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# Comparison of Simulations of Land-use Specific Water Demand and Irrigation Water Supply by MF-FMP and IWFM

Technical Information Record

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This manuscript and associated tables and figures have been reviewed for Bureau Approval and found to be technically sound and well written. This report documents a significant model comparison that has been previously lacking and was not part of the USGS Groundwater Availability project that developed the new hydrologic model of the Central Valley. The report provides a viable source of comparison and summary information needed by other hydrologists that want to choose a code for simulation of complex hydrologic systems requiring the simulation of conjunctive use. The USGS author has responded satisfactorily to peer reviews by Devin Galloway, Western Region Groundwater Specialist, USGS, Sacramento, CA, and Dr. Thomas Harter, Hydrologist, Cooperative Extension, University of California at Davis, Davis, CA. Supervisory review was delegated and provided by Steve Phillips; additional review comments were provided by Peter Martin. Extensive revision to the report occurred as a result of the peer reviews. There are no suggested changes.—Keith G. Kirk, Bureau Approving Official

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**APPROVED**
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**A Technical Information Record of a joint study with U.S. Geological Survey**

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# Abbreviations and Acronyms

| | |
|---|---|
| CADWR | California Department of Water Resources |
| FB | Farm Budget |
| FDS | Farm Demand and Supply |
| HYDMOD | Computer program for calculating hydrograph time series data for MODFLOW |
| IWFM | Integrated Water Flow Model |
| MAD | Maximum allowable depletion |
| MF-FMP | MODFLOW-2005 version 1.6 with the Farm Process version 2 |
| MNW | Multi-Node Well Package |
| OFE | On-farm efficiency |
| RSQ | Square of the Pearson product moment correlation coefficient |
| SCS | Soil Conservation Service |
| USDA | U.S. Department of Argriculture |
| USGS | U.S. Geological Survey |
| ZONEBUDGET | Computer program for calculating subregional water budgets for MODFLOW |

# Abstract

Two hydrologic models, MODFLOW with the Farm Process (MF-FMP) and the Integrated Water Flow Model (IWFM), are compared with respect to each model's capabilities of simulating land-use hydrologic processes, surface-water routing, and groundwater flow. Of major concern among the land-use processes was the consumption of water through evaporation and transpiration by plants. The comparison of MF-FMP and IWFM was conducted and completed using a realistic hypothetical case study.

Both models simulate the water demand for water-accounting units resulting from evapotranspiration and inefficiency losses and, for irrigated units, the supply from surface-water deliveries and groundwater pumpage. The MF-FMP simulates reductions in evapotranspiration owing to anoxia and wilting, and separately considers land-use-related evaporation and transpiration; IWFM simulates reductions in evapotranspiration related to the depletion of soil moisture. The models simulate inefficiency losses from precipitation and irrigation water applications to runoff and deep percolation differently. MF-FMP calculates the crop irrigation requirement and total farm delivery requirement, and then subtracts inefficiency losses from runoff and deep percolation. In IWFM, inefficiency losses to surface runoff from irrigation and precipitation are computed and subtracted from the total irrigation and precipitation before the crop irrigation requirement is estimated. Inefficiency losses in terms of deep percolation are computed simultaneously with the crop irrigation requirement. The seepage from streamflow routing also is computed differently and can affect certain hydrologic settings and magnitudes of streamflow infiltration.

MF-FMP assumes steady-state conditions in the root zone; therefore, changes in soil moisture within the root zone are not calculated. IWFM simulates changes in the root zone in

both irrigated and non-irrigated natural vegetation. Changes in soil moisture are more significant for non-irrigated natural vegetation areas than in the irrigated areas. Therefore, to facilitate the comparison of models, the changes in soil moisture are only simulated by IWFM for the natural vegetation areas, and soil-moisture parameters in irrigated regions in IWFM were specified at constant values . The IWFM total simulated changes in soil moisture that are related to natural vegetation areas vary from stress period to stress period but are small over the entire two-year period of simulation.

In the hypothetical case study, IWFM simulates more evapotranspiration and return flows and less streamflow infiltration than MF-FMP. This causes more simulated surface-water diversions upstream and less simulated water available to downstream farms in IWFM compared to MF-FMP. The evapotranspiration simulated by the two models is well correlated even though the quantity is different.

The different approaches used to simulate soil moisture, evapotranspiration, and inefficient losses yield different results for deep percolation and pumpage. In IWFM, deep percolation is a function of soil moisture; therefore, the constant soil-moisture requirement for irrigated regions, assumed for this comparison, results in a constant deep percolation rate. This led to poor correlation with the variable deep percolation rates simulated in MF-FMP, where the deep percolation rate, a fraction of inefficiency losses from precipitation and irrigation, is a function of quasi-steady state infiltration for each soil type and a function of groundwater head. Similarly, the larger simulated evapotranspiration in IWFM is mainly responsible for larger simulated groundwater pumpage demands and related lower groundwater levels in IWFM compared to MF-FMP.

Because of the differences in features between MF-FMP and IWFM, the user may find that for certain hydrologic settings one model is better suited than the other. The performance of MF-FMP and IWFM in this particular hypothetical test case, with a fixed framework composed of common initial and boundary conditions and input parameter values, does not necessarily predict the performance of MF-FMP and IWFM in a real-world situation with variable framework and parameter values. These differences may affect the evaluation of policies, projects, or water-balance analysis for some hydrologic settings. Generally, both models are powerful tools that simulate a connected system of aquifer, stream networks, land surface, root zone, and runoff processes. MF-FMP simulated the hypothetical test case in about 4 minutes compared to about 58 minutes for IWFM.

**Key Words:** MODFLOW; Farm Process; IWFM; Crop water demand; Streamflow; Groundwater pumping.

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# Introduction

The U.S. Geological Survey (USGS) and the California Department of Water Resources (DWR) have been developing separate updated and upgraded hydrologic models for the Central Valley (Brush et al., 2008; Faunt et al., 2009a,b,c) using different modeling software. The USGS has used MODFLOW-2000 (Harbaugh et al., 2000) with the Farm Process version 1 (Schmid et al., 2006a,b; Schmid and Hanson, 2007), modified as described in Schmid and Hanson (2009a). The DWR has used the Integrated Water Flow Model (IWFM v3.1; Dogrul, 2009a,b). The parallel development of these two regional flow models was facilitated by similar hydrologic data sets used for input, such as streamflow and precipitation. Despite these similarities, these large and complex models are difficult to compare on the basis of individual model features. There is considerable interest in comparing the simulation capabilities of MODFLOW with the Farm Process and IWFM on a smaller and simpler scale. The purpose of this report is to present a comparison of each code's capabilities for simulating land-use processes, surface-water routing, and groundwater flow based on a realistic, but hypothetical, case study. The comparison of land-use processes simulation capabilities focuses predominantly on the consumption of water through direct evaporation and transpiration by plants.

Parallel sets of results produced by MODFLOW-2005 (Harbaugh, 2005) with the Farm Process version 2 (MF-FMP; Schmid and Hanson, 2009b) and by IWFM version 3.1 are compared with respect to parameters of major interest, such as surface-water and groundwater allocations, as well as the water-accounting unit level (i.e., "virtual" farm level) evapotranspiration and deep percolation from farms into the underlying unconfined groundwater system. Additional comparisons address the routing of streamflow and the changes in groundwater levels at selected hypothetical observation wells.

These comparisons identify features of both codes that produce either similar or significantly different results. Explanations for the significant differences are discussed. These discussions also provide the basis for potential improvements of both codes and inform the reader of advantages or limitations for specific applications. The findings of this report will allow more informed comparison of simulation results where the two models or their previous versions are applied to the same area, such as California's Central Valley (Hanson et al., 2010; Faunt et al., 2008, 2009a,b,c; Brush et al., 2008) and the Pajaro Valley (Hanson et al., 2010, 2008). Because the hypothetical problem was designed to allow simulation by both codes, other features that are unique to each code were not used and are not discussed in this report. If the reader is interested in assessing which additional features may be important in future applications, they should review the documentation and related articles referenced in this report.

# Overview of MF-FMP and IWFM Concepts

This section contains a brief overview of conceptual approaches and key differences between MF-FMP and IWFM. The case study, explained in the following sections, is used to highlight conditions under which these differences may lead to different results and to quantify those differences. We then discuss circumstances under which one or the other model representation may be more appropriate. A detailed comparison of theories, approaches and features of the two codes is beyond the scope of this report and is given by a separate report (Dogrul et al., 2011), which will be published simultaneously with this report. Therefore, this report cannot be considered a stand-alone report. This report discusses a comparison of two models, which are based on applications of two different codes to the same hypothetical problem. It expects the reader to be sufficiently familiar with the conceptual approach of each code discussed by the aforementioned report. In this report the term "code" refers to modeling software (ie, MF-FMP or IWFM) and the term “model” refers to the software application to a hypothetical case study. More information on the concept of each code or the rationale of assumptions that underlie each code can be found in each code’s user guide(s) (Dogrul 2009a and 2009b; Schmid et al., 2006a; Schmid and Hanson 2009a, 2009b).

In both codes, conservation equations for a distributed parameter representation of groundwater, stream, lake, root-zone, and land-surface runoff processes are solved simultaneously to simulate a large portion of the hydrologic cycle and agronomic and other human effects on the cycle. Among the mass conservation equations, the same three-dimensional groundwater flow equation is used for both codes and solved for groundwater heads using a finite-element approach in IWFM and a finite-difference approach in MF-FMP. The conservation equations are coupled and can simulate the exchange of water between processes, such as the vertical interaction between surface- and groundwater across a vegetated root zone or non-vegetated unsaturated zone and across streambeds. In the horizontal direction, both codes simulate stream diversions to agricultural and urban lands, and the surface runoff into streams. The codes also simulate the conjunctive use of surface water and groundwater to satisfy the consumptive use requirement of vegetation in excess of the effective precipitation in addition to urban water demands.

## Vertical Interaction between Surface- and Groundwater

In both codes, the vertical interaction between surface- and groundwater can be simulated across a root zone and across streambeds as well as across the deeper unsaturated zone below root zones, non-vegetated areas, or streambed bottoms.

