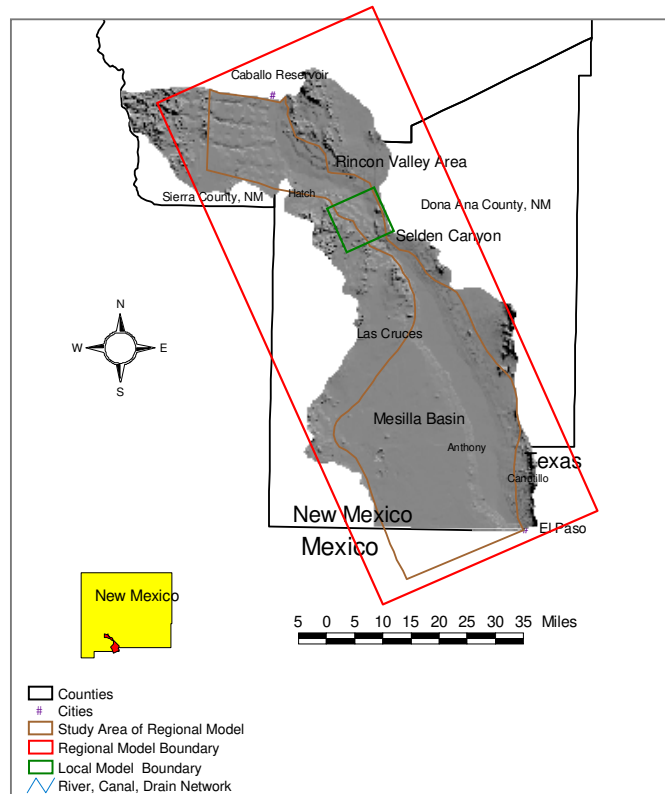December 2009

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By

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Cover figure: Local Rincon model area and regional Rincon and Mesilla model area (modified after Weeden and Maddock 1999)

# Acknowledgements

# Executive Summary

The Elephant Butte Irrigation District desired the construction of a small-scale hydrologic model located in the southern Rincon Valley within the EBID (Rincon Model) using MODFLOW with the Farm Process (MF-FMP). The purpose of the model is to obtain a tool to demonstrate an MF-FMP model on a pilot project scale before adopting MF-FMP for a regional model encompassing the entire EBID and to illustrate how MF-FMP can simulate (a) un-metered historic pumpage, (b) impacts of surface-water and groundwater abstraction on Rio Grande stream and return flow, and (c) scenarios of changing allotments influence deliveries and downstream stream gains/losses.

The local fine resolution Rincon Model is coupled to the pre-existing coarse resolution regional Rincon Valley and Mesilla Basin model (Weeden and Maddock 1999) through boundary conditions derived from the regional model (Tillery and King 2006). The local Rincon Model using MODFLOW-2005 with the Farm Process (MF2K5-FMP2) simulates evapotranspiration, recharge, and farm-well pumping independently but dynamically linked through their dependence on the groundwater level. Therefore, it does not require any data input for the Recharge Package of the regional model (Weeden and Maddock 1999) anymore, which used a lumped net irrigation flux (estimates of recharge minus ET minus farm-well pumping). The local Rincon Model uses standard features of the Farm Process such as the distribution of 15 individual 'family farms' (for larger models: water-balance regions simulated as 'virtual farms'), six crop types, and three typical soil types. Each of these spatial entities is associated with attributes, such as, on-farm efficiency for farms, or crop specific consumptive use, fractions of transpiration and evaporation, root depths, and water stress response for crop types, or capillary fringes for soil types. More recent features of FMP2 are used, for instance, to specify locations of diversion and returnflow points along the stream-canal-drain network, where known, and to let the FMP2 automatically determine these points and associated flows, where not known. This allows the user to enter parameters that are known, whereas the FMP2 can compliment knowledge gaps such as estimates of unknown (i.e., unmeasured) surface-water deliveries or irrigation returnflows.

The model was calibrated using the parameter estimation code UCODE (Poeter et al. 2005) not only by observed groundwater levels and streamflows, but by observed cumulative farm well pumpage. Model parameters allowed to vary during model calibration were the hydraulic conductivity of layer one, the streambed hydraulic conductivity of the Rio Grande and of the Rincon Lateral, the on-farm efficiency, and the fraction of transpiration (latter two are lumped over time and over all farms or crop types, respectively). Several parameters of this UCODE run were highly correlated (efficiency correlated with fractions of transpiration, hydraulic conductivity of Rio Grande streambed correlated with hydraulic conductivity of aquifer layer one). These correlations

could be natural but also could indicate that there may not have been enough information in the observations used to estimate parameter values that allow the analysis of specific farm operation. The scarce number of observations obtained from EBID and USGS sources (47 observations of water levels, streamflows, and cumulative pumpage) appears insufficient for a complex multivariate parameter estimation without high parameter correlations. A better basis of observation data may allow the initiation of an MF-FMP model with simple time-space lumped parameter values, which then are differentiated into estimates varying over associated farms or crop types during the calibration and parameter estimation process. In order to eliminate parameter correlations for the local Rincon Model, the number of estimated parameters was reduced (streambed hydraulic conductivity of the Rio Grande was not used), but efficiency fraction-of-transpiration parameters could be differentiated into estimates for each irrigation season of years 2002 and 2003.

The simulated historic pumpage is one component of the output 'Farm Demand and Supply Budget.' Time series of these budget components reveal four groups of farms with respect to sufficiency and farm-well ownership. The first group consists of farms that own enough wells to compensate for occasional surface-water deficiencies. The cumulative maximum pumping capacity of wells of these farms was not exceeded during this dry-year period. That is, even if these farms were during some times 'surface-water deficient,' they remained 'groundwater sufficient.' The second group includes farms that do not own wells but were able to operate sufficiently by minimizing their inefficient losses. The third group consists of small farms that do not own wells and, even with 100% efficiency, were not able to sustain the necessary crop consumptive use. The last group contains farms that showed no irrigation requirement either because their fields were fallowed or solely fed by rain or phreatophytic uptake from shallow groundwater.

MF-FMP allows sub-dividing the former 'net irrigation flux' of the previous regional Rincon and Mesilla models into individual component that can vary over time and space and can interact dynamically (deep percolation, six different evaporation and transpiration components, and groundwater well pumping). These components are part of the output 'Farm Budget' that includes all physical flows into and out of each farm. 'Farm Budget' components *transpiratory root uptake* and *farm-well pumping* dynamically interact through their mutual dependency on the groundwater level and irrigation demand. For instance, for the pecan dominated farm 7 (Halsell farm), the water-level depletion during 2003 results in a reduction of transpiratory root uptake, hence, increased irrigation demand, and, as a result of allotment-limited surface-water deliveries, ultimately in increased farm-well pumping.

The impact of the entire agriculture system through surface-water and groundwater abstraction on the downstream Rio Grande streamflow can be described by a correlation between streamflows calculated by MF-FMP and HYDMOD and the cumulative farm irrigation pumpage yielded by the 'Farm Demand and Supply' data output file. The same model investigation technique could be applied to a more regional model and downstream streamflow deliveries (e.g., at the NM-TX state line). The result shows non-linear correlations between increasing surface-water or groundwater deliveries and streamflow during irrigation seasons. With increasing pumpage, the streamflow is depleted in the form of an exponential decay. That is, streamflow depletion is non-linearly related to groundwater abstraction and the streamflow depletion diminishes as pumpage reaches highest levels. However, external factors may influence streamflow as well (e.g., natural precipitation and runoff, or constrained deliveries, such as equal appropriation allotments). Relatively high maximum pumping capacities did not constrain the groundwater pumpage in the present Rincon Model.

Model scenarios tried to evaluate the effect of changing surface-water allotment heights specified for each irrigation stress period (1.2, 0.8, 0.4, 0.2, and 0.1 meters = 3.9, 2.6, 1, 0.65, and 0.33 feet) on surface- and groundwater deliveries and Rio Grande streamflow gains and losses (for 08/31/02 and 08/31/03). Increasing the equal appropriation allotment height causes a nonlinear increase in surface-water deliveries, a nonlinear decrease in groundwater pumping, a nonlinear increase in Rio Grande gains along the farming area before tributary drain returnflow, and a nonlinear decrease in Rio Grande gains when including drain returnflows. The model scenarios show the dynamic interdependence of operational constraints, such as surface-water allotments, surface- and groundwater deliveries, returnflows, and streamflow gains/losses. When allowing sufficiently high allotments, diversions are bound by the irrigation demand and, for some farms, by the available streamflow. In the present model, groundwater pumping could potentially be constrained by (relatively high) maximum pumping capacities, which however were not reached. The model scenarios also simulate reductions in drain returnflow to the Rio Grande, which can be explained by a declining water table and less farm irrigation returnflows in times when higher on-farm efficiency is required.

In summary, the local Rincon Model demonstrates how MF-FMP can estimate supplemental historic groundwater use and evaluate the large-scale impact of surface-water allotments on surface- and groundwater deliveries, streamflow, river seepage, and return flows. In the local Rincon Model, these scenarios were applied to hypothetic locations along the Rio Grande upstream and downstream the model farming area. In larger-scale models, MF-FMP can analyze analogous scenarios for instance where the New Mexico/Texas state line crosses the Rio Grande. Coupling the local Rincon Model to the regional Rincon Valley & Mesilla Basin groundwater model (Tillery and King 2006, Weeden and Maddock 1999) produced initial and boundary conditions through the

telescopic mesh refinement technique (TMR). Inaccurate initial groundwater levels derived from the regional model follow errors in ground-surface elevations (up to 14 meters!) and stream-network topography but affected only the first stress period of the local Rincon Model. Instead of the TMR, we propose to use the Local Grid Refinement technology (Mehl et al. 2005), which allows a local model to run simultaneously with a regional model across local model boundaries. For updates of this or any other models using MF-FMP within the EBID, we strongly recommend to obtain a better observation database from additional observation wells and stream gage monitoring, which may require drilling new observation wells or constructing new stream gages along the Rio Grande. A higher density of stream gages would allow the stream gains or losses between these gages to be an additional observation parameter. Also, metered cumulative pumpage of farms should be monitored more densely and in more representative farm locations. Optimally, all farms of an MF-FMP model domain should report cumulative pumpage from their associated farm wells. This would not lead to a redundancy of MF-FMP's ability to simulate farm pumpage, but to the ability to obtain a 'pumpage-calibrated' model that can be transformed into a predictive model driven by management or climate scenarios. Once calibrated by cumulative pumpage data, an MF-FMP model can be one that water managers can keep current by updating variable data or conditions, such as climate data or changing water rights. Hence, it can be used as a design tool to plan water supplies for upcoming water years, for long-term predictive scenarios driven by climate change, and for water appropriation planning and negotiations.

This calibrated local Rincon Model could be compared in various ways to the new regional Rincon and Mesilla model of the New Mexico Office of the State Engineer (OSE model). The local Rincon Model could be compared against either a zone of the current OSE model or a zone of an MF2K5-FMP2-updated version of the OSE model. However, more advantageous than to compare the little local Rincon Model would be to compare regionally the OSE model to an according MF2K5-FMP2 update. This comparison would further delineate how the approaches to evapotranspiration, surface-water deliveries, groundwater pumpage, recharge, and streamflow gains and losses are affected by the decoupled approach used in the current OSE model versus the application with the FMP. These comparisons would help quantify any potential differences and help improve the overall set of hydrologic tools used to help guide the management and allocation of water resources in the Lower Rio Grande. This approach would also facilitate a better tool for making projections of evapotranspiration, surface-water deliveries, groundwater pumpage, recharge, and streamflow gains and losses based on estimates of future short-term or long-term climate.

The following Table 1 provides a synoptic view of the project purposes, the objectives set to meet the purposes, the achievements and finding of the presented study, as well as recommendations and conclusion for this and other studies using MF-FMP along the Lower Rio Grande of New Mexico:

Table 1. Project purpose, objectives, findings, and recommendations and conclusions

| Purpose of current study | Objective to reach purpose | Achievements / Findings | Recommendations / Conclusions / Improvements |
|---|---|---|---|
| Testing MF-FMP on a pilot project scale | Local pilot project model telescoped into truncated Regional Model | Local fine scale model coupled to coarse resolution regional Rincon Model through derived initial and boundary conditions derived. BUT: no more pre-processed 'net irrigation flux' data input required (FMP simulates evapotranspiration, recharge, and farm-well pumping independently but dynamically linked through groundwater-level dependence). | Initial and boundary conditions of telescoped model are biased by inaccurate elevations and stream-network topography.<br><br>Conclusion for other local models:  Instead of the Telescopic Mesh Refinement use Local Grid Refinement technology (child model runs simultaneously with parent model across local model boundaries. |
| Estimate of historic un-metered pumping for family farms | Conversion of lumped 'virtual farm' to distributed family farms<br><br>Model Calibration (some metered pumpage used) | Calibrated model allows grouping family farms with respect to sufficiency:<br>• Surface-water deficient but groundwater sufficient<br>• No well ownership but surface-water sufficient by minimizing inefficient losses through deficit irrigation scenario<br>• No well ownerships and surface-water deficient<br>• No irrigation requirement (fallow or consumptive use satisfied by rain or groundwater uptake) | Additional observation data beneficial for model calibration:<br>• Observation-well monitoring or drilling,<br>• Monitoring of pumpage (more densely and in more representative farm locations – here: only farm with metered pumpage was towards boundary of farmed area!),<br>• Optimally: monitoring of pumpage of all farms (MF-FMP's ability to simulate pumpage not redundant: allows pumpage-calibrated model that can be transformed into predictive model)<br>• Stream gage monitoring or construction (at higher density) → allows stream gains/losses as observation (here: no observation in lack of gages). |
| Impact of surface-water and groundwater abstraction on Rio Grande streamflow and return-flows | Analysis of results of calibrated model for Rio Grande streamflow between hypothetic points. | Model demonstrates non-linearity between supplemental pumpage (dynamically linked to demand and surface-water deliveries) and Rio Grande streamflow (possible explanation: change from gradient to gravity dominated stream seepage). | Conclusion for a regional model using MF-FMP:<br>The same model investigation technique could be applied to a more regional model and downstream streamflow deliveries (e.g., at the NM-TX state line). |
| Impact of changes in allotments on down-stream surface- and groundwater deliveries | Alterations to calibrated model by changing allotment heights. | Model scenarios show dynamic interdependence of operational constraints, such as equal appropriation surface-water allotments, surface- and groundwater deliveries, return-flows, and streamflow gains/ losses. | Conclusion for a regional model using MF-FMP:<br>The same allotment scenarios or other dynamic responses (e.g., response to changes in release or stream inflow) may be demonstrated within the scope of a regional model using MF-FMP |

Table 2 provides a synoptic view of two operational and research questions that were beyond the scope of this study as they only can be answered on a regional scale. However the definition of the some objectives of a regional Rincon Valley and Mesilla Basin Model benefits from recommendations derived from the current pilot project study:

Table 2. Purpose of future study and general objectives and recommendations

| Purpose of future study | General Objectives and Recommendations |
|---|---|
| Impact of change in climate, rights, or policies on growing seasons, streamflow, and reservoir release? | A calibrated regional MF-FMP can be kept current by updating variable data or conditions, such as climate data or changing water rights. Hence, it can be used as a design tool to plan water supplies for upcoming water years, for long-term predictive scenarios driven by climate change, and for water appropriation planning and negotiations. |
| Accuracy of model budget estimates employed by the OSE/ISC? | Comparison of OSE model budget estimates (evapotranspiration, surface-water / groundwater deliveries, streamflow gains/losses, returnflows) based on: <br><br>• Zone in OSE model delineated by farming area of local Rincon Model, or <br>• MF2K5-FMP2 update of OSE model for entire domain. <br><br>Objectives of comparisons: <br><br>• Help quantify potential differences and improve overall set of hydrologic tools used for management and allocation of water resources in the Lower Rio Grande. <br>• Facilitate a better tool for making projections of the above budget terms based on: <br>o estimates of future short-term or long-term climate, or <br>o based on operational or water rights changes. |

# Table of Contents

# List of Figures

# List of Tables

# Introduction and Objectives

Demand and use of water have been increasing along the Lower Rio Grande of New Mexico (LRG) over the past few decades. The Rio Grande Project was originally built around 1916 by the Bureau of Reclamation to deliver surface water to farmers in the upstream Elephant Butte Irrigation District (EBID), the downstream El Paso County Water Improvement District No. 1 (EPCWID), and to make deliveries required by treaty to the Republic of Mexico in Ciudad Juárez. The primary source of water for the Rio Grande Project is surface water runoff in the Rio Grande from southern Colorado and northern New Mexico. This water is stored in two reservoirs, Elephant Butte and Caballo. The Rio Grande Compact is a 1938 interstate agreement among Colorado, New Mexico, and Texas that apportions water to the three states and provides water for delivery to Mexico as dictated in a 1906 treaty between the U.S. and Mexico (King and Maitland 2003). Surface water rights associated with the Rio Grande Project are senior in priority. Farmers in the upstream district, the EBID, supplement their surface water supply with groundwater produced from private wells. In the EBID, groundwater pumping for irrigation use alone may presently be as high as 50,000 to 100,000 AFY in years of full surface water supply by the Rio Grande Project and about 200,000 to 300,000 AFY in low project supply years (Barroll 2005).

