A GIS-Based Regional Planning Tool for Irrigation Demand Assessment and Savings Using SWAT

C. Santhi, R. S. Muttiah, J. G. Arnold, R. Srinivasan

Abstract. *Regional planning for irrigated agriculture requires a thorough understanding of the hydrological processes and spatial and temporal variations associated with hydrological factors such as rainfall, soils, and crops grown in different units of the region. The objective of this study was to improve the capabilities of a basin−scale hydrologic simulation model for regional planning of irrigated agriculture. In this study, a Geographical Information System (GIS) based hydrological model, Soil and Water Assessment Tool (SWAT), was configured as a regional planning tool with a canal irrigation capability for estimating irrigation demand. The tool was capable of simulating hydrological processes associated with soil−plant−water interactions and capable of capturing the spatial and temporal variability of the major factors, which are important in regional planning. The tool was applied to the irrigation districts in the Lower Rio Grande Valley in Texas. It was validated for crop evapotranspiration and canal conveyance efficiency and applied to analyzing the demand and potential water savings of alternative water conservation measures. Estimated potential water savings were 234.2, 65.9, and 194.0 Mm^3 for conservation measures related to on−farm management improvements, replacing sugarcane with corn, and improving canal conveyance efficiency, respectively. Results indicated that on−farm management measures might be as beneficial as improving canal conveyance systems. The planning tool (with hydrological modeling and GIS capabilities) and estimations made would be useful for regional planners and irrigation district managers. The tool could be used for other irrigation systems as well.*

Keywords. *Conservation measures, Geographic information system, Hydrologic simulation model, Irrigation management, Regional planning, Water demand, Water savings.*

The growing water demand to meet urban and industrial needs has raised serious concerns as to the future of irrigated agriculture in many parts of the world (Food and Agriculture Organization, 2000). Since water supplies cross local, state, and even international boundaries, the planning process often requires a basin−wide perspective. Compared to the traditional piece−meal approach of looking at a specific irrigation district or canal segment, a regional planning approach can help to develop a comprehensive vision for future growth, and to develop plans to use the water efficiently among competing users. Regional planning tools must be capable of simulating the physical processes (soil−plant−water relationship) adequately for estimation of crop water demand and efficient utilization of the irrigation water.

Most of the regional planning approaches use gross estimation procedures for water demand (Droogers and Bastiaanssen, 2002) by ignoring soil−water storage or by using average values for soil water storage or crop evapotranspiration (ET). The crop water requirement estimation procedure of the FAO of the United Nations (Doorenbos and Pruitt, 1977) has been widely used across the world. But researchers tend to use average values for effective rainfall and other weather conditions necessary for estimating crop water requirement due to data or computing limitations (Santhi and Pundarikanthan, 2000).

The key parameter involved in regional planning for irrigated agriculture is crop water demand. Crop water demand depends on crop characteristics such as leaf area and rooting depth, soil properties such as available water holding capacity, and hydrological processes such as rainfall and infiltration. The other key issue involved in regional planning for irrigated agriculture is capturing the temporal and spatial variability of the rainfall, soils, and crops in different subunits of the region.

Simulation models can be used as analytical tools for estimating water demand and the impact of water management measures in irrigation systems and at the regional scale, and such models can significantly enhance the ability of planners, practitioners, and researchers to investigate management alternatives. The Command Area Decision Support Model (Prajamwong et al., 1997) was developed to estimate aggregate crop water requirements and study various irrigation water management options in irrigated command areas with multiple fields. The user can input only six soil types and six cropping patterns, and the model allows a maximum of 54 fields for simulation for computational reasons. If the number of fields is greater than 54, then fields with similar cropping patterns and soil types are aggregated into a maximum of

Article was submitted for review in October 2003; approved for publication by the Soil & Water Division of ASAE in December 2004.

The authors are **Chinnasamy Santhi,** Assistant Research Scientist, and **Ranjan S. Muttiah,** Assistant Professor, Department of Geology, Texas Christian University, Fort Worth, Texas; **Jeffrey G. Arnold,** Agricultural Engineer, USDA−ARS Grassland Soil and Water Laboratory, Temple, Texas; and **Raghavan Srinivasan,** Professor, Blackland Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University, Temple, Texas. **Corresponding author:** Dr. Jeffrey G. Arnold, USDA−ARS Grassland Soil and Water Laboratory, 808 E. Blackland Road, Temple, Texas 76502; phone: 254−770−6052; fax: 254−770−6561; e−mail: jgarnold@spa.ars. usda.gov.

54 fields. Hence, this model has limitations for applications to large−scale irrigation systems.

For a canal irrigation system in western Turkey, Droogers and Bastiaanssen (2002) used a surface energy balance land algorithm (SEBAL) to estimate actual ET for two days in a crop season with Landsat thematic mapper images. They also used a hydrologic model, called Soil−Water−Atmosphere−Plant (SWAP) (Van Dam et al., 1997) to simulate ET for the same area assuming a certain distribution of soil properties, planting dates, and irrigation practices. Spatial distribution of ET for the two Landsat days for cotton and grapes were used to validate the model−estimated ET by adjusting planting dates and irrigation practices. These optimized input data were used in the model to estimate the water balance and assess irrigation performance during an irrigation season in 1998.

Comparing the study by Droogers and Bastiaanssen (2002) with the present study, both studies were conducted for a large canal irrigation system using a hydrologic modeling approach with spatial distribution capability, such as GIS or remote sensing, for extracting model inputs. The SWAP model uses crop growth functions and irrigation operations similar to the SWAT model used in the present study, but the methods used for water balance in these models are different (Van Dam et al., 1997; Neitsch et al., 2002). The Droogers and Bastiaanssen (2002) study was performed for a single−year irrigation season (although it could be extended for many years), with a focus on irrigation water delivery performance. The SWAT modeling approach used a long−term simulation (32 years) with a focus on water savings due to different conservation measures to support regional policy planning. The advantage of the modeling approach used by Droogers and Bastiaanssen (2002) is that it can handle inputs such as irrigation practices and planting dates in a probabilistic mode. The limitation is that using remote sensing data for spatial distribution validation on a regular basis is expensive.

The objective of this irrigation study was to improve the capabilities of a basin−scale hydrologic simulation model (SWAT) for regional planning of irrigated agriculture and to apply the model to the Lower Rio Grande Valley (LRGV) in Texas. The SWAT model has GIS capabilities to handle inputs with high spatial resolution, and physically based simulation capabilities with high temporal resolution to simulate physical processes such as hydrology, soil water interaction, and crop growth on a daily basis. These two capabilities give the model an advantage over other approaches used for estimating crop water demand and irrigation water requirement. The first part of this article explains the methodology of the regional planning tool, and the second part explains the application of the tool to estimate water demand and savings in the Lower Rio Grande Valley. It should be noted that this article focuses on water demand and does not deal with water supply.

The Rio Grande Regional Water Planning Group (RGRWPG) is assessing the water demand and supply in the entire Rio Grande region, including the Lower Rio Grande Valley, and developing strategies to manage water shortages in the future (Texas Water Development Board, 2001). It is expected that the developed regional planning tool would support their tasks with better estimation of irrigation water demands and savings with high spatial and temporal resolution.

