Modelling El Paso county water improvement district no.1

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Fecha recibido

Modelación del distrito de riego no.1 del condado de El Paso

Abstract
The Paso del Norte Region is a desert area with limited surface and underground water resources. El Paso County Water Improvement District No.1 (EPCWID#1 or District) plans to implement strategies that save water and reduce salinity. A computer model was created using STELLA© based on statistical analysis using EXCEL©. Existing data used in the research was gathered from the International Boundary and Water Commission (IBWC), United States Bureau of Reclamation (USBR), and EPCWID#1. Regression equations obtained at data collection points on the Rio Grande and within the District controlled the model. Model results compared with actual data yielded good approximation. Three modeling scenarios were run obtaining the annual flow and salt load balances for the EPCWID#1. The results showed a decreasing trend for flow and salt transport. The daily total dissolved solids concentrations (TDS) of three canals inside the EPCWID#1 were obtained for calculating the number of days with unsuitable water quality (TDS>1900 mg/l). The Riverside Canal, which receives treated wastewater discharges, had the highest salinity and the highest number of days with unsuitable water quality.

Key words: Computer modeling, salinity, water management, Rio Grande.

Resumen
La región Paso del Norte es un área desértica con recursos limitados de agua superficial y subterránea. El distrito de riego #1 del condado de El Paso (*El Paso County Water Improvement District #1*, EPCWID#1) planea implementar estrategias para el ahorro del agua y la reducción de la salinidad. Se construyó un modelo de computo usando STELLA® basado en un análisis estadístico utilizando la hoja de calculo EXCEL®. La información usada en este trabajo se recolectó de la Comisión Internacional de Límites y Aguas (*International Boundary and Water Comisión*, IBWC), El Buró de Aprovechamiento de los Estados Unidos (*United States Bureau of Reclamation*, USBR), y EPCWID#1. Las ecuaciones de regresión obtenidas para los puntos de análisis en el Río Grande y dentro del distrito de riego, fueron las que controlaron el modelo de cómputo. Los resultados arrojados por el modelo se compararon con resultados reales, mostrando una buena aproximación. Se simularon tres distintos escenarios, obteniéndose balances del gasto hidráulico y carga anual de sales dentro de EPCWID#1. La concentración diaria de sólidos disueltos totales (SDT) para tres canales dentro del distrito, fue obtenida con el fin de determinar la cantidad de días al año que se presentó una baja calidad de agua (SDT>1900 mg l^{-1}). El Canal Riverside, el cual recibe descargas de aguas residuales tratadas, mostró la mayor concentración de sales y el mayor número de días con agua de baja calidad.

Palabras clave: Modelo de computo, salinidad, manejo del agua, Río Grande.

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Introduction

Water used to meet irrigation demands ranges between 40 and 80 percent of the total water consumption for most countries. For the El Paso region agriculture uses approximately 80 percent of the surface water supply which comes from the Rio Grande. Gowda (1993) collected and analyzed water samples from five different stations along the Rio Grande Basin for a period of 10 years (1980 to 1990), and found that the quality of the Rio Grande water in terms of salinity decreases downstream from Elephant Butte Reservoir (500 mg l^{-1}) to El Paso (850 mg l^{-1}) during summer. Water salinity is lowest (best) during the irrigation season and increases during the non-irrigating months (October-March) when river flows are composed of groundwater seepage, irrigation drains and municipal wastewater discharges. The highest levels of salinity of the Rio Grande occurs from Fort Quitman to Presidio (2000 to 5000 mg l^{-1}) and at the Pecos River (2000 to 4000 mg l^{-1}) (Miyamoto et al., 1995). Salinity of water is a key factor impacting crop yield. Sodium, calcium, and magnesium are the principal cations and chloride, carbonate/bicarbonate, and sulfate are the major anions in water. Water salinity also impacts soils salinity which for many soils controls the leaching of salt form the root zone (Abdel-Dayem, 1997).

A model is usually built by systematic trial-and-error process. “A model must be created in steps of increasing complexity until it is capable of replicating the observed behavior of the system” (Ford, 1999). Several computer models are available for simulating the water quality in rivers and flow in open channels. The models built and sustained by U.S. government agencies are almost universally accepted in developing permit applications and defending design protocols on liability issues (Chin, 2006).

Some computer models are being used in the Paso del Norte Region, which were made by different institutions and have different objectives. BESTSM was created by Boyle Engineering Corporation under contract with EPWU and The Texas-New Mexico Water Commission, and simulates surface water operations for river basins. BESTSM simulates reservoir operations, daily flow routine, and water quality over a time period. The results obtained of BESTSM model, were used by the Texas-New Mexico Commission for the creation of The Water Resources Technical report (El Paso-Las Cruces Regional Sustainable Water Project, 2000). Williams (2001) made a study to determine the occurrence and distribution both temporally and spatially of salt in the Rio Grande. This project was developed using Autoregressive Integrated Moving Average (ARIMA) time series models, and analyzed the data collected in six stations: at San Marcial, below Elephant Butte Dam, below Caballo Dam, at Leasburg Dam, below Mesilla Dam, at El Paso, and Fort Quitman.