## Interaction between Surface-Water and Groundwater across a Root Zone

Both codes simulate the interaction between surface water and groundwater across a root zone but conceptualize the conservation of mass for root zone processes differently. In MF-FMP, inflows that meet the crop evapotranspiration requirements are precipitation, irrigation, and root uptake from groundwater. Outflows are transpiration and evaporation, as separate components, as well as runoff, and deep percolation beneath the root zone. In IWFM, inflows are precipitation and irrigation, and outflows are evapotranspiration, runoff, and deep percolation.

### *Changes in Soil-Water Storage and Groundwater Uptake*

MF-FMP simulates uptake from groundwater as a potential source of water in meeting a portion of the crop evapotranspiration requirements when the capillary fringe above the groundwater level reaches the bottom of the root zone or higher. IWFM does not simulate groundwater uptake but does simulate changes in soil-water storage, which MF-FMP does not.

### *Evapotranspiration*

MF-FMP calculates six separate transpiration and evaporation components fed by precipitation, irrigation, and groundwater on a cell-by-cell basis within a water-accounting unit. IWFM calculates evapotranspiration as a single term for a representative crop computed by area-weighted averaging of evapotranspiration for individual crops within a subregion. In MF-FMP, potential crop evapotranspiration can be specified or calculated as the product of specified reference evapotranspiration and crop coefficients. MF-FMP optionally reduces potential transpiration due to conditions of anoxia and, for non-irrigated areas, of wilting (Schmid et al., 2006a, 2006b) if the specified potential crop evapotranspiration or specified crop coefficient are derived under non-stressed conditions (Allen et al., 1998). This reduction is based on crop-type specific stress responses at defined pressure heads and soil-type specific analytical solutions of vertical pressure head distributions derived from Richards' equation based soil-column models. Anoxia is simulated at pressure heads close to saturation owing to a water level at or above the bottom of the root zone or by similar conditions of a vertically downward propagating wetting front. In addition, a user-specified evaporative fraction of evapotranspiration related to irrigation can reflect a further reduction of potential to actual evaporation ($E_{c\text{-}pot}$ to $E_{c\text{-}act}$) from non-vegetated areas that are not fully wetted. In IWFM, a specified potential evapotranspiration is assumed to already account for conditions of anoxia. That is, IWFM does not simulate conditions of anoxia but of wilting by reducing $ET_{c\text{-}pot}$ to $ET_{c\text{-}act}$ when soil moisture falls below half of field capacity.

### *Surface-Water Runoff*

Both MF-FMP and IWFM simulate inefficiency losses from precipitation and irrigation that do not contribute to the consumptive use of crops and include surface-water runoff and deep percolation below the root zone. For MF-FMP, two separate fractions of losses to surface-water runoff can be specified related to precipitation and to irrigation for each crop type for each stress period or for the entire simulation. MF-FMP also offers to calculate these fractions based on the local (cell-by-cell) slope of the land surface, assuming runoff to be proportional to the slope. In IWFM, surface runoff from irrigation is defined as a "fraction of the total irrigation amount" prior to estimation of consumptive use as opposed to a "fraction of inefficiency losses related to irrigation" in MF-FMP that is estimated after the estimation of consumptive use. To account for the different input parameters in IWFM, the fractions of inefficiency losses from irrigation to surface runoff defined in MF-FMP can be converted to fractions used by IWFM assuming the following equalities:

$$\left(\mathrm{I}-\mathrm{CIR}\right)\mathrm{IE}_{\mathrm{swFMP}}^{\mathrm{I}}=\mathrm{I}\times\mathrm{IE}_{\mathrm{swIWFM}}^{\mathrm{I}} \quad (1)$$

$$\mathrm{CIR}=\mathrm{I}\times\mathrm{OFE} \quad (2)$$

With calculated parameters:

I = actual irrigation amount (total irrigation delivery),

CIR = crop irrigation required to supplement natural supply components in satisfying crop consumptive water use,

$\left(\mathrm{I}-\mathrm{CIR}\right)$ = total inefficiency losses from irrigation as modeled in MF-FMP.

With data input parameters:

$\mathrm{IE}_{\mathrm{swFMP}}^{\mathrm{I}}$ = fraction of inefficiency losses to surface runoff from irrigation as defined by MF-FMP,

$\mathrm{IE}_{\mathrm{swIWFM}}^{\mathrm{I}}$ = ratio of surface runoff from irrigation to total irrigation amount as required by IWFM,

OFE = on-farm irrigation efficiency in MF-FMP and IWFM, defined as the ratio between crop irrigation requirement used beneficially towards crop consumptive use and the total irrigation water delivered.

Substituting (2) into (1) and rearranging, one can obtain the following:

$$\mathrm{IE}_{\mathrm{swIWFM}}^{\mathrm{I}}=\left(1-\mathrm{OFE}\right)\mathrm{IE}_{\mathrm{swFMP}}^{\mathrm{I}} \quad (3)$$

Both OFE and $\mathrm{IE}_{\mathrm{swFMP}}^{\mathrm{I}}$ are parameters specified in MF-FMP and used in (3) to compute $\mathrm{IE}_{\mathrm{swIWFM}}^{\mathrm{I}}$.

IWFM uses a modified SCS curve number method (USDA, 1985), described by Schroeder et al. (1994), to compute the inefficiency losses from precipitation as surface runoff as a function of precipitation rate and the soil-moisture content in the root zone. In IWFM, the retention capacity of the soil decreases and surface runoff increases as the soil moisture increases above one-half of field capacity.

### *Deep Percolation*

Deep percolation is defined in MF-FMP as “the total inefficiency losses less surface-water runoff,” but it is computed implicitly in IWFM using a physically-based soil moisture accounting approach (Campbell, 1974). Deep percolation is accounted for after the crop irrigation requirement is computed in MF-FMP, whereas, in IWFM it contributes to the crop irrigation requirement, which can result in a higher delivery requirement. IWFM assumes that the higher the permeability of the soil, i.e., the greater the deep percolation, the higher the crop irrigation requirement to irrigate the soil to a pre-specified moisture content to achieve a certain crop yield. Thus demand is driven by soil-drainage properties, and irrigation-management practices, as well as crop-water consumption in IWFM. In contrast, in MF-FMP, irrigation demand of agriculture is driven by a maximum possible crop-water consumption that is met by precipitation or irrigation subject to known on-farm efficiencies. Land use processes in both models are directly linked to the aquifer system not only through deep percolation into the groundwater but also through supplemental pumping to satisfy the residual agricultural and urban water demand.

## Interaction between Streams and Groundwater across Streambeds

Both codes simulate the interaction between streams and groundwater across streambeds using similar approaches for streamflow routing but slightly different approaches for stream-aquifer interaction. The representation of stream-groundwater interaction when stream and aquifer are hydraulically disconnected is different in both models. For disconnected conditions, the vertical pressure gradient is assumed to be equal to depth of stream stage plus depth of streambed in MF-FMP but equal to the depth of stream stage in IWFM.

### Interaction between Infiltration and Groundwater across Deeper Unsaturated Zone

Both codes can simulate flow processes in the deeper unsaturated zone beneath the root zone or below non-vegetated areas and the saturated aquifer system but have the option to neglect these processes and to assume instant recharge from deep percolation. MF-FMP can simulate the delay between infiltration from the root zone, un-vegetated areas, or streambeds and recharge into the groundwater across deep unsaturated zones using a kinematic-wave approximation of vertical unsaturated flow. IWFM simulates the attenuation of deep percolation through an unsaturated zone before it recharges a deep groundwater table or the rejection of infiltration in cases where the infiltration rates computed in the root zone module are too high compared to the vertical conductivity of this unsaturated zone.

## Horizontal Interaction between Streams and Land-Use Processes

Aside from vertical interactions between surface water and groundwater, lateral exchange of water between land use processes and the stream network is provided in both models. Both codes simulate surface-water-conveyance systems that distribute and/or receive water from various other hydrologic compartments (other channels/rivers, groundwater, and runoff) represented by either code. Land-use processes in both models are directly linked to the stream network through stream diversions to meet the water demand for irrigated agriculture and irrigated urban landscape and direct runoff from precipitation and agricultural return flow.

## Distribution of Water-Accounting Units and Landscape Attributes

Both IWFM and MF-FMP consider two types of water budgeting for the control volume horizontally delineated by the land surface areas, called “farms” in MF-FMP and “subregions” in IWFM. In IWFM, these water-accounting units include the root zone and, hence, are true control volumes, in MF-FMP, they do not include changes in soil-water storage and, hence, are control interfaces at the land surface. There are two types of budgeting associated with these water-accounting units:

i. mass balance between all physical inflow and outflow components to and from the control volume

ii. economic balance between the irrigation-water demand and the water supply from different surface or groundwater components to meet this demand.

Subregions and farms are the water budgeting units where irrigation-water demands are computed, and a balance between irrigation water supply and demand is sought; the supply-demand balance may or may not be met depending on the amount of the supply with respect to demand. In IWFM, subregions also are used as the smallest computation units for land surface and root-zone flow processes, where infiltration, precipitation runoff, agricultural-return flow, deep percolation, and evapotranspiration (ET) are calculated. In MF-FMP, farms are used as budget units for all physical flows into and out of a farm; this includes natural flows and irrigation-induced deliveries and return flows (Schmid and Hanson, 2009b). Inflows include precipitation, non-, semi-, and fully-routed surface-water deliveries, groundwater well pumping deliveries, evaporation and transpiration from groundwater, and external deliveries from outside the model domain (in case of a supply deficit). Outflows include evaporation and transpiration components, respectively, fed by irrigation, precipitation, and uptake from groundwater, as well as overland runoff and deep percolation.

Each mesh cell is assigned a soil type and related soil properties in each model. Soil property values are user-specified in IWFM, whereas MF-FMP uses words for soil types, for which the MF-FMP code contains intrinsic soil type specific coefficients used to calculate the reduction of groundwater-influenced root uptake by conditions of anoxia or wilting at quasi-steady state reached after time intervals of several days.

