Hydrologic Modeling of a Canal-Irrigated Agricultural Watershed with Irrigation Best Management Practices: Case Study

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Abstract: Simulating irrigation systems by accounting for various water loss rates is necessary while modeling the hydrology of cultivated canal-irrigated watersheds. The existing approaches to modeling canal irrigation use situation-specific optimization procedures. In addition, they are focused on a water management perspective rather than a hydrologic perspective. In this study, an approach is developed to model canal irrigation systems and irrigation best management practices (BMPs) to adequately simulate the water balance of irrigated watersheds. The approach is based on the water requirement of crops, number and frequency of irrigation, and critical crop water requirement stages. Two irrigation BMPs are modeled as water savers rather than physical changes in irrigation appurtenances. Land leveling is modeled by changing model parameters and water management by changes in frequency, timing, and magnitude of irrigation with respect to cumulative precipitation. The developed approach was tested with a 1,692 km^2 intensively cultivated, canal-irrigated watershed using the Soil and Water Assessment Tool (SWAT). Test results suggest that the approach captures water balance and observed runoff hydrograph of the study area adequately. **DOI: 10.1061/(ASCE)HE.1943-5584.0000364.**

CE Database subject headings: Irrigation; Best Management Practice; Water management; Streamflow; Canals; Hydrology; Agriculture; Case studies.

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Introduction

A good understanding of irrigation systems and a proper representation of them in watershed models are required to adequately capture the irrigation return flows when modeling the hydrology of irrigated watersheds. Throughout the world, a wide variety of canal water distribution procedures exist. A monthly or daily schedule of water delivered to each field receiving irrigation is not available anywhere to incorporate it for modeling purposes. Therefore, the next alternative is to use a model to simulate irrigation systems. Modeling the amount and delivery of irrigation water, particularly in large canal systems, is much more complex and difficult than commonly recognized (Ramesh et al. 2009).

Most canal models use some kind of optimization procedure (Santhi et al. 2000, 2005; Ghumman et al. 2006; Ramesh et al. 2009; Lecina et al. 2005; George et al. 2004) such as linear programming. The canal models in general require extensive knowledge of programming and hydraulics, cumbersome to work with and developed for some special situations (Burt et al. 1993). These models also require data such as canal dimensions, canal roughness, and information on seepage, which are very difficult to obtain in most cases. Simple models that focus on hydrologic aspects (amount of flow, irrigation timing and frequency) rather than hydraulics are very sparse. Simulating canal irrigation systems and the capture of irrigation return flows were important to adequately capture the stream flow and water balance for the present study.

The study area is intensively cultivated and irrigated. Water for irrigation is taken from the Rio Grande and moved to the fields through a network of gravity flow canals, ditches, and underground pipelines. Numerous irrigation districts, which are units of government, manage the water distribution. The districts set their own policies and procedures for allocating water. To order water from an irrigation district, the farmers are required to pay a flat fee and submit their name, field, water account number, and the crops planted (water ticket) (Fipps and Pope 1998). Depending on the availability of water in the river and the demand from farmers, water will be allocated to their fields. With a few exceptions, most of the irrigation districts have poor conveyance efficiencies, and therefore lose a lot of water (Fipps and Pope 1999). Irrigation practices consist of flooding the fields with a certain depth of water (depending on the crop) during insufficient rainfall. Modeling this type of water diversion requires a lot of data.

For the same study area (as this study), an attempt was made by Raines and Miranda (2002) to include the water diverted for irrigation in the water balance. It involved development of a monthly irrigation time series on the basis of a set schedule for irrigation (including depth, frequency, and number of irrigations). The irrigation time series is estimated on the basis of annual crop needs for a wet, normal, or dry year and quantity of water. Conveyance efficiency was also considered while incorporating the water diversion information in the Hydrologic Simulation Program-Fortran (HSPF)

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model. However, this approach did not adequately capture the irrigation return flows, and therefore an alternate approach is followed for this study.

After developing the SWAT model setup for the study area (more details in the forthcoming sections of the paper), streamflow modeling was attempted. To model canal irrigation systems present in the watershed, the autoirrigation option available in the model was used to model irrigation of crops. A sensitivity analysis was carried out to identify the most sensitive parameters for flow calibration. Subsequent to sensitivity analysis, a calibration was attempted to match the predicted flow values with that of daily mean observations (the procedure used was the same as that outlined in the following sections of this article). The calibrated predicted results from the model exhibited a complete mismatch in the pattern, timing, and magnitude when compared with the observations ($> 50\%$ underestimation of flows, negative R^2 values with less than 20% Nash and Sutcliffe efficiency). An analysis of model input and results were made to identify the reasons for the mismatch in results. Depth, frequency, and timing of irrigation modeled by the autoirrigation option (already available in the model) were extracted and compared with the information available from the field data, literature, and reports. They exhibited large differences. The depth, frequency, and timing of irrigation modeled by autoirrigation were very different than what might be happening in reality. Moreover, autoirrigation was filling the soil layers just up to field capacity. This may not be accurate in the case of flood irrigation to fields with canals and ditches. The aforementioned factors caused the mismatches between predicted and observed streamflow. Therefore, to adequately model streamflow for the study area, a better procedure than autoirrigation was needed. This prompted the authors to develop an approach to model canal irrigation and incorporate it to simulate the hydrology of the study area. This paper presents the approach developed to model canal irrigation systems, some irrigation best management practices, and the subsequent stream flow modeling.

Methods and Materials

Study Area

The study area is the Arroyo Colorado watershed, which is located in the Lower Rio Grande Valley of south Texas in parts of Hidalgo, Cameron, and Willacy counties (Fig. 1). It is a subwatershed of the Nueces-Rio Grande Coastal basin, also known as the South (Lower) Laguna Madre Watershed (Hydrologic Unit Code 12110208). It is a 1,692 km^2 agricultural watershed with intensive cultivation. Most of the cultivated area receives irrigation from the Rio Grande through a network of canals, ditches, and pipes under a system of irrigation districts. Irrigation practices consist of flooding fields with a specified depth of water during periods of insufficient precipitation to produce desired crop yields. Perennial stream flow in the Arroyo Colorado is primarily sustained by effluent from municipal wastewater treatment plants. Irrigation return flow and point-source discharges supplement the flow on a seasonal basis. The Arroyo Colorado is used as a floodway, an inland waterway, and a recreational area for swimming, boating, and fishing, and it is an important nursery and foraging area for numerous marine species. Urbanization is extensive in the areas directly adjacent to the main stem of the Arroyo Colorado, particularly in the western and central parts of the basin. Principal urban areas include the cities of Mission, McAllen, Pharr, Donna, Weslaco, Mercedes, Harlingen, and San Benito (Rains and Miranda 2002; Rosenthal and Garza 2007).

