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TWRI TR 297

# The Development of a Coordinated Database for Water Resources and Flow Model in the Paso Del Norte Watershed

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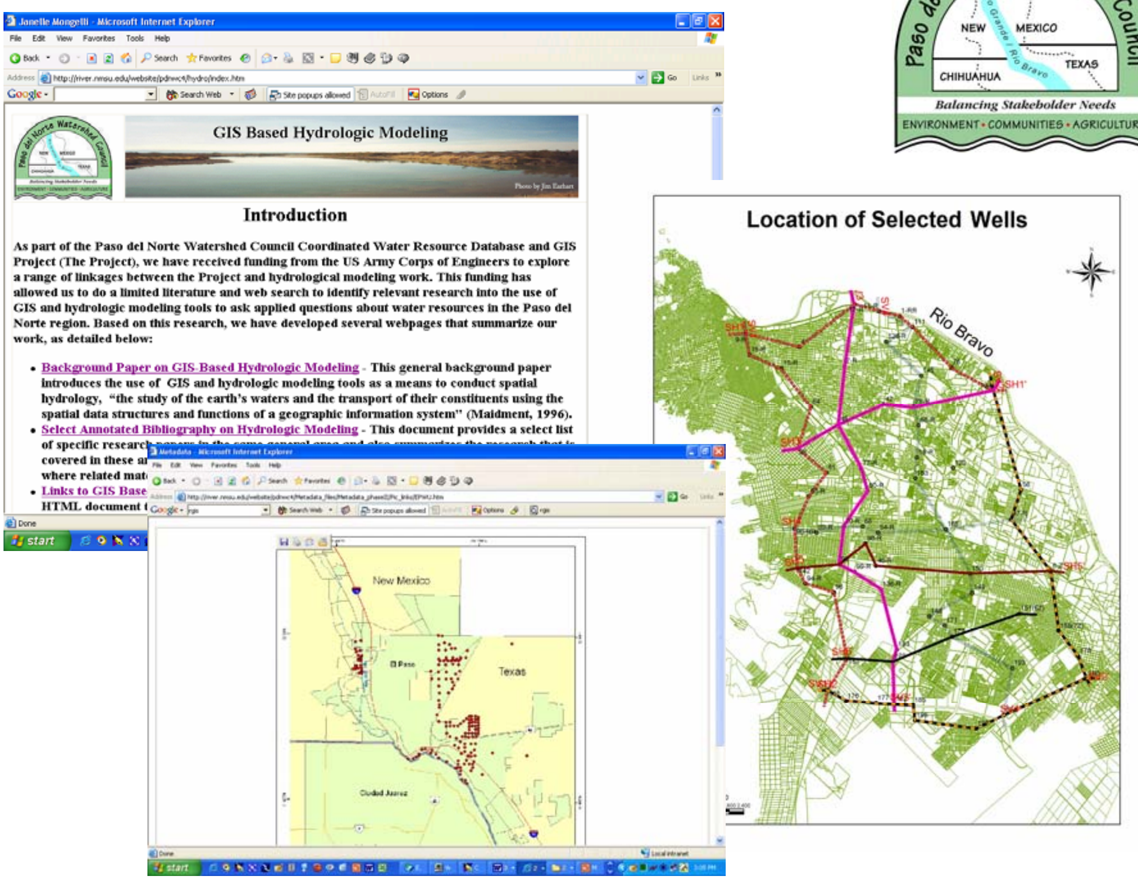
New Mexico Water Resources Research Institute
Texas Water Resources Institute

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# THE DEVELOPMENT OF A COORDINATED DATABASE FOR WATER RESOURCES AND FLOW MODEL IN THE PASO DEL NORTE WATERSHED

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Account Number: TAES/03-PL-02, Modification No. 2

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Texas Agricultural Experiment Station

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**Phase II Final Project Report of Work Completed under the Cooperative Agreement between the U.S. Army Corps of Engineers and Texas Agricultural Experiment Station**

**(TAES/03-PL-02)**
**Modification No. 2**


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# Abstract

This report fulfills the deliverables required by the cooperative agreement between the U.S. Army Corps of Engineers and Texas Agricultural Experiment Station (TAES/03-PL-02: Modification No. 2) on behalf of the Paso del Norte Watershed Council. Tasks accomplished in this phase include (a) review of hydrological models in the region; (b) conceptual model of the Rio Grande flow; and (c) linkage protocol of the coordinated database and hydrological models. In addition, a training workshop on the RiverWare model was offered to regional water stakeholders. Twenty-four trainees attended the workshop at New Mexico State University on December 15-17, 2004. The Project Team also provided review on the FLO-2D model simulation of the Rio Grande flood control scenarios at the U.S. IBWC on August 3, 2005, review of QA/QC procedures of the real-time data collection, and assessment of regional orthophotographic images in 2005.

This Project was conducted by researchers at Texas A&M University (TAMU) and New Mexico State University (NMSU) under the direction of Zhuping Sheng of TAMU. It was developed to enhance the coordinated database, which was originally developed by the Paso del Norte Watershed Council with support of El Paso Water Utilities to fulfill needs for better management of regional water resources and to expand the Upper Rio Grande Water Operations Model (URGWOM) to cover the river reaches between Elephant Butte Dam, New Mexico and Fort Quitman, Texas. In Phase I of this Project (TAES/03-PL-02), hydrological data needed for flow model development were compiled and data gaps were identified. The objectives of this phase were to develop a conceptual model of the Rio Grande flow between Elephant Butte Dam and American Dam by using data collected in the first development phase of the PdNWC/Corps Coordinated Water Resources Database and to enhance the data portal capabilities of the PdNWC Coordinated Database Project.

The first part of this report (corresponding to Task Five of the contract for the Development of a Coordinated Database and GIS for Water Related Resources in the Rio Grande Watershed, written by Sue Tillery, Phillip King and Zhuping Sheng), summarizes the hydrological models developed for surface water and groundwater flows and management of regional water resources in terms of model configuration, advantages, and limitations of each modeling approach. This part of the report also identifies and verifies the availability of relevant hydrological data needed for development of the RiverWare model, especially hydrology of drain return flows. Based on previous modeling studies, the authors evaluated reasonable simplifications (through the use of look-up tables or similar tools) of interaction of surface and groundwater within the Mesilla Basin and Rincon Valley and developed the RiverWare conceptual model for the Rio Grande flow for the selected reaches and within the limits of available data.

The second part of this report was written by C. Brown and B. Creel and summarizes the data portal enhancements to the PdNWC Coordinated Database for its linkage to the URGWOM development. This part of the report describes enhancements to the data portal capabilities of the Project through the development of a low-end user interface that would serve GIS-based graphics of each data set and enhanced metadata of relevant data sets. A literature search of bibliographic resources detailing GIS-based hydrologic modeling in the Paso del Norte region and linkages to these resources are provided via portions of the Project website.

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# THE DEVELOPMENT OF A COORDINATED DATABASE FOR WATER RESOURCES AND FLOW MODEL IN THE PASO DEL NORTE WATERSHED

## Introduction

This part of the report is in response to TASK 5 of the contract for the ***Development of a Coordinated Database for Water Related Resources and Flow Model in the Paso del Norte Watershed*** and was prepared by Suzanne Tillery, J. Phillip King, and Zhuping Sheng. Specifically, the following subtasks are addressed:

"Identify and verify the availability of relevant hydrological data (inflows, outflows and hydrological properties of the river) within the reaches between Elephant Butte Reservoir [New Mexico] (including San Marcial) and El Paso [Texas] needed for development of the RiverWare model, especially hydrology of drain return flows…"

"Evaluate, based on previous modeling studies, reasonable simplifications (through the use of look up tables or similar tools) of interaction of surface and groundwater within the Mesilla Basin and Rincon Valley."

"…develop the RiverWare conceptual model for the Rio Grande [Project] flow for the selected reaches and within the limits of available data…"

The main objective here is to describe a conceptual RiverWare model of the Rio Grande pursuant to the subtask item requirements listed above. In developing the conceptual RiverWare model, the following intermediate objectives were also accomplished:

- Schematics were created that show the major river flows, diversions and return flows along the Rio Grande. The upper portion of the Rio Grande Project was divided into three (3) reaches: the Rincon Reach from Caballo Dam to Leasburg Diversion Dam; the Leasburg Reach from Leasburg Diversion Dam to Mesilla Diversion Dam; and the Mesilla Reach from Mesilla Diversion Dam to the Rio Grande at El Paso.

- A table was produced showing the data availability since 1975 for each of the locations specified in the schematics.

- Some methods used by previous selected modeling studies to simulate the interaction of surface water and groundwater were reviewed and evaluated.

- An ARIMA time-series *transfer function* analysis of the relationship between diversions to Arrey Canal and flow in the Garfield, Hatch, and Rincon drains was completed and compared to the simpler relationships described in the previous modeling studies.

- An ARIMA time-series *transfer function* analysis of the relationship between diversions to Arrey Canal and net ungaged inflow (gains/losses) in the reach between Caballo Dam and Leasburg Diversion Dam was completed.

- The RiverWare conceptual model was constructed based on the reach schematics, available data and ARIMA time-series *transfer function* relationships. This model simulates the Rincon Reach between Caballo Dam and Leasburg Diversion Dam for monthly observed data from 1979 through 1999.

## Reach Schematics

The reach schematics for the conceptual model were developed based primarily on the physiography of the study area and on the locations of the major diversion dams. This conceptual development of the reaches is intended to resemble the actual geometry of the system and also to fit the available data.

The Rio Grande from Caballo Dam New Mexico to El Paso, Texas flows across the Rincon Valley Basin and the Mesilla Bolson as shown in Figure 1. At the southern end of each basin, the Rio Grande crosses a structurally high bedrock constriction. Selden Canyon between Rincon and Leasburg and the El Paso Narrows at El Paso represent these high bedrock zones that delineate the southern end of each basin. These constrictions create separate groundwater systems that are linked by the common river (King and Maitland 2003).

The upper portion of the Rio Grande Project from the river below Caballo Dam to the river at El Paso was divided into three reaches for this conceptual model. These reaches are delineated by the major diversion dams in this length of the Rio Grande and by the physiography of the area. The three reaches are:

- The Rincon Reach,
- The Leasburg Reach, and
- The Mesilla Reach.

These reaches are described in the following sections.

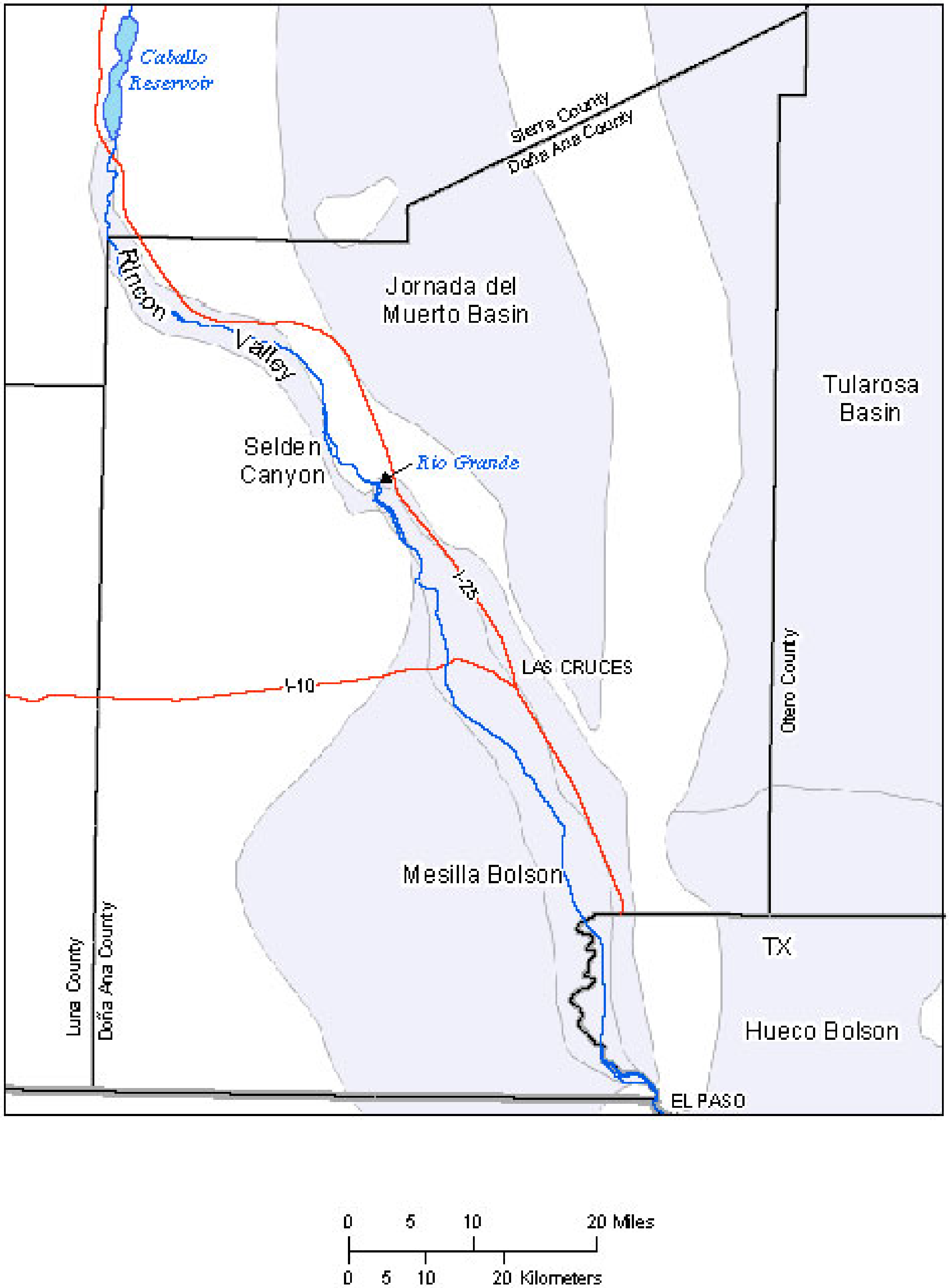



Figure 1. Physiography of the Rio Grande between Caballo and El Paso

## RINCON REACH

The Rincon Reach was created to simulate the Rio Grande between Caballo Dam and Leasburg Diversion Dam. Percha Diversion Dam is located approximately 1 mile south of Caballo Dam and is the initial diversion point of the system. At this location, water is diverted for irrigation into the Arrey Canal and into the Percha Lateral. The Arrey Canal carries the majority of the water diverted at this dam and distributes the irrigation water throughout the entire Rincon Valley. The Percha Lateral diverts a small amount of water to irrigate farms in the vicinity of the diversion dam only. The schematic for this reach is shown in Figure 2.

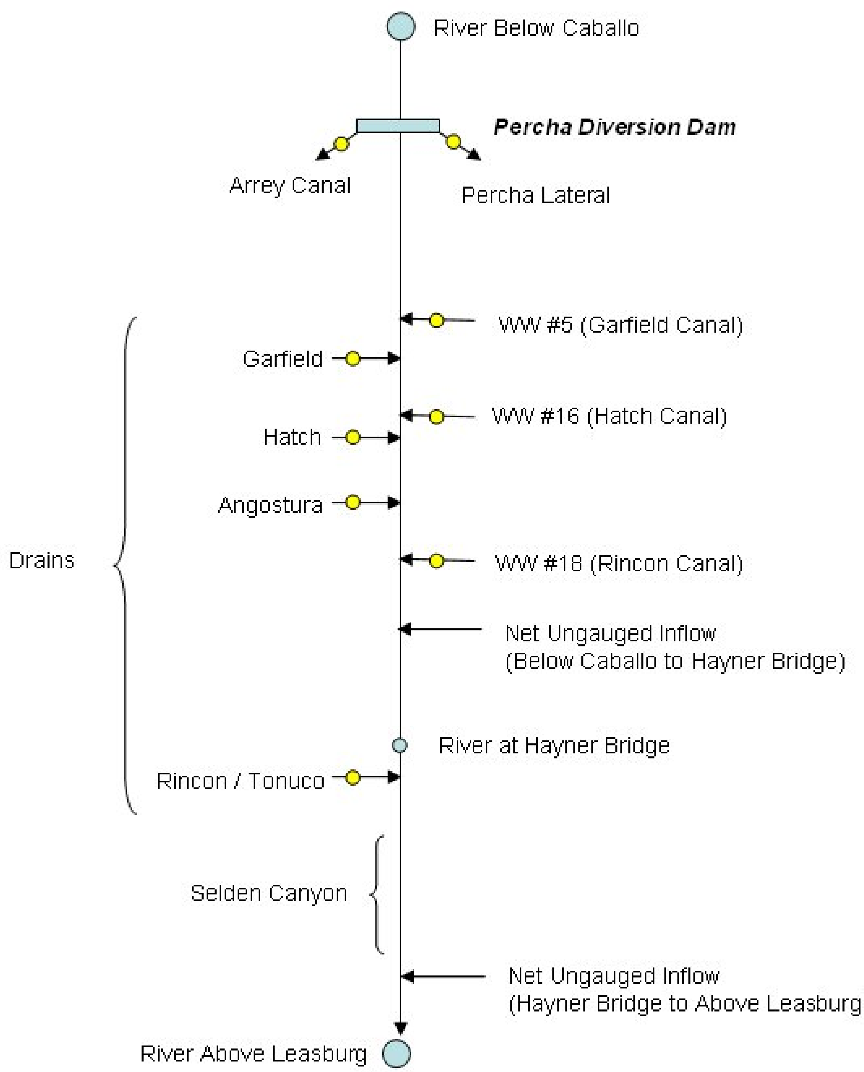



Figure 2. Schematic of the Rincon Reach (blue circles represent the river stations and yellow circles represent diversions and return flows)

These represent gaged flows. All return flows to the river in this reach are from the water diverted to the Arrey Canal.

## LEASBURG REACH

The Leasburg Reach was created to simulate the Rio Grande between Leasburg Diversion Dam and Mesilla Diversion Dam. At the Leasburg Diversion Dam, water is diverted for irrigation into the Leasburg Canal. The schematic for this reach is shown in Figure 3.

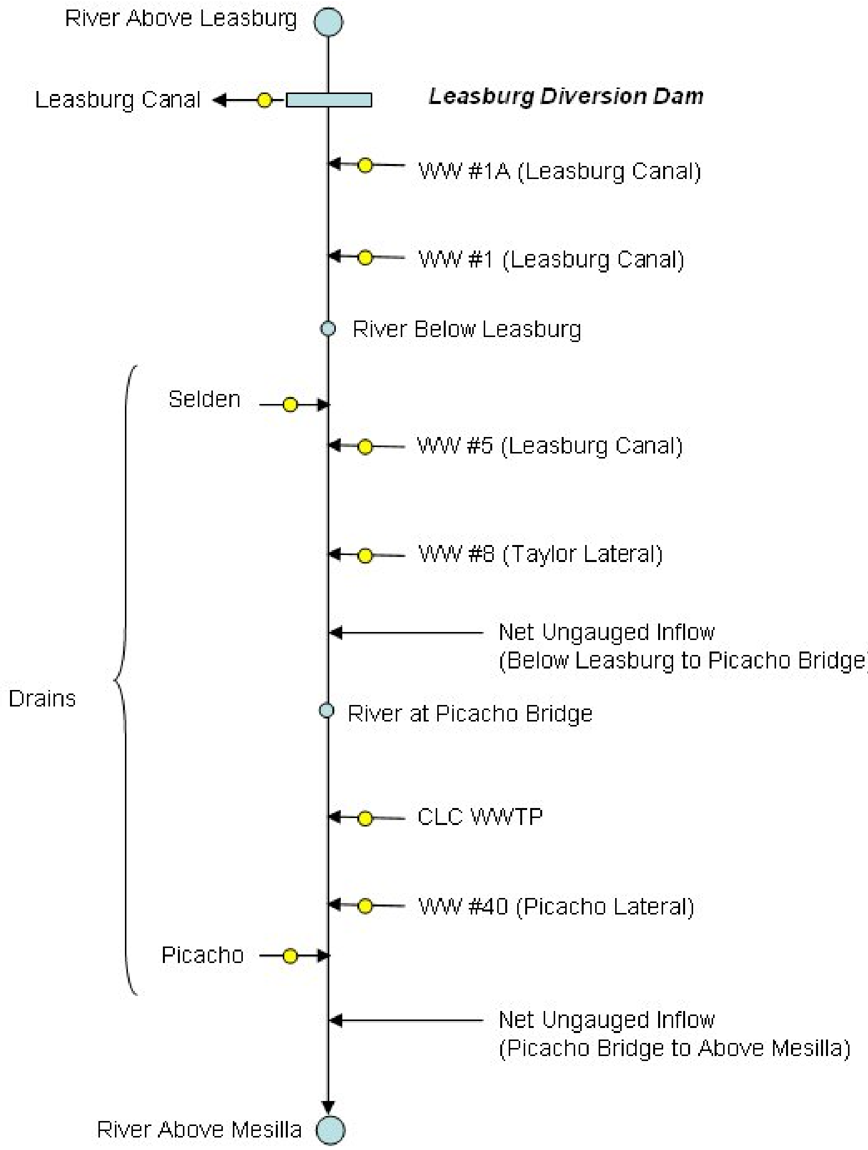



Figure 3. Schematic of the Leasburg Reach (blue circles represent the river stations and yellow circles represent diversions and return flows)

## MESILLA REACH

The Mesilla Reach was created to simulate the Rio Grande between Mesilla Diversion Dam and the Rio Grande at El Paso. At the Mesilla Diversion Dam, water is diverted for irrigation into the Westside Canal, the Eastside Canal, and the Del Rio Lateral. Return flows to the river in this reach occur from each diversion. The schematic for this reach is shown in Figure 4.

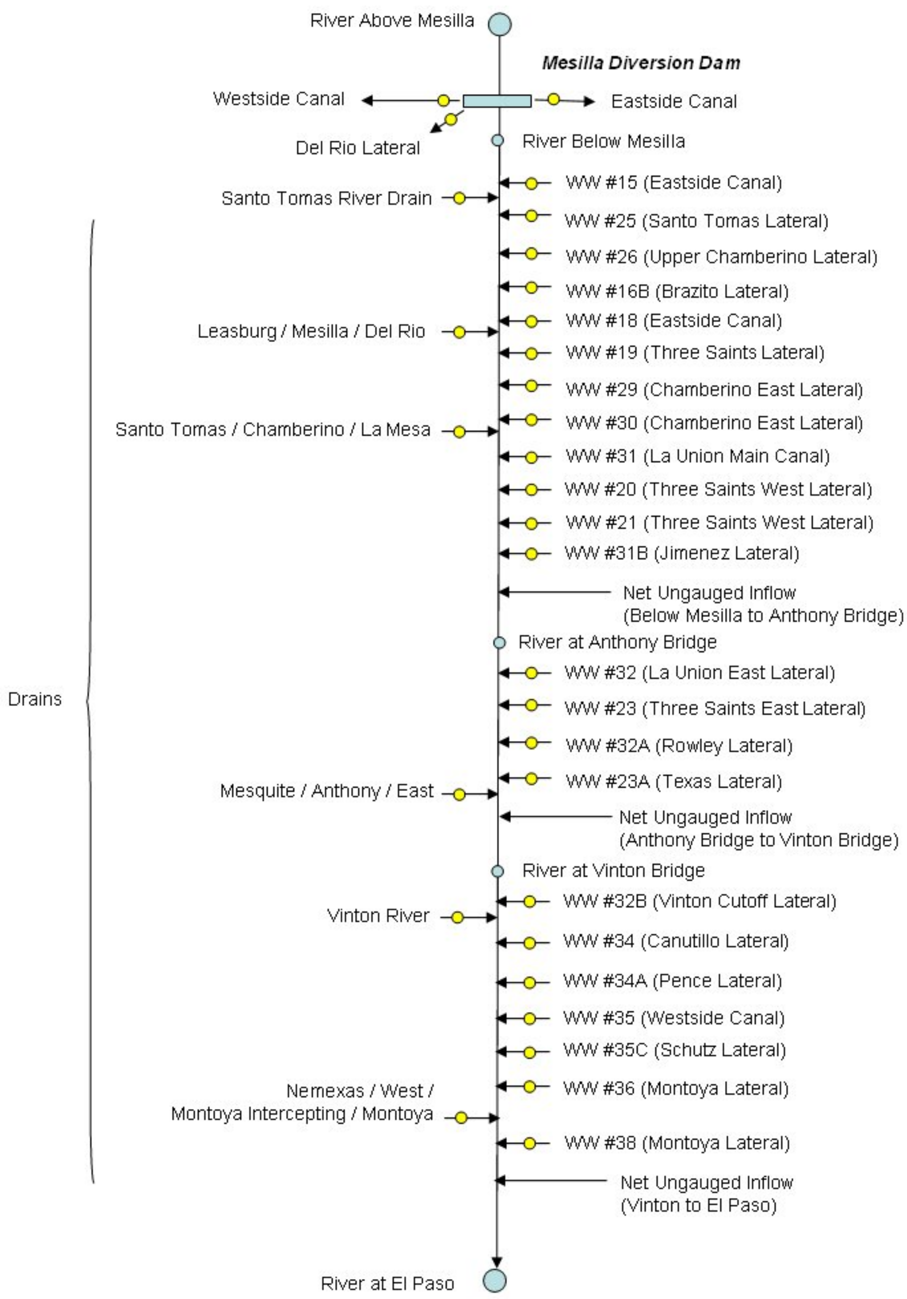



Figure 4. Schematic of the Mesilla Reach (blue circles represent river stations and yellow circles represent diversions and return flows)

# Relevant Hydrological Data

A summary of the flow data available since 1975 is shown in Table 1. This table spans sites along the Rio Grande from below Caballo Dam to the Rio Grande at El Paso. Also indicated in the table is whether the data are daily data, monthly data, or if no data are available. Daily data are needed for flood control planning; while monthly data can be used for transfer function analysis.

Table 1. Available Flow Data Since 1975 (Brown et al. 2004)

| ***Site*** | ***Available Data Since 1975*** [1] |
|---|---|
| *Rio Grande Below Caballo Dam* | 1975-5/2005 (d) |
| *Arrey Canal (Percha Div. Dam)* | 1975-1999 (d), 2000 (n), 2001-2004 (d) |
| *Percha Lateral (Percha Div. Dam)* | 1979-1999 (d), 2000 (n), 2001-2004 (d) |
| *WasteWay (WW) #5 (Garfield Canal)* | 1979-1984 (d), 1985-1986 (n), 1987 (d), 1988-1992 (n) 1993-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Garfield Drain* | 1975-1981 (m), 1982-1999 (d), 2000 (n), 2001-2004 (d) |
| *WW #16 (Hatch Canal)* | 1979-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Hatch Drain* | 1975-1981 (m), 1982-1999 (d), 2000 (n), 2001-2004 (d) |
| *Angostura Drain* | 1975-1983 (m) |
| *WW #18 (Rincon Canal)* | 1979-1999 (d), 2000 (n), 2001-2004 (d) |
| *Rio Grande at Haynor Bridge* | 2001-5/2005 (d) |
| *Rincon/Tonuco Drain* | 1975-1981 (m), 1982-1999 (d), 2000 (n), 2001-2004 (d) |
| *Rio Grande Above Leasburg Dam* | 1975-1983 (d) |
| *Leasburg Canal (at Heading)* | 1975-1995 (d), 1996 (n), 1997-1999 (d), 2000 (n) 2001-6/2003 (d) |
| *WW #1A (Leasburg Canal)* | 1989-1992 (d), 1993 (n), 1994-1997 (d), 1998-2000 (n) 2001-2002 (d) |
| *WW #1 (Leasburg Canal)* | 1997-1999 (d), 2000 (n), 2001-2002 (d) |
| *Rio Grande Below Leasburg Dam* | 1975-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Selden Drain* | 1975-1983 (m) |
| *WW #5 (Leasburg Canal)* | 1979-1999 (d), 2000 (n), 2001-6/2003 (d) |
| *WW #8 (Taylor Lateral)* | 1979-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Rio Grande at Picacho Bridge* | 1991-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *City of Las Cruces WWTP* | 5/1976-2/1996 (d) |
| *WW #40 (Picacho Lateral)* | 1991-1999 (d) |
| *Picacho Drain* | 1975-1983 (m), 1984-1990 (n), 1991-1999 (d) 2000 (n), 2001-6/2003 (d) |
| *Rio Grande Above Mesilla Dam* | (n) |
| *Westside Canal (Mesilla Div. Dam)* | 1975-1983 (d), 1984 (n), 1985-1999 (d), 2000 (n) 2001-6/2003 (d) |
| *Eastside Canal (Mesilla Div. Dam)* | 1975-1999 (d), 2000 (n), 2001-6/2003 (d) |
| *Del Rio Lateral (Mesilla Div. Dam)* | 1975-1992 (d), 1993 (n), 1994-1999 (d), 2000 (n) 2001-6/2003 (d) |

[1] d - daily data, m - monthly data, n - no data

| *Site* | *Available Data Since 1975* [1] |
|---|---|
| *Rio Grande Below Mesilla Dam* | 1985-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *WW #15 (Eastside Canal)* | 1985-1999 (d), 2000 (n), 2001-6/2003 (d) |
| *Santo Tomas River Drain* | 1985-1990 (d) |
| *WW #25 (Santo Tomas Lateral)* | 1985-1999 (d), 2000 (n), 2001 (d) |
| *WW #26 (Upper Chamberino Lateral)* | 1979-1999 (d), 2000-5/2001(n), 6/2001-5/2005 (d) |
| *WW #16B (Brazito Lateral)* | 1985-1990 (d) |
| *WW #18 (Eastside Canal)* | 1985-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Leasburg / Mesilla / Del Rio Drain* | 1975-1980 (m), 1981-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *WW #19 (Three Saints Lateral)* | 1982-1999 (d), 2000 (n), 2001-6/2003 (d) |
| *WW #29 (Chamberino East Lateral)* | (n) |
| *WW #30 (Chamberino East Lateral)* | 1985-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *Santo Tomas/Chamberino/La Mesa Drain* | 1975-1980 (m), 1981-1999 (d), 2000 (n), 2001-5/2005 (d) |
| *WW #31 (La Union Main Canal)* | 1981-1999 (d), 2000 (n), 2001-6/2003 (d) |
| *WW #20 (Three Saints West Lateral)* | 1979-1980 (d), 1981-1984 (n), 1985-1988 (d) |
| *WW #21 (Three Saints West Lateral)* | 1985-1991 (d), 1992-1996 (n), 1997-6/2003 (d) |
| *WW #31B (Jimenez Lateral)* | 1985-1988 (d), 1989-2000 (n), 2001-5/2005 (d) |
| *Rio Grande at Anthony Bridge* | 1986-1989 (d), 1990-2000 (n), 2001-5/2005 (d) |
| *WW #32 (La Union East Lateral)* | 1979-1992 (d), 1993-1996 (n), 1997-1999 (d), 2000 (n)<br>2001-6/2003 (d) |
| *WW #23 (Three Saints East Lateral)* | (n) |
| *WW #32A (Rowley Lateral)* | 1985-1988 (d) |
| *WW #23A (Texas Lateral)* | 1985-1992 (d), 1993-1996 (n), 1997-1999 (d), 2000 (n)<br>2001-6/2003 (d) |
| *Mesquite/Anthony/East Drain* | 1975-1980 (m), 1981-1992 (d), 1993 (n), 1994-5/2005 (d) |
| *Rio Grande at Vinton Bridge* | 1985-1992 (d) |
| *WW #32B (Vinton Cutoff Lateral)* | 1985-1992 (d), 1993-1996 (n), 1997-2002 (d) |
| *Vinton River Drain* | (n) |
| *WW #34 (Canutillo Lateral)* | 1983 (d), 1984 (n), 1985-1992 (d), 1993-1996 (n)<br>1997-2002 (d) |
| *WW #34A (Pence Lateral)* | 1985-1988 (d) |
| *WW #35 (Westside Canal)* | 1980-1992 (d), 1993-1996 (n), 1997-2002 (d) |
| *WW #35C (Schutz Lateral)* | 1985-1988 (d) |
| *WW #36 (Montoya Lateral)* | 1985-1992 (d), 1993-1996 (n), 1997-2002 (d) |
| *Nemexas / West /Montoya Intercept.*<br>*Montoya Drain* | 1975-1980(m), 1981-1995 (d), 1996 (n), 1997-2002 (d)<br>(n) |
| *WW #38 (Montoya Lateral)* | 1985-1992 (d), 1993-1996 (n), 1997-2002 (d) |
| *Rio Grande at El Paso* | 1975-3/2003 (d) |

This data can be found on two websites: the New Mexico Water Resources Research Institute (NMWRRI) website for the data up to 2003 and the Elephant Butte Irrigation District (EBID) website for the data from 2003 to 2005. Directions for accessing this data are given in the following sections.

**NMWRRI DATA**

The NMWRRI data can be found at their website: **http://wrri.nmsu.edu/**
Selecting this website brings up the NMWRRI Home Page, as shown in Figure 5:


Figure 5. NMWRRI Website Home Page

From the NMWRRI home page, select the **WRDIS** option in the left column menu. This brings up the *Water Resources Data and Information System* page, as shown in Figure 6.