In MF-FMP, each cell is assigned a user-defined crop or land-use type ID, which may be variable with simulation time, irrigated or non-irrigated (e.g., rain-fed agriculture, native vegetation), as well as urban, agricultural, or native. In IWFM, each cell area is allocated among four pre-specified land use types (agricultural, urban, native and riparian vegetation) that can be further divided into user-specified crop types. For both MF-FMP and IWFM, physical properties and management practices are user-defined for each crop type. For a detailed list of crop physical and management properties, the reader is referred to the documentation of each model (Dogrul, 2009a, 2009b; Schmid et al., 2006a; Schmid and Hanson, 2009a, 2009b). Land surface and root-zone flow processes are calculated in MF-FMP on a finite-difference cell basis. In IWFM they are computed for each subregion in an aggregate form and distributed to finite-element cells based on the area of each land use type over cells.

Both models use the soil and land use data to compute water demands as well as to route water through the root zone. An important difference between IWFM and MF-FMP is that IWFM computes root-zone flow processes at the subregional level, whereas MF-FMP computes them at cell level, which can yield more detail in areas where water levels or land use is more variable. If IWFM subregions are composed of more than one grid element, this will likely create differences in the results compared to MF-FMP. If each grid element is specified as an individual subregion, then these differences may be minimized. Both models then use either subregions (IWFM) or farms (MF-FMP) as the basis for aggregated water-demand and water-supply computations.

## Water Demand and Supply

The present study demonstrates water demands for irrigated agricultural and urban lands. Non-irrigation related urban, municipal, and industrial water demands can be addressed with both codes (Dogrul et al., 2011) but were not simulated in this study. Therefore, they are not discussed further.

In MF-FMP, the crop-irrigation requirement, CIR, is equal to the portion of the actual evapotranspiration optionally reduced by anoxia and wilting that is not supplied by prior supply components, effective precipitation and uptake from groundwater. CIR is computed for each model cell and iteration at each transient time step, assuming a quasi-steady state between all flows into and out of the root zone that is reached at the end of time intervals typical in MODFLOW. MF-FMP calculates a total irrigation delivery requirement, I, for each cell as the evapotranspirative CIR, which depends on the groundwater head divided by the on-farm efficiency of a particular time step. On-farm efficiency is defined as the fraction of the total irrigation water that is used beneficially on the farm. The total irrigation water demand for a water-accounting unit called “farm” is computed as cell delivery requirements accumulated over all cells within the domain of a farm. CIR is computed only for cells that have land use defined as either urban irrigated landscape or an irrigated agricultural crop and is zero for cells with non-irrigated land use.

IWFM does not reduce the potential crop evapotranspiration rates specified by the user and tries to meet this rate in computing the irrigation water demand. In general, IWFM uses an irrigation-scheduling type approach in computing the irrigation water requirement. When the soil-moisture depletion compared to field capacity reaches a user-specified maximum allowable depletion (MAD), specified for each subregion and crop combination, an irrigation requirement is computed to replenish the moisture up to field capacity, accounting for return flow and deep percolation. The irrigation requirement is zero when soil-moisture depletion is less than MAD. Because deep percolation lowers soil moisture along with crop-water consumption, it also contributes to irrigation-water demand in IWFM. Thus, demand computed in IWFM is a crop-water irrigation demand coupled with a demand to maintain the user-specified soil-moisture storage. IWFM does not utilize groundwater as a source of water in meeting a portion of the crop evapotranspirative requirements.

Precipitation is a component toward crop-water supply for both codes. In addition, groundwater uptake in MF-FMP, and soil-water storage in IWFM also are sources for crop-water supply. Demand for irrigation used to supplement crop consumptive water use is satisfied by several components: imported water from outside the model area (non-routed deliveries), stream diversions (semi-routed deliveries), and groundwater pumping. In MF-FMP, diversions and pumping are constrained by user-specified maximums or by available storage in the stream/aquifer, whichever is smaller. In IWFM, diversions and pumping are limited only by the available storage in the stream or aquifer.

## Summary of Key Differences

- Finite-element approach in IWFM versus finite-difference approach in MF-FMP.

- Different approaches to simulate evapotranspiration, groundwater uptake, and soil-water storage:
  - In MF-FMP, six separate transpiration and evaporation components are fed by precipitation, irrigation, and groundwater uptake. In IWFM, evapotranspiration is a single term that is fed by precipitation, irrigation, and soil-water storage depletion.
  - In MF-FMP, model input evapotranspiration optionally is reduced by anoxic conditions and by non-vegetated areas not being fully wetted. In IWFM, these reductions are not simulated. Both codes offer the reduction of evapotranspiration by conditions of wilting.
- Surface runoff from irrigation defined in IWFM by a “fraction of the total irrigation amount,” and in MF-FMP by a “fraction of inefficiency losses related to irrigation,” estimated prior (IWFM) or after (MF-FMP) the calculation of crop -rrigation requirement, respectively.
- Deep percolation defined in MF-FMP as the total inefficiency losses less surface-water runoff (estimated after the calculation of the crop irrigation requirement) and in IWFM as a function of soil moisture (contributing to the crop-irrigation requirement).
- Different representation of stream-groundwater interaction for streams disconnected from groundwater (vertical pressure gradient equal to depth of stream stage plus depth of streambed by MF-FMP but equal to the depth of stream stage by IWFM)
- Physical and economic water budgets are possible in both codes but dependent on different smallest units of simulation of land-surface and root-zone flow processes (in IWFM, “subregion;’” in MF-FMP, “farm,” collapsible down to one finite different cell).

## Example Problem

A hypothetical example problem is simulated using MF-FMP and IWFM. Though some features of each simulation code are not used, the example problem illustrates the basic features needed for many regional hydrologic models, which include simulations of surface-water and groundwater supplies that are delivered to meet the water demand from irrigated agriculture, as well as the consumption of water by natural vegetation. However, some suppressed features may be important in the real world for specific hydrologic settings or supply and demand architectures. For further details on additional features, the reader is referred to the documentation for MF-FMP (Schmid et al., 2006a, b; Schmid and Hanson, 2009a, b; Harbaugh et al., 2000; Harbaugh, 2005) and for IWFM (Dogrul, 2009a, b).

Some simulation techniques of one code use static approaches by means of user-specified constants, while the other code simulates the same components over space and/or time dynamically. In order to dampen extreme differences between the two codes, and to maximize the effects on groundwater, surface water, and landscape supply and demand components, dynamic elements of each code are not used or are significantly restricted. For MF-FMP, the dynamic link between head-dependent root water uptake and changes in groundwater levels is restricted by creating initial water-level conditions below the sum of root zone and capillary fringe. The groundwater pumpage is drawn from a single aquifer (i.e. model layer) in both models. For IWFM, the dynamic simulation of soil moisture changes is restricted for irrigated farms by minimizing the soil-moisture depletion. That is, for irrigated farms in IWFM, a zero maximum allowable depletion (MAD) is specified and the soil moisture was held at field capacity. However, depletion in soil-moisture storage was simulated for non-irrigated areas.

## Steady-State Model

The objective of the steady-state model was to create initial conditions for the transient model prior to operation of wells, while including surface-water diversion as simulated in the transient model. The example problem is based on a common hydrologic framework, with one unconfined aquifer and three confined homogeneous and isotropic aquifers, represented by four geologic layers separated by three confining beds below layers 1, 2, and 3 (fig. 1). No-flow boundaries are defined along the northern and southern boundaries for all layers and for the eastern and western boundaries of the confined aquifers in layers 1, 2, and 3. General-head boundaries are specified for the eastern and western boundaries of the unconfined aquifer in layer 1, such that the desired simulated head at each boundary is 5 meters below the ground-surface elevation and a mass balance is kept between the inflow at the upper and the outflow at the lower boundary. A common network of streams, canals, and tributaries are used (fig. 2). For the steady-state model, stream inflow and diversion rates are simulated as specified for the first year (fig. 2) of the transient model. The model domain represents an alluvial valley with a slight inclination from west to east, so that the streamflow in canals flows down the sloped land surface from gravity (fig. 1 and fig. 3a). Heads generated by the steady-state simulation (figs. 3b and 3c) are used as initial heads for the transient simulation.

**Figure 1.** Stratigraphy and layer properties for the example problem.

Layer 1:
- unconfined
- $S_y$ = 0.01
- K = 5 m/d

Confining bed at bottom of layer 1:
- $K_v$ = 0.0001 m/d

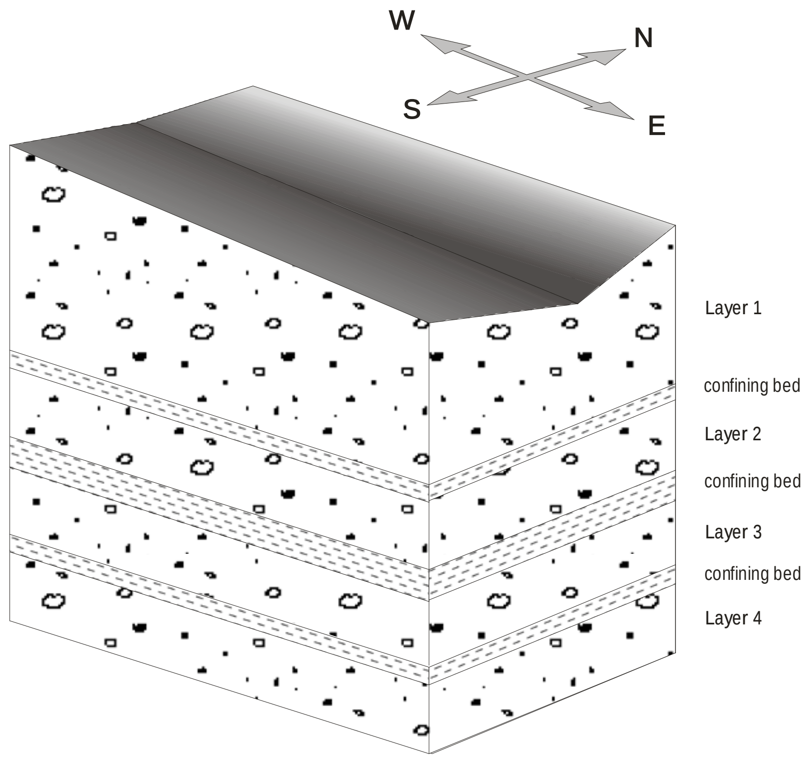
Layer 2:
- confined
- $S_s$ = 0.00001 $m^{-1}$
- T = 200. $m^2$/d

Confining bed at bottom of layer 2:
- $K_v$ = 0.0001 m/d

Layer 3:
- confined
- $S_s$ = 0.00001 $m^{-1}$
- T = 40 $m^2$/d

Confining bed at bottom of layer 3:
- $K_v$ = 0.0001 m/d

Layer 4:
- confined
- $S_s$ = 0.00001 $m^{-1}$
- T = 20. $m^2$/d



## Transient Model

The transient-state simulation adds water-balance subregions (herein referred to as "farms") to the example problem, with a distribution of crop type and associated crop-water-demand driven streamflow diversions, groundwater pumping, and surface or subsurface return flows. The transient simulation spans a period of two years, starting in January of year one, with eight three-month stress periods and weekly time steps. MF-FMP and IWFM input data sets for the example problem are extensive and are not included in this report, but can be made available by request to the authors.