The most dominant land cover category in the watershed is agriculture (54%), and the main crops cultivated are grain sorghum, cotton, sugar cane, and citrus, although some vegetable and fruit crops are also raised. Most of the cultivated area is irrigated. The watershed soils are clays, clay loams, and sandy loams. The major soil series comprise the Harlingen, Hidalgo, Mercedes, Raymondville, Rio Grande, and Willacy (Brown et al. 1980). Most soil depths range from about 1,600 to 2,000 mm.

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

Description of Simulation Model

The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993) is a conceptual continuous simulation model developed to quantify the impact of land management practices on surface water quality in large watersheds (Gassman et al. 2007; Neitsch et al. 2004) (http://www.brc.tamus.edu/swat). It provides a continuous simulation of processes such as evapotranspiration, surface runoff, percolation, return flow, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing, field drainage, crop growth, and material transfers (soil erosion, nutrient and organic chemical transport, and fate). The model can be run with a daily time step, although a subdaily model run is possible with the Green and Ampt infiltration method. It incorporates the combined and interacting effects of weather and land management (e.g., irrigation, planting and harvesting operations, and the application of fertilizers, pesticides, or other inputs). SWAT divides the watershed into subwatersheds using topography. Each subwatershed is divided into hydrological response units (HRUs), which are unique combinations of soil and land cover. Although individual HRUs are simulated independently from one another, predicted water and material flows are routed within the channel network, which allows for large watersheds with hundreds or even thousands of HRUs to be simulated.

SWAT Model Setup of Arroyo Colorado Watershed

The Arc View SWAT interface-extended version (AVSWAT-X) is used for preparing the SWAT model setup of Arroyo Colorado. For delineation of the watershed boundary, a 30-m USGS digital elevation model (DEM) was used. A digitized stream network and a watershed boundary from the previous HSPF modeling study (Rains and Miranda 2002) were used as supporting information for the delineation of the watershed and stream network for the present study. A threshold of 1,600 ha is used for adequate delineation of the stream network. The watershed was eventually discretized into 17 subwatersheds.

Spatial Sciences Lab of Texas A&M University at College Station, using satellite data and a field survey, prepared the land cover map. The map incorporates the present land cover conditions (2004–2007) in the watershed. Crop rotation, irrigation, and dates of planting are also available with the land use map on a farm or field basis. The dominant land cover categories in the watershed are agriculture (54%), range (18.5%), urban (12.5%), water bodies (6%), and sugarcane (4%), although some vegetable and fruit crops are also raised. The soil survey geographic database (SSURGO) soil map was downloaded from USDA Natural Resources Conservation Service (NRCS) for Cameron, Willacy, and Hidalgo counties. The soil properties associated with a particular soil type is derived using the SSURGO soil database tool available with the AVSWAT-X interface. HRUs were delineated on the basis of a

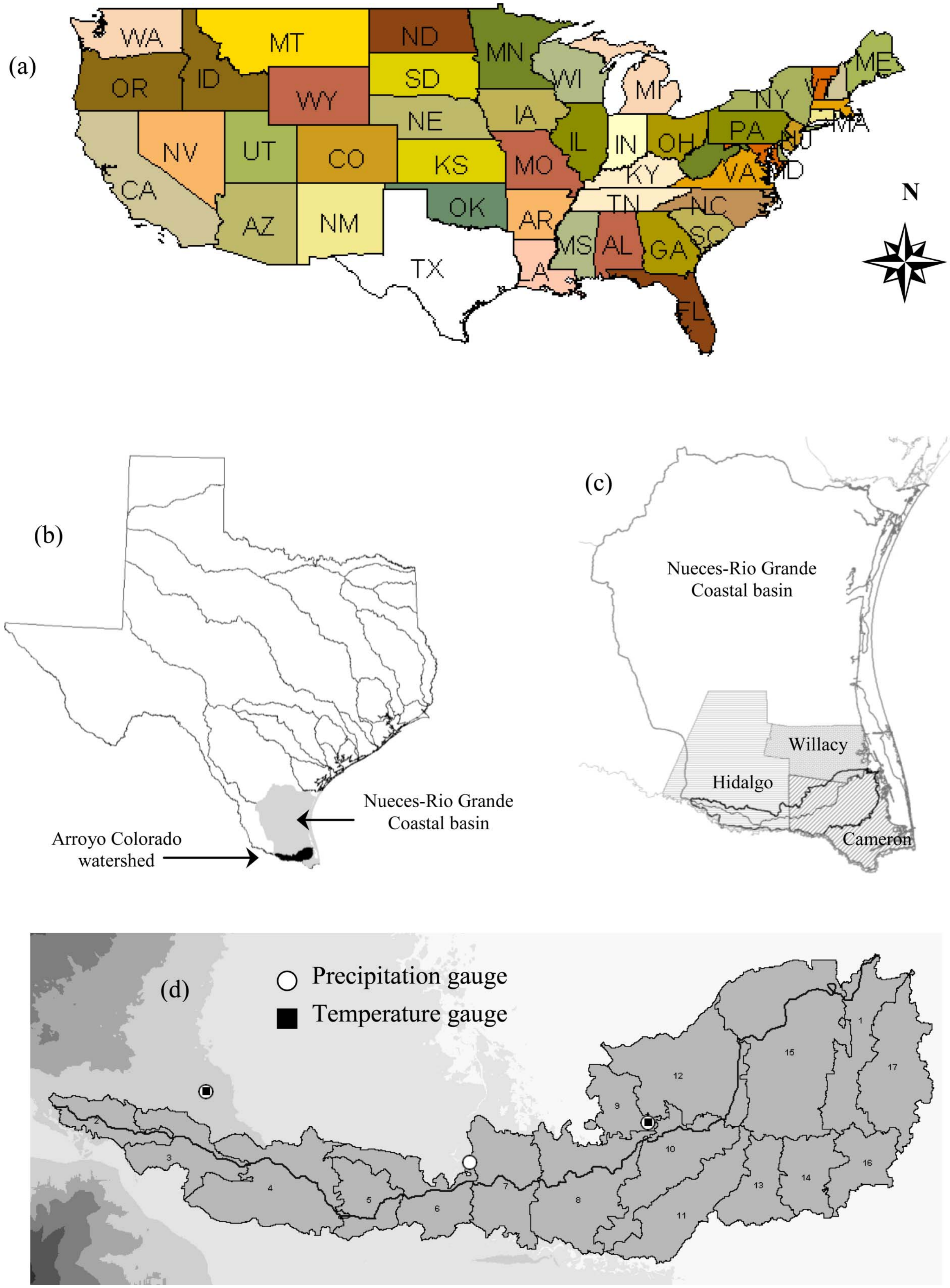

Fig. 1. Location of study area

combination of land use and soil. Thresholds of 2 and 6% were used for land use and soil, respectively, because capturing the variation in land use was more important than soil. Equally, a smaller threshold could have been used for soil as well, which could have resulted in many more HRUs than the present 475 HRUs. In the present delineation, areas as small as 9.1 ha (22.5 acres) are represented as HRUs.