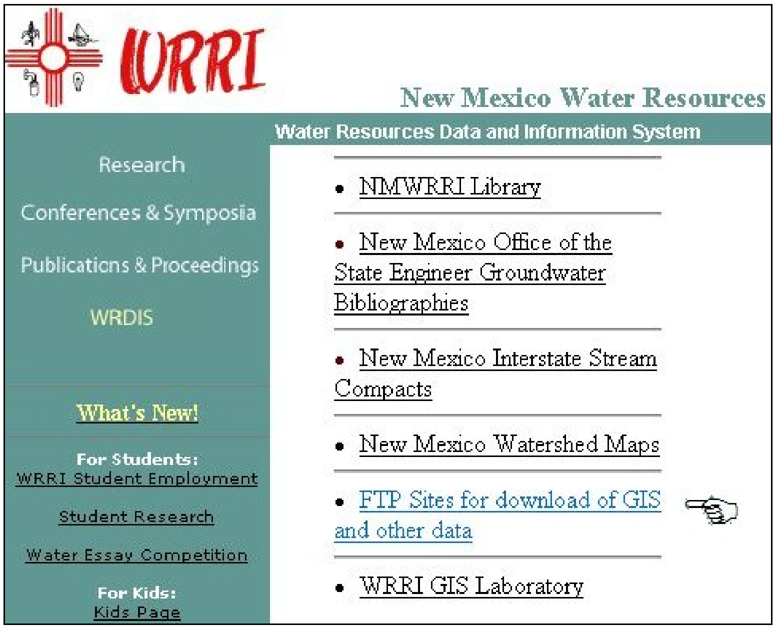



Figure 6. NMWRRI Water Resources Data and Information System Webpage

From this page, select the **FTP Sites for download of GIS and other data** option. This brings up the *FTP sites for Water Resources Data and Information* page, as shown in Figure 7.

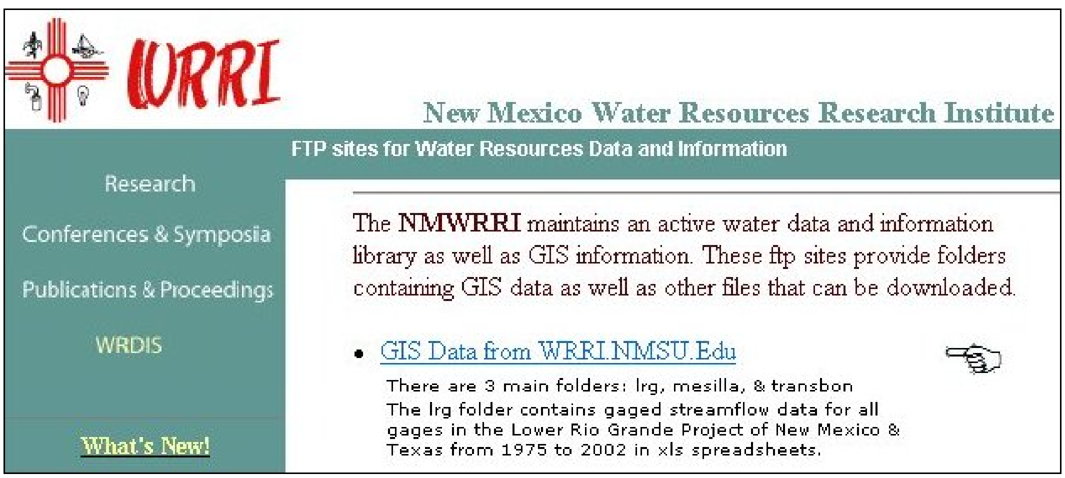



Figure 7. NMWRRI Water Resources Data and Information Webpage

From this page, select the **GIS Data from WRRI.NMSU.Edu** option. This will put you in the *ftp://wrri.nmsu.edu/pub/* directory, which contains several folders as shown in Figure 8.

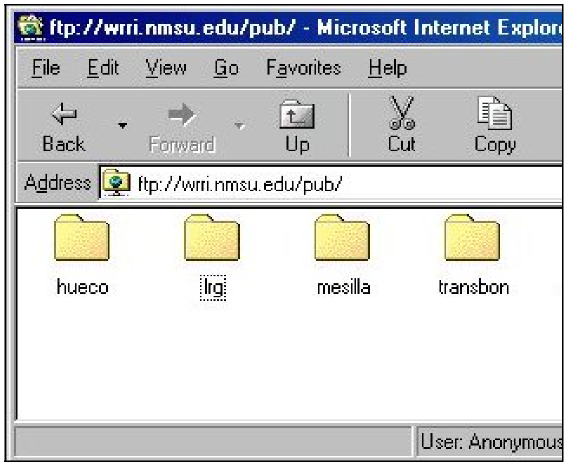


Figure 8. NMWRRI FTP Directory

Open the ***lrg*** folder, which contains sub-folders and one zipped file as shown in Figure 9.

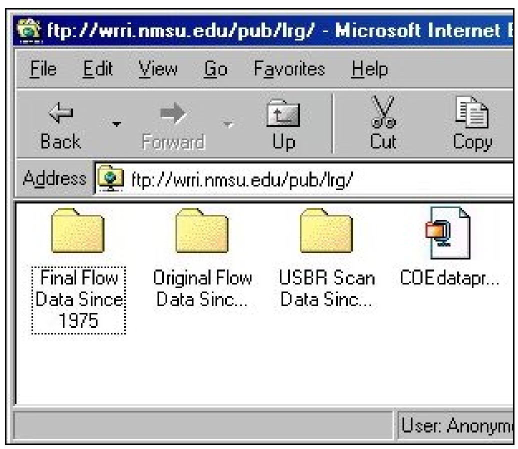


Figure 9. NMWRRI LRG Directory

Now from this location, you can download the NMWRRI data.

- The *Final Flow Data Since 1975* folder contains the excel spreadsheets with the available data from 1975 - 2003,
- The *Original Flow Data Since 1975* folder contains various files containing the original data that were used to create the final flow data files,
- The *USBR Scan Data Since 1975* folder contains .pdf files with scans of all the paper records from the U.S. Bureau of Reclamation (USBR) data from 1975-2003, and
- The *COEdataproject.zip* file contains the document that describes the data collection effort for this data and an excel spreadsheet with a more detailed data availability matrix for the final flow data.

## EBID DATA

The EBID data can be found at their website: **http://www.ebid-nm.org/**
Selecting this website brings up the EBID Home Page, as shown in Figure 10.

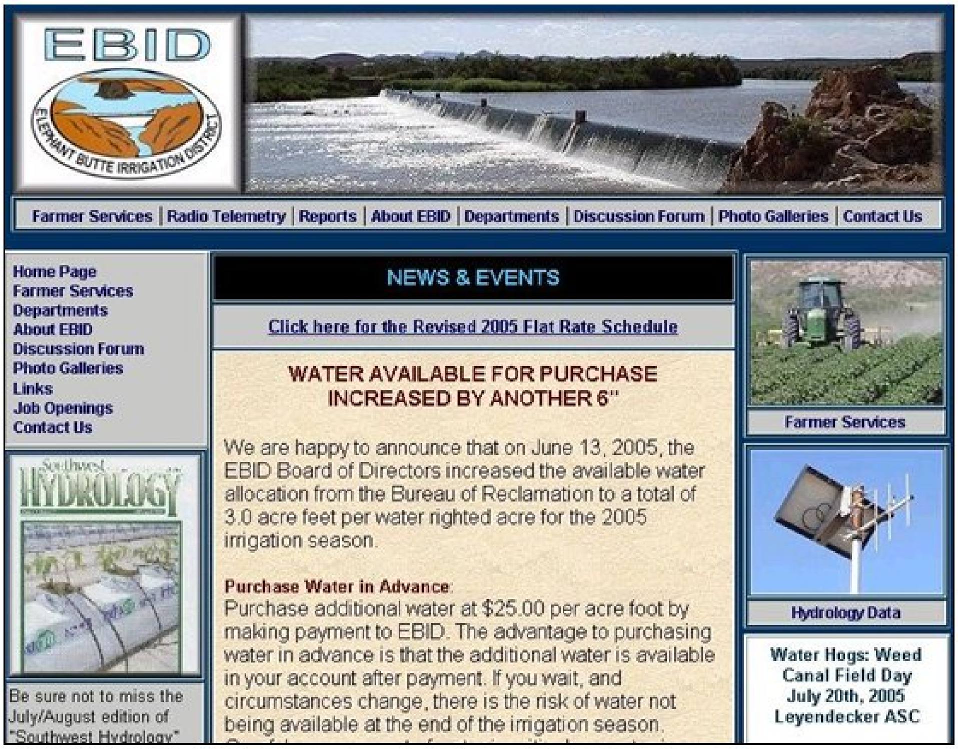


Figure 10. EBID Website Home Page

From this page, select the **Hydrology Data** option on the right, which will bring up the *Hydrology Data* page with the options for data shown in Figure 11.

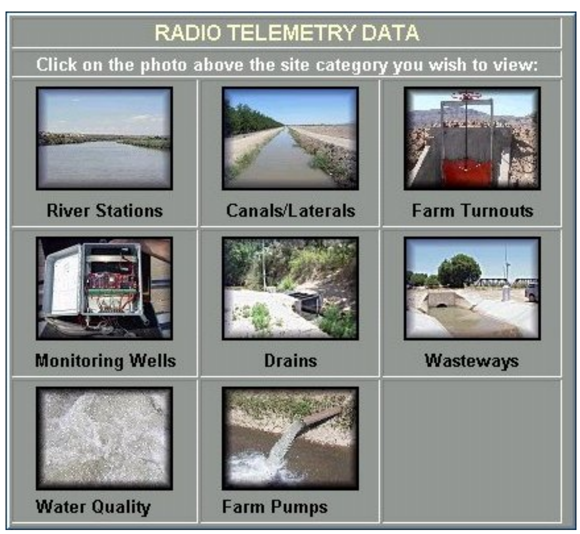


Figure 11. EBID Hydrology Data Options

If you select the **River Stations** option, you will be given the list of river stations shown in Figure 12.

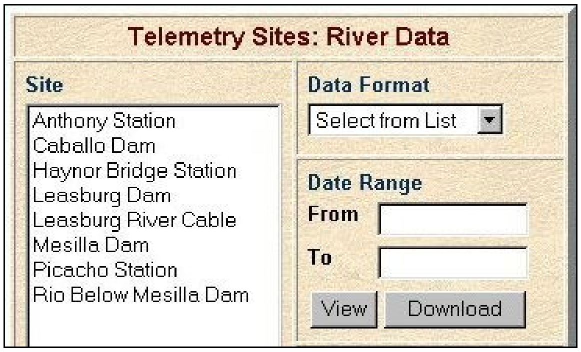



Figure 12. EBID River Station Data Options

Table 2 below is provided to match the names of the EBID River Station sites to the corresponding Available Data sites listed in Table 1.

Table 2. EBID River Station Sites Corresponding to Available Data Sites

| ***EBID River Station Site*** | ***Corresponding Available Data Site*** |
|---|---|
| Caballo Dam | Rio Grande below Caballo Dam |
| Haynor Bridge Station | Rio Grande at Haynor Bridge |
| Leasburg Dam | Rio Grande below Leasburg Dam |
| Picacho Station | Rio Grande at Picacho Bridge |
| Mesilla Dam | Rio Grande below Mesilla Dam |
| Anthony Station | Rio Grande at Anthony Bridge |

If you select the **Drains** options, you will be given the list of drains shown in Figure 13.

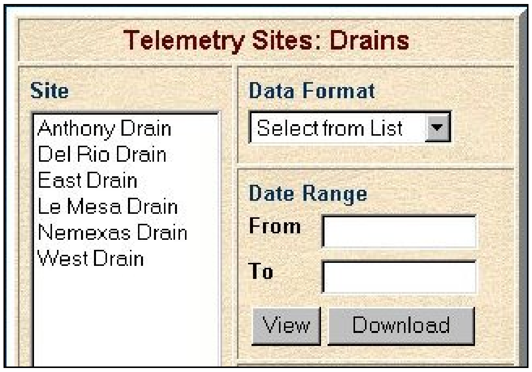



Figure 13. EBID Drain Data Options

Table 3 below is provided to match the names of the EBID Drain sites to the corresponding Available Data sites listed in Table 1.

Table 3. EBID Drain Sites Corresponding to Available Data Sites

| ***EBID Drain Site*** | ***Corresponding Available Data Site*** |
|---|---|
| Del Rio Drain | Leasburg / Mesilla / Del Rio Drain |
| La Mesa Drain | Santo Tomas / Chamberino / La Mesa Drain |
| East Drain | Mesquite / Anthony / East Drain |

If you select the **Wasteways** options, you will be given the list of sites shown in Figure 14.

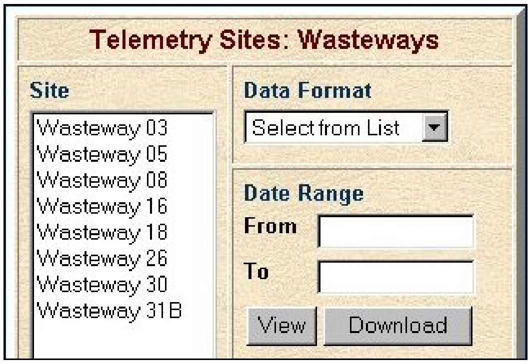



Figure 14. EBID Wasteway Data Options

Table 4 below is provided to match the names of the EBID Wasteway sites to the corresponding Available Data sites listed in Table 1.

Table 4. EBID Wasteway Sites Corresponding to Available Data Sites

| ***EBID Wasteway Site*** | ***Corresponding Available Data Site*** |
|---|---|
| Wasteway 05 | WW #5 (Garfield Canal) |
| Wasteway 08 | WW #8 (Taylor Lateral) |
| Wasteway 16 | WW #16 (Hatch Canal) |
| Wasteway 18 | WW #18 (Eastside Canal) |
| Wasteway 26 | WW #26 (Upper Chamberino Lateral) |
| Wasteway 30 | WW #30 (Chamberino East Lateral) |
| Wasteway 31B | WW #31B (Jimenez Lateral) |

# Review of Existing Hydrological Models

Several hydrological models, such as MODFLOW, Boyle Engineering STream Simulation Model (BESTSM), Soil and Water Assessment Tool (SWAT), and Water Availability Model (WAM) have been developed for surface water and groundwater flows and management of regional water resources in reaches between Elephant Butte Dam in New Mexico and Fort Quitman in Texas. In this section, these models are reviewed in terms of their configuration, advantages, limitations, and regions covered. Associated modeling in economics, ecological environment, and data processing using GIS are also covered. Such review provides insight into the conceptual model configuration and simulation of flow in the Rio Grande needed for further development of Upper Rio Grande Water Operations Model (URGWOM 2005) for reaches between Elephant Butte Dam in New Mexico and Fort Quitman in Texas. The URGWOM was designed to simulate water storage and delivery operations in the Rio Grande from its headwaters in Colorado to below Caballo Dam in New Mexico and for flood control modeling from Caballo Dam to Fort Quitman, Texas, which has been sponsored and supported by six federal agencies: the Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, Bureau of Indian Affairs, the International Boundary and Water Commission (U.S. Section), and the U.S. Army Corps of Engineers. The RiverWare modeling software (RiverWare) was selected to construct the URGWOM. RiverWare, developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado in Boulder, Colorado is a generalized river basin modeling environment that can integrate the analysis of power system economics with other purposes of reservoir systems such as flood control, water supply, recreation, water quality, and navigation. RiverWare is designed to provide river basin managers with a tool for scheduling, forecasting, and planning reservoir operations (URGWOM 2005).

## HYDROLOGICAL AND ASSOCIATED MODELS DEVELOPED FOR THE PASO DEL NORTE WATERSHED

### MODFLOW – MODULAR Three-Dimensional Finite-Difference Groundwater FLOW Model

MODFLOW is a modular, three-dimensional, finite-difference, groundwater flow model that numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method (Harbaugh et al. 2000; McDonald and Harbaugh 1988). MODFLOW simulates steady and transient (nonsteady) flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of both. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be simulated as head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a source of water outside the modeled area and the boundary block. MODFLOW-2000 also incorporates related capabilities such as parameter estimation and linkage with solute transport model.

**Advantages**

MODFLOW has become the de facto standard for simulating groundwater flow, and as such there are many third-party software packages available for pre- and post-processing operations. MODFLOW is a very versatile model and supports almost any size spatial and temporal resolution for simulating complex subsurface systems.

**Limitations**

The key limitation of the model is that it is a regional model, which cannot address local questions such as predicting well yield at a particular location and predicting movement of groundwater on a small scale including well-fields. Although MODFLOW does provide modules to simulate interactions between groundwater and surface water, they are not intended to rigorously model surface water flow. Typically MODFLOW is linked to a surface water model to simultaneously and fully simulate both groundwater and surface water interactions.

**Region Covered**

A number of groundwater hydrology models of the study area have been developed using MODFLOW. Their similarities and differences are summarized below in terms of purposes, scale, time periods, and interaction of groundwater and surface water:

**MODFLOW (Frenzel and Kaehler 1990)**

The groundwater hydrology and geochemistry of the Mesilla Basin in central-southern New Mexico was studied. The broad objective was to assemble geologic, hydrologic, and geochemical information; to analyze and develop an understanding of the system; and to develop predictive capabilities that would contribute to the effective management of the system. The MODFLOW model was used to develop an understanding of the natural, undisturbed hydrologic system and any changes brought about by human activities as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The Mesilla Basin was modeled with 5-layers to simulate hydrologic conditions from 1915 to 1975. The model simulated groundwater flow to and from the Rio Grande and a series of drains that empty into the Rio Grande. The model also simulated evapotranspiration from non-irrigated lands in the Mesilla Valley.

**MODFLOW (Frenzel 1992)**

This model revised the Frenzel and Kaehler (1990) model by eliminating the fifth layer at the bottom of the model and added improved estimates of hydraulic conductivity, transmissivity, and evapotranspiration. The transient time period was also extended to run from 1915 to 1985.

**MODFLOW (Hamilton and Maddock 1993)**

This model revised the Frenzel (1992) model to replace the RIV package (river package) with a modified version of the Stream-Routing package and changed the original boundary condition to isolate water applied to irrigated acreage and canal seepage. The modified version of the Stream-Routing package allows for the simulation of farm water removal from canals and lets diversion be either a percentage of incoming flow or the customary absolute flow value. The transient time period was also extended to run from 1915 to 1990.

**MODFLOW (Lang and Maddock 1994)**

This model revised the Hamilton and Maddock (1993) model to assess the effects of pumping withdrawals and canal lining in the Mesilla Basin under a variety of scenarios. In addition, a comprehensive sensitivity analysis of uncertain model parameters was performed.

**MODFLOW (Weeden and Maddock 1999)**

This model replicates the Hamilton and Maddock (1993) model with the Groundwater Modeling System (GMS), a computer software package that integrates Geographical Information System (GIS) based coverage and groundwater flow and transport models. It also expands the Hamilton and Maddock (1993) model to add the Rincon Valley area north to Caballo Dam. The time intervals of the model were changed to a two-season basis: primary irrigation season from March to October and secondary non-irrigation season from November to February. The transient time period was also extended to run from 1915 to 1995.

**MODFLOW/MT3D (CH2M Hill 2002; Hutchison 2004a)**

The Canutillo model is largely derived from the conceptual models used by Weeden and Maddock (1999), Hamilton and Maddock (1993), and Frenzel (1992) to better represent local conditions in the Canutillo wellfield and to facilitate the eventual development of a contaminant transport model. The model area was decreased from the Rincon and Mesilla valleys. The southern and eastern boundaries remained the same; the northern boundary was moved to near Mesquite, and the western boundary moved to approximately 7.4 miles to the west of the Canutillo well-field. The grid was made uniform at a spacing of approximately 200 meters. Additional canals, drains, and laterals were added. The aquifer model domain is discretized into four layers with different thickness of 216 rows and 135 columns. The transient time period covers from 1915 to 1995. It also includes a solute transport model (MT3D), surface and groundwater water quality data; it takes into account the variation of water quality within the Canutillo wellfield of the Mesilla Basin. This model represents the stream flow system in the Canutillo area well-field slightly better than the 1999 Weeden and Maddock model (CH2M Hill 2002). The model also factors in Rio Grande seepage in the winter and represents heads in an improved way. Based on sensitivity analysis, it seems to be at optimum (CH2M Hill 2002).

### MODFLOW for Hueco Bolson (Heywood and Yager 2003; Hutchison 2004b)

In this version of the Hueco Bolson Model, the Stream Routing (STR) package and the Multi-Aquifer Well (MAW) package were modified to represent the historical dewatering of the aquifer due to pumping. The STR package was modified to simulate continuing stream leakage to the aquifer to the topmost active cell if the upper layer is dry, while the MAW package was modified to support dewatering of model layers by omitting dry cells from the computation of head in the well and apportioning flows to or from the wells in the remaining saturated layers.

The model area covers the Hueco Bolson, extends slightly into the Tularosa Basin in New Mexico, and covers the Hueco Bolson in Texas except for the southeastern tip in Hudspeth County and most of the Hueco Bolson in Mexico. The model grid consists of 165 rows and 100 columns in a variable grid of 500 meters by 500 meters to 1000 meters by 1000 meters, with the finer grid in the area of interest in the El Paso, Texas and Ciudad Juárez, Chihuahua, México area. The model was calibrated with data from 1903 to 1996. More recently, El Paso Water Utility has updated the model to include input data from 1997 to 2002 (Hutchison 2004b).

### MODFLOW for Hueco Bolson in México

The Junta Municipal de Agua y Saneamiento de Ciudad Juárez (JMAS) has also developed MODFLOW model to simulate groundwater flow and head distribution in México as a refinement/parallel model to the one developed by the personnel of the USGS and EPWU. The model was developed to evaluate the impacts of groundwater pumping in Cd. Juárez on the regional groundwater flow (See Appendix A).

## BESTSM - Boyle Engineering STream Simulation Model

BESTSM is a general-purpose, data-driven water accounting and allocation simulation model (Boyle 1994). It starts with streamflow as input to the system. Using a linked node representation of the river system, physical features of the system, such as dams, reservoirs, diversions, canals, pipelines, and wells are then added to the hydrology. Water quality was also represented in the form of conservative chemical constituents including TDS, sulfate and chloride and tracked using a mass balance approach. Institutional and legal constraints are imposed in the form of water right priorities, reservoir operating rules, and project and compact requirements.

### Advantages

Combining the BESTSM with MODFLOW could simulate a physically and operationally complex surface/groundwater system to compare various operational scenarios for planning purposes (Boyle and Parsons 2000). BESTSM by itself is well designed to simulate a river system with institutional and legal constraints such as water right priorities, reservoir operating rules and compacts requirements.

### Limitations

This model is unable to reproduce day-to-day or even year-to-year operational decisions to the extent that such decisions cannot be consistently predicted or to the extent that such decisions may be influenced by factors unrelated to the basin's operation.

### Region Covered

The BESTSM model was applied to represent the surface water system of the Rio Grande from the San Marcial gage above Elephant Butte Reservoir to Riverside Diversion Dam (Boyle and Parsons 2000). Surface water quality is an integral part of the BESTSM model. MODFLOW model (Hamilton and Maddock 1993) was linked with BESTSM to supply important information on interactions between the surface hydrologic system and the adjacent groundwater system of the Mesilla Basin.

## WAM – Water Availability Model & WRAP - Water Right Analysis Package

The state of Texas developed Water Availability Models (WAM) for selected river basins in Texas to support a broad spectrum of water resources planning and management activities (Wurbs 2003a). The model simulates management of the water resources of a river basin or multiple-basin region under a priority-based water allocation system. The WAM system consists of a generalized river/reservoir system management simulation model called the Water Rights Analysis Package (WRAP); a database of water rights, water use and other data; a graphical user interface; GIS tools; and interfaces between the database and WRAP.

The WRAP model (Wurbs 2003a) simulates management of the water resources of a river basin or multiple-basin region under a priority-based water allocation system. This model facilitates assessment of hydrologic and institutional water availability/reliability for existing and proposed water rights. This model may be applied in various other types of planning and management situations to evaluate alternative water management strategies for specified water use scenarios. However, WRAP was designed specifically to facilitate incorporation of a water rights priority system in water availability modeling. The WRAP simulation algorithms are based on allocating available stream flow to each water right in turn in ranked priority order. The WRAP model is generalized for application to any river/reservoir/use system, with input files being developed for the particular river basin of concern. WRAP uses a monthly time step with no limit on the number of years.

### Advantages

The generalized WRAP model provides flexible analysis capabilities for a broad range of water management applications. The WAM/WRAP models may be freely downloaded from the Texas Commission of Environmental Quality (http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html). Information available for download from the Texas Water Resources Institute (TWRI) includes a number of technical reports related to WRAP and the Texas WAM System (http://twri.tamu.edu/reports/2005/tr283.pdf).

**Limitations**
This model does not account for environmental flows to support endangered species or water quality. Also, this model only uses monthly time/steps (which is in the process of being improved), and it has no physical routing capability. The WAM for the Rio Grande reaches within the area covers the river between the New Mexico-Texas state line and Fort Quitman, which does not fully represent hydrological configuration within the Ro Grande Project from Caballo Dam to Fort Quitman.

**Region Covered**
A WAM has been developed by Texas Commission of Environmental Quality (TCEQ) for the reaches between the New Mexico-Texas state line and Fort Quitman in Texas for regional water plans and is under review (TCEQ 2005). WAM/WRAP was developed with the time period of 1940 through 2000. This model uses monthly time steps (Wurbs 2003b).

### SWAT - Soil and Water Assessment Tool with General Algebraic Modeling System (GAMS)

SWAT is a river basin, or watershed scale model, that was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al. 2002). This model is physically based and requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. This information is used to model the physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, and so on. The SWAT model is linked to the economic model coded with the GAMS optimization software that computes the economic modeling parameters (Booker, Michelsen and Ward 2005; Ward et al. 2001).

GAMS was developed by a group of economists in order to facilitate the resolution of large and complex non-linear models (Dumont and Robichaud 2000). GAMS can be used to solve a drought economic mathematical model that is developed to keep track of economic benefits subject to hydrologic and institutional constraints. Used with SWAT, the economic model provides income changes due to low-water flows.

**Advantages**
Using this model is an effective substitute that can be used to estimate impacts of a proposed water policy change without actually carrying it out. It will also provide an assessment of economic benefits, costs, and the size and distribution of those benefits and costs.

**Limitations**
This model does not focus on relations between streamflows and environmental benefits of various kinds, or on endangered species requirements and human values and benefits associated with those requirements. SWAT is a long-term, yield model and is not designed to simulate detailed, single-event flood routing. It also does not simulate irrigation delivery systems, just natural river systems.

**Region Covered**
The SWAT was used to simulate the Rio Grande Basin, from Colorado through New Mexico to Fort Quitman, Texas (Ward et al. 2001). The baseline drought scenario used was the 1942-1985 period with seasonal time intervals.

## RIOFISH - River-basin Information Organizer for Fisheries Investigation, Simulation, and Heuristics

The RIOFISH model is designed to analyze the impact of proposed fisheries-related management decisions in the hydrology, ecology and economy of river basins in New Mexico (Cole et al. 1995). This model organizes information into simulations of reservoir inventories and can be used to forecast resource and angler response to management strategies applied in different possible planning environments. It may also be used to facilitate decisions based on anticipated angler benefit and agency management costs. Input data consists of water levels; reservoir exchange rate; concentrations of nutrients; suspended matter and organic matter; temperature; solar radiation; fish stocking rate and regulations; fish introduction, removals and mortality effects; and road and boat ramp access.

**Advantages**
This model incorporates economic benefits into the hydrology model in order to make better management decisions.

**Limitations**
RIOFISH is not a general purpose model that can be used for any area. It was developed for specific reservoir fisheries in New Mexico.

**Region Covered**
RIOFISH simulates hydrologic, biologic, and socioeconomic interactions in 16 large reservoir fisheries of the Rio Grande, and the Canadian, Pecos, and San Juan rivers (Cole et al. 1990; Cole et al. 1995)

## Genetic Algorithm Based Technique Model

Genetic algorithms are a class of search techniques quite different from conventional optimization methods (King et al. 1995). This model uses a genetic algorithm-based technique to provide a management tool for improving the economic performance of river basin management. Such a river management model would be capable of portraying both the physical response to and economic benefits of particular operating strategies. Some hydraulic and economic components of the RIOFISH model (Cole et al. 1990) were also incorporated.

**Advantages**
This model includes optimization for economic benefits. It can be used to evaluate and find better operating strategies based on economic benefits. Genetic algorithms offer greater flexibility in less time, as they impose no constraints on the way the system is simulated and they are not significantly affected by the size of the problem.

**Limitations**
This model may not simulate the behavior of the system with complete accuracy, but it is representative of the complexity required to do so.

**Region Covered**
This model was applied to the problem of optimizing the operation of a complex simulation model of the Rio Grande Project in southern New Mexico (King et al. 1995). This project includes Elephant Butte Dam to American Diversion Dam, Texas. Data from 1990 were used for this model in 52 one-week time steps.

As discussed above, each model has its own advantages and limitations with different geographic coverage. Some of the models dealt with surface water and groundwater interaction, which will be discussed in detail in next section. Other models have been developed for the region but are not covered in the report (Appendix A). A table summarizing the comparison of some numerical models is included in Appendix B.

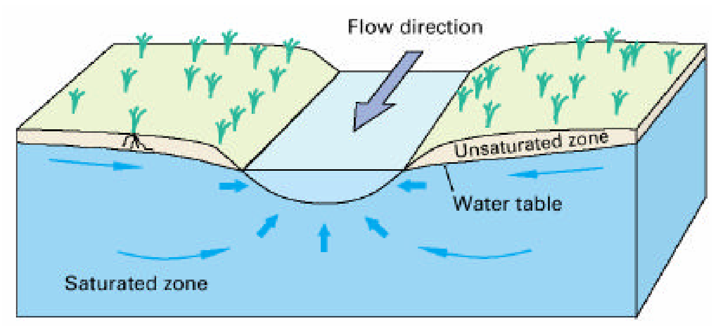
## PROTOCOLS FOR SIMULATION OF INTERACTION OF SURFACE WATER AND GROUNDWATER

### Characterization of interaction between surface water and groundwater

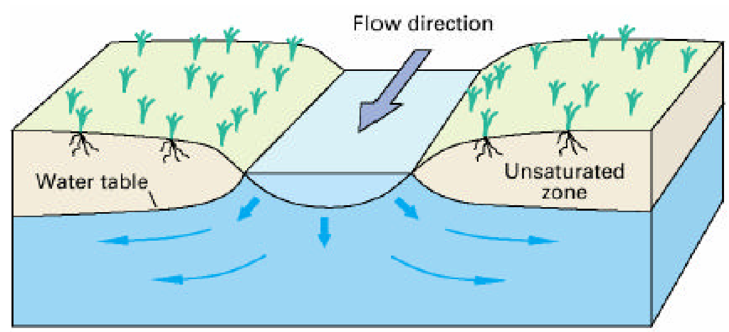
Surface and groundwater systems in the Paso del Norte region are in continuous dynamic interaction. Groundwater can be a source for surface water by supplying base flow and maintaining wetlands in times of low precipitation. On other occasions, surface water can recharge groundwater as seepage through the stream bed. Over-pumping of aquifers can lead to lowered stream and lake levels.

Streams either gain water from inflow of groundwater (gaining stream; Figure 15a) or lose water by outflow to groundwater (losing stream; Figure 15b). Many streams do both, gaining in some reaches and losing in other reaches. Furthermore, the flow directions between groundwater and surface water can change seasonally as the level of the groundwater table changes with respect to the stream-surface level or can change over shorter timeframes when rises in stream surfaces during storms cause recharge to the streambank. Under natural conditions, groundwater makes some contribution to streamflow in most physiographic and climatic settings. Thus, even in settings where streams are primarily losing water to groundwater, certain reaches may receive groundwater inflow during some seasons. Losing streams can be connected to the groundwater system by a continuous saturated zone (Figure 15b) or can be disconnected from the groundwater system by an unsaturated zone (Figure 15c).

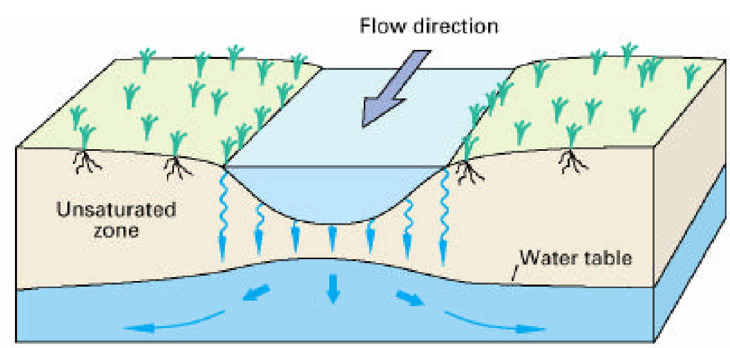
For a gaining stream, stream gaining may be reduced by groundwater pumping. When the aquifer water level is lowered by pumping, the hydraulic head difference between stream and aquifer will be reduced, resulting in less gaining in the stream or even turning the gaining stream into a losing stream when pumping stresses become large enough to reverse the flow direction between the stream and the aquifer.




(a) Gaining stream




(b) Losing stream




(c) Losing stream that is disconnected from the groundwater surface

Figure 15. Interaction of Streams and Groundwater (from Alley et al. 1999)

In some situations, stream seepage (losses to the aquifer) may be affected by groundwater pumping and natural variations in aquifer water level. When the aquifer water level is near land surface, seepage from the river is partially controlled by the hydraulic gradient between surface water and groundwater (see Figure 15b). Activities or events that result in a lowering of the groundwater level, such as groundwater pumping, induce more seepage from the stream. Conversely, events that cause the aquifer water level to rise (recharge events) will result in a decrease in stream seepage. If aquifer water levels rise above the level of the stream, what was previously a losing stream reach will become a reach that is gaining water from the aquifer.

Another hydrologic condition exists that is very important in understanding surface and groundwater interaction. A surface water body is perched above an aquifer when aquifer water levels are well below the bed of the river, stream, or lake (Figure 15c). Under these conditions, water will seep from the surface water body to the groundwater, but the surface water body will not be affected by aquifer water levels and consequently does not change in response to groundwater pumping. Nearby groundwater pumping will cause a lowering of the water table, but will not affect surface water supplies.

In the Paso del Norte watershed, the irrigation network including canals, laterals, and drains further complicates river flow by diverting water from the river system and discharging operational spills and return flow from the irrigation field into the river. The irrigation network also interacts with the shallow aquifer through infiltration from canals and laterals and collecting return flows from the irrigation field (shallow or perched groundwater) through drains.

