Final Report

Estimating the water balance of Texas coastal watersheds with SWAT

A case study of Galveston and Matagorda Bay

A Final Report for the Texas Water Development Board

Project 2009-483-0890

January 20, 2011

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Summary

The SWAT (Soil and Water Assessment Tool) model was used to estimate terrestrial inflow to Galveston and Matagorda bays from their contributing watersheds. In this report, the term "terrestrial inflows" represents the sum of gauged inflows from gauged subbasins plus model-generated flows from ungauged subbasins. Return flows and diversions from the contributing subbasins are not included in this flow calculation. However, that information would be required to calculate total freshwater inflow actually reaching a bay. The estimated inflow results were compared to estimates obtained using the Texas Rainfall-Runoff (TxRR) model developed by the Texas Water Development Board (TWDB). The TWDB estimates used for comparison with SWAT results include observed gauged flow plus estimated ungauged flow, which also did not include return and diverted flow.

SWAT is a spatially distributed, continuous model that can be used to estimate flow, sediment, and nutrients at a variety of scales, 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 and groundwater flow as well as channel processes. And third, the calibrated model can be developed to analyze scenarios such as using BMPs (best management practices), land use changes, climate change, and more.

In this study, two watersheds, Galveston and Matagorda bays, 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) provided topography, land cover and soil data came from the Natural Resource Conservation Service (NRCS), the National Climate Data Center (NCDC) provided weather data, and U.S. Geological Survey stream gauge stations provided flow data.

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 as to the model as reservoirs, and point sources were set up in each subbasin for future use.

Model calibration was conducted using flow observations from USGS stream gauge stations, and SWAT-estimated total terrestrial inflow to the bays was compared to the estimates made by TWDB using the TxRR model. Daily streamflow estimated at each gauging station showed

acceptable to good correlation with observed values, with R^2 ranging from 0.42 to 0.71 and NSE (Nash-Sutcliff Efficiency) ranging from 0.25 to 0.56. Modeled monthly streamflow showed much better agreement when compared with observed flows, with R^2 ranging from 0.62 to 0.84 and NSE ranging from 0.60 to 0.85. Statistics showed that SWAT performed well in estimating monthly total terrestrial inflow in each bay. SWAT estimates and TWDB estimates (using TxRR) showed very high correlation. The models estimated that average annual inflow to Galveston Bay was 13,756,795 ac-ft (SWAT) and 12,535,276 ac-ft (TWDB). Using a monthly comparison, the correlation coefficient between the two estimates was 0.950. For Matagorda Bay, SWAT's average annual inflow estimate was 4,273,940 ac-ft, and TWDB's was 4,253,407 ac-ft, giving a correlation coefficient of 0.886.

Introduction

Texas Water Development Board (TWDB) has been estimating freshwater inflows from ungauged watersheds to coastal bays using the Texas Rainfall-Runoff (TxRR) model, which predicts inflows to the bays based on the Soil Conservation Service Curve Number method (SCS-CN). Recently, TWDB requested the development of a Soil and Water Assessment Tool (SWAT) for estimating surface inflows to the bays with up-to-date technology and data. Accordingly, this project was initiated to develop and apply a SWAT model to two Texas estuaries in order to estimate terrestrial inflow and to evaluate model performance when compared with the TxRR model presently used by TWDB. In this report, the term "terrestrial inflows" represents bay inflow that excludes diverted and return flow. SWAT estimated total bay inflow for both gauged and ungauged subbasins using a calibrated model setting for gauged subbasins. On the other hand, the TxRR model estimated total inflow as the sum of observed inflows from subbasins that are gauged plus model-generated flows from subbasins that are ungauged. Although not considered, return flows and diversions from the subbasins would be required to calculate the total freshwater inflow actually reaching a bay. In this pilot study, SWAT estimated the daily and monthly terrestrial inflow to two bay watersheds, Galveston and Matagorda. These two were chosen because Galveston Bay watershed is an example of an urbanized watershed while Matagorda Bay watershed as an example of rural watershed

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) evaluate the accuracy and applicability of using the SWAT model for estimating the quantity of terrestrial inflow to estuaries when compared with the TxRR model currently used by the TWDB; 3) estimate inflow to the estuary by including gauged and ungauged subbasins; and finally, 4) develop methodologies and procedures for estimating terrestrial inflow to the estuaries as required by TWDB.

Methodology

Study Area

Galveston 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. Galveston Bay watershed has a total drainage area of approximately 6,220 $mile^2$ (16,100 km^2) while Matagorda Bay watershed's area is 4,480 $mile^2$ (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. Galveston Bay watershed is considered an urbanized watershed and includes the city of Houston and its surrounding metro area. Guided by TWDB, 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.

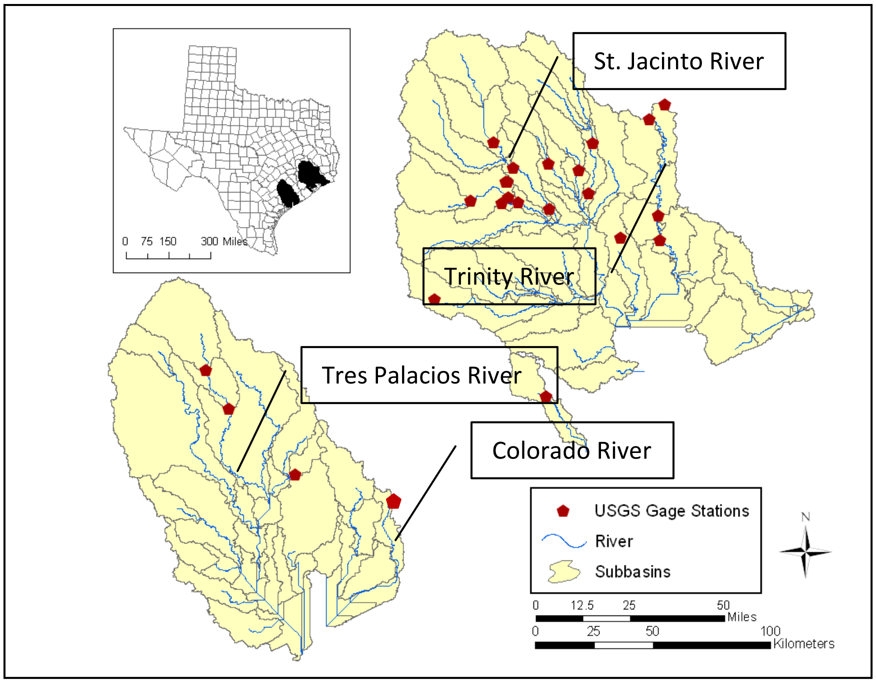

Figure 1. Matagorda (left) and Galveston (right) bay watersheds

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.