The land use map came up with the information on crop rotation, irrigation, and dates of planting. However, the information was lost after reclassification of the land use map in the format

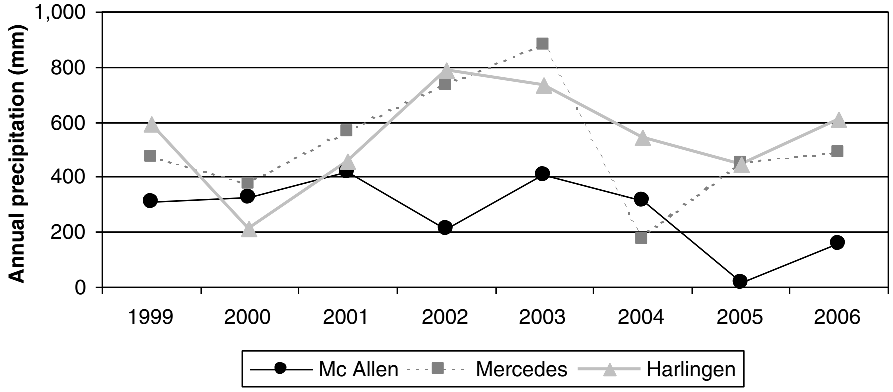

Fig. 2. Variation of annual precipitation in the watershed

required for the SWAT model. Therefore, the reclassified land use map and the original land use map were intersected [in Arc View geographic information system (GIS)]to have all the land-use–related information together. After this, the crop rotation for a particular HRU is allotted using the following procedure:

1. Every cultivated land parcel is associated with a crop rotation information,
2. More than one land parcel exists for a HRU within a subbasin (same combination of land use and soil can occur in different parts of the subbasin),
3. Area of land parcels with similar crop rotation are added together to estimate the total area that comes under a particular crop rotation, and
4. All the different crop rotations were sorted on the basis of total area; the crop rotation with the maximum area was allotted to the HRU as the crop rotation for the HRU.

Dates of planting were obtained from the land use map. The duration of crops were obtained from crop fact sheets from Texas A&M Extension publications on the basis of what tentative harvest dates are identified for each crop (Stichler and McFarland 2001; Trostle and Porter 2001; Stichler et al. 2008; Vegetable Team Production 2008; Wiedenfeld and Enciso 2008; Wiedenfeld and Sauls 2008). Dates of harvest collected during visits to the watershed were used along with the preceding information. Typically, there are two tillage operations (in conventional tillage) for each crop, one soon after the harvest of the previous crop and the other midway between the harvest of the previous crop and the planting of the present crop. In conservation tillage, one tillage operation (mostly soon after harvest of the previous crop) or no tillage operation is performed (Andy Garza, Texas State Soil and Water Conservation Board, Harlingen, personal communication). All the management operations such as tillage, planting, and harvest were scheduled on nonrainy days (in reality, these operations were less likely to have happened on rainy days). Irrigation of crops will be discussed in the subsequent sections of the paper.

Table 1. Observations Available for Calibration and Validation

Parameter	Data availability		
Precipitation	McAllen	Mercedes	Harlingen
Temperature	McAllen		Harlingen

Observations Used

Seven years (2000–2006) of daily mean observations of precipitation, air temperature, and stream flow were used for model calibration and validation. Precipitation data from three stations were used (Figs. 1 and 2); temperature data from two stations were used (Table 1). The weather data were obtained from Texas State Climatologist Office located at Texas A&M University at College Station. Stream flow data for two stations were obtained from International Boundary and Water Commission one near Llano Grande at FM 1,015 south of Weslaco (G1) and the other near US 77 in southwest Harlingen (G2). There are 21 permitted dischargers in the Arroyo Colorado Basin: 16 are municipal, three are industrial, and two are shrimp farms. The discharge permit limits of the municipal plants range from 1.5 to 37.8 million L (0.4 to 10 million gal.) per day. The shrimp farms discharge infrequently (Rains and Miranda 2002).

Irrigation of Crops

Tentative quantity, timing, and frequency of irrigation required for major crops (e.g., sorghum, cotton, and sugar cane) were obtained from NRCS and the Texas State Soil and Water Conservation Board (TSSWCB) staff in the watershed. Crop fact sheets published by Texas A&M Extension were also collected to estimate the irrigation information for the crops (Table 2) (Stichler and McFarland 2001; Trostle and Porter 2001; Cruces 2003;

Table 2. Frequency, Timing, and Amount of Irrigation for Different Crops in the Watershed

Crop	Total water requirement, mm (in.)	Number of irrigations	Critical crop growth stages needing irrigation	Irrigation requirement (days after planting)
Sorghum	458 (18)	3	1 week before booting, 2 weeks past flowering	30, 60, 84
Cotton	508 (20)	3	Stand establishment, prebloom, shortly after boll set	25, 56, 94
Sugarcane	1,270 (50)	7	Establishment, grand growth, ripening	75, 105, 145, 190, 235, 275, 305
Corn	508 (20)	3	Tasseling, silking, kernel fill	48, 70, 95
Citrus	1,143 (45)	6	Prebloom, flower bud induction, fruit set, cell expansion, ripening	65, 100, 135, 195, 250, 320
Sunflower	304 (12)	2	20 days before flowering, 20 days after flowering	45, 85
Onion	635 (25)	3	Stand establishment, bulb initiation, maturity	15, 60 (if dry), 90, 115, 135