## Simulation of interaction between surface water and groundwater

To better understand and simulate the flow in the Rio Grande, the interaction of surface water and groundwater should be included in the model configuration. In this section, several methods were evaluated, which include developing modules as part of the MODFLOW package, such as river module (McDonald and Harbaugh 1988), streamflow routing module (Prudic 1989) and drain module (McDonald and Harbaugh 1988) or coupling/linking surface water flow model and groundwater flow model such as MODBRNCH (Swain and Wexler 1996), linked BESTSM and MODFLOW (Boyle and Parsons 2000; Hamilton and Maddock 1993).

### River Modules in MODFLOW

The river package in the MODFLOW is designed to simulate the effects of flow between surface water features and groundwater system, in which terms representing seepage to and from the surface water features must be added to the groundwater flow equation for each cell affected by the seepage.

**Method**

Assuming that measurable head losses between the stream and the aquifer are limited to those across the streambed layer itself, underlying model cell remains fully saturated, flow between the stream and the groundwater system is given based on Darcy's law by

$$QRIV = KLW/M\ (HRIV - h_{i,j,k}) \quad (1)$$

or

$$QRIV = CRIV\ (HRIV - h_{i,j,k}) \quad (2)$$

where

| | |
|---|---|
| *HRIV* | = *the head in the river* |
| $h_{i,j,k}$: | = *the head at the node in the cell underlying the river reach* |
| *CRIV:* | = *the hydraulic conductance of the stream-aquifer interconnection. In case that a discrete riverbed layer is present, CRIV = KLW/M, where K is hydraulic conductivity of riverbed material, L is length of reach, W is width of the river and M is thickness of riverbed. Otherwise, CRIV = KLW/(HRIV-RBOT).* |

For the case that head at the bottom of the riverbed is equal to head in the cell,

$$QRIV = CRIV\ (HRIV - h_{i,j,k}),\ \text{when}\ h_{i,j,k} > RBOT \qquad (3)$$

For the case that head at the bottom of the riverbed is equal to elevation of bottom of riverbed layer,

$$QRIV = CRIV\ (HRIV - RBOT),\ \text{when}\ h_{i,j,k} <= RBOT \qquad (4)$$

where

| | |
|---|---|
| RBOT | = *the elevation of the bottom of the riverbed* |

In many instances, the assumption used in this model that a discrete low-permeability riverbed layer is present does not hold. Even if there is a different way to calculate CRIV in case that no discrete riverbed layer is present, it is still expected to get a result that is not precise.

Also, in many instances, the assumption that the underlying model cell remains fully saturated, that is, water level does not drop below the bottom of the riverbed layer, does not hold.
The flow from the river to groundwater systems or in the opposite direction is in general a three-dimensional process, and its representation in this model through a single conductance term can never be more than approximate.

In this model, it is simply assumed that the river-aquifer interaction is independent of the location of the stream reach within the cell, and that the level of water in the stream is uniform over the reach, and constant over each stress period. Often, this assumption does not hold in reality.

### Stream Routing Package (STR1) in MODFLOW-96

The Streamflow-Routing package is a modification of the river package (Prudic 1989; Harbaugh and McDonald 1996). It is designed to route flow through one or more rivers, streams, canals, or ditches in addition to computing leakage between the streams and the aquifer system. Streams superimposed on the aquifer are divided into reaches and segments. A segment is a stream or diversion in which streamflow from surface sources are added at the beginning of the segment or subtracted at the end of segment. A reach is the part of a segment that corresponds to an individual cell in the finite-difference grid.

**Method**
Streamflow is accounted for by specifying flow for the first reach in each segment that enters the modeled area, and then computing streamflow to adjacent downstream reaches in each segment as equal to flow in the upstream reach plus or minus leakage from or to the aquifer in the upstream reach. The leakage to or from a stream is computed by Darcy's law same as described in the river package section. In addition, the package offers an option for computing the stream stage in each reach. The stream stage is derived from the Manning formula (Ozbilgin and Dickerman 1984) with an assumption of incompressible steady flow in the stream at a constant depth:

$$d = \left( \frac{Qn}{CwS^{1/2}} \right)^{3/5} \tag{5}$$

Where
*d* = *the stream depth*
*Q* = *the discharge in each reach*
*n* = *Manning's roughness coefficient*
*S* = *the slope of the stream channel*
*w* = *the width of the stream channel*
*C* = *a constant*

Compared to the river package, this model considers the volume of streamflow in each river segment, and will increase streamflow in areas of gaining reaches and reduce streamflow by water lost through riverbed seepage. The stream package permits representation of intermittent streams in MODFLOW. It is especially useful in systems in the headwaters of small streams. The program limits the amount of groundwater recharge to the available streamflow. It permits two or more streams to merge into one with flow in the merged stream equal to the sum of the tributary flows. The program also permits diversions from streams. This model is not recommended for modeling the transient exchange of water between stream reaches and shallow groundwater when the objective is to examine short-term effects caused by rapidly changing streamflows or rapidly changing solute source terms.

## New Streamflow Routing Package in MODFLOW-2000

New Streamflow Routing (SFR1) package replaces the previous stream package (STR1), with the most important difference being that stream depth is computed at the midpoint of each reach instead of at the beginning of each reach, as was done in the original stream package (Prudic et al. 2004). This approach allows for the addition and subtraction of water from runoff, precipitation, and evapotranspiration within each reach. The SFR1 package has five options for simulating stream depth and four options for computing diversions from a stream. The options for computing stream depth are: a specified value, Manning's equation (using a wide rectangular channel or an eight-point cross section), a power equation, or a table of values that relate flow to depth and width. Each stream segment can have a different option. Outflow from lakes can be computed using the same options. Because the wetted perimeter is computed for the eight-point cross section and width is computed for the power equation and table of values, the streambed conductance term no longer needs to be calculated externally whenever the area of streambed changes as a function of flow. The concentration of solute is computed in a stream network when MODFLOW-GWT is used in conjunction with the SFR1 package. The concentration of a solute in a stream reach is based on a mass-balance approach and accounts for exchanges with (inputs from or losses to) groundwater systems.

**Method**

In this formulation, transient leakage across the streambed could change depending on both the stream head and the aquifer head calculated during the time step. In the SFR1 package, the conductance term is calculated from hydraulic conductivity, stream length, and streambed thickness, which is read in the data input, and stream width, which is either read in the data input or computed on the basis of streamflow (Prudic et al. 2004) using Equation 1. This creates greater flexibility for the user, allows for conductance to vary as a function of stream wetted width, and eliminates the need to externally estimate the conductance term.

Stream depth is used in the program to compute the head in each reach by adding stream depth to the top of the streambed for each reach. Stream depth is computed at the midpoint of each reach. Unless a constant stream depth is specified, flow at the midpoint ($Q_{mdpt}$) is computed prior to computing stream depth. Flow at the midpoint is computed as:

$$Q_{mdpt} = Q_{sri} + Q_{trb} + 0.5(Q_{ro} + Q_{ppt} - Q_{et} - Q_L) \quad (6)$$

where $Q_{sri}$ is a specified inflow at the beginning of the first reach of any segment; the sum of tributary flow; $Q_{trb}$ is flow from upstream segments into the first reach of a segment; $Q_{ro}$ is the direct overland runoff to a reach; $Q_{ppt}$ is precipitation that falls directly on a reach; $Q_{et}$ evapotranspiration from a reach; $Q_L$ is the leakage through the streambed and includes leakage from the stream reach to the aquifer ($Q_{Lo}$) and from the aquifer to the stream reach ($Q_{Li}$). The leakage term is positive when leakage is from the stream reach to the aquifer and negative when leakage is from the aquifer to the stream reach, hence it is subtracted from the other terms.

Because flow at the midpoint of a reach is partly dependent on streambed leakage, which is dependent on stream depth and, therefore, on flow, Equation 6 is nonlinear, and is solved iteratively using Newton's method or Newton-Raphson method (Burden and Faires 1997) until the root of the equation is estimated within a specified tolerance.

## Drain Package in MODFLOW

The drain package in MODFLOW is designed to simulate the effects of features such as agricultural drains, which remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation, so long as the head in the aquifer is above that elevation.

**Method**

The drain function is described by the following equation pair:

$$QD_{i,j,k} = CD_{i,j,k}(h_{i,j,k} - d_{i,j,k}), \text{ when } h_{i,j,k} > d_{i,j,k} \quad (7)$$

for the case that head in the aquifer is above the median drain elevation in which the water flows from aquifer to drain. The coefficient $CD_{i,j,k}$ is a lumped (or equivalent) conductance describing all of the head loss between the drain and the region of cell i, j, k in which the head $h_{i,j,k}$ can be assumed to prevail.

$$QD_{i,j,k} = 0, \text{ when } h_{i,j,k} <= d_{i,j,k} \quad (8)$$

for the case that head in the aquifer is below the median drain elevation in which the drain has no effect.

In drain package, it is assumed that the head within drain prevails and is approximately equal to the median drain elevation. In real life, this assumption cannot hold, since the actual head within drain often is not at the fixed point of median drain elevation. To calculate $CD_{i,j,k}$, approximate equations for conductance for the three flow processes should be developed. However, in most cases, the developed equations are not precise due to lack of detailed information. The use of average value of head for a cell i, j, k as the value of $h_{i,j,k}$ and the assumption that the head prevails at some distance from the drain, also leads to a result that is not precise.

## MODBRNCH-Coupled Groundwater Flow Model (MODFLOW) and Surface Water Model (BRANCH)

MODBRNCH (Swain and Wexler 1996) is designed to simulate groundwater and surface water accurately and their interaction by coupling two widely accepted models, namely, MODFLOW for groundwater and BRANCH for surface water. MODFLOW-96 (Harbaugh and McDonald 1996) simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined; BRANCH simulates steady or unsteady flow in a single open-channel reach (branch) or throughout a system of branches (network) connected in a dendritic or looped pattern by solving the one-dimensional equations of continuity and momentum for the river flow. Channel-aquifer flows are leakage through a confining layer or riverbed. Computation of this leakage in the groundwater and surface-water systems allows these processes to be coupled for simulation purposes.

### Method

The groundwater flow equation is solved using the finite-difference approximation. The BRANCH model uses a weighted four-point, implicit, finite-difference approximation of the unsteady-flow equations. A leakage term has been added to the equations in the BRANCH model and was coupled through the leakage quantity to the MODFLOW-96 model.

(1) Models incorporation of leakage

$$Q = KB(Z-h)/b \quad (9)$$

when head in aquifer h is above the river bottom, or

$$Q = KB(Z-Z_{BOR})/b \quad (10)$$

when the head in aquifer h is below the river bottom; where Q is outflow per unit length of channel, which is considered as the result of leakage cross riverbed here; B is channel top width; Z is the stage in the channel; h is the head in aquifer; b is the thickness of the riverbed; and $Z_{BOR}$ is the elevation of river bottom. Q is then added in the corresponding continuity equation in BRANCH code.

(2) Drying and rewetting of river channel
A scheme is developed that retains a small flow in the channel by creating a small theoretical area below the riverbed.

(3) Steady-state simulation
Remove the time-dependent terms in the corresponding continuity and momentum equations in BRANCH code.

MODBRNCH allows simulation of groundwater and surface water interactions with sophisticated models of both MODFLOW and BRANCH. The modified BRANCH code applied in MODBRANCH operates from subroutine package in MODFLOW. The option of allowing BRANCH code to pass its arrays from main arrays from MODFLOW is very useful.

In the modified BRANCH code applied in MODBRNCH, terms describing leakage between a river and aquifer are added to the continuity equation. MODBRNCH applies an option to allow channel to dry and rewet and a steady-state option, which have shown their usefulness in some sample runs. MODBRNCH is very applicable when rapid stream and aquifer changes are modeled in a well-connected system.

The interactive solution scheme applied in MODBRNCH requires multiple repetition of each MODFLOW time step. As a result, the modified BRANCH code cannot be used with the standard MODFLOW package and requires a special version of modified MODFLOW. MODBRNCH does not simulate density driven transport. Specification of the head at the ocean without a correction for the higher density salt water would decrease model accuracy. MODBRNCH has relatively poor performance according to the evaluation criteria of regulatory acceptance, GIS integration, and platform-flexibility of operating system.

## Linked BESTSM-MODFLOW

As described in the previous section, BESTSM is a general accounting model for surface water flow and quality, while MODFLOW is a modular finite difference model for groundwater flow. This section will demonstrate how surface water and groundwater models are linked together.

### Method

BESTSM and MODFLOW models (Boyle and Parsons 2000, Hamilton and Maddock 1993, respectively) were linked to each other so that information produced by one can be passed to other. The BESTSM (Boyle and Parsons 2000) must be supplied with information on interaction between the surface water system and the groundwater system. They include river gains from groundwater and river losses to groundwater, drain discharges, return flows from irrigation pumping, and river losses associated with irrigation pumping. Likewise, MODFLOW (Hamilton and Maddock 1993) must be supplied with information related to surface water conditions, mainly river and canal flows, to simulate properly groundwater conditions. Figure 16 shows how information is shared between BESTSM and MODFLOW.

A linear flow routing was used for a reach,

$$I_2^t = c_0 O_1^{t} + c_1 O_1^{t-1} + G^t \qquad (11)$$

where

| | |
|---|---|
| $I_2^t$: | *inflow at the downstream node 2 of the reach at time t* |
| $O_1^t$ and $O_1^{t-1}$ | *outflow from the upstream node 1 at current time step t and last time step (t-1)* |
| $G^t$: | *gains or losses at current time step within the reach* |
| $c_0$ and $c_1$: | *coefficients for flow routing as defined below* |

$$c_0 = 1.0 - \frac{Travel \;\; time \;\; (hrs)}{24 \;\; hrs}$$

$$c_1 = 1.0 - c_0$$

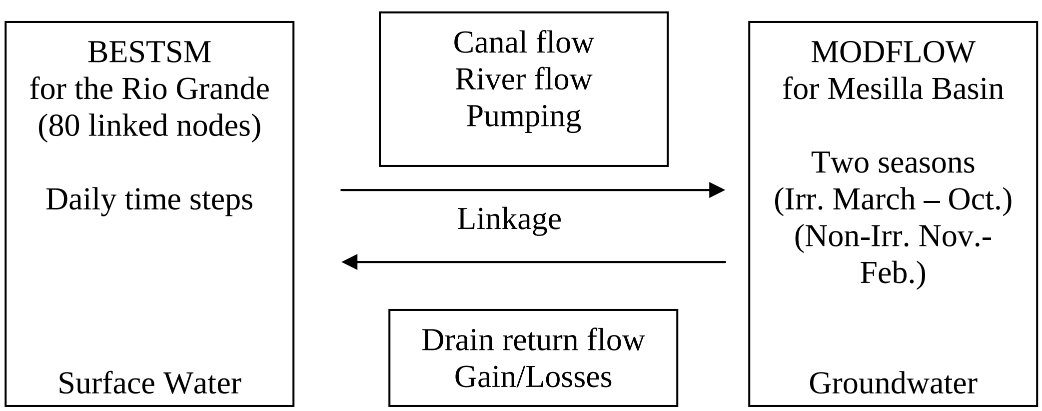



Figure 16. Flow Chart of the Linked BESTSM-MODFLOW Model (modified from Boyle and Parsons 2000)

Other models simulate the interaction of surface water and groundwater (Blum et al. 2002), such as SWAT-MODFLOW (Perkins and Sophocleous 2000), HSPF (Hydrologic Simulation Program-Fortran) - MODFLOW (Said et al. 2005), Integrated Ground and Surface Water Model (IGSM Montgomery Watson 1993), and Integrated Hydrology Model (InHM, VanderKwaak 1999). They are out of the scope of this work and not covered in this report.

## SELECTED PREVIOUS MODELING STUDIES

Several selected models were found that simulated the surface and/or groundwater systems of the Rincon Valley. The results from these models related to the interactions of surface water and groundwater are summarized below.

### Weeden and Maddock's groundwater model

Weeden and Maddock (1999) did a groundwater model study for the Rincon Valley and Mesilla Basin. In the study, Weeden and Maddock did a regression analysis of gross diversion at Arrey Canal versus losses for 1947-1975. The authors then used the average of these results for the years 1976-1995. This study found that from the gross diversion, the average values were: 43 percent canal losses, 42 percent delivered to farms, and 15 percent returned to the river. In their document, they also described other, earlier methods for estimating losses and drain flows:

1. Hamilton and Maddock (1993) found from a regression analysis on gross diversions at Arrey Canal versus canal losses that the canal losses are approximately 40 percent of the gross diversion. These losses include water lost to seepage, riparian ET, and operational spills.

2. Wilson and others (1981) found from a regression analysis for 1947-1976 that the canal losses in the Rincon Valley were 43 percent of the gross diversion.

   $$y = 0.4347x \qquad (12)$$

   where

   $x$ = *the gross diversion at Arrey Canal (AF)*
   $y$ = *the canal losses (AF)*

   This regression analysis had an $R^2 = 0.7871$.

3. Maddock and Wright Water Engineers (1987) studied the relationship between groundwater levels and drain flow. They found a high correlation between depth-to-water and drain flow. They also found that the water table fluctuates by about 2 feet during the irrigation season, rising as irrigation water is applied, then falling as irrigation water diminishes. An estimation method for drain flow was not necessary for their groundwater model, since the model allows flowing downstream from the drains based on head differential determined from groundwater levels.

## Boyle & Parsons linked surface/groundwater model

Boyle and Parsons Engineering (2000) used their BESTSM surface water model to represent the surface water system of the Rio Grande Project from the San Marcial gage above Elephant Butte to Riverside Diversion Dam. A MODFLOW groundwater model was linked with BESTSM to evaluate the groundwater aspects of the Mesilla Basin. The equation they used to calculate gains and losses in the reach between Percha Diversion Dam and Leasburg Diversion Dam was:

*Gain/Loss = Rio Grande below Leasburg – Rio Grande below Caballo + Arrey Canal – Garfield Drain – Hatch Drain – Angostura Drain – Rincon Drain + Leasburg Canal* (13)

Monthly values were used in the calculation, and the resulting monthly gain/loss values were distributed uniformly over the month by BESTSM to obtain daily values. These daily values were input into the BESTSM model at the Rio Grande above Leasburg node. Their analysis of drain flow in relation to diversion data at Percha Diversion Dam resulted in the following assumptions:

1. Efficiency of use for Percha Diversion Dam diversions was approximately 80 percent with respect to the river. Accordingly, 20 percent of the diversions return directly to the river.

2. The following distribution was used to distribute the return flows to the drains:
   a. 31 percent to Garfield drain
   b. 30 percent to Hatch drain
   c. 5 percent to Angostura drain
   d. 34 percent to Rincon drain

3. The following pattern was used to model the timing of the return flows:
   a. 30 percent in the same month
   b. 25 percent in the following month
   c. 25 percent in the following month
   d. 20 percent in the following month
   e.

Boyle (2000) used a linear flow routing procedure:

$$I_2^t = c_0 O_1^t + c_1 O_1^{t-1} + G^t \qquad (14)$$

where

$I_2^t$ = *the inflow to node 2 for day t*

$O_1^t$ = *the outflow from node 1 for day t*

$O_1^{t-1}$ = *the outflow from node 1 for previous day*

$c_0$ = *the routing coefficient. Fraction of outflow from node 1 which reaches node 2 the same day*

$c_1$ = *the routing coefficient. Fraction of outflow from node 1 which reaches node 2 the next day*

$G^t$ = *the gain for day t. This includes stream gains and losses, tributary inflows and stream diversions*

The coefficients are:

$$c_0 = 1.0 - \frac{Travel\ time\,(hrs)}{24\ hrs} \tag{15}$$

$$c_1 = 1.0 - c_0 \tag{16}$$

where the *Travel time* can be estimated from the length of the reach (*L*) and the average velocity (*V*) of the reach:

$$Travel\ time = \frac{L}{V} \tag{17}$$

2.2 miles per hour was used as the average velocity for this reach, and 43.6 miles was used for the length of the reach (Percha Dam to Leasburg Dam). This results in:

*travel time* = *19.82 hours*
$c_0$ = *0.174242*
$c_1$ = *0.825785*

## URGWOM surface water model

The focus of the Upper Rio Grande Water Operations Model (URGWOM) surface water model for the Rincon Valley reach of the Rio Grande is on flood-control operations and transport of floodwater. Surface water diversion data for agricultural purposes and subsequent return flow data are not used in this model. Diversions, return flow and unmeasured tributary inflows are represented as an unidentified component of a loss-coefficient applied to the reach. For complete details of this model, see URGWOM 2002.

The variable time lag routing method is used in URGWOM, and the following steps were used to develop loss coefficients and local inflows in the reach between Caballo and Leasburg (generally using the most recent 30-year period of data):

1. The lag time for the reach was estimated by dividing the reach length (about 45 mi) by the wave velocity. Since wave velocity varies with discharge, the travel time lag (*TL, hours*) also varies with discharge (*Q, cfs*). These values were plotted and a power equation was derived:

$$TL = 1507.1Q^{-0.632} \tag{18}$$

with $R^2 = 0.94$

At the time of this URGWOM study, RiverWare did not accept power equations, so this relationship was incorporated into a table for use in the model, as shown in Table 5:

Table 5. Travel Time Lags for Indicated Flow Rate – Caballo to Leasburg

| *Q (cfs)* | 50 | 200 | 500 | 750 | 1000 | 3000 | 6000 |
|---|---|---|---|---|---|---|---|
| *TL (hrs)* | 127 | 53 | 30 | 23 | 19 | 10 | 6 |

2. The travel time lags were then calibrated by multiplying the travel time lags by multipliers (for example, 0.5, 0.8, 1.0, 1.2, and 1.5) to provide a series of routed flows. These routed flows were then compared to the observed flows at the downstream gage, and the multiplier that minimized the standard error of the predicted routed flow versus the observed downstream flow was chosen. The table of calibrated time lags versus flow rates was updated using this multiplier (which turned out to be 1.5), as shown in Table 6.

Table 6. Calibrated Time Lags for Indicated Flow Rate

| *Q (cfs)* | 50 | 200 | 500 | 750 | 1000 | 3000 | 6000 |
|---|---|---|---|---|---|---|---|
| *TL (hrs)* | 191 | 79 | 44 | 35 | 29 | 14 | 9 |

3. A routed hydrograph was created by routing the upstream-observed hydrograph using the appropriate multiplier for travel time lag.

4. The dataset was filtered to determine only loss relations. Data were kept for days when the routed flow was greater than the downstream-observed flow in groups of three or more consecutive days.

5. The filtered downstream-observed data were plotted versus the filtered routed hydrograph. A regression analysis was performed on this data.

6. Monthly regression coefficients were created for each calendar month by using daily data in the regression analyses of the filtered data. The slope of the linear regression line of best fit was chosen to represent the loss coefficient. The regressions were computed with both y-intercept and y-intercept forced to zero. If the results were not significantly different, then the y-intercept forced to zero line was used.

7. A 'routed with losses' hydrograph was created using the monthly regression coefficient minus one and the appropriate y-intercept for the overall routed hydrograph.

8. A local inflow hydrograph was created to represents gains within the reach by subtracting the 'routed with losses' hydrograph from the downstream-observed hydrograph. The resulting values for loss coefficients and y-intercepts are shown in Table 7.

Table 7. Adopted Monthly Loss Coefficients and Y-intercepts

| | *0 – 1500 cfs* | | *1500 – 2500 cfs* | | *2500 – 1,000,000 cfs* | |
|---|---|---|---|---|---|---|
| | *Loss Coef* | *Y-Intercept* | *Loss Coef* | *Y-Intercept* | *Loss Coef* | *Y-Intercept* |
| *Jan.* | -0.09 | 0 | -0.05 | 0 | -0.05 | 0 |
| *Feb.* | -0.27 | 0 | -0.05 | 0 | -0.05 | 0 |
| *Mar.* | -0.25 | 0 | -0.25 | 0 | -0.05 | 0 |
| *Apr.* | -0.30 | 0 | -0.30 | 0 | -0.05 | 0 |
| *May* | -0.28 | 0 | -0.28 | 0 | -0.05 | 0 |
| *Jun.* | -0.27 | 0 | -0.27 | 0 | -0.05 | 0 |
| *Jul.* | -0.22 | 0 | -0.22 | 0 | -0.05 | 0 |
| *Aug.* | -0.26 | 0 | -0.26 | 0 | -0.05 | 0 |
| *Sep.* | -0.30 | 0 | -0.05 | 0 | -0.05 | 0 |
| *Oct.* | 0.05 | -441 | -0.05 | 0 | -0.05 | 0 |
| *Nov.* | -0.04 | 0 | -0.05 | 0 | -0.05 | 0 |
| *Dec.* | -0.09 | 0 | -0.05 | 0 | -0.05 | 0 |

These loss coefficients and y-intercepts do not apply to a flood-flow situation, since the data they were derived from were mostly in the low to moderate flow range rather than the flood-flow range.

## EVALUATION OF SELECTED PREVIOUS MODELING STUDIES

The Weeden and Maddock (1999) model method and the Boyle & Parsons (2000) model method were applied to data for the years 1979 through 1999 for Garfield, Hatch, and Rincon drains. The results from using these methods were then evaluated for the adequacy of the models used. For a regression model to be considered adequate, the coefficient of determination, $R^2$, should be close to 1, and the residuals from the model should be independent and have the attributes of a white noise process, that is,

1. have mean = 0
2. have a constant variance about the mean, with most points within ± 2 standard errors (se), and
3. have no observable pattern or trend in the data

The results from applying these methods to the data are evaluated in the following sections.

## Weeden and Maddock evaluation

Weeden and Maddock (1999) estimated a 15 percent return flow to the river from gross diversions to the Arrey Canal. Using data from 1979 through 1999 and plotting actual return flow alongside the return flow estimated by using this method gives the graph shown in Figure 17.

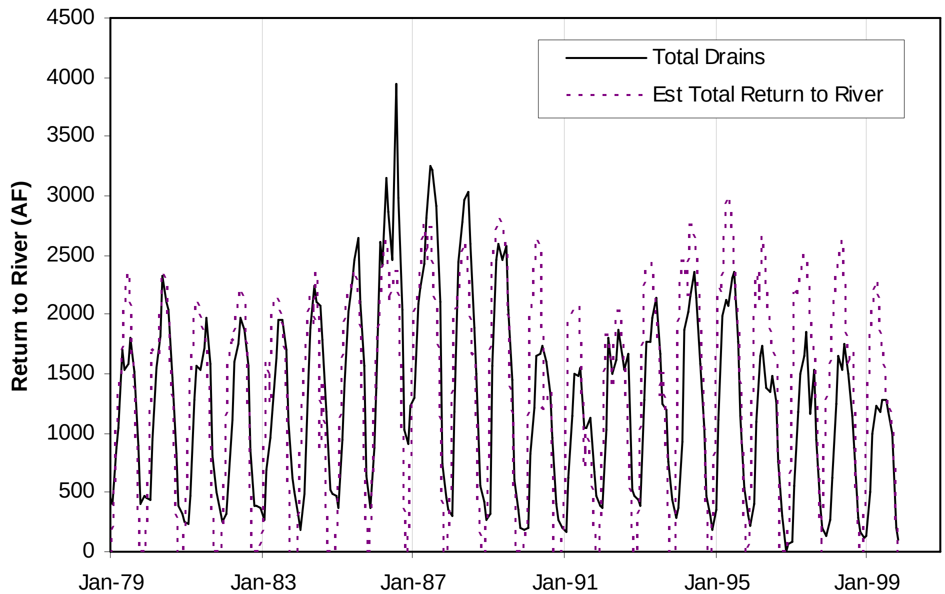
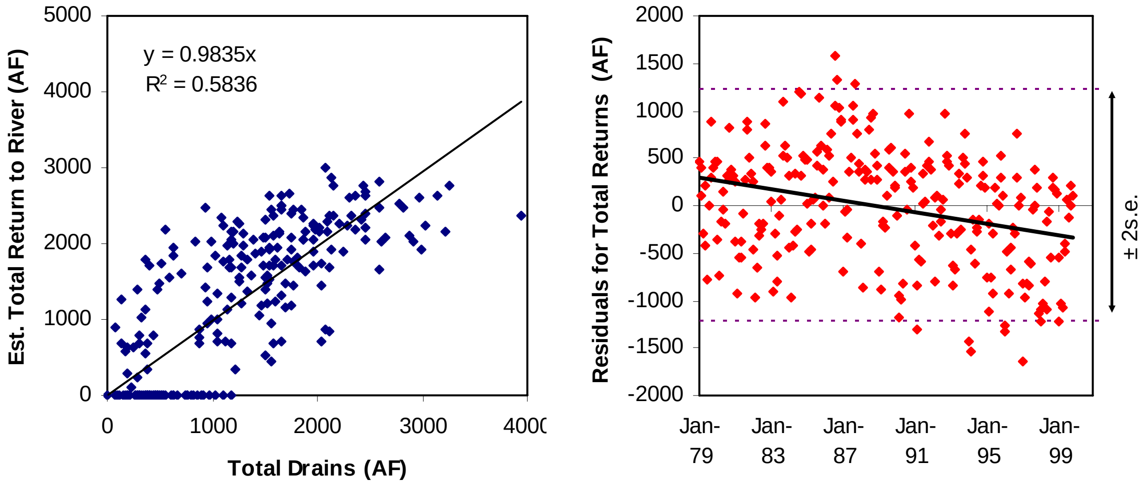



Figure 17. Return Flow to the River - Weeden and Maddock (1999) Method

This graph shows that the Weeden and Maddock method tends to overestimate high flows and underestimate low flows.

The estimated total return to the river was plotted against the actual total return to the river (or total drain flow) and is shown in Figure 18a. A linear regression with the intercept forced to zero was done, and the regression line and parameters were added to this graph. The $R^2$ value of 0.5836 for the regression is not very close to 1, indicating this may not be the best fit for the data. The line may be affected by the large number of near-zero values.

The residuals from this analysis are shown in Figure 18b, and they indicate a violation of the assumptions of constant variance about a mean of zero and no observable trend.




(a) (b)

Figure 18. Regression Results (a) and Residuals (b) - Weeden and Maddock (1999) Method

## Boyle & Parsons Engineering model evaluation

Boyle & Parsons (2000) estimated a 20 percent return flow to the river from gross diversions to Arrey Canal. These return flows were distributed to the drains over four months. Using data from 1979 through 1999, and plotting actual drain flow alongside the drain flow estimated by using this method gives the graph shown in Figure 19 for Garfield drain, Figure 20 for Hatch drain, and Figure 21 for Rincon drain.