The example includes six farms and a total of twelve farm wells (fig. 2). Some of the farm wells are coincident with the contiguous farm areas, but several are located in areas that do not coincide with farm areas. The example also includes six crop or land-use types (alfalfa, pecans, onions, urban landscape, native vegetation, and riparian vegetation) characterized by a spatial pattern that does not change over time, that is, without any crop rotation, fallow periods, or changing land use (fig. 4). Three soil types are represented by silt, silty clay, and sandy loam (fig. 5). Farm 5 and Farm 6 are "virtual farms" representing irrigated urban landscape vegetation and non-irrigated natural vegetation (native and riparian), respectively. For the urban area, non-irrigation water use, e.g., domestic or industrial water use, is not simulated.

In the example model, known non-routed deliveries are available as the primary source of water supply. The problem simulates four types of non-routed deliveries to Farms 1–5 that could represent separate and different deliveries from, for example, federal and state agencies, irrigation districts, municipalities, or private water companies.

Routed surface-water deliveries conveyed by two diversion canals (fig. 2) are a secondary source. The diversion canals are part of a river/canal conveyance system comprising eleven segments that receive a constant river stream inflow into the uppermost stream segment (fig. 2). The canal bed elevations are specified as depths below the ground-surface elevation, which are linearly interpolated between the endpoints of the canal segments. For the steady-state and for the first year of the transient simulation, the streamflow into the model area is 50,000 $m^3$/day, and the diversion into each canal is 10,000 $m^3$/day (fig. 2). For the second year, drier conditions are assumed, with a twenty percent drop in stream inflow and diversions (40,000 and 8,000 $m^3$/day, respectively). Irrigated farms, including Farm 5 (urban), do not extend to the irrigation canal or to the river; therefore, surface water can only be conveyed as routed streamflow along a canal to a certain point, where it is then diverted as pipe flow to a farm (semi-routed surface-water deliveries; (fig. 2). Semi-routed surface-water deliveries to upstream Farms 1 and 3 have priority over such deliveries to the respective downstream Farms 2 and 4. No equal or prior appropriation water rights allotments are used.

A third form of irrigation water deliveries are farm wells that are available to supply any additional irrigation demand not met by precipitation or surface water. The maximum capacities of all farm wells are set to very high discharge rates in MF-FMP (100,000 $m^3$/d) to allow pumping only to be limited by the available aquifer storage. In IWFM, pumping cannot be restricted by maximum well-pumping capacities and is limited *a priori* only by the aquifer storage. All farms also receive water as precipitation, which is the first source of water for any period of time prior to estimating demand for any potential irrigated water supplies.

In the example problem, many of the crop, climate, and farm attributes are allowed to vary over time. For example, the root depths, crop consumptive use, precipitation, fractions of transpiration and evaporation from consumptive use, and on-farm irrigation efficiency are specified for each stress period.

For the simulation with MF-FMP, two separate fractions of inefficiency losses to surface-water runoff are specified for each of the six crop or land-use types for the entire simulation: one related to precipitation and another one related to irrigation. For the example model, “fractions of inefficiency losses from irrigation to surface runoff,“ as specified for the MF-FMP data input, are converted to “fractions of the total irrigation amount” for IWFM using equation (3) to account for the expected IWFM input parameters. The surface-water runoff from Farms 1–5 computed by each code is returned to a non-diversion stream reach (drain) nearest to the lowest elevation of a farm (fig. 2). Return flow from virtual Farm 6 (natural vegetation) is distributed over reaches of non-diversion segments located within Farm 6 and prorated by the length of each reach. This feature represents the fully-routed return flows that distribute the return flow over all adjacent non-diversion stream segments for each farm (Schmid and Hanson, 2009b).

For irrigated Farms 1–5, MAD in IWFM was set to zero to replicate the steady-state soil moisture assumption in MF-FMP and the soil moisture was held at field capacity. However, depletion of soil moisture storage was simulated for the non-irrigated area, Farm 6.

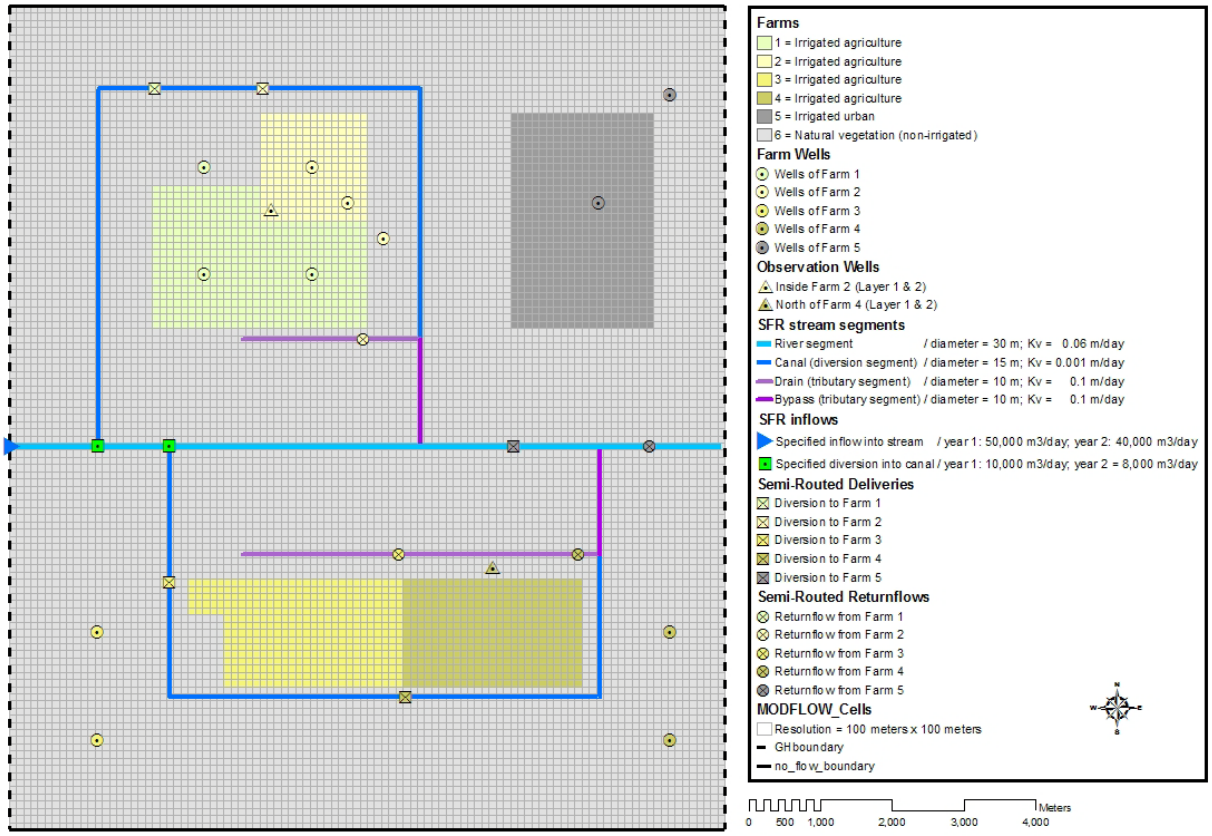
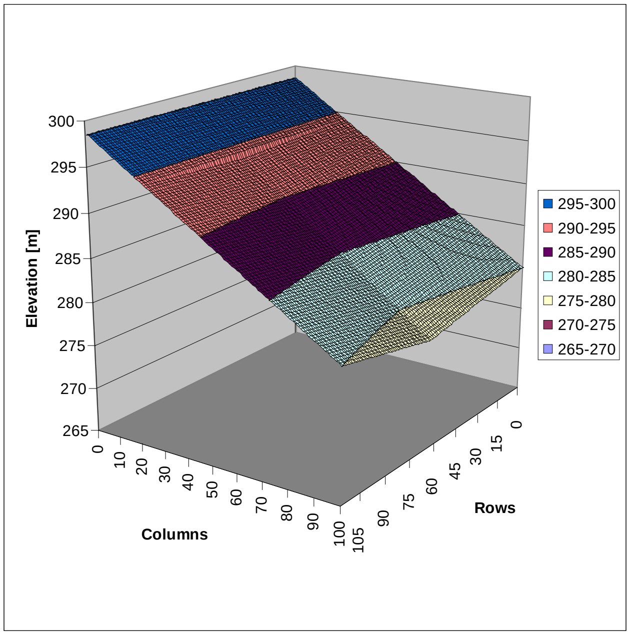
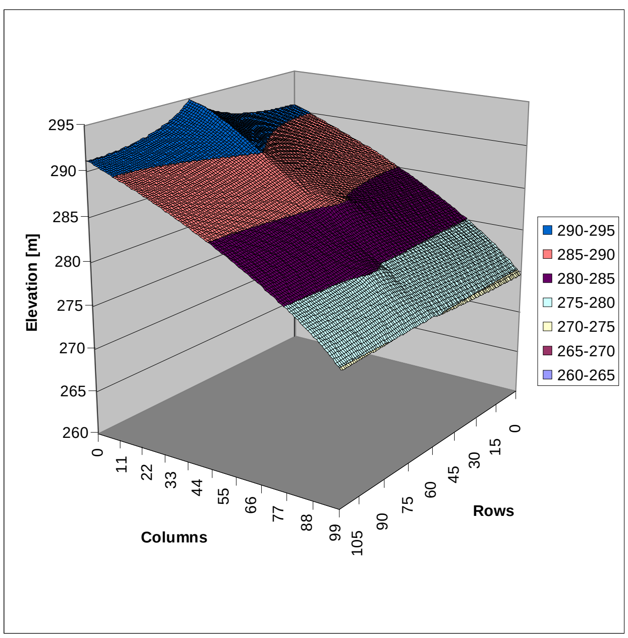



**Figure 2**. Model domain, grid resolution, boundary conditions, distribution of farms and farm wells, and streamflow routing network with points of diversion to farms.