METHODOLOGY

SOIL AND WATER ASSESSMENT TOOL

The proposed regional planning tool uses a GIS−based hydrologic simulation model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2002; www.brc.tamus.edu/swat), developed by the USDA Agricultural Research Service (USDA−ARS). SWAT is a physically based simulation model operating on a daily time step. It was developed to simulate land management processes and rainfall−runoff processes with a high level of spatial detail by allowing the watershed to be divided into subbasins. Each subbasin is divided into several land use and soil combinations, called hydrologic response units (HRUs). The subbasin simulation processes of SWAT include major components such as hydrology, weather, erosion, soil temperature, crop growth, and agricultural management.

With regard to crop growth and management, SWAT uses the single crop growth modeling approach (Williams et al., 1984). The SWAT model can simulate management practices such as planting, fertilizer application, irrigation, tillage, pesticide application, harvest, and kill (termination) operations. These operations can be scheduled by date or by heat unit, which represents the operation time by a degree−day index from seed onset. SWAT has options to estimate the potential evapotranspiration (PET) by different methods such as modified Penman−Monteith (Monteith, 1965; Allen et al., 1989), Hargreaves (Hargreaves et al., 1985), and Priestley−Taylor (Priestley and Taylor, 1972). The model has several built−in databases for crops, soils, fertilizers, tillage, and pesticides. The crop database has information on physiological characteristics by crop. The soil database has information on soil properties including texture, bulk density, water holding capacity, and horizon depths. The tillage database has information on depth and mixing efficiency by implement. The fertilizer database has information on the organic and mineral constituents of different fertilizers. The pesticide database has information on the half−life period, water solubility factor, and soil adsorption coefficient, normalized for soil organic carbon content, for each pesticide. Additional details on the model can be found in Arnold et al. (1998) and Neitsch et al. (2002).

SWAT has been applied widely to address problems related to water quantity and quality across the U.S. and in other countries (Arnold et al., 1999). It has also been applied to study the long−term impacts of different water and agricultural management practices from large− and small−scale watersheds (Srinivasan et al., 1998; Santhi et al., 2001). SWAT has been integrated into the U.S. Environmental Protection Agency's modeling framework, Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), for use by state and federal agencies (Di Luzio et al., 2002). However, it has only been applied to a limited extent in irrigation water management. Arnold and Stockle (1991) used SWAT to simulate supplemental irrigation from on−farm ponds, crop yield, and furrow diking, but they ignored irrigation through canal networks.

DEVELOPMENT OF THE CANAL IRRIGATION COMPONENT OF SWAT

A new canal irrigation routine was added to the SWAT model to simulate canal irrigation. Managing canal irrigation systems as irrigation districts is a common practice in

countries like the U.S. In this modeling approach, each irrigation district and associated canal system is considered as a subwatershed. The crop fields within the district are represented by HRUs within the subwatershed. The overall concept of the canal routine is given in figure 1, and detailed description is provided in this section. The canal irrigation routine was linked appropriately to other routines within SWAT. Additionally, changes were made as follows to read some of the inputs required using the existing input files and to produce separate output files specific for this study:

- To read inputs for canal−related variables such as canal dimensions, canal capacity, target limits for irrigation water release for each district, and canal segments with different lining material and hydraulic conductivity for seepage estimation.
- To read the application efficiency by crop HRU.
- To write output files at the HRU level showing crops grown, crop ET, and depth of irrigation water, and to write output files at the district level showing crop water demand, canal losses, total water demand, and irrigation water releases.

Estimation of Crop Water Demand

Crop Irrigation Scheduling

The user can input a schedule (specifying the depth of irrigation, time, and source of irrigation) for irrigating the crop in an HRU, or an automated irrigation triggering approach can be used based on crop water stress or soil moisture depletion. Crop water stress is a function of actual ET and potential ET. Soil moisture deficit is the depleted depth of water below field capacity. When there is a crop stress, an irrigation event is triggered and water is applied to the triggered HRU depending on either the user−specified depth or to a certain depth as the water available in the canal. This is depth of irrigation water applied to the HRU. Irrigation water applied to a crop HRU is used to fill the soil layers to field capacity beginning with the soil surface layer and working downward until all the water applied is used or

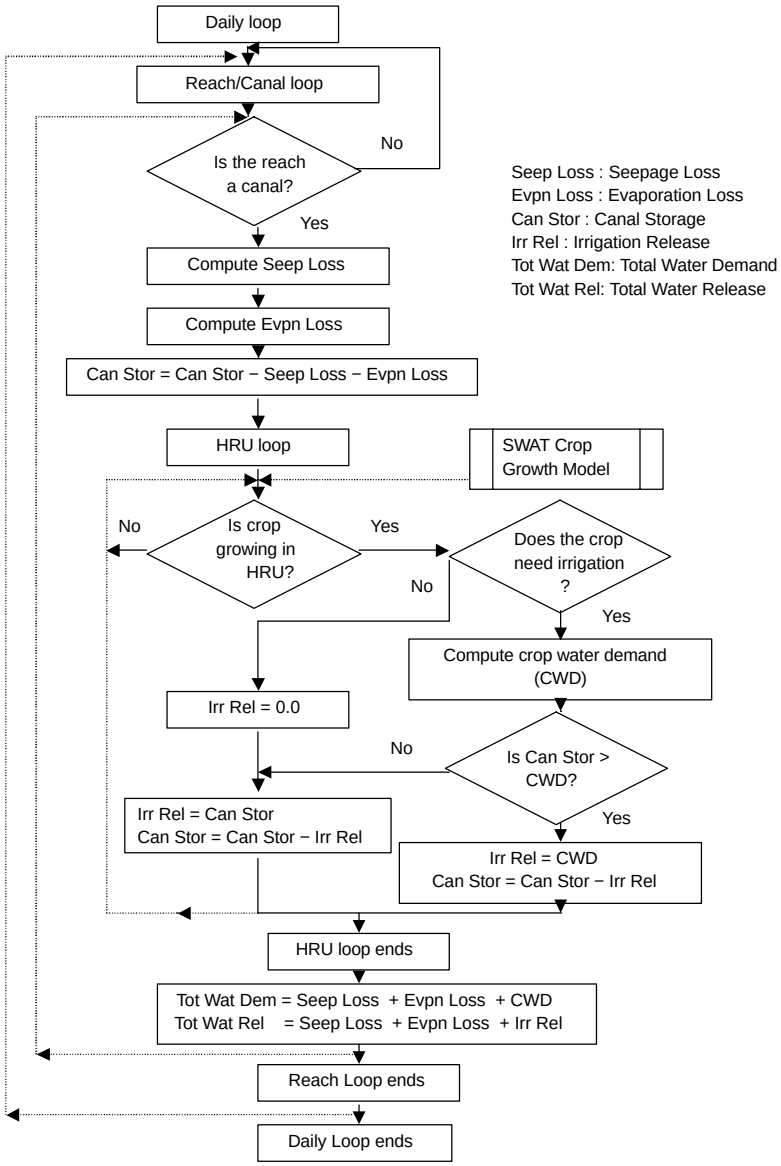


Figure 1. Canal irrigation component of SWAT.

the soil profile reaches field capacity. Soil depth is based on soil horizon, and the model divides the soil horizon into a maximum of ten layers. Maximum rooting depth varies with the crop grown in the HRU. Usually, the maximum rooting depth does not go beyond soil depth, and irrigation water is applied only to the rooting depth. When water is applied, it is used to fill the soil layers to field capacity as needed.