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 Galveston and Matagorda bay watersheds ranges from -1 to 593 feet (Figure 2). Near the coast, the area is very flat; the average slope of Galveston Bay and Matagorda Bay watersheds is 0.99% and 0.61%, respectively.

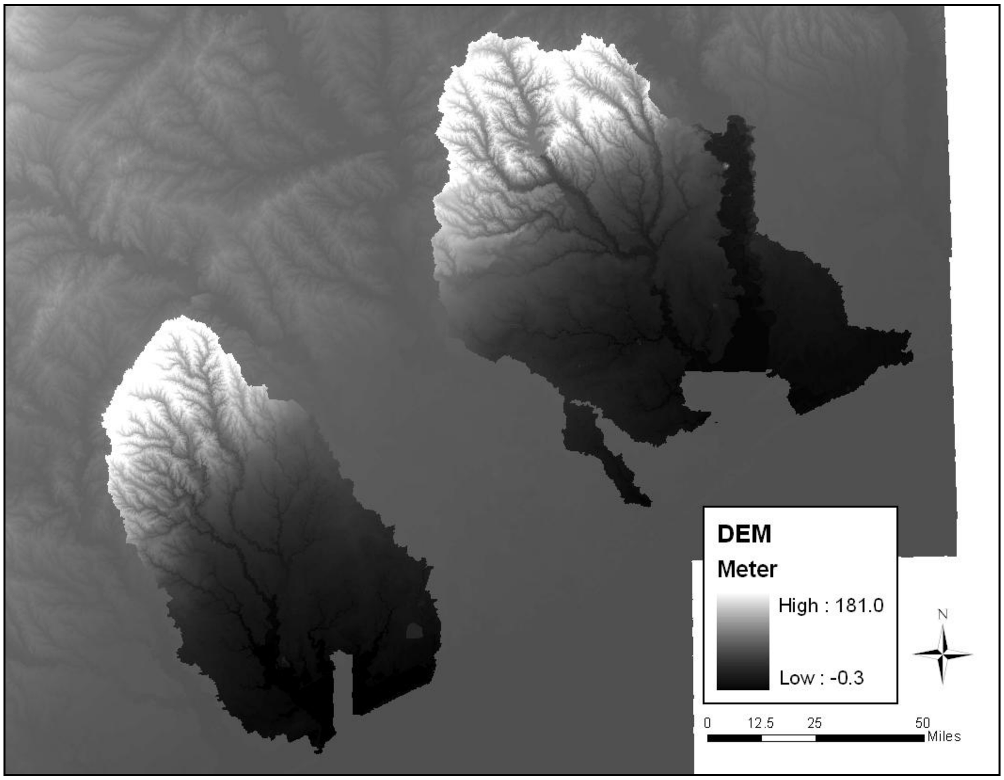

Figure 2. National elevation dataset (NED) of Matagorda (left) and Galveston (right) bay watersheds

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 Galveston Bay watershed consists primarily of urban areas (23.8%) and pastureland (21.9%). In Matagorda Bay watershed, on the other hand, pastureland accounts for the largest portion (43.9%), nearly half 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%

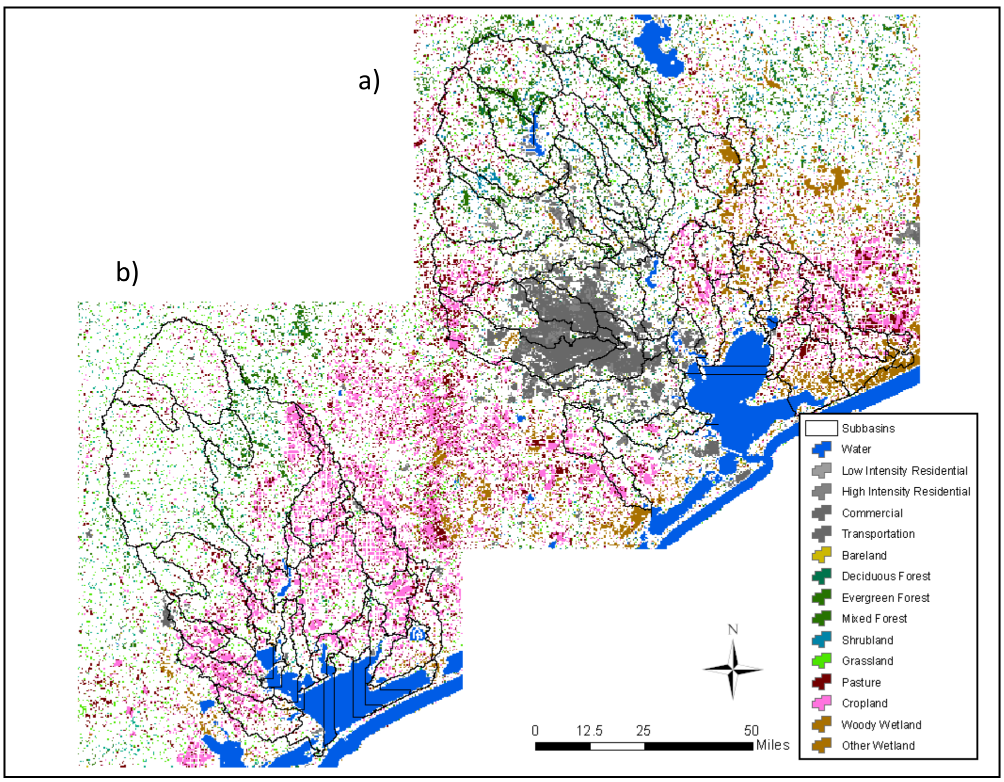

Figure 3. National Land Cover Dataset (30-m) created in 2001 for a) Galveston Bay and b) Matagorda Bay watersheds.