Ground-Surface Elevation (a)




Head Distribution in Unconfined Layer at
Steady State (b) Depth to Water level at Steady State (c)



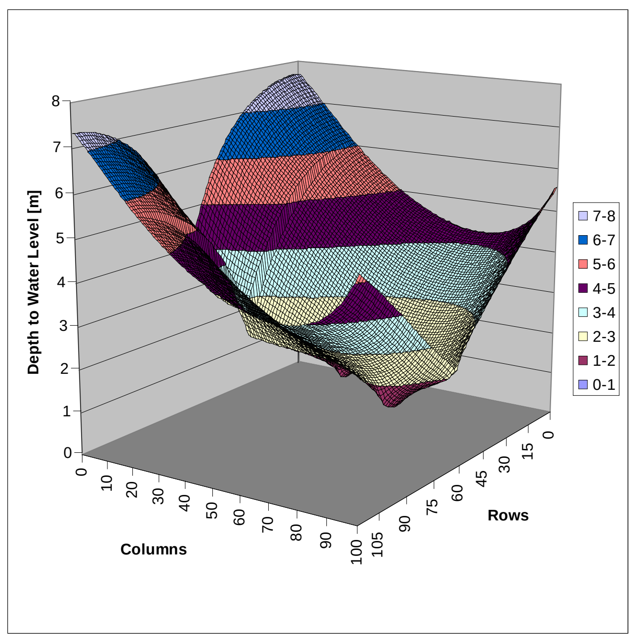




**Figure 3**. (a) Ground-surface elevation, (b) head distribution, and (c) depth to water level of unconfined alluvial aquifer at steady state.

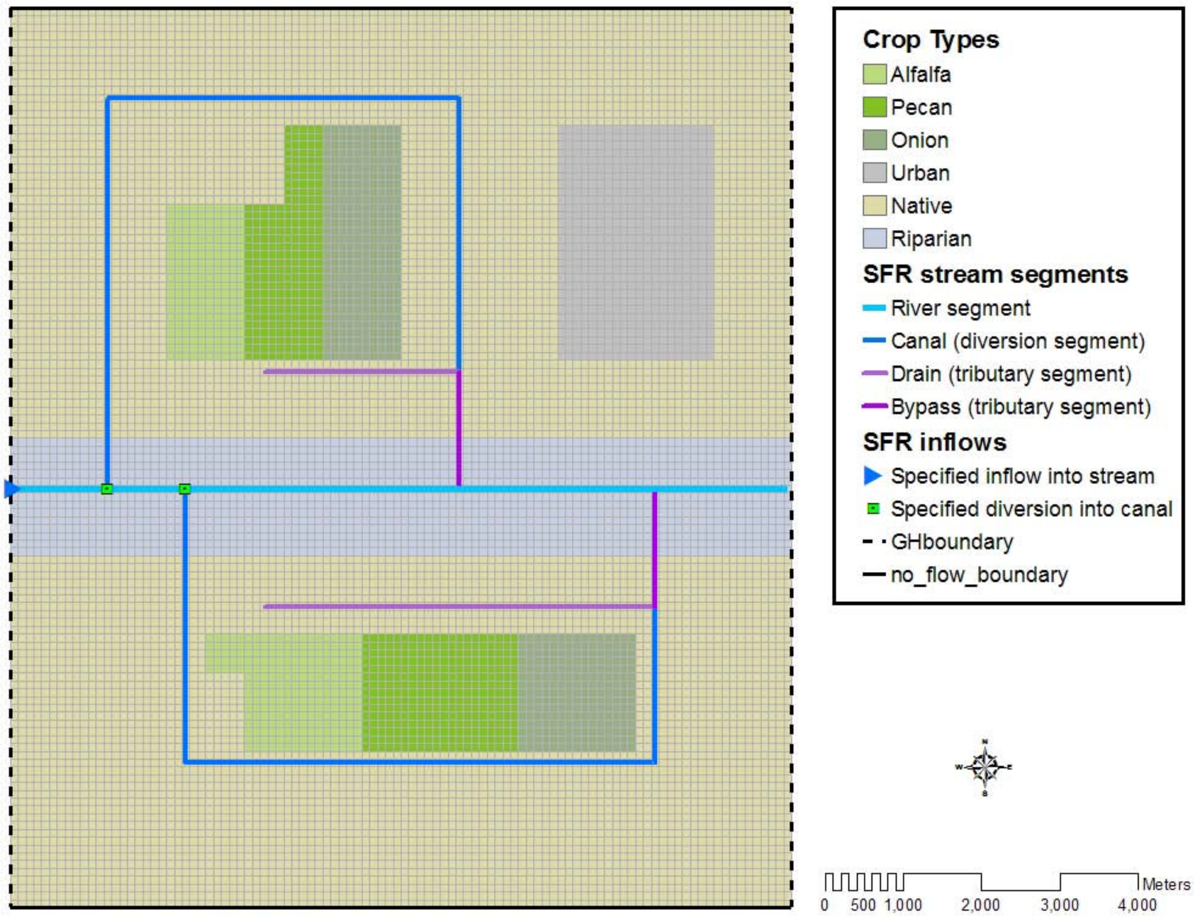



**Figure 4**. Model domain with distribution of crop and land-use types.

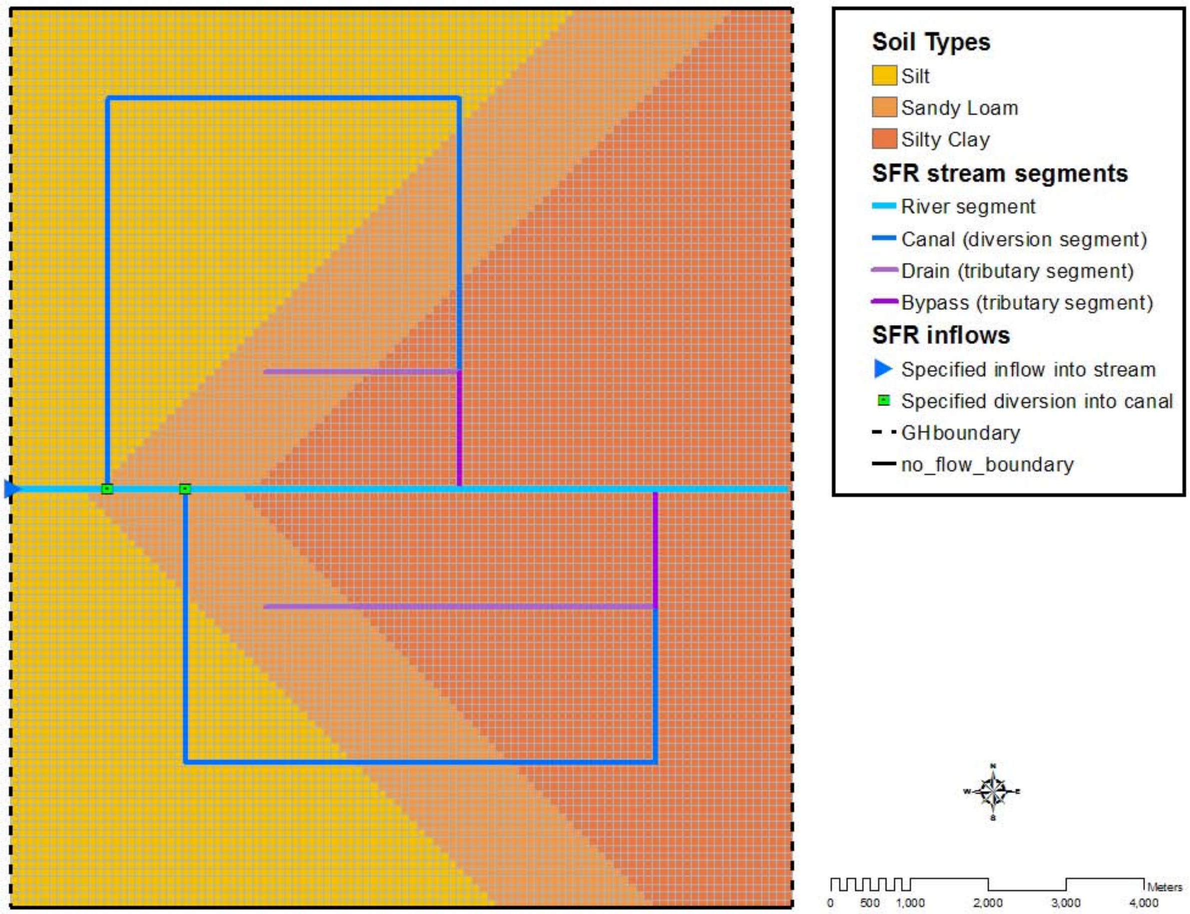



**Figure 5.** Model domain with distribution of soil types.

## Spatial and Temporal References for Comparison

For the transient MF-FMP and IWFM models, water-budget components, streamflows, and water levels at observation wells are compared using common spatial and temporal references to help discern how the two models perform for various parts of the hydrologic flow system. Budget components of water allocation and consumption are probably the most important comparison parameters because these components drive many of the other inflows and outflows.

The first sub-section discusses the comparison of hydrologic budgets. Two different spatial references are used for water-budget comparisons. At the ground surface, water-accounting units (Farms 1–6) are used as spatial reference for an economic balance of irrigation water demand and supply and for a detailed budget of physical flows into and out of a farm. Within the groundwater domain, the entire groundwater model domain and individual zones below each farm represent reference volumes for a budget of all flows into and out of the groundwater.