Crop Water Demand

The volume of water required for crop water demand and irrigation is estimated from the depth of irrigation, crop area in HRU, and application efficiency. This procedure is repeated for all triggered crop HRUs in a given day:

$$\mathrm{CWD} = 10.\sum_{i=1}^{i=n}\left(\frac{ID_i \cdot CHA_i}{AE_i}\right) \quad (1)$$

where

CWD = crop water demand for the given day (m^3)
i = crop HRU number
n = number of crop HRUs triggered for the given day
ID_i = depth of irrigation water (mm)
CHA_i = crop HRU area (ha)
AE_i = application efficiency of the crop HRU (%).

In this equation, CHA_i and AE_i are input data to the model, and ID_i is estimated by the model depending on the water available in the canal.

The model verifies if the crop is growing in the HRU and if there is a stress on any given day (fig. 1). In this study, crop stress−based triggering for irrigation is used. When there is a crop stress (when the actual ET over potential ET falls below 0.8), the model estimates the crop water demand (eq. 1) and an irrigation event is triggered. For a given irrigation event, SWAT determines the amount of water available in the canal (source) and compares it to the crop water demand. If the amount available is less than the crop water demand, the model will only apply the available water to the crop HRUs. If the water available in the canal is not adequate to meet the water requirement in all crop HRUs in a given day, irrigation will be triggered in subsequent days in the deficit HRUs, depending on the rainfall, soil moisture, and crop stress conditions in the fields.

Estimation of Seepage Losses in the Canal

The loss of water due to seepage from irrigation canals constitutes a substantial part of the usable water (Swamee et al., 2000). Perfect canal lining can prevent seepage loss, but cracks can develop in the lining, and the performance of the canal lining deteriorates with time. Wachyan and Ruston (1987) examined several canals and reported that even a well maintained canal with 99% good lining reduces seepage only by 30% to 40%. In this approach, the model accounts for variations in seepage losses occurring in canal segments with different lining materials, such as concrete, earth, and polyvinyl chloride (PVC). Seepage losses in the canal are estimated with the following equation:

$$S_{loss} = \sum_{i=1}^{i=n} K_{chi} \cdot ST \cdot P_{chi} \cdot L_{chi} \quad (2)$$

where

S_{loss} = canal seepage losses in a given day (m^3)
i = canal segment with specific lining material
n = number of canal segments with different lining materials
ST = canal storage time (h)
K_{chi} = effective hydraulic conductivity of the channel alluvium for segment i (mm h^{-1})
P_{chi} = wetted perimeter for segment i (m)
L_{chi} = canal length for segment i (km).

In the above equation, K_{chi}, P_{chi}, and L_{chi} are inputs to the model.

Estimation of Evaporation Losses from the Canal

The other form of water loss from canals is through evaporation. Evaporation losses from the canal are calculated (Neitsch et al., 2002) as:

$$E_{ch} = coef_{ev} \cdot E_o \cdot L_{ch} \cdot W \cdot fr_{\Delta t} \quad (3)$$

where

E_{ch} = evaporation from the canal for the day (m^3)
$coef_{ev}$ = evaporation coefficient for different climatic regions
E_o = daily potential evaporation estimated from the modified Penman−Monteith method (mm)
L_{ch} = canal length (km)
W = canal width at water level (m)
$fr_{\Delta t}$ = fraction of the time step in which water is flowing in the canal
Δt = time step (day).

In the above equation, L_{ch} and $coef_{ev}$ are inputs to the model, and the model estimates the other variables.

Total Water Demand and Releases

Total water demand in the canal or irrigation district for a given day is estimated by summing the crop water demand, seepage, and evaporation losses (fig. 1). Based on the estimation of total water demand for a given day, water for irrigation is released in the canal or irrigation district from the main river or water system. It should be noted that irrespective of the number of HRUs or the extent of crop area triggered for irrigation in a given day, the actual number of HRUs, or the extent of crop area irrigated, depends on the available water released for irrigation in the canal on that day and the capacity of the canal. Hence, in a given irrigation day, the required amount of irrigation water to be released to the canal from the main system is important. Excess release may result in excess seepage losses, and inadequate release may result in water stress in certain crop HRUs. In order to facilitate better estimation of release to the canal, the crop water demand is estimated at the beginning of each day of the simulation based on the number of HRUs triggered for irrigation in a given day. Then the irrigation release to the canal is made according to the estimated crop water demand, including allowances for canal losses and canal capacity. If some of the HRUs triggered on that day cannot be irrigated due to canal capacity limitations, they will be triggered for irrigation on subsequent days.

Study Area

Physical Description

The Rio Grande region is one of the fastest growing areas of Texas, and McAllen is ranked as the third fastest growing city in the U.S. Water from the Rio Grande River is shared between the U.S. and Mexico based on a 1944 treaty.

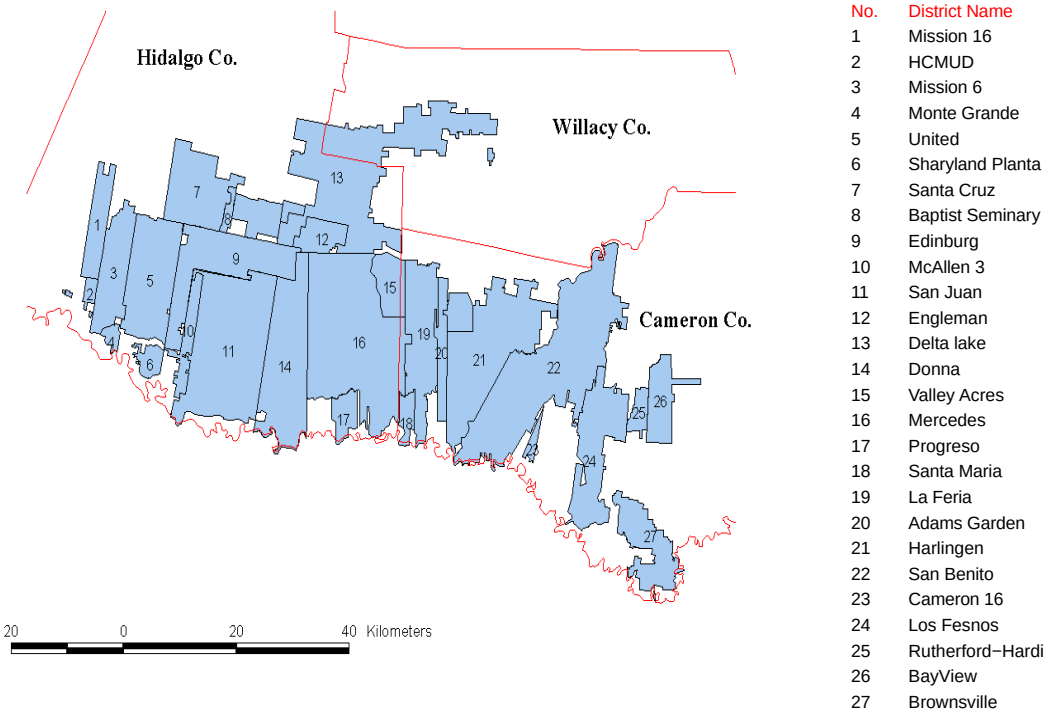
Agriculture in the LRGV plays a vital role in the Texas economy. However, recent agricultural, urban, and industrial development on both sides of the border has posed serious challenges to managing limited water resources. The LRGV gets water through joint regulation of the Amistad and Falcon reservoirs. Most of the water in the Rio Grande region is used for irrigation in the LRGV, where approximately 750,000 people live and irrigated farming is practiced extensively. The irrigation districts in the valley supply water users primarily in Cameron, Hidalgo, and Willacy counties (fig. 2). The average annual rainfall in the LRGV is 625 mm. Major crops grown are grain sorghum, cotton, corn, cabbage and other vegetables, citrus, and sugarcane. The main cropping season is from February/March through July/August (except for perennials such as sugarcane and orchard crops). Major soils in the valley are sandy clay loam (Hidalgo series), clay loam (Raymondville and Mercedes series), clay (Harlingen series), silty clay loam (Laredo series), and fine sandy loam (Willacy series).

