gauged subbasin and contributing subbasin that lies above the gauging station in both the Galveston and Matagorda watersheds. The land use percentages are portions of the total area from each contributing subbasin and are not from the original land cover dataset but from the SWAT-processed HRUs. This means any land use category covering less than 5% of the total subbasin area was not included in this distribution.

Most subbasins with gauging stations are located in the upper part of the watershed in both the Galveston and Matagorda bays, and the land use categories within these subbasins consist mainly of forest and hay.

Table 6. Land use distributions of year 2001 in each gauged subbasin. The total area includes the gauged subbasins and contributing subbasins that lie above the gauged subbasin.

Land use	Gauging stations in Galveston				Gauging stations in Matagorda	
	08070500 7*	08070200 1, 3, 5, 12*	08068500 16, 15*	08069000 30*	08164000 2,7*	08162600 10*
Water	0%	0%	0%	0%	0%	0%
Urban	8%	2%	20%	32%	0%	0%
Forest	32%	51%	33%	9%	20%	0%
Agricultural	0%	0%	0%	14%	0%	58%
Hay	23%	11%	21%	45%	61%	42%
Rangeland	21%	15%	16%	0%	19%	0%
Wetland	16%	21%	11%	0%	0%	0%
Total	100%	100 %	100%	100%	100%	100%

* Subbasin numbers

4) NEXRAD enhanced weather data

Weather data from the NCDC were enhanced with daily NEXRAD data. NEXRAD is GRID–based, high-resolution rainfall data (4 x 4 km) measured with the Doppler weather radar that is operated by the National Weather Service. While weather station data represents weather conditions at a point location, NEXRAD covers an area with a mosaic map.

Weather station data were adjusted and enhanced by NEXRAD using a NEXRAD Process Tool from 2000–2008. NEXRAD data is available from 1995 in most areas but is considered good only after 2000. Therefore, weather data used in this study were a combination of weather station data before 2000 and NEXRAD-enhanced weather station data after 2000. The NEXRAD Process Tool compares data between weather stations and NEXRAD and statistically enhances weather station data using NEXRAD data. After processing weather data, each subbasin has its own representative weather "station" rather than 20 weather stations representing entire watersheds. This allows for more accurate depiction of local weather conditions.

5) Lakes

Two lakes, Lake Conroe and Lake Houston, were set up as reservoirs in the Galveston Bay SWAT project. A large reservoir operation can be included and simulated in SWAT to more accurately assess the hydrological processes of a large watershed. Lake Conroe began operating in January 1973, and Lake Houston began operating in April 1954. Reservoir parameters, such as operation starting date, surface area, and volume of water at the principle spillway were obtained through personal communication with the San Jacinto River Authority and the City of Houston. Lake Houston does not have an emergency spillway (Berry, 2010). Parameter values used in the Galveston Bay SWAT project are summarized in Table 7.

Table 7. SWAT input information used for two lakes in the Galveston Bay watershed

Lake information	Lake Conroe	Lake Houston
Operation start date	Jan. 1973	Apr. 1954
Area to emergency spillway (ha)	11,934	N/A
Storage volume to emergency spillway (1,000 m^3)	872,422	N/A
Area to principle spillway (ha)	8,943	4,953
Storage volume to principle spillway (1,000 m^3)	570,912	181,032

6) Point sources

This study did not include any point sources, but they were set up in most modeled subbasins for future use. All outputs from point sources were set to zero in this project.

7) Agricultural practices

One of the important factors affecting sediment and nutrient loads is agricultural practices. Non-point source pollution, such as from fertilizers and pesticides, has important effects on surface and ground-water quality through irrigation and rainfall runoff, soil infiltration and percolation.

In this project, simplified assumptions were made to describe agricultural practices. The agricultural land in the watershed is simulated as typical row-crop agriculture land (AGRR) with automatic irrigation and plant growth based on heat unit scheduling. The plant growth component of SWAT is a simplified version of the EPIC plant growth model. As in EPIC, phonological plant development is based on daily accumulated heat units. To measure the total heat requirements of a plant, the accumulation of daily mean air temperatures above the plant's base temperature is recorded over the period of the plant's growth and expressed in terms of heat units. The heat index used by SWAT is a direct summation index. Each degree of the daily mean temperature above the base temperature (minimum temperature for plant growth) is one heat unit

(Neitsch et al., 2009). Crop growth will only occur on those days where the mean daily temperature exceeds the base temperature. The base temperature data is available in the SWAT databases (.crop) and the user defines the daily average temperature data. This method assumes that the rate of growth is directly proportional to the increase in temperature. SWAT assumes that all heat above the base temperature accelerates crop growth development and does not consider the impact of harmful high temperatures on the plant growth (Neitsch et al., 2009). In this project, the default scheduling of SWAT model for planting, harvesting, and fertilization based on heat units was considered to determine the management operations schedule. The timing of the operations is expressed as fractions of the total heat units for the plant or fraction of maturity. For example, the fraction of total heat units for harvest operation is 1.16. The fraction is greater than 1.0 because corn is allowed to dry prior to harvesting. The fraction of total heat units for automatic fertilization and tillage operations was set to 0.15 for occurring the tillage and fertilization automatically in the beginning of the plant growth. The automatic irrigation operation occurs after planting depend on the soil water deficit.

According to the NRCS the crop types in the Galveston and Matagorda Bay watersheds are corn, rice, and sorghum; the dominant crop is corn. The typical fertilization rate for corn is 150 kg N and 58 kg P per hectare but 50% of mentioned fertilizer rate was used in the agricultural lands because the USDA, NASA Cropland Data Layer (CDL) shows that about 50% of agricultural land is fallow each year. The typical fertilization rate for hay fields is 64 kg N with at least two hay cutting (Narasimhan et al., 2010). Fertilizer is not used in the urban area. The majority of the cropland is cultivated using field cultivators or tillage ID 61 in SWAT. According to the report from Texas Integrated Pest Management most growers throughout the state prepare the land for planting by disking and/or using a field cultivator. The presented agricultural practices and rates are only for the purposes of annual nutrient load estimation; it is not applicable for daily or weekly simulation. Agricultural practices for cultivated land and hay are defined as follows:

Practices	**Heat Units**
AGRR	
Fertilizer application: 30 kg elemental phosphorus	0.15
Fertilizer application: 75 kg elemental nitrogen	0.15
Tillage operation: Field Cultivator Ge15ft	0.15
Planting	0.15

Auto irrigation (Auto water stress: 85%)	0.16
Harvest and kill operation	1.20
Hay	
Fertilizer application: 64 kg elemental nitrogen	0.15
Tillage operation: Field Cultivator Ge15ft	0.15
Planting	0.15
Harvest only operation	0.60
Harvest only operation	0.85
Harvest and kill operation	1.20

8) Soil supporting practice factor

Assuming no practice supported and contouring, the soil support practice factor was set to one for agriculture and hay fields. For water and wetlands it was set to 0. Because the real values of soil support factor were not available and there was no evidence that the sediment loading from different land uses is equal to the typical sediment loading, the soil support practice factor (USLE_P) was set to one for the both Matagorda and Galveston watersheds.

9) Initial concentration of nutrient in the soil layers

Default initial concentration of solution P in all soil layers is 5 mg per kg in the native vegetation and unmanaged land and a concentration of 25 mg per kg soil in the cultivated land. Initial nitrate levels in the soil layer are varied by depth. The default initial concentration of nitrate at the top 10 mm of soil is 7 mg per kg soil and decreases exponentially with depth to less than 1 mg per kg soil at the 2-meter depth. The initial concentration of organic nitrogen is assigned based on organic carbon content from the soil database and assumes a C:N ratio of 14:1 and N:P ratio of 8:1 (Narasimhan et al., 2010).

10) Wetlands

Wetlands within the subbasins receive inflow from fraction of the subbasin area; In the other word, SWAT simulates the wetlands as a unique water body within a subbasin. The volume of water entering the wetland is subtracted from the surface runoff, lateral flow and groundwater loadings to the main channel (Neitsch et al., 2009).

2.5. Sensitivity Analysis

Parameter sensitivity analysis was performed using the SWAT Calibration and Uncertainty Program (SWAT-CUP). It enables sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models (Abbaspour, 2011). The current version, SWAT-CUP 4.3.2, enables us to calibrate parameters of all soil layers, management methods, and crops. Table 8 shows the results of global sensitivity analysis for suspended sediment, nitrate, organic nitrogen and phosphorus. Six parameters were sensitive to sediment only. From 128 parameters influencing water quality variables, five parameters were sensitive to organic N, four parameters were sensitive to nitrate and five parameters were sensitive to organic and mineral P. The parameters definition is available in Appendix A. To clarify the role of those parameters in the nutrient cycle of the soil layer as well as movement and transformation in the stream, a simple scheme of nitrogen and phosphorus cycling is presented in Figure 8 and Figure 9.

Table 8. List of sensitive SWAT parameters

	SWAT name	Description	Units
Sediment	CH_N2	Manning’s n value for the main channel	coefficient
	SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channelsediment routing	coefficient
	PRF	Peak rate adjustment factor for sediment routing in the main channel	coefficient
	SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	coefficient
	CH_COV2	Channel erodibility factor	coefficient
	CH_COV1	Channel cover factor	coefficient
Nitrate	CDN	Denitrification exponential rate coefficient	ratio
	NPERCO	Nitrate percolation coefficient	coefficient
	SDNCO	Denitrification threshold water content	coefficient
	CMN	Rate factor for humus mineralization of active organic nutrients (N and P)	ratio
Organic N	ERORGN	Nitrogen enrichment ratio for loading with sediment	ratio
	BIOMIX	Biological mixing efficiency	coefficient
	BC3	Rate constant for hydrolysis of organic N to NH4	1/day
	NPERCO	Nitrate percolation coefficient	coefficient
	RS4	Organic N settling rate coefficient	1/day
Mineral P	PSP	Phosphorus availability index	coefficient
	BC4	Organic N settling rate coefficient	coefficient
	PHOSKD	Phosphorus soil partitioning coefficient	coefficient
Organic P	PSP	Phosphorus availability index	coefficient
	ERORGP	Phosphorus enrichment ratio for loading with sediment	ratio
	BIOMIX	Biological mixing efficiency	coefficient

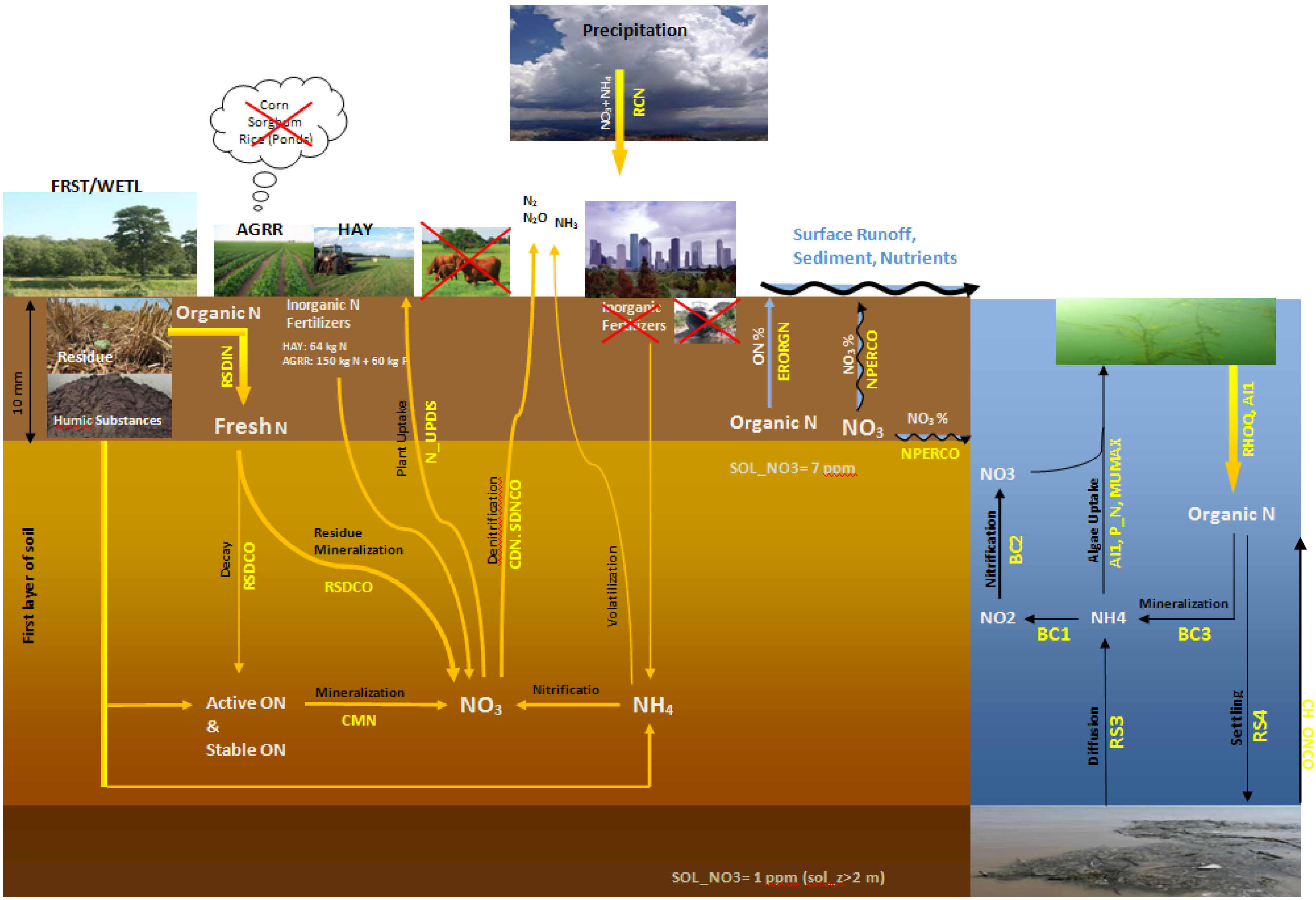


Figure 8. Scheme of nitrogen cycle in the soil layer, as well as movement and instream processes in SWAT. Red cross indicates that the component was not modeled.