The EBID provides water to 90,640 water-righted acres in New Mexico. Farmers grow pecans, alfalfa, cotton, vegetables including onions, lettuce, cabbage, and chile, and other forage and miscellaneous crops. There is a general increase in acreage of pecans, and a declining acreage of cotton. Overall, irrigated acreage in the EBID decreased to about 75,000 acres. However, the full 90,640 acres maintains appurtenant water rights (King and Maitland 2003) and the depletion of water has been almost steadily increasing (Barroll 2005), which might mainly be due to increased groundwater pumping for expanding pecan orchards.

A measure to control the fully appropriated water use in the EBID is the adjudication of water rights. This includes both surface and groundwater, as required by the New Mexico Office of the State Engineer, OSE, (King and Maitland 2003) acknowledging that surface water and groundwater behave as a single resource. Most

junior groundwater rights were established prior to 1982, when groundwater in the LRG finally had fallen under the jurisdiction of the State of New Mexico. Following its regulatory agenda, the OSE has expressed intentions to increase regulation on groundwater use, for instance to order the metering of wells (Barroll 2005).

Yet, while surface water deliveries are generally known, well pumpage in the EBID is still far from being fully metered, which is typical for many other irrigated areas of the United States. Without available data on metered pumpage, it is of great advantage to simulate historical pumpage by an integrated numerical computer model in order provide groundwater pumping as a key adjudication parameter instead of estimating pumpage indirectly, for instance from power records or land-use maps.

The EBID has expressed a general interest in a district wide computer model using MODFLOW with the Farm Process (MF-FMP) (MODFLOW-2000 with Farm Process vs. 1, MF2K-FMP1: Harbaugh et al. 2000; Schmid et al. 2006; MODFLOW-2005 with Farm Process vs. 2, MF2K5-FMP2: Harbaugh 2005; Schmid and Hanson 2009) to simulate supplemental groundwater pumping for irrigation. MF-FMP was initially developed in light of the adjudication situation in the lower Rio Grande of New Mexico. A new modeling tool was required in lieu of metered groundwater pumping as a means to more accurately estimate spatially and temporally distributed pumping in models throughout the United States. This new technique will supersede the external pumping estimates that are implicitly accounted for in 'net irrigation flux,' NIF, of a previous regional groundwater flow model encompassing the Rincon Valley and Mesilla Basin (Weeden and Maddock 1999). The NIF is defined as the sum of net diversions minus agricultural consumptive use plus recharge from rainfall (Frenzel and Kaehler 1992; Hamilton and Maddock 1993; Lang and Maddock 1995; Weeden & Maddock 1999). The new technique can also be used to verify the validity or replace the external unlinked spreadsheet approach 'Farm Module' used by the Office of the State Engineer / Interstate Stream Commission (OSE/ISC).

Using MF-FMP can be of considerable value to answer five major questions, which both the OSE/ISC and water managers of the EBID are seeking to answer for the irrigation setting of the Lower Rio Grande of New Mexico:

1. What was the historic groundwater pumping for farm irrigation related to any configuration of water-accounting units (e.g., individual farms, compounds of farms defined as 'virtual farms,' entire irrigation district)?

2. How do the consumptive-use-driven surface-water and groundwater abstractions impact the Rio Grande streamflow and its return flows?

3. How do scenarios of reservoir release, farm demand, and conjunctive surface-water / groundwater supply influence the delivery of downstream streamflow (e.g., at the state line)?

4. How does climate change result in more rain-related streamflow and less snow-melt related streamflow combined with a longer growing season affect the scenarios of reservoir release and downstream streamflow (e.g., at the state line)?

5. How accurate are regional estimates of evapotranspiration, pumpage, returnflows, and recharge employed by the OSE/ISC that are not dynamically coupled to precipitation, groundwater uptake and streamflow?

The EBID has desired the completion of a small-scale local MF-FMP model located in a narrow part of the southern Rincon Valley within the EBID (Rincon Model), where boundary conditions are easy to define (early stages of this model by Tillery and King 2006). The main purpose of completing the Rincon Model is to obtain a tool to demonstrate an MF-FMP model on a pilot project scale before adopting MF-FMP for a new regional model encompassing the entire EBID. The purpose of the Rincon Model is further to illustrate how MF-FMP helps answering the first three of the above questions (historic pumping?, how does surface-water and groundwater abstraction impact Rio Grande Streamflow and return flows?, how do reservoir and farm operations impair downstream deliveries?).

However, it is beyond the scope of the Rincon Model to answer question 4 (impact of climate change on growing seasons, streamflow, and reservoir release?). Only a predictive regional model that includes the reservoirs and is driven by regional or global climate models will be able to answer question 4. Similarly, only a regional update or upgrade of the OSE/ISC's Lower Rio Grande Model (SSPA 2007) using MF-FMP will be able to answer question 5 (accuracy of model budget estimates employed by the

OSE/ISC?). Answering question 5 may be critical in assuring that the regulation of water allocations that are based on the regional model are as accurate and representative of changing field conditions as possible. This can only be accomplished for historical or future scenarios with a model that links flows dynamically, such as MODFLOW with FMP.

A first objective of the local Rincon Model was to simulate un-metered groundwater pumpage that was needed to supplement surface-water irrigation for the years 2002 and 2003 initially for a lumped virtual farm encompassing the entire farmed area (Tillery and King 2006) and in a second step for a set of distributed farms as presented in this report. A second objective was to calibrate the model by or compare the model with measurements of water levels, cumulative farm well pumpage, and streamflows recorded over the duration of the simulation. A third objective was to illustrate results of the calibrated model, for instance, output options that yield estimates of historic groundwater pumpage for 'family farms' defined as parcels aggregated by the same last name or how the surface-water and groundwater abstraction impacts the Rio Grande streamflow and its return flows. A fourth and final objective was to elaborate on how scenarios of allotment changes influence the conjunctive surface-water / groundwater supply and accordingly the Rio Grande stream gains or losses?

The next section discusses briefly the development of boundary conditions (Tillery and King 2006) as boundaries of a local Rincon Model that is embedded in a pre-existing regional groundwater model, which encompasses the entire EBID and both the Rincon Valley and Mesilla Basin (Weeden and Maddock 1999). The third section describes the conceptual features of MF-FMP applied to the local Rincon using a set of distributed farms. The fourth section discusses the model calibration and parameter estimation process and compares calibrated results against measurements for part of the simulation period. The fifth section provides results of the calibrated model and of model scenario using changed surface-water allotments. Finally, lessons learned from the local Rincon Model for larger application to the entire EBID and the future outlook is discussed.

# Local Rincon Model Embedded in Regional Model

The study area (Figure 1) chosen for this Local Rincon Model is sited in the Southern Rincon Valley, between Hatch and Selden Canyon, New Mexico.
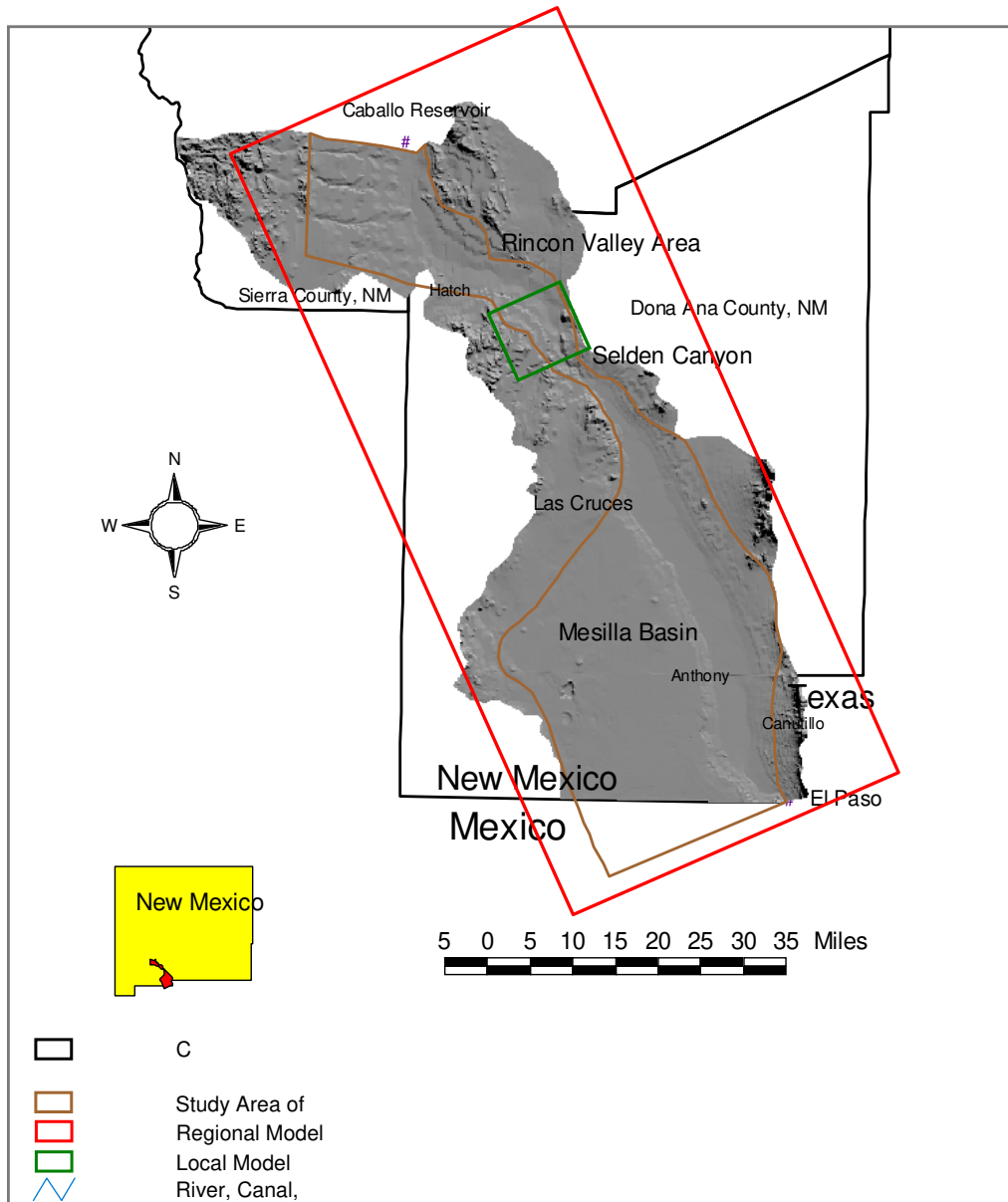


Figure 1. Local Rincon model area and regional Rincon and Mesilla model area (modified after Weeden and Maddock 1999)

Figure 1 shows the extent of the local model boundary in green color within the wider area of the Lower Rio Grande of New Mexico and in relation to the previous Regional Rincon Valley and Mesilla Basin Groundwater Model (Weeden and Maddock 1999) in red color. Figure 2 shows an enlargement of the extent of the local model boundary and the farm area simulated by the Farm Process within the local MODFLOW-2005 model (MF2K5-FMP2). This section discusses the development of a local MODFLOW-2000 (MF2K) groundwater flow model in the southern Rincon Valley with a refined grid (local Rincon model) and the conversion to MF2K5-FMP2.

In summary, the development stages of the local Rincon model using MF2K-FMP2 are:

1) Regional MODFLOW-96 model of the Rincon and Mesilla Valleys (Weeden and Maddock 1999);

2) Regional MODFLOW-2000 model of the Rincon Valley (Regional model in 1) truncated by Mesilla Basin and converted from MF96 to MF2K) (Tillery and King 2006);

3) Local MODFLOW-2000 model of the southern Rincon Valley (telescoped into regional model in 2) (Tillery and King 2006);

4) Local MODFLOW-2005 model of the southern Rincon Valley using the Farm Process (based on boundary and initial conditions, time and space discretization, and hydraulic properties of local model in 3).
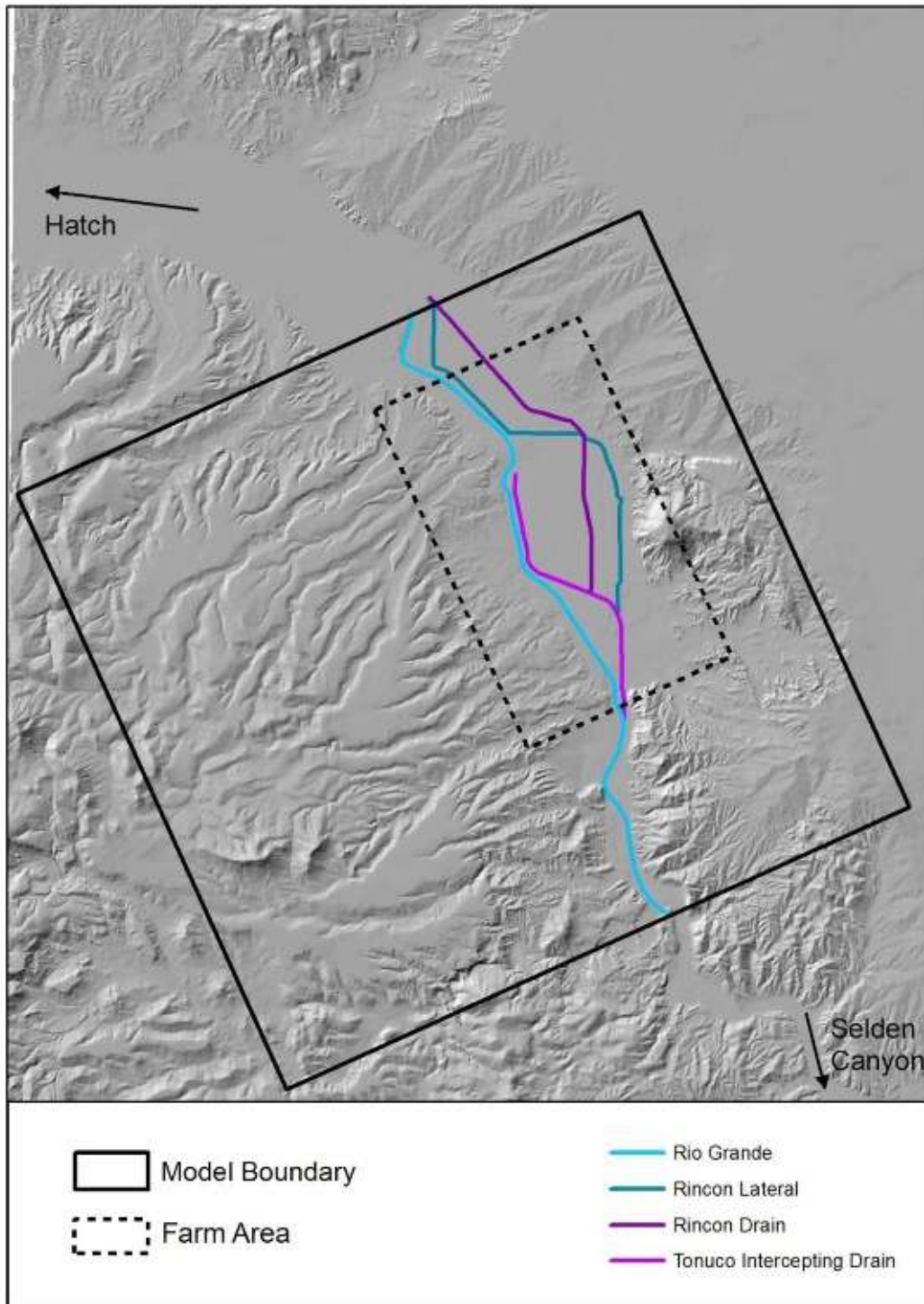
Figure 2. Topography and location of local model boundary and farm area in Rincon Valley.

## Regional Rincon Model (MODFLOW-2000)

The local Rincon model was telescoped into a regional MF2K model of the Rincon Valley (regional Rincon model) (Tillery and King 2006). To develop the regional Rincon model, an existing MODFLOW-96 groundwater flow model that encompasses the entire Rincon and Mesilla Valleys (Weeden and Maddock 1999; Harbaugh and McDonald 1996).

Figure 1 was truncated by the Mesilla Basin south of Selden Canyon (after row 51, and after column 39) and converted from MF96 to MF2K (Tillery and King 2006) using the executable MF96TO2K.EXE, which is provided with the MF2K software. Weeden and Maddock used a modified executable of MF96 that allowed for specifying percentage of water diverted and amount of water used by crops in the STR Streamflow Routing Package (Prudic 1989). The truncated Streamflow Routing Package data file (STR) was converted to the new SFR Streamflow Routing Package file format of MF2K (Tillery and King 2006).

Time and space discretization of the regional MF96 Rincon and Mesilla model and of the truncated regional MF2K Rincon model are as follows:

- Time period from 1915 to 1995 with 2 stress periods per year (extended to February 2004 for truncated regional Rincon model):
    - 4-months non-irrigation from November to February (1-month time steps),
    - 8-months irrigation from March to October (2-months time steps).

- The spatial resolution of the grid varies from approximately 800 to 1500 meters on a side.