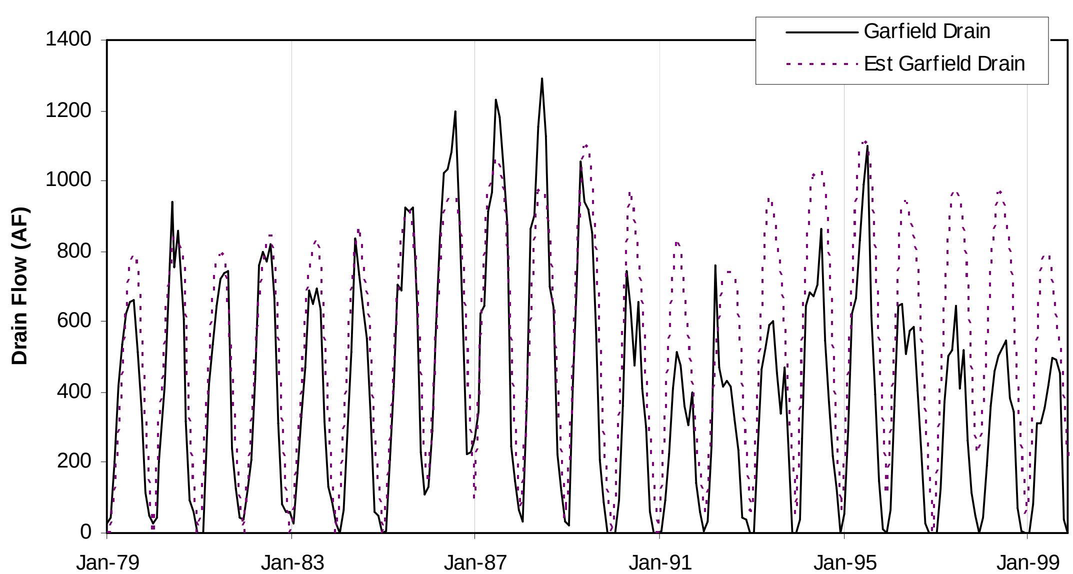



Figure 19. Garfield Drain Return Flow – Boyle & Parsons (2000) Method

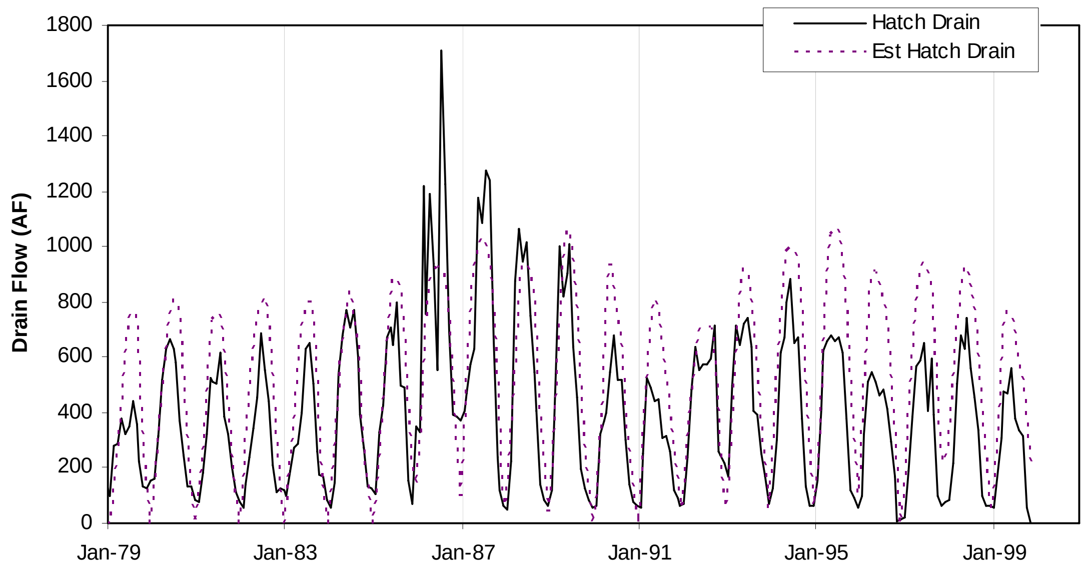



Figure 20. Hatch Drain Return Flow - Boyle & Parsons (2000) Method

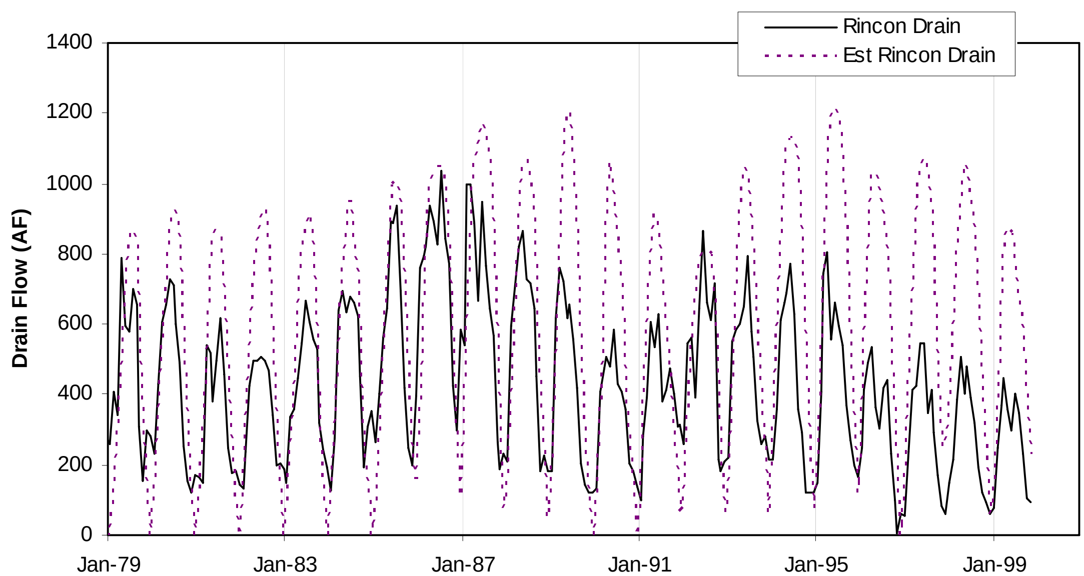
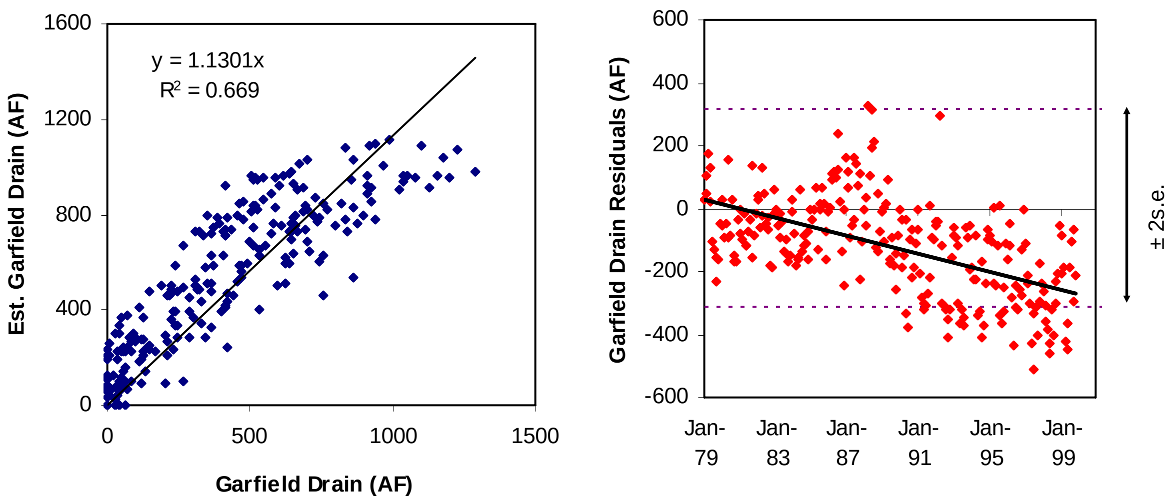



Figure 21. Rincon Drain Return Flow - Boyle & Parsons (2000) Method

Similar to the Weeden and Maddock estimates, Boyle & Parsons estimates for the drain flows tend to overestimate the high flows and in the case of Rincon drain, underestimate the low flows.

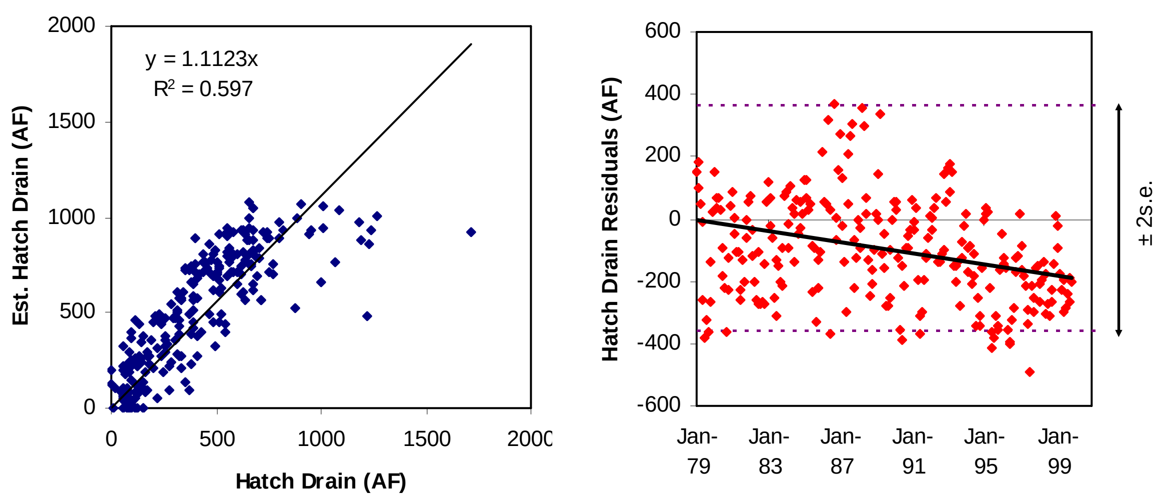
The estimated drain flow was plotted against the actual drain flow and is shown in Figure 22a for Garfield drain, Figure 23a for Hatch drain, and Figure 24a for Rincon drain. Linear regressions with the intercept forced to zero were done for each drain, and the regression lines and parameters were added to these graphs. The $R^2$ values of 0.669 for Garfield drain, 0.597 for Hatch drain, and 0.521 for Rincon drain are not very close to 1, indicating this method may not be the best fit for the data.

The residuals from these analyses are shown in Figure 22b for Garfield drain, Figure 23b for Hatch drain, and Figure 24b for Rincon drain. The residuals for all three drains indicate violation of the assumptions of mean equal to zero, constant variance about a mean of zero, and no observable trend.



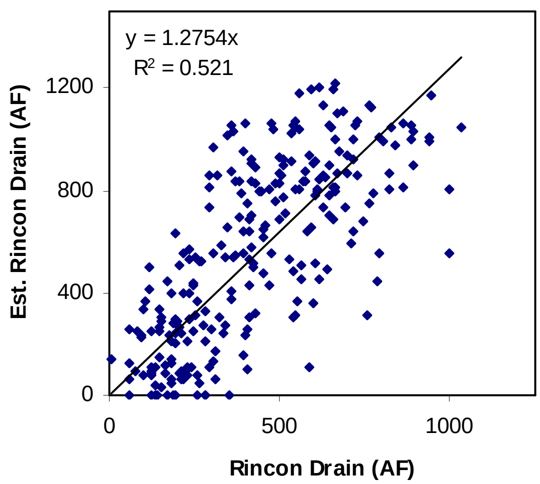

(a) (b)

Figure 22. Garfield Drain Regression (a) and Residuals (b) - Boyle & Parsons (2000) Method

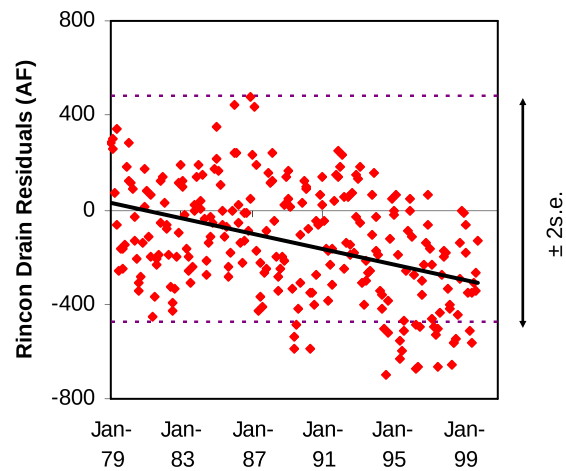



(a) (b)

Figure 23. Hatch Drain Regression (a) and Residuals (b) - Boyle & Parsons (2000) Method




(a)




(b)

Figure 24. Rincon Drain Regression (a) and Residuals (b) - Boyle & Parsons (2000) Method

## Summary

The estimates from using these methods result in residuals that violate the assumptions of a white noise process. This indicates that statistically these models are not adequate to use for this data. The assumption that the residuals form a white noise process means that the residuals need to be independent of each other. However, flow data can be time-series data that are not independent of each other, with residuals that are also not independent of each other (Haan 1986). Using ordinary regression analysis for this type of data and violating the independent errors assumptions has three important consequences (SAS 2000):

1. Statistical tests of the significance of the parameters and the confidence limits for the predicted values are not correct,
2. The estimates of the regression coefficients are not as efficient as they would be if the autocorrelation were taken into account, and
3. The ordinary regression residuals contain information that could be used to improve the prediction of future values.

# ARIMA Time-series Transfer Function Analysis

Physical models, such as those described in the previous sections, are useful for modeling the physical processes of a system. However, these models typically oversimplify some of the relationships between the diversions and return flows of the system, and although they may adequately simulate the physical processes involved, statistically they do not always provide a good fit to the data. Using a statistical method that accounts for current and past values in predicting a future value when modeling a physical system will provide a representation of the physical processes while maintaining statistical cohesion.

The statistical method chosen for modeling the relationships between the diversions and drain return flows along the upper portion of the Rio Grande Project is the **A**uto**R**egressive **I**ntegrated **M**oving-**A**verage (ARIMA) model. This type of model analyzes and forecasts equally spaced univariate time-series data. The predictions made by this model are from a linear combination of a variable's own past values, past errors (or residuals) and current and past values of other time-series. When an ARIMA model includes other time-series as input variables, the model is sometimes referred to as an ARIMA *transfer function model*. In a *transfer function model*, instead of assuming the residuals are independent, the residuals can be represented by an AutoRegressive Moving Average (ARMA) model (SAS 2000).

To model the interactions of surface and groundwater in the Rincon Valley, the main variables of interest are: diversion, conveyance infiltration, deep percolation from irrigation, groundwater withdrawal, and precipitation. The variable with the largest effect on the interactions is diversion, so this is the time-series variable used for the input series in a *transfer function model* that predicts drain flows and reach gains/losses. Even though groundwater withdrawals can be significant, groundwater pumping is correlated strongly to diversions, so using the diversion data will also indirectly account for groundwater pumping.

*Transfer function models* for the relationships between the diversion to Arrey Canal and drain-flow and reach gains/losses in the Rincon Valley were derived. The results from using these models were then compared to the results from the earlier selected modeling studies and to an ordinary linear regression analysis. Monthly data from 1979 through 1999 were primarily used for this analysis. The drain flow data were log transformed prior to performing the model estimation and forecasts by using the following equation:

$$Z = LN\left(Y + C\right) \qquad (19)$$

where

$Y$ = *drain flow (AF/M)*
$Z$ = *natural log of (drain flow + C)*
$C$ = *10; a constant added to the data series before taking the natural log*

One of the requirements for this type of analysis is that the variance values remain constant. If the variance is not constant, a natural log transform can be introduced that will stabilize the variance. The data can also be shifted if there are zeroes in the data so that valid log values can be taken. Neither the log transform nor the shift of the data affects the correlation of the data, which is the main property used in the time-series analysis. To retransform the forecast values for *Z* back to flow data *Y*, the following equation was used:

$$Y = \exp\left(Z + \frac{se^2}{2}\right) - C \qquad (20)$$

where *Se* = *the standard error of the forecast Z*

The reason this equation is not the exact inverse of a LN equation is that when the forecast value is simply exponentiated to retransform the data back, the equation gives a forecast for the median of the series, but underpredicts the mean of the original series. To predict the expected value of the series, the standard error of the forecast also needs to be taken into account (SAS 2000). Note that in the forecast equations developed in the following sections, values for the forecast Z and for residuals in the observed months 1 through 24 cannot always be calculated. It is therefore assumed that these values are equal to 0 for these months. This will introduce a bias into the forecasts for the early months after month 24, so it is recommended to have at least several years of observed data before using the *transfer function* equations to forecast data.

This document assumes the reader has some familiarity with ARIMA *transfer function* methods, and therefore will not provide detailed explanations for the results presented herein. For complete descriptions of ARIMA *transfer function* and results, see Box and Jenkins (1976) and SAS (2000).

## GARFIELD DRAIN ANALYSIS

Monthly data from 1979-1999 for the Garfield drain and Arrey Canal were used for this analysis.

### ARIMA transfer function analysis

The *SAS System for Windows, V9.1,* statistical software package was used to estimate model parameters. The results calculated by this software are shown in Table 8.

Table 8. Conditional Least Squares Estimation Results for Garfield Drain

| *Parameter* | *Estimate* | *Standard Error* | *t Value* | *Approx Pr > \|t\|* | *Lag* | *Variable* |
|---|---|---|---|---|---|---|
| $\theta_1$ | 0.85743 | 0.03858 | 22.22 | <.0001 | 12 | logGarfield |
| $\phi_1$ | 0.59033 | 0.05353 | 11.03 | <.0001 | 1 | logGarfield |
| $\phi_2$ | 0.29164 | 0.06412 | 4.55 | <.0001 | 11 | logGarfield |
| $\omega_o$ | 0.00005041 | 0.00001313 | 3.84 | 0.0002 | 0 | Arrey |

| | |
|---|---|
| Variance Estimate | 0.21667 |
| Std Error Estimate | 0.465478 |
| Number of Residuals | 240 |

The *transfer function model* for the Garfield drain with the Arrey Canal as the input series is:

$$\left(1-B^{12}\right)Z_t = \omega_o\left(1-B^{12}\right)X_t + \frac{\left(1-\theta_1 B^{12}\right)}{\left(1-\phi_1 B\right)\left(1-\phi_2 B^{11}\right)}a_t \tag{21}$$

where

| | |
|---|---|
| $Z_t$ | = *LN (Garfield drain flow + C) at time period t* |
| $X_t$ | = *diversion to Arrey Canal at time period t (AF)* |
| $a_t$ | = *residuals =* $Z_t$ *(actual) -* $Z_t$ *(predicted)* |
| *B* | = *back-shift operator, used to take differences over time of a value.* |
| | *For example:* |
| | $\left(1-B^{12}\right)Z_t = Z_t - Z_{t-12}$ |
| | $\left(1-\theta_1 B^{12}\right)a_t = a_t - \theta_1 a_{t-12}$ |
| *T* | = *time period* |
| $\omega_o$ | = *regression coefficient for Arrey Canal* |
| $\phi_1$, $\phi_2$ | = *autoregressive parameters for the residuals ARMA model* |
| $\theta_1$ | = *moving-average parameter for the residuals ARMA model* |

This model expands into the following equation to calculate the one-step ahead forecast values for Garfield drain:

$$\begin{aligned}\hat{Z}_{n+1} = {} & Z_{n-11} + \phi_1 Z_n - \phi_1 Z_{n-12} - \phi_1\phi_2 Z_{n-11} + \phi_1\phi_2 Z_{n-23} + \\ & \phi_2 Z_{n-10} - \phi_2 Z_{n-22} + \omega_o (X_{n+1} - X_{n-11} - \phi_1 X_n + \\ & \phi_1 X_{n-12} + \phi_1\phi_2 X_{n-11} - \phi_1\phi_2 X_{n-23} - \phi_2 X_{n-10} + \\ & \phi_2 X_{n-22}) - \theta_1\left(Z_{n-11} - \hat{Z}_{n-11}\right)\end{aligned} \tag{22}$$

where

| | |
|---|---|
| $\hat{Z}_{n+1}$ | = *forecast for LN (Garfield drain + C) for first month after observed data (AF)* |
| $Z_{n-i}$ | = *LN (Garfield drain + C) at month n-i* |
| $X_{n-i}$ | = *Arrey Canal (AF) at month n-i* |
| *n* | = *number of observations* |
| *i* | = *number of months of lag* |
| $\phi_1$ | = *0.59033* |
| $\phi_2$ | = *0.29164* |
| $\theta_1$ | = *0.85743* |
| $\omega_o$ | = *0.00005041* |
| *se* | =*0.46548* |
| *C* | = *10* |

**ARIMA transfer function results**

Plotting the actual Garfield drain data and the ARIMA time-series one-step ahead forecasts for Garfield drain gives the graph shown in Figure 25.

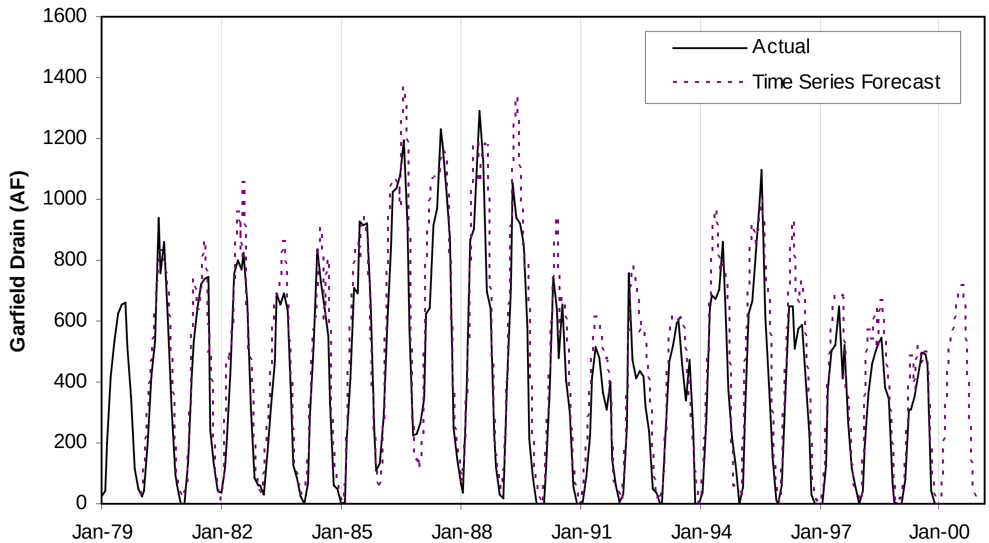
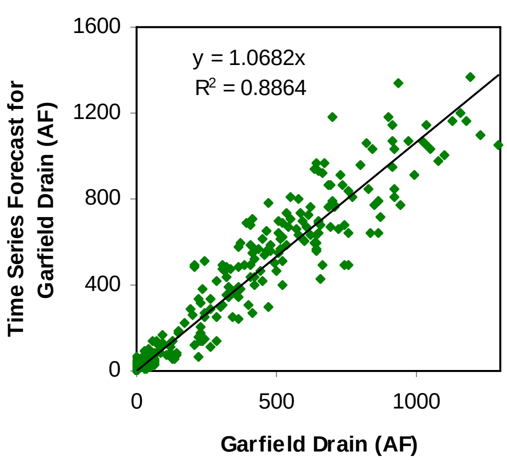
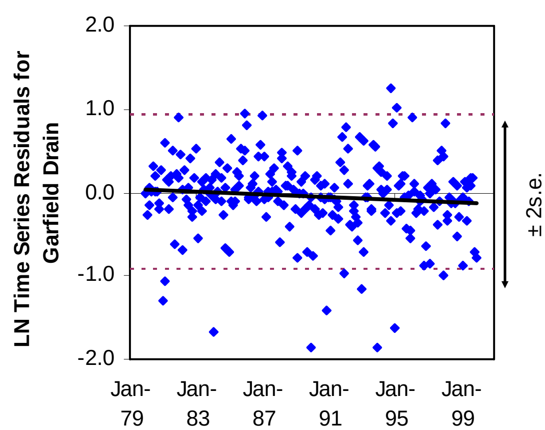



Figure 25. ARIMA Transfer Function Forecast for Garfield Drain

This graph shows that the one-step ahead forecast tracks well with the historic data. A correlation of the forecast data versus the actual data was done to check the model fit, and the residuals were plotted as shown in Figure 26a and Figure 26b, respectively.




(a)




(b)

Figure 26. Correlation (a) and Residuals (b) from Garfield Drain ARIMA Forecast

The ARIMA time-series correlation results in a higher $R^2$ value (0.8864) than the Boyle method estimate (0.669), indicating a better fit to the data. The residuals do not have an obvious trend and are consistent with the attributes of a white noise process, indicating the model may be adequate for this data.

**Linear regression comparison**

An ordinary linear regression analysis of monthly Garfield drain flow versus Arrey Canal flow, gives the relationship shown in Figure 27. This graph shows quite a bit of scatter and a lower $R^2$ value (0.5316) than the ARIMA (0.8864) analysis. Using this linear relationship to forecast the flow in Garfield drain from diversions to Arrey gives the graph shown in Figure 28.

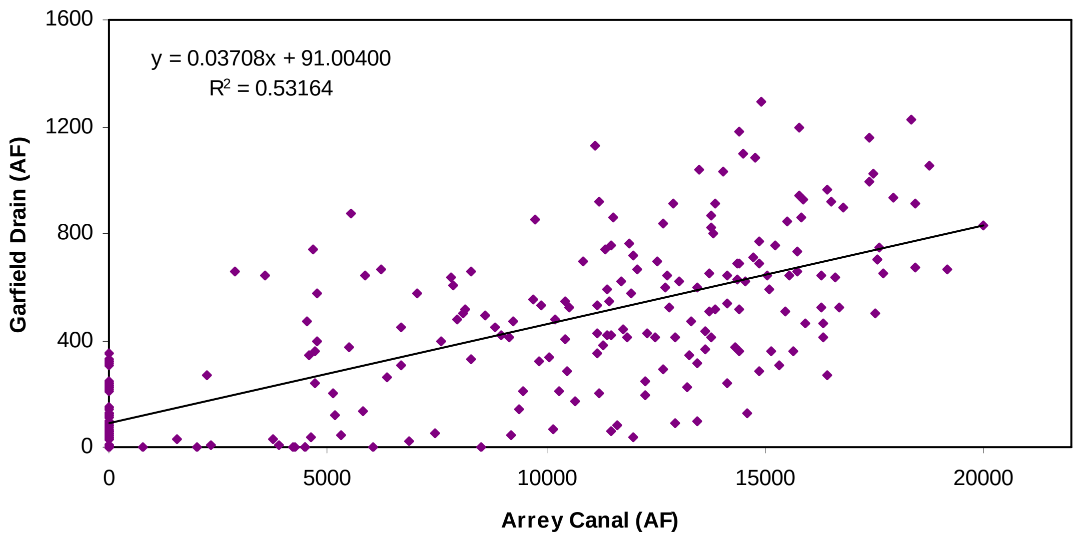



Figure 27. Ordinary Linear Regression for Garfield Drain versus Arrey Canal

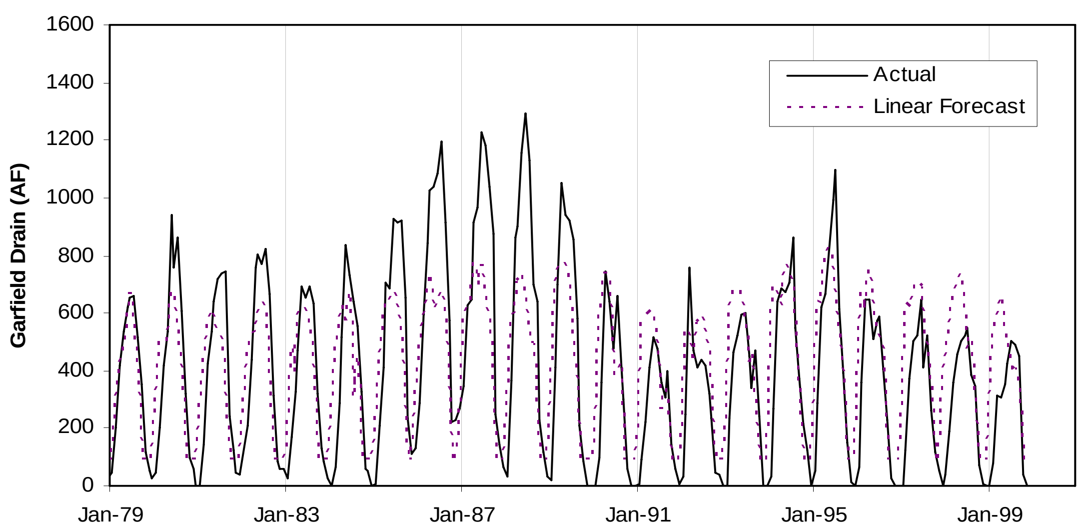
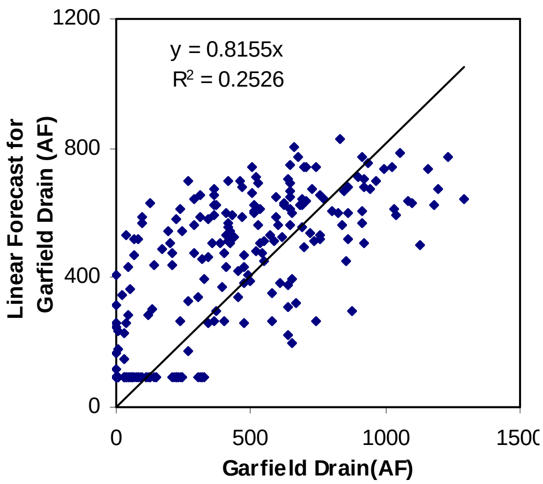
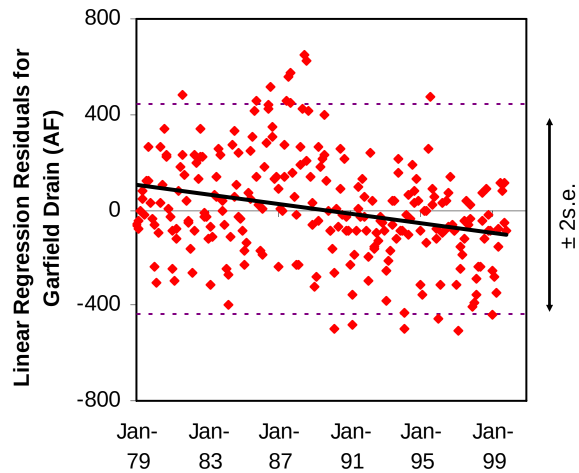



Figure 28. Forecast from Linear Regression for Garfield Drain

This graph shows that similar to Maddock and Weeden, and Boyle estimates the high flows tend to be underestimated and the low flows tend to be overestimated. A correlation of the forecast data versus the actual data was done to check the model fit, and the residuals were plotted as shown in Figure 29a and Figure 29b, respectively.




(a)




(b)

Figure 29. Correlation (a) and Residuals (b) from Garfield Drain Regression Forecast

The correlation $R^2$ value of 0.2526 indicates this model is a poor fit to the data. The residuals for this model indicate violation of the assumptions of constant variance about a mean of zero, and no observable trend. Together, these results indicate that this model is not adequate to represent the relationship between diversions to Arrey Canal and Garfield drain flow.

## HATCH DRAIN ANALYSIS

Monthly data from 1979 through 1999 for the Hatch drain and Arrey Canal were used for this analysis.

### ARIMA transfer function analysis

The *SAS System for Windows, V9.1,* statistical software package was used to estimate model parameters. The results calculated by this software are shown in Table 9:

Table 9. Conditional Least Squares Estimation Results for Hatch Drain

| *Parameter* | *Estimate* | *Standard Error* | *t Value* | *Approx Pr > \|t\|* | *Lag* | *Variable* |
|---|---|---|---|---|---|---|
| $\theta_1$ | 0. 76483 | 0. 04816 | 15.88 | <.0001 | 12 | logHatch |
| $\phi_1$ | 0. 66718 | 0. 05275 | 12.65 | <.0001 | 1 | logHatch |
| $\phi_2$ | 0. 23490 | 0. 06722 | 3.49 | 0.0006 | 10 | logHatch |
| $\omega_o$ | 0. 00004534 | 9.37931E-6 | 4.83 | <.0001 | 0 | Arrey |

| | |
|---|---|
| Variance Estimate | 0. 107424 |
| Std Error Estimate | 0. 327756 |
| Number of Residuals | 240 |

The *transfer function model* for the Hatch drain with the Arrey Canal as the input series is:

$$\left(1-B^{12}\right)Z_t = \omega_o\left(1-B^{12}\right)X_t + \frac{\left(1-\theta_1 B^{12}\right)}{\left(1-\phi_1 B\right)\left(1-\phi_2 B^{10}\right)}a_t \qquad (23)$$

where

| | |
|---|---|
| $Z_t$ | = *LN (Hatch drain flow + C) at time period t* |
| $X_t$ | = *diversion to Arrey Canal at time period t (AF)* |
| $a_t$ | = *residuals =* $Z_t$ *(actual) -* $Z_t$ *(predicted)* |
| B | = *back-shift operator, used to take differences over time of a value* |
| *t* | = *time period* |
| $\omega_o$ | = *regression coefficient for Arrey Canal* |
| $\phi_m$ | = *autoregressive parameter(s) for the residuals ARMA model* |
| $\theta_1$ | = *moving-average parameter for the residuals ARMA model* |

This model expands into the following equation to calculate the one-step ahead forecast values for Hatch drain:

$$\begin{aligned}\hat{Z}_{n+1} = {} & Z_{n-11} + \phi_1 Z_n - \phi_1 Z_{n-12} - \phi_1\phi_2 Z_{n-10} + \phi_1\phi_2 Z_{n-22} + \\ & \phi_2 Z_{n-9} - \phi_2 Z_{n-21} + \omega_o(X_{n+1} - X_{n-11} - \phi_1 X_n + \\ & \phi_1 X_{n-12} + \phi_1\phi_2 X_{n-10} - \phi_1\phi_2 X_{n-22} - \phi_2 X_{n-9} + \\ & \phi_2 X_{n-21}) - \theta_1(Z_{n-11} - \hat{Z}_{n-11})\end{aligned} \qquad (24)$$

where

| | |
|---|---|
| $\hat{Z}_{n+1}$ | = *Forecast for LN (Hatch drain + C) for first month after observed data (AF)* |
| $Z_{n-i}$ | = *LN (Hatch drain + C) at month n-i* |
| $X_{n-i}$ | = *Arrey Canal (AF) at month n-i* |
| *n* | = *number of observations* |
| *i* | = *number of months of lag* |
| $\phi_1$ | = *0.66718* |
| $\phi_2$ | = *0.23490* |
| $\theta_1$ | = *0.76483* |
| $\omega_o$ | = *0.00004534* |
| *se* | = *0.327756* |
| *C* | = *10* |

## ARIMA transfer function results

Plotting the actual Hatch drain data with the ARIMA time-series one-step ahead forecast for Hatch drain gives the graph shown in Figure 30.