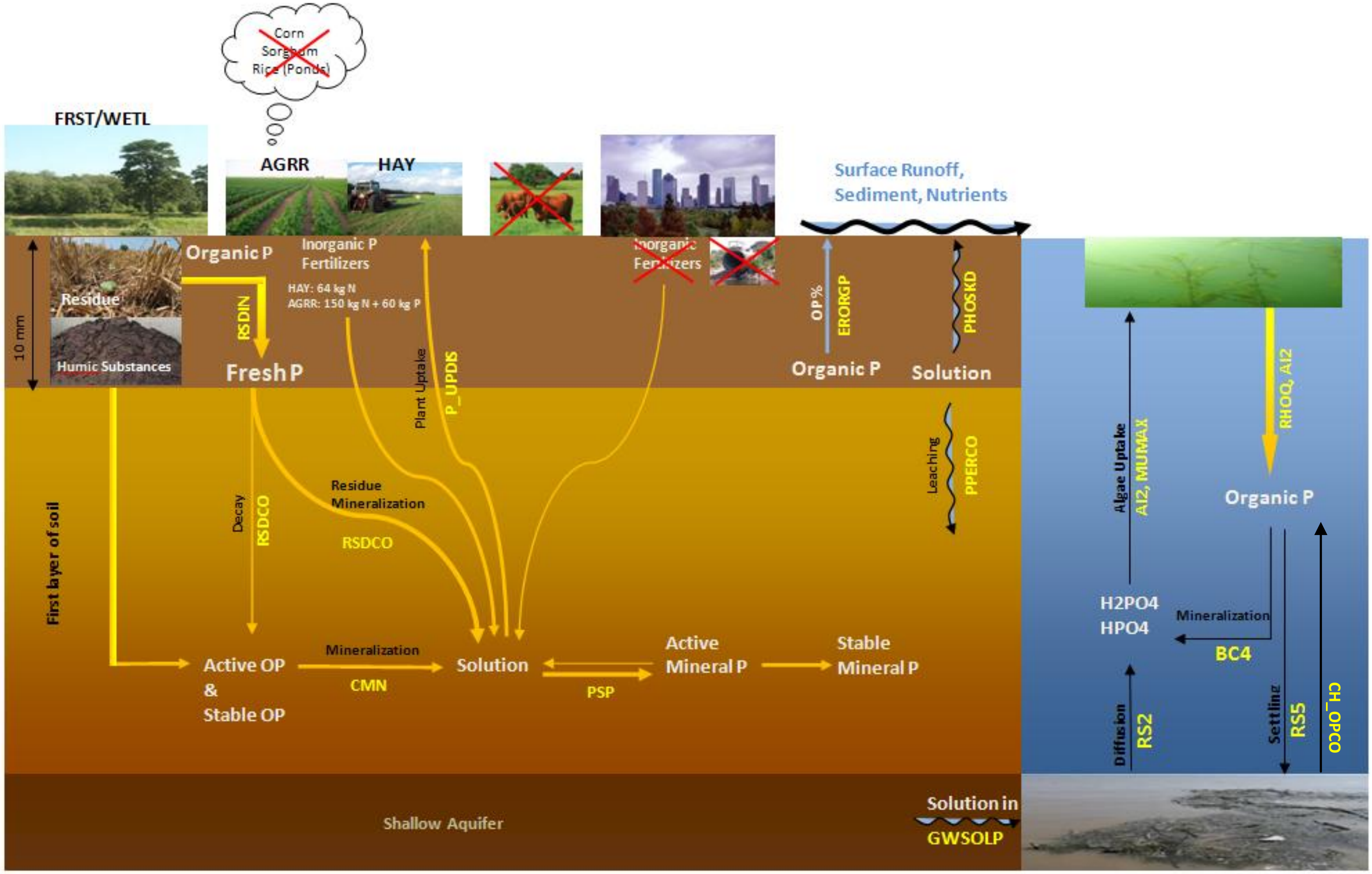


Figure 9. Scheme of phosphorus cycle in the soil layer, as well as movement and in-stream processes in SWAT. Red cross indicates that the component was not modeled.

2.6. Model Calibration and Validation

Sediment and nutrient were calibrated on mean annual and monthly basis. The model first calibrated for mean annual loads and some of the appropriate parameters were adjusted until the predicted annual sediment and nutrient loads was approximately match the measured loads from USGS gauges or estimated loads from the previous studies. Calibration and validation periods were determined based on the streamflow calibration (1991-2000) and validation (1977-1990) periods in the first phase, suspended sediment and nutrient data availability. The streamflow calibration period for some of the gauging stations was taken from 1991 to 2008, but the plotted graphs and statistics revealed that the predicted streamflow at the selected gauging stations for sediment and nutrient calibration matched well to the observed streamflow for years before 2000. Therefore, sediment and nutrients were calibrated from 1991 to 2000. Time periods with available data, however, varied among the gauging stations (Table 9).

Monthly calibration process was performed using the SWAT automatic calibration tool, SWAT_CUP SUFI2 (Abbaspour, 2011). Using SWAT_CUP the modeler is able to calibrate many parameters to predict nutrients at multiple gauge stations simultaneously. Orthophosphate is referred to as mineral P, and for calibration purposes it is assumed that organic P is the difference of observed mineral P subtracted from total P. For statistical analyses for the calibration and validation, coefficient of determination and Nash-Sutcliffe model efficiency (NS) (Nash and Sutcliffe, 1970) were examined.

2.6.1. Sediment Calibration and Validation

Galveston

Mean annual calibration and validation were performed by comparing the simulated sediment load from the reservoirs to mean annual sediment load from the lake survey studies by TWDB. The Lake volumetric survey studies on Lake Conroe and Lake Houston conducted by TWDB were considered as the data for mean annual sediment calibration.

The simulated sediment load from drained sub-watersheds to Lake Conroe (Subbasin 4) was compared to the estimated sediment load from a volumetric survey of Lake Conroe. The estimated reduction in storage capacity, if compared to the original volume was about 17,308,217.14 m^3 (14,032 acre-feet). This equates to an estimated loss of 6.52 metric tons/ha (610 acre-feet) per year during the 23 years (1973 to 1996) between the TWDB's survey and the initial date impoundment began. Assuming a bulk density of 1 Mg m^{-3} for lake sediment (Smith et al., 2002 and Philips et al., 2004), the mean annual sediment load into the lake is approximately 751,700 metric tons/yr. According to the data in Sullivan et al. (2003) the estimated sediment yield from Lake Conroe to the Galveston Bay is 189 metric tons/km^2 or 218,000 metric tons/yr.

According to a sedimentation survey performed in 1965 the Lake Houston had lost 14,535,349.97 m^3 (11,784 acre-feet) of its capacity due to sedimentation since completion of the reservoir in 1955 to 1965. Twenty nine years later, a second survey was performed by the TWDB's Hydrographic Survey Program. Results from the survey indicated that estimated reduction in storage capacity, compared to the 1965 survey, was 14,354,028.14 m^3 (11,637 acre-feet). This equates to an estimated loss of 494,996.26 m^3 (401.3 acre-feet) per year during the last 29 years (1966-1994). Based on Bulletin 5912, Lake Houston retained 87% of the sediment that flowed into the reservoir. Assuming a bulk density of 1 Mg m^{-3} for lake sediment (Smith et al., 2002 and Philips et al., 2004), the sediment discharge from Lake Houston was estimated about 64,350 metric tons/yr.

Due to the lack of available suspended sediment data at the watershed inlet (Romayor) the input sediment yield from the Trinity River to the Galveston Bay (Reach 48) was adjusted to 70,000 metric tons/yr according to the previous studies. The sediment inputs from the Trinity River to the Galveston Bay was estimated about 70,000 metric tons/yr (1.6 metric tons/km^2) based on 1964-1989 sediment sampling at Liberty by TWDB and estimated sediment loading by Philips et al. (2004) (Philips et al., 2005).

Monthly suspended sediment was calibrated and validated against the data from USGS gauging stations 08068500 (Reach 15) and 08069000 (Reach 30) from 1991 to 2000 and 1984 to 1990, respectively. Simulated sediment from SWAT for the 1991 to 2000 period (10 years) was compared to the measured sediment, and appropriate input parameters were adjusted until the predicted sediment load was approximately equal to that measured. The parameters and their default and adjusted value for sediment calibration are presented in Table 10.

Matagorda

For mean annual calibration, the simulated sediment load from Subbasins 2 and 7 from 1991 to 2000 was compared to mean annual suspended sediment load from USGS gauge station 08164000 (Figure 6). The simulated sediment load from drained watersheds to Lake Texana

(Subbasin 12) was compared to the estimated sediment load from a Lake sediment survey conducted by TWDB in 2011. Using the depth sounder devices, TWDB collected nearly 244,000 data points over cross-sections totaling approximately 257.50 km (160 miles) in length to estimate current and initial bathymetric surface. Following analysis of the sounding data, TWDB selected seven locations where sounding data had been previously collected to collect sediment core samples. Combining the information from sediment cores and sounding data helped to identify the post-impoundment sediment Interface. The difference between the current surface and the pre-impoundment surface yields a sediment thickness value at each sounding location (TWDB, 2010). The 2010 TWDB sedimentation survey indicates Lake Texana has accumulated 14,138,168.82 metric tons (11,462 acre-feet) of sediment since impoundment in 1980, which is equivalent to approximately 471,190.06 metric tons per year (382 acre-feet per year). Assuming a bulk density of 1 Mg m^{-3} for lake sediment (Smith et al., 2002 and Philips et al., 2004), the mean annual sediment load into the lake is approximately 471,190.06 metric tons per year. Based on the studies on Lake Texana, Lake Texana retained 32% of the sediment that flowed into the reservoir (Longley 1994); so, the sediment discharge from Lake Texana was estimated about 320,409.2 metric tons per year.

Monthly suspended sediment was calibrated and validated against the data from USGS gauging station 08164000 (Lavaca River near Edna) from 1991 to 2000 and 1980 to 1990, respectively. The parameters and their default and adjusted value for sediment calibration are presented in Table 11.

2.6.2. Nutrient Calibration and Validation

Galveston

Nutrient calibration and validation were performed based on estimated monthly total nitrogen, total phosphorus, organic nitrogen, organic phosphorus, NO3, and orthophosphate from Caney Creek at the gauging station 08070500 (Subbasin 7), East Fork San Jacinto River at gauging station 08070200 (Subbasins 1, 3, 5 and 12) from 1991 to 2000 and 1984 to 1990, respectively. After ensuring that the model successfully predicted the monthly nutrient loads from the uplands, the parameters influence the predicted nutrient in the subbasin or HRU scale were set to fit the simulated and estimated monthly nutrient loading from the Turkey Creek at gauging station 08069000 (Subbasin 30).