Time-series of weekly time steps are plotted for the economic balance between the total farm delivery requirement and all available supplies, such as non-routed deliveries, semi-routed deliveries, and farm-well pumping (figs. 6-10). This type of budget demonstrates how well the supply components fulfill the demand side, and how groundwater pumping supplements insufficient surface-water supply. Because effectively no limit is imposed on pumping from the farm wells (maximum well capacity is set to a very large value), the drawdowns in layer 2, over which the wells are screened, can reach the bottom of this aquifer and cause an imbalance between the delivery requirement and the available supply. Inflows of the physical budget of water-accounting units are precipitation, non-routed deliveries, semi-routed deliveries, well pumping, and evapotranspiration from groundwater. Evapotranspiration, runoff, and deep percolation are outflows. For cumulative flow rates of these farm-budget components, correlation diagrams and stacked bar charts are plotted for cumulative flow rates for each farm aggregated over all stress periods (fig. 11) and for each stress period aggregated over all farms (fig 12). In addition, time-series of weekly time steps of actual inflow and outflow components are created (figs. 13-14). For IWFM, changes in soil-water storage also are included in the time series. Then block diagrams of flow rates and cumulative volumes of inflows, outflows, and storage changes for the entire groundwater domain were created. Groundwater inflows and outflows are stream leakage, farm net recharge, farm well pumping, and boundary flows.

The second sub-section discusses water-level comparisons. For the MF-FMP and IWFM models, head distribution maps of the unconfined aquifer in layer 1, and the confined aquifer in layer 2, during the peak growing season in the second year (figs. 17, 18, 19, 20) are provided for comparison of the spatial changes in groundwater storage. Changes in groundwater storage and water-level are generally more pronounced in areas of water-use related stresses than in areas that are subject to less stressed natural flow fields. Hence, time series of water levels are of particular interest in areas dominated by water-use related stresses. However, because water levels in individual high-discharge production wells may exaggerate differences between the two models, two representative observation wells are used that are located in-between areas with only natural flows and areas of maximum irrigation-related stresses. One observation well is located in the center of a cluster of five production wells belonging to Farm 1 and Farm 2, and the other one is south of a gaining drain and north of Farm 4 (fig. 2, table 1). Because the production wells are pumping from layer 2, hydrographs are obtained for layers 1 and 2 for both observation wells (fig. 21).

The third subsection discusses streamflow comparisons. Streamflow hydrographs are observed (fig. 2, table 1) for flows into and out of diversion reaches (fig. 22-23) and return-flow reaches (fig. 24-25). Diversion reaches are those where diversions of semi-routed deliveries to farms occur. Return-flow reaches are those where return flows enter a reach of the stream network that is nearest to the lowest elevation of a particular farm. For Farms 1–4, return flows enter tributary drains. For Farm 5 (urban), return flow enters a river segment. For Farm 6 (native and riparian vegetation), return flow is prorated over all non-diversion segments. Differences between flows into and out of these stream reaches approximate stream losses related to the diversion of semi-routed deliveries, or gains related to semi-routed return flows, respectively.

This approximation ignores minor gains and losses from surface runoff and stream seepage in the particular reach. Deliveries approximated by this method can highlight periods of streamflow deficiencies to meet the delivery requirements. When the streamflows are sufficient, hydrographs for semi-routed deliveries should be approximately equal to stream inflows minus stream outflows from a reach. When they are insufficient, hydrographs for semi-routed deliveries should match the stream-inflow hydrographs because the entire streamflow will be diverted. Streamflow that is not directly affected by the deliveries or return flows is gauged at the main stem of the river, downstream of all farms between the stream reach that receives the return flow from Farm 5 and the stream outflow from the model at the eastern most stream reach (fig. 2, table 1; fig. 25 as blue dotted line). The streamflow is expected to represent the cumulative effect upstream diversions and return flows have on the river, if gauged downstream of all farms and upstream of the model boundary, where boundary effects may influence the streamflow. Difference in streamflow between MF-FMP and IWFM may not only be related to different rates of return flow, but also stream seepage. Thus, stream seepage for both models also was compared at the main stem of the river at reach 10 of segment 11 (fig. 26).

| **Hydrograph Gauges** | **Spatial Reference in MODFLOW** | | | | | **Spatial Reference in IWFM** |
|---|---|---|---|---|---|---|
| | Layer | Row | Column | | | Groundwater Node |
| Observation wells | 1 | 29 | 37 | | | 2837 |
| | 1 | 79 | 86 | | | 7868 |
| | Farm | Row | Column | Segment | Reach | Stream Node |
| River streamflow and stream seepage | n/a | 62 | 92 | 11 | 10 | 452 |
| Delivery-related streamflow | 1 | 12 | 21 | 2 | 59 | 72 |
| | 1 | 12 | 36 | 2 | 74 | 87 |
| | 1 | 81 | 23 | 6 | 20 | 217 |
| | 1 | 97 | 56 | 6 | 69 | 266 |
| | 1 | 62 | 71 | 10 | 14 | 430 |
| Return-flow-related streamflow | 1,2 | 47 | 50 | 3 | 18 | 162 |
| | 3 | 77 | 55 | 7 | 23 | 336 |
| | 4 | 77 | 80 | 7 | 48 | 361 |
| | 5 | 62 | 90 | 11 | 8 | 450 |

Table 1: Location of hydrograph gauges in MF-FMP and IWFM models

## Comparison of Hydrologic Budgets

The hydrologic system depicted in fig. 2 is driven mainly by the imposed boundary conditions and by water demands computed for each of the farms. Any difference in the groundwater heads and streamflows simulated by MF-FMP and IWFM can be attributed partly to the different conceptualization and techniques used in both models for the simulation of water demands, root zone, and overland-runoff processes, and partly to the differences in streamflow routing methods. For this reason, economic and physical hydrologic budgets for the farms produced by each model will be compared first. Then, resulting differences in groundwater and streamflow patterns will be analyzed with the aide of ZONEBUDGET (Harbaugh, 1990) for MF-FMP and Z-BUDGET (Dogrul, 2007) for IWFM.

### *Hydrologic Budgets of Irrigated Water-Accounting Units*

Time-series of farm-water demand and supply show how each model simulates the total requested delivery requirement (i.e. demand) for each farm and the available supply components. Both MF-FMP and IWFM define demand as the irrigation water necessary to satisfy crop evapotranspiration requirements that are not met by precipitation and, in MF-FMP's case, uptake from groundwater, increased sufficiently to compensate for the inefficiency losses to deep percolation and to runoff return flow. However, the conceptual approach to computing the crop evapotranspiration requirement, the sources of water to meet this requirement, and the inefficiency losses, differ between the two models as summarized in section "Overview of MF-FMP and IWFM Concepts," or described in more detail in Dogrul et al. (2011).

Even though there are differences between the two models as described above, they are able to simulate a similar dynamic and hierarchy of the components utilized to meet the water demand in the agricultural areas. That is, in both models, farms are supplied in priority order by non-routed deliveries, by semi-routed surface-water diversions, and by groundwater pumping (figs. 6-10). However, the models treat the allocation of non-routed water transfers slightly differently. In IWFM, the entire amount of non-routed deliveries is utilized because the requested demand is always higher than the potentially available non-routed deliveries. In MF-FMP, the demands are somewhat lower than in IWFM and, consequently, occasionally lower than the available non-routed deliveries. MF-FMP is implicitly demand-driven but supply-constrained. Therefore, it uses only the lesser of the requested demand and the specified non-routed deliveries toward satisfying the total farm delivery requirement. For Farms 2 and 3, in stress period 1 of year 1, specified non-routed deliveries slightly exceed the requested demand, and the excess water is not delivered, which reduces the actual non-routed deliveries to the lesser demands (fig. 7 and 8). If, optionally, the user specifies to deliver excess non-routed deliveries, then a secondary choice would have to be made whether to dispose the excess water either to the groundwater or to the stream network. Similarly, IWFM can be run in either “full supply” or “supply adjustment” mode to adjust the surface-water deliveries and groundwater pumping to meet the irrigation water demand. However, for the sake of comparison with MF-FMP, only semi-routed deliveries and groundwater pumping were adjusted, and non-routed deliveries were kept at user-specified values. In this example, IWFM delivers all non-routed deliveries as specified and, potentially, can use any amount in excess of the delivery requirement to resupply soil moisture or simulate additional deep percolation.

Even though the demand generally is higher in IWFM, the farms located upstream along the canals receive sufficient surface water in both models and do not need much supplemental groundwater pumping. In the example, the simulated final groundwater-pumping rate always meets the pumping requirement (Farms 1 and 3; fig. 6 a, b and fig. 7 a, b).

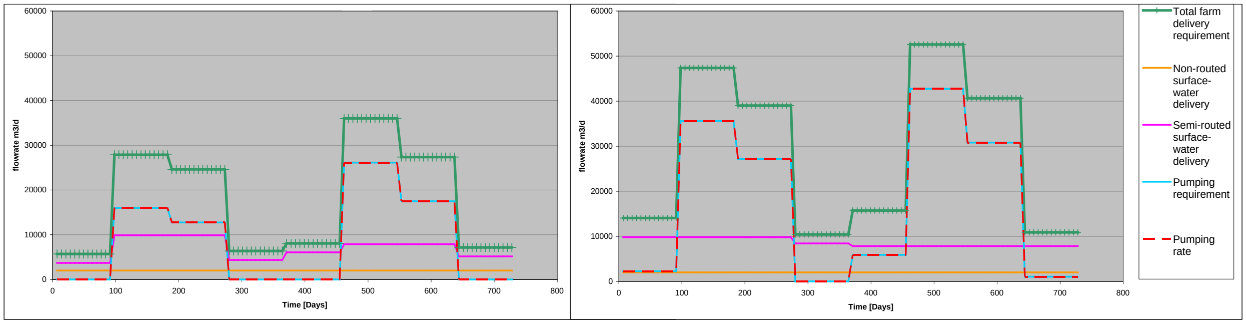



**Figure 6:** Time series of Demand and Supply of Farm 1 by MF-FMP (a: left) and IWFM (b: right).

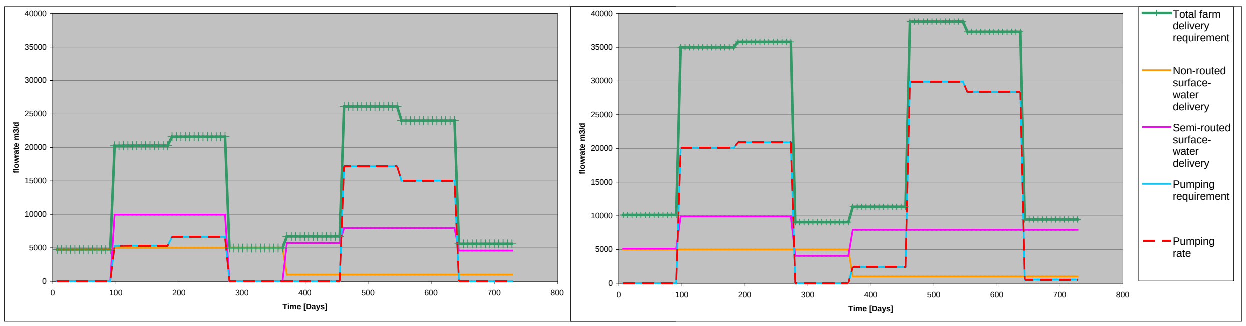



**Figure 7:** Time series of Demand and Supply of Farm 3 by MF-FMP (a: left) and IWFM (b: right)

In both models, farms located downstream from the canals can receive semi-routed surface water only during non-growing seasons and are entirely dependent on water transfers and groundwater supplies during growing seasons (Farms 2 and 4, figs. 8 and 9).