- The model is discretized vertically an upper unconfined layer 1, a convertible confined/unconfined layer 2, and two confined layers 3 and 4.

The data files of the regional Rincon and Mesilla model included the time period 1915 through 1995. The model period of the future local Rincon model using the Farm Process extends from November 2001 until February 2004. Therefore, the time period of the truncated regional Rincon model needed to be extended from 1995 to February 2004

before running the telescopic mesh refinement for the local Rincon model. The diversion to the Arrey Canal and flow in the Rio Grande below Caballo Dam were the only streamflow data required to extend the model. This data was acquired as part of a data collection effort for surface water flow in the Lower Rio Grande (Brown et al. 2004). When data was missing for Arrey Canal, it was assumed that the diversion to Arrey Canal was equal to 11% of the flow below Caballo. This was based on the typical historical relationship between flow below Caballo and diversion to Arrey Canal. Precipitation data for 1996 through February 2004 was taken from the Las Cruces Plant Science Center website (NMSU 2004). The extension was done by finding a historic year with a similar amount of precipitation for the year, and then the ET or recharge for that historic year was used for the new year.

## Local Rincon Model (MODFLOW-2000)

The telescopic mesh refinement programs (Leake and Claar 1999) were modified (Tilley and King 2006) to handle the MF2K data file formats of the regional Rincon model and used to create perimeter boundary conditions for the embedded local Rincon model and to interpolate data input sets for the refined grid of the local model. The perimeter boundary conditions in local models created with the telescopic mesh refinement are specified using the Flow and Head Boundary Package, version 1, or FHB1 Package (Leake and Lilly 1997). The local model boundary encompasses the simulated farm area. The distance between the farm area and southern model boundary near Selden Canyon was assumed sufficient to minimize any boundary effects on the farm area.

Other interpolated data input sets were generated for the refined grid and coordinate system of the local Rincon model for the following packages: Basic Package (BAS6), Discretization Package (DIS), Block-Centered Flow Package (BCF6), Well Package (WEL), Recharge Package (RCH), the Evapotranspiration Package (EVT), and Streamflow Routing Package (SFR).

Characteristics of the local MF2K Rincon model are as follows:

- The model covers a farm area located in the southern Rincon Valley,

- Time period from 1915 to February 2004 with 2-stress periods per year (same as truncated regional model):

    o 4-months non-irrigation from November to February (1-month time steps),

    o 8-months irrigation from March to October (2-months time steps).

- The spatial resolution of the grid is approximately 50 by 50 meters within the farm area and increasing towards the model boundaries.

- The model is discretized vertically an upper unconfined layer 1, a convertible confined/unconfined layer 2, and two confined layers 3 and 4 (same as truncated regional model).

## Local Rincon Model (MODFLOW-2005 with the Farm Process)

The local Rincon Model that was derived by the telescopic mesh refinement of the regional Rincon model was run for a period from 1915 to 2004. The resulting heads for November 2001 were used as initial heads for the final short-term local Rincon Model using MODFLOW-2005 with the Farm Process version 2 (MF2K5-FMP2). For this local Rincon model using MF-FMP, the stress periods were modified to change from 2-stress periods per year to 4-stress periods per year. The non-irrigation stress periods covered the same time period so these were left the same. The original 8-month irrigation stress period was proportionately divided into three irrigation stress periods. Percents for each stress period were distributed to match the percents of flow below Caballo for each time period.

The main modifications from the local MF2K Rincon model to the local MF2K5-FMP2 Rincon Model are:

- The time period of the simulation is November 2001 through February 2004 (for 9-stress periods) with 4-stress periods per year (with weekly time steps), which are a combination of irrigation and climate seasons:

  o 4-months non-irrigation from November until February,

  o 3-months irrigation from March until May (Growing periods of cotton and spring vegetable start during this period),

  o 3-months irrigation from June until August (Peak irrigation season and monsoon season), and

  o 2-months irrigation from September until October (Full vegetation period).

- The initial conditions for the local MF2K5-FMP2 Rincon Model were taken at Nov 2001 from the full run of local MF2K Rincon model from 1915 to Nov 2004.

- The data input for the Streamflow Routing Package (SFR) was restructured and corrected based on data derived from the GIS shape file of the stream routing network obtained by the EBID, such as location coordinates (row, column), reach identification (segment no., reach no.), and reach length. In addition streambed elevations were adjusted according to surface elevations derived from 10m Digital Elevation Models (DEMs) since streamflow gains and losses are very sensitive to this data.

- In the data input file for the Discretization Package (DIS), ground-surface elevations interpolated from the regional model were found to be inaccurate and were substituted with surface elevation data derived from 10-meter DEMs.

- In the regional models and the local MF2K model, evapotranspiration was simulated by the Evapotranspiration (EVT) package and net irrigation flux (estimates of recharge minus ET minus farm-well pumping) by the Recharge (RCH) package. These packages were removed from the local MF2K5-FMP2 model, which simulates components of evaporation and transpiration (related to irrigation, precipitation, and groundwater uptake), as well as deep percolation or

recharge (with or without delay), and farm-well pumping. These flow terms are simulated independently but dynamically linked through their dependence on the groundwater levels, precipitation, and surface-water deliveries.

## Features of the Farm Process Applied to Local Rincon Model

The local Rincon Model using the Farm Process was initially developed for just one virtual farm encompassing the entire farmed area in the model (Tillery and King 2006). This initial model is not described here. While the present model simulates distributed farms (parcels grouped by owners last name) and uses many recent features of the Farm Process version 2 for MODFLOW-2000 (Schmid and Hanson 2009), some simpler features still stem from the one-virtual-farm model, which was developed over the years 2004 to 2006. Therefore, some FMP input parameters are quite well defined, while others are of simpler concept (e.g., not varying over time or space) or are simply estimates. One example is the input parameter of consumptive use (= potential crop evapotranspiration) used in this model, which now in FMP2 potentially could be defined as the time-varying crop coefficient and reference evapotranspiration multipliers of the consumptive use product. Fractions of transpiration and evaporation as well as pressure heads, which define a stress response function, were assumed to be equal for all crops and all times. On-farm efficiency was estimated as one lumped value for all farms and all times.

More recent options of FMP2 are, for instance, the approach to use specified locations of diversion and returnflow points along the stream-canal-drain network, where known, and to let the FMP2 automatically determine these points, where not known. This allows the user a level of control to enter parameters that are known, whereas the FMP2 can compliment knowledge gaps.

## Boundary Conditions

The boundary conditions of the local Rincon Model include stream-aquifer interaction of the Rio Grande, laterals, and drains simulated by the upgraded version of the Streamflow Routing Package SRF7 (Niswonger and Prudic 2005), flow and head boundaries at the up-gradient (northwestern) and down-gradient (southeastern) edge of the model domain (Figure 1) simulated by the FHB package, and the mountain-front recharge simulated by the well package, WEL. The model also includes more localized precipitation values for the period from November 2001 until February 2004 from nearby station Derry and Leasburg compared the precipitation data used for the time extension of the converted Regional Model from 1996 through 2004 used precipitation data from the Las Cruces Plant Science Center website (NMSU 2004). While precipitation was an implicit component of the pre-calculated net irrigation flux specified in the Recharge Package data input files of previous regional models (Frenzel and Kaehler 1992; Hamilton and Maddock 1993; Lang and Maddock 1995; Weeden and Maddock 1999), it is an explicit flux specified directly in the Farm Process data input file.

A more accurate representation of precipitation is important because the Farm Process dynamically estimates the supplemental crop water supply through surface-water deliveries and groundwater pumping based on the prior availability of natural components from precipitation and uptake from groundwater.

## Farms, Crop Types, and Soil Types

GIS shape files acquired via proprietary written communication from the EBID provide the distribution of 15 family farms, 6 crop types, and 3 typical soil types (generalized from Map Unit soil types of the SSSD, State Soil Survey Database). The GIS polygon feature classes were then converted into two-dimensional array of integer identifiers for farm-ID, crop-type-ID, and soil-type-ID.

### Distribution of Farms and Farm Related Attributes in FMP

In the FMP, a farm can be any spatial feature of interest for common water-accounting. In the Rincon model, a farm was defined by parcels associated with the same

last name (family farms). For the potential supplemental delivery of groundwater to farms, the FMP requires to attribute these farms to farm wells, which was achieved by associating irrigation wells in the area with the owner's last name as listed by the water database of the New Mexico Office of the State Engineer (NMOSE 2008).

The only farm-related attribute in the Rincon model is the initial on-farm efficiency equal to the crop irrigation requirement divided by total deliveries at a farm head gate. For this simple application, the on-farm efficiency was estimated to be at 65%. This estimate is lumped over all farms and held constant over time. During the calibration process, the initial on-farm efficiency can be refined as an estimated parameter, subject to sufficient observations.

The final on-farm efficiency printed to the 'Farm Demand and Supply' file is a composite efficiency of all model cells in a farm. For each farm, this composite efficiency was printed together with the farm demand and supply budget for each iteration, each time step, or selected time steps either to the list file, to an ASCII file called FDS.OUT. The composite efficiency is an area weighted average of either the simulated head-dependent efficiencies (IEBFL=3) of all model cells in a farm, weighted by the area of each cell. IEBFL=3, the initial efficiency of 65% is only used to determine the initially needed total delivery to a model cell. However over the iterative course of solution, the total delivery is considered constant, which means that a head-dependent change in the crop irrigation requirement can lead to a change in simulated efficiency. For instance, if slightly rising water levels lead to phreatophytic uptake of pecan orchards then the FMP dynamically will simulate a reduced irrigation requirement and, hence, the efficiency will increase.

Another reason why efficiency may change is the selection of the deficit irrigation scenario (IDEFFL=-1). If the calculated total delivery requirement is greater than the delivery that can be made available to the cell, then the FMP assumes that the farmer will operate more efficiently by minimizing inefficient losses. That is, the efficiency during deficiency situations is the ratio between the available delivery and the crop irrigation requirement. The crop will go into deficiency, when the available delivery is less than the

original crop irrigation requirement. The FMP assures in this situation a reduction in actual crop evapotranspiration and evapotranspiration from groundwater.

The distribution of farms and farm wells are shown in Figure 3. Maximum well pumping capacities of each farm well are data entered as FMP data input.
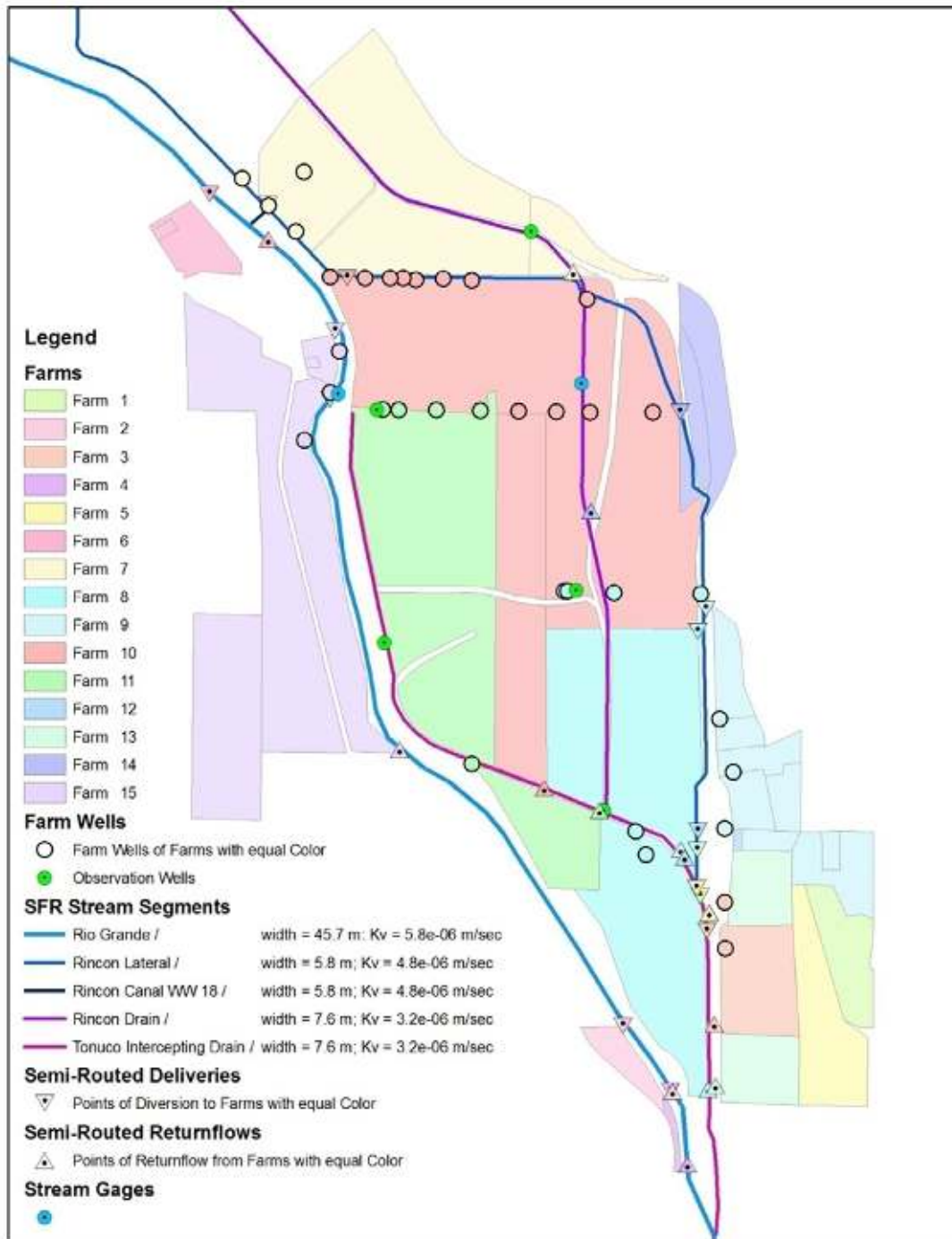


Figure 3. Map showing distribution of farms and farm wells, streamflow routing network with points of diversion to farms and points of returnflow from farms, and observation wells and observation stream gages.
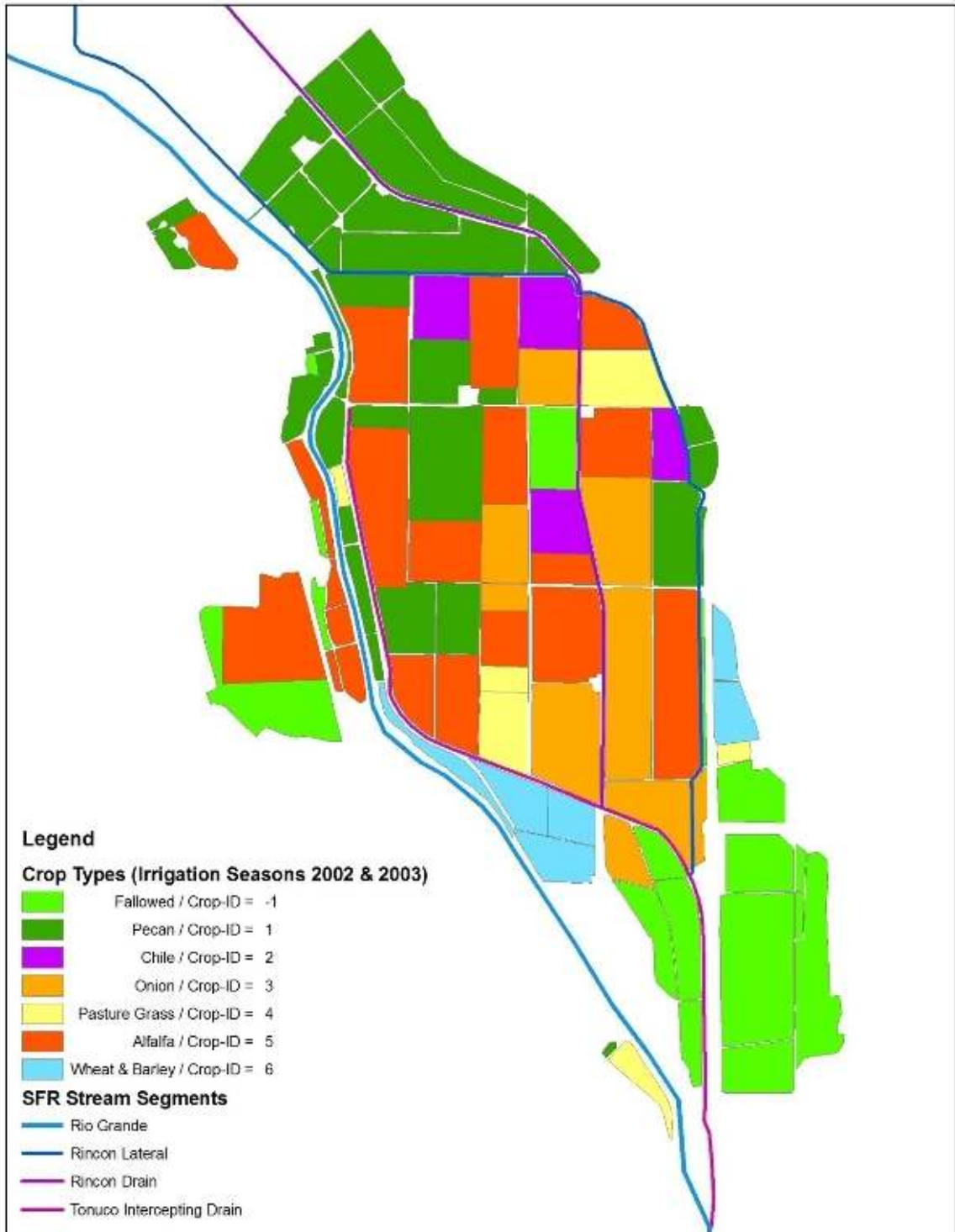
Figure 4. Map showing distribution of crop types.