About half portion of nutrient loads from Subbasin 30 is inorganic nutrients generated by municipal and industrial sources because it includes some parts of City of Houston and its metro area. The municipal and industrial discharges were not considered in this project, so to avoid affecting the model parameterization by the point source discharges, first, the model was calibrated using the water quality data at the gauging stations in the upland subbasins (Reach 7, Caney Creek and 12, East Fork San Jacinto River). After ensuring that the model successfully predicted the monthly nutrient loading from the upland subbasins, the parameters influence on nutrient prediction in the subbasin or HRU scale were set to fit the simulated and estimated nutrient loading from Subbasin 30. Organic and inorganic phosphorus samples were only available for calibration period (Table 12).

Matagorda

Nutrient calibration was performed based on mean annual and monthly data. In the first step for nutrient calibration, parameters were adjusted to agree with the estimated total nitrogen loading by LCRA (1997 report) from drainage area to the gauging stations at Lava River near Edna (Subbasin 2 and 7), Gracitas Creek/Placedo Creek (Subbasins 11 and 15), Tres Placios River (Subbasin 10) and Lake Texana (Subbasin 12) for calibration period (1986 to 1993) (Figure 10). In 1993, a study was conducted by the LCRA in conjunction with TPWD, TWDB and TNRCC to determine the freshwater inflow needs of the Matagorda Bay system. As part of the study, they estimated the total nitrogen from gaugd and ungauged sub-watersheds to the Matagorda Bay system (Lavaca-Colorado estuary) for a dry year, 1984, and wet year, 1987. Nitrogen loading was calculated by using flow data collected by USGS and water quality data collected by TNRCC or USGS. Total nitrogen loading from ungauged sub-watersheds was calculated by using ungauged inflow data and the standard total nitrogen concentration for runoff water from different landuses (LCRA, 1997). The methods used in LCRA study fallow the applied methodology by TWDB for determination of total nitrogen load to the Matagorda Bay (Longley, 1994), however, TWDB did not estimate the total nitrogen by sub-watersheds as was done by LCRA. Total phosphorus from gauged sub-watersheds was compared to the estimated total phosphorus loading from gauged sub-watersheds of Colorado_Lavaca watershed to the bay by Longley, 1994 and Ward and Armstrong, 1980.

In the second step, model calibration was performed using the monthly nutrient load from gauging stations 08164000 and 08162600. Due to the lack of data, time periods with available data varied among the gauging stations. Table 5 shows that the available data at gauge station 08164000 (Subbasin 10 in the Matagorda Bay watershed) is limited to years 1977 to 1980 which does not cover the calibration period from 1986 to 1993. Therefore, the basin-wide parameters with the extension .bsn and .wwq in Table 13 were only adjusted using the nutrient data at gauge station 08164000 (Reach 7). Some parameters values presented in Tables 10 through 13 have ranges because each gauged subbasin had a different condition and a different parameter setting was applied. For example, in Table 13, organic P settling rate (RS5) ranged from 0.05 within the gauged sub-watersheds to 0.1 within the sub-watersheds above Lake Texana. Municipal WWTPs and industrial point source discharges were not included in this study.

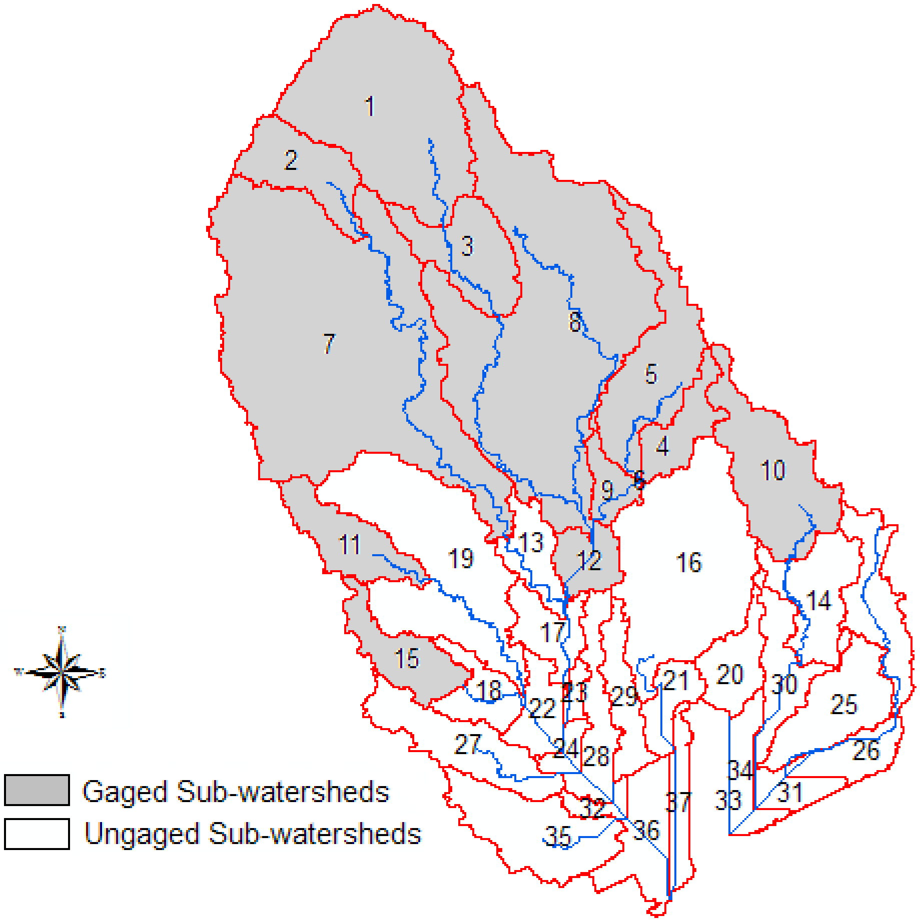


Figure 10. Gauged sub-watershed used for nutrient calibration

Table 9. USGS gauging station data and the period of calibration and validation. The calibration period was selected for the latter half of the entire data period.

Galveston watershed

Water quality	Subbasin	Gauging stations	Calibration period	Validation period	Warm-up period
Total suspended sediment	15	08068500	1991-2000	1984-1990	1975-1983
	30	08069000			
Total nitrogen	7	08070500	1991-2000	1984-1990	1975-1983
	12	08070200			
	30	08069000			
Total phosphorus	7	08070500	1991-2000	1984-1990	1975-1983
	12	08070200			
	30	08069000			
Organic nitrogen	7	08070500	1991-2000	1984-1990	1975-1983
	12	08070200			
	30	08069000			
Organic phosphorus*	7	08070500	1991-2000	-	1975-1983
	12	08070200			
	30	08069000			
Mineral phosphorus	7	08070500	1991-2000	-	1975-1983
	12	08070200			
	30	08069000			
NO_3	7	08070500	1991-2000	1984-1990	1975-1983
	12	08070200			
	30	08069000			

Matagorda watershed

Water quality	Subbasin	Gauging stations	Calibration period	Validation period	Warm-up period
Total suspended sediment	7	08164000	1991-2000	1980-1990	1975-1979
Total nitrogen	7	08164000	1986-1993	1980-1985	1975-1979
	10	08162600	1977-1980	-	1975-1976
Total Phosphorus	7	08164000	1986-1993	1980-1985	1975-1979
	10	08162600	1977-1980	-	1975-1976
Organic nitrogen	7	08164000	1986-1993	1980-1985	1975-1979
	10	08162600	1977-1980	-	1975-1976
Organic phosphorus*	7	08164000	1986-1993	1980-1985	1975-1979
Mineral phosphorus	7	08164000	1986-1993	1980-1985	1975-1979
NO_3	7	08164000	1986-1993	1980-1985	1975-1979
	10	08162600	1977-1980	-	1975-1976

* Due to the lack of data it is assumed that ORGP=TP-MINP

Table 10. Parameter values for sediment calibration (gauging stations) used in the Galveston Bay watershed SWAT project

Parameter name	Description	Default value	Input value	Units
CH_N2.rte	Manning's n value for the main channel	0.014	0.014-0.15	coefficient
SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001	0.004	coefficient
PRF.bsn	Peak rate adjustment factor for sediment routing in the main channel	1	1	coefficient
SPEXP.bsn	Exponent parameter for calculating sediment re-entrained in channel sediment	1	1	coefficient
CH_COV1.rte	Channel cover factor	Bagnold Equation	0.005-0.6	coefficient
CH_COV2.rte	Channel erodibility factor	Bagnold Equation	0-1	coefficient

Table 11. Parameter values for sediment calibration (gauging stations) used in the Matagorda Bay watershed SWAT project

Variable	Description	Default Value	Input Value	Units
CH_N2.rte	Manning's n value for the main channel	0.014	0.03 - 0.12	coefficient
CH_COV1.rte	Channel cover factor	Bagnold Equation	0.5	coefficient
CH_COV2.rte	Channel erodibility factor	Bagnold Equation	1	coefficient
SPCON.bsn	Linear parameter for calculating the maximum amount of sediment	0.0001	0.004	coefficient
PRF.bsn	Peak rate adjustment factor for sediment routing in the main channel	1	1	coefficient
SPEXP.bsn	Exponent parameter for calculating sediment re-entrained	1	1	coefficient

Table 12. Parameter values for nutrient calibration (gauging stations) used in the Galveston Bay watershed SWAT project

Parameters	Description	Default value	Input Value	Units
BIOMIX.mgt	Biological mixing efficiency	0.2	0.4 - 0.77	coefficient
ERORGP.hru	Phosphorus enrichment ratio for loading with sediment	Calculated (Menzel 1980)	1.1- 5	ratio
ERORGN.hru	Nitrogen enrichment ratio for loading with sediment	Calculated (Menzel 1980)	1.1- 5	ratio
RS2.swq	Benthic P source rate coefficient	0.05	0.015-0.05	mg P/m^2-day
RS3.swq	Benthic NH4 source rate coefficient	0.5	0.62-0.84	mg N/m^2-day
RS4.swq	Organic N settling rate coefficient	0.05	0.001-0.05	day^{-1}
RS5.swq	Organic P settling rate coefficient	0.05	0.05-0.56	day^{-1}
BC1.swq	Decay rate for NH4 to NO2	0.55	0.48-0.94	day^{-1}
BC2.swq	Decay rate for NO2 to NO3	1.1	0.47-1.22	day^{-1}
BC3.swq	Rate constant for hydrolysis of organic N to NH4	0.21	0.20-0.27	day^{-1}
BC4.swq	Rate constant for hydrolysis of organic P to mineral P	0.35	0.057-0.60	day^{-1}
CH_ONCO.rte	Organic nitrogen concentration in the channel	0	0.004-0.015	ppm
CH_OPCO.rte	Organic phosphorus concentration in the channel	0	0-0.002	ppm
RCN.bsn	Concentration of nitrogen in rainfall	1	0.44	mg N/Liter
CMN.bsn	Rate factor for humus mineralization of active organic nutrients (N and P)	0.0003	0.0016	ratio
CDN.bsn	Denitrification exponential rate coefficient	1.4	2.8	ratio
SDNCO.bsn	Denitrification threshold water content	0.05	0.13	ratio
N_UPDIS.bsn	Nitrogen uptake distribution	20	65	scaling constant
P_UPDIS.bsn	Phosphorus uptake distribution	20	17	Scaling constant
NPERCO.bsn	Nitrate percolation coefficient	0.2	0.13	coefficient
PPERCO.bsn	Phosphorus percolation coefficient	10	11.4	coefficient
PHOSKD.bsn	Phosphorus soil partitioning coefficient	175	170.5	m^3/mg
PSP.bsn	Phosphorus availability index	0.4	0.26	weighted constant
RSDCO.bsn	Residue decomposition	0.05	0.05	coefficient

	coefficient			
AI1.wwq	Fraction of algal biomass that is nitrogen	0.08	0.08	mg N mg^{-1} algae
AI2.wwq	Fraction of algal biomass that is phosphorus	0.015	0.011	mg P mg^{-1} algae
MUMAX.wwq	Maximum specific algal growth rate at 20˚ C	2	1	day^{-1}
RHOQ.wwq	Algal respiration rate at 20˚	0.3	0.3	day^{-1}

Table 13. Parameter values for nutrient calibration (gauging stations) used in the Matagorda Bay watershed SWAT project

