TECHNICAL NOTE:

ESTIMATION OF FRESH WATER INFLOW TO BAYS FROM GAGED AND UNGAGED WATERSHEDS

T. Lee, R. Srinivasan, J. Moon, N. Omani

ABSTRACT. *The long-term estimation of fresh water inflow to coastal bays is important for understanding and managing estuarine coastal ecosystems. The Texas Water Development Board (TWDB) has estimated the total fresh water inflow to bays in Texas using the TxRR (Texas Rainfall-Runoff) model, which is a simple rainfall-runoff relation model. Recently, TWDB requested to develop and apply the SWAT model using up-to-date technologies for estimating inflow to the bays.*

Two watersheds were selected for a pilot study; one represents an urbanized watershed draining into Galveston Bay (Galveston watershed) and the other represents a rural watershed draining into Matagorda Bay (Matagorda watershed). Two separate SWAT models were developed, one for each watershed. Weather data from weather stations were enhanced and adjusted using NEXRAD (Next Generation Radar) precipitation data.

Model calibration and validation was conducted using daily flow observations from USGS stream gage stations (gaged) and the same parameter settings were applied to the rest of the watersheds (ungaged). The total fresh water inflow to the bays by the SWAT model was compared to the estimation by the TxRR model. The daily streamflow calibration at each gage station showed an acceptable coefficient of determination (r^2) ranging from 0.496 to 0.736 with Nash-Sutcliffe coefficient (NS) ranging from 0.372 to 0.643. The correlation and NS for model validation, however, did not show a good agreement and the possible explanation can be applying recent landuse data for model runs for earlier years. The monthly streamflow estimation showed much better agreement between observed and modeled flows; r^2 for calibration ranged from 0.647 to 0.916 and NS ranged from 0.613 to 0.941. The correlation for validation ranged from 0.485 to 0.694 for r^2 and from 0.461 to 0.772 for NS. The comparison of the SWAT and TxRR models' estimation showed a good agreement in monthly total inflow to the bays. The coefficient of determination between the monthly estimations in the Galveston and Matagorda watersheds by the two models was 0.948 and 0.900, respectively.

Keywords. *Inflow to bay, Large watershed, SWAT, TxRR, Ungaged watershed.*

Fresh water inflow to bays supports natural and economical benefits including aquatic life, market activities, and recreation. The estimation of fresh water inflow to coastal bays for quality, quantity, and its temporal variation is important to understand coastal hydrology and help future management. The Texas Water Development Board (TWDB) has made efforts to estimate the quantity and quality of fresh water and analyze the role of the fresh water in Texas (Longley, 1994). They have been using the Texas Rainfall-Runoff (TxRR) model (Matsumoto, 1992), which predicts inflows to the bays based on the Soil Conservation Service Curve Number method (SCS-CN). Recently, TWDB requested the application of the Soil and Water Assessment Tool (SWAT) model for estimating surface inflows to the bays with up-to-date technology and data. Accordingly, this project was initiated to develop and apply the model to estimate fresh water inflow to two Texas estuaries as a pilot study and to evaluate the model performance as compared to the TxRR model presently in use by the TWDB. This transition of modeling framework will help to estimate the total amount of incoming water to the bays using more recent and reliable data and technology with finer spatial and temporal resolution. In this study, the daily and monthly fresh water inflow to the bays from two watersheds (Galveston Bay and Matagorda Bay Watershed) was estimated. The amount of fresh water inflow from both the SWAT and TxRR models in this study included surface runoff and base flow eventually entering to the bays and did not include any diverted and return flow to and from agricultural, municipal, and industrial usage.

The objectives of this study were; first, to apply the SWAT model using up-to-date technology such as Geographic Information System (GIS) data and Next Generation Radar (NEXRAD) weather data for two watersheds – Galveston Bay Watershed as an example of urbanized watershed and Matagorda Bay Watershed as an example of rural watershed;

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second, to calibrate and validate the model based on gaged sub-watersheds and apply their parameter settings to ungaged sub-watersheds; and third, to evaluate the accuracy and applicability of the SWAT model performance on estimating the total quantity of fresh water inflow to the bays as compared to the estimate by the TxRR model.