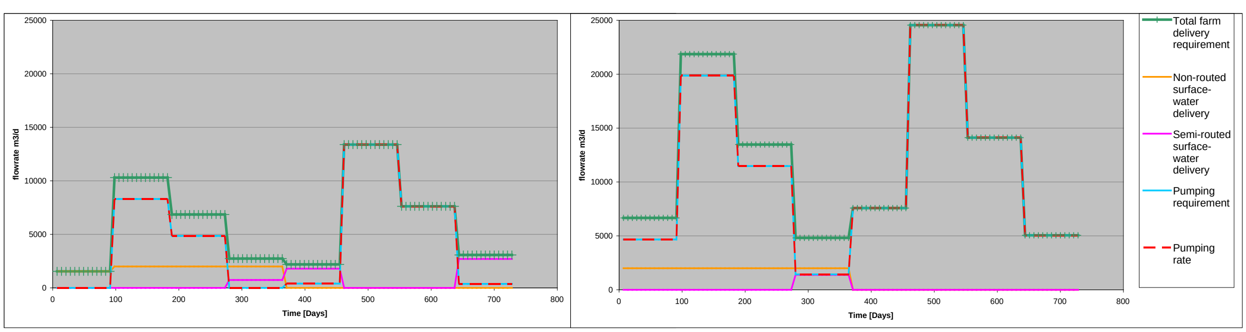



**Figure 8:** Time series of Demand and Supply of Farm 2 by MF-FMP (a: left) and IWFM (b: right)

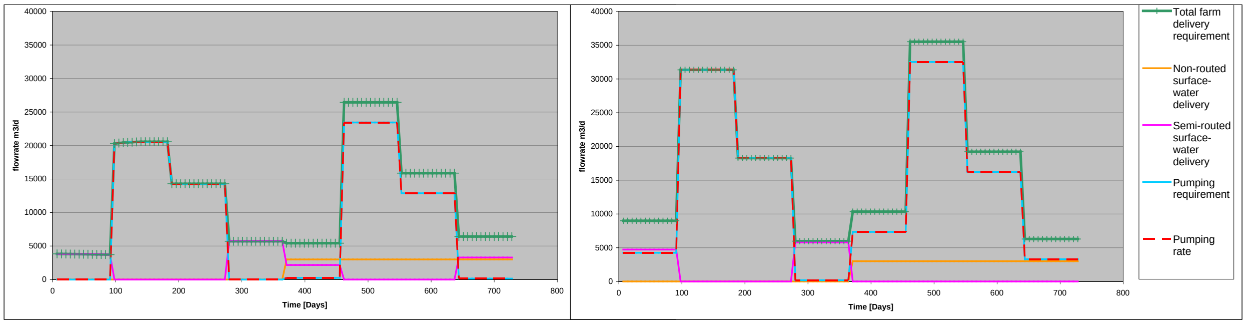



**Figure 9:** Time series of Demand and Supply of Farm 4 by MF-FMP (a: left) and IWFM (b: right)

Significant differences occur between the two models for times of groundwater deficiency at the most downstream agricultural Farm 4 and the urban area, Farm 5 (fig. 9 and 10). In IWFM, higher demands lead to groundwater overdraft and to a depletion of the aquifer in layer 2, over which all wells in both models are screened.

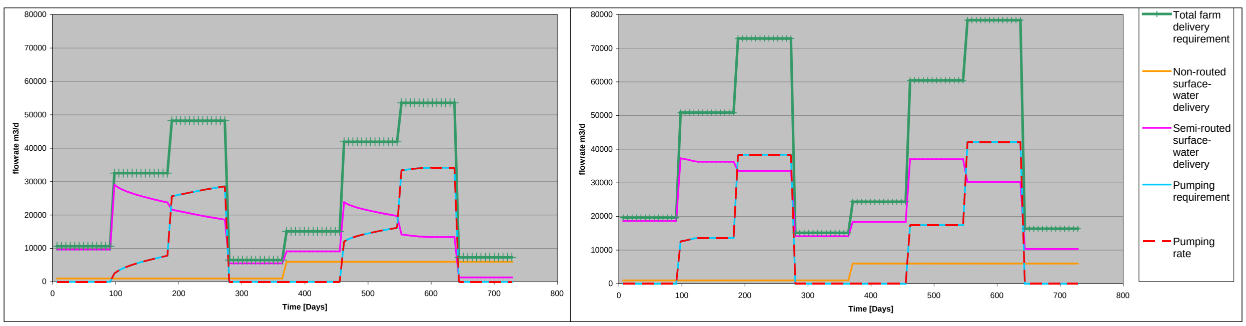



**Figure 10:** Time series of Demand and Supply of Farm 5 by MF-FMP (a: left) and IWFM (b: right)

*Physical Hydrologic Budgets of Irrigated and Non-Irrigated Water-Accounting Units*

Two types of correlation diagrams and stacked bar charts were generated, where cumulative flow rates of farm budget components were plotted for each farm, aggregated over all stress periods (comparison by farms; fig. 11), and for each stress period, aggregated over all farms (comparison by stress periods; fig 12). The correlation diagrams (figs. 11 a, 12 a) allow for quantification of the similarities between models, as well as the detection of differences, and whether seasonal or farm-based aspects are responsible for these differences. The slope and the regression coefficient of a best-fit line for each farm budget component numerically demonstrate how output from the models compares.

In addition, the correlation of the two models by stress periods or by farms is numerically demonstrated by the Pearson's Correlation Coefficient, RSQ, (tables 2 and 3) which, for linear regressions, is equal to the regression coefficient $R^2$ (figs. 11 a, 12 a). In general, the models are more correlated to each other when comparing budget flow rates of farms aggregated over all stress periods than budget flow rates of each stress period aggregated over all farms.

For budget flow rates of farms aggregated over all stress periods, most parameters of the two models correlate reasonably well when comparing by farms (table 2), but reveal a range of high discrepancies from farm to farm between the MF-FMP and IWFM model results. The discrepancy between MF-FMP and IWFM parameters is defined as follows:

Discrepancy [%] = ([MF-FMP – IWFM] / [(MF-FMP + IWFM) / 2])* 100 (4)

For instance, for the semi-routed deliveries, Q-srd-in, the range stretches from –61 to +116 % for Farms 5 and 2, respectively, even though the overall RSQ for this parameter for all farms is 97%. With respect to surface-water allocations, the models are well correlated. The fluctuation of discrepancies reveals the “ripple” effect that a change in demand has on surface-water deliveries to un-appropriated deliveries at downstream farms, where deliveries to upstream farms are prioritized. That is, in IWFM, higher demands lead to higher diversions in upstream farms, compared to MF-FMP, and leave less water available to downstream farms than in MF-FMP. Therefore, the upstream farms are characterized by negative discrepancies between semi-routed deliveries computed by MF-FMP and IWFM, and by positive ones for downstream farms.

For budget flow rates of farms aggregated over all stress periods, the lowest correlation was observed for farm-well pumping, Q-wells-in, with an RSQ of 81% (table 2). Supplemental farm-well pumping depends on availability of higher-priority delivery components, such as semi-routed deliveries. The main reason for the low RSQ likely resides in the accordingly different residual demands for supplemental groundwater from upstream to downstream farms.