Martinez (2002) developed a system dynamics model for surface flow in the Upper Rio Grande Basin. The objectives of this study were to compile and analyze stream gauge data from the Upper Rio Grande including surface water withdrawals from the southern New Mexico portion of the Rio Grande, and flow releases from Elephant Butte and Caballo Dam to El Paso, and Fort Quitman. URGWOM was created by six different agencies: the Bureau of Reclamation, U.S. Geological Survey, Bureau of Indian Affairs, U.S. Fish and Wildlife Service, the International Boundary and Water Commission (U.S. Section) and the U.S. Army corps of Engineers (Sheng, 2008). URGWOM was created using the RiverWare modeling software, which was developed by the Center for advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado in Boulder. URGWOM simulates water storage and delivery operations in the Rio Grande, from its headwaters in Colorado to below Caballo Dam in New Mexico. Also the model is used for flood control from Caballo Dam to Fort Quitman, Texas.

The model described in this study was built using STELLA©, which is a system dynamics object-oriented based modeling software developed by MM High Performance Systems, Inc (2000). System dynamics refers to the fundamental patterns of change in a system. A system dynamics model helps users understand why these patterns occur. The objective is to improve understanding as an aid in decision making (NHS, 2005). In this work, a system dynamics model was developed for simulating water flows and TDS within El Paso County Water Improvement District #1, which is part of the Paso del Norte Region as shown in figure 1.

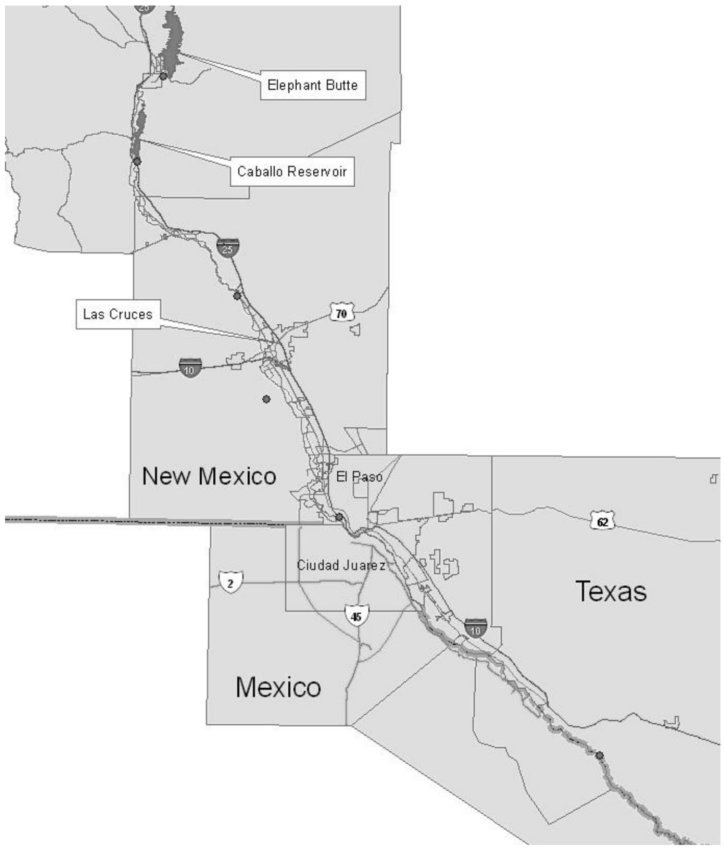

Figure 1. Rio Grande Project Map (NMSU, Department of Geography)

The use of the irrigation computer model and a statistical analysis of EPCWID#1 water distribution and quality data has led to the identification of management options for more efficient water allocation and salinity damage reduction into the irrigation system. Water quantity and salinity data within the District was only available for the years 1997 to 1999. An important aspect of the research was the identification of information gaps inside the EPCWID#1. As shown in figure 2, the Paso del Norte region covers the Rio Grande Basin from Elephant Butte Dam, New Mexico to Fort Quitman, Texas. This region is shared by two countries: U.S and Mexico, and three different states: New Mexico, Texas, and Chihuahua.

The surface water of the Paso del Norte Region comes from the Rio Grande River; this water is stored in the Elephant Butte and Caballo Reservoirs. An annual average flow of 1,156.45 $x10^6$ cubic meters (937,570 acre-feet) reaches Elephant Butte Reservoir, but it can vary from 140.73 $x10^6$ to 3,491.9 $x10^6$ cubic meters (114,100 to 2,831,000 af) (EPCWID#1, 2007). The Elephant Butte Irrigation District (EBID) is the greatest supplier of surface water in the state of New Mexico. The EBID supplies water to more than 36,400 hectares (90,000 acres) of water right lands, divided between over 8000 constituents (EBID, 2007). "A treaty between the United States and Mexico, signed on May 21, 1906, guaranteed an annual delivery to Mexico of 74 million m^3 (60,000 acre feet) of water in perpetuity" (EPCWID#1, 2007). This water is delivered at the head of the Acequia Madre, the Mexican canal located in Ciudad Juarez, Chihuahua. The surface water of El Paso County is used for irrigation of agricultural lands, but is also used for municipal and industrial consumption (USBR, 2007).