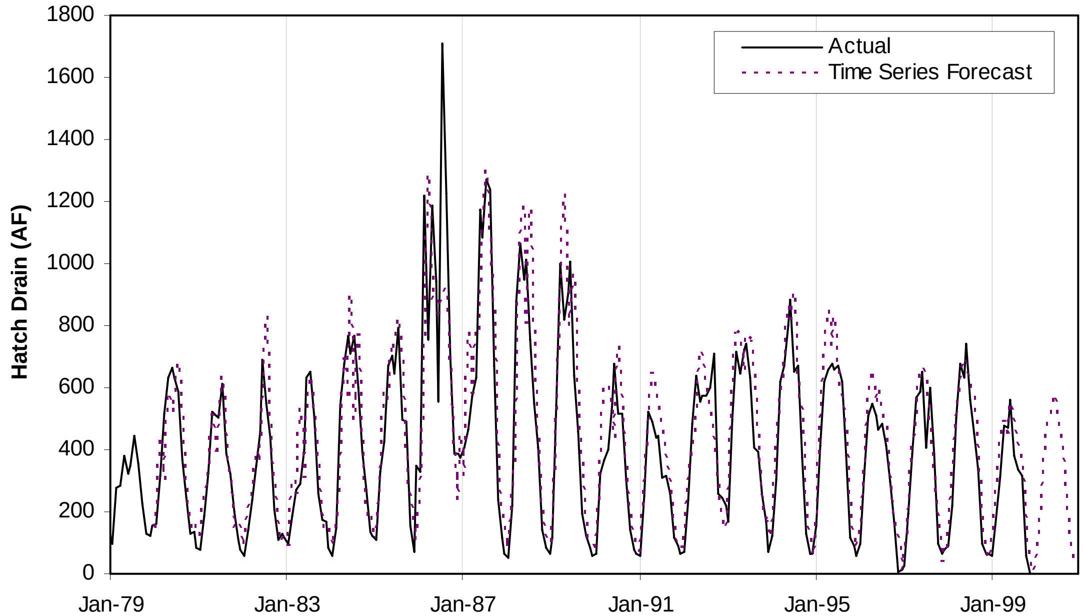
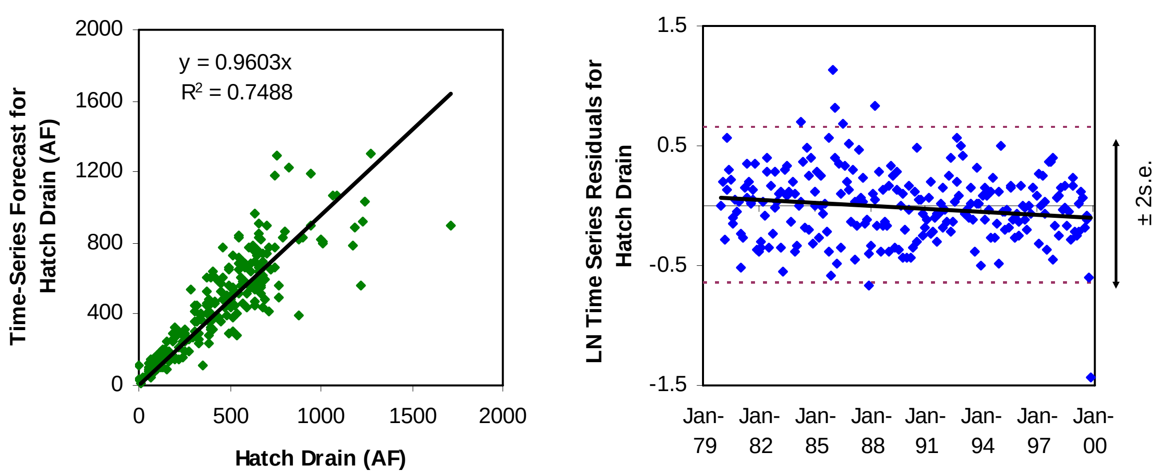



Figure 30. ARIMA Transfer Function Forecast for Hatch Drain

This graph shows that the one-step ahead forecast tracks well with the actual data. A correlation of the forecast data versus the actual data was done to check the model fit, and the residuals were plotted as shown in Figure 31a and Figure 31b, respectively.




(a) (b)

Figure 31. Correlation (a) and Residuals (b) from Hatch Drain ARIMA Forecast

The ARIMA time-series correlation results in a higher $R^2$ value (0.7488) than the Boyle method estimate (0.669), indicating a better fit to the data. The residuals do not have an obvious trend and are consistent with the attributes of a white noise process, indicating the model may be adequate for this data.

### Linear regression comparison

An ordinary linear regression of monthly Hatch drain flow versus Arrey Canal flow gives the relationship shown in Figure 32.

This graph shows quite a bit of scatter and a lower $R^2$ value (0.52238) than the ARIMA (0.7488) analysis. Using this relationship to forecast the flow in Hatch drain gives the graph shown in Figure 33.

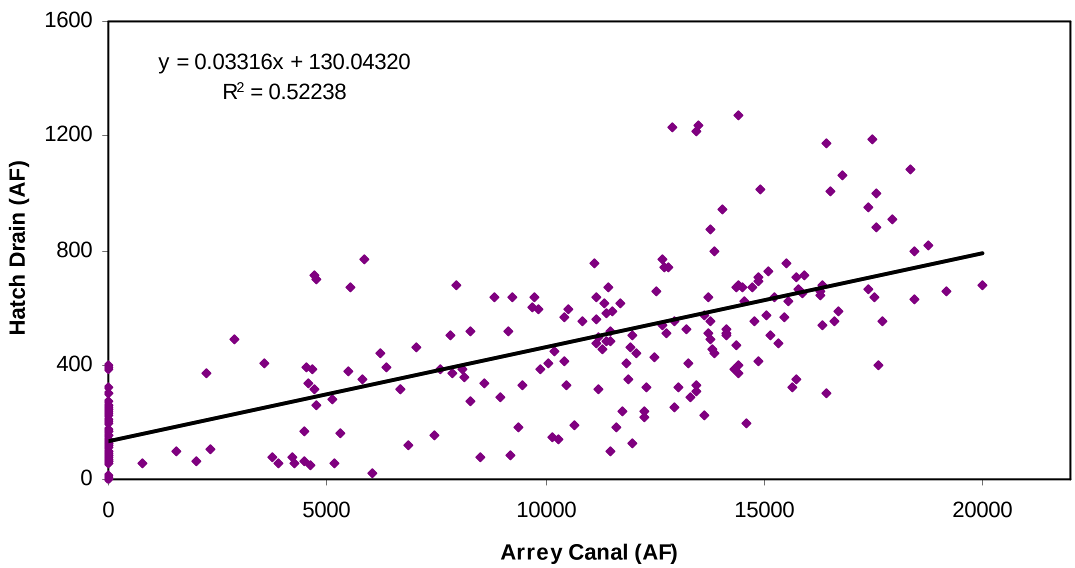



Figure 32. Ordinary Linear Regression for Hatch Drain versus Arrey Canal

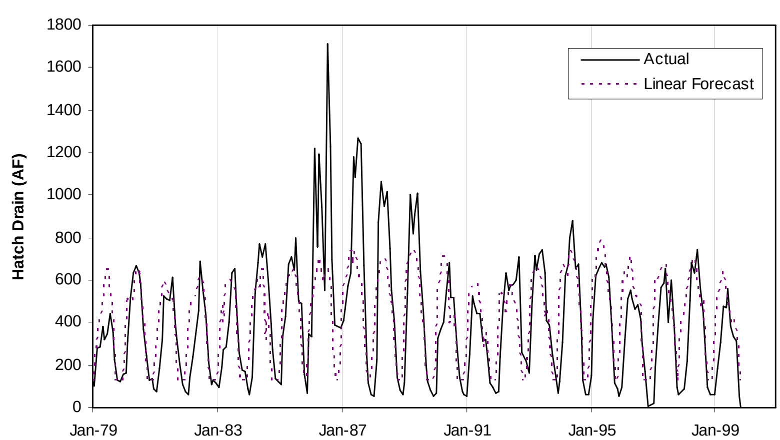
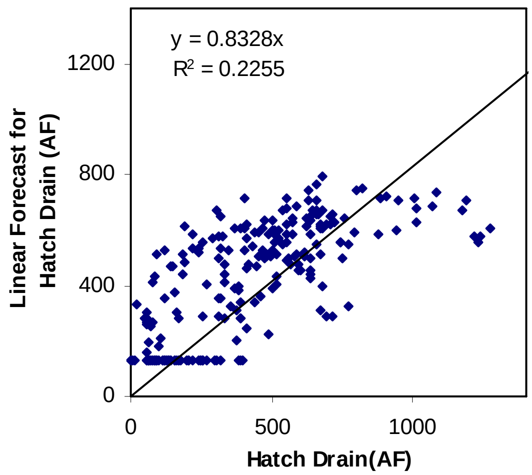
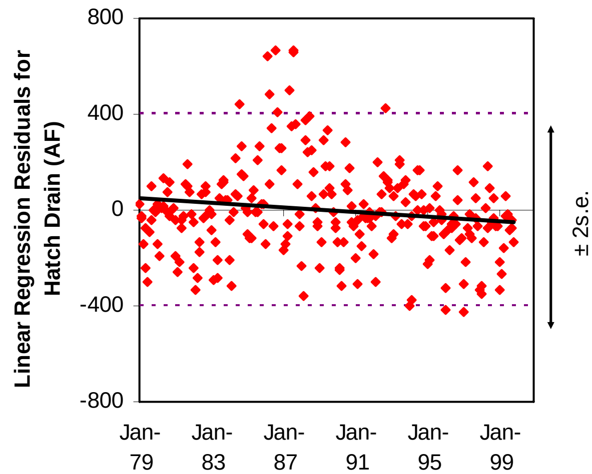



Figure 33. Forecast from Linear Regression for Hatch Drain

This graph shows that high flows tend to be underestimated and low flows tend to be overestimated. A correlation of the forecast data versus the actual data was done to check the regression fit, and the residuals were plotted as shown in Figure 34a and Figure 34b, respectively.




(a)




(b)

Figure 34. Correlation (a) and Residuals (b) from Hatch Drain Regression Forecast

The correlation $R^2$ value of 0.2255 indicates this model is a poor fit to the data. The residuals for this model violate the assumption of constant variance about a mean of zero. Together, these results indicate that this model is not adequate to represent the relationship between diversions to Arrey Canal and Hatch drain flow.

## RINCON DRAIN ANALYSIS

Monthly data from 1979 through 1999 for the Rincon Drain and Arrey Canal were used for this analysis.

### ARIMA transfer function analysis

The *SAS System for Windows, V9.1,* statistical software package was used to estimate model parameters. The results calculated by this software are shown in Table 10.

Table 10. Conditional Least Squares Estimation Results for Rincon Drain

| *Parameter* | *Estimate* | *Standard Error* | *t Value* | *Approx Pr > \|t\|* | *Lag* | *Variable* |
|---|---|---|---|---|---|---|
| $\theta_1$ | 0.69104 | 0.04899 | 14.11 | <.0001 | 12 | logRincon |
| $\phi_1$ | 0.61520 | 0. 05149 | 11.95 | <.0001 | 1 | logRincon |
| $\omega_o$ | 0.00002759 | 8.91748E-6 | 3.09 | 0.0022 | 0 | Arrey |

| | |
|---|---|
| Variance Estimate | 0. 092808 |
| Std Error Estimate | 0. 304645 |
| Number of Residuals | 240 |

The *transfer function model* for the Rincon drain with the Arrey Canal as the input series is:

$$\left(1-B^{12}\right)Z_t = \omega_o\left(1-B^{12}\right)X_t + \frac{\left(1-\theta_1 B^{12}\right)}{\left(1-\phi_1 B\right)}a_t \tag{25}$$

where

| | |
|---|---|
| $Z_t$ | = *LN (Rincon drain flow + C) at time period t* |
| $X_t$ | = *diversion to Arrey Canal at time period t (AF)* |
| $a_t$ | = *residuals =* $Z_t$ *(actual) -* $Z_t$ *(predicted)* |
| $B$ | = *back-shift operator, used to take differences over time of a value* |
| $t$ | = *time period* |
| $\omega_o$ | = *regression coefficient for Arrey Canal* |
| $\phi_1$ | = *autoregressive parameter for the residuals ARMA model* |
| $\theta_1$ | = *moving-average parameter for the residuals ARMA model* |

This model expands into the following equation to calculate the one-step ahead forecast values for Rincon drain:

$$\hat{Z}_{n+1} = Z_{n-11} + \phi_1 Z_n - \phi_1 Z_{n-12} + \omega_o(X_{n+1} - X_{n-11} - \phi_1 X_n + \phi_1 X_{n-12}) - \theta_1\left(Z_{n-11} - \hat{Z}_{n-11}\right) \tag{26}$$

where

| | |
|---|---|
| $\hat{Z}_{n+1}$ | = *Forecast for LN (Rincon drain + C) for first month after observed data (AF)* |
| $Z_{n-i}$ | = *LN (Rincon drain + C) at month n –i* |
| $X_{n-i}$ | = *Arrey Canal (AF) at month n-i* |
| $n$ | = *number of observations* |
| $i$ | = *number of months of lag* |
| $\phi_1$ | = *0.61520* |
| $\theta_1$ | = *0.69104* |
| $\omega_o$ | = *0.00002759* |
| *se* | = *0.304645* |
| $C$ | = *10* |

**ARIMA transfer function results**

Plotting the actual Rincon Drain data with the forecast Rincon drain data gives the graph shown in Figure 35.

This graph shows that the one-step ahead forecast tracks well with the actual low flow data. A correlation of the forecast data versus the actual data was done to check the model fit, and the residuals were plotted as shown in Figure 36a and Figure 36b, respectively.

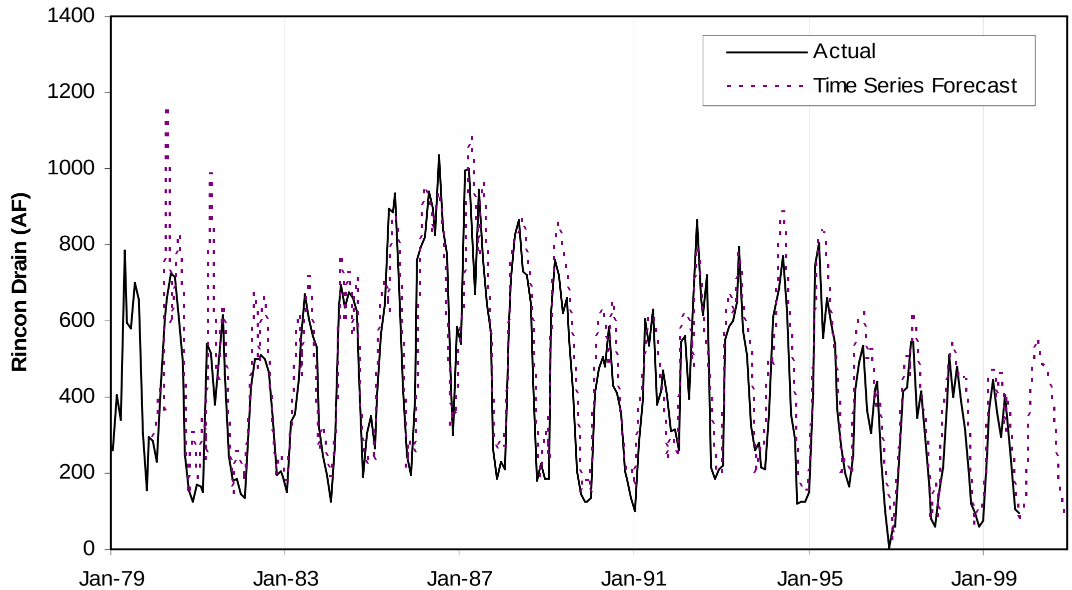
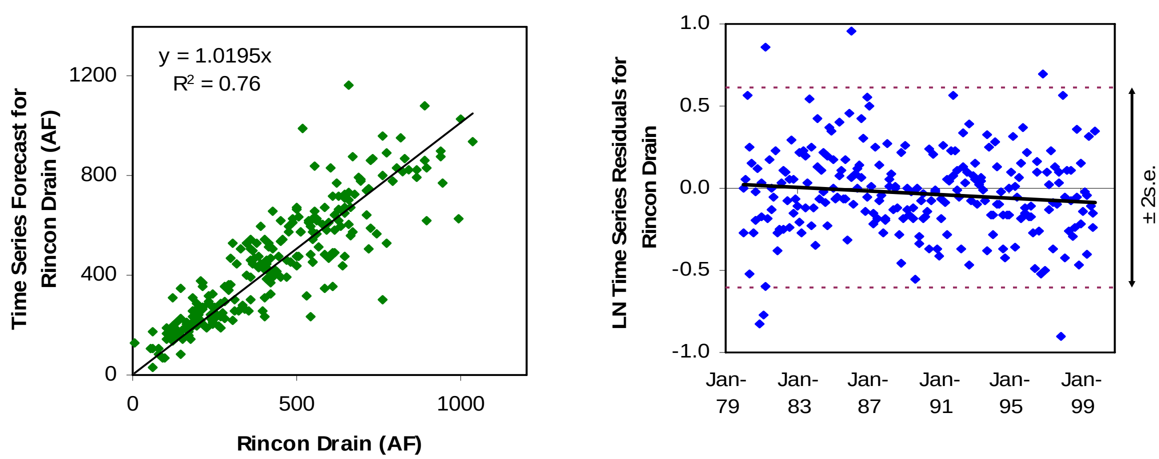



Figure 35. ARIMA Transfer Function Forecast for Rincon Drain




(a) (b)

Figure 36. Correlation (a) and Residuals (b) from Rincon Drain ARIMA Forecast

The ARIMA time-series correlation results in a higher $R^2$ value (0.76) than the Boyle method estimate (0.669), indicating a better fit to the data. The residuals do not have an obvious trend and are consistent with the attributes of a white noise process, indicating the model may be adequate for this data.

## Linear regression comparison

An ordinary linear regression of monthly Rincon Drain flow versus Arrey Canal flow gives the relationship shown in Figure 37.

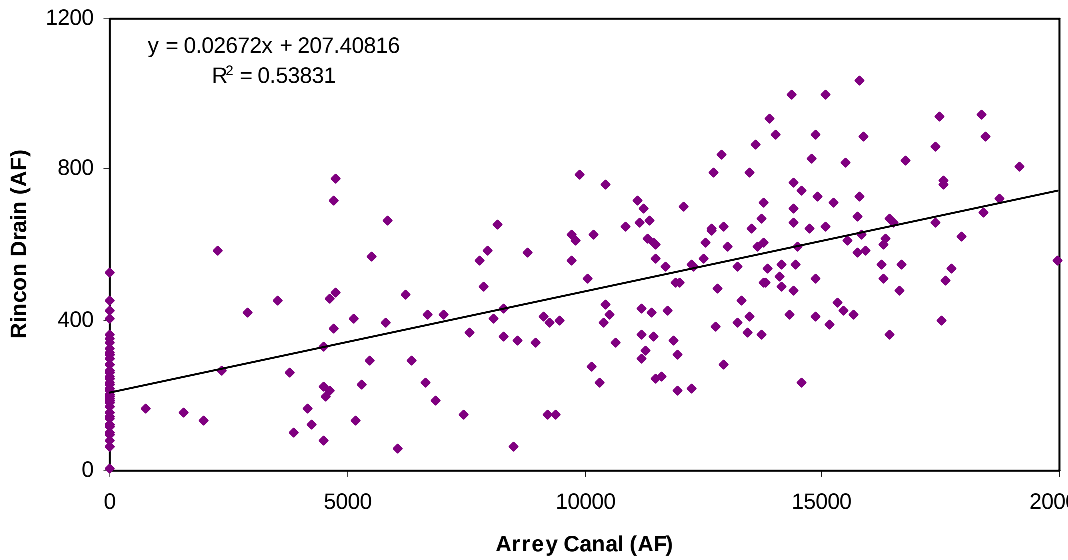



Figure 37. Ordinary Linear Regression for Rincon Drain versus Arrey Canal

This graph shows quite a bit of scatter and a lower $R^2$ value (0.53831) than the ARIMA (0.76) analysis. Using this relationship to forecast the one-step ahead flow in the Rincon drain gives the graph shown in Figure 38.

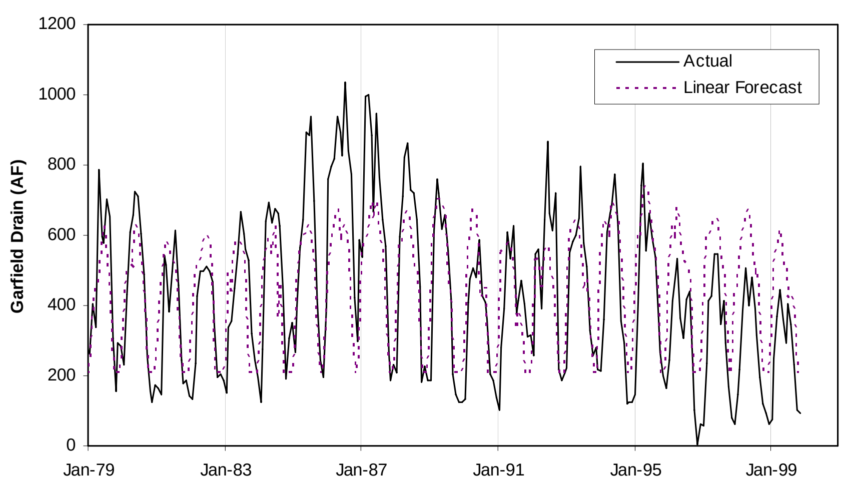
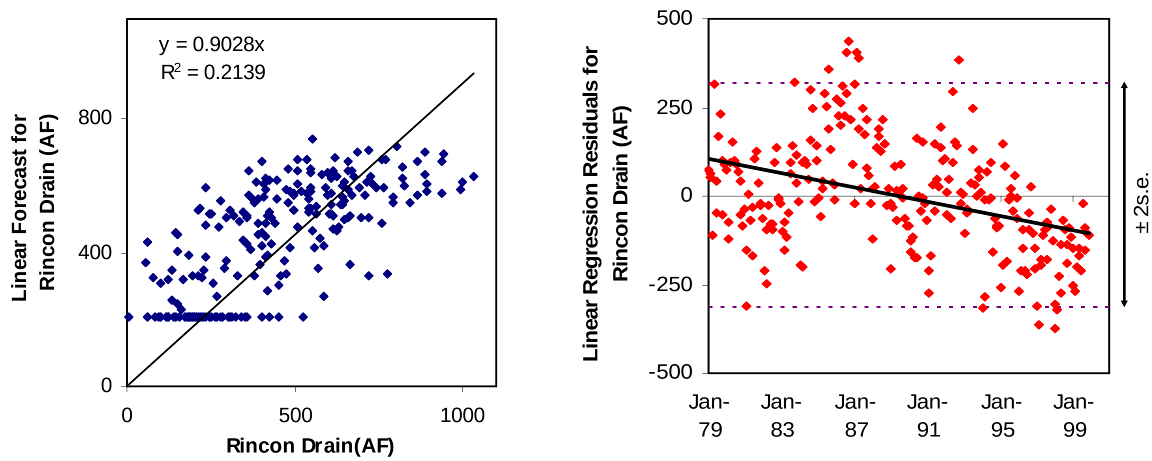



Figure 38. Forecast from Linear Regression for Rincon Drain

This figure shows a tendency to overestimate the low flows and underestimate the high flows. A correlation of the forecast data versus the actual data was done to check the regression fit, and the residuals were plotted as shown in Figure 39a and Figure 39b, respectively.




(a) (b)

Figure 39. Correlation (a) and Residuals (b) from Rincon Drain Regression Forecast

The correlation $R^2$ value of 0.2139 indicates this model is a poor fit to the data. The residuals for this model violate the assumptions of constant variance about a mean of zero, and no observable trend. Together, these indicate that this model is not adequate to represent the relationship between diversions to Arrey Canal and Rincon drain flow.

## REACH GAINS/LOSSES ANALYSIS

Monthly data from 1979 through 1983, and 1993 through 1999, were used to analyze the gains/losses in the reach between Caballo Dam and Leasburg Dam. The actual Gain/Loss values were calculated as:

$$\begin{aligned} \textit{Gain/Loss} = {} & \textit{Rio Grande below Leasburg} - \textit{Rio Grande below Caballo} + \\ & \textit{Arrey Canal} + \textit{Percha Lateral} - \textit{Garfield Drain} - \\ & \textit{Hatch Drain} - \textit{Rincon Drain} - \textit{WW\#5 (Garfield Canal)} - \\ & \textit{WW\#16 (Hatch Canal)} - \textit{WW\#18 (Rincon Canal)} + \textit{Leasburg Canal} \end{aligned} \quad (27)$$

The years chosen for the analysis were the years that had data for all of the components of this equation.

### ARIMA transfer function analysis

The *SAS System for Windows, V9.1,* statistical software package was used to estimate model parameters. The results calculated by this software are shown in Table 11.

Table 11. Conditional Least Squares Estimation Results for Gains/Losses

| *Parameter* | *Estimate* | *Standard Error* | *t Value* | *Approx Pr > \|t\|* | *Lag* | *Variable* |
|---|---|---|---|---|---|---|
| $\theta_1$ | 0.41377 | 0.09059 | 4.57 | <.0001 | 12 | GainLoss |
| $\phi_1$ | 0.57736 | 0. 07246 | 7.97 | <.0001 | 1 | GainLoss |
| $\omega_o$ | -0.25968 | 0.14369 | -1.81 | 0.0730 | 0 | Arrey |

| | |
|---|---|
| Variance Estimate | 14257190 |
| Std Error Estimate | 3775.869 |
| Number of Residuals | 240 |

The *transfer function model* for the Gains/Losses with the Arrey Canal as the input series is:

$$\left(1 - B^{12}\right)Y_t = \omega_o\left(1 - B^{12}\right)X_t + \frac{\left(1 - \theta_1 B^{12}\right)}{\left(1 - \phi_1 B\right)}a_t \tag{28}$$

where

$Y_t$ = *Gains/losses at time period t*
$X_t$ = *diversion to Arrey Canal at time period t (AF)*
$a_t$ = *residuals* = $Y_t$ *(actual)* - $Y_t$ *(predicted)*
$B$ = *back-shift operator, used to take differences over time of a value.*
$t$ = *time period*
$\omega_o$ = *regression coefficient for Arrey Canal*
$\phi_1$ = *autoregressive parameter for the residuals ARMA model*
$\theta_1$ = *moving-average parameter for the residuals ARMA model l*

This model expands into the following equation to calculate the one-step ahead forecast values for Gains/Losses:

$$\begin{gathered}\hat{Y}_{n+1} = Y_{n-11} + \phi_1 Y_n - \phi_1 Y_{n-12} + \omega_o(X_{n+1} - X_{n-11} - \\ \phi_1 X_n + \phi_1 X_{n-12}) - \theta_1\left(Y_{n-11} - \hat{Y}_{n-11}\right)\end{gathered} \tag{29}$$

where

$\hat{Y}_{n+1}$ = *Gains/Losses for first month after observed data (AF)*
$X_{n-i}$ = *Arrey Canal (AF) at month n-i*
$n$ = *number of observations*
$i$ = *number of months of lag*
$\phi_1$ = *0.57736*
$\theta_1$ = *0.41377*
$\omega_o$ = *-0.25968*

**ARIMA transfer function results**

A comparison of the actual Gains/Losses data with the forecast Gains/Losses data gives the graph shown in Figure 40.

This graph shows that the one-step ahead forecast for Gains/Losses is not as good as the forecasts for the drains. This may be due to both the more variable nature of Gains/Losses and to having less actual data to use for the transfer function analysis. A correlation of the forecast data versus the actual data was done to check the model fit, and the residuals were plotted as shown in Figure 41a and Figure 41b, respectively.

The residuals graph Figure 41b shows a possible increase in the variance of the Gains/Losses. Without a complete data set it is impossible to say definitively, since often the variance at the beginning of a time-series forecast is not consistent with the variance of the rest of the forecast period. This is due to the bias at the beginning of the forecast as described earlier. Even so, this correlation is still acceptable to forecast Gains/Losses.

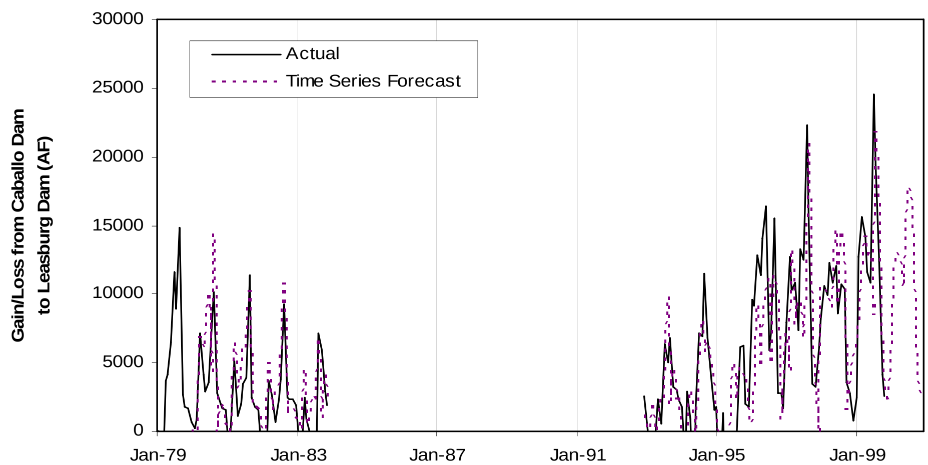



Figure 40. ARIMA Transfer Function Forecast for Gains/Losses

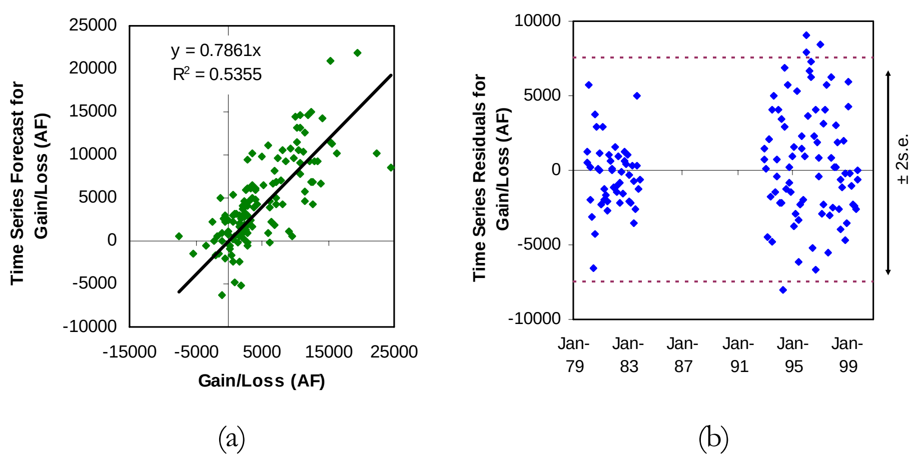



Figure 41. Correlation and Residuals for Gains/Losses ARIMA Forecast

### Linear regression comparison

Doing an ordinary linear regression of monthly Gains/Losses versus Arrey Canal flow gives the relationship shown in Figure 42.

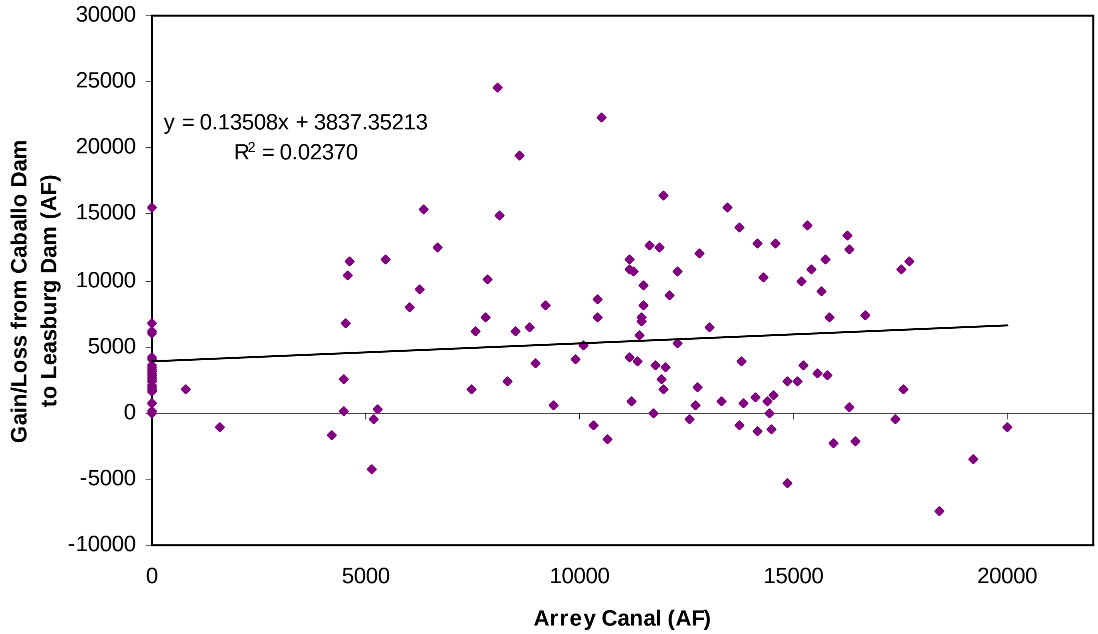



Figure 42. Ordinary Linear Regression for Gains/Losses versus Arrey Canal

This figure shows virtually no correlation between the diversion at Arrey Canal and the Gains/Losses between Caballo Dam and Leasburg Diversion Dam. Clearly, simple linear regression cannot be used for estimating gains/losses in this reach.

# RiverWare Conceptual Model Design

For the initial implementation of the RiverWare conceptual model for the Rincon Reach, the time period used was January 1979 to January 2000, with observed data for 1979 through 1999. The time interval used is monthly, and the following locations in the model are specified as input data:

- River below Caballo
- WW #5 (Garfield Canal)
- WW #16 (Hatch Canal)
- WW #18 (Rincon Canal)
- Angostura Drain (set to all zero data)

All input data are in units of acre-feet/month. These data are transformed to a dimensionless form for processing in the ARIMA *transfer functions* equations. The results from the ARIMA analysis are then transformed back to units of acre-feet/month for the links to the inflow and outflow nodes on the RiverWare objects. This is necessary for two reasons: 1) to circumvent RiverWare automatic conversions on monthly data based on the number of days in the month, and 2) the exponential function does not work with units of acre-feet/month on the value to be exponentiated.

Data for the Arrey Canal is forecast using an ARIMA *transfer function* that was developed with the Rio Grande below Caballo flow data as the input series. Then data for Percha Lateral, the drains and Gains/Losses in the reach are forecast using the ARIMA *transfer functions* with the forecast Arrey Canal flow as the input series.

The layout for this model includes nodes for the diversions, for the drain and wasteway return flows, and for the flow at the river stations. This layout is shown in Figure 43.