Materials and Methodology

Study Area

Galveston Bay and Matagorda Bay watersheds are located in the southeastern coastal area of Texas in the United States (fig. 1). Both watersheds drain into their respective estuaries which are connected to the Gulf of Mexico. Galveston Bay watershed was selected as an urbanized watershed, and Matagorda Bay Watershed was selected as a rural watershed. The total drainage area of the Galveston and Matagorda watersheds is approximately 16,100 and 11,600 km^2, respectively. The Galveston Bay watershed in this study was delineated mainly by the San Jacinto River with some of the Trinity River sub-watersheds included (fig. 1), which was based on watershed delineation guidance provided by TWDB. The Galveston Bay watershed includes the city of Houston and its metro area (population of about 6 million). The Matagorda Bay watershed was delineated mainly by the Tres Palacios River though some sub-watersheds were included for the Colorado River on the right side of watershed, which also was guided by TWDB.

SWAT

The SWAT model (Arnold et al., 1998) is a physically-based, continuous simulation model developed for a watershed assessment of short- and long-term hydrology and water quality. The model requires extensive input data, which can be aided by GIS data and interface (Di Luzio et al., 2002). The model divides watersheds into a number of sub-watersheds and adopts the concept of the hydrologic response unit (HRU), which represents the unique property of each parameter such as landuse, soil, and slope. The SWAT model is able to simulate rainfall-runoff based on separate HRUs which are aggregated to generate output from each sub-watershed. The SWAT model is a combination of a series of modules including water flow and balance, sediment transport, vegetation growth, nutrient cycling, and a weather generator. The SWAT model can establish various scenarios detailed by different climate, soil, and land cover as well as agricultural activity schedule including crop plant, tillage, and Best Management Practices (BMPs). In this study, ArcSWAT version 2.3.4 was used.

Data

National Elevation Dataset (NED) at 30-m resolution was obtained from Natural Resources Conservation Service (NRCS) Data Gateway website (NRCS, 2009). Digital elevation dataset was used for automatic delineation of watershed boundaries and channel networks. Elevation in both Galveston and Matagorda Bay watersheds ranges from -0.3 to 180 m. The elevation near the coastal area is mostly flat, and the average slope of the Galveston Bay and Matagorda Bay watersheds is 0.99% and 0.61%, respectively.

National Landcover Dataset (NLCD) created in 2001 also was obtained from the NRCS Data Gateway website. While a more recent version of landuse data was available, the landuse data in 2001 was considered and used because the model simulation in this study is for historical period 1975. The percentage of each landuse category is summarized in table 1. The largest landuse types in the Galveston Bay watershed are urban (23.8%) and pastureland (21.9%). In the Matagorda Bay watershed, on the other hand, pastureland takes the largest portion (43.9%), nearly half of entire watershed.