EPCWID#1 delivers water to about 27,920 hectares (69,000 acres) of water right lands, divided in 32,727 accounts. Hudspeth County is located on the south side the El Paso County line, in the Rio

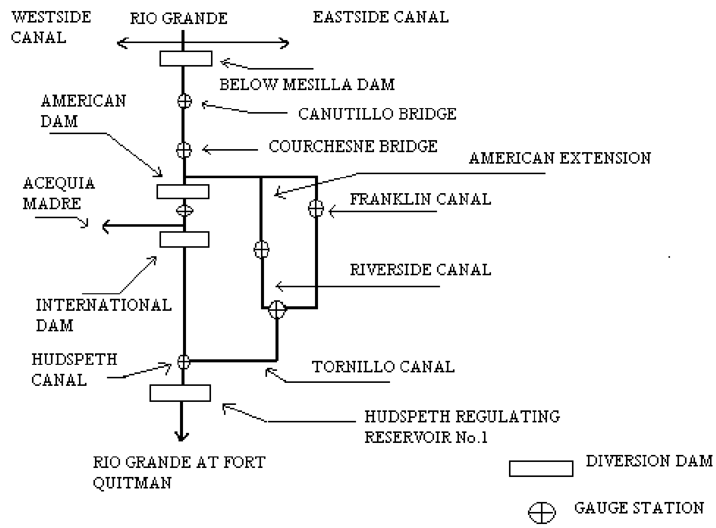

Figure 2. Schematic drawing of the EPCWID#1.

Grande. Hudspeth County Conservation and Reclamation District No.1 (HCCRD#1) provides irrigation water to 7,280 hectares (18,000 acres) in the Hudspeth County, Texas. The HCCRD#1 uses the waste and drainage return flows from The Rio Grande Project leaving the El Paso County (EPCWID#1, 2007).

Model description

Surface water is the primary source of water for the irrigation system of El Paso County. Groundwater is usually used for irrigation only during drought. However, groundwater (wells) interactions with the irrigation system were not studied because data collection on groundwater pumping is just now being initiated. Therefore, the model was focused on the surface water data. During the construction of the irrigation model, no field studies were done.

The first step in model development was the identification of the problem (MM High Performance Systems, 2000). The District needs to establish strategies to handle low flow years and to reduce salinity. A computer model is needed to simulate the flow and salinity behavior for low flow scenarios. Next, water flow inputs and outputs were identified for the system using the flow diagram shown in figure 3.

Daily water flow data used in this project was from the years 1997 to 1999 within the District. These are the only years where both flow and TDS data are available for building flow vs. TDS regressions. Time series flow and TDS data for the Rio Grande were available at El Paso (Courchesne Bridge), and Rio Grande at Fort Quitman from 1934 to 1999 from the U.S. Geological Survey (USGS). These time series were used for comparison with the 1997-1999 data, to see how typical these years were. A descriptive statistics was made from 1934 to 1999 for water flow of the Rio Grande at El Paso. The mean flow was 509 million m^3 $year^{-1}$, with a standard deviation of 285 million m^3 $year^{-1}$. The yearly flows of Rio Grande at El Paso were 595, 563, and 564 million m^3 $year^{-1}$ for 1997, 1998, and 1999 respectively.

The correlation between salinity and water flow was critical for this project. All the water quality data for flow used in this project was obtained from EPCWID#1. Electrical conductivity (mS cm^{-1} at 25°C) measurements were taken no more than two dozen times per year for each site, and usually during the irrigation season. The total dissolved solids (TDS) to EC_{25} ratio used in the reports was 0.68. During the building of the sector of the model at Fort Quitman, water flow, and water quality data of the IBWC metering station near Colonia Luis Leon was used. The unique TDS data available was for the years 1990 to 1993, and it was used for calibration purposes. The IBWC discontinued this metering station in 1994. Time series of yearly salt load of Rio Grande at El Paso (Courchesne Bridge)

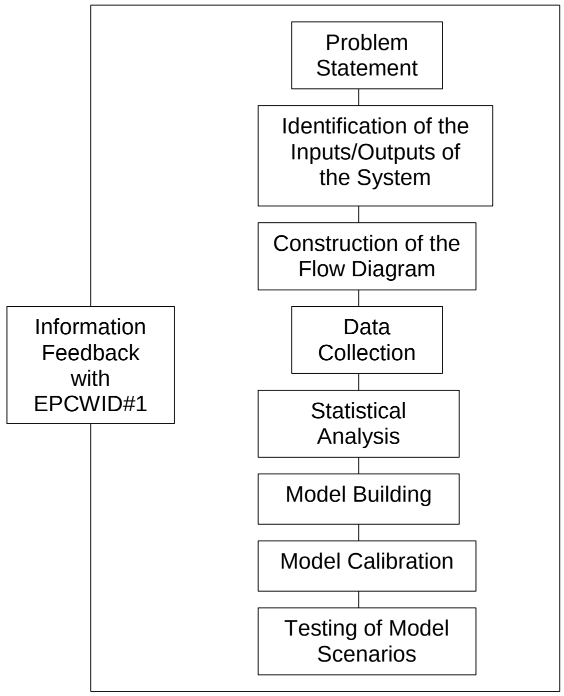

Figure 3. Schematic of the irrigation district model development

from 1934 to 1994 were built using data from Williams (2001).