Organization Description

Each irrigation district is managed by a district manager. Each district holds water rights for irrigation and municipal demands. Similarly, farmers in the district hold water rights for irrigation on a per hectare (acre) basis. Depending on the land area owned for water rights, farmers receive the irrigation water allocation during the season. The general guideline for a farmer's water rights is approximately 7617 m^3 of water per hectare (2.5 acre−foot of water per acre), provided the water supply is not limited. Farmers decide on the need for irrigation water by evaluating the crop stress based on their farming experience and by how much water is available to them through water rights. They place water orders with the district manager during the crop season. Based on the water orders received, the district manager places water orders with the Rio Grande water master. Depending on the water available in the Falcon and Amistad reservoirs located in the Rio Grande River, the Rio Grande water master allocates the quantity of water to the district according to the district's water rights. The district manager in turn distributes the water to the farmers, who ordered according to their water rights. In general, farmers get the required water if the water supply is adequate. During scarce periods, depending on the water available in the upstream reservoirs, farmers may get equal allocations on a per hectare basis according to their water rights. Farmers are responsible for managing the crop water needs within their farms with the available water.

Model Inputs

The Arcview−Geographic Information System interface of the 2000 version of SWAT (Di Luzio et al., 2004) was used to generate SWAT input files. The study area was the irrigation districts of the Lower Rio Grande Valley. Irrigation district GIS maps and canal GIS maps were collected from the Texas Cooperative Extension unit of the Texas A&M University System (TAMUS, 2000). As each irrigation district is managed individually for water rights and allocation, each irrigation district was considered as a subbasin, or subwatershed, in this modeling approach. Canal maps were used to define the canal dimensions and lining conditions (lined or unlined) of the different canal segments in each district. Recently available high−resolution (30 m) land use maps (for 1992) from the U.S. Geological Survey (USGS) and soil maps (SSURGO) from the National Resources Conservation Service (NRCS) were used for creating HRUs (land use and soil combinations). In the past, irrigation districts did not maintain historical information on crop acreage. District managers are just beginning to maintain information about crops grown and their crop acreage. Hence, the 1992 USGS land use map and 1992 Agricultural Census information were used to identify the major crops



No.	District Name
1	Mission 16
2	HCMUD
3	Mission 6
4	Monte Grande
5	United
6	Sharyland Planta
7	Santa Cruz
8	Baptist Seminary
9	Edinburg
10	McAllen 3
11	San Juan
12	Engleman
13	Delta lake
14	Donna
15	Valley Acres
16	Mercedes
17	Progreso
18	Santa Maria
19	La Feria
20	Adams Garden
21	Harlingen
22	San Benito
23	Cameron 16
24	Los Fesnos
25	Rutherford−Hardi
26	BayView
27	Brownsville

Figure 2. Irrigation districts in the Lower Rio Grande Valley, Texas.

grown and their areas in each district. Different crop fields within the irrigation district were represented by HRUs.

Growing season and generalized management practices for crops were collected through extension personnel (Texas Cooperative Extension unit and county agents) and used for creating management inputs. The modified Penman−Monteith method (Monteith, 1965; Allen et al., 1989) was used for estimating the potential evapotranspiration. Long−term weather data, such as daily precipitation and maximum and minimum air temperatures, were collected from the stations closest to each district and used for modeling. For example, the average annual rainfall was about 690 mm for the Brownsville irrigation district. The daily averages of the minimum and maximum air temperatures were about 18.0°C and 28.2°C, respectively. The weather generator available within SWAT (Nicks, 1974; Sharpley and Williams, 1990) was used to generate solar radiation, relative humidity, and wind speed. Simulated daily average, minimum, and maximum solar radiation values were about 18.5, 11.0 (winter), and 25.0 (summer) MJ m^{-2} day^{-1}, respectively. Simulated daily average, minimum, and maximum wind velocities were about 5.2, 4.2, and 6.3 m s^{-1}, respectively. The simulated solar radiation was reliable and reasonable when verified with the observed data from the National Solar Radiation Weather Database (NREL, 2004). Variations in the weather data for other districts were minor.

Model Calibration of Crop ET and Canal Conveyance Efficiency

The irrigation districts in the LRGV were simulated from 1967 through 1998 (32 years). The major water losses in an irrigation system are crop ET and canal conveyance losses (seepage and evaporation). Hence, the model was verified for these two parameters. Simulated mean crop ET values for major crops were compared with the estimated mean crop ET values (average of 30 years) reported for the region (Borrelli et al., 1998; Mc Daniels, 1960). Simulated mean crop ET values were obtained by averaging the ET values across all years and for the same type of crop HRUs. As only long−term average crop ET values were available for comparison for this region, separate calibration and validation time periods were not considered. However, simulated minimum and maximum ET values are provided for different crops grown to reflect the variations. As adequate care was taken to input the crop management practices based on field information, simulated crop ET matched fairy well with reported crop ET without any calibration. Similarly, the model was calibrated for the conveyance losses reported for different irrigation districts (Fipps and Pope, 1999) by adjusting the hydraulic conductivity of the channel alluvium to reflect canal losses in each district. Conveyance efficiencies reported for most of the irrigation districts were in the range of 70% to 90% (Fipps and Pope, 1999).

Management Scenarios

The calibrated model was used to study the impact on water demand and the potential water savings through implementation of various water conservation measures. These scenarios were related to on−farm improvements, changes in cropping pattern, and improvements to the canal conveyance system. These scenarios were analyzed by simulating the system hydrology using daily historical weather information for 1967 through 1998. Inputs associated with each management scenario are described below.

Reference Scenario

The reference scenario was developed to reflect the existing conditions of the LRGV. The reference scenario used the inputs as discussed earlier in the Model Inputs section. Different crop areas in the irrigation districts were estimated using the 1992 USGS land use maps and Agricultural Census data. An on−farm application efficiency of 75% was assumed for crop grown areas in all irrigation districts due to lack of field−measured information for individual districts. In general, application efficiency reported for surface irrigation is about 60% (Brouwer et al., 1989). On−farm improvements such as metering, poly pipelines, and drip irrigation systems have been implemented to some extent in most of the irrigation districts. Hence, an application efficiency of 75% was assumed for the reference scenario. Application efficiency was read as input at the HRU level for all crop HRUs and was used for calculations, as shown in equation 1. The canal conveyance losses in the districts were set at the calibrated values.