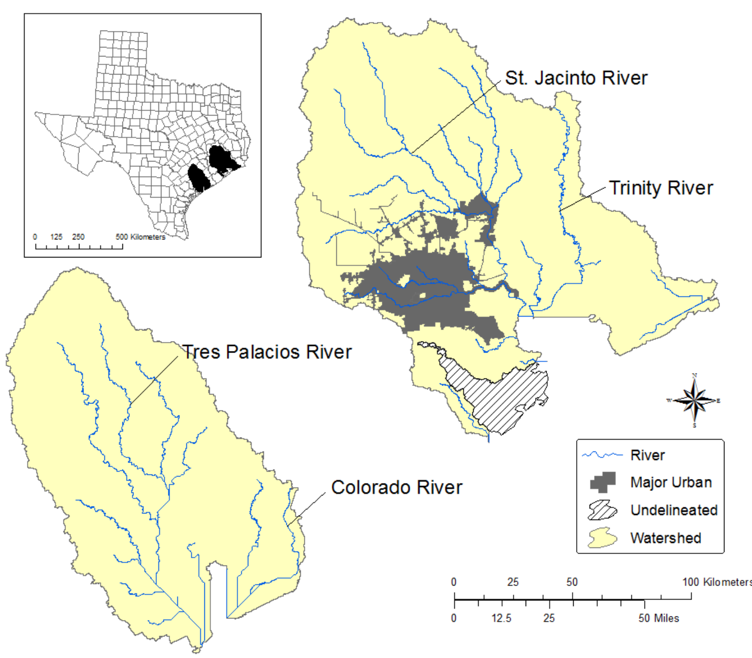


Figure 1. Galveston Bay and Matagorda Bay watersheds. There was an area that the SWAT model was not able to delineate at selected 15,000-ha maximum drainage area threshold.

Table 1. Landuse categories as determined by the National Landcover Dataset (2001) in each watershed.

Landuse Type	Watershed	
	Galveston (%)	Matagorda (%)
Water	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

SSURGO (Soil Survey Geographic) data was obtained from the NRCS Data Gateway as a shape file and was converted to GRID format at 30-m resolution. SSURGO data for soil was used and the major soil types in the Galveston Bay watershed are Lake Charles (clay) and Bernard (clay loam); they cover 10.0% and 7.7%, respectively, of total watershed area. In the Matagorda Bay watershed, Ligon (loam, 20.7%) and Dacosta (sandy clay loam, 11.5%) are the major soil types.

For HRU generation in the SWAT model, the threshold that is represented as percentages of each landuse and soil type was set up at 5%; meaning any landuse area more than 5% of a subbasin area was considered as an HRU and from that portion of landuse, any soil type area more than 5% was considered as an HRU. This threshold was set up to avoid creating too many HRUs which would cause this to be a time-consuming process.

Weather data including precipitation and temperature (minimum and maximum) were collected from the National Climate Data Center (NCDC) website (NCDC, 2009) for weather stations within and near the watersheds during the period of 1970 to 2008. Other weather parameters including solar radiation, wind speed, and relative humidity were simulated by WGEN (Weather Generator), which is embedded in the SWAT model. There are a total of 20 weather stations used in this study (11 in the Galveston watershed and 9 in the Matagorda watershed). When there was missing data, ranging from a couple of days to months, data from the nearest weather station was used. In the case, there were only a couple of days of missing temperature data and temperatures were estimated by linear estimation between the last and the next available day.

Stream gage station data was obtained from USGS (United States Geological Survey). There were a total of 21 stations available in both watersheds. Among those stations, only eight stations for the Galveston watershed and three stations for the Matagorda watershed were used (fig. 2). All other stations were eliminated because they either had too much missing data or were located in a minor tributary and could not be analyzed.

Gage station 08066500 and 08162500 were used as inlets to the model for the Galveston and Matagorda watersheds, respectively. Station 08066500 was for the inlet to the Galveston watershed from the Trinity River (Romayor, Tex.), which is the northeast corner of the Galveston watershed. Station 08162500 was for the inlet to the Matagorda watershed from the Colorado River (Bay City, Tex.), which is in the east corner of the Matagorda watershed. Stream flow data from those two gage stations was input into the model, because the upper watershed (above this gage station) was not included in this study. The number of total gage stations used for model calibration, therefore, is six gage stations in the Galveston watershed, and two gage stations in the Matagorda watershed.