A statistical analysis was made from 1934 to 1994 for salt loads of the Rio Grande at El Paso. The mean salt load was 0.375 million tons year^{-1}, with a standard deviation of 0.176 million tons year^{-1}. The calculated yearly salt load of Rio Grande at El Paso using the data collected by EPCWID#1 were 0.452, 0.441, and 0.435 million tons year^{-1} for 1997, 1998, and 1999 respectively. Miyamoto *et al.* (1995) did a study of flow and salt balance for the Paso del Norte Region, this research included a mass balance for Rio Grande at El Paso. The research used data from 1969 to 1989, and the results are showed in table 1. These results show that for that period of time, the irrigation district received approximately 577 million m^3 of water per year, and 0.467 million tons of salt per year. These results were used for comparison with the results obtained from the running of the STELLA© model.

The irrigation system computer model was divided in thirteen sectors to facilitate the system understanding. This sectors are: Rio Grande below Mesilla Dam to Rio Grande at Canutillo Bridge, Rio Grande at Canutillo Bridge to Rio Grande at Courchesne Bridge, Rio Grande below American Dam, Rio Grande below International, American Canal to Franklin Canal, Franklin Canal to Ascarate Waste way, American Extension to Riverside Canal, Franklin/Riverside Canal to Tornillo Canal, Tornillo Canal to Hudspeth Canal, Hudspeth Feeder, Hudspeth Regulating Reservoir No.1, Rio Grande at Hudspeth County, Rio Grande at Fort Quitman. Table 2 shows the data points used for the different sectors of the model, the parameters used and the source of data of each point. For most of the sectors, data from years 1997 and 1998 were used for the calibration of the model, and 1999 data was used to compare actual versus calculated data by the model.

The U.S. International Boundary Water Commission (IBWC) was the source of the water flow data at the gauging stations along the Rio Grande. The exception was the flow data at the Rio Grande below Mesilla Diversion Dam gauging station, which was collected by U. S. Bureau of Reclamation (USBR). EPCWID#1 provided the data for irrigation flows in canals and drains inside the district's irrigation system.

Table 1. Flow and salt load balance of Rio Grande at El Paso for years 1969-1989 (Miyamoto et al., 1995).

Location	River	Annual flow 10^6 m^3	Flow –weighted salinity dS m^{-1}	Salt concent. mg l^{-1}	Salt Load 10^6 tons
Inflow					
El Paso-Fort Quitman	Rio Grande	547	1.12	777	0.425
El Paso-Fort Quitman	Sewage	30	2*	1390	0.042
		577			0.467
Outflow					
American	Diversion	-332	1.12	777	
Mexican	Diversion	-65	1.12	777	-0.051
Fort Quitman	Rio Grande	-169	3.05	2083	-0.352
		-566			-0.403
Balance		**11**			**0.064**

Table 2. The irrigation district model sectors, data points, parameters used, and data sources.

Location	Data source			
	I.B.W.C.	U.S.B.R.	E.P.C.W.I.D#1	E.P.W.U.
Rio Grande below Mesilla Dam		Flow	TDS	
Rio Grande at Canutillo Bridge	Flow		TDS	
Rio Grande at Courchense Bridge	Flow		TDS	
American Dam	Flow		TDS	
International Dam	Flow		TDS	
Franklin Canal			Flow, TDS	
Ascarate Wasteway			Flow	
Riverside Canal			Flow, TDS	
Tornillo Canal			Flow, TDS	
Hudspeth Feeder Canal			Flow	
Fabens Waste Channel			Flow, TDS	
Tornillo Drain			Flow	
Tornillo Wasteway #2			Flow	
Riverside Wasteway #1			Flow	
Riverside Wasteway #2			Flow	
Rio Grande at Fort Quitman	Flow	TDS		
Effluent from Northwest WWTP				Flow
Effluent from Haskell WWTP				Flow
Effluent from Bustamante WWTP				Flow

The EPWU was the data source for water flow for diversions into the two water treatment plants, and effluents from the three wastewater treatment plants operated by El Paso Water Utilities (EPWU). Two of these wastewater treatment plants-the Haskell Street and the Bustamante-discharge directly into the Riverside Canal most of the time (EPWU, 2007).

Governing equations

A recurrent problem was the lack of data for flows and salinity in lateral and sub-lateral canals and drains inside EPCWID#1 for use the model. Also, information about irrigated acreage by canal, lateral and/or sub-lateral was not available. The objective of this model was to simulate the water flows and salinity in each one of the thirteen sectors of the irrigation system. Regression analysis of data was used to find the curve equations that control the computer model for most system sectors. Years 1997 and 1998 were used for calibration purposes, and 1999 data was used to compare results. The exception was the Rio Grande at Fort Quitman, where data from 1990 to 1993 was used for calibration purposes. Table 3 shows regression equations used for the building of the irrigation model of EPCWID#1 using STELLA© software. In most of the sectors of the model, a total sum of flows was made; it was the sum of all available input flows minus the sum of all available output flows. The total sums were compared versus actual flows at the end of each sector to obtain regression equations that control the computer model.

Model validation

After introducing the governing equations of the system into the model, the next step was to run the model using the 1999 data. The computer model created simulates the behavior of flows; TDS, accumulated flows, daily salt load, and accumulated salt load for 1999 for most sectors. After running the model it was calibrated by comparing the calculated daily flows and TDS data with the actual 1999 daily flows and actual 1999 TDS data. Flow simulations generated by the model varied in accuracy for different sectors, but in general there was good approximation (in sectors where flow data was available). The accumulated calculated flow/accumulated actual flow ratio for different sectors for 1999 is presented in table 4.