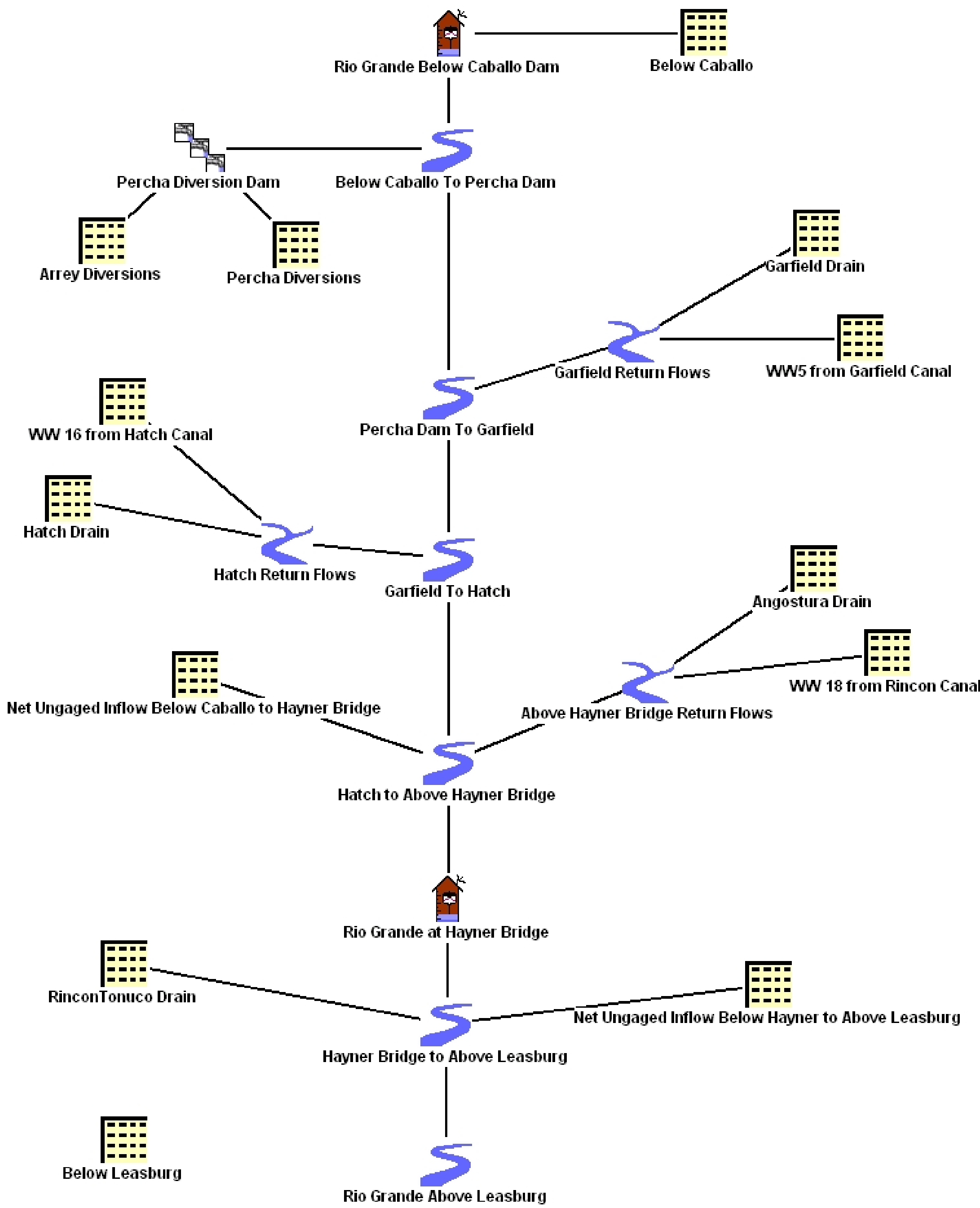



Figure 43. RiverWare Conceptual Model Layout

An additional data object for Below Leasburg data is included to compare the Rio Grande above Leasburg flow results from this model with the actual flow data at that location.

The additional forecast equations that are used by the conceptual model are described in the following sections. The first two years of the simulation (1979 and 1980) cannot be forecast by the ARIMA *transfer function* equations, as some of the forecast equations require up to 24 months of past data. Therefore, historic data for 1979 and 1980 are used for those years instead of forecast data.

## FORECAST EQUATION FOR ARREY CANAL

The *transfer function* equation for the Arrey Canal uses the Rio Grande below Caballo flow data as the input series. The forecast equation is:

$$\hat{Y}_{n+1} = Y_{n-11} + \phi_1 Y_n - \phi_1 Y_{n-12} + \omega_o X_{n+1} - \omega_o X_{n-11} - \omega_o \phi_1 X_n + \omega_o \phi_1 X_{n-12} - \theta_1 \left( Y_{n-11} - \hat{Y}_{n-11} \right) \quad (30)$$

where

$\hat{Y}_{n+1}$ = *forecast for Arrey Canal diversion for first month after observed data (AF)*
$X_{n-i}$ = *Rio Grande below Caballo (AF) at month n-i*
$n$ = *number of observations*
$i$ = *number of months of lag*
$\phi_1$ = *0.43048*
$\theta_1$ = *0.74759*
$\omega_o$ = *0.054395*

Then if the forecast value is less than zero, it is set equal to zero.

## FORECAST EQUATION FOR PERCHA LATERAL

The *transfer function* equations for Percha Lateral use the forecast Arrey Canal flow data as the input series. The forecast equation is:

$$\hat{Z}_{n+1} = Z_{n-11} + \phi_1 Z_{n-4} - \phi_1 Z_{n-16} + \omega_o (X_{n+1} - X_{n-11} - \phi_1 X_{n-4} + \phi_1 X_{n-16}) - \theta_1 (Z_{n-11} - \hat{Z}_{n-11}) \quad (31)$$

$$\hat{Y}_{n+1} = \exp\left( \hat{Z}_{n+1} + \frac{se^2}{2} \right) - C \quad (32)$$

where

| | |
|---|---|
| $\hat{Y}_{n+1}$ | = *forecast for Percha Lateral for first month after observed data (AF)* |
| $\hat{Z}_{n+1}$ | = *forecast for LN (Percha Lateral + C) for first month after observed data* |
| $Z_{n-i}$ | = *LN (Percha Lateral + C) at month n-i* |
| $X_{n-i}$ | = *Arrey Canal (AF) at month n-i* |
| $n$ | = *number of observations* |
| $i$ | = *number of months of lag* |
| $\phi_1$ | = *0.17095* |
| $\theta_1$ | = *0.64641* |
| $\omega_o$ | = *0.0001330* |
| $se$ | = *0.355677* |
| $C$ | = *10* |

Then if the forecast value is less than zero, it is set equal to zero.

## FORECAST EQUATION FOR GAIN/LOSSES (CABALLO DAM TO HAYNOR BRIDGE)

The forecast for Gains/Losses (Net Ungaged Inflow below Caballo to Haynor Bridge in Figure 43) from below Caballo Dam to Haynor Bridge is derived from the forecast for Gains/Losses from below Caballo Dam to Leasburg Dam. The distance between Caballo Dam and Haynor Bridge is approximate 75 percent of the distance between Caballo Dam and Leasburg Dam, so this same proportion was applied to the total reach gains/losses term.

The forecast equation is therefore:

$$\hat{Y}_{n+1} = 0.75\,\hat{X}_{n+1} \qquad (33)$$

where

| | |
|---|---|
| $\hat{Y}_{n+1}$ | = *forecast for Gain/Loss from Caballo to Haynor for first month after observed data (AF)* |
| $\hat{X}_{n+1}$ | = *forecast for Gain/Loss from Caballo to Leasburg for first month after observed data (AF)* |

## FORECAST EQUATION FOR GAIN/LOSSES (HAYNOR TO ABOVE LEASBURG)

Similar to the calculation for forecast for Gains/Losses from Caballo Dam to Haynor Bridge, the Gains/Losses from Haynor Bridge to above Leasburg Dam (Net Ungaged Inflow below Haynor to above Leasburg in Figure 43) are assigned the remaining 25 percent of the gains/losses from Caballo to Leasburg.

The forecast equation is:

$$\hat{Y}_{n+1} = 0.25\,\hat{X}_{n+1} \qquad (34)$$

where

$\hat{Y}_{n+1}$ *= forecast for Gain/Losses from Haynor Bridge to Leasburg Dam for the first month after observed data (AF)*

$\hat{X}_{n+1}$ *= forecast for Gain/Losses from Caballo Dam to Leasburg Dam for the first month after observed data (AF)*

# Conceptual Model Results

The conceptual RiverWare model described herein produces the results shown in the following sections for the sites forecast using the transfer functions. A comparison of the actual flow above Leasburg Diversion Dam to the forecast flow is made to test the validity of this model.

## ARREY CANAL RESULTS

Plotting the results for Arrey Canal from the RiverWare conceptual model and the actual Arrey Canal data results in the graph shown in Figure 44. This graph shows that the conceptual model results follow the actual data quite closely.

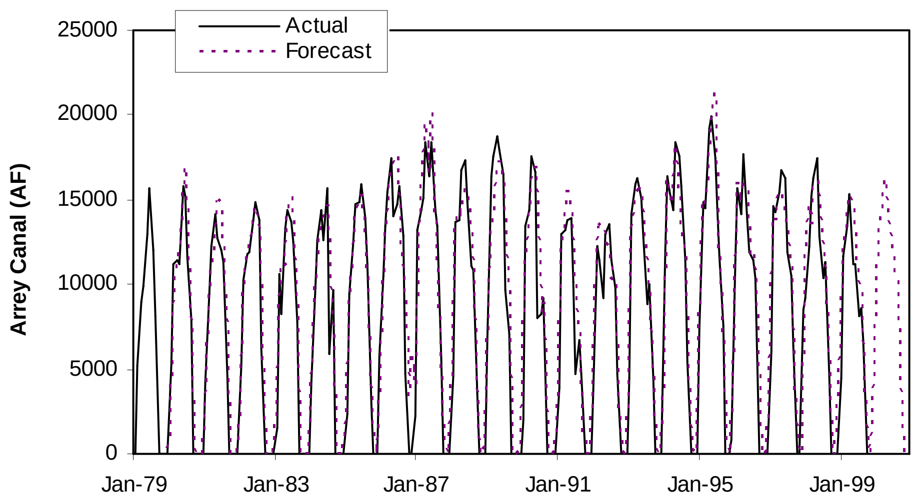



Figure 44. Arrey Canal Results from Conceptual Model

The correlation check of the conceptual model forecast data versus the actual data for Arrey Canal is shown in Figure 45.

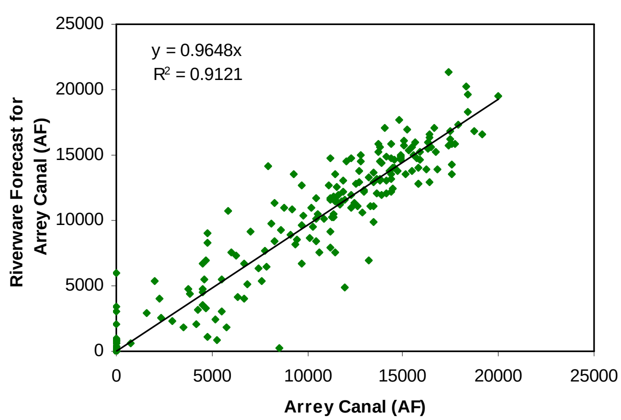



Figure 45. Arrey Canal Regression from Conceptual Model Results

## PERCHA LATERAL RESULTS

Plotting the results for Percha Lateral from the conceptual RiverWare model and the actual Percha Lateral data results in the graph shown in Figure 46. This graph shows that the conceptual model results follow the actual data fairly well, but are not as close as the results from the Arrey Canal.

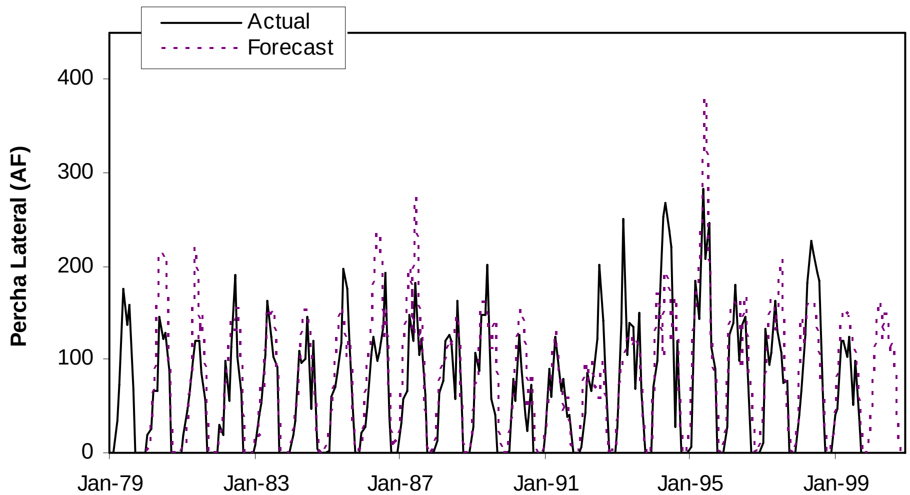



Figure 46. Percha Lateral Results from Conceptual Model

The correlation check of the forecast data versus the actual data for Percha Lateral is shown in Figure 47.

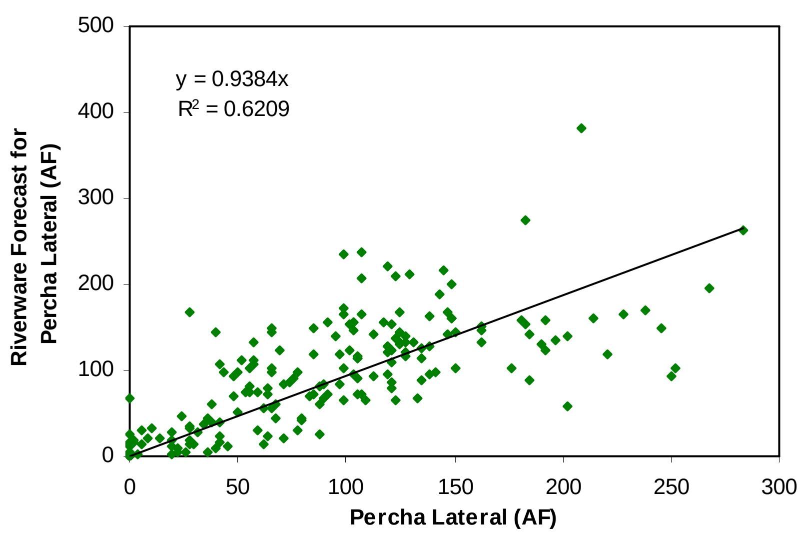



Figure 47. Percha Lateral Regression from Conceptual Model Results

## GARFIELD DRAIN RESULTS

Plotting the results for Garfield drain from the conceptual RiverWare model and the actual Garfield drain data results in the graph shown in Figure 48. This graph shows that the conceptual model results follow the actual data fairly well.

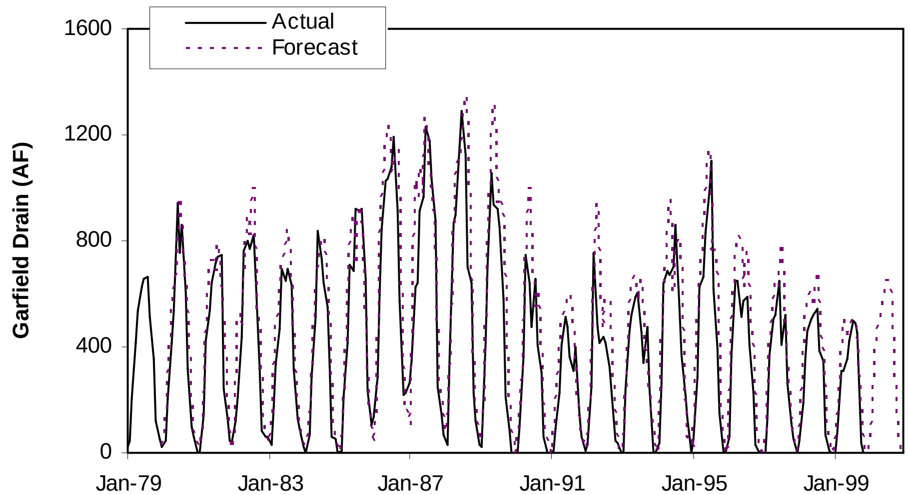



Figure 48. Garfield Drain Results from Conceptual Model

The correlation check of the forecast data versus the actual data for Garfield drain is shown in Figure 49.

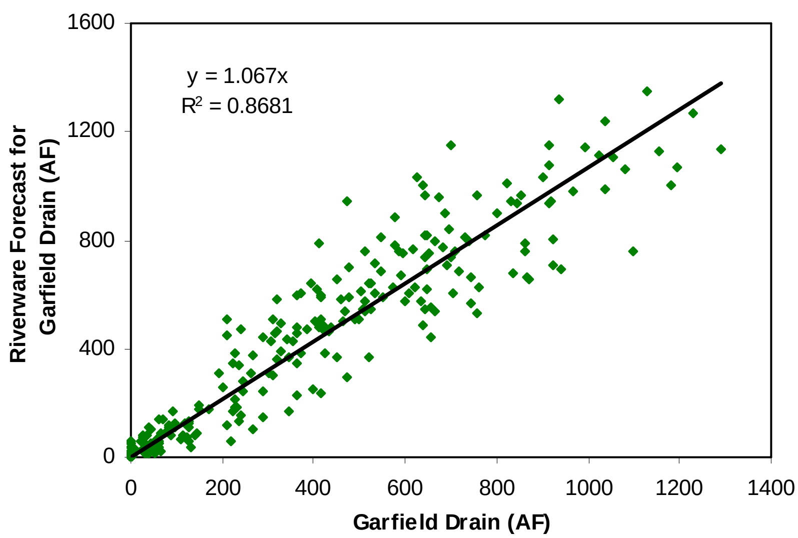



Figure 49. Garfield Drain Regression from Conceptual Model Results

## HATCH DRAIN RESULTS

Plotting the results for Hatch drain from the RiverWare conceptual model and the actual Hatch drain data results in the graph shown in Figure 50. This graph shows that the conceptual model results follow the actual data fairly well.

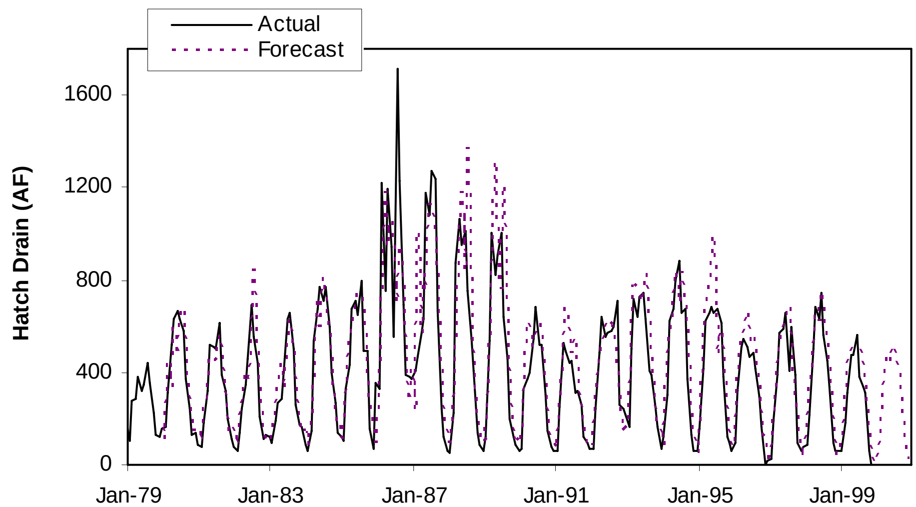



Figure 50. Hatch Drain Results from Conceptual Model

The correlation check of the forecast data versus the actual data for Hatch drain is shown in Figure 51.

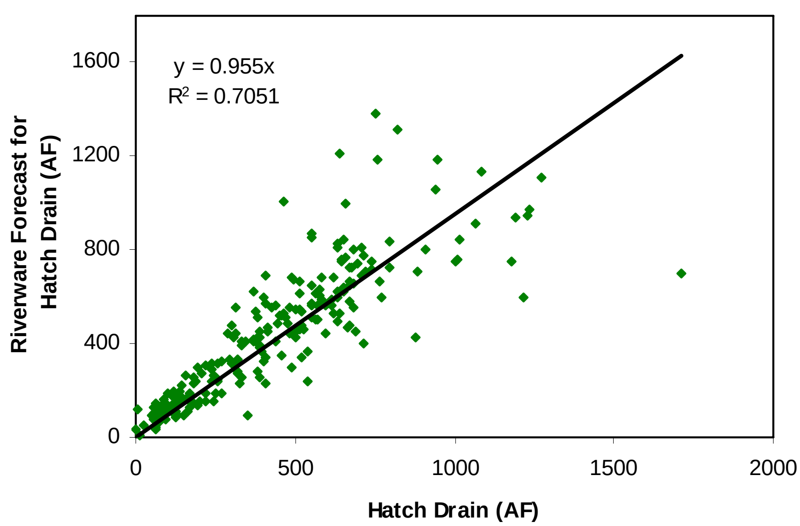



Figure 51. Hatch Drain Regression from Conceptual Model Results

## RINCON DRAIN RESULTS

Plotting the results for Rincon drain from the RiverWare conceptual model and the actual Rincon drain data results in the graph shown in Figure 52. This graph shows the conceptual model results follow the actual data fairly well.

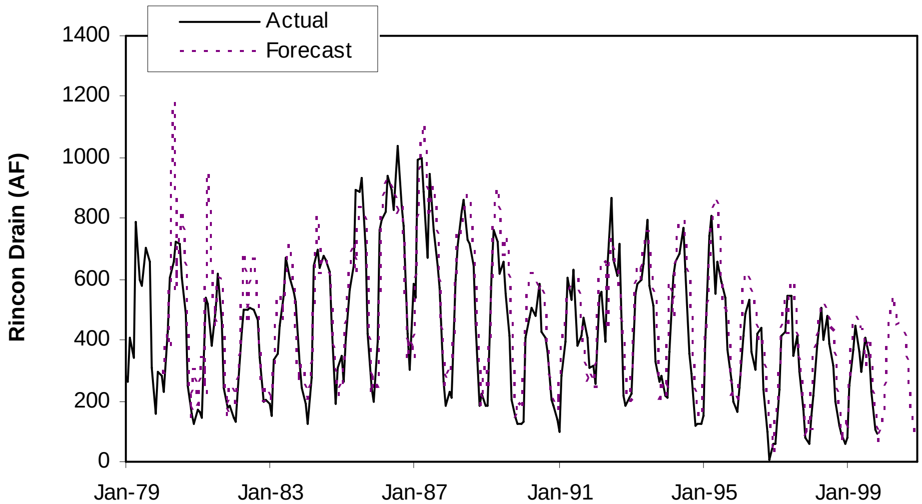



Figure 52. Rincon Drain Results from Conceptual Model

The correlation check of the forecast data versus the actual data for Rincon drain is shown in Figure 53.

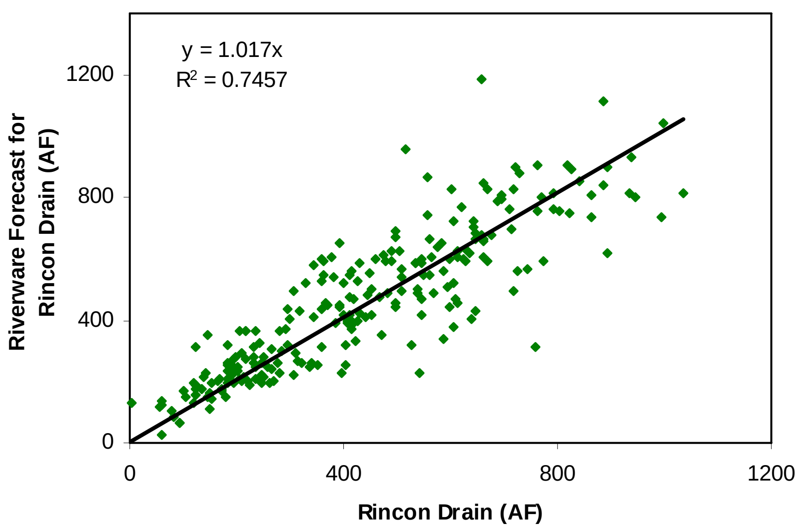



Figure 53. Rincon Drain Regression from Conceptual Model Results

## GAIN/LOSSES CABALLO TO LEASBURG RESULTS

Plotting the results for Gains/Losses from the RiverWare conceptual model and the actual Gains/Losses data results in the graph shown in Figure 54.

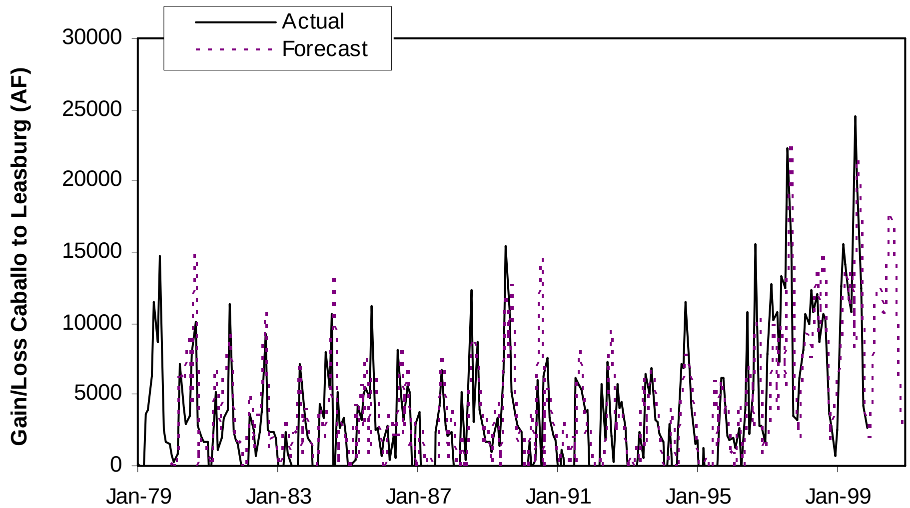



Figure 54. Gain/Loss Results from Conceptual Model

The correlation check of the forecast data versus the actual data for Gains/Losses is shown in Figure 55.

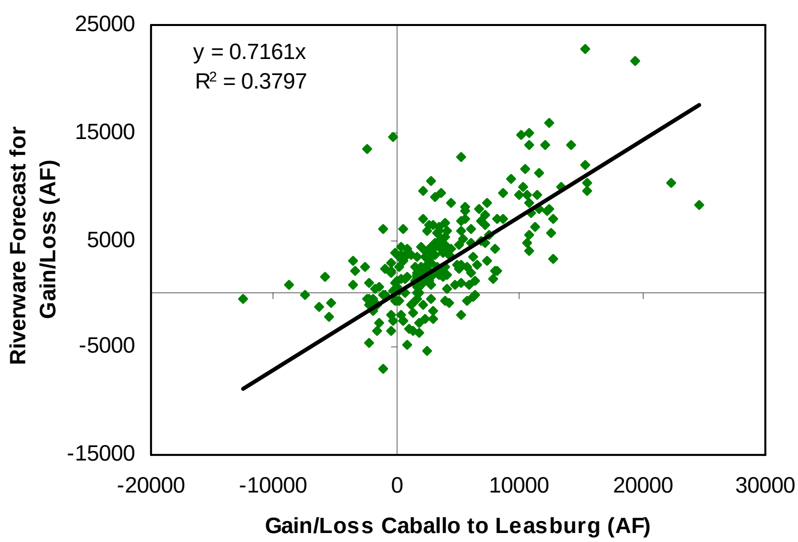



Figure 55. Gain/Loss Regression from Conceptual Model Results

## RIVER ABOVE LEASBURG RESULTS

As a check of these locations as a system, the forecast results from the RiverWare conceptual model for the Rio Grande above Leasburg were compared to the actual data of Rio Grande below Leasburg plus Leasburg Canal. This comparison is shown in Figure 56.

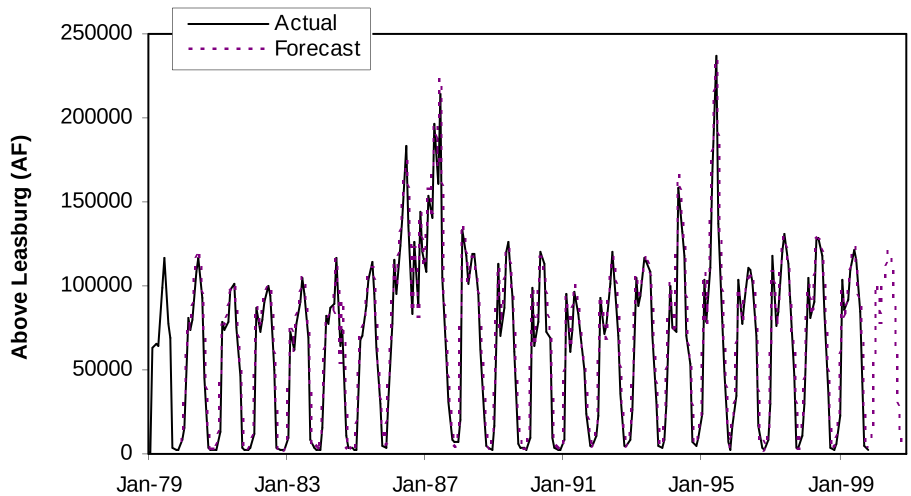



Figure 56. Above Leasburg Results from Conceptual Model

The correlation check of the forecast data versus the actual data for River above Leasburg Dam is shown in Figure 57.

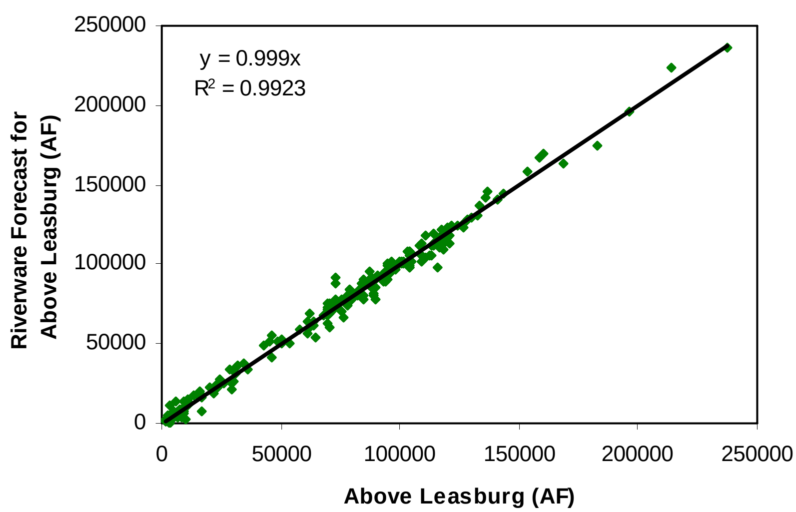



Figure 57. Above Leasburg Regression from Conceptual Model Results

## SUMMARY

Simple linear relationships can be derived to estimate flow in the drains from the diversion at Arrey Canal. In general, these relationships will tend to underestimate high flows and overestimate low flows. This study found that using ARIMA *transfer functions* improves the accuracy of the forecasts for the drain flows and that these forecasts tend to track better with the actual data than the simple linear relationship forecasts. Figure 58 shows the estimates from the selected models, the estimates from the ARIMA *transfer function* model, and the actual combined drain flow for Garfield, Hatch, and Rincon drains plotted together on the same graph.

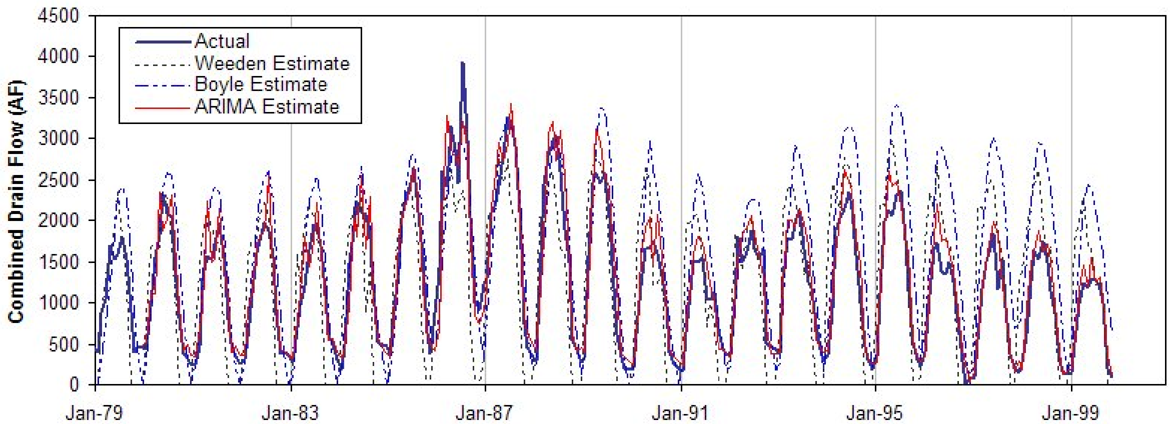



Figure 58. Comparison of Estimates of Total Drain Flow

This graph clearly shows that the ARIMA transfer function results are closer to the actual data than the results from the other methods.

Statistical comparisons may also be done to detect which model provides the best fit of the data. Table 12 provides of summary of some statistics commonly used to evaluate the fit of a model.

Table 12. Comparison of Statistics from Models

| | *Boyle & Parsons Method* | | | *Weeden and Maddock Method* | *ARIMA Transfer Function Method* | | |
|---|---|---|---|---|---|---|---|
| | *Garfield* | *Hatch* | *Rincon* | *Total Drains* | *Garfield* | *Hatch* | *Rincon* |
| SSE | 9632925 | 10491863 | 19378640 | 94585204 | 3660700 | 4914718 | 3191851 |
| RSSE | 3104 | 3239 | 4402 | 9725 | 1913 | 2217 | 1787 |
| RMSE | 196 | 204 | 277 | 613 | 124 | 143 | 115 |
| $R^2$ | 0.669 | 0.597 | 0.521 | 0.584 | 0.886 | 0.749 | 0.760 |

The **SSE** statistic is the *sum of squares due to error*; the **RSSE** statistic is the *square root of the sum of squares due to error*; the **RMSE** statistic is the *root mean-square error*; and $\mathbf{R^2}$ is the *coefficient of determination* for a linear regression, with intercept zero, of the estimated drain flow versus the actual drain flow. Two of these statistics are commonly used to evaluate the fit of a model to the data. The RMSE represents the spread remaining after fitting a statistical model to the data, with lower values for RMSE representing better model fits. $R^2$ indicates how much of the variability in the dependent variable is explained by the model, with values closer to 1 representing better model fits (Haan 1986).