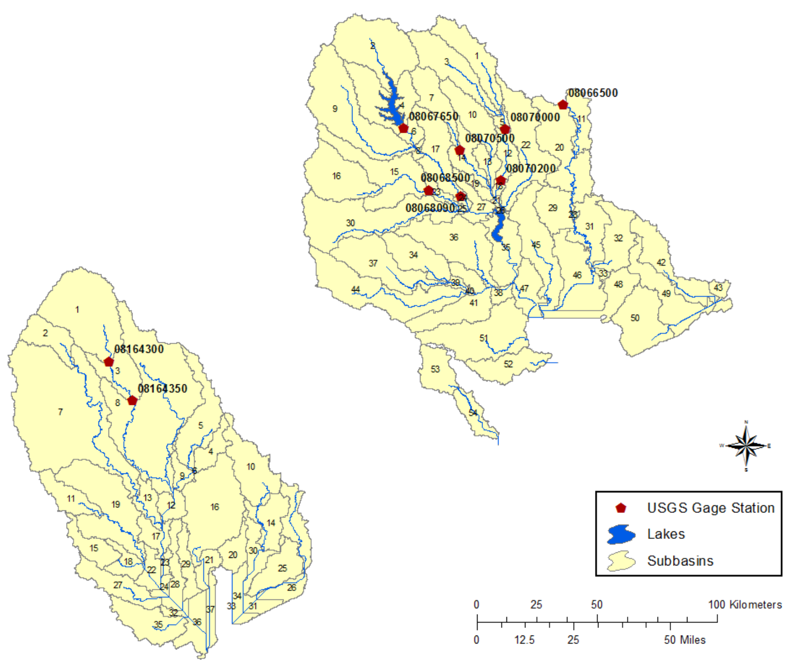


Figure 2. Sub-watersheds and USGS gage stations used in both watersheds. Only six gage stations in the Galveston watershed and two gage stations in the Matagorda watershed were used due to the data availability.

Project Set up

Two separate projects were set up for each watershed in SWAT. Model run period was from 1975 to 2008 including two years of model warm-up period (1975-1976). All GIS data used in the SWAT model was projected to Albers Equal Area with North American 1983 for datum.

Watershed Delineation

Each watershed and sub-watershed was delineated using a DEM in the SWAT model. Maximum drainage area thresholds for Galveston and Matagorda Bay watersheds were set at 15,000 and 10,000 ha, respectively, in order to match the sub-watershed maps provided by TWDB. A part of the Galveston Bay watershed was not delineated (fig. 1), because the SWAT model was not able to delineate such a flat area using the 15,000-ha threshold. In order to delineate those sub-watersheds, a much lower threshold should be used, but would result in too many sub-watersheds throughout the rest of the watershed. The flow from this undelineated watershed was estimated from the sub-watersheds near the area similar in size (sub-watershed 51 and 52, fig. 2) and the flow from those sub-watersheds was added on to the total inflow to the bay to fill the gap.

NEXRAD Enhanced Weather Data

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

Data from weather stations were adjusted and enhanced by NEXRAD from 2000 to 2008. NEXRAD data is available from 1995 in most areas but there was an accuracy issue for data from 1998 to 1999 (Jayakrishnan et al., 2004). Therefore, weather data used in this study was a combination of weather station data before 2000 and NEXRAD-enhanced weather data after 2000.

Lakes

Two lakes, Lake Conroe and Lake Houston, were set up as reservoirs in the Galveston Bay SWAT project (fig. 2). The parameter values used in the Galveston Bay SWAT project are summarized in table 2. Lake Conroe began operation in January 1973, and Lake Houston began operation in April 1954. Reservoir parameters, such as operation starting month/year, surface area, and volume of water to fill up the principle spillway, were obtained by personal communication with the San Jacinto River Authority and the city of Houston. Lake Houston does not have an emergency spillway.

Table 2. Information for two lakes in the Galveston Bay watershed which were used as SWAT input.

Lake Information	Lake Conroe	Lake Houston
Operation begins	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

Model Calibration and Validation

Calibration and Validation for Each Gage Station

Daily stream flows estimated by the model from 1977 to 2008 (32 years) were manually calibrated and validated against available USGS gage stations (fig. 2 and table 3) using a split-sample approach, where the later years were selected for calibration and the earlier years were selected for validation. The later years were selected for validation because the landuse used in this study was for the year of 2000, which may have discrepancy from the years in the beginning of the model period. These gage stations are located in the upper or middle of watershed and no gage stations are available at the outlet. The flow data from those gage stations had various time periods and are summarized in table 3. For statistical analyses for the calibration and validation, coefficient of determination and Nash-Sutcliffe model efficiency (NS) (Nash and Sutcliffe, 1970) were examined.