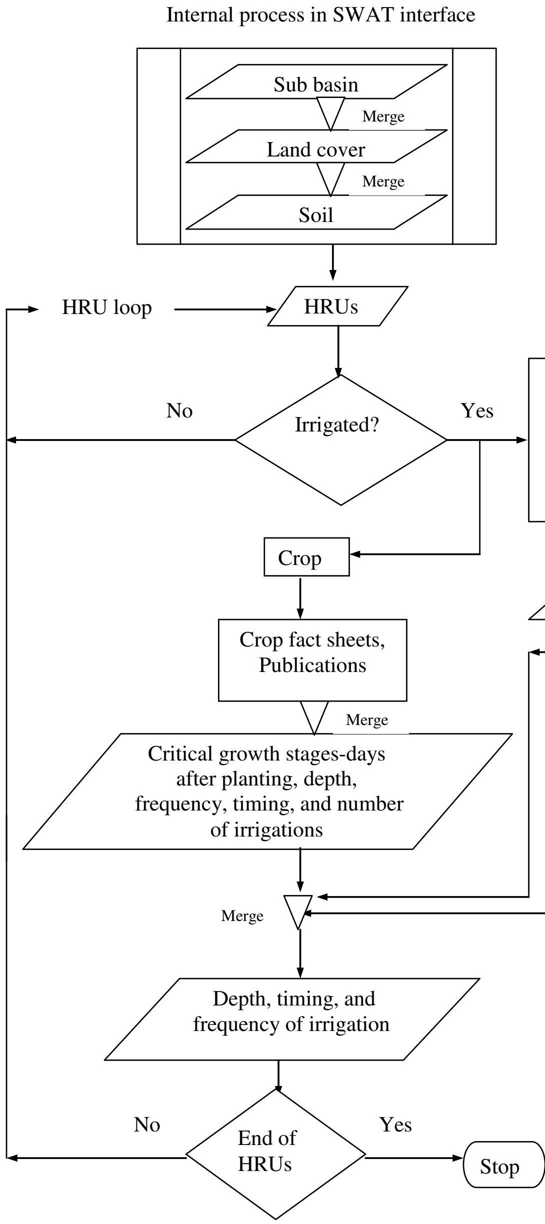

Fig. 3. Modeling canal irrigation in the watershed model setup

Fipps 2005; Stichler et al. 2008; Vegetable Team Production 2008; Wiedenfeld and Enciso 2008; Wiedenfeld and Sauls 2008). To model canal irrigation, the following procedure is used. Land cover map, soil map, and subbasin map were overlaid using GIS tools, and a comprehensive map was prepared that has all three types of information (HRU information). A HRU under agriculture land cover can be either irrigated or not irrigated. If irrigated, the model followed the canal irrigation procedure. Information on irrigation districts for the study area was available in the form of a map from the Irrigation Technology Center, Texas A&M University. In addition, the average water conveyance efficiency for each irrigation district was available separately. These data were combined and merged with the HRU map to identify the irrigation district that comes under each HRU. This has conveyance efficiency information for each HRU. For this study, conveyance efficiency includes all losses in the irrigation distribution system from river-water diversion to the fields. Knowing the conveyance efficiency with depth of water application for each irrigation for each crop, the tentative quantity of water that could have been diverted from the source for irrigating the crop can be estimated (Fig. 3). For estimating depth, duration, and frequency of irrigation, several publications and reports were referred to, and critical crop growth stages at which irrigation is essential were estimated. For scheduling irrigation in the model setup, the timings were estimated on the basis of probable days of irrigation (identified by looking at the daily water stress values reported by the model for the simulation that involves no irrigation event for any crop in any HRU) and the critical crop growth stages requiring irrigation as reported in the literature and field data.

Representing Irrigation Best Management Practices in the Watershed Model Setup

There are four irrigation practices that farmers adopt in this watershed, the details of which are given in the following sections. Collectively, these practices may be considered best management practices (BMPs) because of their potential to reduce both water conveyance losses and soil erosion. Simulation of these four BMPs within a watershed model setup is discussed in this section.

Irrigation Land Leveling (NRCS Practice Code 464)

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

Irrigation Water Conveyance, Pipeline (NRCS Practice Code 430)

The irrigation water conveyance, pipeline BMP is the installation of underground thermoplastic pipeline (and appurtenances) as a part of an irrigation system to replace canal lining. The decision to line a canal or replace the canal using a pipeline is often made on the basis of how much water is conveyed in the canal. In practice, small district irrigation canals or lateral canals with capacity less than 2.83 m^3/s (100 ft^3/s) will be replaced with pipeline. This BMP reduces water conveyance losses and prevents soil erosion or loss of water quality. Some of the design and planning considerations include working pressure, friction losses, flow velocities, and flow capacity. On average, this BMP can reduce water use by 11% [Texas Water Development Board (TWDB) 2005]. In a hydrologic modeling study involving a relatively large watershed, it is not practical to consider all the pipe network, irrigation appurtenances, and the associated pressure, friction losses, flow velocity, and capacity. Therefore, irrigation water conveyance, pipeline is modeled by increasing the conveyance efficiency of HRU (a random number between one and 11). In other words, the amount of water diverted to the field from the source is decreased.

Irrigation System-Surface Surge Valves

This BMP is often implemented to replace an on-farm ditch with a gated pipeline to distribute water to furrow irrigated fields. A surge irrigation system applies water intermittently to furrows so as to create a series of on-off periods of either constant or variable time intervals. The system includes butterfly valves or similar equipment that will provide equivalent alternating flows with adjustable time periods. Surge flow reduces runoff by increasing uniformity of infiltration and reducing the duration of flow as the water reaches the end of the field. It also increases the amount of water delivered to each row and reduces deep percolation of irrigation water near the head of the field. The amount of water saved by switching to surge flow is estimated to be between 10 and 40% (TWDB 2005) and is dependent on soil type and timing of operations. Physical representation and modeling of the operation of butterfly values for each field in a large watershed system will be tedious. Additionally, methods do not exist to model them from a hydrologic perspective. Therefore, irrigation system-surface surge valve are simulated by increasing the conveyance efficiency (by a random number between 10 and 40) while calculating the water diverted for irrigation.

Irrigation Water Management (NRCS Practice Code 449)

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

Assumptions and Limitations

In the study area, BMPs are located throughout the watershed, and they serve a smaller area, in general. In terms of SWAT model setup of Arroyo Colorado watershed, this implies that within a subbasin, BMPs exist in some, many, or all of the HRUs. Representing each BMP separately and analyzing the results is not practical. Instead, the collective area of each type of BMP within a subbasin with the same land cover (cultivated) is estimated and an HRU within the same subbasin (having the same land cover) having area approximately equal to the collective area of all BMPs is selected, and it is assumed that that particular HRU has all the BMPs of a certain type. This assumption is valid with the SWAT model configuration for which all the loads from an HRU are integrated at the subbasin level. The version of SWAT model used in this study will not spatially locate the HRUs within a subbasin. Therefore, the preceding assumption will capture the overall effect of BMPs within a subbasin. However, it will not capture the effect of BMP on individual HRUs (reality) where the crop rotation is different in each HRU. For water diversion to irrigate the crops in the watershed, unlimited supply of water from the source (Rio Grande) is assumed, which may not be the case in reality where the supply is affected by water availability, rainfall during the year, and evaporative and seepage losses.

The irrigation BMPs, if practiced on a cultivated land, will save water. Therefore, for the purpose of modeling, the irrigation BMPs are conceptualized as potential water savers instead of physical representation in terms pipes, surge valves, and management practices. In particular, the irrigation BMPs are represented in the model as an increase in conveyance efficiency or a decrease in water diverted from the source (Table 3). Although this is not a replacement for data for each field (which is not practical) for each year, this will adequately capture the collective effect of BMPs in the watershed. Although irrigation water management appears like three individual BMPs (involving magnitude, timing, and frequency of irrigation) it is modeled as a single BMP because the term "irrigation water management" collectively includes magnitude, frequency, and timing of irrigation.