Since the Weeden and Maddock method combines all the drains, it cannot be directly compared to the other methods which estimate flow for each drain separately. Comparing the statistics for the Boyle & Parsons method to the ARIMA *transfer function* method shows that the transfer function method has lower RMSE values for all three drains and higher $R^2$ values for all three drains. This indicates that the *transfer function* method provides a better fit of the data than the Boyle & Parsons method.

Deriving and implementing the *transfer function* equations is more difficult and time consuming than developing a simple linear relationship, but these equations will provide more accurate results. In the Rincon Valley, there are only three major drains returning to the river, so the errors from the linear relationships in this reach may not be significant. However, in the Mesilla Valley numerous drains return significant amounts of water to the river. In this reach, the errors from the linear relationships may be substantial, especially during high flow periods when the linear relationships typically underestimate the amount of drain flow. This could result in inadequate planning for the higher actual amount of drain flow returning to the river.

# Data Portal Enhancement

Prepared by Christopher Brown and Bobby Creel

## BACKGROUND

The Rio Grande is the only major source of renewable water in the Paso del Norte region within which El Paso, Texas; Las Cruces, New Mexico; and Ciudad Juárez, Chihuahua, México lie. Historically, a wide variety of water resource data including surface water flow and water quality data and groundwater data have been collected by numerous agencies and stakeholders. Access to these data has been on an *ad hoc* basis, with little coordination across agencies or across the region. The New Mexico Texas Water Commission and the Paso del Norte Watershed Council (PdNWC) have worked together for the last several years to generate the funding needed to advance coordinated access to regional water resource data. With the generous support of the El Paso Water Utilities (EPWU), the Albuquerque District Office of the United States Army Corps of Engineers (USACE), and the Rio Grande Basin Initiative funded by the U.S. Department of Agriculture, the Watershed Council has been successful in advancing the PdNWC Coordinated Water Resources Database Project (Project).

To assist water resource managers and researchers, Project staff has developed a prototype system for compiling data on river flow and water quality and serving the data via web-based query tools. An operational website (www.pdnwatershed.org) was established by the PdNWC and put online through the New Mexico Water Resources Research Institute (NMWRRI). See Figure C1 in the Appendix C for a graphic depicting the front page of the Project website. The website provides access to a range of databases that house water resource data in the Paso del Norte region. The majority of these databases exist on servers in other agencies, and the Project website acts as a portal to these databases. The Project also hosts datasets housed internally in the server maintained by the NMWRRI. To provide access to these distributed datasets, the Project uses a Geographic Information System (GIS)-based user interface to provide spatial area-of-interest tools that employ GIS maps to allow users to click on spatial features of interest. These map features then link to either off-site URLs of websites that contain data or to files housed internally on the Coordinated Water Resources Database Project server. Through this interface, users are able to view and download a range of hydrological data including gauge stations, river flow, diversions, return-flow from drains, well information, groundwater levels, and groundwater quality. These data sets, although housed at different agencies, are accessed via one user interface.

As the above referenced work was completed, Project staff compiled final reports that detail the development of the Project and ideas for future work to build on the successful ArcIMS website pilot project (see Final Project Report, Paso del Norte Watershed Council, Coordinated Water Resources Database Project, Phase I, 2004, and Phase II, 2005). Project staff also hosted two workshops to present the Coordinated Database and GIS to watershed agencies. The intent of these workshops was to share Database access, operations, and uses with a wide range of potential users and gather ideas for future development from the participants.

As Project staff advanced the above-referenced work, we became aware of the potential to link our ongoing database development efforts with the modeling efforts of the Upper Rio Grande Water Operations Model (URGWOM) being developed and advanced by staff of the USACE)/Albuquerque Office and other agencies participating in the URGWOM Memorandum of

Understanding. See the URWOM website hosted by the USACE offices at http://www.spa.usace.army.mil/urgwom/default.htm for detail concerning the URGWOM modeling activities. To explore these linkages, the USACE extended Phase II of its financial support of the PdNWC Coordinated Water Resources Database Project in June of 2004, generating Task Order # 8 between the New Mexico Water Resources Research Institute and Texas A&M University Agricultural Research and Extension Center. Task Six of this Phase II work was to enhance the data portal capabilities of the Project through the development of a low end user interface that would serve GIS-based graphics of each data set and enhanced metadata of relevant data sets. Under this Task, Project staff also conducted a literature search of bibliographic resources detailing GIS-based hydrologic modeling in the Paso del Norte region; linkages to these resources are provided via portions of the Project website, as detailed below.

## PROJECT ACTIVITIES AND OUTCOMES

**Bibliographic Research -** Early in the Project period, staff conducted a review of existing literature of GIS-based hydrologic modeling, both in a general sense and related to work being conducted specifically in the Paso del Norte region of the Rio Grande Basin. The results of this work included a narrative report of general GIS-based hydrologic modeling and a select annotated bibliography of this type of research. These documents are included in the Coordinated Water Resources Database Project website from which data are served; this outcome provides a linkage from the earlier Project work funded by the EPWU to work supported by the USACE funding. The project team also compiled results of GIS-based hydrologic modeling that was more specific to the study area and built a series of ".html files" that linked to various project websites that summarized these research activities. These documents are available at http://river.nmsu.edu/website/pdnwc4/hydro/index.htm, and this page is depicted in Figure C2 in the Appendix C.

**Low-End User Interface–** The ArcIMS interface that was developed for Phase II of the EPWU-funded project provides considerable utility to users in creating and modifying GIS maps of spatial features linked to water resources data in the region and also using these ArcIMS maps to provide a direct linkage to these data. However, this interface does not provide a straightforward ability to download spatial data sets involved. Project staff worked to develop an alternate means of downloading GIS data sets that also provided a non ArcIMS-based interface to relevant metadata and water resource data. Initial work in this area involved Web-based research into how other organizations were serving these types of data. This research revealed that several agencies used a straightforward, table-based interface by which metadata, spatial datasets, and links to other data providers are served to the user in a very easy to use manner. See the New Mexico Regional Geographic Information System Program website at http://rgis.unm.edu/ and the Tijuana River Watershed Data Clearinghouse being hosted by the San Diego State University Department of Geography at http://geography.sdsu.edu/Facilities/Data/Clearinghouse/trw.html for examples of this approach. Graphics of these sites are included as Figures C3 and C4 in Appendix C.

Based on this research, Project staff developed a similar type of table that would readily serve downloadable spatial datasets and GIS layers and relevant metadata in a format compliant with the Federal Geographic Data Committee (FGDC). Concurrent with this work, Project staff also worked to enhance the actual content of metadata files being developed, specifically using the Metadata Editor of ArcGIS to update key metadata elements identified in earlier stages of Project work and generate FGDC compliant metadata in the format of ".html files" that could be served from the

Project website. This table-based user interface also provides access to internally housed and externally linked water resource datasets and links to a series of static GIS graphics. These static GIS maps depict the spatial features to which water resource data are linked and the areas of interest that are served by these spatial features; they also provide linkages back to metadata specific to the spatial features of interest. A sample of these GIS graphics is provided in Figure C5 in the Appendix. This table-based interface is served as the Metadata and Data Download link of the Coordinated Water Resources Database Project, http://river.nmsu.edu/website/pdnwc4/Metadata.htm. A graphic depicting this is also provided as Figure C6 in the Appendix C.

**Linking USACE and EPWU Projects via Imagery Archive –** During the course of this work, Project staff learned that the USACE/Albuquerque District Office had compiled a range of digital orthophotography/ortho-quarter quads (eDOQQs) and digital topography datasets (eTOPOs) for areas of the southwestern U.S. coincident with the Project's study area. Through discussions between Project staff and USACE staff, access was arranged to these datasets, and Project staff employed a large capacity portable hard drive to secure copies of these files and loaded them on the Project server at NMWRRI Staff then developed a series of ".html files" that served up an image map and series of companion map graphics that allow a user to access both digital orthophotography/ortho-quarter quads (eDOQQs) and digital topography datasets (eTOPOs). The access page for these datasets is depicted in Figure C7 in the Appendix C and is available at http://river.nmsu.edu/website/pdnwc4/wwwroot/ftp2.html.

## FUTURE PROJECT ACTIVITIES

At the time of completion of this final report, Project staff was finalizing arrangements for Phase III of USACE funding support for the Coordinated Water Resources Database Project. Under the Scope of Work and related Task Order for this Phase of funding, Project staff will focus on strengthening the linkages between the Coordinated Water Resources Database Project and the RiverWare/URGWOM modeling activities being directed by Dr. Philip King of the NMSU Department of Civil Engineering and Dr. Zhuping Sheng of the Texas A&M University Agricultural Research and Extension Center at El Paso, Texas. Specifically, the following tasks are those to be pursued to enhance linkages between these modeling activities and the data portal functions of the Coordinated Water Resources Database Project (Dr. Christopher Brown & Dr. Bobby Creel will lead these project tasks):

- Assess the data needed for expansion of the URGWOM, identify data gaps, generate data needed from historic data using empirical methods, and recommend additional data collection efforts for both surface water and groundwater data.
- Implement a data transfer interface between the coordinated database and hydrologic models based on the EPWU Phase II evaluation of data transfer protocols. It is anticipated that this will involve working with the Data Management Interface of the RiverWare modeling software, work to be advanced in consultation with Dr. King and Dr. Sheng.

As the USACE funded Phase III work proceeds, we also envision exploring enhanced linkages between this work and that funded under the U.S. Bureau of Reclamation Challenge Grant that was recently awarded to the EPWU, with subcontracts to PdNWC and Coordinated Water Resources Database Project staff. Through these efforts we seek to advance continually improving, coordinated access to regional water resource data in the Paso del Norte region.

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# Appendix A: Groundwater Data in the Paso del Norte Watershed Linkage to Modeling Efforts at UACJ

**by**
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## Summary

This appendix discusses modeling efforts of groundwater data of interest that were used at UACJ-CIG to evaluate and characterize sedimentary deposits forming aquifer formations located at the urban areas of Ciudad Juárez on the Mexican side of the Hueco Bolson located at the Paso del Norte transboundary region. Well data were provided by the Technical Department at JMAS (Junta Municipal de Agua y Saneamiento) and evaluated throughout different master degree theses in the Environmental Engineering Degree Program hosted by the Department of Civil and Environmental Engineering (DICA) at the Institute of Engineering and Technology (IIT) of UACJ. The products of these models were provided to JMAS as partial results of ongoing binational research efforts being conducted by several regional universities, such as UACJ, TAMU, UTEP, NMSU, NMT, Cal State-LA, and UofA, as well as consulting firms, such as Hawley Geomatters, Inc. Different modeling packages were used while modeling the subsurface environment of aquifer formations in Ciudad Juárez. Rockware-Earth Science and GIS Software, integrated geologic data acquired for borehole logs, and lithologic cuttings from well drillings were analyzed and visualized while using the different tools available within the software. These products were displayed and visualized on a 3D environment while creating solid models of the sedimentary deposit packages forming the local aquifers found at different locations where these wells were drilled within the urban area of Ciudad Juárez. Out of approximately 200 wells located in the city, only 63 were used to characterize and standardize lithologic characteristics described on JMAS hard copy geologic cuttings from drilled wells. Cross sections were mapped showing the subsurface extension of these sediments forming unconsolidated aquifer formations while assuring geospatial specifications, such as X and Y coordinates and well head elevation. These research products have been published at international meetings such as the 2$^{nd}$ Transboundary Watershed Management Symposium. Further studies are underway while using ModFlow-Pro software, modeling the hydrogeologic dynamics of groundwater movement as well as its hydrogeochemistry trends throughout time within the same area of study.

## Introduction

Ciudad Juárez is the largest metropolitan area located at the Paso del Norte (PdN) within the state of Chihuahua, with more than 1.3 million people consuming approximately 350 liters of water per person per day (Ibañez 2002). Since Ciudad Juárez does not have a surface water treatment plant to treat surface water allocations from the 1907 Water Treaty to produce potable water, 100 percent of the needed water for different uses within the city comes directly from the aquifer formation of the transboundary Hueco Bolson as well as from other surrounding watersheds (i.e., Conejos-Medanos to the west side of the City of Juárez, which is scheduled to start operations in 2005). The increase demands for water resources on this metropolitan area have created over pumping of aquifer formations where groundwater levels at some points within the city's well fields have created a reverse trend on the natural hydraulic gradient (Figure A1).

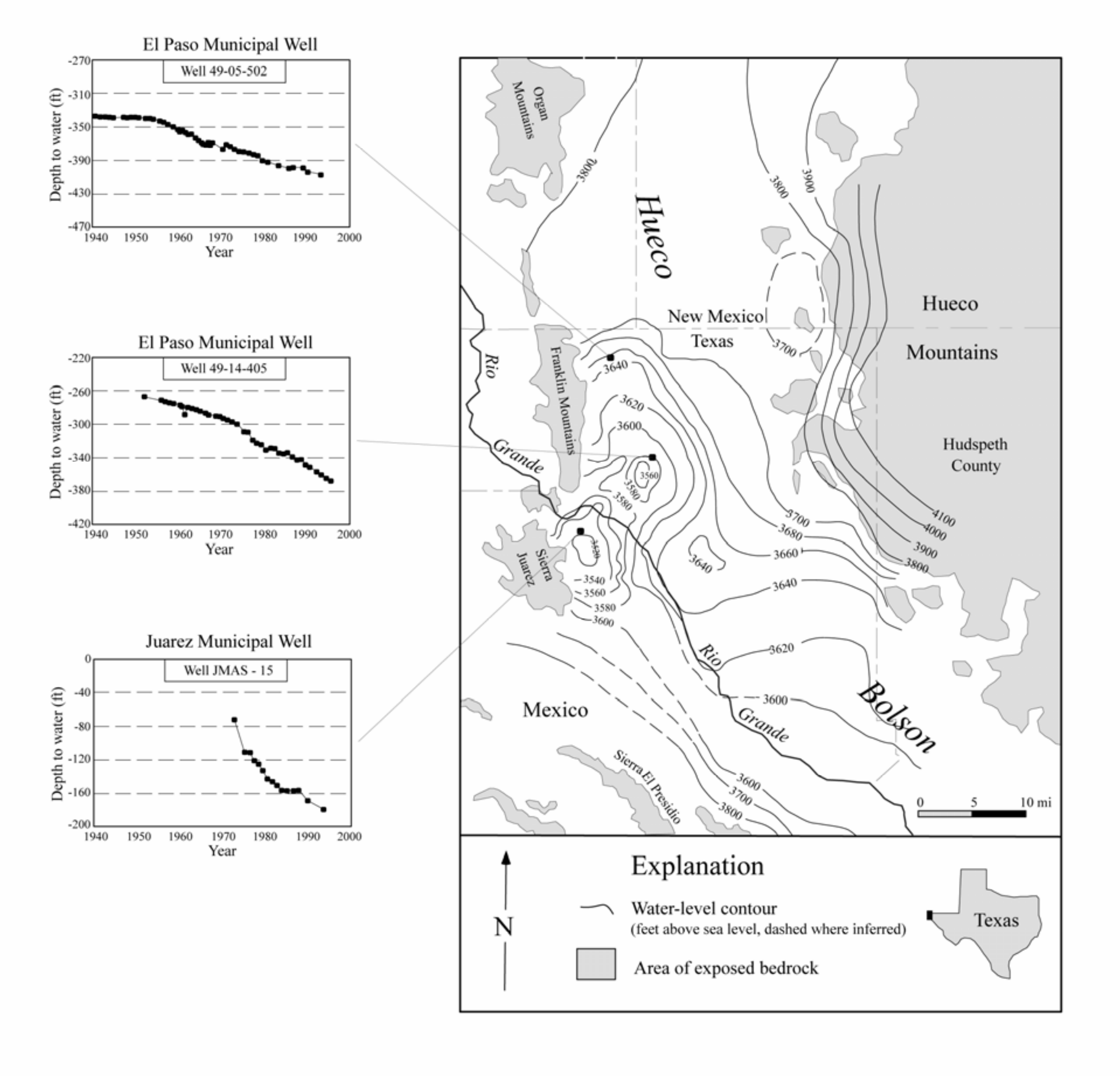


Figure A1. Hydraulic gradient and cones of depression at Paso del Norte (Hibbs et al. 2003)

The cones of depression at these aquifer formations are concentrated in the downtown areas of Juárez and El Paso, where the oldest wells are located. The water table at these points has shown a decrease through time on both sides of the border as demonstrated on Figure A1, where the depth of the water table has increased during a period of 61 years from 1940 to 2000. Predevelopment groundwater flowpaths were dominated by natural topographic features where groundwater flowed from north to south into México (Hibbs et al. 2003).

International transboundary research groups formed by several regional universities in the PdN region have taken the challenge of characterizing the transboundary sedimentary deposits while creating cross sections of the geologic settings of the area (Hawley 2001; Hawley and Richardson 2001; Hawley and Kennedy et al. 2001; Hibbs et al. 2001). Figure A2 displays a 3D map with cross sections taken under consideration for stratigraphic characterization of sedimentary deposits and lithologic recognition (Hawley 2001).

The light gray polygon in Figure A2 represents the geographic extension of the Hueco Bolson where the two major cities of Ciudad Juárez and El Paso are located on the transboundary watershed. Blue lines represent the cross sections of interest where the stratigraphic characterizations were taken as an example of these cross sections, where E'-G (Figure A3) is the most important one for the present study, displaying the main sedimentary packages within this cross section. The Upper Santa Fe-Camp Rice/Fort Hancock formations (USF-2 in Figure A3) are mostly comprised of lithofacies assemblages, a product of the dynamic hydraulic processes of the ancestral Rio Bravo/Rio Grande. Other packages include the Middle Santa Fe (MSF) and the Lower Santa Fe Group (LSF), which are deeper within the sedimentary package that form the aquifer formations (Hawley and Kennedy 2004).

This appendix provides a brief overview of the groundwater modeling efforts on the Mexican side of the Hueco Bolson where well fields that provide water to the city of Juárez are located. The research group has undertaken this effort while sharing information and results with the authorities at the Junta Municipal de Agua y Saneamiento (JMAS) of Ciudad Juárez. Modeling and lithologic characterizations of geologic cuttings from drilled wells in Ciudad Juárez are been evaluated under the supervision of Dr. John Hawley from Hawley Geomatters, Inc., and master's degree theses of these studies have been written by graduate students of the Environmental Engineering and Ecosystems program located within the School of Engineering and Technology of UACJ. This report concludes with a series of 3D models and cross sections of the upper Santa Fe Group (deposits of ~250 m depth), which comprise the sedimentary deposit of the ancestral Rio Bravo/Rio Grande. These cross sections are products of a joint collaboration with other regional universities from both México and the United States, working on the hydrogeochemistry and isotopic signature of the groundwater resources along an extended transboundary area, which comprise the Tularosa and Hueco Bolson (both México and US sides) as well as Mesilla aquifers. The present models on the Mexican side of the Hueco Bolson might help to define a more detailed package of sedimentary materials to be incorporated into other ongoing binational modeling efforts, such as the one taken by El Paso Water Utilities (EPWU) while using other computer software (i.e., ModFlow Pro) that could define hydrogeologic properties and hydrogeochemical interactions of the aquifer formations in the Hueco Bolson.

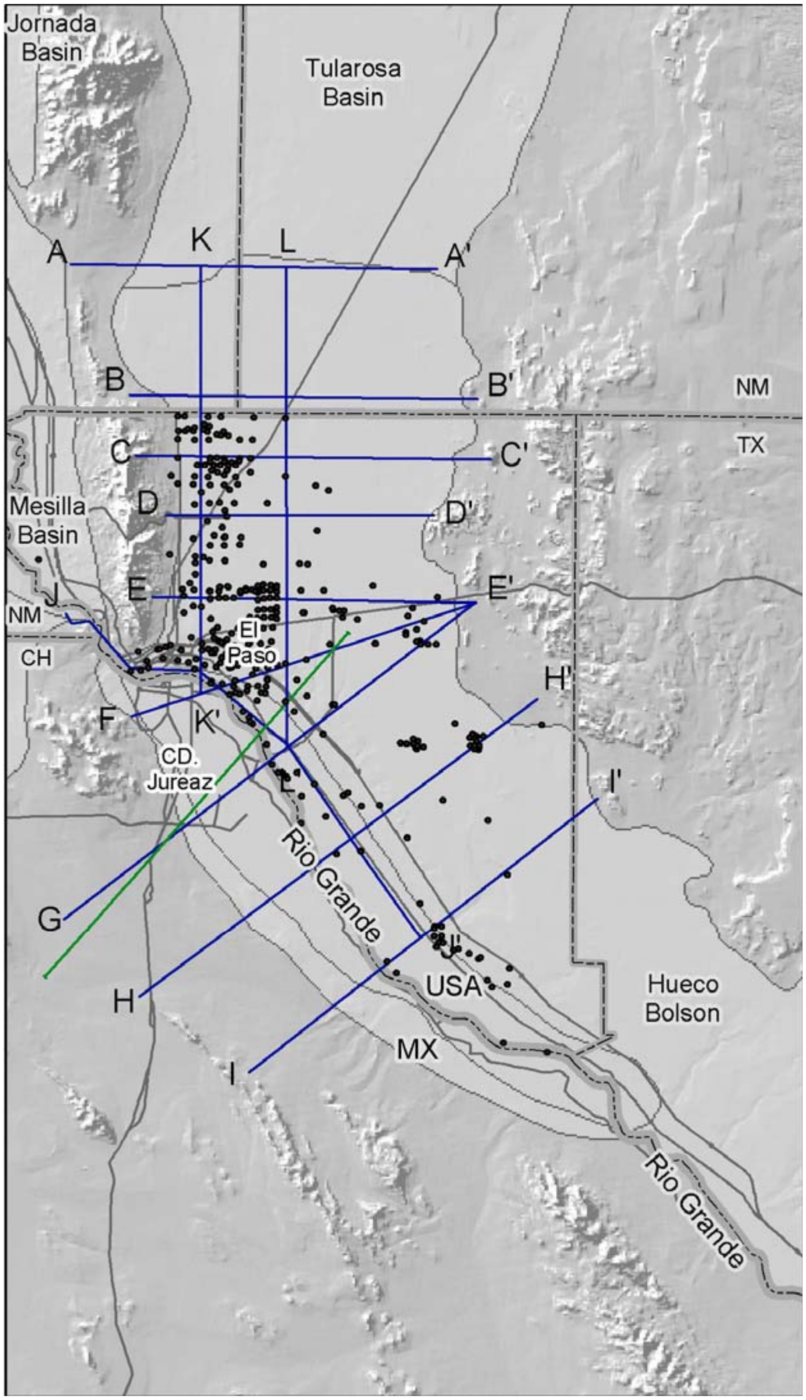


Figure A2. Cross sections for stratigraphic characterization at the PdN Region (Hawley and Kennedy 2004)

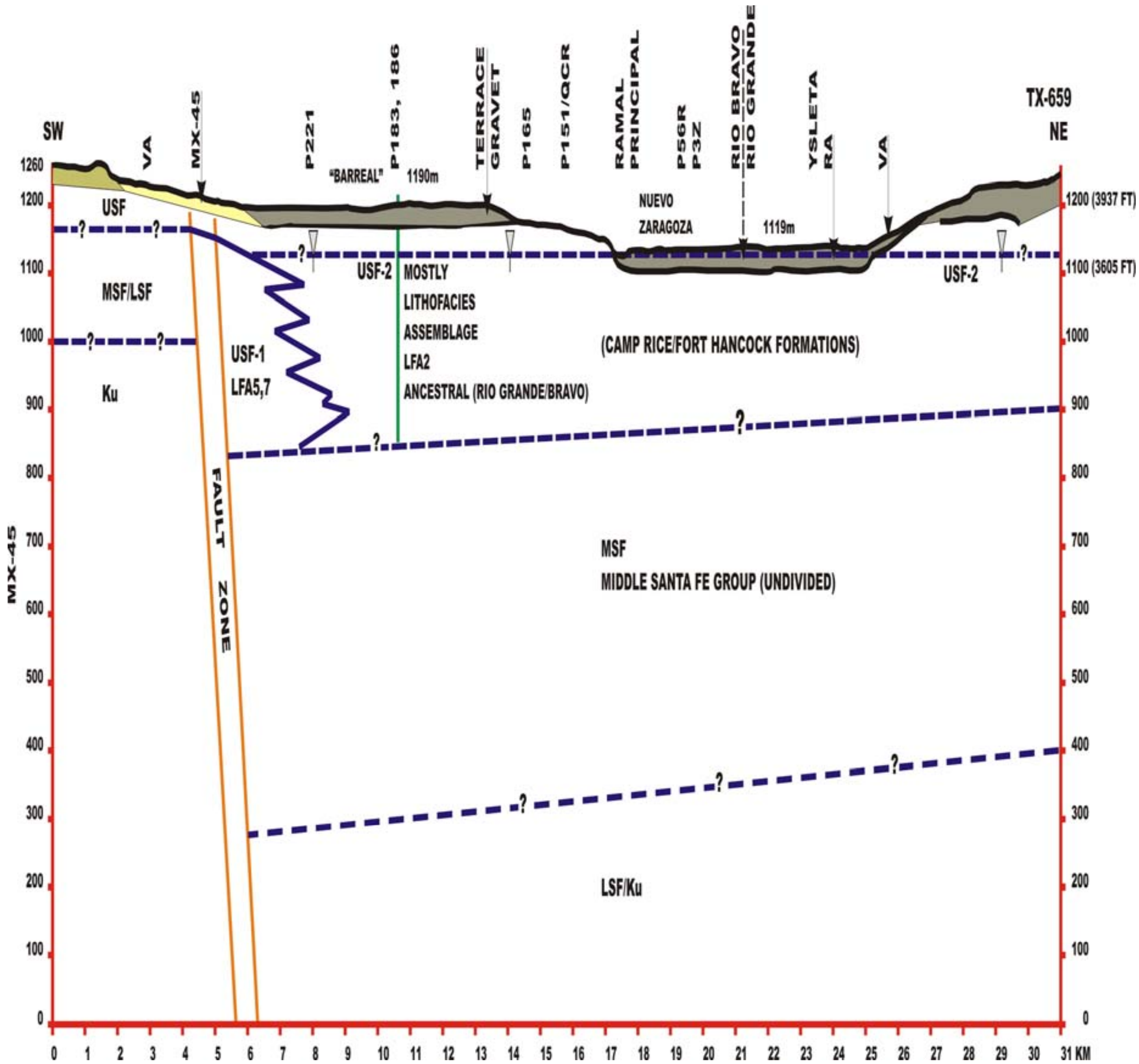


Figure A3. Cross section of sedimentary packages at the transboundary PdN region (Hawley and Kennedy 2004)

## Modeling Efforts at UACJ

The modeling efforts at UACJ are concerned with identifying the stratigraphic characterization of geologic cuttings taken by the JMAS when wells were drilled in Ciudad Juárez. The software used to integrate the databases was RockWorks v.2002, which integrates a geologic management, analysis, and visualization environment. This modeling environment allows the user to integrate geophysical or geochemical measurements, observed lithologies, stratigraphic contacts, water levels, and fractures, as well as downhole well surveys, displaying logs, surfaces, thickness models, fence diagrams and solid models in a 3D visualization environment.

Data gathering inconsistencies while describing the type of geologic materials being drilled were common in the recent past. These inconsistencies were created while field procedures were taken by different teams of drillers who were responsible for data capturing from geologic drill cuttings taken by JMAS. Out of more than 200 wells drilled at the research area (Figure A4), only 63 wells were considered and evaluated on their descriptions while being included on the modeling procedures for this report. Figure A4 displays a map of the study area with dots representing the well locations from which lines of cross sections were considered for the purpose of this study. Ten lines of wells were created where lithologic cuttings were representative of the sedimentary packages of the well fields located at the urban area of Ciudad Juárez (Figure A5).

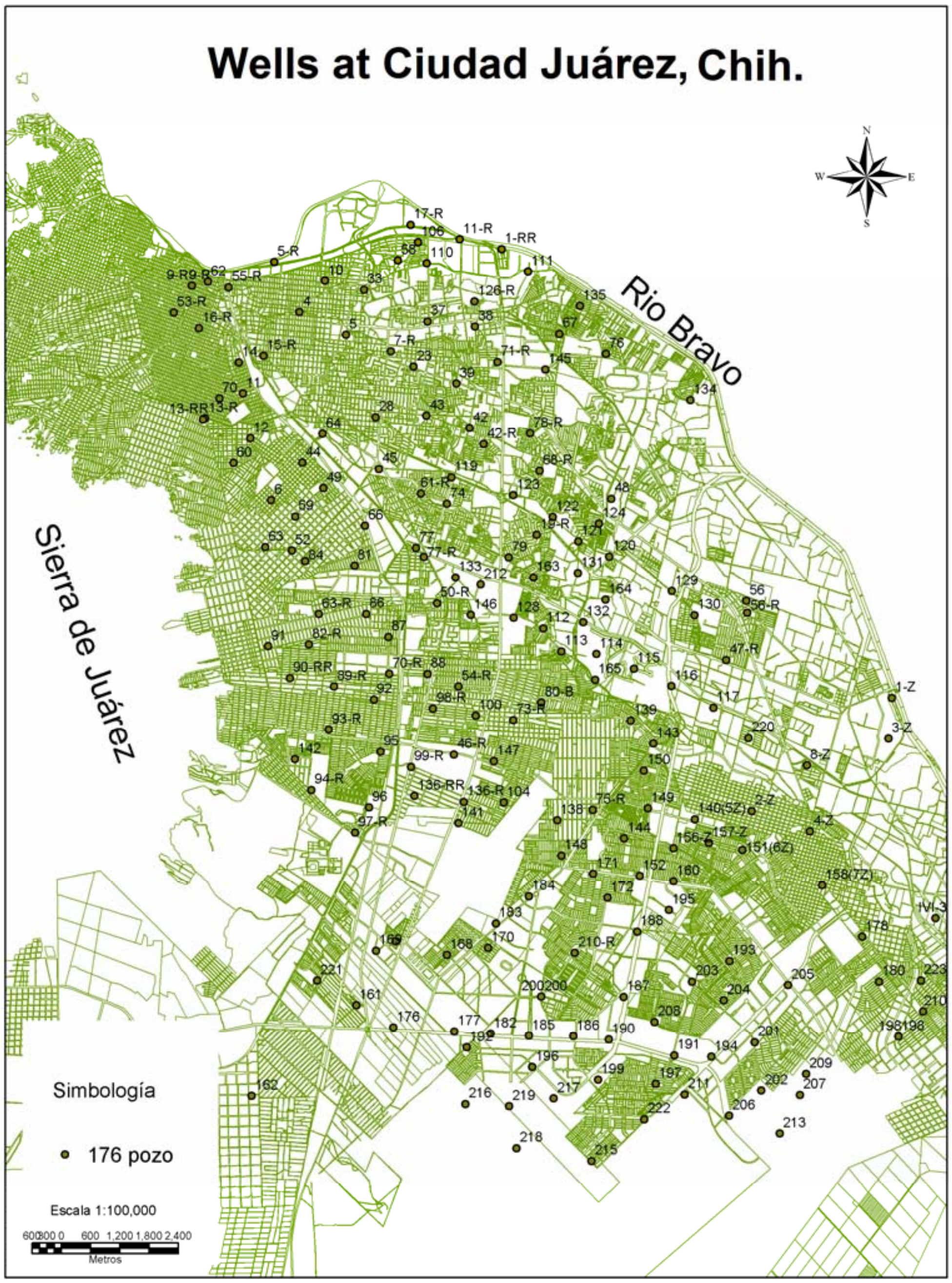


Figure A4. Location and ID number of well fields at the Ciudad Juárez urban area

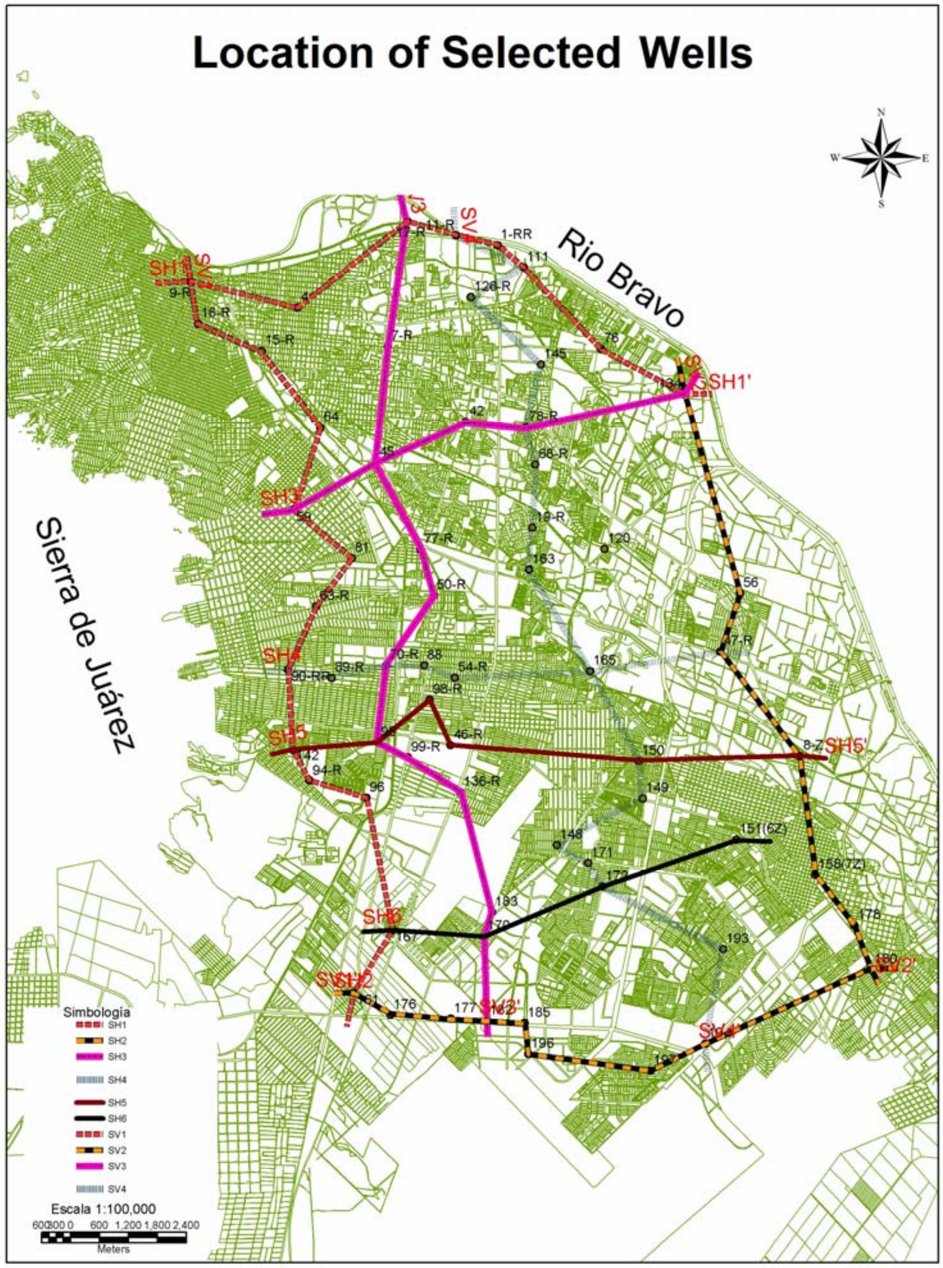


Figure A5. Cross sections under consideration for the CJ urban area modeling of sedimentary deposits (Leos 2004)

Some of these cross sections show the complex array of sedimentary deposits that the Upper Santa Fe-Camp Rice/Fort Hancock formations (USF-2 in Fig. A3) display. These are representative of the recent geologic past where pre-development conditions controlled the type and volume of load the Rio Bravo/Rio Grande used to carry while intense and extended torrential rains fell on the Rio Bravo/Rio Grande watershed (Fig. A6).