Parameters	Description	Default value	Input Value	Units
BIOMIX.mgt	Biological mixing efficiency	0.2	0.4 - 0.46	coefficient
ERORGP.hru	Phosphorus enrichment ratio for loading with sediment	Calculated (Menzel 1980)	1- 3.5	ratio
ERORGN.hru	Nitrogen enrichment ratio for loading with sediment	Calculated (Menzel 1980)	1- 5	ratio
RS2.swq	Benthic P source rate coefficient	0.05	0.05	mg P/m^2-day
RS3.swq	Benthic NH4 source rate coefficient	0.5	0.54	mg N/m^2-day
RS4.swq	Organic N settling rate coefficient	0.05	0.07	day^{-1}
RS5.swq	Organic P settling rate coefficient	0.05	0.05-0.1	day^{-1}
BC1.swq	Decay rate for NH4 to NO2	0.55	0.8	day^{-1}
BC2.swq	Decay rate for NO2 to NO3	1.1	1.54	day^{-1}
BC3.swq	Rate constant for hydrolysis of organic N to NH4	0.21	0.2-0.4	day^{-1}
BC4.swq	Rate constant for hydrolysis of organic P to mineral P	0.35	0.05-0.5	day^{-1}
CH_ONCO.rte	Organic nitrogen concentration in the channel	0	0.0008-0.005	ppm
RCN.bsn	Concentration of nitrogen in rainfall	1	0.85	mg N/Liter
CMN.bsn	Rate factor for humus mineralization of active organic nutrients (N and P)	0.0003	0.001	ratio
CDN.bsn	Denitrification exponential rate coefficient	1.4	1.76	ratio
SDNCO.bsn	Denitrification threshold water content	0.05	0.9	ratio
N_UPDIS.bsn	Nitrogen uptake distribution	20	50	scaling constant
P_UPDIS.bsn	Phosphorus uptake distribution	20	90	Scaling constant

NPERCO.bsn	Nitrate percolation coefficient	0.2	0.32	coefficient
PPERCO.bsn	Phosphorus percolation coefficient	10	11	coefficient
PHOSKD.bsn	Phosphorus soil partitioning coefficient	175	200	m^3/mg
PSP.bsn	Phosphorus availability index	0.4	0.22	weighted constant
RSDCO.bsn	Residue decomposition coefficient	0.05	0.047	coefficient
MUMAX.wwq	Maximum specific algal growth rate at 20˚ C	2	1	day^{-1}
RHOQ.wwq	Algal respiration rate at 20˚	0.3	0.3	day^{-1}

* Subbasin 10 was considered for calibrating local parameters affecting the nutrient load only, so the basinwide parameters with .bsn and .wwq extension were adjusted using the calibration dataset of Subbasin 7.

2.6.3. Determination of SWAT parameters at ungauged subbasins

Identical to the applied method in Phase I, comparison of sediment and nutrient loads from the ungauged and gauged subbasins of the Galveston and Matagorda Bay watersheds was conducted by extending and applying parameter settings from the calibration of gauged subbasins to ungauged subbasins. To apply the appropriate parameters to ungauged sub-watersheds in the Galveston watershed (Table 14), the ungauged sub-watersheds were classified into two classes: 1) Urbanized sub-watersheds included the city of Houston and its surrounding metro area and 2) Rural sub-watersheds included the Dickinson Bayon (Subbasin 52), Chocolate Bayon (Subbasin 54), Lower San Jacinto, Lower Trinity, Cedar Bayon (Subbasin 45), and west Bay. The limited number of adjusted parameters for Subbasin 30 was applied to the urbanized subbasins because of their special characteristics. For example the concentration of soluble P in the groundwater (GWSOLP) of the urban areas was estimated higher than the rural, or their channel cover characteristics (CH_N2) are different from the rural subbasins. Nutrient load from industrial and municipal return flow and diverted flow were not included in this study. The average for each parameter from the calibration was applied to ungauged sub-watersheds of the Matagorda watershed (Table 15).

Table 14. Parameter values for ungauged subbasins used in the Galveston Bay SWAT project

Parameters	Description	Default value	Input value		Units
			Other subbasins	Urbanized subbasins	
CH_N2	Manning's n value for the main channel	0.014	0.12-0.15	0.12	coefficient
CH_COV1.rte	Channel cover factor	Bagnold Equation	0.005-0.09	0.3	coefficient
CH_COV2.rte	Channel erodibility factor	Bagnold Equation	0-1	1	coefficient
BIOMIX.mgt	Biological mixing efficiency	0.2	0.6	0.6	coefficient
ERORGP.hru	Phosphorus enrichment ratio for loading with sediment	0	2.6	5	ratio
ERORGN.hru	Nitrogen enrichment ratio for loading with sediment	0	3.5	4.5	ratio
GWSOLP.gw	Soluble phosphorus concentration in groundwater flow	0	0.17	0.5	mg P Liter^{-1}
CH_ONCO.rte	Organic nitrogen concentration in the channel	0	0.008	0.004	ppm
CH_OPCO.rte	Organic phosphorus concentration in the channel	0	0.001	0.002	ppm
RS2.swq	Benthic P source rate coefficient	0.05	0.034	0.034	mg P/m^2-day
RS3.swq	Benthic NH4 source rate coefficient	0.5	0.25	0.25	mg N/m^2-day
RS4.swq	Organic N settling rate coefficient	0.05	0.027	0.027	day^{-1}
RS5.swq	Organic P settling rate coefficient	0.05	0.05	0.05	day^{-1}
BC1.swq	Decay rate for NH_4 to NO_2	0.55	0.66	0.66	day^{-1}
BC2.swq	Decay rate for NO_2 to NO_3	1.1	0.93	0.93	day^{-1}
BC3.swq	Rate constant for hydrolysis of organic N to NH4	0.21	0.24	0.24	day^{-1}
BC4.swq	Organic N settling rate coefficient	0.35	0.33	0.33	day^{-1}

Table 15. Parameter values for ungauged subbasins used in the Matagorda Bay SWAT project

Parameters	Description	Default value	Input Value	Units
CH_N2.rte	Manning's n value for the main channel	0.014	0.08	coefficient
CH_COV1.rte	Channel cover factor	Bagnold Equation	0.5	coefficient
CH_COV2.rte	Channel erodibility factor	Bagnold Equation	1	coefficient
BIOMIX.mgt	Biological mixing efficiency	0.2	0.43	coefficient
ERORGP.hru	Phosphorus enrichment ratio for loading with sediment	0	2.25	ratio
ERORGN.hru	Nitrogen enrichment ratio for loading with sediment	0	3	ratio
RS2.swq	Benthic P source rate coefficient	0.05	0.05	mg P/m^2-day
RS3.swq	Benthic NH4 source rate coefficient	0.5	0.54	mg N/m^2-day
RS4.swq	Organic N settling rate coefficient	0.05	0.07	day^{-1}
RS5.swq	Organic P settling rate coefficient	0.05	0.05	day^{-1}
BC1.swq	Decay rate for NH4 to NO2	0.55	0.8	day^{-1}
BC2.swq	Decay rate for NO2 to NO3	1.1	1.54	day^{-1}
BC3.swq	Rate constant for hydrolysis of organic N to NH4	0.21	0.2-0.3	day^{-1}
BC4.swq	Rate constant for hydrolysis of organic P to mineral P	0.35	0.27	day^{-1}
CH_ONCO.rte	Organic nitrogen concentration in the channel	0	0.003-0.005	ppm

3. Results

3.1. Mean Annual Suspended Sediment and Nutrient Loading from Gauged Sub-watersheds

Simulated sediment and major nutrients (total N and total P) for calibration period were compared to the measured sediment and nutrient loads and some of the input parameters were adjusted until the predicted annual sediment and nutrient loads from fresh water and channel erosion was approximately equal to the measured. The rest of the input parameters were adjusted during the monthly sediment and nutrient calibration. Tables 16 to 19 summarize mean annual sediment, total nitrogen and total phosphorus for calibration and validation periods from gauged sub-watersheds and Reservoirs. Table 16 shows that the simulated sediment loading from the

Lake Houston was predicted twice greater than the reported sediment loading by TWDB. One possible reason could be that the simulated sediment loading by SWAT includes the total sediment loads from Subbasin 35 and Lake Houston; due to the watershed segmentation by SWAT it was not possible to predict the sediment discharge at the reservoir outlet. In general, the model has under-estimated the sediment loading from the reservoirs in compare with the TWDB estimations.

The predicted mean annual total nitrogen from the Matagorda Bay gauged sub-watersheds shows better agreement in compare with the measured loads by NRCC for validation period while it is not satisfactory for calibration period. A possible reason is that the total nitrogen loading by LCRA was measured using the data period from 1977 to 1987 which covers the model validation period from 1980 to 1985.

Table 16. Calibration and validation for mean annual sediment loading from the Galveston Bay gauged sub-watersheds

Reach	Observed Calibration (ton)	Modeled Calibration (ton)	Difference Calibration (%)	Observed Validation (ton)	Modeled Validation (ton)	Difference Validation (%)
To the Lake Conroe	751,700	699,200	-6.9	751,700	373,000	-50
To the Lake Houston	491,000	513,200	+4.5	491,000	312,100	-36
From the Lake Houston	64,350	189,000	+194	64,350	124,000	+93

Table 17. Calibration and validation for mean annual sediment loading from the Matagorda Bay gauged sub-watersheds

Reach	Observed Calibration (ton)	Modeled Calibration (ton)	Difference Calibration (%)	Observed Validation (ton)	Modeled Validation (ton)	Difference Validation (%)
7	175,000	106,200	-39	63,000	68,120	+8
8, 9 (Above Lake Texana)	471,200	450,000	-4.5	471,200	386,120	-18
12 (Reservoir)	320,400	316,000	-1.3	320,400	191,900	-50

Table 18. Calibration and validation for mean annual nitrogen loading from the Matagorda Bay gauged sub-watersheds

Reach	Observed (LCRA, 1997)			Modeled Calibration (ton)	Difference Calibration (%)	Modeled Validation (ton)	Difference Validation (%)
	Dry year (ton)	Wet year (ton)	Average (ton)				
7	68	468	266.5	160.7	-40	211.2	-21
10	190	207	198.8	145.7	-27	189.9	-4.5
11,15	28	137	82.5	62.7	-24	87.9	+6.6
12 (Reservoir)	420	1021	720.5	653	-9	738.4	+2.5

Table 19. Calibration and validation for mean annual phosphorus loading from the Matagorda Bay gauged sub-watersheds.

Gauged Watershed	Longley, 1994 (ton)	Ward and Armstrong, 1980 (ton)	Modeled Calibration (ton)	Difference Calibration (%)	Modeled Validation (ton)	Difference Validation (%)
Matagorda	-	-	197.4	-	198.8	-
Colorado River (Inlet)	-	-	799	-	478	-
Total	520	890	998	+12 to +90	675	-24 to +30

3.2. Monthly Suspended Sediment Loading from Gauging Stations

Table 20 summarizes monthly suspended sediment calibration and validation statistical analyses from gauged subbasins. Model performance statistics used to assess calibration efforts indicate that SWAT model estimates are good, with a range of 0.65 to 0.88 for R^2 and NSE ranging from 0.55 to 0.75 for both watersheds. Validation results also correlate well, ranging from 0.53 to 0.67 for R^2 and from 0.43 to 0.50 for NSE.

Figure 11 shows that the duration curves of estimated and predicted monthly sediment loads from Subbasins 15 in the Galveston Bay watershed did not fit well in October 1994. Based on the H-GAC, the Texas Division of Emergency Management (DEM) report, the flood event history of the coastal region of Texas shows that severe flooding occurred on October 1994 and 1998 (10/16/1994 to 10/18/1994, 10/17/1998 to10/18/1998, and 11/12/1998 to 11/14/1998). As SWAT is a continuous time model, the model is not designed to simulate detailed, single-event flood routing (Neitsch et al., 2009). The model may underestimate the sediment load especially for a single storm event because it does not simulate bed load transport (Narasimhan et al., 2010).

Another reason could be an uncertainty in performance of regression models in estimation of sediment values outside the calibration dataset using limited number of suspended sediment samples from 1986 to 1990.

Lack of information about in-stream processes can be another source of uncertainty. Suspended sediment load dramatically varies due to changes in the value of sensitive parameters affecting in-stream process such as peak rate adjustment and Manning's n factor.

In the low flow seasons, the irrigation water from agricultural lands can influence the sediment loading from cropland or bedload, so any uncertainties in the amount and frequency of irrigation can decrease the model accuracy in sediment prediction.

Channel erosion controls the peak loads and dramatically affects the sediment load routed into the reach as well. In this project the in-stream processing parameters were determined by calibration, but it is strongly suggested to use the measured parameter values or at least compare the simulated channel deposition and degradation with the measured values.