Improving Application Efficiency

Several on−farm measures such as water metering systems, poly pipelines, and drip and sprinkler irrigation systems are recommended by district managers for saving water. Fipps and Pope (1999) and Fipps (2000) made estimates of water savings due to on−farm measures in a few districts and reported water savings factor ranging from 10% to 20%. A target efficiency improvement of 20% over the existing efficiency is envisioned for this study. In order to study the impact of these on−farm improvements on water demand and potential water savings, a scenario was developed by simulating the on−farm efficiency at 95% for all crop HRUs in the irrigation districts using equation 1. Other inputs remained the same as in the reference scenario. Regional planning is made with a long−term vision considering the year 2050. On−farm application efficiency (95%) was chosen in order to find the maximum water that could be conserved from the agriculture sector so as to accommodate future urban and industrial development in this region. For the present study, on−farm improvements in all the districts were considered to be uniform (20% increase in application efficiency). However, it can be varied from district to district, depending on the extent of implementation. Model scenario runs could be made easily with different application efficiency values, if needed.

Crop Diversification: Replacing Sugarcane with Corn

Sugarcane is a cash crop grown in most of the districts. It is also a high water demand crop, requiring water almost throughout the year, and it is difficult to meet the water demand during scarce years. One of the planning options was to study the impact of replacing sugarcane with corn. For simulating this scenario, all sugarcane grown in the irrigation districts was replaced with corn. Crop management files for the sugarcane growing area were replaced with corn crop management files.

Improving Canal Conveyance Efficiency

Being a relatively older irrigation system, the canals are in poor condition in some of the districts, and they cause significant losses of water through seepage. District manag−

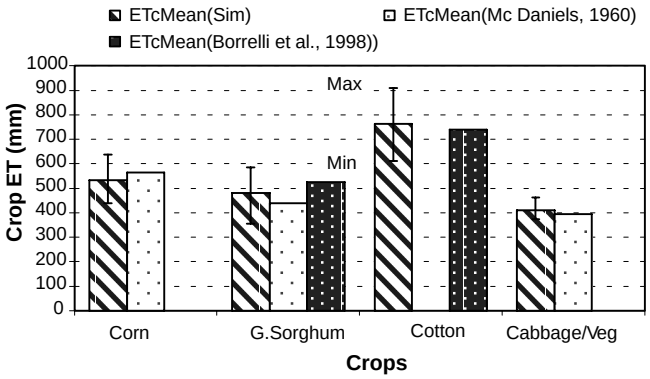


Figure 3. Simulated and reported crop ET for major crops.

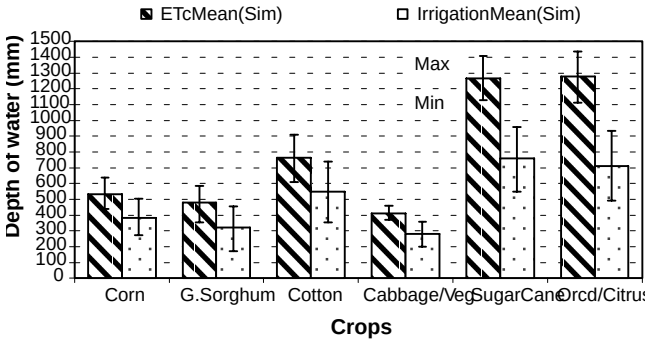


Figure 4. Simulated crop ET and depth of irrigation for major crops.

ers are working on rehabilitating and improving the canal system. The regional planning group is interested in knowing the potential water savings that could be obtained by improving the canal system from the existing level. Hence, a scenario was analyzed by simulating the canal system in the districts at 90% to 95% efficiency levels. For simulating this scenario, depending on the lining material and canal condition, the hydraulic conductivities of different canal segments were adjusted (eq. 2) until the canal losses were minimized or until the conveyance efficiency reached 90% to 95% in each district.

Management Scenario Analyses

Crop water demand and total water demand including canal losses for the irrigation districts were estimated for each scenario, and the potential water savings that could be obtained were estimated with respect to the reference scenario. Results are presented as cumulative total water demand for different water conservation measures per year (annual average of 32 years) and percentage of water savings per year with reference to the total water demand of the reference scenario.

Results and Discussion

Model Calibration of Crop ET and Canal Conveyance Efficiency

Simulated mean crop ET values for the major crops were compared with the estimated crop ET values from Borrelli et al. (1998) and Mc Daniels (1960) for the region (fig. 3). Simulated mean crop ET values for the major crops were reasonably close to the reported mean crop ET values. The minimum and maximum lines shown for the simulated crop ET values reflect temporal variations in weather. Simulated depth of irrigation values for the major crops (fig. 4) were close to the reported values (Jensen et al., 1990; Robert Wiedenfeld, Texas Agricultural Experiment Station, Weslaco, Texas, and Thomas Gerik, Texas Agricultural Experiment Station, Temple, Texas, personal communication, May, 2003; Brodie, 1990; Droogers and Bastiaanssen, 2002). The model was calibrated for the conveyance losses reported for different irrigation districts (Fipps and Pope, 1999) by adjusting the hydraulic conductivity of the channel alluvium to reflect canal losses in each district with reasonable accuracy (within 10% of difference) (fig. 5). The statistics indicate a good correlation between reported and simulated conveyance efficiency in the districts.

Management Scenarios

Crop water demand for the reference scenario (fig. 6) followed the trend of the irrigated area in the district. Districts such as Delta Lake, San Benito, Mercedes, San Juan, Donna, and Harlingen have more irrigated area; hence, the crop water demand is greater in those districts compared to other districts. Obviously, water allocation and water rights in those districts are also greater, as water rights are based on irrigated area. The difference between the total water demand and crop water demand reflects the canal losses (fig. 6). Canal losses are greater in districts such as San Benito, Delta Lake,

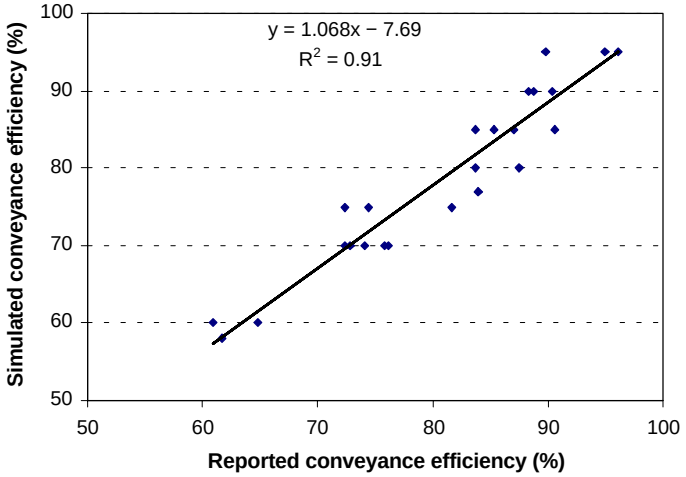


Figure 5. Comparison of reported and simulated conveyance efficiency of the irrigation districts.