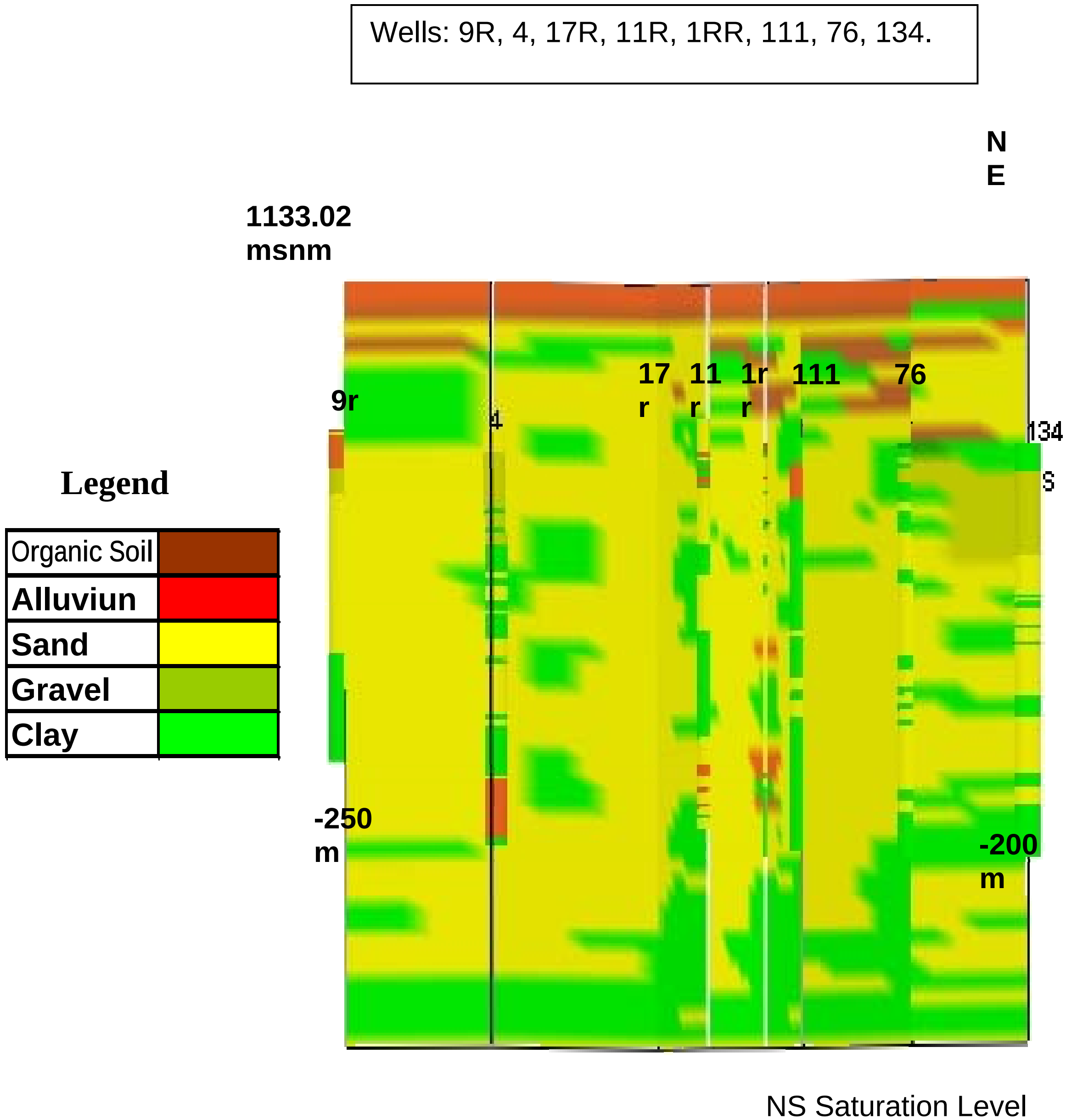


Figure A6. Cross section on line SH 1 extended along the alluvial floodplain of the Rio Bravo-Rio Grande. Depth is in meters below land surface (Leos 2004).

Extended clay lenses (light-green) are dispersed along layers of more homogeneous sand (yellow) and gravels (dark-green), which all together comprise a semiconfined aquifer shown by this cross section. It was created by the line of wells taken under consideration for modeling the sedimentary packages of this aquifer formation. A more detailed package of surface sedimentary deposits represents the more organic alluvial (red) sediment on the agricultural soils in the valley (brown).

An effort to extend the analysis of these deposits was undertaken while extrapolating all 63 wells on a 3D visualization of the aquifer formations in the urban area of Ciudad Juárez. These models represent a graphical configuration of these sediments extended along the study area (Fig. A7).

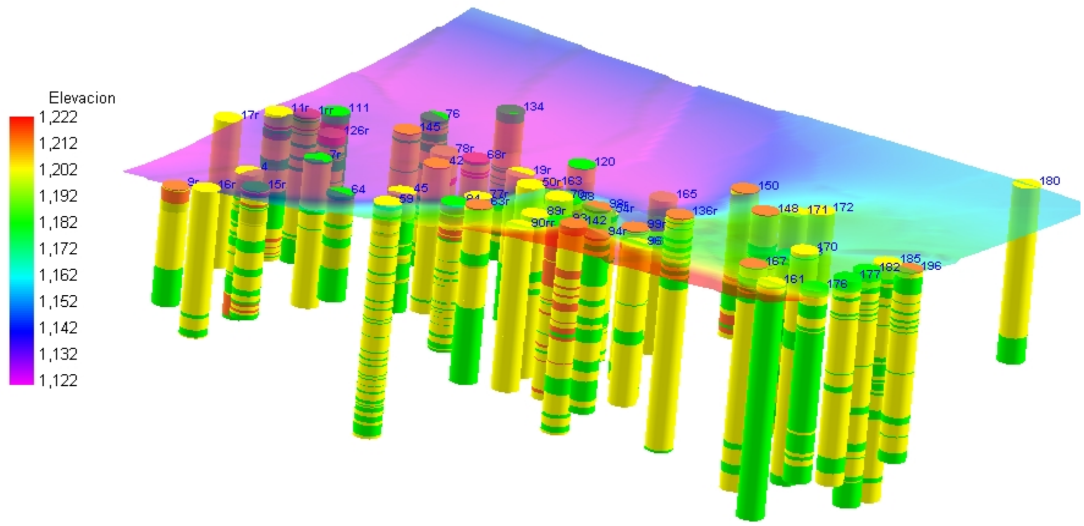


Figure A7. Graphical representation in 3D of well field at Ciudad Juárez. Purple sheet represents cones of depression located at downtown area (Dominguez et al. 2004).

**Conclusions**

Sedimentary packages of aquifer formations on the Mexican side of the Hueco Bolson have been modeled while using specialized software. These models represent a potential source of information to understand the geospatial correlations of sediments forming the aquifers at the study site at depths of ~250 m from surface elevation. Also, the potential to interpret linkages of groundwater quality and salinization processes at the study site is a possibility with these models. Another potential application is the definition of depth and width on the productive and impermeable layers within the aquifer formations in the area to model the hydrogeologic dynamic conditions of the aquifer with specialized software (i.e., ModFlow Pro). More detailed analysis is required on the other wells and a correlation with borehole logs is currently ongoing at CIG-UACJ.

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## Appendix B: Summary of Different Numerical Models Developed for the Paso del Norte Watershed

**Table B 1. Summary of Numerical Models Developed for the Paso del Norte Watershed**

| **Model** | **MODFLOW (Frenzel and Kaehler, 1990)** | **MODFLOW (Frenzel, 1992)** |
|---|---|---|
| Authors' Name | Frenzel and Kaehler, 1990 | Frenzel, 1992 |
| Purposes | Assess the effects of groundwater withdrawal in the Mesilla Basin on flow in the Rio Grande. | Reassess the effects of groundwater withdrawal in the Mesilla Basin on flow in the Rio Grande. |
| Method | Solve 3-dimensional groundwater flow equations for a porous media by using a finite element method (FDM). | |
| Hydrologic system | Multiple aquifers with drains (DRN), canals and the river (RIV) | Multiple aquifers with drains (DRN), canals and the river (RIV) |
| Geographic Coverage | Mesilla Basin (1,110 square miles), Dona Ana County New Mexico and El Paso County Texas | Mesilla Basin, Dona Ana County New Mexico and El Paso County Texas |
| Grid configuration | 36 rows, 64 columns, and 5 layers. | 36 rows, 64 columns, and 4 layers. |
| Stress or time periods | 16 stress periods for 1915 to 1975 | 22 stress periods for 1915 to 1985 |
| Time step | | |
| Reference | Frenzel, P.F. and C.A. Kaehler. 1990. Geohydrology and Simulation of Groundwater Flow in the Mesilla Basin, Doña Ana County, New Mexico, and El Paso County, Texas, *with a section on Water quality and geochemistry by S.K. Anderholm*. U.S. Geological Survey, Open File Report 88-305, 1990. | Frenzel, P.F. 1992. Simulation of Groundwater Flow in the Mesilla Basin, Doña Ana County, New Mexico, and El Paso County, Texas, Supplement to Open-File Report 88-305, U.S. Geological Survey, Water-Resources Investigations Report 91-4155, 1992. |

**Table B1. Summary of Numerical Models Developed for the Paso del Norte Watershed (cont.)**

| **Model** | **MODFLOW (Hamilton and Maddock, 1993)** | **MODFLOW (Lang and Maddock, 1994)** |
|---|---|---|
| Name | Hamilton and Maddock, 1993 | Lang and Maddock, 1994 |
| Purposes | Assess impacts of groundwater pumping … | Assess effects of pumping and canal lining in the Mesilla Basin under a variety of scenarios. |
| Method | Solve 3-dimensional groundwater flow equations for a porous media by using a finite element method (FDM). | Solve 3-dimensional groundwater flow equations for a porous media by using a finite element method (FDM). |
| Hydrologic system | Multiple aquifers with drains (DRN), canals and the river (STR1). | Multiple aquifers with drains (DRN), canals and the river (STR1). |
| Geographic Coverage | Mesilla Basin | Mesilla Basin |
| Grid Configuration | 36 rows, 64 columns, and 4 layers. | 36 rows, 64 columns, and 4 layers. |
| Period | 27 stress periods for 1915 to 1990 | 27 stress periods for 1915 to 1990 |
| Time steps | | |
| Reference | Hamilton, S.L. and T. Maddock, III, 1993, Application of a Ground-Water Flow Model to the Mesilla Basin, New Mexico and Texas, Department of Hydrology and Water Resources, University of Arizona. | Lang, P.T. and T. Maddock, III, 1994, Simulation of Groundwater Flow To Assess the Effects Of Pumping and Canal Lining On the Hydrologic Regime Of the Mesilla Basin, Doña Ana County, New Mexico & El Paso County, Texas, Department of Hydrology and water Resources, University of Arizona. |

**Table B1. Summary of Numerical Models Developed for the Paso del Norte Watershed (cont.)**

| **Model** | **MODFLOW (Weeden and Maddock, 1999)** | **MODFLOW/MT3D (CH2M Hill, 2002)** |
|---|---|---|
| Authors' Name | Weeden and Maddock, 1999 | CH2M Hill, 2002 |
| Purposes | Expand the model into the Rincon Valley and implement with GMS to assess different operational scenarios. | Assess impacts of groundwater withdrawal on flow and water quality |
| Method | FDM for groundwater flow. | FDM for both groundwater flow and water quality. |
| Hydrologic systems | Multiple aquifers with drains (DRN), canals and the river (STR1) | Multiple aquifers with drains (DRN), canals and the river (STR1) |
| Coverage | Rincon Valley (335 sq. miles) and Mesilla Basin (1,110 sq. miles) | Canutillo wellfield within Mesilla Basin. |
| Grid Configuration | 148 row, 56 columns and 4 layers | 216 row, 135 columns and 4 layers |
| Stress or time Period | 163 stress periods for 1915 to 1995; specified on a seasonal basis: primary irrigation season from March to October and secondary non-irrigation season from November to February. | 163 stress periods for 1915 to 1995. |
| Time Step | | |
| Reference | Weeden, A. and T. Maddock III: 1999, Simulation of Groundwater Flow in the Rincon Valley Area and Mesilla Basin, New Mexico and Texas, University of Arizona Research Laboratory for Riparian Studies and Department of Hydrology and Water Resources. | CH2M Hill, 2002. *Groundwater Modeling of the Canutillo Wellfield*. Final Report prepared for El Paso Water Utilities Public Service Board.<br>Hutchison, W.G. 2004 Documentation of Files for Canutillo Wellfield Groundwater Flow Model, EPWU Hydrogeology Report 04-03, El Paso Water Utilities, Texas. |

**Table B1. Summary of Numerical Models Developed for the Paso del Norte Watershed (cont.)**

| **Model** | **BESTSM/MODFLOW** | **MODFLOW for Hueco Bolson (Heywood and Yager, 2003 and Hutchison, 2004b)** |
|---|---|---|
| Authors' Name | Boyle Engineering Stream Simulation Model | Heywood and Yager, 2003 and Hutchison, 2004b |
| Purposes | Combining the BESTSM model with MODFLOW can simulate a physically and operationally complex surface/groundwater system to compare various operational scenarios for planning purpose only. | |
| Method | Linked surface water (BESTSM) and groundwater model (MODFLOW)<br>Water quality in the form of conservative constituents including TDS, sulfate and chloride | STR package was modified to simulate continuing stream leakage to the aquifer to the topmost active cell if the upper layer is dry. The MAW package was modified to support dewatering of model layers by omitting dry cells from the computation of head in the well and apportioning flows to or from the wells in the remaining saturated layers. |
| Hydrologic systems | The Rio Grande from the San Marcial gage above Elephant Butte Reservoir to Riverside Diversion Dam and Mesilla Basin. | Hueco Bolson aquifer with drains (DRN), canals and the river (STR1). |
| Coverage | Some USGS daily flow data are available beginning in 1899; Uninterrupted flow data are only available beginning in 1925 for the Rio Grande below Elephant Butte Reservoir and the Rio Grande at El Paso gages. | Hueco bolson and extends slightly into the Tularosa Basin in New Mexico, covers the Hueco in Texas except for the southeastern tip in Hudspeth County, and most of the Hueco in México |
| Grid Configuration | Linked nodes and MODFLOW grids as the Hamilton model | 165 rows and 100 columns and 10 layers. |
| Stress or time Period | Two seasons for groundwater model.(1925-1995) | 96 stress period for 1903 to 1996 & 1997 to 2002 |
| Time Step | Daily time step for surface water | |
| Reference | Boyle Engineering Corporation, 1994. BESTSM, Boyle Engineering Stream Simulation Model, Documentation and User's Manual, Version 4.0<br>Boyle and Parsons, 2000. Boyle Engineering Corporation and Parsons Engineering Science, 2000. Hydrologic Modeling Report, April 2000. | Heywood, C. and Yager, R., 2003. Simulated ground-water flow in the Hueco Bolson: an alluvial-basin aquifer system near El Paso, Texas. U.S. Geological Survey Water-Resources Investigation Report 02-4108.<br>Hutchison, W.G. 2004b, Hueco Bolson Groundwater Conditions and Management in the El Paso Area, EPWU Hydrogeology Report 04-01, El Paso Water Utilities, Texas. |

**Table B1. Summary of Numerical Models Developed for the Paso del Norte Watershed (cont.)**

| **Model** | **WRAP (**Water Rights Analysis Package**)** | **SWAT (**Soil and Water Assessment Tool**) with GAMS** |
|---|---|---|
| Authors' Name | Wrubs, 2001 | Ward, et al. 2001. |
| Purposes | Simulate management of the water resources of a river basin, or multiple-basin region, under a priority-based water allocation system. | Predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. |
| Method | Water rights accounting with priority | |
| Hydrologic systems | Reservoir storage, water supply diversions, return flows, environmental instream flow needs, and hydroelectric power generation | Climate, HRUs, ponds/wetlands, groundwater, main channel |
| Coverage | Caballo or New Mexico state line to Fort Quitman, Texas | Colorado – Gulf of México |
| Grid Configuration | Node-linked network | Subbasin/subwatershed. |
| Stress or time Period | | Monthly/annual |
| Time Step | Monthly (No limit on the number of years) | Daily time step |
| Reference | http://ceprofs.tamu.edu/rwurbs/wrap.htm<br>http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html<br>Reference and Users Manual for the Water Rights Analysis Package (WRAP), by Ralph A. Wurbs, Civil Engineering Department, Texas A&M University, TR-180, Texas Water Resources Institute, College Station, Texas, July 2001 | Ward, F.A., R. Young, R. Lacewell, J.P. King, M. Frasier, J.T. McGuckin, C. DuMars, J. Booker, J. Ellis and R. Srinivasan. 2001, *Institutional adjustments for coping with prolonged and sever drought in the Rio Grande Basin*, New Mexico WRRI Technical Completion Report No. 317.<br>http://www.brc.tamus.edu/swat<br>Soil & Water Assessment Tool Theoretical Documentation Version 2000, Published 2002 by Texas Water Resources Institute, College Station, Texas, TWRI Report TR-191<br>Soil & Water Assessment Tool User's Manual Version 2000, Theoretical Documentation & User's Manual, Published 2002 by Texas Water Resources Institute, College Station, Texas, TWRI Report TR-192 |

**Table B1. Summary of Numerical Models Developed for the Paso del Norte Watershed (cont.)**

| **Model** | **RIOFISH (**River-basin Information Organizer for Fisheries Investigation, Simulation, and Heuristics**)** | **Genetic Algorithm Based Technical Model** |
|---|---|---|
| Authors' Name | Cole, et al. 1995 | King, et al. 1995 |
| Purposes | simulation of river and reservoir hydrology, water quality, organic loads, fish production and catchable sportfish, catch rates, recreational days, and angler benefits | To provide a management tool for improving the economic performance of river basin management. |
| Method | RIOFISH is composed of three components, run separately or integrated and simulating the hydrology, ecology and socio-economics of a sportfishery program management system. Model users have access and control of numerous inputs for each component and receive output information about the consequences of input changes. | uses a genetic algorithm based technique to portray both the physical response to and economic benefits of particular operating strategies |
| Hydrologic systems | Reservoirs | River basin |
| Coverage | 16 large reservoirs along the Rio Grande, the Canadian, Pecos, San Juan rivers in New Mexico. | includes the Rio Grande reaches between Elephant Butte Reservoir to American Diversion Dam, TX |
| Grid Configuration | | |
| Stress or time Period | Limited in length by the needs of model users. | |
| Time Step | | 52 one-week time steps |
| Reference | Cole, R.A., T.J. Ward, F.A. Ward, R.A. Deitner, R.W. Rodden, S.M. Bolton, and K.A. Green-Hammond. 1995, *RIOFISH: A Comprehensive Management System Model for New Mexico Sport Fisheries. Las Cruces, New Mexico*. New Mexico Water Resources Research Institute, NMSU. WRRI Completion Report Number 291, 230 pp. | King, J.P., F.A. Ward, H.S. Fahmy and M.W. Wentzel. 1995. Economic Optimization of River Management Using Genetic Algorithms. New Mexico Water Resources Research Institute Technical Completion Report, November 1995. |

# Appendix C: Demonstration of Data Distribution and Download


Figure C1. Front page of the Project website, available at www.pdnwatershed.org.

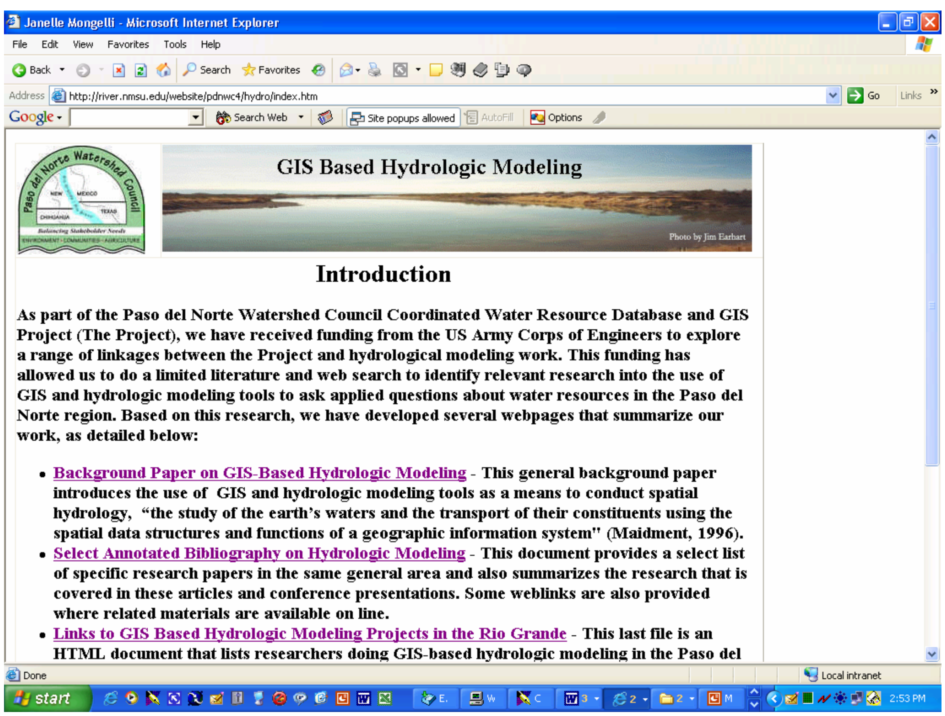


Figure C2. Access page for bibliographic information on GIS and hydrologic modeling, available at http://river.nmsu.edu/website/pdnwc4/hydro/index.htm.

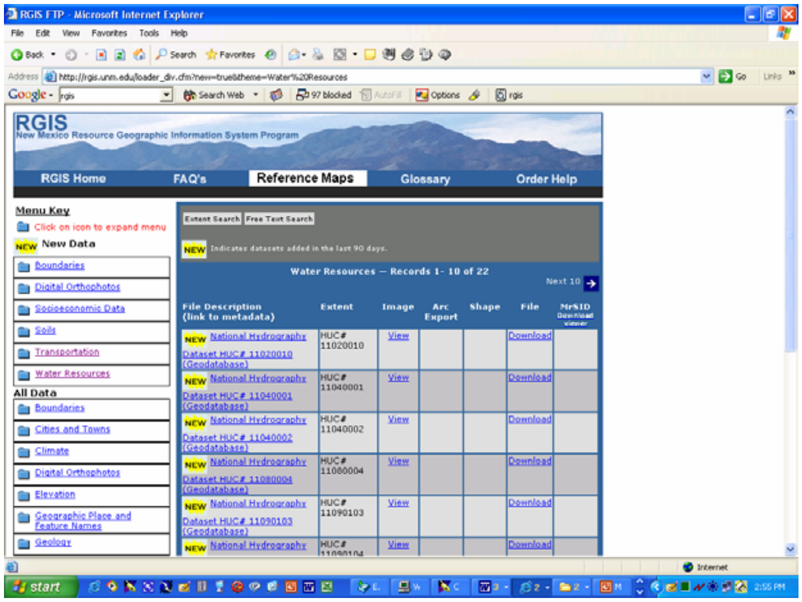


Figure C3. Table-based user interface for GIS data download hosted by the New Mexico Regional Geographic Information System website, available at http://rgis.unm.edu/.

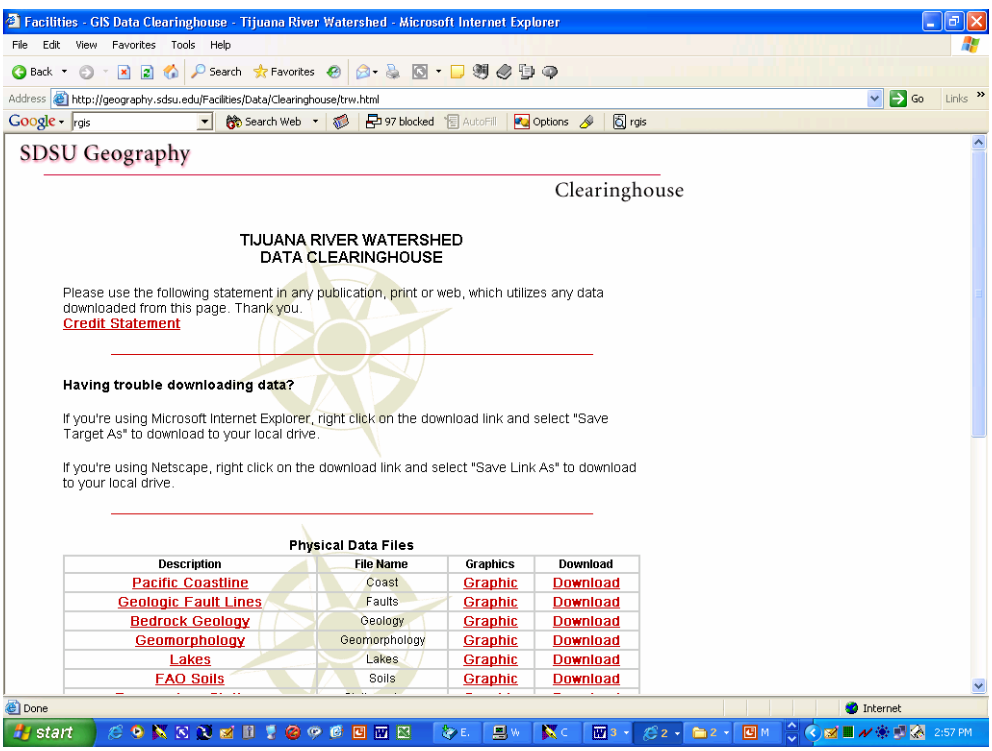


Figure C4. Table-based user interface for GIS data download provided for the Tijuana River Watershed Data Clearinghouse, hosted by SDSU Department of Geography, available at http://geography.sdsu.edu/Facilities/Data/Clearinghouse/trw.html.

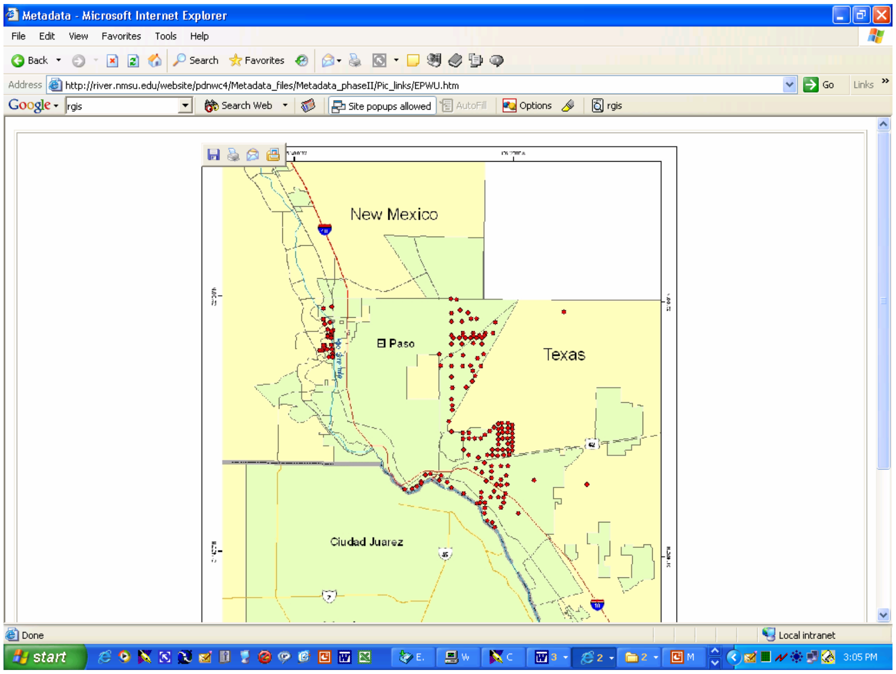


Figure C5. Sample GIS graphic provided by link from table-based user interface at http://river.nmsu.edu/website/pdnwc4/Metadata_files/Metadata_phaseII/pic_links/epwu.htm.


Figure C6. Table-based user interface for the Coordinated Water Resources Database Project data access and download utility, available at http://river.nmsu.edu/website/pdnwc4/Metadata.htm.

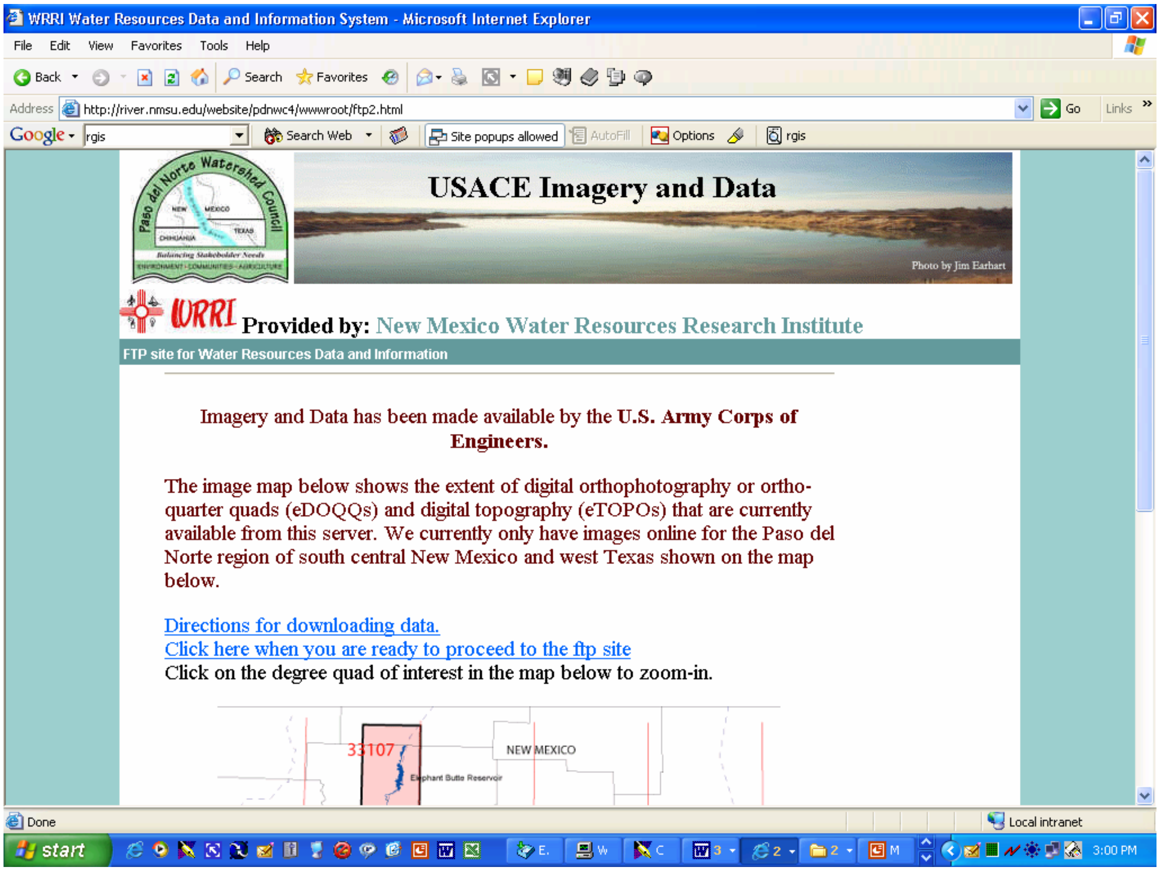


Figure C7. Access page for USACE digital orthophotography or ortho-quarter quads (eDOQQs) and digital topography (eTOPOs), available at http://river.nmsu.edu/website/pdnwc4/wwwroot/ftp2.html.