Modeling Options Used

Daily model runs were made for this study. The NRCS curve number method [Soil Conservation Service (SCS) 1956] was used for

Table 3. Water Diverted for Irrigation with and without BMPs

Subbasin	Year	Crop	Water diverted without BMPs, mm (in.)	Water diverted with BMPs, mm (in.)
3	2001	Sugarcane	2,105 (83)	1,601 (63)
3	2002	Sugarcane	1,524 (60)	1,160 (46)
3	2003	Sugarcane	1,814 (71)	1,380 (54)
3	2004	Sugarcane	1,052 (41)	801 (32)
8	2000	Cotton	677 (27)	552 (22)
8	2001	Corn	677 (27)	552 (22)
8	2002	Cotton	677 (27)	552 (22)

Table 4. Model Parameters and Their Range Considered for Sensitivity Analysis

Parameter	Definition	File name	Range of values	
			Minimum	Maximum
ALPHA_BF	Base flow recession constant (days)	.gw	0.001	1
SURLAG	Surface runoff lag coefficient (days)	.bsn	0.001	15
AWC	Available water capacity	.sol	−50%[a]	+50%[a]
CH_K 1,2	Effective hydraulic conductivity of channel (mm/hr)	.rte, .sub	0.025	150
CH_N 1,2	Manning's n value for the main and tributary channels	.rte, .sub	0.01	0.07
CN2	SCS runoff curve number for moisture condition II	.mgt	−4.0[b]	+4.0[b]
EPCO	Plant uptake compensation factor	.hru	0.001	1
ESCO	Soil evaporation compensation factor	.hru	0.001	1
GW_DELAY	Delay time for aquifer recharge (days)	.gw	0.001	100
GW_REVAP	Groundwater revap coefficient	.gw	0.02	0.2
GWQMN	Threshold water level in shallow aquifer for base flow (mm)	.gw	0.01	100
Ksat	Saturated hydraulic conductivity (mm/h)	.sol	−50%[a]	+50%[a]
MUSK_CO1	Weighting factor for influence of normal flow on storage time constant value	.bsn	0.01	10
MUSK_CO2	Weighting factor for influence of low flow on storage time constant	.bsn	0.01	10
OVR_N	Manning's n value for overland flow	.hru	0.05	0.8

[a]Value varies with land use; changes by multiplying a ratio within the range.
[b]Value varies with land use; changes by adding/subtracting a value within the range.

modeling flow. Hargreaves evapotranspiration (ET) estimation method along with Muskingum channel routing procedure were used. Model simulation was made from 1999–2006 with one-year warm-up (1999) to initialize realistic values for various model parameters. Weather and flow data from 2000–2003 was used for calibration and from 2004–2006 for validation. The model warm-up period was restricted to one year because of limited availability of data. Longer periods of model warm-up (usually recommended) might have resulted in a different set of calibrated results. SWAT model source code was modified such that the soil layers can accept water until saturation during an irrigation event. This kind of change accepted the entire depth of irrigation water when modeled. This was not occurring when autoirrigation was used, which restricted the depth of irrigation until the field capacity of soils

Sensitivity Analysis

A sensitivity analysis was conducted to identify the model parameters sensitive to daily stream flow. The sensitivity was indexed, and the parameters with a high sensitivity index were used for calibration. The Latin hypercube sampling method incorporated with one-factor-at-a-time analysis technique (LHS-OAT) was used in this study. The LHS-OAT method is a highly efficient global method based on the Monte Carlo simulation, but it uses a stratified technique that reduces computational time (van Griensven et al. 2006). It subdivides each parameter into N intervals and assumes the parameter is uniformly distributed within each interval. Random values of the parameters are generated such that the parameter is sampled only once for each interval. The total number of model runs is $N * (K + 1)$, where N = number of intervals, and K = number of parameters.

On the basis of the literature review (Muleta and Nicklow 2005; Neitsch et al. 2004; Kannan et al. 2007; Di Luzio and Arnold 2004; Immerzeel and Droogers 2008), 15 parameters often used in calibrating flow were selected (Table 4) for the sensitivity test. The 15 parameters ($K = 15$) were divided into 10 intervals ($N = 10$) of equal probability. Therefore, a total of 160 model runs was made for the LHS-OAT sensitivity analysis. This is far better than the number of model runs required by a local method, where every possible combination of parameters is simulated.

In the OAT analysis method, the derivatives of the model output are calculated for each parameter (x_i) as a small perturbation (Δx_i) is added while other parameters are fixed. The change in the model output is entirely attributed to Δx_i. A sensitivity index, defined as a normalized change in the model output divided by a normalized change in the input parameter, is useful to facilitate a direct comparison of parameters (Wang et al. 2005):

$$S_{ij} = \frac{\frac{|M(x_1,\ldots,x_i+\Delta x_i,\ldots,x_K)-M(x_1,\ldots,x_i,\ldots,x_K)|}{M(x_1,\ldots,x_i+\Delta x_i,\ldots,x_K)+M(x_1,\ldots,x_i,\ldots,x_K)}}{|\Delta x_i|/x_i}$$

where S_{ij} = relative partial effect of parameter x_i around the Latin hypercube point j; K = number of parameters; and M = model output. In this study, M represents daily flow for the gauging station selected for sensitivity analysis. The partial sensitivity index values for x_i are averaged to get the final sensitivity index (S_i).

A public domain FORTRAN code developed by van Griensven and Meixner (2003) was adapted for this sensitivity analysis with the SWAT model. The sensitivity analysis uses the predicted stream flow during 2000–2003. In SWAT, many physically based parameters vary at the HRU level, and thus, a significant number of parameters need to be assessed for the sensitivity analysis, while each parameter has little influence on the model output. Therefore, these parameters were assessed in a clustered way by adding or multiplying relative changes to the default values [e.g., $-4 \sim +4$ for curve number condition 2 (CN2) or $-25 \sim +25\%$ for available water capacity (AWC)].

Table 5. Average Predicted Crop Parameters for the Watershed

Parameter	Irrigated		Rain fed	
	Sorghum	Cotton	Sorghum	Cotton
ET (mm)	417.6	463.1	147.8	260.0
Biomass (t/ha)	20.6	9.9	8.2	5.3
Leaf area index	2.7	3.8	2.3	2.7
Yield (t/ha)	9.3	4.6	3.7	2.4

Calibration

The parameters identified as sensitive to stream flow were divided into certain intervals, and a semiautomated calibration procedure was designed to do flow calibration. The calibration program runs for all the possible combination of parameters within the parameters used for calibration and the ranges considered. For example, if three parameters were used for calibration and each parameter has four possible values, then the total number of calibration model runs will be 64 ($4 \times 4 \times 4$). The calibration program has some built-in tools for calculating model performance measures [e.g., Nash and Sutcliffe Efficiency (Nash and Sutcliffe 1970), R^2, and mean absolute error] for each calibration model run. The combination of parameters that brought the best model performance was used for looking at the sediment and nutrient results.