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 Galveston Bay watershed are Lake Cha and Bernard, covering 10.0% and 7.7%, respectively, of the total watershed area. In 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 20 weather stations were used in this study, 11 for Galveston Bay watershed and nine for 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.

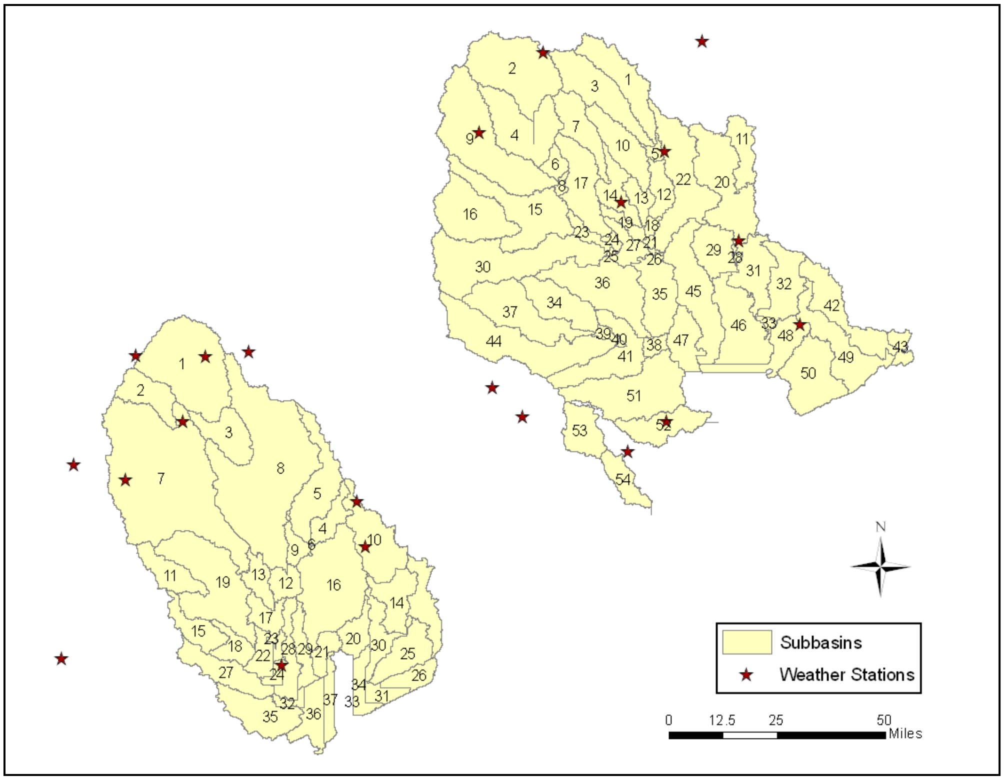

Figure 4. Weather stations used in this project; numbers indicate subbasin ID.

5) USGS gauging stations

The USGS (U.S. Geological Survey) provided flow data at stream gauging stations, 21 of which were available in the watersheds (Figure 5). Of those stations, only eight in 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.

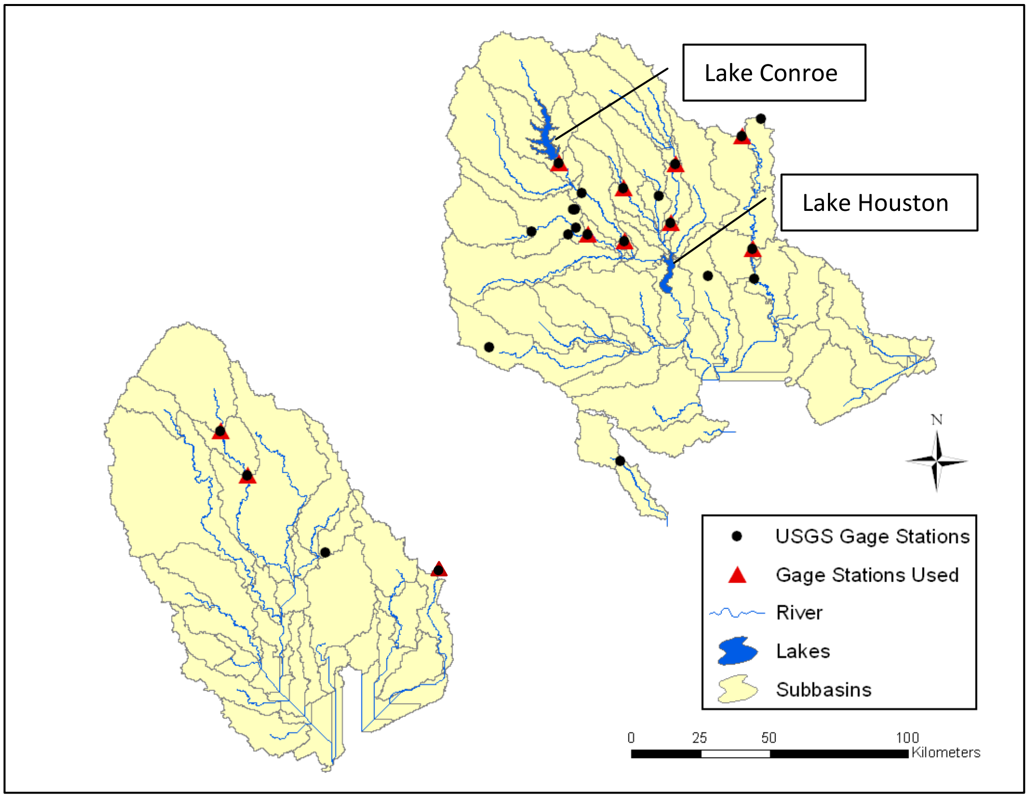

Figure 5. USGS gauging stations available in both watersheds

Gauging stations 08066500 and 08162500 were used as inlets for Galveston 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 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 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 Galveston Bay watershed, and two gauging stations and one inlet were used in Matagorda Bay watershed.