Table 20. Model performance in estimating monthly sediment (calibration and validation)

Watershed	Station #	Subbasin #	Calibration		Validation	
			R^2	NSE*	R^2	NSE
Galveston Bay watershed	08068500	16, 15	0.88	0.75	0.53	0.50
	08069000	30	0.65	0.55	0.67	0.43
Matagorda Bay watershed	08164000	2, 7	0.75	0.71	0.63	0.50

*NSE: Nash Sutcliffe model efficiency

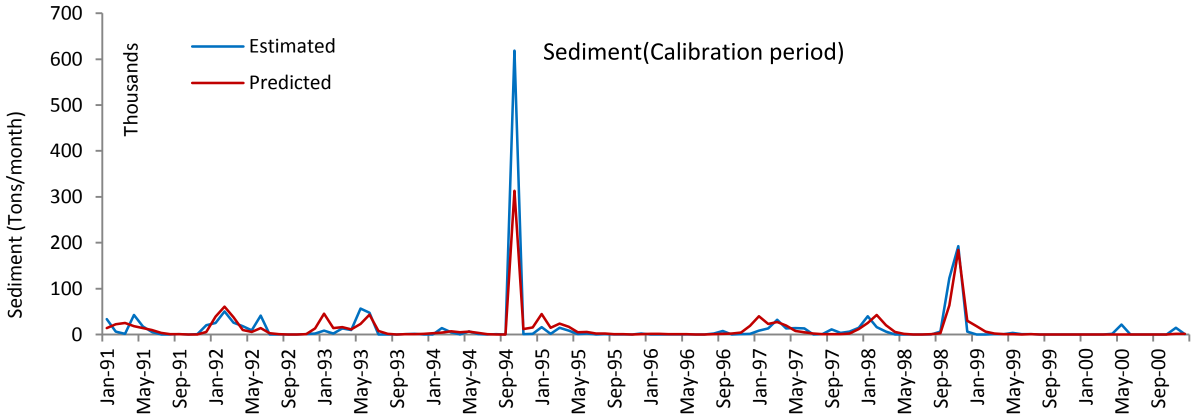


Figure 11. Observed and predicted monthly sediment for calibration period from Subbasins 15, Galveston Bay watershed

3.3. Monthly Nutrients Loading from Gauging Stations

Table 21 summarizes monthly nutrient calibration and validation results from gauged subbasins. The model performed well in prediction of all nutrient loads except nitrate; the table shows poor performance in prediction of nitrate from the gauging stations in the Galveston Bay watershed, while the model performance was better in the Matagorda Bay watershed. Nitrate loading from the upland Subbasins 1, 3, 5, 7 and 12 (East Fork San Jacinto River and Caney Creek) in the Galveston Bay watershed was less than 10% of the total nitrogen loading, so the effect of poorly predicted NO_3 was negligible in predicting the total nitrogen loading from these subbasins.

The worst result in Table 21 is related to the nutrient loading from Subbasin 30 including the city of Houston and its suburbs. SWAT model has under-predicted the nutrient loading from Subbasin 30. According to this table, the model failed to predict the inorganic N and inorganic P from Subbasin 30 but successfully predicted the organic N and organic P. A possible reason is that the data of municipal WWTPs and industrial point source discharges in the subbasins were not considered in nutrient load calibration. Inorganic N and P account for approximately half of the contributed total N and P from Subbasin 30 to the streams. The uncertainty plot (95% prediction uncertainty or 95PPU) in Figure 12 shows that the poor prediction of mineral P at Reach 30 was not related to calibration parameters in Table 12. Setting the parameter ranges equal to the maximum physically meaningful ranges and failing to bracket the estimated data by green color uncertainty band indicates that the problem is not parameter calibration (Abbaspour, 2011).

The worst statistical result in the in the Matagorda Bay watershed is related to prediction of nitrate from Subbasin 10 (Tres Palacios River) with R^2 0.5 and NSE 0.13. The cultivated lands and hay fields cover 42% and 58% of the area of subbasin 10 and it looks the poor prediction of nitrate is related to fertilizer or manure input data.

The model performance in prediction of total phosphorus was better than the total nitrogen prediction with R^2 between 0.50 and 0.87 while NSE ranged from 0.24 to 0.85. Validation results for both nitrogen and phosphorus did not show acceptable correlation. A possible reason is that the land use map in this study was created for year 2001 while the validation period was from 1980 to 1985. For example, correlation for the validation period was poor in Subbasin 7 in the Galveston Bay watershed in comparison to Subbasin 12 because the model has under-predicted the nitrogen loads from subbasin 7 for validation period (Figure 13). It is not unexpected to get unsatisfactory results for the validation period (1984-1990) because the land use map of 2001 was used for model calibration purpose; Based on the land use products from TWDB#0804830788, there was urban development in Subbasin 7 from 1992 to 2001, although this does not seem to be the main reason for poor validation results. Under-prediction of nitrogen loading can be due to the agricultural land conversion or changing the frequency of fertilization or grazing and manure distribution during the past 30 years as well.

In a nutshell, the model successfully predicted the total nitrogen and total phosphorus from the all gauged subbasins except the loading from Subbasin 30 in the Galveston Bay watershed due to the absence of point source discharges in the modelling.

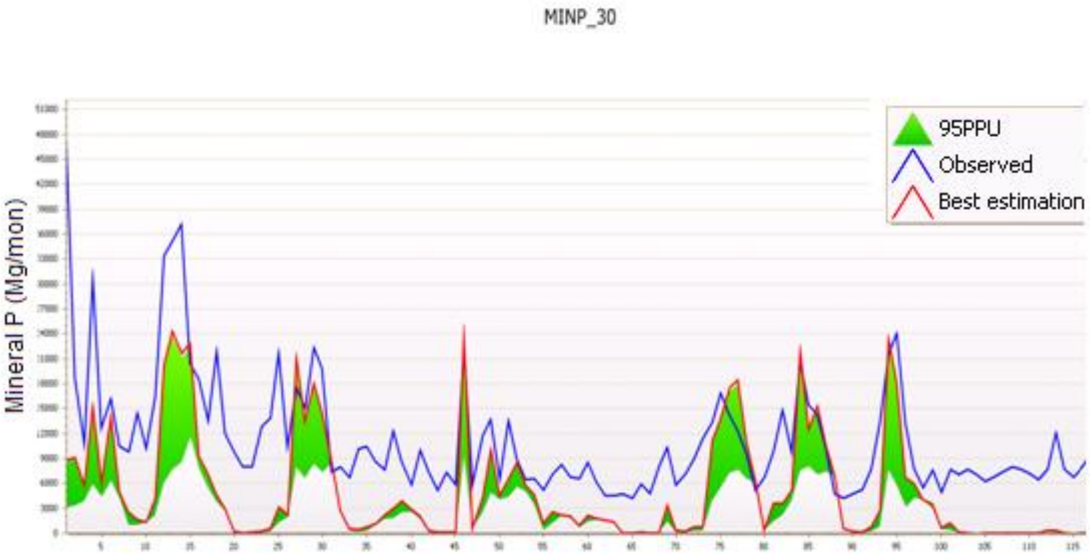


Figure 12. 95 PPU plot, illustration of the uncertainty in inorganic P prediction in relation with parameter uncertainty at Subbasin 30 Galveston watershed

Table 21. Model performance in estimating monthly nutrients (calibration and validation)

Galveston

	Station #	Subbasin #	Calibration		Validation	
			R^2	NSE	R^2	NSE
TN	8070500	7	0.77	0.65	0.58	0.21
	8070200	12	0.90	0.84	0.89	0.87
	8069000	30	0.66	-0.15	0.42	-0.73
TP	8070500	7	0.84	0.82	0.41	0.24
	8070200	12	0.77	0.85	0.45	0.31
	8069000	30	0.50	0.24	0.20	-0.73
ORGN	8070500	7	0.73	0.61	0.61	0.26
	8070200	12	0.79	0.79	0.43	0.38
	8069000	30	0.69	0.55	0.46	0.26
ORGP	8070500	7	0.81	0.80	-	-
	8070200	12	0.77	0.77	-	-
	8069000	30	0.50	0.22	-	-
MINP	8070500	7	0.81	0.72	-	-
	8070200	12	0.81	0.75	-	-
	8069000	30	0.17	-0.61	-	-
NO3	8070500	7	0.17	-2.75	0.14	-1.84
	8070200	12	0.50	0.02	0.34	-0.18
	8069000	30	0.27	-4.36	0.00	-6.91

Matagorda

	Station #	Subbasin #	Calibration		Validation	
			R^2	NS	R^2	NS
TN	8164000	7	0.77	0.38	0.47	0.38
	8162600	10	0.61	0.45	-	-
TP	8164000	7	0.76	0.46	0.45	0.26
	8162600	10	0.87	0.80	-	-
ORGN	8164000	7	0.85	0.56	0.43	0.34
	8162600	10	0.82	0.66	-	-
ORGP	8164000	7	0.77	0.55	0.41	0.25
MINP	8164000	7	0.56	0.34	0.47	0.29
NO3	8164000	7	0.59	0.42	0.63	0.48
	8162600	10	0.50	0.13	-	-

* Subbasin 10 was considered for calibrating local parameters affecting the nutrient load only.

The duration curves of predicted and estimated total N and P before and after parameter calibration at Reach 7 are presented in Figure 13. Figure 14 shows the estimated and predicted monthly total N and total P loads for calibration and validation period at Reach 12 in the Galveston Bay watershed. Some over-predicted peaks are observed on the months with flood events (Figure 14). As SWAT is a continuous time model, the model is not designed to simulate detailed, single-event flood routing (Neitsch et al., 2009). Figure 14 shows the uncalibrated model had better performance in the prediction of total phosphorus while dramatically under-predicted the total nitrogen. It is likely due to the conversion of agricultural lands to hay/pasture during the past 30 years and consequently high concentration of nitrogen in the top soil layer.

As concluded in Phase I, correlation for the validation period was worse in the Galveston Bay watershed than in the Matagorda Bay watershed due to the fact that a much larger portion of the Galveston Bay watershed has urbanized since the 1980s while the Matagorda Bay Watershed has experienced relatively little change in land use. The two important factors for improving simulation results are determining fertilization operation parameters and including point source loads in the model.