Annual flow and salt load balance using 1999 data

After running the computer model using 1999 data, the annual flow and annual salt load balance for EPCWID#1 was calculated. The stations on the Rio Grande used for this purpose were Rio Grande at Courchesne Bridge, diversions to Acequia Madre, and Rio Grande at Fort Quitman. The stations inside the EPCWID#1 used for this purpose were located on the Franklin Canal, the Riverside Canal, and the Tornillo Canal. The balance is divided in

Table 3. Regression equations used for the building of the irrigation model of El Paso County using Stella Software.

Description	Dependent variable	Regression equation	r^2
Rio Grande below Mesilla Dam	TDS (mg l^{-1})	$y= 14010\ x^{-0.2493}$	0.6013
Rio Grande at Canutillo Bridge	Flow (m^3 day^{-1})	Y=1.9872x +4866.9	0.9123
Rio Grande at Canutillo Bridge	TDS (mg l^{-1})	y=-0.0002x +1051.7	0.676
Rio Grande at Courchense Bridge	TDS (mg l^{-1})	$y= 218608x^{-0.3916}$	0.8407
Rio Grande at Courchense Bridge	Flow (m^3 day^{-1})	y= 1.7418+113343	0.9263
Rio Grande below American Dam	TDS (mg l^{-1})	y= 0.9483x +13.222	0.9617
Rio Grande below American Dam during irrigation season	Flow (m^3 day^{-1})	y= 0.9276x +49095	0.8088
Rio Grande below American Dam during non- irrigation season	Flow (m^3 day^{-1})	Y=0.8724x +87229	0.837
Franklin Canal	TDS (mg l^{-1})	y= 0.9661x +40.933	0.9811
Riverside Canal	TDS (mg l^{-1})	y= 1.4026x -305.59	0.9266
Riverside Canal during irrigation season	Flow (m^3 day^{-1})	y= 0.9607x -93240	0.9876
Riverside Canal during non- irrigation season	Flow (m^3 day^{-1})	y= 0.9019x +2514.3	0.7298
Tornillo Canal	TDS (mg l^{-1})	y= 0.9036x +121.39	0.823
Tornillo Canal	Flow (m^3 day^{-1})	y= 0.264x +8492	0.7353
Hudspeth Feeder Canal	Flow (m^3 day^{-1})	y= 0.6507x +71756	0.5605
Rio Grande at Fort Quitman	TDS (mg l^{-1})	$y= 498439x^{-0.4161}$	0.8917
Rio Grande at Fort Quitman	Flow (m^3 day^{-1})	y= 0.9542x+152280	0.9004

two segments: flow of channels inside EPCWID#1, and flow of Rio Grande outside the EPCWID#1. Table 5 presents the annual flow and salt load balance using 1999 data. The first segment shows the difference in flow and salt load among the Franklin, Riverside, and Tornillo Canal. The Franklin and Riverside canals are both fed by a single flow diversion at the American Dam. Both canals eventually join to feed the Tornillo Canal as shown in figure 4 **(**after discharging into lateral and sub-lateral canals). The Riverside Canal is the most important canal inside the EPCWID#1 (based on the amount of water delivered). The Riverside Canal also receives the treated effluent from the Haskell and the Roberto Bustamante Wastewater Treatment Plant (EPWU, 2007). The balance shows the combined deliveries of the Franklin and Riverside canals in the El Paso Valley (positive value in the balance). The combined delivery was 321 million m^3, before reaching the Tornillo Canal. Also, deliveries from both the Franklin and Riverside canals contained (positive value in the balance) 251,000 tons of salt that was released into laterals and sub-laterals before reaching the Tornillo Canal. The second segment shows the difference in flow and salt load between the Rio Grande at Courchesne Bridge and the Rio Grande at Fort Quitman.

Diversions at the International Canal into the Acequia Madre into Mexico amounted to 72 million m^3, with a salt load of 38,000 tons. In this segment, the Rio Grande had a flow gain (positive value in the balance) of 320 million m^3, and a slight gain in salt load of 41,000 tons. This result shows that most of the salt load carried out of the Rio Grande at Courchesne Bridge through the EPCWID#1, came

Table 4. The Accumulated calculated flow/Accumulated actual flow ratio for different sectors for 1999.

Sector	accumulated calculated flow/ accumulated actual flow ratio
Rio Grande at Canutillo Bridge	0.948
Rio Grande at Courchesne Bridge	1.057
Rio Grande below American Dam	0.896
American Extension-Riverside	0.988
Franklin/Riverisde- Tornillo Canal	0.965
Hudspeth Feeder	0.919
Rio grande at Fort Quitman	0.737

Table 5. Annual flow and salt load balance for three segments: Rio Grande upstream the EPCWID#1, main canals inside the EPCWID#1, and Rio Grande downstream the EPCWID#1 for 1999.