Table 6. Model Performance Evaluation for Stream Flow

Period	Nash and Sutcliffe efficiency (%)	R^2	Mean (m^3/s) Predicted	Mean (m^3/s) Observed
G1 calibration	52.5	0.55	3.8	3.8
G1 validation	53.4	0.61	3.7	5.1
G2 validation	60.4	0.61	6.0	6.9
G2 validation	41.6	0.59	6.0	8.2

Results and Discussion

The developed approach for modeling canal irrigation adequately captured the timing and frequency of irrigation for different crops and therefore improved the daily stream flow predictions (this will be discussed subsequently in this section). In terms of quality, the newly developed approach is far better than using the autoirrigation option of the model and some of the other methods previously adopted for modeling the study area. The irrigation BMPs (except leveling) in this study are modeled as water savers rather than alterations in the irrigation distribution system. The average water savings (or less water diverted from the source) for each BMP modeled by this study vary widely. Example results for sugarcane in subbasin 3 and cotton And corn in subbasin 8 are given in Table 3. Both the subbasins have all four different types of irrigation BMPs discussed in this paper. On an average, 24% less water is diverted from the source for irrigating sugarcane in subbasin 3 by adopting irrigation BMPs. Similarly, about 18% less water is diverted from the source for irrigating corn and cotton in subbasin 8 with BMPs. The authors certainly cannot rule out the possibility of having different numbers for the percentage of water saved for these two example cases because of the nature of the approach adopted to model irrigation BMPs.

Sensitivity analysis results is the starting point of a detailed discussion on flow results. Out of the 15 flow-related parameters included for sensitivity analysis, only five of them were found most

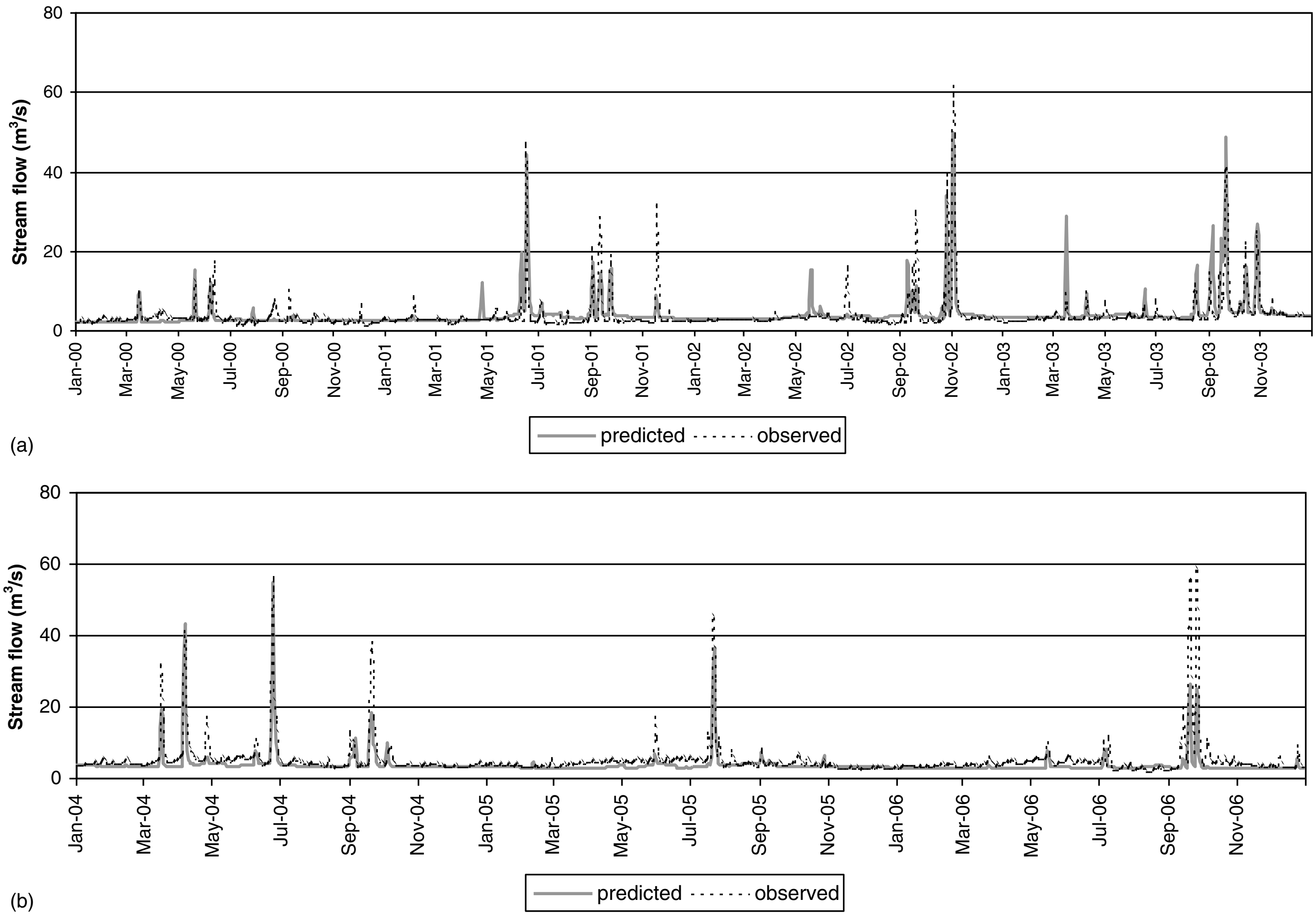

Fig. 4. (a) Daily stream flow for Arroyo Colorado near Llano Grande at FM 1015, south of Weslaco, calibration period; (b) daily stream flow for Arroyo Colorado near Llano Grande at FM 1015, south of Weslaco, validation period

sensitive. They were available water capacity (AWC), soil evaporation compensation factor (ESCO), plant evaporation compensation factor (EPCO), groundwater reevaporation coefficient (GWREVAP), and surface runoff lag factor (SURLAG). Therefore, they were included for calibration. Interestingly, CN2 was not sensitive for this watershed. The probable reason is CN2 affects surface runoff in the model. In the watershed, surface runoff is dominant during monsoon and rainy months, which is a short period during the year. During the major portion of the year, ET and subsurface flow dominate (e.g., base flow, irrigation return flows) the hydrology, and therefore, CN2 is not very sensitive, and the parameters that affect ET and subsurface flow are very sensitive.

With respect to water balance, on average, ET (645 mm) and stream flow (155 mm) account for about 800 mm of water per year (without considering minor losses such as deep aquifer recharge and channel transmission losses). Out of this 800 mm, 620 mm is compensated by precipitation and the rest (about 180 mm) by irrigation. This outlines the importance of irrigation in the water balance and the need for adequate representation of irrigation to crops in the watershed model setup. The predicted crop parameters from the model look reasonable (Table 5).