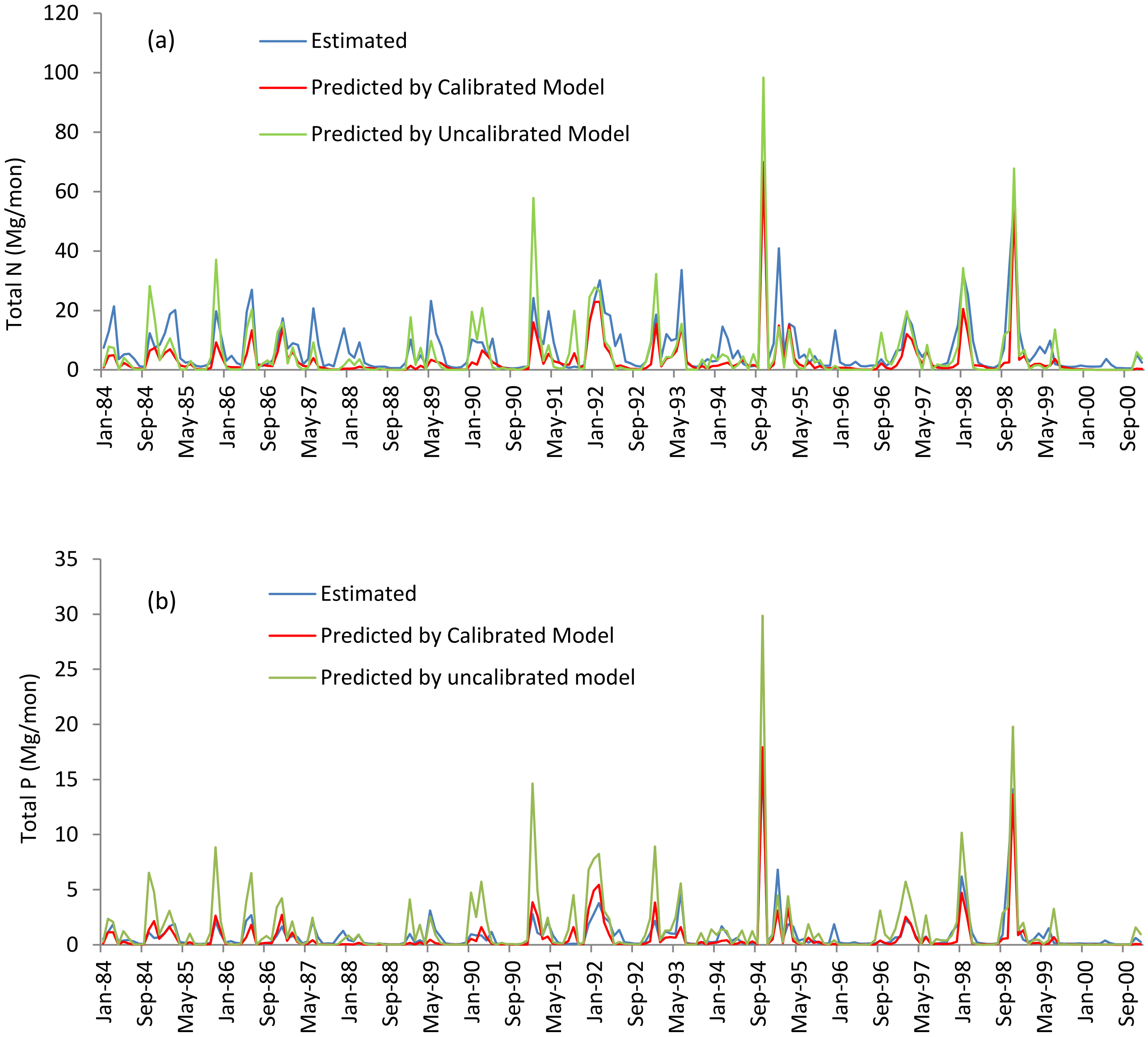
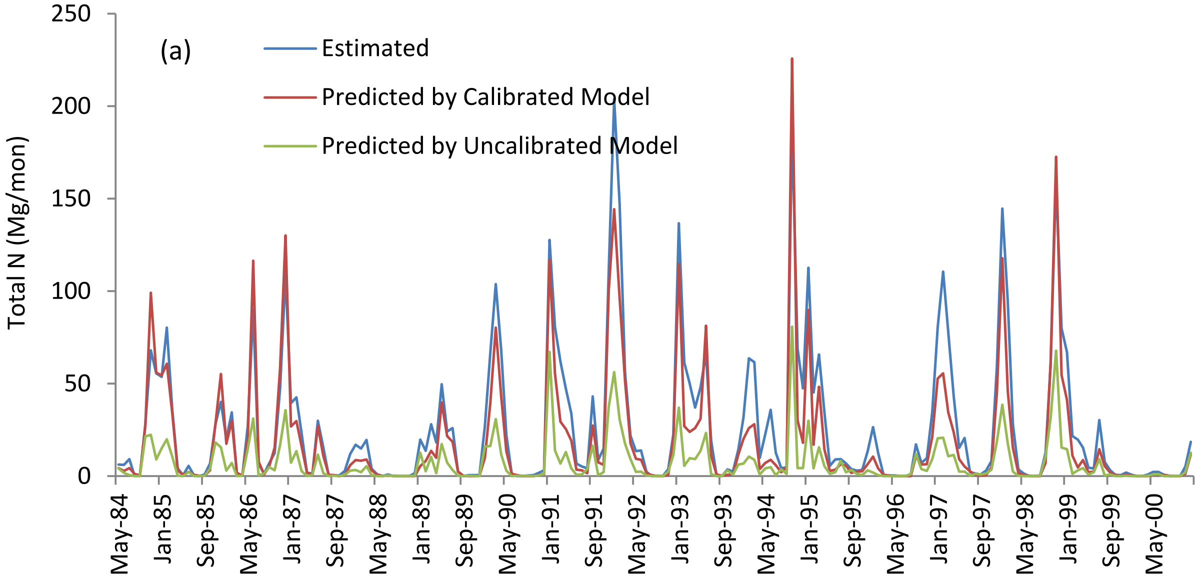


Figure 13. Predicted and estimated a) total N load before and after calibration at Subbasin 7 b) Total P before and after calibration for calibration and validation periods at Subbasin 7, Galveston Bay watershed



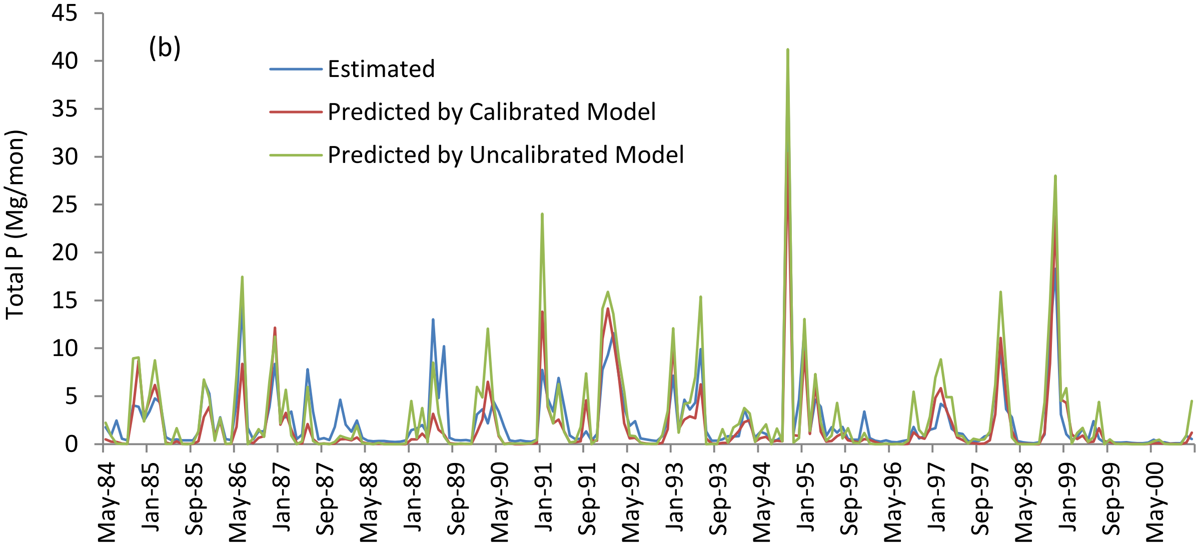


Figure 14. Predicted and estimated a) total N load before and after calibration at Subbasin 12 b) Total P before and after calibration for calibration and validation periods at Subbasin 12, Galveston Bay watershed

3.4. Sediment and Nutrient Loads from Gauged and Ungauged Subbasins

The simulated mean annual sediment delivery from ungauged sub-watersheds is presented in the Tables 22 and 23. It was not possible to compare the mean annual simulated sediment loading from ungauged sub-watersheds with the measured loading due to the lack of available information in sediment delivery from ungauged portion of the Matagorda watershed.

The average sediment delivery from Trinity River Basin to the Galveston Bay is estimated 70,000 ton/yr by Philips et al. (2004, 2005). Due to the lack of data from the inlet of the Galveston Bay watershed, the total nutrient loading from the Trinity River Basin to the bay was ignored. However, that information would be required to calculate total nutrient loads actually reaching a bay. The monthly sediment and total N from the Colorado River basin to the Matagorda were estimated at Gauging Station 08162000 at Wharton located upstream of the Matagorda inlet point, Gauge station 05162500 near Bay City.

Average annual sediment yield from ungauged sub-watersheds and entire Galveston watershed to the bay from 1977 to 2005 were compared to the estimated sediment yield from fresh water by Philips et al. (2005) (Table 22) and the results showed good agreement with their estimations.

Mean annual total N and P loads to the Galveston Bay over a 29-year period from 1977 to 2005 were compared to the estimated loading for an average year by Armstrong and Ward (1993), for the Galveston Bay Non-point Sources project (GBNEP) (Tables 24 and 25). In 1996, the nutrient supplied to the Trinity-San Jacinto Estuary from gauged stream inflows, ungauged rainfall runoff, returned waste water, and direct rainfall on the estuary surface was estimated by TWDB for three years (1988, 1989, and 1990) (Brock et al., 1996). In Tables 24 and 25 simulated total N and P are compared to those estimated loads from fresh water. Armstrong and Ward estimated the total loads from the major rivers while the TWDB considered the major rivers and minor streams within the coastal drainage area (Philips et al., 2005). The simulated total N and P by SWAT shows good agreement with the estimated loads by Ward and Armstrong (1993) while the model has under-predicted the total N and P about 50% in comparison to a 3-year estimations by TWDB.

The mean annual estimation of sediment delivery to the bay from ungauged sub-watersheds and the entire Matagorda watershed by the SWAT model was about 486,000 and 921,000 ton/yr, respectively, where the sediment delivery from Colorado River Basin from 1975 to 2000 was estimated about 1,151,000 ton/yr. Total loading to the Matagorda Bay is sum of the sediment delivery from the Matagorda watershed and Colorado River Basin (Lavaca-Colorado River Basin) estimated about 2,217,600 ton/yr. The results showed that the predicted specific sediment delivery from gauged sub-watersheds was 0.79 ton/hawhile it was estimated 0.91 ton/ha within the ungauged sub-watersheds by SWAT.

Average annual total nitrogen and phosphorus from ungauged sub-watersheds and the entire Matagorda watershed to the bay from 1977 to 2005 were compared to the estimated nutrient loads from fresh water by the LCRA and Longley 1994 (Tables 26 and 27). Depend on the data availability, the mean annual nutrient loads were compared with the total nutrient loads from the Matagorda watershed or from the Matagorda and Colorado River Basin (Lavaca-Colorado River Basin) to the bay. SWAT model considerably under-predicted the the total nitrogen from ungauged sub-watersheds in compare to LCRA 1997 (-19%) and Longley 1994 (-68%).Total phosphorus from ungauged sub-watersheds was between the estimated loads by Longley 1994 and Ward and Armstrong 1980.

Table 22. Mean annual sediment delivery to the Galveston Bay over a 29-year period from 1977 to 2005

	SWAT drainage area (km^2)	Philips et al. (2005)		SWAT (ton*/yr)	Difference (%)
		(ton*/yr)	(ton*/km^2)		
Ungauged sub-watersheds	7,720	-	-	882,800	-
Galveston Bay watershed	16,130	967,800	60	1,032,100	+6.6
Trinity River Basin at Liberty	45,242	70,000	1.6	105,900	+51
Total loading to the Galveston Bay	59,246	1,037,800	-	1,138,000	+9.6

* Metric tons

Table 23. Mean annual sediment delivery to the Matagorda Bay over a 29-year period from 1977 to 2005

	SWAT drainage area (km^2)	Sediment (ton*/yr)	Sediment (ton*/km^2)
Gauged sub-watersheds	5,711	435,200	76
Ungauged sub-watersheds	5,323	485,930	91
Matagorda Bay watershed	11,034	921,130	83
Colorado River Basin to the Bay	109,152	1,151,000	10
Total loading to the Matagorda Bay	120,404	2,217,600	18

* Metric tons

Table 24. Mean annual total N load to the Galveston Bay over a 29-year period from 1977 to 2005

Ungauged sub-watersheds	SWAT drainage area (km^2)	SWAT 29-year (ton^*/yr)	GBNEP Ave. year (ton^*/yr)	Difference (%)	SWAT** (ton^*/yr)	Brock et al. 1996** (ton^*/yr)	Difference (%)
Ungauged sub-watersheds	$7,720^{***}$	6,377	6,400	-0.3	3,872	8,400	-54
Galveston Bay watershed	16,130	5,447	-	-	4,431	-	-

* Metric tons
** Average loading for a 3-year period, 1988, 1989, and 1990
*** The reported area of ungauged sub-watersheds by Ward and Armstrong is 6624 km2.

Table 25. Mean annual total P load to the Galveston Bay over a 29-year period from 1977 to 2005

	SWAT drainage area (km^2)	SWAT 29-year (ton^*/yr)	GBNEP Ave. year (ton^*/yr)	Difference (%)	SWAT** (ton^*/yr)	Brock et al. 1996** (ton^*/yr)	Difference (%)
Ungauged sub-watersheds	$7,720^{***}$	1,040	1,100	-5.4	979.5	1,800	-46
Galveston Bay watershed	16,130	1,475	-	-	1,293	-	-

* Metric tons
** Average loading for a 3-year period, 1988, 1989, and 1990
*** The reported area of ungauged sub-watersheds by Ward and Armstrong is 6624 km^2.