LOCATION	Annual Flow (10^6 m^3)	Salt Load (10^6 ton)
Inside EPCWID#1		
Franklin Canal	82	0.063
Riverside Canal	338.4	0.27
Tornillo Canal	-99.5	-0.082
Balance	**320.9**	**0.251**
Outside EPCWID#1		
Rio Grande at Couchersne Bridge	564.1	0.435
Acequia Madre	-71.9	-0.038
Rio Grande at Fort Quitman	-171.8	-0.356
Balance	**320.4**	**0.041**

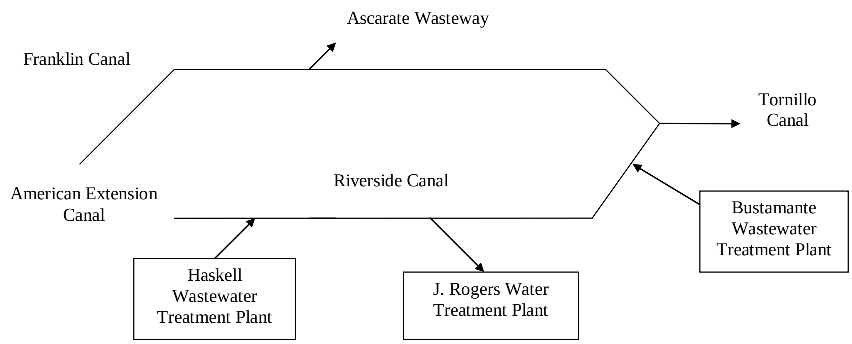

Figure 4. Schematic drawing of the three main canals inside EPCWID#1.

back to the Rio Grande as irrigation return flow.

After comparing the results from table 5 (annual flow and salt load for actual 1999 data) with the results from table 1 (Salt load balance of Rio Grande at El Paso for years 1969-1989), results obtained from model using actual 1999 data, are very consistent with work done by Miyamoto et al, for flow and salt load of Rio Grande at El Paso, Mexican diversion (Acequia Madre), and Rio Grande at Fort Quitman over a 20 year period of record. This comparison shows that year 1999 had an annual flow just above the average according to the Miyamoto's research.

Modeling scenarios

The modeling scenarios selected for this project were based on a statistical analysis that was made using USGS data from 1934 to 1999 for water flow and TDS of the Rio Grande at El Paso. The mean flow was 509.26 million m^3 $year^{-1}$, with a standard deviation of 285.46 million m^3 $year^{-1}$. The mean salt load was 0.375 million tons $year^{-1}$, with a standard deviation of 0.176 million tons $year^{-1}$. Three were the selected scenarios: a) the mean flow +1 standard deviation, b) the mean flow –1 standard deviation, and c) the mean flow –1.5 standard deviation.

The first scenario represents a year with high flow; the second scenario represents a year with low flow, and the third scenario represents a year with severe drought (for the third scenario, the mean-1.5 standard deviation was used instead the mean flow -2 standard deviation to avoid negative values in the results). The scenarios two and three were selected in order to observe the water flows and salinity trends during drought conditions, which are critical conditions for salt accumulation on the irrigated lands. These both two scenarios were used also to calculate the daily TDS along the year for the three main canals inside the EPCWID#1.

The computer model was run for the three selected scenarios using the 1999 data, just adjusting the 1999 yearly flow with a knob to match with the amount desired for the yearly flow of the selected scenario. After running the computer model for the three scenarios, the yearly flow and salt load balance for EPCWID#1 was calculated for each scenario. The stations on the Rio Grande used for this purpose were Rio Grande at Courchesne Bridge, diversions to Acequia Madre, and Rio Grande at Fort Quitman. The stations inside the EPCWID#1 used for this purpose were located on the Franklin Canal, the Riverside Canal, and the Tornillo Canal.

Results of model scenarios

For scenario 1, the calculated yearly flow was 794 million m^3 $year^{-1}$ based on the sum of the mean flow plus one standard deviation (509 million m^3 $year^{-1}$ + 285 million m^3 $year^{-1}$). For scenario 2, the yearly flow was 224 million m^3 $year^{-1}$ (509 million m^3 $year^{-1}$ - 285 million m^3 $year^{-1}$). For scenario 3, the yearly flow was 81 million m^3 $year^{-1}$ (509 million m^3 $year^{-1}$ –428 million m^3 $year^{-1}$). After running the computer model for the three scenarios, the annual flow and annual salt load balances for EPCWID#1 were calculated. Table 6 shows an annual flow and annual salt load balance comparison of the three model scenarios.

The balances are divided in two sectors: the system

Table 6. Comparison of annual flow and salt load balance for the three model scenarios.

Location	Scenario 1		Scenario 2		Scenario 3	
	Annual Flow (10^6 m^3)	Salt Load (10^6 tons)	Annual Flow (10^6 m^3)	Salt Load (10^6 tons)	Annual Flow (10^6 m^3)	Salt Load (10^6 tons)
Inside EPCWID#1						
Franklin Canal	114.8	0.078	32.8	0.035	11.5	0.018
Riverside Canal	457.8	0.303	159.7	0.205	87	0.188
Tornillo Canal	-133.9	-0.095	-47.8	-0.061	-25.4	-0.053
Balance	**438.7**	**0.286**	**144.7**	**0.179**	**73.1**	**0.153**
Outside EPCWID#1						
Rio Grande at Couchersne Bridge	789.8	0.534	225.6	0.249	79.4	0.132
Acequia Madre	-71.9	-0.038	-31.6	-0.017	-11.5	-0.006
Rio Grande at Fort Quitman	-218.3	-0.406	-102.1	-0.269	-71.9	-0.223
Balance	**499.6**	**0.09**	**91.9**	**-0.037**	**-4**	**-0.097**

inside the EPCWID#1, and the system outside the EPCWID#1. The balances show Franklin and Riverside canals discharged 438, 145, and 73 million m^3 of water for scenarios one, two, and three respectively, onto irrigated lands served by these canals. Also, releases from both the Franklin and Riverside canals contained (positive value in the balance) 286,000, 179,000, and 153,000 tons of salt that was deposited through the laterals and sub-laterals before reaching the Tornillo Canal, for scenarios one, two, and three respectively. The second segment shows the difference in flow and salt load between the Rio Grande at Courchesne Bridge and the Rio Grande at Fort Quitman. In this segment, the Rio Grande had flow gains of (positive value in the balance) of 500, and 92 million m^3 for scenarios one and two respectively.