Table 2. List of available USGS gauging stations in 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.

Project Setup

In SWAT, two separate projects were set up for each watershed. The modeled period lasted from 1975 to 2008 and included a two-year model warm-up period (1975–1976). All data used in the SWAT model was projected to Albers Equal Area with North American 1983 for datum. This section explains the set up 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 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 Galveston Bay watershed was not delineated (Figure 6) 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 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 6). Those subbasins were selected because they are geographically adjacent, their area is similar, and thus, precipitation was assumed to be similar.

Figure 6. 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.

2) Subbasins and HRUs

Automatic subbasin delineation, based on given threshold areas and manual input of subbasin outlets, generated 54 subbasins for Galveston Bay watershed and 37 for Matagorda Bay watershed (Figure 4). SWAT then divided each subbasin into more detailed HRUs. HRUs represent unique combinations of land use, soil type, and slope. 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 Galveston and Matagorda bay watersheds, respectively. These HRUs can be used for analyses on a particular land use or soil type.

3) Land use distribution in each gauged watershed

Table 3 shows the percentage of each land use category in each gauged subbasin and contributing subbasins that lie above the gauging station in both Galveston and Matagorda bay 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 (see previous section). This means any land use categories covering under 5% of the total subbasin area were not included in this distribution.

Most subbasins with gauging stations were located in the upper part of the watershed in both Galveston and Matagorda bays, and the land use categories within these subbasins consist mainly of forest and rangeland (Table 3).

Table 3. Land use distributions 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	
	08067650	08070000	08070500	08070200	08068500	08068090	08164300	08164350
Water	6.8%	0.0%	0.0%	0.0%	0.0%	3.2%	0.0%	0.0%
Urban	2.9%	0.4%	7.6%	2.2%	19.9%	6.4%	0.0%	0.0%
Forest	40.5%	53.8%	32.3%	51.5%	32.9%	35.1%	0.0%	13.6%
Agricultural	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pastureland	22.7%	12.2%	22.5%	10.4%	20.9%	24.1%	100.0%	82.3%
Rangeland	12.9%	13.5%	21.1%	15.1%	15.7%	14.9%	0.0%	4.2%
Wetland	14.2%	20.1%	16.5%	20.8%	10.7%	16.2%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

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 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 4.

Table 4. 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 point sources, but they were set up in most modeled subbasins for future use. During this study, all output from point sources was set to zero.

Model calibration and validation

1) Calibration and validation for each gauging station

Daily streamflows were calibrated against USGS gauging station data; however, time periods with available data varied by gauging station (Figure 5 and Table 2). However, calibration periods usually only encompass half of the total available data period. Flow data from the later years were selected for calibration while the earlier years were selected for validation because the land use data used in this study was from 2001 and may have discrepancies between data from the beginning of the model period (Table 5).

Since there were a limited number of gauging stations available in the watersheds, and because they were located in the middle of each watershed, parameter adjustments were conducted only in subbasins upstream of those stations. Agricultural, industrial, and municipal return flow and diverted flow were not included in this study, and it was assumed that they did not greatly impact model calibration at each gauging station because all stations are located above Houston, the major city in the modeled area. Statistical analyses used in calibration included total flow, average flow, correlation coefficient, the slope-of-fit line, and Nash-Sutcliffe model efficiency (Nash and Sutcliffe, 1970). The calibration procedure continued until modeled flow matched well with observed flow based on the factors above.

Table 5. USGS gauging station data and the period of calibration and validation. The calibration period was selected for the latter half of entire data period.

Watershed	Gauging Stations	Data Period	Calibration	Validation
Galveston Watershed	08067650	1977 - 2000	1991 - 2000	1977 - 1990
	08070000	1977 - 2008	1991 - 2008	1977 - 1990
	08070500	1977 - 2008	1991 - 2008	1977 - 1990
	08070200	1984 - 2000	1991 - 2000	1984 - 1990
	08068500	1977 - 2008	1991 - 2008	1977 - 1990
	08068090	1984 - 2000	1991 - 2000	1984 - 1990
Matagorda Watershed	08164300	1977 - 2000	1991 - 2000	1977 - 1990
	08164350	1981 - 1989 1996 - 2000	1996 - 2000	1981 - 1989

Table 6 and Table 7 list parameters calibrated for streamflow and their default and adjusted value ranges. Some parameters have a range of values because different values were applied to some subbasins.

Table 6. Parameter values for streamflow calibration (gauging stations) used in the Galveston Bay watershed SWAT project

Variable	Description	Default Value	Input Value	Units
GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.15 – 0.2	
GWQMN	Groundwater storage required for return flow	0	1,000	mm
ALPHA_BF	Baseflow alpha factor	0.048	0.048 – 0.4	$Days^{-1}$
SURLAG	Surface runoff lag time	4	5	hr
SOL_AWC	Soil available water	0.08 – 0.13	0.05 – 0.5	mm
ICN	Land cover/plant code	Soil moisture	Plant ET	

Table 7. Parameter values for streamflow calibration (gauging stations) used in the Matagorda Bay watershed SWAT project

Variable	Description	Default Value	Input Value	Units
GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.02 – 0.2	
GWQMN	Groundwater storage required for return flow	0	1,000	mm
ALPHA_BF	Baseflow alpha factor	0.048	0.4	$Days^{-1}$
SOL_AWC	Soil available water	0.08 – 0.13	0.6	mm

2) Comparison of terrestrial inflow to the bays

Comparison of terrestrial inflow to both Galveston and Matagorda bays was conducted by extending and applying parameter settings from the calibration of gauged subbasins to ungauged subbasins. In addition, for each bay, SWAT's flow output was compared with TWDB's terrestrial inflow estimates calculated using TxRR (observed flow from gauged subbasins plus estimated flow from ungauged subbasins). For this comparison, parameters were adjusted only in ungauged subbasins, which were not considered during calibration (see previous section).