Table 26. Mean annual total nitrogen loads to the Matagorda Bay over a 29-year period from 1977 to 2005

	SWAT estimated area (km^2)	SWAT (ton^*/yr)	LCRA, 1997 wet-dry year (Average)	Difference (%)	Longley, 1994 (ton^*/yr)	Difference (%)
Gauged sub-watersheds	6,553.7	1,325	706-1,830 (1,268)	+4.5	-	-
Ungauged sub-watersheds	4,480.3	1,161	1,290-1,585 (1,438)	-19	3,950	-68
Matagorda Watershed	11,034	2,490	1,996-3,415 (2,706)	-8.6	-	-

* Metric tons

Table 27. Mean annual total phosphorus delivery to the Matagorda Bay over a 29-year period from 1977 to 2005.

	SWAT drainage area (km^2)	SWAT (ton*/yr)	Longley, 1994 (ton*/yr)	Difference (%)	Ward and Armstrong, 1980 (ton*/yr)	Difference (%)
Gauged sub-watersheds	6,553.7	246	-	-	-	-
Ungauged sub-watersheds	4,480.3	265	300	-11.6	200	+33
Matagorda Bay watershed	11,034	511	-	-	-	-
Total loading to the Matagorda Bay (Lavaca-Colorado)	120,404	1,101	820	+34	1090	+1

* Metric tons

4. Analysis

4.1. Mean Annual Sediment and Nutrient Loads Distribution by Landuse

Figures 15 and 16 illustrate sediment and nutrient loading for the Galveston Bay watershed and Matagorda Bay watershed by each landuse category. Cropland, which accounts for 26% of the entire Matagorda Bay watershed, is the main water pollutant, contributing about 71% of sediment, 59% of total N and 80% of total P. Pasture/hay, which encompasses almost 44% of the watershed, generates relatively less sediment 26%, total P 33% and total N 16%. The main water degradation in the Galveston Bay watershed in the absence of point source discharges is cropland covering nearly 6% of the watershed accounts for almost 32%, 31%, and 34% of the sediment, total nitrogen and phosphorus delivered to rivers and streams.

It was estimated that a certain portion of the contributed sediment from HRUs would be deposited at main channels. It was predicted that the 33% of sediment load from the Matagorda and Colorado River Basin is deposited in the main channels, while the average deposition for Lavaca River Basin and Lake Texana dam was estimated 23% and 42%. Nearly 27% of the sediment delivery from the Galveston Bay watershed's HRUs was estimated to deposit in the rivers and streams.

Only about 38% of total N and 40% of total P from the Matagorda Bay watershed reaches the bay while 49% of total P from the Galveston Bay watershed delivered to the bay. There was 30% increase in total N loading from the Galveston Bay watershed to the bay due to the high concentration of nitrogen in the channel bedload.

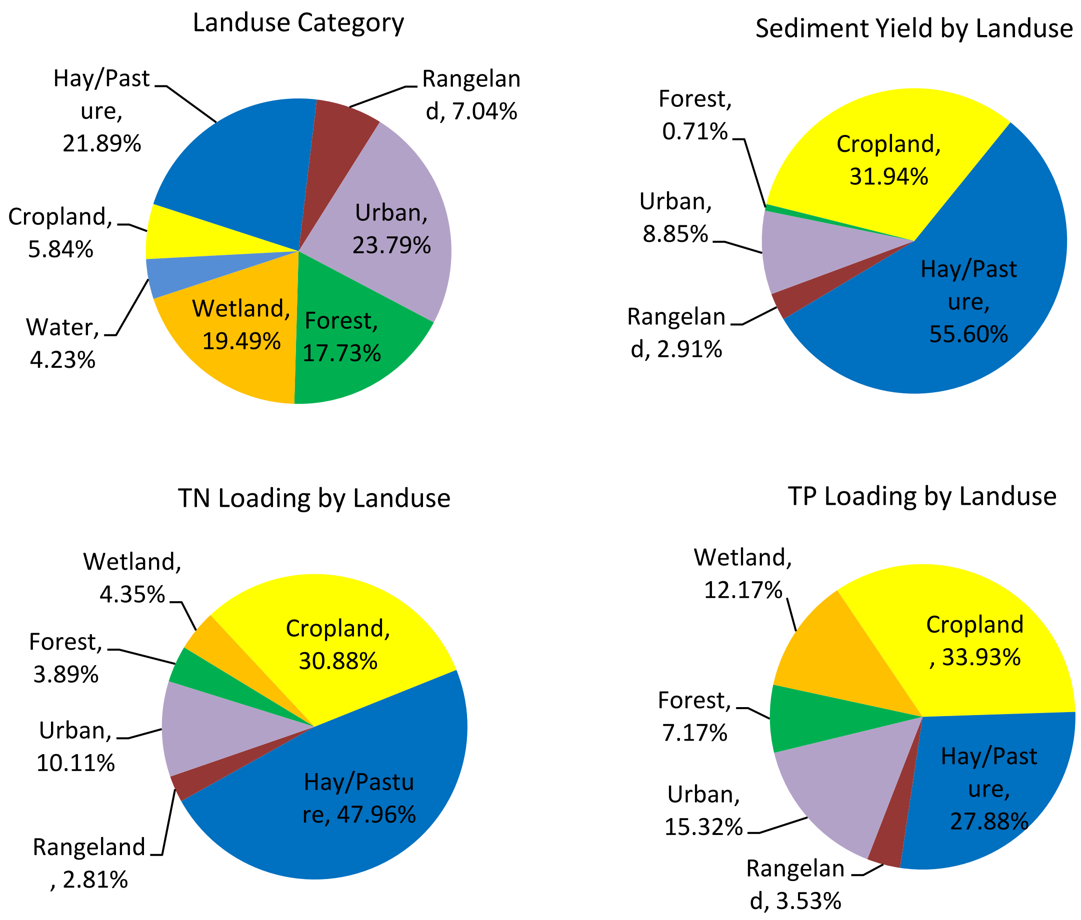


Figure 15. Sediment and nutrients loadings by landuse, Galveston Bay watershed

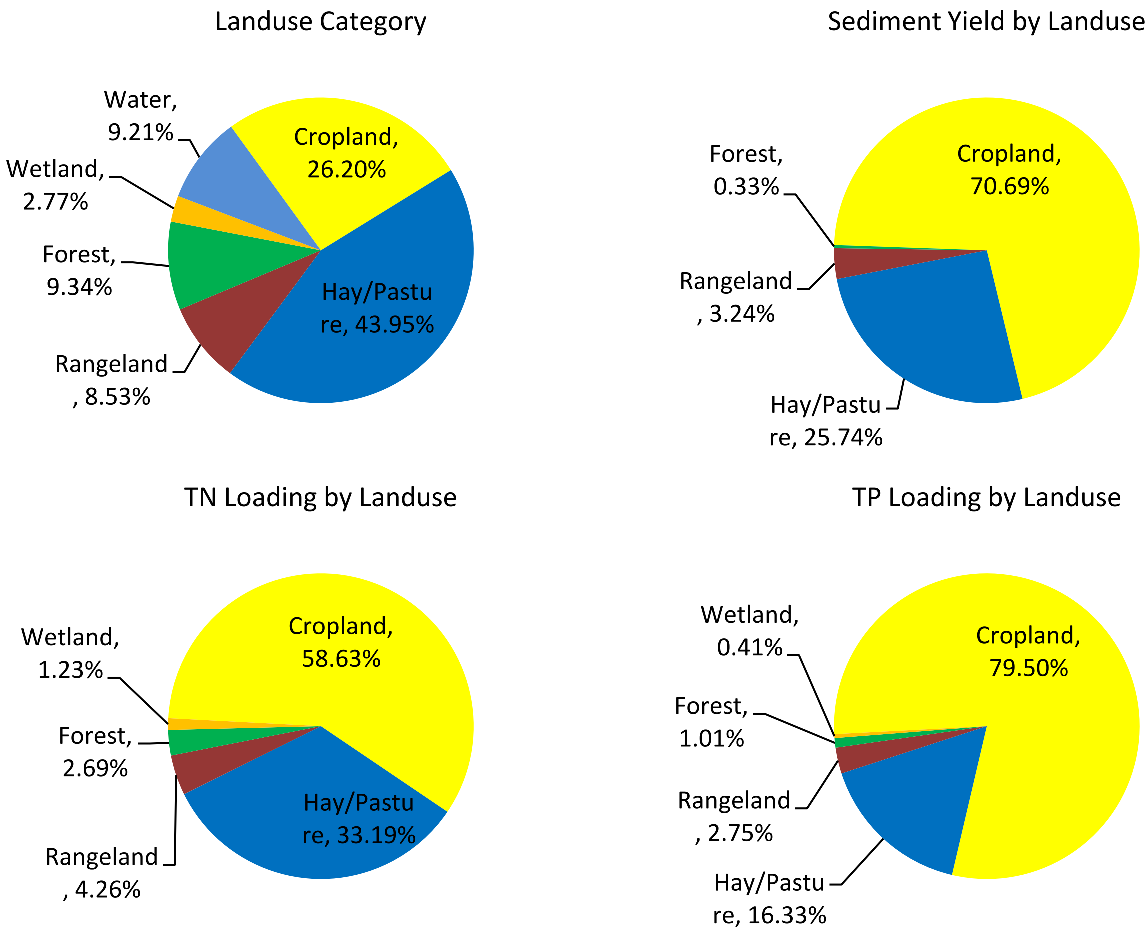


Figure 16. Sediment and nutrients loadings by landuse, Matagorda Bay watershed

4.2. Mean Annual Sediment and Nutrient Loads Distribution by Subbasin

Figure 17 through Figure 22 show sediment and nutrients loadings by subbasins. There are small areas of watershed severely eroded in the eastern parts of the Matagorda Bay watershed and northern parts of the Galveston Bay watershed. There is general trend that the eastern parts of the Matagorda Bay watershed generate more sediment and nutrients (red in maps), while the southern half of the Galveston Bay watershed contributes higher portion of nutrients to the bay.

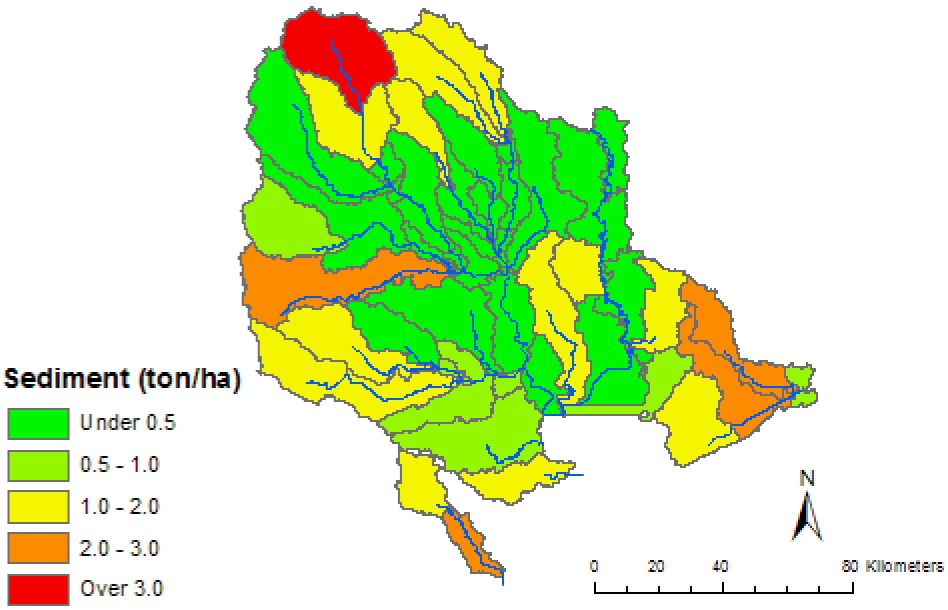


Figure 17. Sediment yield (ton/ha) by overland flow predicted by SWAT, Galveston Bay watershed