Tables 4 and 5 list the parameters and their default and adjusted value range for streamflow calibration for both watersheds. In both watersheds, base flow and ground water were the main factors to be adjusted. The range of parameter values indicates that different values were used for each gage station. For example, 'soil available water' parameter was 0.05 mm in the calibration for a gage station and 0.5 mm for other gage station.

Table 3. USGS gage station data and the period of calibration and validation. [a]

Watershed	Gage 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

[a] Calibration period was selected for the latter half of entire data period.

Table 4. Parameter values for streamflow calibration (gaged sub-watersheds) in the Galveston Bay watershed.

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	1-5	h
SOL_AWC	Soil available water	0.08-0.13	0.05-0.5	mm

Table 5. Parameter values for streamflow calibration (gaged sub-watersheds) in the Matagorda Bay watershed

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

Fresh Water Inflow to the Bays

The calibrated parameter settings were applied to the ungaged sub-watersheds where no gage stations were available, thus no calibration was able to be conducted. Some parameters values shown in tables 4 and 5 have ranges because each gaged sub-watersheds had a different condition and a different parameter setting was applied. For example, ground water re-evaporation coefficient (GW_REVAP) ranged from 0.15 to 0.2 for the Galveston watershed and 0.02 to 0.2 for the Matagorda watershed. The average for each parameter from the calibration was applied to ungaged sub-watersheds in order to estimate total surface inflow to the bays.

Fresh water inflow to Galveston and Matagorda bays was calculated in a way that each flow output from the SWAT model (there were multiple outlets in each watershed) was summed for each watershed and compared with the fresh water inflow estimation by TWDB using the TxRR model. The TxRR model estimation used here was the sum of recorded gaged flow and estimated flow by TxRR for ungaged sub-watersheds. However, the SWAT model estimation was all modeled flow from both gaged and ungaged sub-watersheds. Agricultural, industrial, and municipal return flow and diverted flow were not included in this modeling study.

RESULTS

DAILY STREAM FLOW

Daily stream flow calibration and validation results at gaged sub-watersheds are summarized in table 8. Model performance for calibration indicates that the SWAT model estimations are acceptable with the range of r^2 from 0.496 to 0.736 while NS ranged from 0.372 to 0.643 for both watersheds. Validation results, however, did not show a good correlation, with a range between 0.261 and 0.489 for r^2 and -0.736 and 0.312 for NS. The possible explanation is that the landuse data used in this study was created for 2001 and the landuse may have been dramatically changed, particularly for the Galveston watershed. The correlation was worse for the validation period in the Galveston watershed than in the Matagorda watershed because there was much more landuse alteration (e.g. urbanization) in the Galveston watershed since the 1990s, while there was not much change in landuse in the Matagorda watershed. Those landuse alterations may have interfered and changed hydrology including infiltration, surface runoff, channel routing, and groundwater.

MONTHLY FLOW

Stream Flow at Gage Stations

Statistical analyses for model performance were much better for monthly streamflow estimates (table 9) than daily streamflow. For the calibration period, r^2 ranged from 0.647 to 0.916 while NS ranged from 0.613 to 0.941, while model performance for the validation period ranged from 0.485 to

Table 6. Parameter values for ungaged sub-watersheds in the Galveston Bay watershed.

Variable	Description	Default Value	Input Value	Units
GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.17	
GWQMN	Groundwater storage required for return flow	0	1,000	mm
ALPHA_BF	Baseflow alpha factor	0.048	0.1	$days^{-1}$
SURLAG	Surface runoff lag time	4	1-5	h
SOL_AWC	Soil available water	0.08-0.13	0.1	mm

Table 7. Parameter values for ungaged sub-watersheds in the Matagorda Bay watershed.