For scenario three, the flow balance shows a flow loss of 4 million m^3. This result implies the extensive use of pumping wells during drought periods to satisfy domestic and agricultural needs which is the actual case. The salt load balance for scenario one shows a slight gain in salt load of 90,000 tons. For scenarios two and three, the salt load balances present salt losses of 37,000, and 97,000 tons respectively. These results can be explained by the increase in salinity of the return flows, and unaccounted salt inputs to the system like the pumping wells used to satisfy the domestic and agricultural supply, which has a higher salinity than surface water.

For scenario two and three, daily calculated TDS graphs for the Franklin, the Riverside and the Tornillo Canal are presented. Table 7 shows a typical classification of water quality for irrigation purposes (USBR, 2007). Water containing TDS more than 1900 mg l^{-1} is generally considered unsuitable for agriculture.

Table 7. Quality Classification of Water for Irrigation.

Water class	TDS (mg l^{-1})
Excellent	<160
Good	160-480
Permissible	480-1300
Doubtful	1300-1900
Unsuitable	>1900

Figure 5 shows daily calculated TDS at Franklin Canal for scenarios 2 and 3. For Scenario 2, the daily calculated TDS for this canal varies from 612 to 2505 mg l^{-1}. The water quality of the Franklin Canal is considered unsuitable for agriculture eighty-three days along the year (TDS>1900 mg l^{-1}), none of these days occurs during the irrigation season (March to October). For scenario 3, the daily calculated TDS varies from 895 to 3740 mg l^{-1}. The water quality of the Franklin Canal was unsuitable for agriculture a hundred and thirty four days along the year.

Figure 6 shows the daily calculated TDS at the Riverside Canal for scenario 2 and 3. For scenario 2, daily calculated TDS varies from 500 to 3270 mg l^{-1}. The water quality of the Riverside Canal is considered unsuitable for agriculture a hundred and

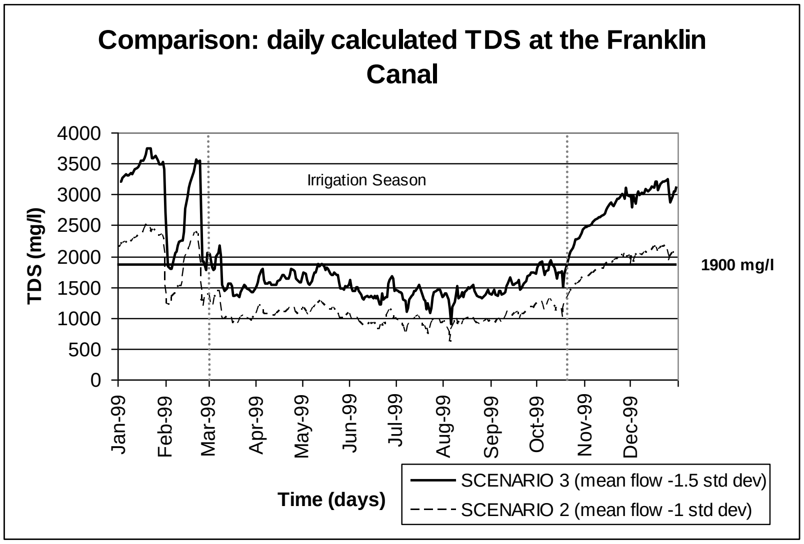

Figure 5. Daily TDS comparison of scenarios 2 and 3 for Franklin canal.

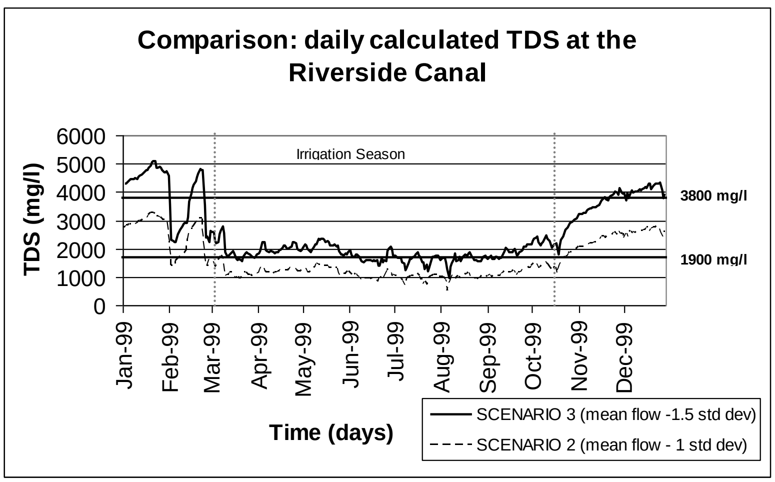

Figure 6. Daily TDS comparison of scenarios 2 and 3 for Riverside Canal.

eight days over the year. For scenario 3, daily calculated TDS varies from 1335 to 5070 mg l^{-1}. The water quality of the Riverside Canal is considered unsuitable two hundred and twenty one days over the year (TDS>1900 mg l^{-1}), eighty-six of these days occurred during the irrigation season. An issue of critical importance is that from the two hundred and twenty one days with unsuitable water quality, seventy-eight days have salinity higher than 3800 mg l^{-1} (two times the value for unsuitable water for irrigation purposes). The increase in salinity in the Riverside Canal due to effluent discharges from the Haskell Street and Roberto Bustamante Wastewater Treatment Plants.