*Distribution of Crop Types and Crop-Type Related Attributes in FMP*

The Rincon model includes six crop types assessed for the years 2002 and 2003 (Figure 4). While MF2K5-FMP2 also allows keeping the crop distribution constant over the course of the simulation, in the present study the crop distribution was allowed to change from non-irrigation to irrigation seasons. The crop distribution was allowed to rotate only with respect to one distribution for irrigated crops for the two irrigation seasons from March to October of 2002 and 2003 (stress periods 2, 3, 4, and 6, 7, 8) and another distribution for pecans orchards and fallowed fields for three off-seasons from November to February 2001/2002, 2002/2003, and 2003/2004 (stress periods 1, 5, and 9). The consumptive uses of chile, onions, pasture grass, and wheat & barley were assumed to be similar and were given the same consumptive use data input flux values. Only Pecans and Alfalfa were given individual consumptive use flux values (Figure 5).
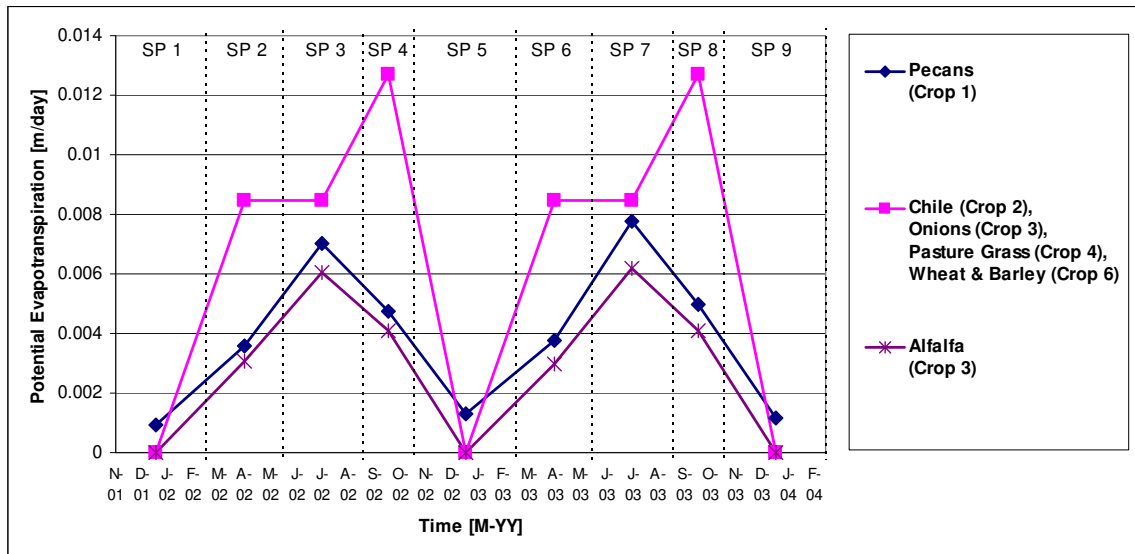


Figure 5. Time series of consumptive use as potential evapotranspiration of crop types.

For this simple application of the Rincon Model, crop consumptive use fluxes (= potential crop evapotranspiration) were read in the FMP data input file. However, in the FMP, also crop coefficients for individual crops types or for virtual crop types (crop groups) can be utilized jointly with reference evapotranspiration fluxes. The individual values for initial-, mid-, and end-season crop coefficients as well as the durations for initial, development, mid, and late growth stages are available through various sources of

17

literature (e.g., Food and Agriculture Organization of the United Nations irrigation and drainage page 56 in Allen et al. 1998). For each crop type or crop group, averages over each stress period can be specified in the FMP data input file. Time-varying crop coefficients allow the different vegetation to be active at different times of the year as they each cycle through their seasonal growth stages. The use of crop coefficients for model crop types is one of the new features of FMP2 (Schmid and Hanson 2009).

Crop specific parameters in FMP2 include fractions of transpiration and evaporation of the crop consumptive, which were assumed to be constant for all crops and all stress periods, where crops exist (fraction of transpiration, FTR = 0.9, fraction of evaporation related to precipitation, FEP = 0.1, fraction of evaporation related to irrigation, FEI = 0.05). Noticeably, by assuming fallow conditions for all crop types but Pecans, the potential evaporation of fallow fields is taken to be equal to a reference evapotranspiration that is read for each stress period and, hence, fractions of transpiration and evaporation do not apply (source for reference ET: averages of data from stations Derry and Leasburg). While in the present application FTR, FEP, and FEI were held constant, the FMP allows in general varying these parameters on a stress period basis.

The separate simulation of transpiration and evaporation is an essential difference of MF2K5-FMP2 to many other hydrologic models, which assume a common extinction depth for a joint evapotranspiration term. In FMP, the evaporation from groundwater is extinct at a depth to water level equal to a specified capillary fringe; the transpiration from groundwater is extinct at a depth to water level equal to the root zone plus the capillary fringe.

The fraction of evaporation that is related to exposed areas wetted by precipitation, FEP, depends on the exposed non-vegetative bare soil surface wetted by precipitation. Even though, in reality, transpiration and evaporation may be related non-linearly, we simplify the fraction of evaporation to be equal to the complement of the fraction of transpiration, that is, FEP = 1 – FTR. The fraction of evaporation related to irrigation depends on the fraction of the exposed soil surface that is wetted by irrigation (Allen et al. 2005, or Allen et al. 1998). Unlike soil surface wetted by precipitation, the exposed areas wetted by irrigation may not be entirely wetted. The extent to which the

exposed area is wetted depends on the irrigation method used, which, in reality, often follows a particular crop type. For the present application we assumed the virtual crop types 1 through 3 in the example model, we assume the fraction of evaporation related to irrigation to be constrained by a 50% wetting of the open and exposed area. Fractions of transpiration and evaporation are FMP parameters (Schmid et al. 2006) that bear a high uncertainty and MF2005-FMP2 models are quite sensitive to these parameters (Schmid et al. 2008). While the assumption of FTR=0.9, FEP=0.1, and FEI=0.05 are certainly just rough estimates of these fraction, improved parameters may potentially be gained during the model calibration and parameter estimation process (see respective section).

Native vegetation, for example, riparian vegetation, was assumed not to factor considerably in the hydrologic balance compared to the highly consumptive irrigated farms and was not simulated. However, in the FMP in general, such vegetation could be simulated as non-irrigated 'crop' in a virtual farm equal to the native vegetation area.

The depth of the root zone, another crop specific data input in FMP, was kept constant for all crop types except for alfalfa, for which it was allowed to vary over each irrigation year. Therefore root depth was specified for all crop types for every stress period (IRTFL=2) (Figure 6).
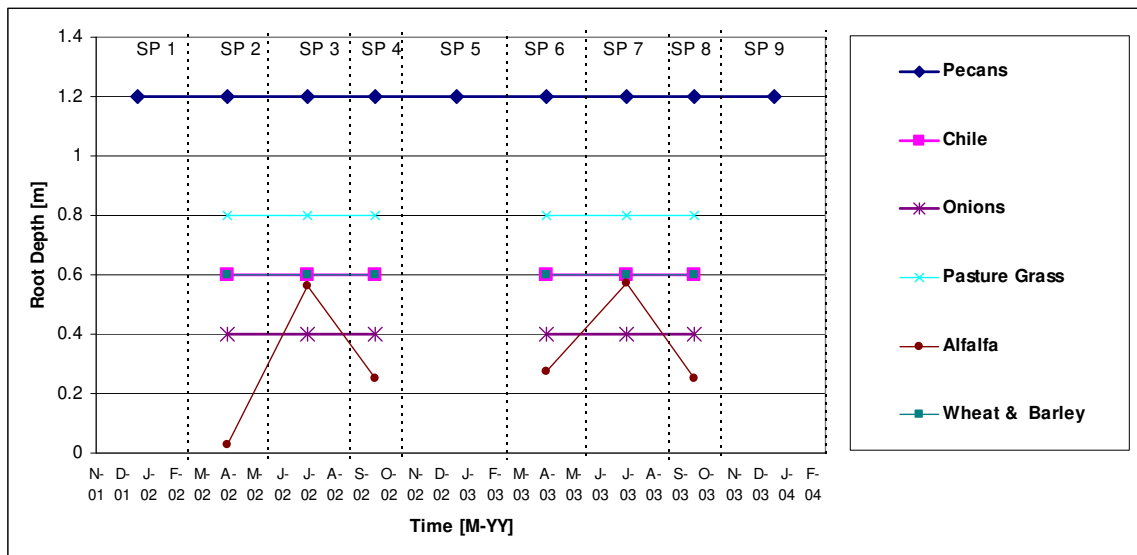


Figure 6. Time series of root depths of crop types.

In general, fractions of inefficient losses to surface-water runoff can be specified for each virtual crop type for the each stress period. For the present simple application, we chose to relate this fraction to the surface-slope calculated internally by the FMP from the ground-surface elevation (IIESW=0) and, hence, no data input was required. In the southern Rincon Valley, basin-level irrigation dominates and losses to surface-water runoff are not likely.

Crop consumptive use, root zone depths, fractions of transpiration and evaporation, and fractions or inefficient losses to surface-water runoff are all crop specific parameters that can vary from stress period to stress period. Contrary to that, pressure heads that define stress-response function coefficients are the only one crop related set of parameters that is specified for the entire simulation. Noticeably, in FMP2 a stress response function can be defined under both unsaturated and saturated conditions for either negative or positive pressure heads, at which uptake is either zero or at maximum. In the Rincon model, the same stress response function was defined by four pressure heads for all six crop types. None of the crops was allowed to be able to take up water under saturated conditions. Notice that, in reality, the response of the root uptake to stress cause by anoxia and wilting would be quite different, for instance, for pecans and wheat.

*Distribution of Soil Types and Soil-Type Related Attributes in FMP*

For the Rincon model, Map Unit soil types of the Soil Survey Geographic Database (SSURGO) for Doña Ana County (SSURGO, 2002/2003) were provided as GIS shape file by the EBID and generalized to three representative soil-types available in the FMP (SANDY LOAM, SILTY CLAY and SILT) (Figure 7). These three soil types have code-intrinsic coefficients built into the FMP-code, which define a soil-type specific analytical solution of the reduction of transpiration by anoxia or wilting. The original soil types Sandy Loam and Loamy Sand were assigned as SANDY LOAM; the Silty Clay, Clay and Clay Loam were assigned as SILTY CLAY; and Silty Loam and Loam were assigned as SILT. Capillary fringes were specified for Sandy Loam with 1.3 meters, for Silty Clay with 1.5 meters, and for Silt with 1.8 meters.
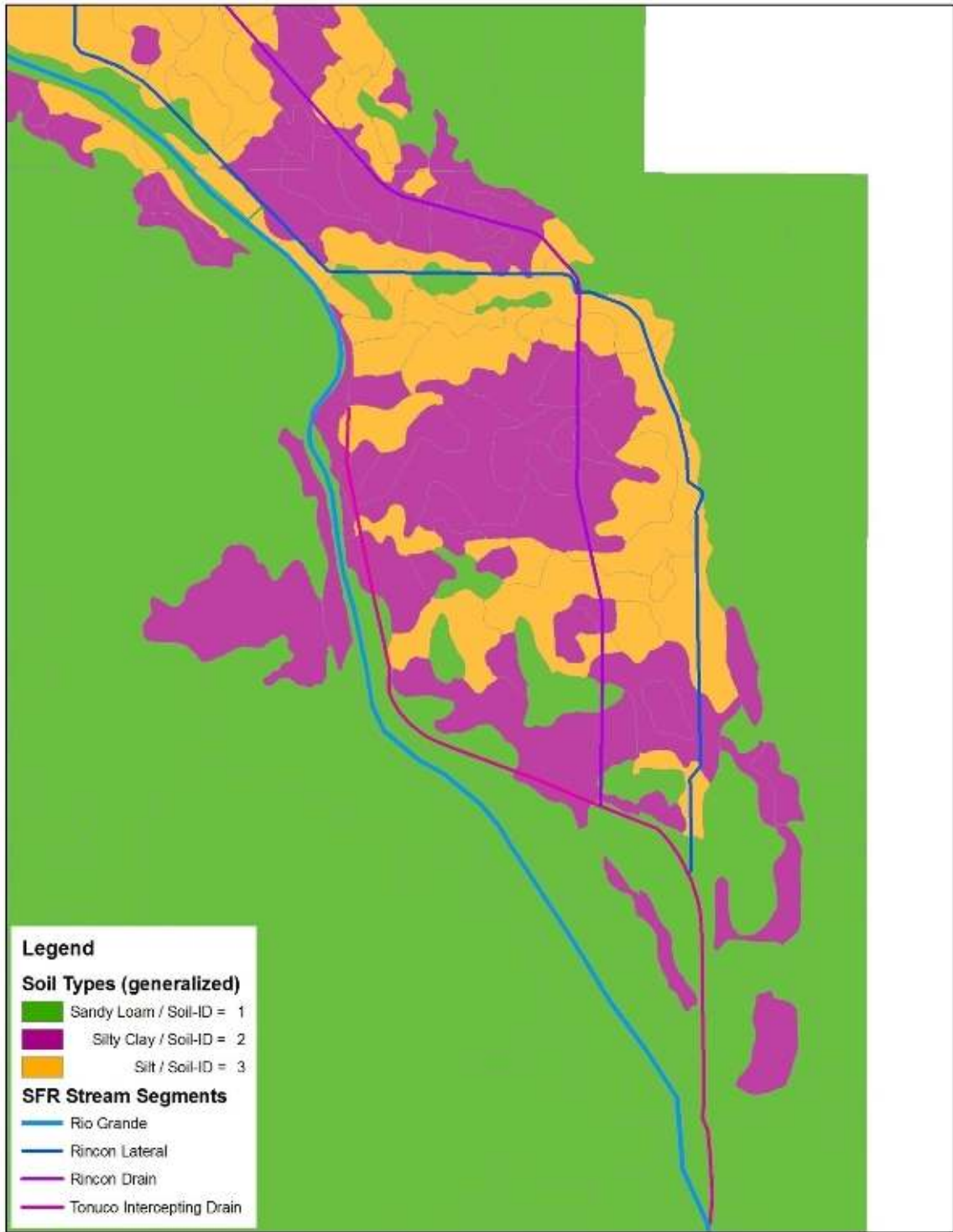
Figure 7.  Map showing distribution of soil types.

## Ground-Surface Elevation

The ground-surface elevation (GSE) enters the model both in the Discretization Package data input file for the top of layer one as well as in the Farm Process data input file as a reference for root depths and transpiration and evaporation extinction depths. The during the telescopic mesh refinement, the GSE from the regional Rincon model was interpolated and distributed over the refined grid of the local Rincon model. In the farm area (corner points: row 4 / column 10, row 4 / column 86, row 127 / column 10, row 127 / column 86), the average deviation from 10 meter Digital Elevation Model data was only -0.22 meters. However, the average of the absolute deviation was 14.15 meters. At the location of an EBID observation well (row 65, column 57), the difference was 24.3 meters. Consequently, the GSE used for the 'one-farm' local Rincon Model was discarded and replaced with surface spot elevation data of the 10-meter DEM projected to each model cell.

## Surface-Water Routing

GIS shape files acquired from the EBID provide the locations of the Rio Grande, the Rincon Drain, the Tonuco Intercepting Drain, and the Rincon lateral. The streamflow network and its hydraulic properties are depicted in Figure 3.

The surface-water diversions from the Rincon Lateral and occasionally directly out of the Rio Grande to irrigated farms were simulated as so-called 'semi-routed' or 'fully-routed deliveries' (SRDs or RDs). In FMP, the simulation of SRDs is defined as the simulation of routed streamflow by the linked SFR2 Package through an open-channel conveyance network to a user-specified point of diversion that is remote from the receiving farm. From this 'remote head gate,' water is then diverted to the farm in non-routed form, that is, no streamflow routing is simulated. The simulation of RDs is defined as simulation of routed streamflow by the linked SFR2 Package through an open-channel conveyance network directly to an automatically detected point of diversion from the uppermost reach of a series of reaches of a stream segment located within a farm. SRDs or RDs may be limited by the available streamflow or by legal constraints such as equal

appropriation allotment heights. In the Rincon model, the following equal allotment heights are specified for each stress period (Table 3):

Table 3.  Equal appropriation allotment heights for each stress period

| Stress Period | Allotment (m) |
|---|---|
| 1 | 0.0 |
| 2 | 0.4 |
| 3 | 0.4 |
| 4 | 0.1 |
| 5 | 0.0 |
| 6 | 0.4 |
| 7 | 0.4 |
| 8 | 0.1 |
| 9 | 0.0 |

Even though these allotment height values are semi-hypothetic, they are within the scope of values used by the EBID. In response to the drought of 2003, the EBID lowered the allotment height to 4 inches, which coincides with 0.1 meters used for the late-season stress periods 4 and 8 (EBID 2003).