Predicted daily flow results after calibration are shown in Table 6 and Figs. 4(a) and 5(a) along with corresponding observations. In general, there is a close correspondence between predictions and observations during the calibration period [Fig. 4(a) and 5(a)]. This is further confirmed by acceptable values of model performance evaluation statistics (Moriasi et al. 2007) such as $R^2 > 0.5$ and a Nash and Sutcliffe efficiency of more than 50% and similar predicted and observed means (Table 6). The timing, pattern, and magnitude of the predicted runoff hydrograph closely follows the observed hydrograph for both stream flow gauges. However, in both the gauges, some of the small runoff events are overestimated, and some peaks are underestimated. Most of the overestimated small peaks occur during May, and there are some in March. There is a high possibility for irrigation events during these months. Therefore, the small overestimated events could have resulted from a sudden increase in modeled soil water values (because of irrigation) coupled with small precipitation events. The underestimated peaks could be improved but at the cost of overall increase in magnitude of the entire predicted hydrograph.

During the validation period, there is mostly underestimation of stream flow in both the gauges [Figs. 4(b) and 5(b)]. This could be explained by the fact that the validation years are dry with less rainfall when compared with the calibration period (Fig. 2). Problems with modeling dry years are already documented in some of the previous SWAT studies (e.g., Fohrer et al. 2001; Chanasyk et al. 2003; Bosch et al. 2004; Chu and Shirmohammadi 2004; Du et al. 2005). In reality, precipitation on a dry soil will sometimes result in appreciable runoff attributable to some soil sealing, crusting, and smearing. Dry years are likely to face these conditions, which are

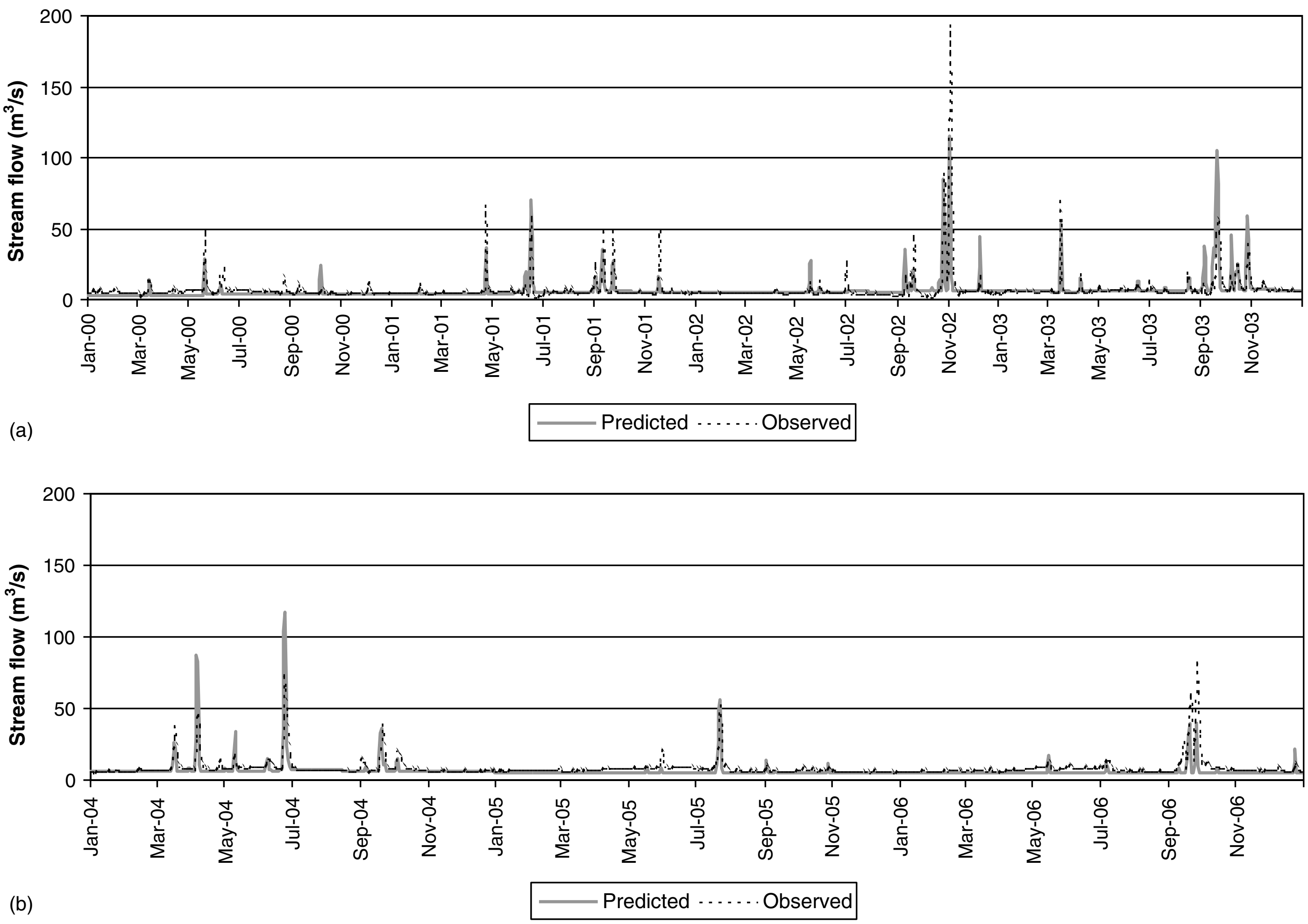

Fig. 5. (a) Daily stream flow for Arroyo Colorado near US 77 South, west of Harlingen, calibration period; (b) Daily stream flow for Arroyo Colorado near US 77 South, west of Harlingen, validation period