In gauged subbasins, some parameter values altered during calibration have ranges depending on the watershed, as shown in Table 6 and Table 7. For example, the groundwater re-evaporation coefficient (GW_REVAP) ranges from 0.15 – 0.2 for Galveston Bay watershed and 0.02 – 0.2 for Matagorda Bay watershed. Parameter values are different at each gauging station because each subbasin has slightly different conditions. When applying those parameter values to ungauged subbasins, the average parameter value from gauged subbasins was applied as shown in Table 8 and Table 9. For example, the average value for GW_REVAP throughout all gauged subbasins in the Galveston Bay watershed was 0.07, so this value was applied to all ungauged subbasins. Some of the parameters did not noticeably impact flow (e.g., baseflow alpha factor), so they were not included in the parameters applied to the ungauged subbasins.

Comparison statistics examined included: total accumulated flow during the modeling period, monthly average flow, the correlation coefficient between SWAT and TxRR estimates, the slope-of-fit line, and Nash-Sutcliffe model efficiency.

Table 8. Parameter values for ungauged subbasins used in the Galveston Bay SWAT project

Variable	Description	Default Value	Input Value	Units
CN2	SCS runoff curve number	59 - 92	Increased by 5	
GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.07	
SOL_AWC	Soil available water	0.08 – 0.13	0.01	mm

Table 9. Parameter values for ungauged subbasins used in the Matagorda Bay SWAT project

Variable	Description	Default Value	Input Value	Units
GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.2	
ALPHA_BF	Baseflow alpha factor	0.048	0.04	$Days^{-1}$

Results

Daily streamflow

1) Streamflow at gauging stations

Table 10 summarizes daily streamflow calibration and validation results from gauged subbasins. Model performance statistics used to assess calibration efforts indicate that SWAT model estimates are acceptable, with a range of 0.496 to 0.736 for R^2 and NSE ranging from 0.372 to 0.643 for both watersheds. Validation results, however, did not correlate well, ranging from 0.261 to 0.489 for R^2 and from -0.736 to 0.312 for NSE. One possible explanation for the poor validation results is that land use may have changed dramatically, particularly for Galveston Bay watershed, since 2001 when the land use dataset was created. As expected, correlation for the validation period was worse in Galveston Bay watershed than Matagorda Bay watershed due to the fact that a much larger portion of Galveston Bay watershed has urbanized since the 1970s while Matagorda Bay watershed has experienced relatively little change in land use.

Table 10. Model performance in estimating daily flow (calibration and validation)

Watershed	Station #	Subbasin #	Calibration		Validation	
			R^2	NSE	R^2	NSE
Galveston Bay Watershed	08067650	4	0.676	0.636	0.287	0.024
	08070000	5	0.496	0.418	0.289	-0.515
	08070500	7	0.667	0.372	0.267	-0.123
	08070200	12	0.630	0.469	0.263	-0.696
	08068500	15	0.645	0.558	0.340	-0.039
	08068090	17	0.651	0.581	0.261	-0.736
Matagorda Bay Watershed	08164300	1	0.636	0.582	0.451	0.244
	08164350	3	0.736	0.643	0.489	0.312

*NSE: Nash Sutcliffe model efficiency

Differences between observed and modeled daily streamflow, averaged over the entire model period at each gauging station, range from -6.5% (08067650) to +43% (08068090) with an average difference of +9.9% (Table 11). Standard deviations between observed and modeled daily flow are similar.

Table 11. Daily streamflow for the entire model period

Watershed	Station #	Subbasin #	Daily average flow (ft^3/s)		Standard deviation	
			Obs.	Mod.	Obs.	Mod.
Galveston Bay watershed	08067650	4	536.9	501.5	1936	1989
	08070000	5	268.4	264.9	890	971
	08070500	7	91.8	98.9	357	470
	08070200	12	314.3	385.0	1038	1279
	08068500	15	332.0	321.4	1247	1392
	08068090	17	667.5	960.7	2790	3045
Matagorda Bay watershed	08164300	1	144.8	137.7	908	975
	08164350	3	183.7	222.5	915	1148

Monthly flow

1) Streamflow at gauging stations

Model performance analyses yielded much better results for monthly streamflow estimates (Table 12) than daily streamflow. For the calibration period, R^2 ranged from 0.647 to 0.916 while NSE ranged from 0.613 to 0.941. Model performance for the validation period ranged from 0.485 to 0.694 for R^2 and 0.461 to 0.772 for NSE. For the same reason given above, the correlation coefficient and NSE were lower for the validation period.

Table 12. Model performance on monthly streamflow calibration and validation

Watershed	Station #	Subbasin #	Calibration		Validation	
			R^2	NSE	R^2	NSE
Galveston Bay Watershed	08067650	4	0.916	0.906	0.670	0.772
	08070000	5	0.761	0.672	0.693	0.632
	08070500	7	0.693	0.613	0.485	0.558
	08070200	12	0.830	0.836	0.694	0.628
	08068500	15	0.647	0.714	0.520	0.616
	08068090	17	0.855	0.834	0.674	0.461
Matagorda Bay Watershed	08164300	1	0.859	0.882	0.665	0.703
	08164350	3	0.861	0.941	0.632	0.627

*NSE: Nash Sutcliffe model efficiency

2) Total terrestrial inflow to the bays

Total terrestrial inflow estimates to both Galveston and Matagorda bays, as developed by TWDB (using TxRR), were compared with SWAT model estimates. Annual average flow and monthly flow statistics are summarized in Table 13. Flow from the undelineated subbasins was estimated using the sum of average flow from subbasins 51 and 52 (see the Project Setup/Watershed Delineation section under Methodology), and it was added to total inflow. The total average flow from both subbasins was 621.6 ft^3/s, which is about 3.3% of total terrestrial inflow.