In MF2K-FMP2, usually diversion rates are specified for a diversion from a main stem river into canal segments ('river-to-canal' diversions). However, in the present model, the main diversion of the Rincon lateral occurs north of the northern model boundary. Therefore, Tillery and King (2006) assumed flow rates of the Rincon lateral where it enters the model domain to be inflows into a virtual 3-reach segment at the northern boundary and allowed all streamflow to be diverted from this segment into a downstream segment, which represents the Rincon lateral (segment 6). This way the Rincon lateral is technically still considered a 'diversion segment,' from which fully routed deliveries may occur.

Where locations of head gate were assumed to be known they are specified as locations of points of diversion for semi-routed deliveries. Where no head-gate locations are specified, the FMP automatically assumes the head gate to be the most upstream reach of a canal segment passing through farm cells (in this case segment 6 for the Rincon Lateral). This was demonstrated for farms 7, 10, and 14 (Table 4).

Table 4. Location coordinates of diversion points specified and automatically found

| Semi-routed delivery locations specified | | | Semi-routed delivery locations found by FMP | | | | Comments |
|---|---|---|---|---|---|---|---|
| Farm | Row | Column | Row | Column | Segment | Reach | |
| 1 | 103 | 55 | 103 | 55 | 7 | 3 | found as specified |
| 2 | 113 | 40 | 113 | 40 | 1 | 174 | found as specified |
| 3 | 107 | 54 | 107 | 54 | 7 | 8 | found as specified |
| 4 | 122 | 42 | 122 | 42 | 1 | 185 | found as specified |
| 5 | 102 | 55 | 102 | 55 | 7 | 2 | found as specified |
| 6 | 8 | 36 | 8 | 36 | 1 | 35 | found as specified |
| 7 | 0 | 0 | 10 | 42 | 6 | 31 | head gate automatically found |
| 8 | 75 | 68 | 75 | 68 | 6 | 144 | found as specified |
| 9 | 73 | 70 | 73 | 70 | 6 | 140 | found as specified |
| 10 | 0 | 0 | 21 | 47 | 6 | 48 | head gate automatically found |
| 11 | 33 | 39 | 33 | 39 | 1 | 71 | found as specified |
| 12 | 96 | 58 | 96 | 58 | 6 | 175 | found as specified |
| 13 | 98 | 57 | 98 | 57 | 6 | 178 | found as specified |
| 14 | 0 | 0 | 51 | 77 | 6 | 109 | head gate automatically found |
| 15 | 26 | 43 | 26 | 43 | 1 | 60 | found as specified |

Similarly, where locations along the tributary drain segments are known to receive returnflows, they are specified. Where no returnflow location is known, zeros are specified for the row and column of the diversion point. In this case, the FMP automatically assumes the returnflow to be prorated over reaches of tributary drain segments passing through a farm (none found in this case). Where neither a returnflow location is known, nor a tributary drain segment passes through a farm, the FMP assumes that any reach of the tributary drain segments (segments 3, 4, 5, 7 for the Rincon Drain and Tonuco Intercepting Drain) that is nearest to the lowest elevation of farm will receive the returnflow (Table 5).

Table 5.  Location coordinates of returnflow points specified and automatically found

| Semi-routed returnflow locations specified | | | Semi-routed returnflow locations found by FMP | | | | Comments |
|---|---|---|---|---|---|---|---|
| Farm | Row | Column | Row | Column | Segment | Reach | |
| 1 | 0 | 0 | 105 | 55 | 7 | 5 | nearest location automatically found |
| 2 | 122 | 42 | 122 | 42 | 1 | 185 | found as specified |
| 3 | 0 | 0 | 117 | 50 | 7 | 22 | nearest location automatically found |
| 4 | 126 | 40 | 126 | 40 | 1 | 191 | found as specified |
| 5 | 0 | 0 | 105 | 55 | 7 | 5 | nearest location automatically found |
| 6 | 13 | 40 | 13 | 40 | 1 | 44 | found as specified |
| 7 | 31 | 72 | 31 | 72 | 3 | 63 | found as specified |
| 8 | 123 | 46 | 123 | 46 | 7 | 32 | found as specified |
| 9 | 0 | 0 | 97 | 55 | 5 | 14 | nearest location automatically found |
| 10 | 84 | 43 | 84 | 43 | 4 | 72 | found as specified |
| 11 | 89 | 48 | 89 | 48 | 4 | 82 | found as specified |
| 12 | 0 | 0 | 98 | 55 | 5 | 15 | nearest location automatically found |
| 13 | 0 | 0 | 123 | 47 | 7 | 31 | nearest location automatically found |
| 14 | 0 | 0 | 57 | 62 | 3 | 102 | nearest location automatically found |
| 15 | 73 | 29 | 73 | 29 | 1 | 123 | found as specified |

Adjustments were made to the data input file from the 'one-farm' local Rincon model. The location and length of reaches were projected from GIS shape file data of a stream-canal-drain network intersected with the model grid. To assure the required upstream-downstream sequence within each segment, reaches were sorted first by segment, then by row, then by latitude, because all streams in the model run north-south.

New streambed elevations were derived from the upstream and downstream ends of each stream segment from the 10-meter DEM data. The top of streambeds are assumed

to run at a certain depth below the 10-meter DEM surface elevation of the valley floor: Rio Grande (2 to 3 m), drains (3 m), lateral (0.5 m).

## Model Calibration and Parameter Estimation

Calibration was automated using the non-linear regression parameter estimation code UCODE (Poeter et al. 2005). Model parameters allowed to vary during model calibration were the hydraulic conductivity of layer one (Hyd_ly1), the streambed hydraulic conductivity of the Rio Grande (sfr1) and the Rincon Lateral (sfr6), the lumped on-farm efficiency (fmp_eff), and the fraction of transpiration (fmp_ftr). Fractions of evaporation related to precipitation and irrigation are expected to be correlated with the fraction of transpiration and, therefore, were expressed as derived parameters linearly correlated with FTR. In reality, the fraction of evaporation related to irrigation may be correlated non-linearly. For instance, for cases where the wetting does not extend to the entire open and exposed area, the evaporation under irrigation conditions may be further reduced than the evaporation under precipitation conditions. In the present local Rincon Model, the irrigation method is basin level irrigation which, for pecan orchards, will wet the entire exposed area. However, other crop types like onions or chiles are cropped as row crops and the exposed area is expected to be wetted only partially.

In addition to more traditional model calibration to water level and streamflow observations, the Farm Process allows the calibration of simulated versus observed cumulative farm-irrigation pumpage. Observation data were obtained from the EBID (EBID 2008) in form of recorded water levels of one monitoring well, streamflow for two gages, and cumulative irrigation-well pumpage for one farm. Additional water level observations could be acquired from the USGS for six USGS observation wells on three sampling dates (USGS 2008). The EBID monitoring well 'Rincon#6' is located in Kit Carson farms (model farm 10) at latitude 32.60311, longitude 107.00497. The stream gages are the 'Haynor Bridge' gage at the Rio Grande at latitude 32.61343 and longitude 107.01996 and a gage located at the Rincon Drain at latitude 32.61408 and longitude 107.00473. The cumulative pumpage was recorded for the Thurston farm (model farm

15). One objective of the relatively simple local Rincon Model is to demonstrate the abilities of a combined use of MF-FMP and UCODE for future, more complex use in the same or wider EBID area. Locations of all observation wells and the two stream gages can be found in Figure 3. The influence of the 'cumulative pumpage of farm 15' may be greatest for this parameter-sensitive group of observations due to the spatial isolation of farm 15 (Hunt et al. 2006). However, the influence of two observations of 'cumulative pumpage of farm 15' (for years 2002 and 2003) was considered desirable to the extent that the observations are reliable (Yager 1998), which was assumed here.

UCODE adjusts the squared model residual by a weight resulting in dimensionless residuals. The weighting scheme tried to bring weighted residuals of very different observation value ranges (cumulative pumpage of farm 15: order of $1E^{+4}$, water levels: order of $1E^{+3}$, river stream flows: order of $1E^{+0}$ to $1E^{+1}$, lateral stream flows: order of $1E^{-2}$) into a similar order of magnitude. Questionable observations measured during the beginning of the model period were penalized and important observations that deviate considerably from the simulated value were awarded. The initial UCODE run without parameter adjustment revealed relatively large initial residuals for early water levels of the hydrograph of the EBID observation well. Initial water levels for November 2001 were derived from the coarse-resolution regional Rincon Model and may not be accurate. Therefore, water levels and streamflows during the first stress periods were given very low weights.

The first UCODE run using parameter adjustment converged, but several parameters were highly correlated. Parameter pairs fmp_eff /fmp_ftr and sfr1/Hyd_ly1 showed correlation coefficients of 1.00 and 0.86, respectively. Correlations greater than 0.95 could indicate that there may not have been enough information in the observations used in the regression to estimate parameter values individually. In the presented Rincon Model, the scarce number of observations (47) is most likely insufficient for a multivariate parameter estimation. However the same model or other models in the region could potentially be calibrated through parameter estimation that includes both parameters of on-farm efficiency and fraction of transpiration without a significant correlation.

The estimation of parameters of efficiency and fraction of transpiration still lumped over all farms or crop types, respectively, but distributed over all stress periods also resulted in numerous high correlations between these time-variable parameters. This result is expected considering that these parameters might be similar for each same period of both years or that parameters of preceding periods might dominate antecedent conditions for following periods.

Another unsuccessful attempt was made to estimate efficiencies and fractions of transpiration differentiated for each year by selected farms and by groups of crops, respectively. As before, lack of observation data may cause parameters to be correlated. Even though these calibration attempts were not successful in the current case, other models with a better basis of observation data may allow the initiation of an MF-FMP model with a simple time-space lumped parameter value, which then can be differentiated into estimates varying over time or associated farms or crop types during the calibration and parameter estimation process.

To eliminate parameter correlations for the local Rincon Model, the number of estimated parameters was reduced. Parameter sfr1 was not used and parameters fmp_eff and fmp_ftr were estimated separately in individual parameter estimation runs. However, these separate runs were able to differentiate the parameters fmp_eff and fmp_ftr originally lumped over the entire simulation into estimated values for fmp_eff1, fmp_eff2, and fmp_ftr1, fmp_ftr2 for each irrigation season of years 2002 and 2003. Off-season values were not estimated. These UCODE runs were successful and yielded very similar correlation coefficients or sums of weighted residuals tallied by observation groups (Table 6):

Table 6.  Goodness of fit of simulated versus measured observations

|  | sum of weighted residuals [dimensionless] | | correlation coefficient | |
| --- | --- | --- | --- | --- |
|  | run using efficiencies | run using fractions of transpiration | run using efficiencies | run using fractions of transpiration |
| water levels | 1718.40 | 1717.57 | 0.728 | 0.727 |
| cumulative pumpage | 0.0196 | 0.0370 | 1.000 | 1.000 |
| Streamflows | 2160.51 | 2160.49 | 0.959 | 0.959 |
| All observations | 3878.93 | 3878.10 | 1.000 | 1.000 |

Noticeably, the correlation coefficients are not very informative as the magnitude of the cumulative pumpage estimates dominates the regression. More telling are the sums of weighted residuals, which indicate that the UCODE run using efficiencies was slightly better with respect to the cumulative pumpage of farm 15, which is considered the most important observation.

The sensitivity analysis (Figure 8) shows that the UCODE-run using efficiencies depict a higher composite sensitivity than the run using fractions of transpiration. When using equal fractional perturbation amounts of these two parameters, obviously adjusting the on-farm efficiency parameter leads to a better calibration of the cumulative pumpage of farm 15. This observation is of significant importance as either one of the two parameters is difficult to obtain or to estimate in the real world. To avoid parameter correlations, the sensitivity of each parameter was checked in separate runs under the assumption that other parameter not used for parameter estimation is parameterized well as model input. In the case of the relatively simple Rincon Model, the on-farm efficiency was adjusted and the fraction of transpiration was pre-estimated at a value of 0.9. Algorithms that use crop coefficients, basal crop coefficients, and fractions of soil surface wetted by irrigation (Allen et al. 1998; Allen et al. 2005) to reach better estimates of the fraction of transpiration, the fraction of evaporation related to precipitation, and the fraction of evaporation related to irrigation can be obtained from the author on request.
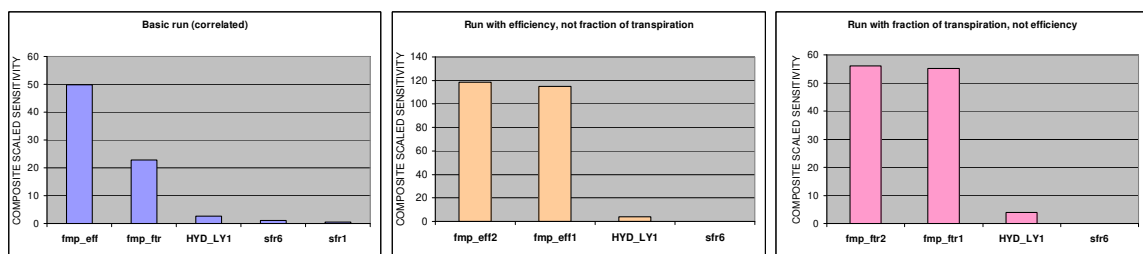


Figure 8.  Composite scaled sensitivities of three UCODE runs.

The calibration results of the two successful UCODE runs (Table 7) shows that only a very small change in the efficiency parameters (-0.22% and 0.31%) or fractions of transpiration (0.46% and -0.69%) lead to the respective optimal solution. Other parameters, which cause very little to no sensitivity (streambed conductivity of Rincon Lateral, hydraulic conductivity of layer one) experienced virtually the same big changes.

While these estimates of hydraulic conductivities are technically possible, as shown, they do depend on jointly estimated parameter causing high sensitivity, which constrain the parameter estimation.

Table 7. Parameter estimation results

| | Run using efficiencies | | | | Run using fractions of transpiration | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | sfr6 | HYD_LY1 | fmp_eff1 | fmp_eff2 | sfr6 | HYD_LY1 | fmp_ftr1 | fmp_ftr2 |
| Initial values | 4.76E-06 | 7.00E-05 | 0.650 | 0.650 | 4.76E-06 | 7.00E-05 | 0.900 | 0.900 |
| Final values | 1.00E-07 | 6.04E-04 | 0.649 | 0.652 | 1.00E-07 | 6.08E-04 | 0.904 | 0.894 |
| Change | -4656.00% | 88.42% | -0.22% | 0.31% | -4656.00% | 88.48% | 0.46% | -0.69% |
| Change (log) | 23.96% | -29.08% | 0.50% | -0.72% | 23.96% | -29.18% | -4.62% | 6.16% |

Henceforth, the results of the 'UCODE run using efficiencies' were used for the calibrated local Rincon Model. Further discussions of the model calibration below and the discussion of the results of the calibrated Rincon Model described in the next section rest on 'UCODE run using efficiencies.'

The best correlation between simulated data and measured observations (Figure 9) was achieved for the cumulative pumpage of farm 15, which was allowed to be an observation most influential on the model calibration.