Figure 7 shows the daily calculated TDS at the Tornillo Canal. Daily calculated TDS varies from 600 to 3000 mg l^{-1}. The water quality of the Tornillo Canal was unsuitable for agriculture a hundred and four days during the year (TDS>1900 mg l^{-1}). For scenario3, daily calculated TDS varies from 968 to 4580 mg l^{-1}. The water quality of the Tornillo Canal was unsuitable for agriculture two hundred and one days during the year (TDS>1900 mg l^{-1}), sixty-six of these days occurred during the irrigation season. Like in the case of Riverside Canal, from the days with unsuitable water quality, forty-six days have salinity higher than 3800 mg l^{-1}. None of these days with salinity equal or higher

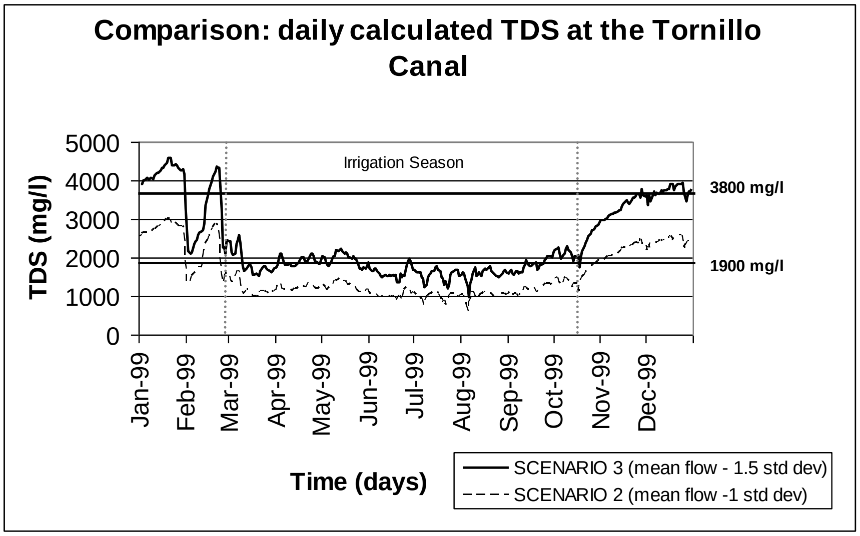

Figure 7. Daily TDS comparison of scenarios 2 and 3 for Tornillo Canal.

than 3800 mg l^{-1} occur during the irrigation season.

Conclusions

This research resulted in the development of a system dynamics model for EPCWID#1. Even though this model does not include the surface water- groundwater interactions the results do, however, illustrate the impacts of ground water pumping on surface water flows and salinity as shown in the mass balances for the three scenarios.

Regression equations that control the model were obtained varying in their determination coefficient r^2 (see table 3). Flow results generated by the model varied in accuracy for different sectors, but in general with good approximation (see table 4). A comparison of the results of the table 5 (annual flow and salt load for actual 1999 data) with the results of the table 1 (Salt load balance of Rio Grande at El Paso for years 1969-1989), shows that 1999 results of flow and salt load for Rio Grande at El Paso, Mexican diversion, and Rio Grande at Fort Quitman had an annual flow just above the average according to the Miyamoto et al research. After running the model for the three selected scenarios, the daily TDS of the three main canals for scenarios two and three (drought and severe drought) were obtained. The results show very high salinity concentrations inside EPCWID#1 under low flow conditions. These results imply a high salt deposition on the irrigated lands. All the three canals have their lowest water quality (highest salinity) during the winter months, and for both the two low flow scenarios, the Riverside Canal presents the highest values of TDS and the highest number of days with the lowest water quality (see figure 6). The salinity increase in the Riverside Canal is caused by discharges to the canal from the Haskell Street and Roberto Bustamante Wastewater Treatment Plants. Salt deposition into EPCWID#1 can be monitored by establishing a permanent water quality monitoring program. The monitoring of TDS is critical during low flow periods. In addition, the use of underground water with high salinity levels for irrigation should be avoided. For that reason, groundwater pumping for irrigation purposes should be closely monitored in order to evaluate its impact on the system and to establish when this water should be used directly on the field or if it must be blended previously with surface water in order to reduce its salinity level. Salinity problems are currently mitigated by the application of excess water during years of high allotments which are created by heavy snowfall in the San Luis Valley Mountains of Southern Colorado. This water is distributed near the end of an agricultural season in order to leach salts from the soil. This model can be improved through the collection of minimal additional data within the District. The model can then be used to assist with the identification of specific lands with salinity problems. Perhaps the greatest benefit of this type of model is the ability of system manager to "play" with model controls and observe the impact of selected annual flow conditions on salinity within the District and movement of salt loads downstream out of the District.

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