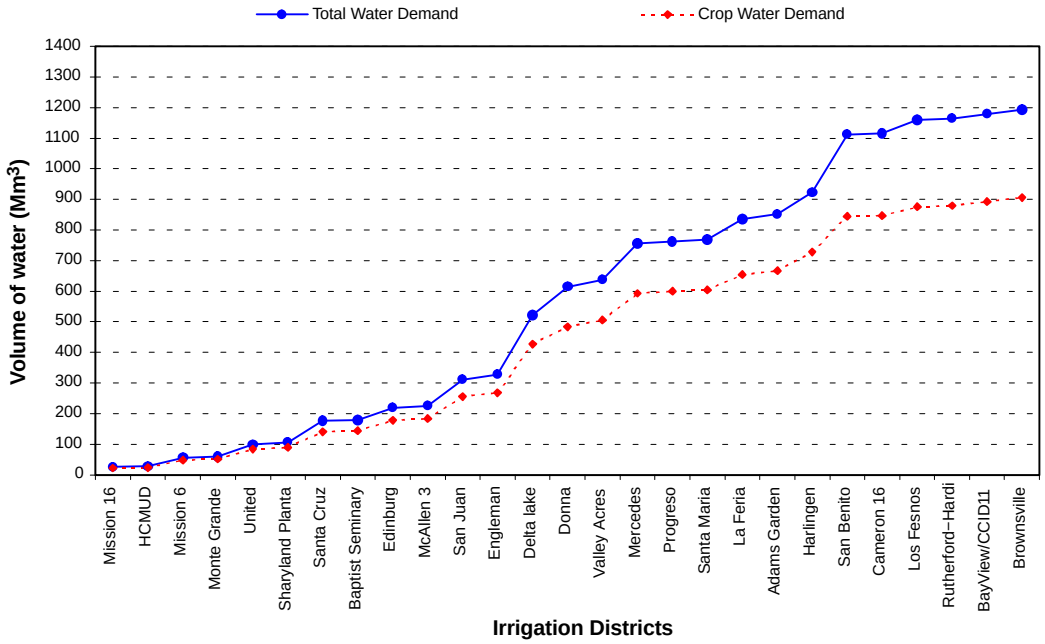


Figure 6. Cumulative crop water demand and total water demand for the reference scenario.

and Mercedes and indicate the need for canal system improvements.

Figure 7 presents the cumulative total water demand for the various water conservation measures; the difference between the conservation measures and the reference scenario provides the potential water savings for the individual district. The percentage of potential water savings was estimated (fig. 8) with reference to the total water demand of the reference scenario using the potential water savings of each measure (fig. 7).

Depending on the irrigated area in the districts, the potential water savings that could be expected from on−farm improvement measures varied (fig. 7). Although the potential water savings were less than 3 Mm^3 in some of the districts such as HCMUD, Monte Grande, Sharyland Plantation, and Baptist Seminary, the percentage of water savings (in the order of 15% to 20%) with respect to the total water demand (fig. 8) in those districts indicated that the benefits might contribute considerably to water conservation.

Mean crop ET and depth of irrigation water required were about 1280 mm and 780 mm for sugarcane and 530 mm and 390 mm for corn, respectively (fig. 4). Hence the replacement of sugarcane with corn resulted in potential water savings of 6% to 7% of the total water demand in the districts

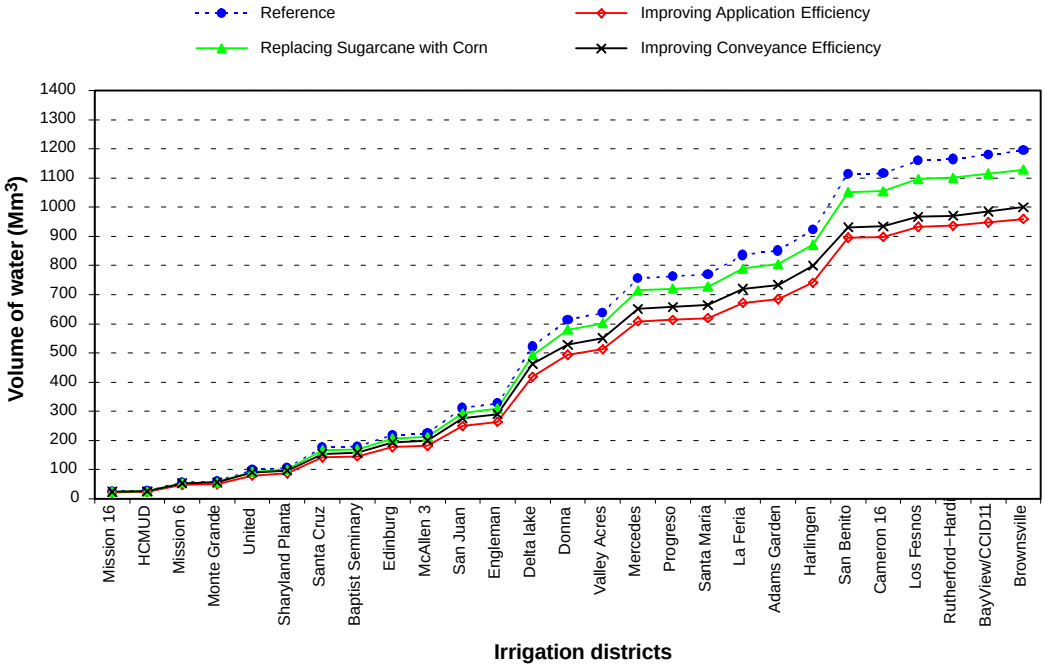


Figure 7. Cumulative total water demand for different conservation measures.