Other observation parameters revealed an improvement from the correlation of initial simulated versus measured values to the correlation of final simulated versus measured values. This result is driven by the objective to calibrate the local Rincon Model for simulated pumpage as the parameter of interest. The lowest correlation coefficients were achieved for groundwater levels and Rincon Drain streamflow. However, these correlations are influenced by outliers of simulated values of water levels or streamflow (oval circles in Figure 9), which were found not reliable during the first few time steps of the simulation. These outliers were given lower weights compared to other observations in the respective group and had little effect on the parameter estimation.
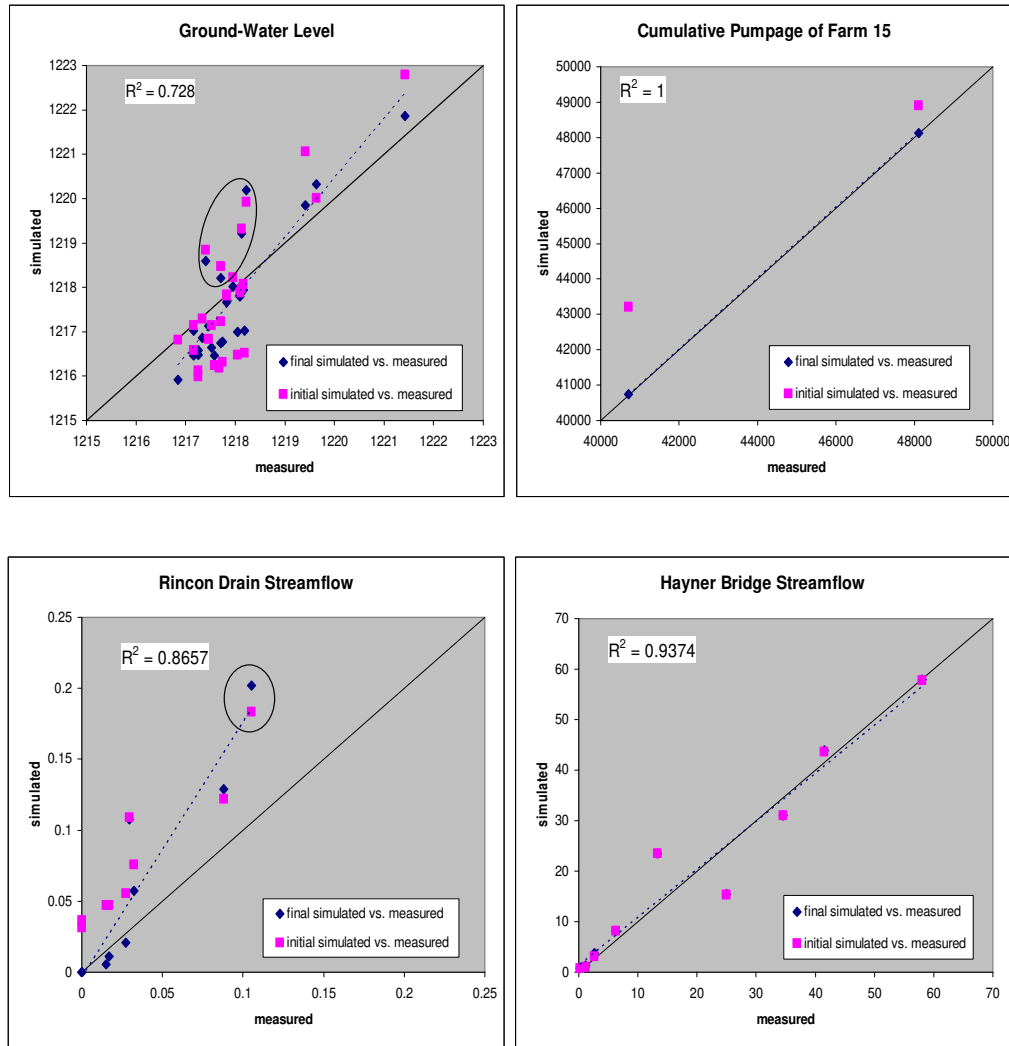
Figure 9. Correlation between simulated and measured observations (oval circles: outliers during first few time steps)

Time series of measured versus simulated groundwater levels and streamflows are demonstrated for the EBID observation well 'rincon#6' (Figure 10), for a Rincon Drain gage (Figure 11), and for the Rio Grande at Haynor Bridge (Figure 12). Aside from early-time outliers, all simulated groundwater levels stay approximately within a meter from the measured values. Similarly, aside from the averaged simulated Rincon Drain streamflow for stress period one, the average simulated streamflow approaches the average measured values well. The good fit between measured and simulated Rio Grande streamflows at Haynor Bridge is not surprising, as the specified inflow into the Rio Grande (SFR segment 1) is based on historic records. However, the good fit does indicate

that specified stream inflow at the northern model boundary was defined well and that and simulated stream gains or losses were simulated accurately between the northern model boundary and the downstream gage at Haynor Bridge. However, in addition to streamflow observations, a direct calibration for stream losses or gains could improve the model calibration, which then would require the monitoring of a second Rio Grande stream gage. The same holds true for the Rincon Drain.
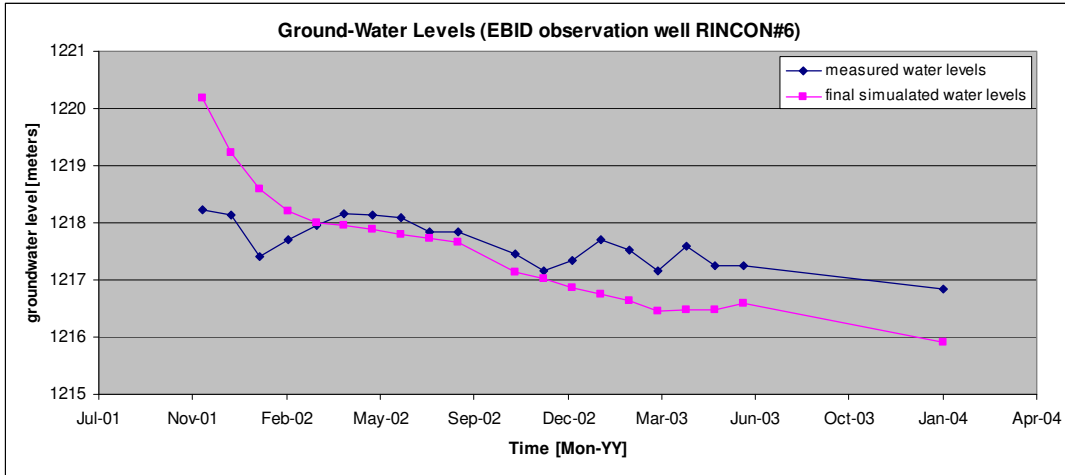


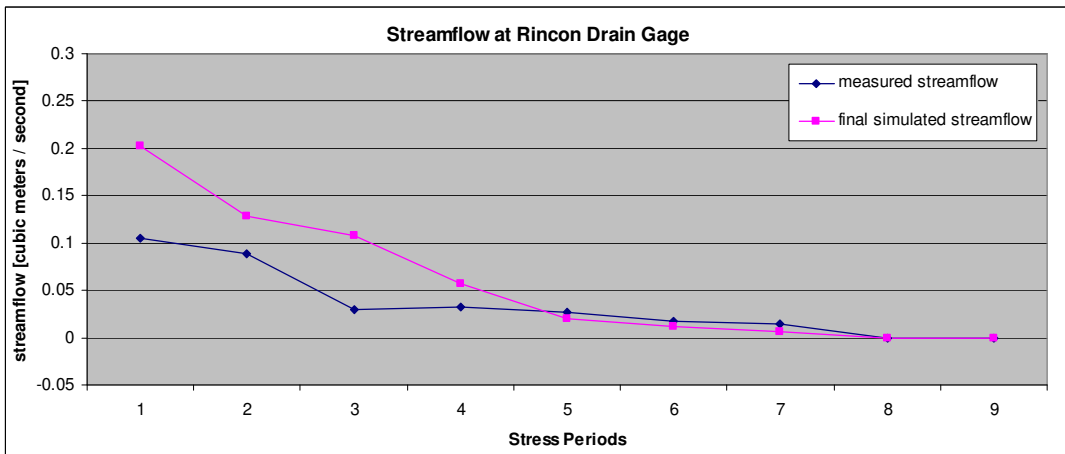Figure 10. Time series of measured versus simulated water levels in EBID obs. well.



Figure 11. Average measured versus simulated streamflow at Rincon Drain gage.
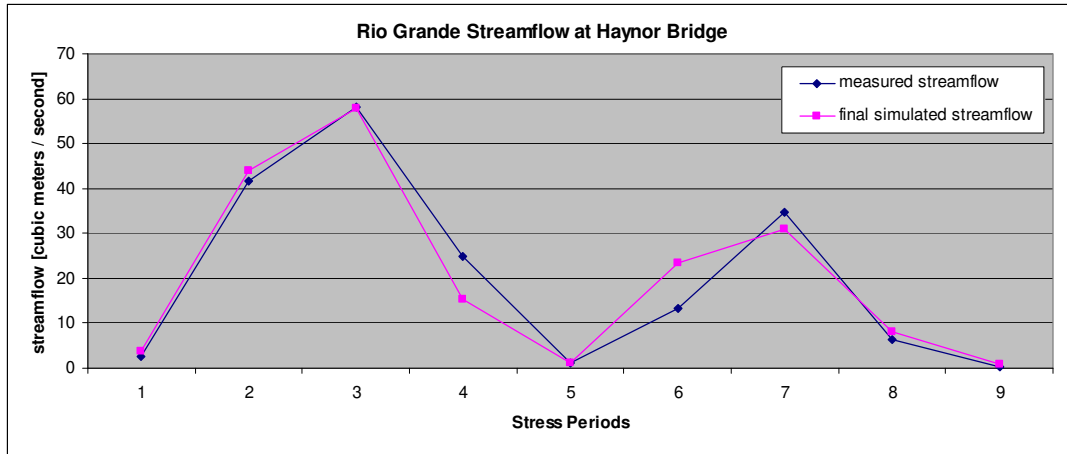
**Rio Grande Streamflow at Haynor Bridge**

Figure 12. Average measured versus simulated streamflow at Haynor Bridge gage.

A model calibration with increased weights for large water level or streamflow residuals or without the use of cumulative pumpage as an observation could yield a much better correlation of simulated versus measured water levels and streamflows but then lack prediction accuracy when estimating cumulative pumpage.

## Model Results and Scenarios

As stated in the Introduction and Objectives section of this report, the calibrated local Rincon Model can be used to help the Elephant Butte Irrigation District answer the following questions pertinent to its conjunctive use management:

1. What was the historic groundwater pumping for farm irrigation related to family farms as simulated in the Rincon Model or larger water accounting units?

2. How does the consumptive-use-driven surface-water and groundwater abstraction impact the Rio Grande streamflow and its return flows?

3. How do future scenarios of allotment changes influence the conjunctive surface-water / groundwater supply and the Rio Grande stream gains or losses?

The next section describes how Question 1 can be answered by the standard MF-FMP data output, such as the 'Farm Demand and Supply Budget' or the 'Farm Budget' of

physical farm in- and outflow. Both budgets contain the simulated historic pumpage. Question 2 can be described by building a correlation between streamflows calculated by MF-FMP and the Hydrograph Time Series Package, HYDMOD (Hanson and Leake, 1998), and by cumulative farm irrigation pumpage yielded by the MF-FMP's 'Farm Demand and Supply' data output. Question 3 will be discussed in a separate section called 'Results of Rincon Model Scenarios.'

## Results of Current Calibrated Rincon Model

The simulated historic pumpage is only one of several components of a budget of Farm Demand and Supply components that the Farm Process writes to an ASCII file called FDS.OUT (if ISDPFL=1). In the Rincon Model, the 'deficit irrigation' scenario was assumed (IDEFFL=-1), where the initial supply and demand rates reflect the initial assessment of resources and irrigation demands at the beginning of each time step and where the final components show how the irrigation demand was reduced to fit the available supply. For the deficit irrigation scenario, this reduction is achieved in the model by first improving the on-farm efficiency, if necessary to 100%, and second by reducing the crop consumptive use such that the transpiration and evaporation from irrigation cannot exceed the supplied irrigation. Notably, by running the deficiency scenario, the user can simulate the reduced actual evapotranspiration of crops that follows droughts. This, in turn allows the model to simulate reduced crop yields. Farms that are not associated with farm wells are lacking groundwater as irrigation source and, hence, are deficit irrigating with the surface-water resource that is constrained by limited streamflow and equal appropriation allotments.

Examples for farms that 'own' farm wells to supplement the surface-water deliveries that are limited by equal appropriation allotments (specified for as allotment height, ALLOT, for each stress period, multiplied by the cropped farm area, and divided by the duration of a time step) are farms 7, 8, 9, 10, 11, and 15 (e.g., farm 7: Figure 13).
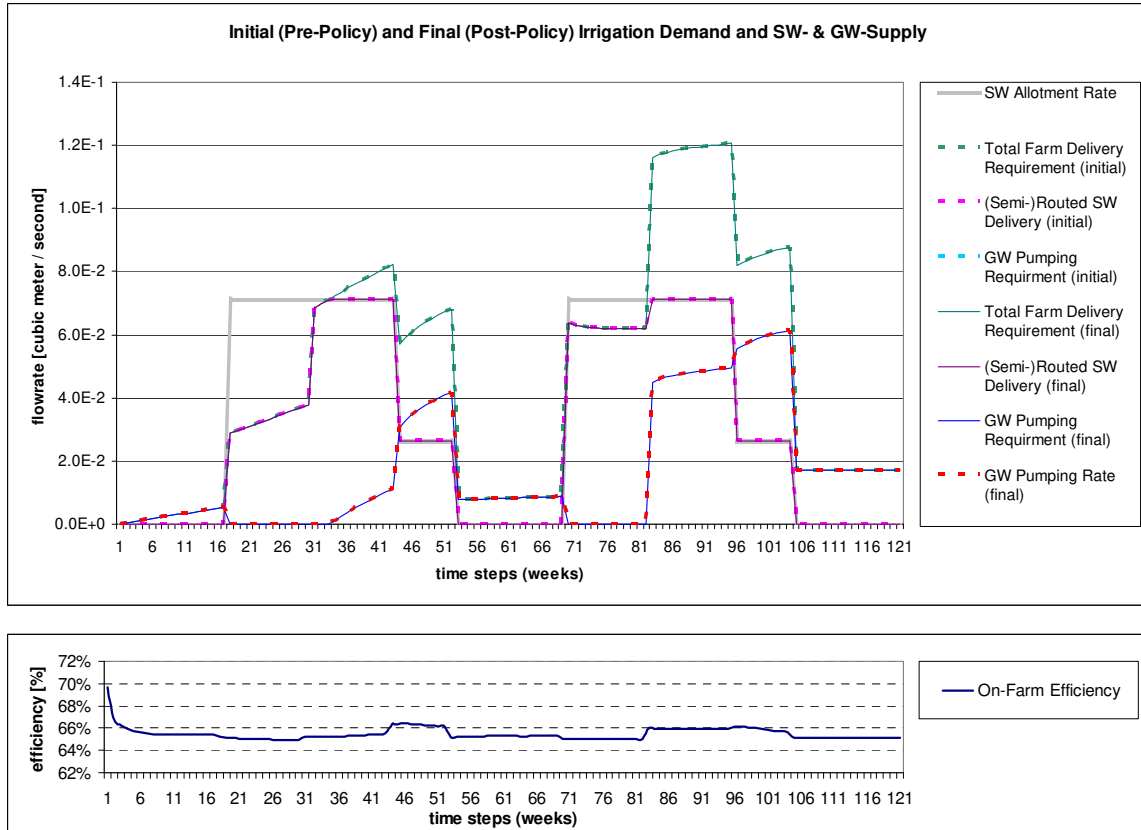
Figure 13. Farm Demand and Supply components and simulated on-farm efficiency for Farm 7 (GW = groundwater; SW = surface water).

The cumulative maximum well pumping capacities of these farms are all high enough in order not to pose any constraints on supplemental pumping. These farms may have experienced a 'surface-water insufficiency' especially during the drought year of 2003, but were simulated as being 'groundwater sufficient.' Examples for farms that needed to improve their on-farm efficiency above the preset 65% but not to 100% in order to reach sufficiency are farms 6 and 14 (e.g., farm 6,: Figure 14).

Figure 14. Farm Demand and Supply components and simulated on-farm efficiency for Farm 6 assuming a deficit irrigation scenario in response to a deficit situation (GW = groundwater; SW = surface water).