Variable	Description	Default Value	Input Value	Units
GW_REVAP	Groundwater re-evaporation coefficient	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

Table 8. Model performance on daily flow for calibration and validation.

Watershed	Station No.	Calibration		Validation	
		R^2	NS[a]	R^2	NS
Galveston Bay watershed	08067650	0.676	0.636	0.287	0.024
	08070000	0.496	0.418	0.289	-0.515
	08070500	0.667	0.372	0.267	-0.123
	08070200	0.630	0.469	0.263	-0.696
	08068500	0.645	0.558	0.340	-0.039
	08068090	0.651	0.581	0.261	-0.736
Matagorda Bay watershed	08164300	0.636	0.582	0.451	0.244
	08164350	0.736	0.643	0.489	0.312

[a] NS: Nash Sutcliffe model efficiency.

Table 9. Model performance on monthly streamflow calibration and validation.

Watershed	Station No.	Calibration		Validation	
		R^2	NS[a]	R^2	NS[a]
Galveston Bay watershed	08067650	0.916	0.906	0.670	0.772
	08070000	0.761	0.672	0.693	0.632
	08070500	0.693	0.613	0.485	0.558
	08070200	0.830	0.836	0.694	0.628
	08068500	0.647	0.714	0.520	0.616
	08068090	0.855	0.834	0.674	0.461
Matagorda Bay watershed	08164300	0.859	0.882	0.665	0.703
	08164350	0.861	0.941	0.632	0.627

[a] NS: Nash Sutcliffe model efficiency.

0.694 for r^2 and 0.461 to 0.772 for NS. For the same reason as daily estimation, the coefficient of determination and NS was lower for the validation period.

Total Surface Inflow to the Bays

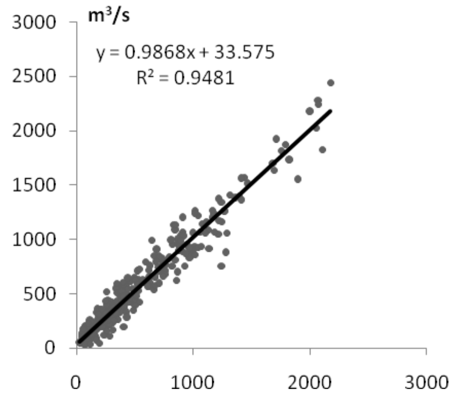
Total surface inflow estimation to both Galveston Bay and Matagorda Bay by SWAT was compared to the estimation by the TxRR model in order to determine the applicability of the SWAT model for fresh water estimation in the coastal bays. Again, the TxRR model estimates in this study was the sum of recorded gage flow and model estimates for ungaged sub-watersheds by TxRR. Annual average flow and statistics including standard deviation, coefficient of determination, and slope of fit line for both watersheds are summarized in table 10. The flow from undelineated watersheds in the Galveston Bay watershed was estimated as the flow from sub-watershed 51 and 52, and the flow was added into the total inflow to the bay as mentioned earlier.

For Galveston Bay, the annual average estimation of the TxRR and SWAT models was 497.5 and 524.5 m^3/s, respectively, where the SWAT model estimated flow 7.3% larger than the TxRR model. The SWAT model's annual estimation for Matagorda Bay was 163.8 m^3/s, which was 1.5% larger than the TxRR model estimation (161.3m^3/s). The difference between the estimation by two models was much larger in the Galveston watershed than in the Matagorda watershed. The reason seems to be more dramatic changes of landuse by urbanization in the Galveston watershed during the past couple of decades, while the model used landuse data created in 2001 as mentioned earlier. Another possible reason for the discrepancy can be explained by overestimation by the SWAT model that used the parameter settings from gaged sub-watersheds to apply them to ungaged sub-watersheds. However, the parameters in the model were adjusted mostly to reduce over-estimated groundwater during the calibration, thus, parameter adjustment helped to reduce total inflow to the bays while the SWAT model still over-estimated the total inflow. Therefore, applying parameter settings to ungaged sub-watersheds in this study may not be the reason for discrepancies although ungaged sub-watersheds are unknown and uncertain. The coefficient of determination (r^2), however, shows good agreement between the two estimates, 0.948 and 0.900, respectively, with 0.987 and 0.861 for the slope of fit line for each watershed, although a paired t-test showed the mean change of monthly estimation from both models is significantly different from 0 (p value < 0.01). Figure 3 shows