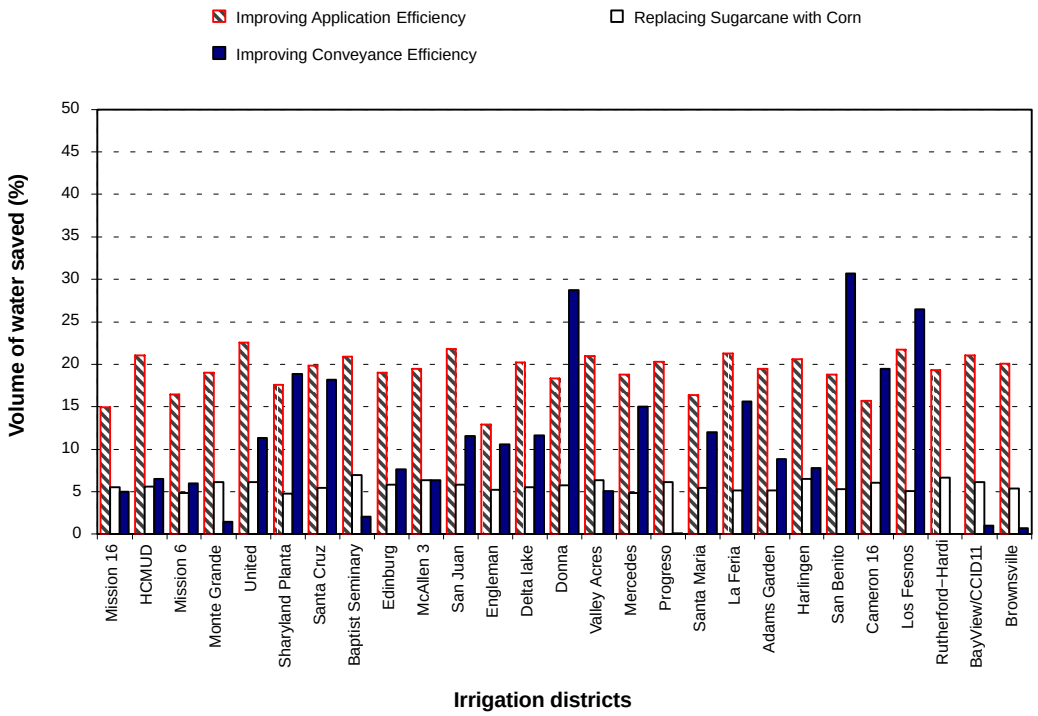


Figure 8. Percentage of water savings for different conservation measures.

(fig. 8), depending on the sugarcane area replaced. Percentages of sugarcane area replaced with respect to the irrigated area in the districts were 6% to 7%.

Conveyance loss is an issue in some of the irrigation districts in the LRGV. Improving the physical conditions of the canal systems (90% to 95% of conveyance efficiency level) is expected to result in potential water savings of 1% to 30% of the total water demand in the irrigation districts (fig. 8). Potential water saving in a district depends on the length and density of canals and the physical conditions (lining and leakage in joints) of the canals apart from crop water demand. Some of the districts have long canals in the order of 180 to 200 km in length, either earthen or concrete lined. For illustration, the San Benito district has an earthen canal system with a length of about 200 km, with some canals in poor conditions, causing higher canal losses. The new routines within SWAT can help to quantify the water savings that could be obtained through canal system improvements in this district.

Variations in percentage of potential water savings for different conservation measures between the districts (fig. 8) clearly indicate the spatial and temporal variations in weather conditions, crops grown, soil types, and physical conditions of the canal systems, and therefore variations in hydrology. The district managers could use the percentage of potential water savings for different conservation measures (fig. 8) to prioritize the measures for implementation based on benefits. For illustration, improving on−farm measures can bring better benefits in the San Juan district, whereas improving conveyance systems can bring better benefits in San Benito.

Total water savings that could be expected for the entire Lower Valley Region by improving the on−farm measures, replacing sugarcane with corn, and improving canal conveyance efficiency are reported in figure 9. The results indicate that on−farm management measures might be as beneficial as improving the canal conveyance systems. The benefit of changing crops (replacing sugarcane with corn) is less than that of the other two scenarios because the percentage of sugarcane area replaced was only about 6% to 7% of the irrigated area. Regional planners can use such quantitative information (fig. 9) for future planning strategies for efficient utilization and management of the limited water resources in the region.

Fipps (2000) has estimated the total potential water savings as 196.9 Mm^3 for a drought condition and 260.2 Mm^3 for a normal condition due to canal conveyance system improvements. For on−farm improvements, he reported savings of 215.3 and 278.9 Mm^3 for drought and normal conditions, respectively. Comparing these estimates with model results for canal conveyance system improvements and on−farm improvements (fig. 9), the model results are reasonable, given the differences between the approaches used in estimation. Estimates made by Fipps (2000) include

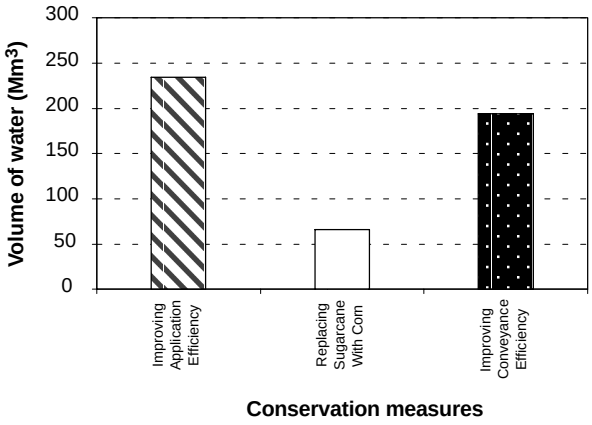


Figure 9. Total water savings for the Lower Rio Grande Valley for different conservation measures.

the Maverick irrigation district, which is in Maverick County and was not considered in the simulation study. The model estimate is the long−term average of 32 years, and it is a physically based simulation considering all the variations in soils, land use, crops grown, weather, canals, and hydrological processes. Considering these differences between the approaches used for estimation, the model results are reasonable.

The results presented herein were based on using currently available data for the districts for modeling. The results are subject to change as better data become available. This is because measured data on seepage losses, application efficiency, and actual area irrigated by crops were not readily available for the individual districts.

CONCLUSIONS

A GIS−based modeling tool for regional planning for irrigated agriculture was presented in this article. The tool was demonstrated with application to irrigation districts in the Lower Rio Grande Valley in Texas by analyzing the demand and potential water savings of alternative water conservation measures. The potential water savings estimated were 234.2, 65.9, and 194.0 Mm^3 for conservation measures related to on−farm management improvements, replacing sugarcane with corn, and improving canal conveyance efficiency, respectively (fig. 9). The results indicated that on−farm management measures might be as beneficial as improving the canal conveyance systems. Estimates made in the present study are based on currently available data. Availability of measured data on seepage losses, application efficiency, and irrigated area by crop for individual districts would be useful for better estimates and to establish a baseline for system improvements.

The advantages of the modeling tool are that it is capable of simulating the hydrological and agricultural management processes (soil−water−plant interactions) extensively and that it can capture the spatial and temporal variability of the major inputs in large irrigation systems. The capability of the modeling tool for regional planning was demonstrated with quantitative assessment of several management scenarios and water savings expected for the irrigation districts in the Lower Rio Grande Valley. The model's capability is not limited to the scenarios demonstrated here. Several other scenarios, such as impact of changes in irrigated area, water deficits, and/or combinations of the scenarios could also be analyzed. Although the modeling tool was demonstrated with the irrigation district configuration, it could be adapted to other irrigation system configurations in other countries.

The tool could be used by the planners and managers for several purposes and at different levels:

- At the district level, the costs involved in implementing each scenario and the benefits associated with it could be worked out based on the potential water savings. Based on this cost−benefit analysis, decision makers could identify a better water management or conservation measure for implementation, or prioritize different management measures for individual districts. Similarly, decision makers could prioritize the various districts in the irrigation system for water management improvement and resource allocation.
- At the regional level, the regional planning group could use the planning tool to make quantitative assessment of demands and water savings under several conditions and develop comprehensive plans for the future growth of the region with efficient allocation of water for different uses.