Examples for farms that needed to reach 100% efficiency and yet potentially still experience reductions in consumptive use are farms 2 and 4 (e.g., farm 4: Figure 15).
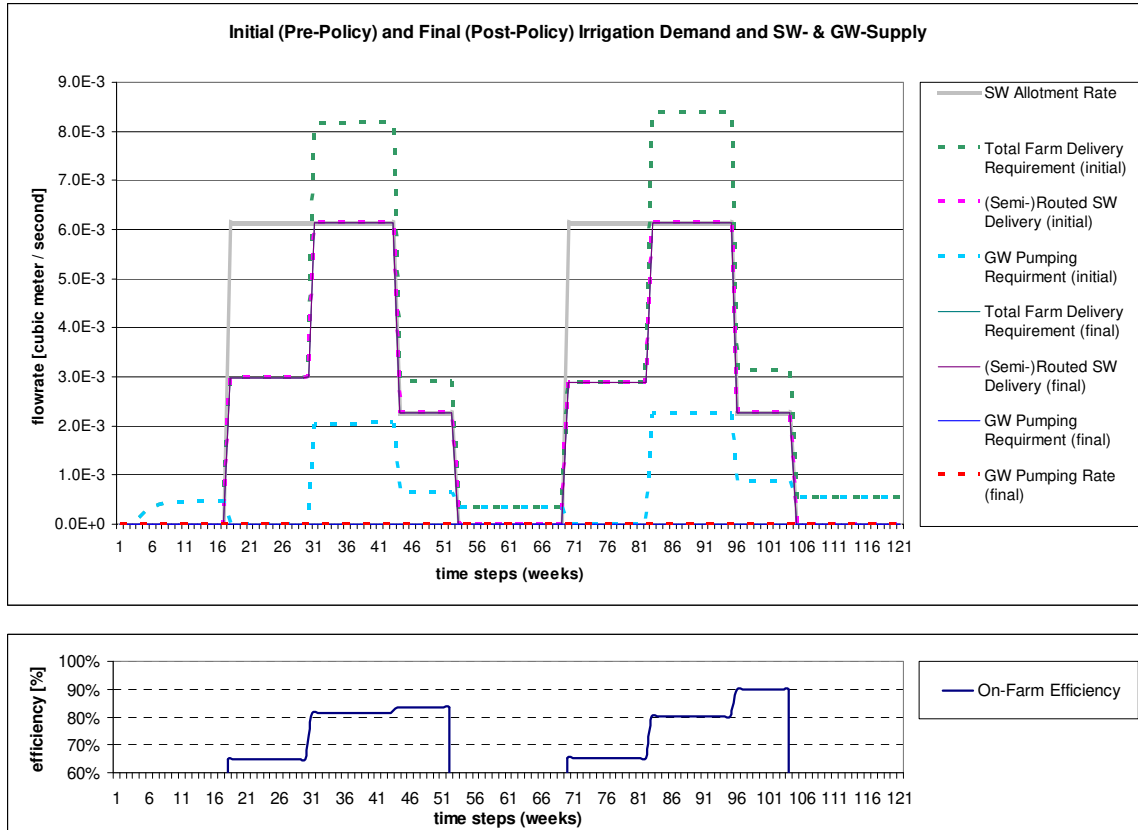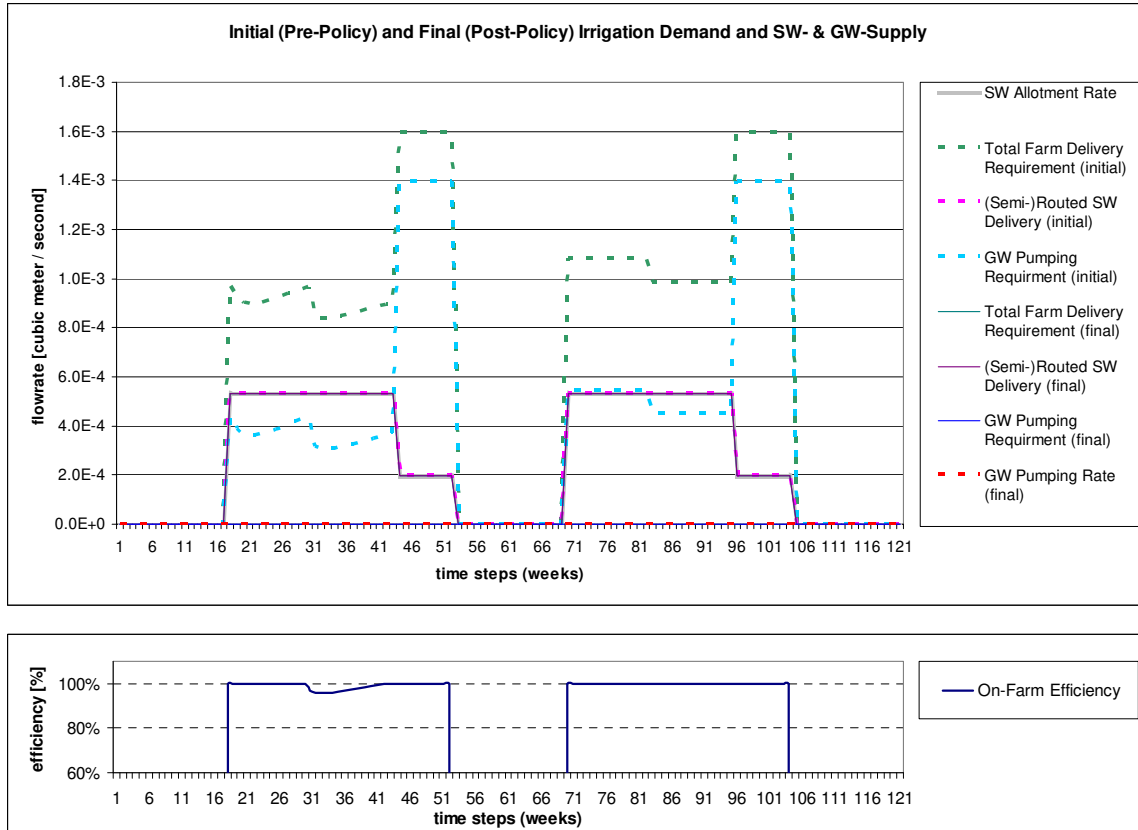
Figure 15. Farm Demand and Supply components and simulated on-farm efficiency for Farm 4 assuming a deficit irrigation scenario in response to a deficit situation.

The hydrologic budget of the landscape can be analyzed for each individual farms by means of the Farm Budget, which is written to an ASCII file FB_DETAILS.OUT (if IFBPFL=2). This detailed farm budget includes all physical flows into and out of a farm. Natural inflow components are precipitation (Q-p-in), evaporation (Q-egw-in) and transpiration (Q-tgw-in) from groundwater uptake. Non-natural inflows are semi-routed, or fully routed surface-water (Q-srd-in, Q-rd-in) and groundwater supply (Q-wells-in) components (example: Farm 7, Figure 16 top). In the FMP, known deliveries to irrigated areas, such as water imported via pipeline, can be simulated as non-routed deliveries (Q-nrd-in) but were not specified for the Rincon Model as the irrigation water supply within the EBID is self contained. In case of deficiency, the FMP calculates any other potential external deliveries required to balance supply with the simulated demand (Q-ext-in). However, in the present case, 'deficit irrigation' was used as one of the five response scenarios to a deficit situation (IDEFFL=-1) offered by the FMP. The deficit irrigation

scenario reduces the crop water consumption to the available delivery components. That is, all values for external deliveries, Q-ext-in, are zero. Outflow components are evaporation from precipitation, irrigation, and groundwater uptake (Q-ep-out, Q-ei-out, Q-egw-out), transpiration from precipitation, irrigation, and groundwater uptake (Q-tp-out, Q-ti-out, Q-tgw-out), runoff (Q-run-out), and percolation below the root zone (Q-dp-out) (example: Farm 7, Figure 16 bottom). Total rates of inflow (Q-tot-in) and outflow (Q-tot-out) are also included with the detailed farm budget components as well as cumulative volumes (not shown in Figure 16).
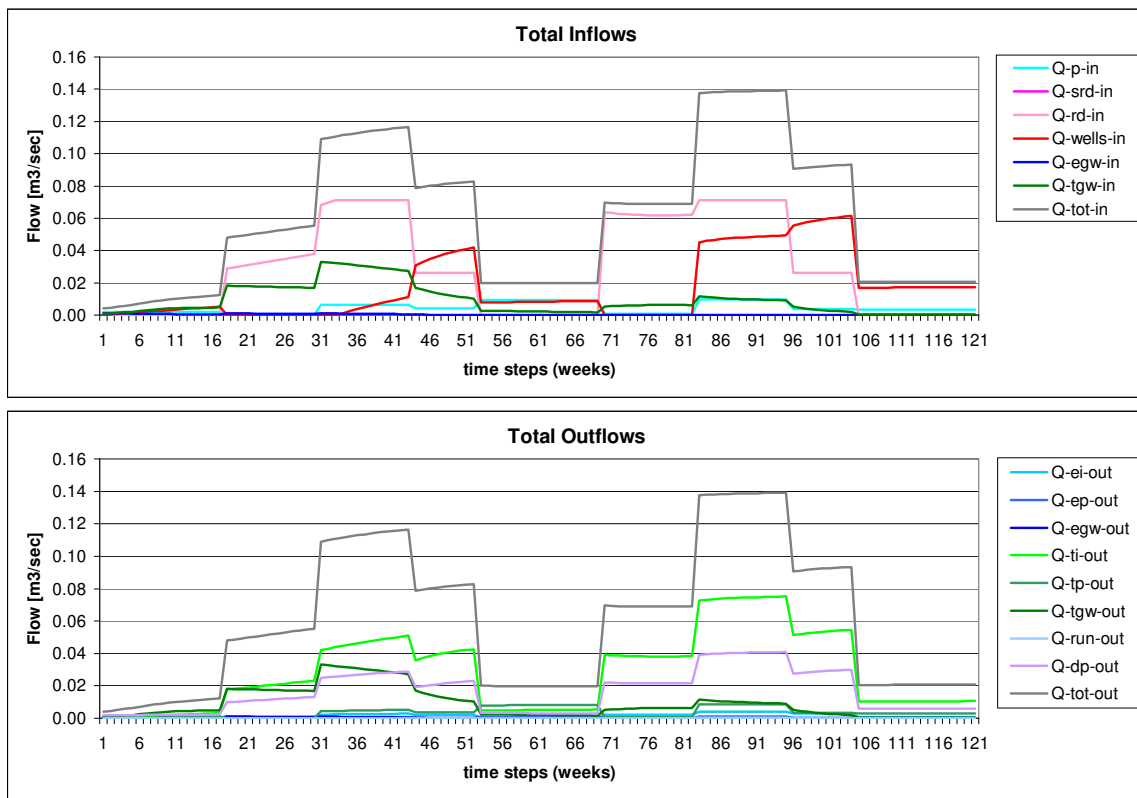


Figure 16. Time series of inflows and outflows components of the physical Farm Budget.

Alternatively these budgetary flow components can be viewed for selected periods of time or individual stress periods or time steps, as shown for Farm 7 for the fourth time step of stress period 8 (Figure 17).

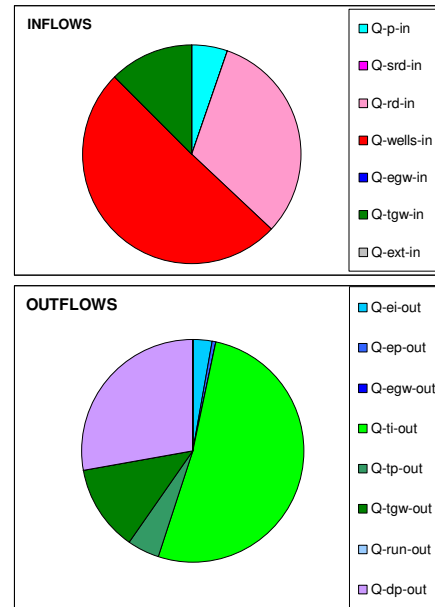| Farm Budget for: | | |
|---|---|---|
| Farm: | Stress Period: | Time Step: |
| 7 | 4 | 9 |
| | | |
| Volumetric Flowrates [L3/T, here m3/sec] | | |
| INFLOWS: | | |
| Precipitation | Q-p-in | 0.0042806 |
| Non-routed deliveries to farm | Q-nrd-in | 0 |
| Semi-routed deliveries from remote canal | Q-srd-in | 0 |
| Fully routed deliveries from adjacent canal | Q-rd-in | 0.026311 |
| Farm well pumping | Q-wells-in | 0.041808 |
| Evaporation from groundwater | Q-egw-in | 0.000042498 |
| Transpiration from groundwater | Q-tgw-in | 0.010294 |
| External deliveries | Q-ext-in | 0 |
| | | |
| TOTAL INFLOW INTO FARM | TOTAL IN | 0.082736 |
| OUTFLOWS: | | |
| Evaporation from irrigation | Q-ei-out | 0.0023699 |
| Evaporation from precipitation | Q-ep-out | 0.00042805 |
| Evaporation from groundwater | Q-egw-out | 0.000042498 |
| Transpiration from irrigation | Q-ti-out | 0.042659 |
| Transpiration from precipitation | Q-tp-out | 0.0038525 |
| Transpiration from groundwater | Q-tgw-out | 0.010294 |
| Surface-water runoff | Q-run-out | 0.00012755 |
| Deep percolation | Q-dp-out | 0.022963 |
| Non-routed deliveries out of farm | Q-nrd-out | 0 |
| Excess non-routed deliveries returned to remote canal | Q-srd-out | 0 |
| Excess non-routed deliveries returned to adjacent canal | Q-rd-out | 0 |
| Excess non-routed deliveries injected into farm-wells | Q-wells-out | 0 |
| TOTAL OUTFLOW OUT OF FARM | TOTAL OUT | 0.082736 |
| IN - OUT: | | 3.04E-08 |
| DISCREPANCY [%] | | 0 |

Figure 17. Farm Budget for Farm 7 for a specific stress period and time step.

MF-FMP allows sub-dividing the former 'net irrigation flux' of the previous regional Rincon and Mesilla models into individual components (deep percolation, six evaporation and transpiration components, groundwater well pumping). Not only are these components simulated and visualized individually as demonstrated in Figure 17, but also can they dynamically influence each other and vary over time (Figure 16). In the example of Farm 7, transpiratory root uptake during peak irrigation season stress periods 2 and 3 (June through October, 2002) allow the pecan dominated farm to benefit from phreatophytic uptake, which results in a lesser need for surface- and groundwater deliveries. In the drought year 2003, when groundwater levels are somewhat depleted, phreatophytic uptake is nearly eliminated and cannot contribute to the crop water demand anymore. That is, for the peak irrigation stress periods 7 and 8 (June through October, 2003), farm-well pumping is simulated to be much higher than the year before to reach the higher irrigation demand (Figure 16).

The question of how the consumptive-use-driven surface-water and groundwater abstraction impacts the Rio Grande streamflow can be described by a correlation between the cumulative surface-water deliveries or cumulative farm irrigation pumpage yielded by

the 'Farm Demand and Supply' data output file (FDS.OUT) and Rio Grande streamflows calculated by MF-FMP and HYDMOD. The objective is to show how the entire agriculture system affects the streamflow at a point downstream the entire area. Therefore, the streamflow to be investigated here is taken to be the Rio Grande streamflow south of the entire farm model area and south of the Rincon Drain returnflow into the Rio Grande. The same model investigation technique could be applied to a more regional model and downstream streamflow deliveries (e.g., at the NM-TX state line).

The result (Figure 18) shows non-linear correlations between increasing surface-water or groundwater deliveries and streamflow at times where these deliveries matter (that is, during peak irrigation seasons). With increasing pumpage, the streamflow is depleted. However, this streamflow depletion is not linearly but non-linearly related to groundwater abstraction. That is, the streamflow depletion diminishes as pumpage reaches highest levels. This observation is consistent other research describing the course of stream seepage with increasing pumpage (Bouwer and Maddock 1997). Stream losses are expected to rise linearly when dominated by the pumping-related increasing gradient between the heads in the stream and the aquifer. However, stream seepage behaves more and more curvilinear with increasing drawdown when controlled by gravity and asymptotically approaches a maximum rate when finally becoming disconnected from groundwater. A verification of whether the Rio Grande along the irrigated agricultural in the Rincon Model indeed disconnects from the aquifer was beyond the scope of this study. At this point, the objective of the study was merely to demonstrate that the model using MF-FMP has the ability to show this non-linear relationship. Naturally the described non-linear correlation between Rio Grande streamflow and cumulative pumpage has to be viewed with caution as it is not independent of other external factors that influence streamflow, such as natural precipitation and runoff, or constrain deliveries, such as equal appropriation allotments. The groundwater pumpage in the present Rincon Model was not constrained.
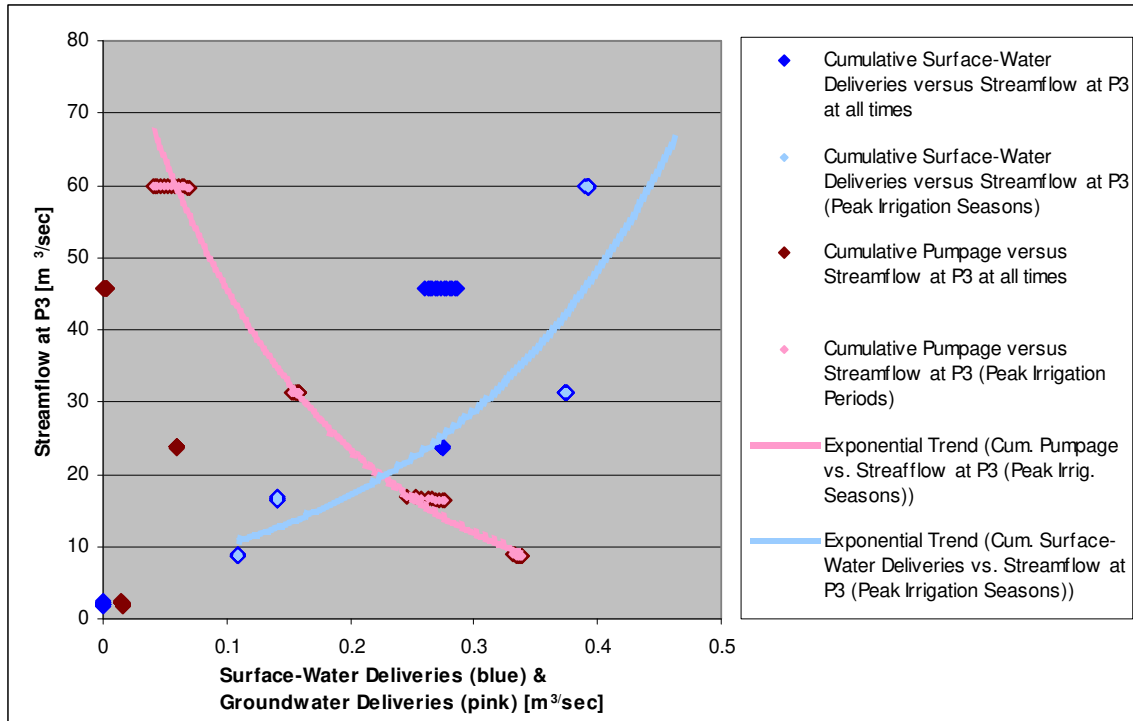
Figure 18. Relationship between surface- or groundwater deliveries and streamflow at Point P3 located south of the returnflow of the Rincon Drain back into the Rio Grande.