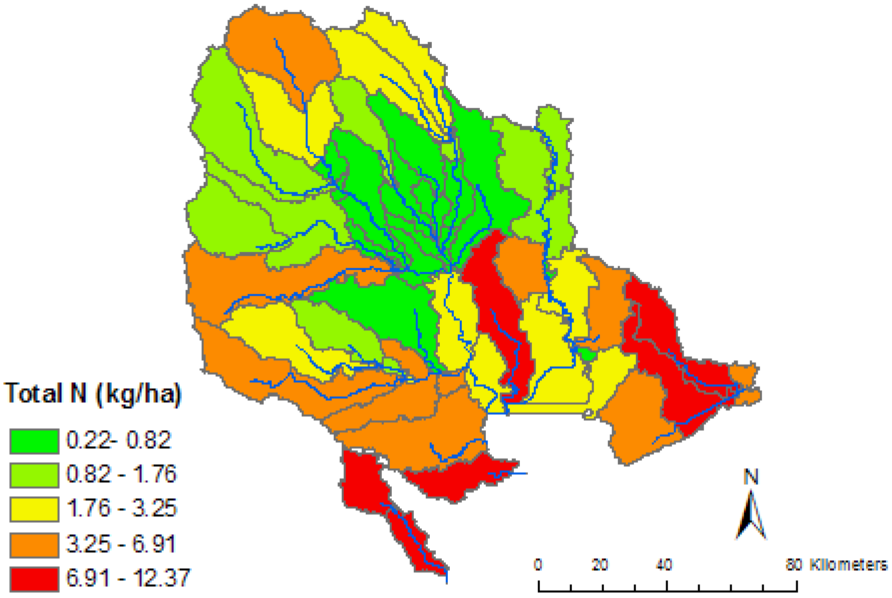


Figure 18. Total Nitrogen loading (kg/ha) by overland flow predicted by SWAT, Galveston Bay Watershed

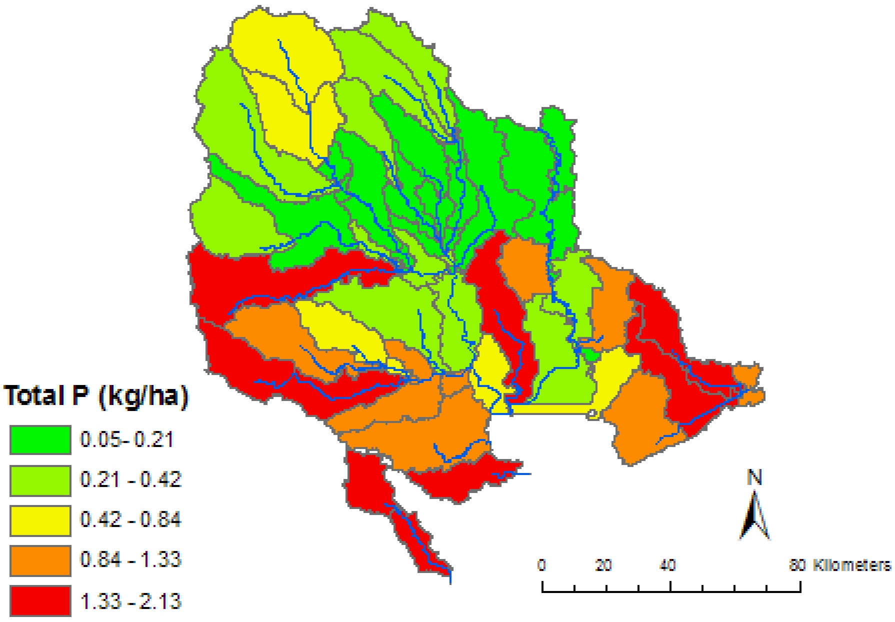


Figure 19. Total Phosphorous loading (kg/ha) by overland flow predicted by SWAT, Galveston Bay Watershed

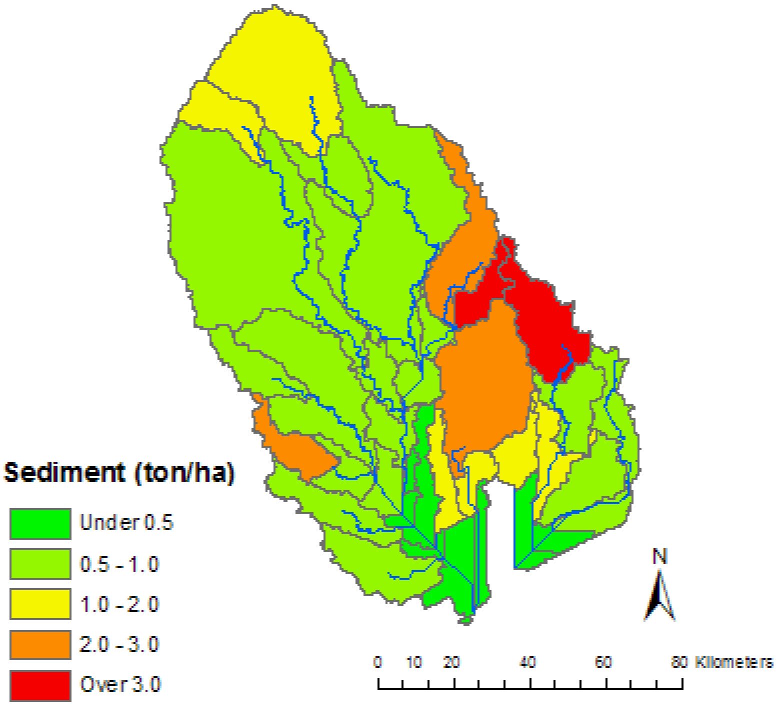


Figure 20. Sediment yield (ton/ha) by overland flow predicted by SWAT, Matagorda Bay watershed

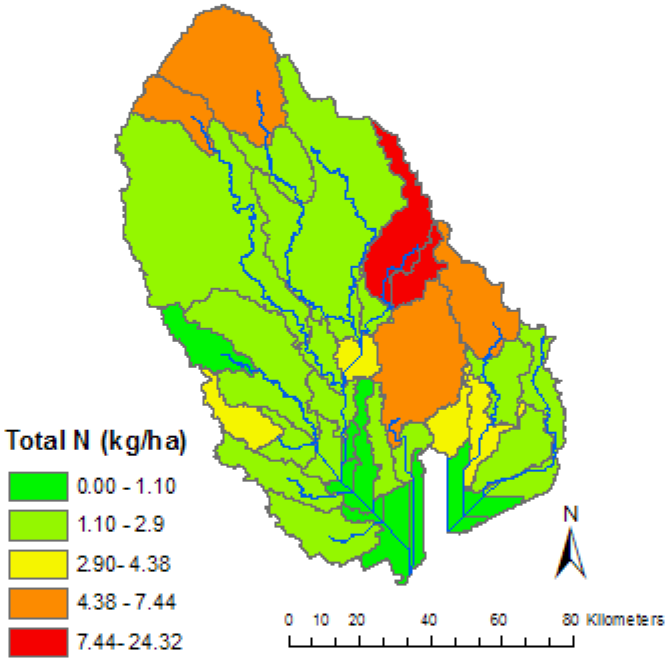


Figure 21. Total Nitrogen loading (kg/ha) by overland flow predicted by SWAT, Matagorda Bay watershed

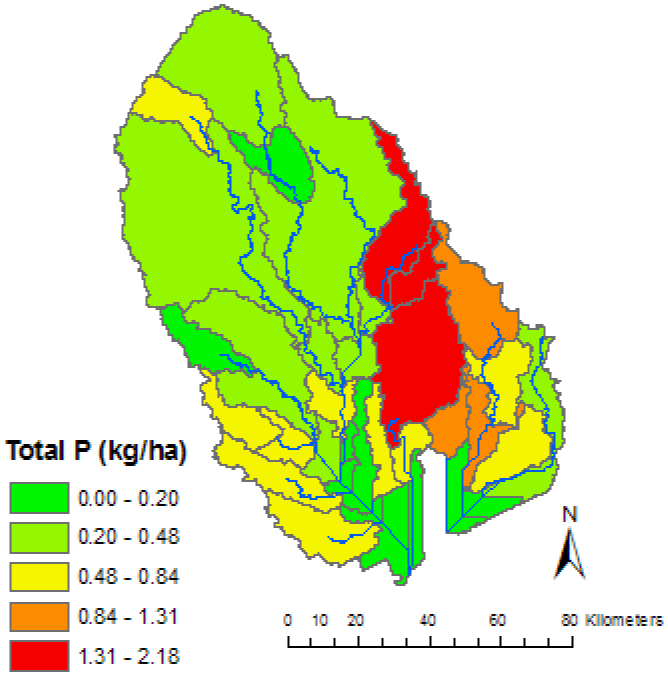


Figure 22. Total Phosphorous loading (kg/ha) by overland flow predicted by SWAT, Matagorda Bay watershed

5. Conclusion

This study was conducted to develop SWAT models for the Galveston Bay and Matagorda Bay watersheds to estimate terrestrial sediment and nutrient loads from fresh water. For both the Galveston and Matagorda Bay watersheds, a separate project was set up. The mean annual calibration for sediment, total N and total P was performed relaying on the estimated annual load by previous studies. In gauged subbasins, SWAT was calibrated for monthly sediment, nitrate, organic nitrogen, total nitrogen, organic phosphorus, mineral phosphorus and total phosphorus at USGS gauging stations, and the total output from each subbasin was estimated.

The models were then validated and their parameter settings were extended to ungauged sub-watersheds. The output of the watersheds from the SWAT model was compared to the reported mean annual sediment and nutrient loads from fresh water.

Monthly sediment calibration at each gauging station showed good correlation, with an R^2 ranging from 0.65 to 0.88 and an NSE ranging from 0.55 to 0.75. Validation results also correlate acceptable, ranging from 0.53 to 0.67 for R^2 and from 0.43 to 0.50 for NSE. The channel sediment deposition was estimated about 33% and 27% for the Matagorda Bay watershed and Galveston Bay watershed, respectively. Sediment deposition is highly sensitive to channel erosion factors that should be selected based on literatures or field measurement.

Comparison between observed and modeled monthly nutrient loads showed that the model had a good performance for predicting the organic N and P but the prediction of inorganic N and P was unsatisfactory. A possible reason for the failure to accurately predict inorganic nutrients is simplified assumptions to model the agricultural operations and management. The uncertainty analysis showed that the poor prediction of nitrate load was not related to the model parameterization. The two important factors, fertilization operations parameters and point source discharges, should be determined to improve the simulation results.

Only about 38% of total N and 40% of total P from the Matagorda Bay watershed reaches the bay while 49% of total P from the Galveston Bay watershed delivered to the bay. There was 30% increase in total N loading from the Galveston Bay watershed to the bay due to the high concentration of nitrogen in the channel bedload.

The high nutrient deposition could be due to the high sediment deposition in the channels. However, the literature indicates that the SWAT needs further improvement to in-stream modeling routines. Nitrogen loading from channels bedload has critical role in total N estimation. Modelling the wetlands within the subbasins slightly reduced the sediment and nutrient loading about 3 to 4 percent.

SWAT is a capable tool to evaluate the impact of agricultural managements, BMPs, point source removal, land use change and climate change on watershed. Finally, using similar methodology and model setting, SWAT can be applied to other Texas coastal watersheds. These capabilities should be explored in future work.

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Appendix A

RNGB: Range-Brush

FRSD: Forest-Deciduous

FRSE: Forest-Evergreen

AGRR: Agricultural Land-Row Crops

WETF: Wetlands-Forested

BERM: Bermudagrass, plant cover of urban areas

BIOMIX.mgt: Biological mixing efficiency

BC3.swq: Rate constant for hydrolysis of organic N to NH4

BC4.swq: Rate constant for mineralization of organic P

CDN.bsn: Denitrification exponential rate coefficient

CH_COV1.rte: Channel cover factor

CH_COV2.rte: Channel erodibility factor

CH_N2.rte: Manning’s n value for the main channel

CMN.bsn: Rate factor for humus mineralization of active organic nutrients (N and P)

ERORGN.hru: Nitrogen enrichment ratio for loading with sediment

ERORGP.hru: Phosphorus enrichment ratio for loading with sediment

NPERCO.bsn: Nitrate percolation coefficient

PHOSKD.bsn: Phosphorus soil partitioning coefficient

PPERCO.bsn: Phosphorus percolation coefficient

PRF.bsn: Peak rate adjustment factor for sediment routing in the main channel

PSP.bsn: Phosphorus availability index

RS2.swq: Benthic P source rate coefficient

RS3.swq: Benthic NH4 source rate coefficient

RS4.swq: Organic N settling rate coefficient

RS5.swq: Organic P settling rate coefficient

RCN.bsn: Concentration of Nitrogen in rainfall

RSDCO.bsn: Residue decomposition coefficient

SPCON.bsn: Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channelsediment routing

SDNCO.bsn: Denitrification threshold water content

SPEXP.bsn: Exponent parameter for calculating sediment re-entrained in channel sediment routing