In Galveston Bay the difference in average annual inflow between TWDB (using TxRR) and SWAT is 1,221,519 ac-ft, with the SWAT model estimating greater inflow of 13,756,795 ac-ft per year (9.7%). The difference in average annual inflow for Matagorda Bay is 20,533 ac-ft, with the SWAT model estimating greater inflow of 4,273,940 ac-ft per year (0.5%). The monthly correlation coefficients, 0.950 (Galveston) and 0.886 (Matagorda), have a slope-of-fit line that is close to 1, showing that the two estimates agree well. Figure 7 and Figure 9 show a comparison of monthly terrestrial inflows to the bay for each watershed, and Figure 8 and Figure 10 compare the accumulated monthly terrestrial inflow to each bay.

Table 13. Comparison of flow estimates between TWDB, using TxRR, and SWAT

Period: 1977 – 2005	Galveston Bay		Matagorda Bay	
	TxRR	SWAT	TxRR	SWAT
Annual average flow (ac-ft)	12,535,276	13,756,795	4,253,407	4,273,940
Monthly Correlation coefficient	0.950		0.886	
Slope-of-fit line	0.996		0.833	

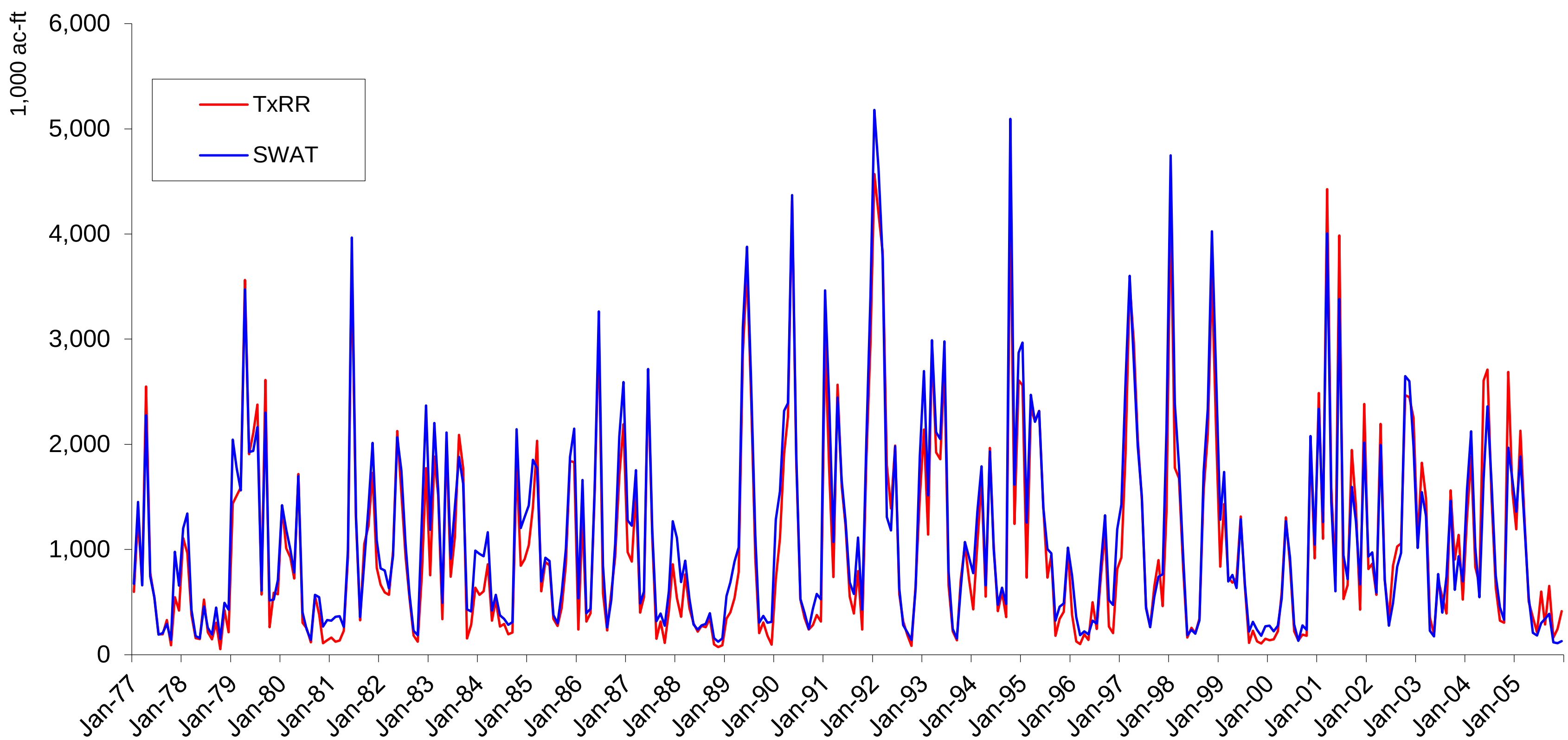

Figure 7. Monthly inflow estimation for Galveston Bay

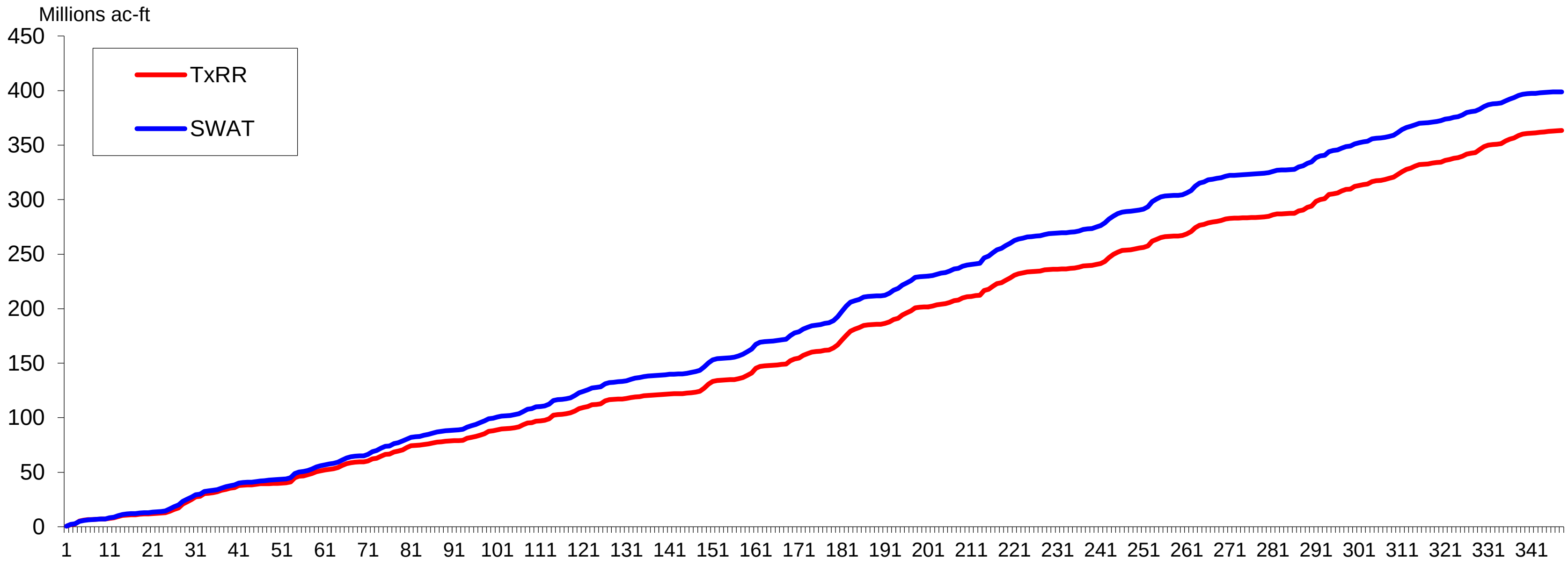

Figure 8. Accumulated monthly inflow to Galveston Bay

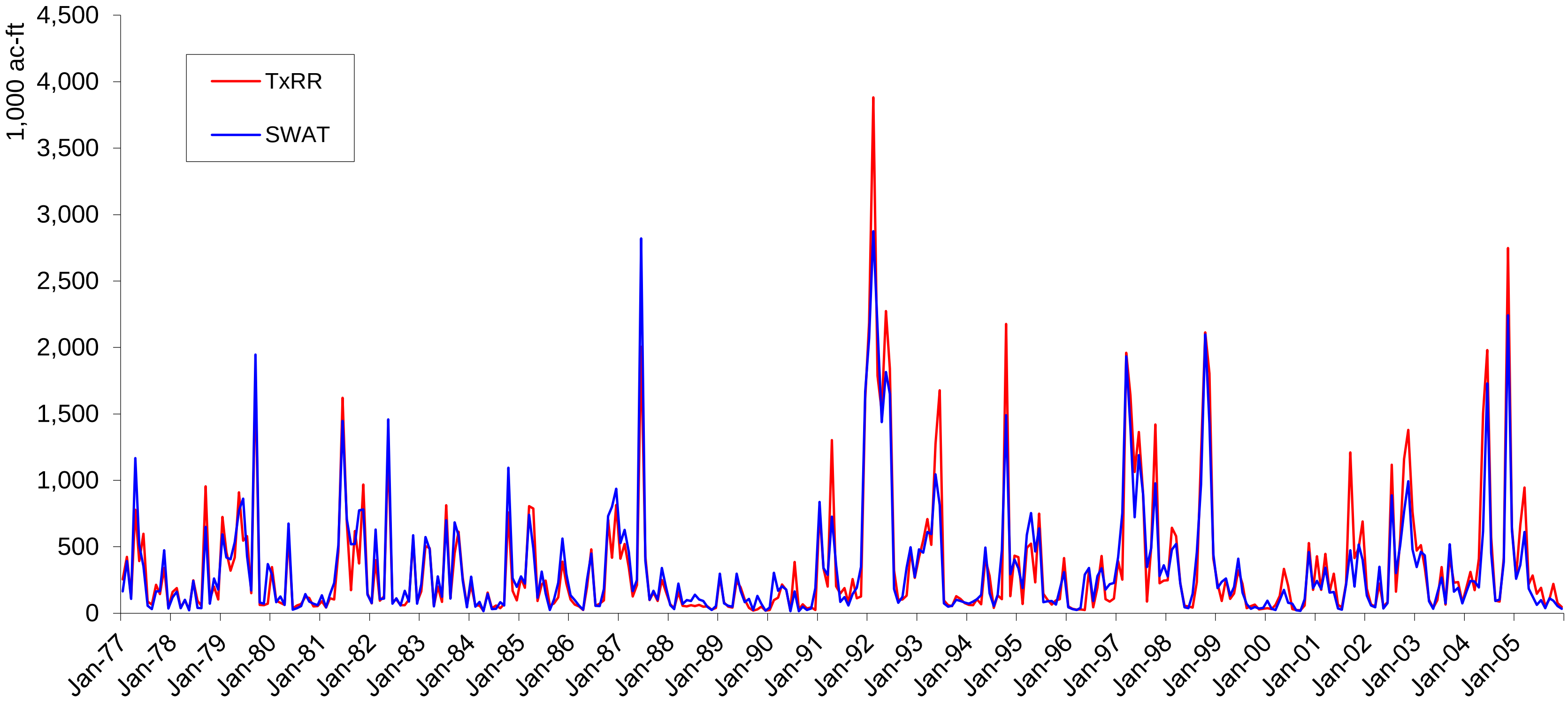

Figure 9. Monthly inflow estimation for Matagorda Bay

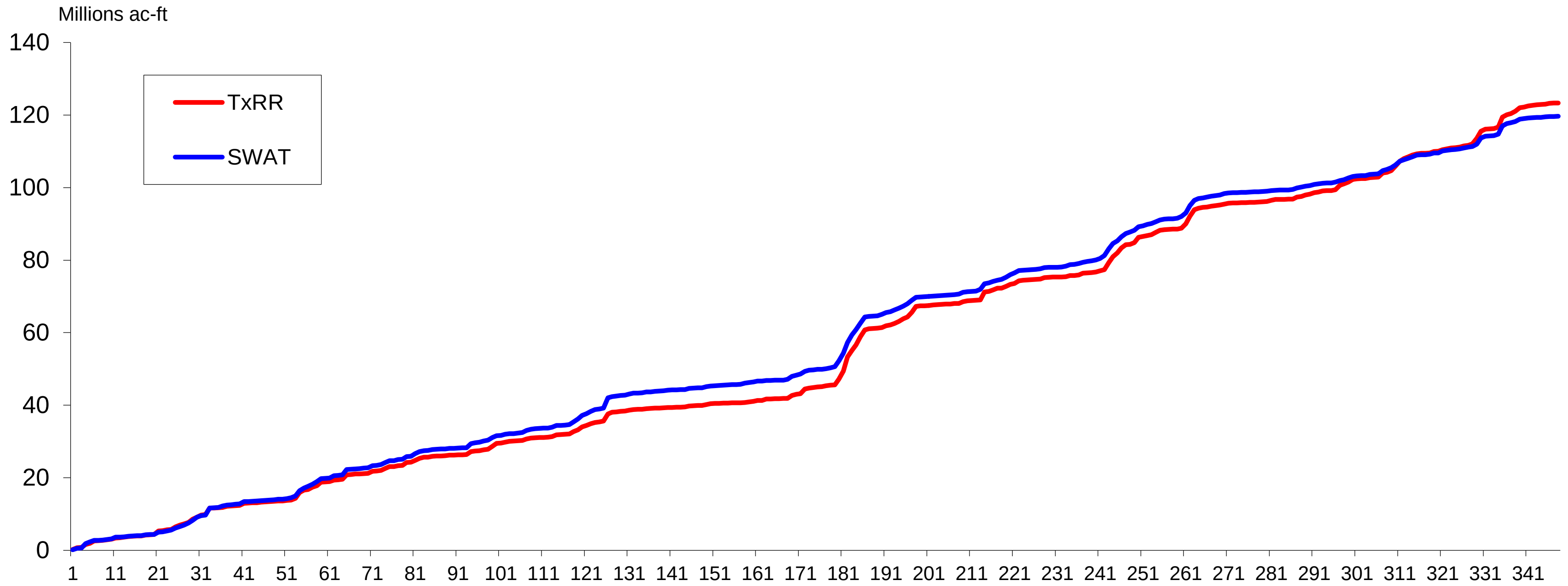

Figure 10. Accumulated monthly inflow to Matagorda Bay

Conclusion