The model used HYDMOD (Hanson and Leake 1998) to generate streamflow hydrographs at Point 3 (Figure 19). HYDMOD in conjunction with MF-FMP provides a tool to look at cumulative surface-water return flows at any point along the stream network. One real world application of this option is to allow water managers of different states participating in a stream compact to evaluate the effect of cumulative return flows of a stream prior to reaching a state line.

## Results of Rincon Model Scenarios

Model scenarios tried to evaluate the effect that changes in surface-water allotment heights have on (a) surface- and groundwater deliveries and (b) Rio Grande streamflow gains and losses. Potential stream gains and losses were evaluated using streamflow hydrographs generated by HYDMOD at three points along the Rio Grande passing by the farming area. Point 1 is located upstream slightly north of the farming area. Point 2 is located downstream just south of the farming area, but still before the

41

drain returnflows enter the Rio Grande. Point 3 is located downstream south of the farming area and just after the drain returnflows enter the Rio Grande (Figure 19).
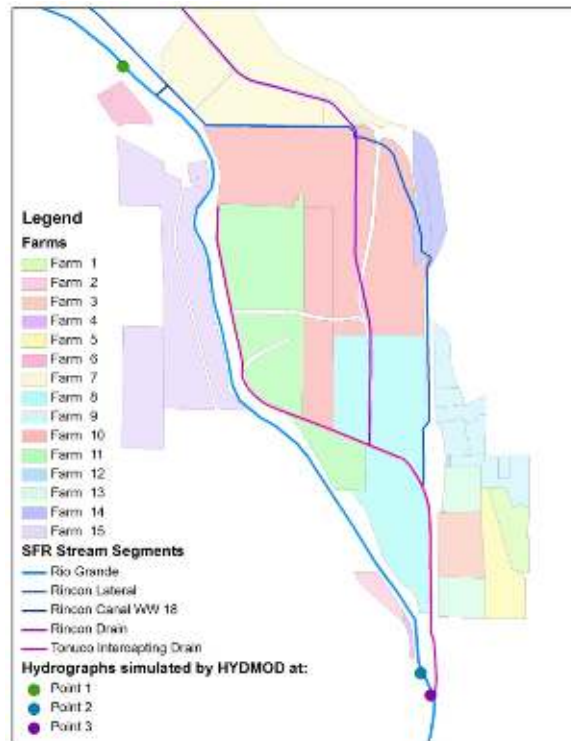


Figure 19.  Location of points at which hydrographs are simulated by HYDMOD.

Time series of deliveries and stream gains for the basic model run (allotment height = 0.4 meters) show peak surface-water deliveries during both irrigation years (Figure 20 a) with peak groundwater pumping following the surface-water delivery peaks with some delay in times when surface-water allotments are limited (Figure 20 b). However, only during year 2002, part of the diverted water entered the river back through drain returnflows, which led to gains between Point 2 and 3 right before and after the tributary drain inflow (Figure 20 d). During year 2003, a declining groundwater table cause drains to gain less water, which might be the main factor for a lesser drain returnflow back into the river. Another result of a declining water table is that phreatophytic uptake is reduced or ceases and irrigation demands are dynamically increasing. While having even slightly less surface-water deliveries available in 2003, higher irrigation demands will dynamically result in the simulation of many farms

operating on a higher efficiency, which, in turn, results in reduced returnflows. In summary, a declining water table, less aquifer leakage into drains, less phreatophytic uptake, higher irrigation demands, and higher efficiency in a deficiency situation are a series of dynamically linked processes that cause drain returnflows to be diminished in 2003. Nevertheless, along the stretch of the Rio Grande that passes by the model farm area, the river still only gained and did not lose streamflow.

While the time series were plotted for the basic calibrated model with an allotment height of 0.4 m, scenarios were run for changing allotment heights (allotment heights = 1.2, 0.8, 0.4, 0.2, and 0.1 meters). For two time snapshots (at 08/31/02 and 08/31/03), the effect of changing allotments on surface-water and groundwater deliveries as well as Rio Grande streamflow was studied.
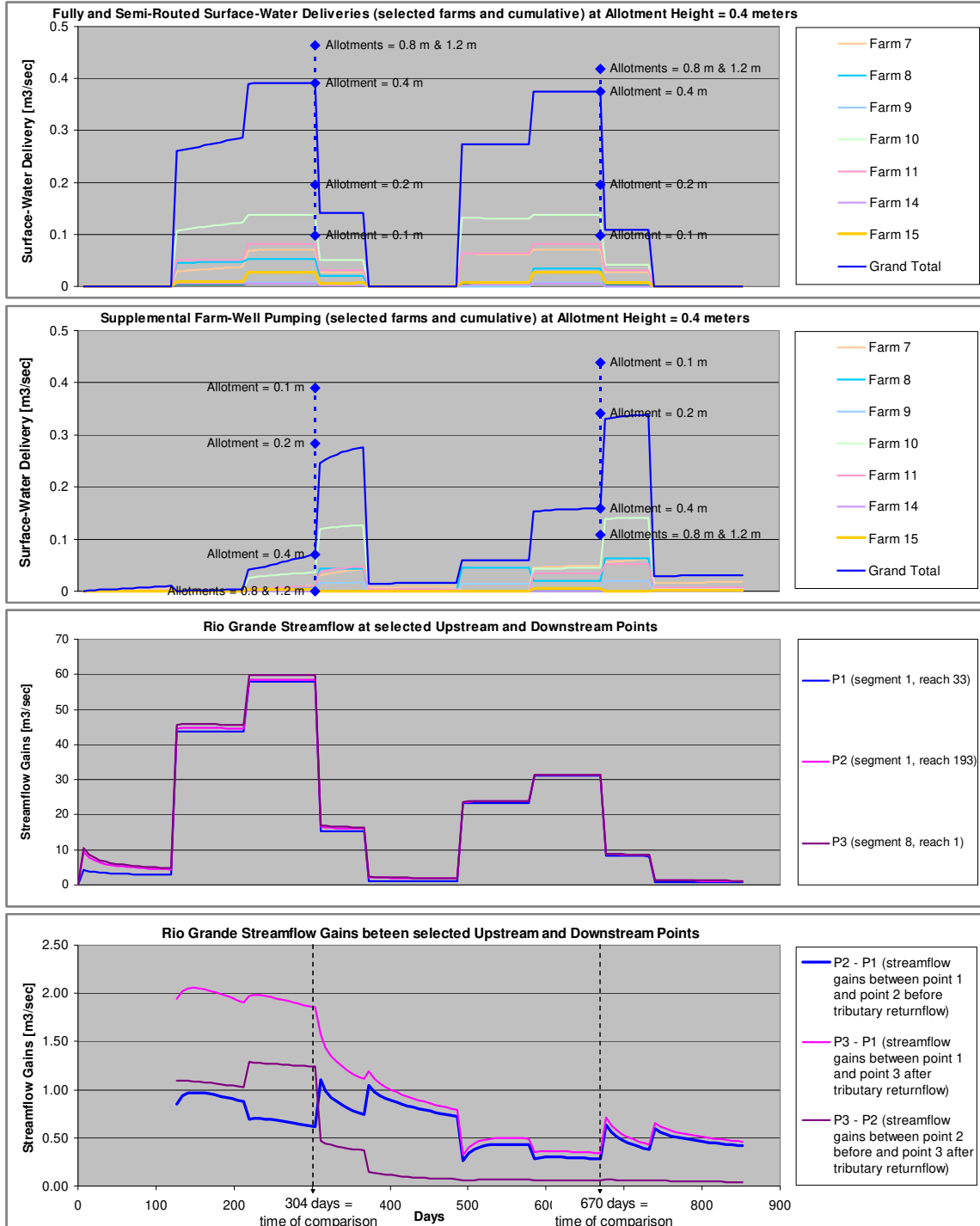
Figure 20. Time series of surface-water and groundwater deliveries (a, b) and Rio Grande streamflow (c) and streamflow gains (d).

The scenario studies reveal that increasing the equal appropriation allotment height causes:

➢ a nonlinear increase in surface-water deliveries (Figure 21);

➢ a nonlinear decrease in groundwater pumping (Figure 21);

➢ a nonlinear increase in Rio Grande gains between Point 1 upstream the farmed area and Point 2 downstream before tributary drain returnflow (Figures 22, 23);

➢ a nonlinear decrease in Rio Grande gains between Point 1 upstream the farmed area and Point 3 beyond the tributary drain returnflow (Figures 22, 23);

➢ a nonlinear decrease in Rio Grande gains between Point 2 directly before and Point 3 directly after the tributary returnflow (Figures 22, 23)
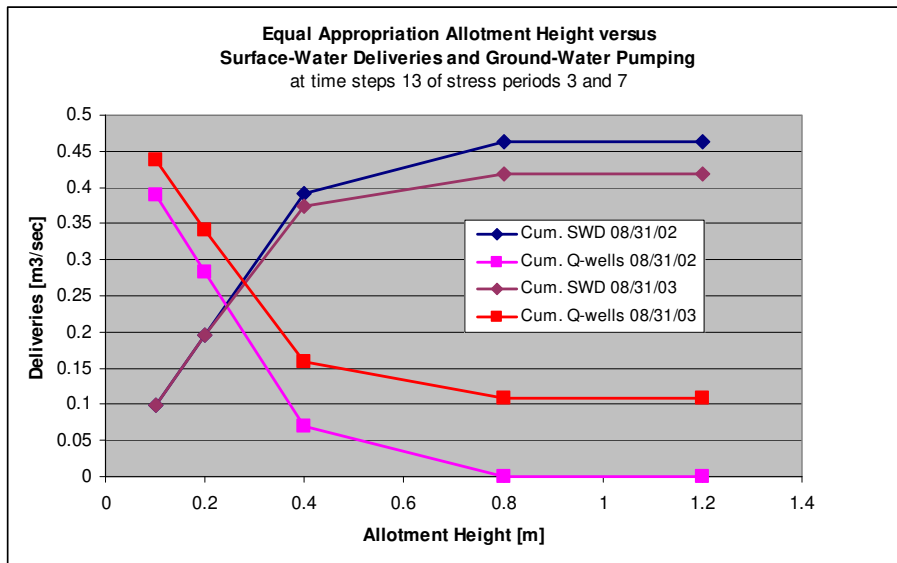


Figure 21. Impact of variable allotments on surface- and groundwater deliveries.
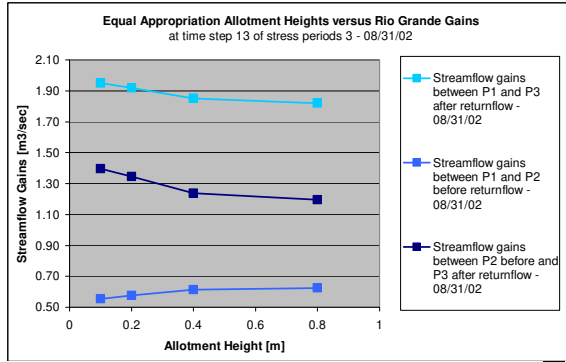
Figure 22.  Impact of variable allotments on Rio Grande gains for 08/31/2002.
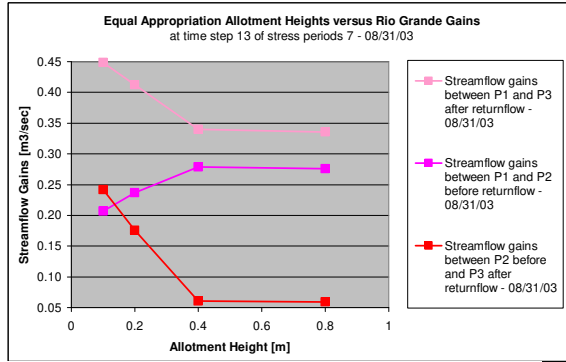


Figure 23. Impact of variable allotments on Rio Grande gains for 08/31/2003.

Surface-water deliveries to farms within the EBID are generally equally appropriated. Equal appropriation allotments for each irrigation season assure that there is no priority of one over the other farm based on seniority. Yet, in drought years, downstream farms may not receive the entire allotment even though upstream farms abide by allotment regulations. When looking at a cluster of farms, such as simulated by the local Rincon Model, increasing allotments leads to a linear increase in surface-water deliveries, and hence a linear decrease in supplemental farm-well pumpage. However, when allowing high allotments (Figure 21, allotment height = 0.8 m), diversions become less or not dependent on allotment constraints but on the required demand. Potentially, diversion could also be constrained by limited available streamflow. In this model, even though the Rio Grande streamflow is reduced in 2003 compared to 2002 (Figure 20 c), streamflow is not yet posing any limitation on diversions from the river. However, some farms (7, 8, 9, and 10) are assumed to be supplied from the Rincon Lateral, which, in 2003, did not carry sufficient streamflow to supply farm 8, 9, and 10 downstream from farm 7 to its entitled allotment. In the presented model scenario for 08/31/2002, the highest allotments allow almost all irrigation demand to be satisfied through surface-water deliveries (for day 304 = 08/31/2002), which leads to zero groundwater pumpage. This is not the case in the scenario for 08/31/2003, where irrigation demand is higher due to the lack of phreatophytic uptake and surface-water deliveries may be limited for some farms (e.g., farm 8, 9, and 10).

46

The impact of variable allotments on the Rio Grande gains follows for both snapshots a nonlinear behavior. The difference between 2002 and 2003 is that a big portion of the overall gains in 2002 came from the returnflow (dark blue curve in Figure 22), where as a nearly dried-out drain in 2003 cannot contribute significantly to the Rio Grande streamflow anymore (pink curve in Figure 23).

The model demonstrates the ability of MF-FMP to simulate nonlinear responses deliveries, returnflows, and streamflow to changes in allotments that may not be present in other (regional) models of the Lower Rio Grande. Other dynamic responses (e.g., response to changes in release or stream inflow) could also be demonstrated, but would go beyond the scope of this project and are potential analysis for future work.

## Conclusions, Recommendations, Outlook

The local Rincon Model explains how MF-FMP allows water managers to estimate supplemental groundwater use required to sustain the crops growth for historic periods in lieu of metered groundwater pumping. The model also showed how joint use of the FMP and the Streamflow Routing Package within a MODFLOW model permits the evaluation of the large-scale impact of surface-water allotments on surface- and groundwater deliveries, streamflow, river seepage, and return flows. In the local Rincon Model, these scenarios were applied to hypothetic locations upstream and downstream the model farming area. In larger-scale models, MF-FMP can be applied to an analogous scenario analysis for instance at the New Mexico/Texas state line.

Telescoping a preliminary local Rincon Model into a truncated version of the pre-existing regional Rincon Valley & Mesilla Basin groundwater model (Tillery and King 2006, Weeden and Maddock 1999) produced initial and boundary conditions through the telescopic mesh refinement (TMR) technique. A preliminary version of the local Rincon Model using MODFLOW-2000 without the Farm Process was run for a period from 1915 to 2004 (Tillery and King 2006) and resulting heads for Nov. 2001 were used as initial heads for the local Rincon Model (Nov. 2001 – Feb. 2004) using MODFLOW-2005 with

the Farm Process version 2 (MF2K5-FMP2). Problems associated with this approach were that data input of the Discretization and Streamflow Routing packages for the finer-resolution local Rincon Model using MODFLOW-2000 (Tillery and King 2006) was interpolated from inaccurate coarse-resolution ground-surface elevation and stream network data stemming from the regional model. For the MF2K5-FMP model, this data input could be corrected using 10 meter Digital Elevation Models and GIS shape files obtained by the EBID. Local model initial and boundary conditions (flow and head boundary and mountain front boundary conditions) derived from the regional model may also be somewhat inaccurate, yet, affected only the first few time steps of the first stress period of the local Rincon Model. Affected initial water levels and streamflow data were given low influence during the calibration process. In order to minimize 'hard-wired' boundary conditions derived from the regional model, we propose to use the Local Grid Refinement technology (Mehl and Hill 2005), which would allow the local model – contrary to the TMR – to run simultaneously with the regional model and across local model boundaries.

For updates of this or any other models using MF-FMP within the EBID, we strongly recommend to obtain a better observation data base from additional observation well and stream gage monitoring, which may require drilling new observation wells or constructing new stream gages along the Rio Grande. A higher density of stream gages would allow the stream gains or losses between these gages to be an additional observation parameter. Also cumulative pumpage of farms should be monitored more densely and in more representative farm locations. The cumulative pumpage was only available from a small farm located in the periphery of the model farming area (farm 15 = Thurston farm). Optimally, all farms of an MF-FMP model domain should report cumulative pumpage from their associated farm wells. This would not lead to a redundancy of the MF-FMP ability to simulate farm pumpage, but to the ability to obtain a 'pumpage-calibrated' model that can be transformed into a predictive model driven by management or climate scenarios.

Once calibrated by cumulative pumpage data, an MF-FMP model can be one that water managers can keep current by updating variable data or conditions, such as climate data or changing international water rights. Hence, it can be used as a design tool to plan water supplies for upcoming water years, for long-term predictive scenarios driven by climate change, and for water appropriation planning and negotiations with other agencies.

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