It should be noted that the modeling tool has certain limitations. For example, this tool could be used for planning at the regional level or district level to address several "what if" situations, but not for actual day−to−day water scheduling and distribution. However, there is a potential scope for developing such capability within the model. The irrigated cropping area remains constant throughout the modeling period and cannot be varied from year to year, as happens in the field. Due to this limitation, modeling results of water demand and releases cannot be compared directly with the actual demand and releases made in the irrigation system for water delivery performance assessment. A demand−based approach had been used in the present study. In this approach, crop water demand is met assuming that adequate water is available. It does not consider conditions of water availability in the upstream reservoirs. There is a plan to incorporate the water supply side in the near future. When water availability is limited, two approaches can be used, as appropriate to the particular irrigation system: allocating the available water equally to farmers on a per hectare basis, depending on farmers' water rights, or allocating the available water over a reduced irrigated area to meet crop demand.

ACKNOWLEDGEMENTS

The authors acknowledge the USDA−Cooperative State Research, Education, and Extension Service for providing funding for this assessment work through Texas Water Resources Institute under Agreement No. 2003−34461−13278 and Agreement No.2001−45049−01149. The authors also acknowledge the faculty of the Agricultural Extension and Economics Departments of Texas A&M University, Dr. Thomas Gerik and Dr. Robert Wiedenfeld of the Texas Agricultural Experiment Station, the irrigation district managers in the Lower Rio Grande Valley, and others who helped by sharing data.

REFERENCES

Allen, R. G., M. E. Jensen, J. L. Wright, and R. D. Burman. 1989. Operational estimates of evapotranspiration. *Agronomy J.* 81(4): 650−662.

Arnold, J. G., and C. O. Stockle. 1991. Simulation of supplemental irrigation from on−farm ponds. *J. Irrigation and Drainage Eng., ASCE* 117(3): 408−424.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large−area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resources Assoc.* 34(1): 73−89.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and P. M. Allen. 1999. Continental−scale simulation of the hydrologic balance. *J. American Water Resources Assoc.* 35(5): 1037−1051.

Borrelli, J. G., B. Fedler, and J. M. Gregory. 1998. Mean crop consumptive use and free−water evaporation for Texas. Texas Water Development Board Grant No. 95−483−137. Lubbock, Texas: Texas Tech University, Department of Civil Engineering.

Brodie, H. 1990. Estimating irrigation water requirements. Fact Sheet No. 447. College Park, Md.: University of Maryland, Maryland Cooperative Extension.

Brouwer, C., K. Prins, and M. Heibloem. 1989. Irrigation water management: Irrigation scheduling. Training Manual No. 4. Rome, Italy: United Nations FAO.

Di Luzio, M., R. Srinivasan, and J. G. Arnold. 2002. Integration of watershed tools and SWAT model into BASINS. *J. American Water Resources Assoc.* 38(4): 1127−1142.

Di Luzio, M., R. Srinivasan, and J. G. Arnold. 2004. A GIS−hydrological model system for the watershed control of agricultural nonpoint and point sources of pollution. *Trans. in GIS* 8(1): 113−136.

Doorenbos, J., and W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24. Rome, Italy: United Nations FAO.

Droogers, P., and W. G. M. Bastiaanssen. 2002. Irrigation performance using hydrological and remote sensing modeling. *J. Irrigation and Drainage Eng., ASCE* 128(1): 11−18.

Food and Agriculture Organization. 2000. Deficit irrigation practices. Water Reports No. 22. Rome, Italy: United Nations FAO.

Fipps, G. 2000. Potential water savings in irrigated agriculture for the Rio Grande Planning Region (Region M). College Station, Texas: Texas A&M University, Texas Agricultural Extension Service.

Fipps, G., and C. Pope. 1999. Irrigation district efficiencies and potential water savings in the Lower Rio Grande Valley of Texas. College Station, Texas: Texas A&M University, Texas Agricultural Extension Service.

Hargreaves, G. L., G. H. Hargreaves, and J. P. Riley. 1985. Agricultural benefits for Senegal River basin. *J. Irrigation and Drainage Eng., ASCE* 111(2): 113−124.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. Evapotranspiration and irrigation water requirements. ASCE Manual No. 70. New York, N.Y.: ASCE.

Mc Daniels, L. L. 1960. Consumptive use of water by major crops in Texas. Bulletin No. 6019. Austin, Texas: Texas Board of Water Engineers.

Monteith, J. L. 1965. Evaporation and the environment. In *The State and Movement of Water in Living Organisms: 19th Symposium, Society for Experimental Biology*, 205−234. Cambridge, U.K.: Cambridge University Press.

Neitsch, S. L., J. G. Arnold, J. R. Williams, J. R. Kiniry, and K. W. King. 2002. Soil and Water Assessment Tool (Version 2000). Model documentation. GSWRL 02−01, BREC 02−05, TR−191. College Station, Texas: Texas Water Resources Institute.

Nicks, A. D. 1974. Stochastic generation of the occurrence, pattern, and location of maximum amount of rainfall. In *Proc. Symposium on Statistical Hydrology*, 154−171. Misc. Publ. No. 1275. Washington, D.C.: USDA.

NREL. 2004. National solar radiation weather database. National Renewable Energy Laboratory. Available at: http://rredc.nrel.gov/solar; www.me.utexas.edu/~solarlab. Accessed 10 August 2004.

Prajamwong, S., G. P. Merkley, and R. G. Allen. 1997. Decision support model for irrigation water management. *J. Irrigation and Drainage Eng., ASCE* 123(2): 106−113.

Priestley, C. H. B., and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large−scale parameters. *Mon. Weather. Rev.* 100(2): 81−92.

Santhi, C., and N. V. Pundarikanthan. 2000. A new planning model for canal scheduling of rotational irrigation system. *Agric. Water Management* 43: 327−343.

Santhi, C., J. D. Atwood, J. Lewis, S. R. Potter, and R. Srinivasan. 2001. Environmental and economic impacts of reaching and doubling the USDA buffer initiative program on water quality. In *Proc. 2001 ASAE Annual International Meeting*, CD−ROM. St. Joseph, Mich.: ASAE.

Sharpley, A. N., and J. R. Williams, eds. 1990. EPIC − Erosion Productivity Impact Calculator. Model documentation. Tech. Bulletin No. 1768. Washington, D.C.: USDA−ARS.

Srinivasan, R., J. G. Arnold, and C. A. Jones. 1998. Hydrologic modeling of the United States with the Soil and Water Assessment Tool. *International J. Water Resources Development* 14(3): 315−325.

Swamee, P. K., G. C. Mishra, and B. R. Chahar. 2000. Design of minimum seepage loss canal sections. *J. Irrigation and Drainage Eng., ASCE* 126(1): 28−32.

TAMUS. 2000. District management system program. College Station, Texas: Texas A&M University, Texas Cooperative Extension.

Texas Water Development Board. 2001. Adopted regional water plan. Rio Grande Regional Water Plan (Region M) Report, January 2001. Austin, Texas: Texas Water Development Board.

Van Dam, J. C., J. Huygen, J. G. Wesseling, R. A. Feddes, P. Kabat, P. E. V. Van Walsum, P. Groenendijk, and C. A. Van Diepen. 1997. Theory of SWAP, version 2.0. Technical Document No. 45. Wageningen, The Netherlands: Wageningen Agricultural University.

Wachyan, E., and K. R. Rushton. 1987. Water losses from irrigation canals. *J. Hydrology* 92(3−4): 275−288.

Williams, J. R., C. A. Jones, and P. A. Dyke. 1984. A modeling approach to determine the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129−144.