This study was conducted to develop SWAT models for Galveston and Matagorda bays and to test SWAT's ability to estimate terrestrial inflow to the bays. In gauged subbasins, SWAT was calibrated for streamflow at USGS gauging stations, and the SWAT-estimated total output from each subbasin was compared to terrestrial inflow estimates generated by TWDB using the TxRR model.

Using the most recent GIS datasets, SWAT is capable of estimating flow, sediment, and nutrients at various temporal scales with automatic data processes. For both Galveston and Matagorda bay watersheds, two separate projects were set up. Calibration was conducted for subbasins that were upstream from available gauging stations. Then, the same parameter settings were applied to the remaining subbasins in order to compare bay inflow with previous estimates developed by TWDB using TxRR.

Daily streamflow calibration at each gauging station showed acceptable correlation, with R^2 ranging from 0.496 to 0.736 and NSE ranging from 0.372 to 0.643. However, during validation, NSE and R^2 did not show good agreement, with R^2 values ranging from 0.261 to 0.489 and NSE values from 0.736 to 0.312. A possible explanation is that the land use data created in 2001 may not have accurately represented the validation period, which included the 1970s and 1980s. This explanation also accounts for the larger inflow estimated for Galveston Bay watershed where major urbanization occurred. A comparison between observed and modeled monthly streamflow showed much better