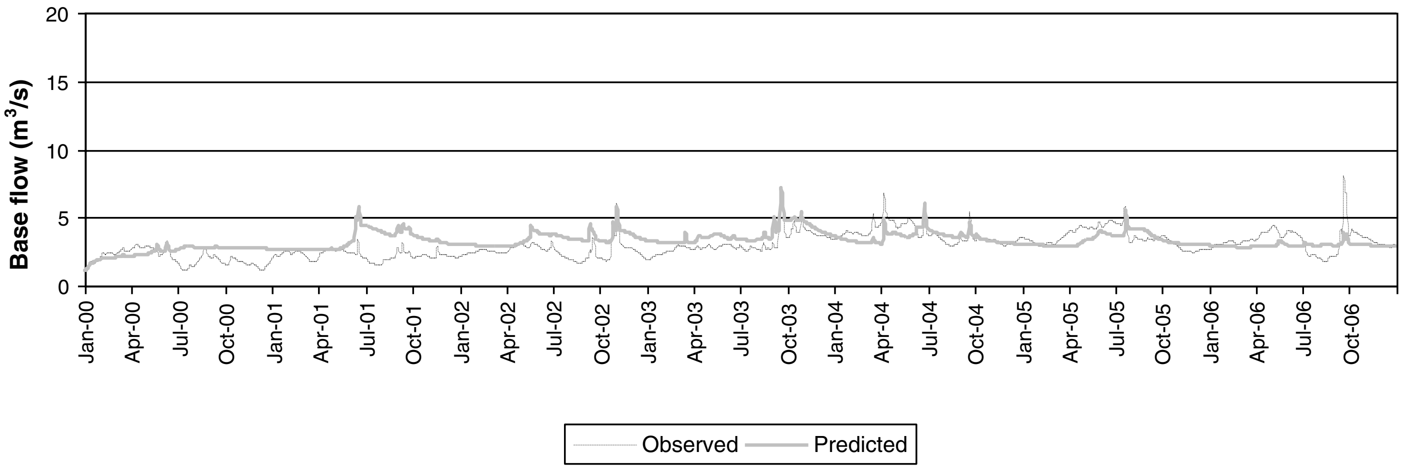

Fig. 6. Base flow for Arroyo Colorado near Llano Grande at FM 1015, south of Weslaco

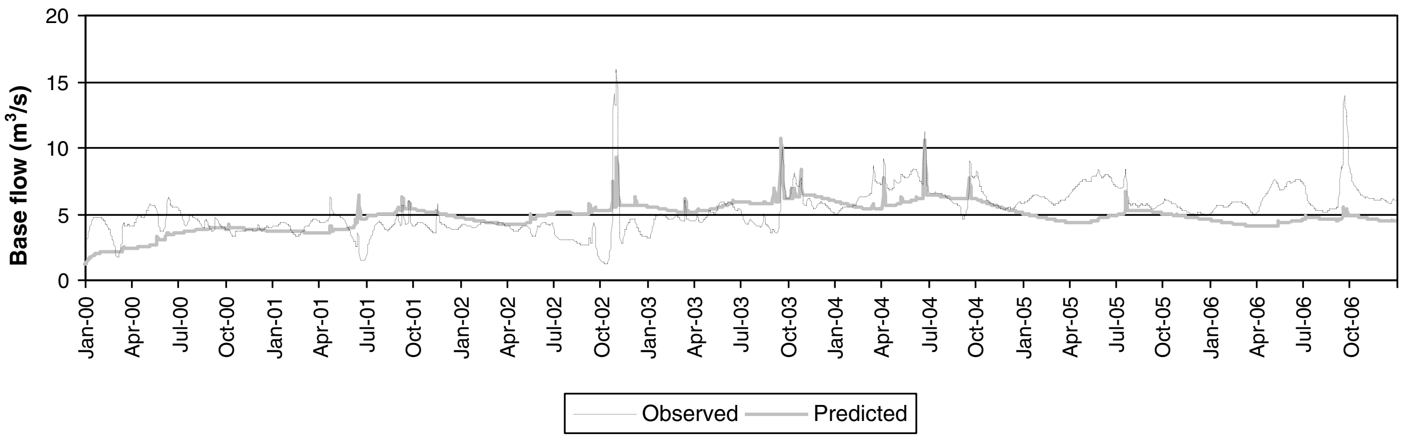

Fig. 7. Base flow for Arroyo Colorado near US 77 South, west of Harlingen

not simulated by the model. Therefore, underestimation of flow is likely in dry years. One particular event in the validation period during the end of September in year 2006 was very much underestimated. This occurs for both stream flow gauges. Attempts were made to improve the predicted flow of that particular event with parameterization. However, only marginal improvement was possible and that too was coupled with an overall increase in magnitude of the entire predicted hydrograph. A trade-off was made between overall model performance and improvement of the particular event during September 2006. Any incorrect crop rotation or omission of irrigation operations to some fields during that period might have caused the underestimation of flow for that event. However, the overall model performance during validation period is acceptable (Table 6).

Partitioning of flow into surface and subsurface components is also important when analyzing the hydrology of watersheds.

Table 7. Model Performance Evaluation for Base Flow

Period	Mean (m^3/s)	
	Predicted	Observed
G1 calibration	3.2	2.5
G1 validation	3.3	5.5
G2 calibration	4.5	4.3
G2 validation	5.0	6.3

Therefore, base flow was separated from both the predicted and observed stream flow using the same technique [an automated recursive digital filter technique developed by Arnold et al. (1995)] and compared for stream gauges located near Weslaco and Harlingen. They are shown respectively in Figs. 6 and 7. From Figs. 6 and 7 it can be observed that there are under- and overestimations of base flow for both gauges. However, the predictions are slightly better for the validation period. In both Weslaco and Harlingen, the base flow is overestimated during the calibration period and underestimated during validation (Table 7). The underestimation of base flow during the validation period is consistent with the underestimation of stream flow during the validation period. The largest mismatch of predicted and observed base flow occurs in September 2006 for both gauges. This should be responsible for the mismatch of stream flow during the same period (outlined previously in this section). The next largest mismatch of base flow occurs during June–July 2001 for the Mercedes gauge and during October–November 2002 for Harlingen. Parameterization did not help to improve these mismatches. Therefore, uncertainties in input could be attributed for these base flow mismatches. The Nash and Sutcliffe efficiency and the R^2 values associated with the base flow predictions are not as good as for stream flow. However, the magnitudes of predicted base flow are reasonably close to observed values. Given the uncertainties in many of the input variables, prediction of base flow at this level of accuracy is considered adequate for application of the flow-calibrated model for modeling water quality.

Summary and Conclusions

Hydrologic modeling of a 1,692 km^2 intensively cultivated, irrigated coastal watershed is carried out using SWAT. Distribution of water to crops by a canal irrigation system and adoption of irrigation best management practices are important parts of the watershed hydrologic system. Therefore, within the SWAT model setup, an approach was developed to model the canal irrigation system on the basis of water requirements of different crops, their critical crop growth stages, and the number of irrigations required as reported in existing literature and crop fact sheets. Irrigation land leveling was simulated by changing the slope and slope length of HRUs. Irrigation water management was simulated by changing the frequency and timing of irrigation in accordance with precipitation. The other two BMPs were modeled by decreasing the water diverted for irrigation (increase in conveyance efficiency). After inclusion of these, the model setup was calibrated using 4 years of daily data from the year 2000, after a sensitivity analysis to find the most sensitive parameters for calibration. The model performance evaluation was carried out to judge the quality of the hydrologic modeling results and the irrigation approaches used. The developed approaches for modeling canal irrigation and irrigation BMPs adequately predicted the irrigation return flows and the overall magnitude, timing, and pattern of hydrograph similar to observations; without them, there was a mismatch between predicted and observed hydrographs, suggesting the importance of adequate modeling of irrigation systems to capture the hydrology of cultivated-irrigated watersheds. The developed approaches for modeling canal irrigation and irrigation BMPs show great potential for application to similar cultivated watersheds with irrigation distribution systems.

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