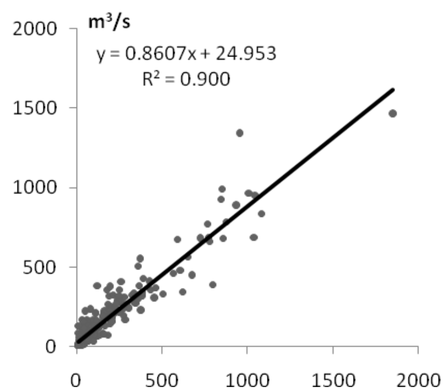
Table 10. Comparison of flow estimation between TxRR and SWAT.

Period: 1977-2005	Galveston Bay		Matagorda Bay	
	TxRR	SWAT	TxRR	SWAT
Annual average flow (m^3/s)	497.5	524.5	161.3	163.8
Standard deviation	449.4	455.5	236.4	214.5
Monthly coefficient of determination (r^2)	0.948		0.900	
Slope of fit line	0.987		0.861	

2001 and it may have not properly represented the validation period, which included the 1970s and 1980s. The monthly streamflow estimation showed better agreement between observed and modeled flows, where r^2 for calibration ranged from 0.647 to 0.916 and NS ranged from 0.613 to 0.941. The correlation for validation ranged from 0.485 to 0.694 for r^2 and from 0.461 to 0.772 for NS. The comparison of the SWAT and TxRR model's estimation showed a good agreement in monthly total inflow. The average annual inflow to Galveston Bay was estimated at 497.5m^3/s by the SWAT model and at 524.5m^3/s by the TxRR model. The coefficient of determination between the monthly estimations by two models was 0.948 with the slope of fit line at 0.987. For Matagorda Bay, the average annual inflow was estimated at 161.3m^3/s by the SWAT model and at 163.8m^3/s by the TxRR model. The coefficient of determination between two models was 0.900 with the slope of file line at 0.861. The SWAT model constantly over-estimated than the TxRR model and the difference between these models was larger in the Galveston watershed because the landuse dataset created in 2001 was used for this estimation. The urbanization in the Galveston watershed has changed the landuse much more dramatically than in the Matagorda watershed. Overall, however, this study demonstrated the successful application of the SWAT model to estimate the inflow to both bays.



(a) Galveston Bay watershed



(b) Matagorda Bay watershed

Figure 3. Scatter plots for monthly inflow estimation at each watershed.

monthly scatter plots between the SWAT and TxRR model's estimation for each watershed.

Conclusion

This study was conducted for the application of the SWAT model to estimate fresh water inflow to Galveston Bay and Matagorda Bay. The daily flow calibration was conducted for available USGS gage stations for upstream sub-watersheds from each station. The model was then validated and their parameter settings were extended to ungaged sub-watersheds. The output of each watershed from the SWAT model was compared to the fresh water inflow estimation conducted by TWDB using the TxRR model.

The daily stream flow calibration at each gage station showed an acceptable coefficient of determination (r^2) ranging from 0.496 to 0.736 with NS ranging from 0.372 to 0.643. The correlation and NS for validation, however, did not show a good agreement, with values ranging from 0.261 to 0.489 for r^2 and from -0.736 to 0.312 for NS. The possible explanation is that the landuse data was created in and for

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