agreement. During calibration, R^2 ranged from 0.647 to 0.916, and NSE ranged from 0.613 to 0.941. During validation, R^2 ranged from 0.485 to 0.694 and NSE ranged from 0.461 to 0.772. Furthermore, SWAT and TWDB monthly total inflow estimates agreed well. SWAT estimated that the average annual inflow to Galveston Bay was 13,756,795 ac-ft while TxRR estimated 12,535,276 ac-ft. The correlation coefficient between the two monthly estimates was 0.950. For Matagorda Bay, SWAT estimated an average annual inflow of 4,273,940 ac-ft, and TxRR estimated 4,253,407 ac-ft. The correlation coefficient was 0.886.

Based on the results of this study, the SWAT model successfully estimated inflow to both bays. There are several advantages of the SWAT model over TxRR. First, SWAT estimates streamflow at a finer spatial and temporal resolution, which allows users to examine flow output at a particular subbasin on a particular day. Second, based on the models developed in this study, SWAT can estimate sediment and nutrient loading from each subbasin as well as total loading of the bay. Third, SWAT is capable of building and evaluating scenarios including, but not limited to, BMPs, point source removal, land use change, and climate change. Finally, using similar methodology and model setting, SWAT can be applied to other Texas coastal watersheds. Both reason two, three and four should be considered for future work.

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