| | FID | Q-p-in | Q-nrd-in | Q-srd-in | Q-wells-in | Q-etgw-in | Q-tot-in | Q-et-out | Q-run-out | Q-dp-out | Q-tot-out | Q-storage-change | Q-in-minus-out | Discre-pancy [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MF2K | 1 | 1,504,913 | 1,456,000 | 4,987,729 | 6,581,502 | 0 | 14,530,144 | 9,629,155 | 2,349,759 | 2,551,230 | 14,530,144 | 0 | 0 | 0.00% |
| | 2 | 644,963 | 686,873 | 476,219 | 3,179,905 | 0 | 4,987,959 | 2,960,733 | 1,080,412 | 946,814 | 4,987,959 | 0 | 0 | 0.00% |
| | 3 | 1,146,600 | 2,156,903 | 4,198,106 | 4,018,661 | 575 | 11,520,845 | 8,958,743 | 1,149,951 | 1,412,151 | 11,520,845 | 0 | 0 | 0.00% |
| | 4 | 1,074,938 | 1,092,000 | 1,356,066 | 6,507,395 | 7,276 | 10,037,674 | 6,750,348 | 1,765,062 | 1,522,264 | 10,037,674 | 0 | 0 | 0.00% |
| | 5 | 1,719,900 | 2,548,000 | 9,585,966 | 7,510,106 | 231 | 21,364,203 | 14,849,555 | 4,885,986 | 1,628,662 | 21,364,203 | 0 | 0 | 0.00% |
| | 6 | 26,873,438 | 0 | 0 | 0 | 84,495 | 26,957,933 | 26,334,153 | 295,883 | 327,897 | 26,957,933 | 0 | 0 | 0.00% |
| IWFM | 1 | 1,590,907 | 1,456,000 | 6,297,628 | 13,241,682 | 0 | 22,586,217 | 16,475,547 | 3,942,027 | 2,168,643 | 22,586,217 | 0 | 0 | 0.00% |
| | 2 | 733,824 | 728,000 | 126,040 | 8,074,484 | 0 | 9,662,348 | 6,342,337 | 2,242,041 | 1,077,969 | 9,662,348 | 0 | 0 | 0.00% |
| | 3 | 1,278,459 | 2,184,000 | 5,524,594 | 9,298,938 | 0 | 18,285,991 | 14,903,619 | 1,791,830 | 1,590,541 | 18,285,991 | 0 | 0 | 0.00% |
| | 4 | 1,146,600 | 1,092,000 | 957,447 | 10,325,930 | 0 | 13,521,977 | 9,827,999 | 2,527,690 | 1,166,288 | 13,521,977 | 0 | 0 | 0.00% |
| | 5 | 1,866,091 | 2,548,000 | 18,086,634 | 10,130,162 | 0 | 32,630,887 | 22,985,518 | 7,751,503 | 1,893,866 | 32,630,887 | 0 | -0 | 0.00% |
| | 6 | 25,735,437 | 0 | 0 | 0 | 0 | 25,735,437 | 25,281,372 | 0 | 47 | 25,281,419 | -430,966 | 454,018 | 0.09% |
| MF2K minus IWFM | 1 | -85,995 | 0 | -1,309,898 | -6,660,180 | 0 | -8,056,073 | -6,846,392 | -1,592,268 | 382,587 | -8,056,073 | -0 | | |
| | 2 | -88,861 | -41,127 | 350,179 | -4,894,579 | 0 | -4,674,389 | -3,381,604 | -1,161,629 | -131,156 | -4,674,389 | 0 | | |
| | 3 | -131,859 | -27,097 | -1,326,488 | -5,280,277 | 575 | -6,765,146 | -5,944,876 | -641,879 | -178,390 | -6,765,146 | -0 | | |
| | 4 | -71,662 | 0 | 398,619 | -3,818,535 | 7,276 | -3,484,303 | -3,077,650 | -762,628 | 355,976 | -3,484,303 | 0 | | |
| | 5 | -146,191 | 0 | -8,500,668 | -2,620,055 | 231 | -11,266,684 | -8,135,963 | -2,865,517 | -265,204 | -11,266,684 | 0 | | |
| | 6 | 1,138,001 | 0 | 0 | 0 | 84,495 | 1,222,496 | 1,052,781 | 295,883 | 327,851 | 1,676,515 | 430,966 | | |
| Ratio: MF2K IWFM [%] | 1 | 94.59% | 100.00% | 79.20% | 49.70% | n/a | 64.33% | 58.45% | 59.61% | 117.64% | 64.33% | n/a | | |
| | 2 | 87.89% | 94.35% | 377.83% | 39.38% | n/a | 51.62% | 46.68% | 48.19% | 87.83% | 51.62% | n/a | | |
| | 3 | 89.69% | 98.76% | 75.99% | 43.22% | n/a | 63.00% | 60.11% | 64.18% | 88.78% | 63.00% | n/a | | |
| | 4 | 93.75% | 100.00% | 141.63% | 63.02% | n/a | 74.23% | 68.68% | 69.83% | 130.52% | 74.23% | n/a | | |
| | 5 | 92.17% | 100.00% | 53.00% | 74.14% | n/a | 65.47% | 64.60% | 63.03% | 86.00% | 65.47% | n/a | | |
| | 6 | 104.42% | n/a | n/a | n/a | n/a | 104.75% | 104.16% | n/a | 699569.52% | 106.63% | n/a | | |
| Dis-crepancy [%] | 1 | -5.56% | 0.00% | -23.21% | -67.20% | n/a | -43.41% | -52.45% | -50.61% | 16.21% | -43.41% | n/a | | |
| | 2 | -12.89% | -5.81% | 116.29% | -86.98% | n/a | -63.81% | -72.70% | -69.93% | -12.96% | -63.81% | n/a | | |
| | 3 | -10.87% | -1.25% | -27.29% | -79.30% | n/a | -45.39% | -49.83% | -43.64% | -11.88% | -45.39% | n/a | | |
| | 4 | -6.45% | 0.00% | 34.46% | -45.37% | n/a | -29.58% | -37.13% | -35.53% | 26.48% | -29.58% | n/a | | |
| | 5 | -8.15% | 0.00% | -61.44% | -29.71% | n/a | -41.73% | -43.01% | -45.35% | -15.06% | -41.73% | n/a | | |
| | 6 | 4.33% | n/a | n/a | n/a | n/a | 4.64% | 4.08% | n/a | 199.94% | 6.42% | n/a | | |
| RSQ | | **1.00** | **1.00** | **0.97** | **0.81** | **n/a** | **0.75** | **0.84** | **0.98** | **0.85** | **0.73** | **n/a** | | |

Table 2: Farm-Budget components for each farm aggregated over all stress periods

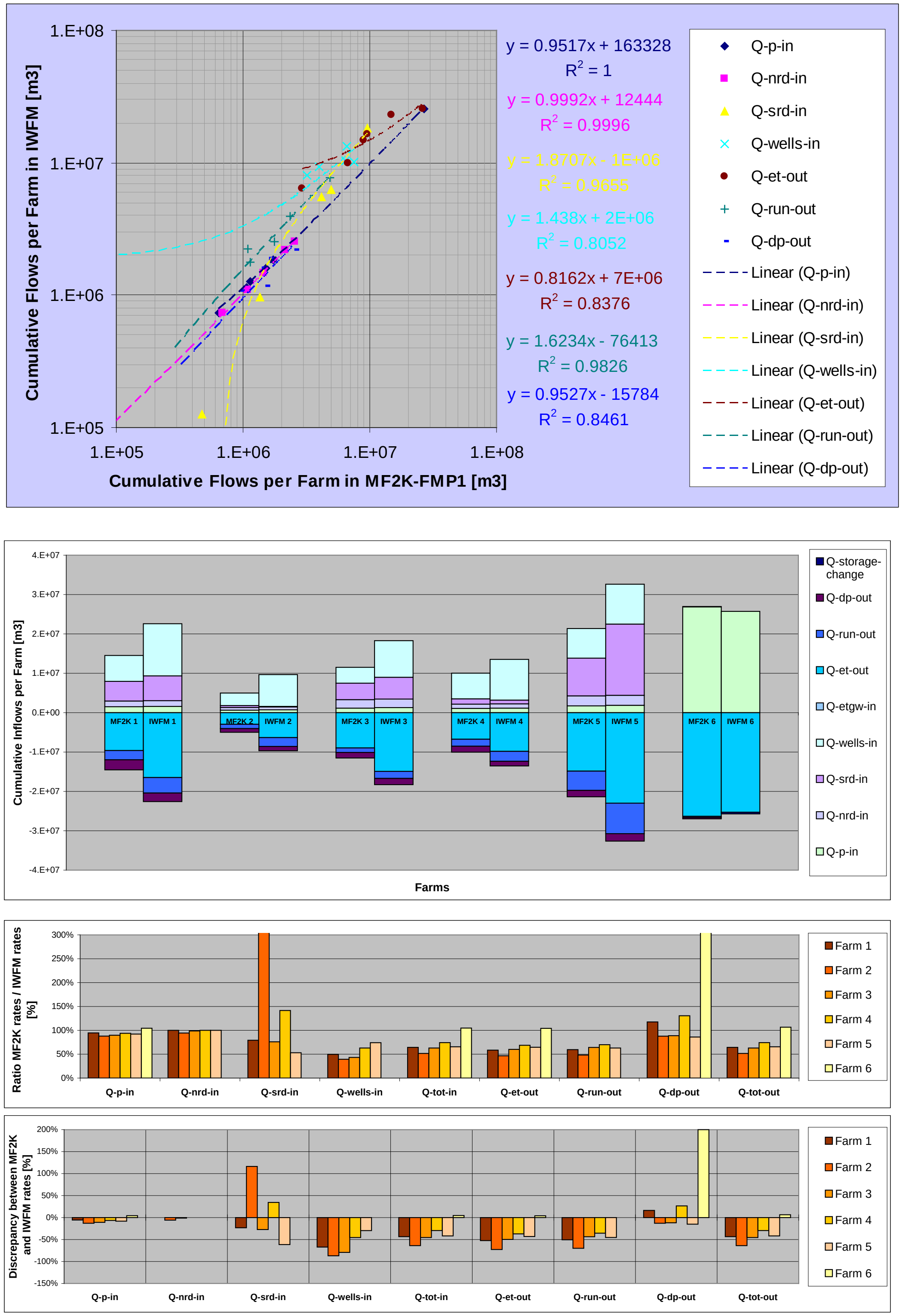



**Figure 11**. a, b, c, d: Farm-Budget components for each farm aggregated over all stress periods ((a) linear regressions for input and output components of the landscape for the entire model region, (b) cumulative inflow and outflows, (c) ratios of MF-FMP to IWFM rates, and (d) discrepancies between MF-FMP and IWFM rates).

For budget flow rates of stress periods aggregated over all farms, the lowest correlation was observed for the deep percolation, Q-dp-out, with an RSQ of only 6%. This is a result of the nearly constant deep percolation flow rates in IWFM for all stress periods, (fig. 13; dotted maroon line for Farm 1) and the fact that in MF-FMP deep percolation is proportional to simulated inefficiency losses (table 3). The reason for constant deep percolation in IWFM is, for this model comparison exercise, the MAD in Farms 1–5 are set to zero to replicate the assumption of steady-state conditions adopted by MF-FMP. This leads to an additional demand to replenish soil moisture, which is refilled to field capacity. As described in the previous section, IWFM computes deep percolation as a function of soil moisture. Therefore, constant soil moisture at field capacity produces a constant deep percolation, and related water demand, to supply water for restoring soil moisture to field capacity. Constraining the soil moisture at field capacity generates higher deep percolation rates than if MAD were set to a more realistic value.

Another parameter of low correlation per stress period is the evapotranspiration, Q-et-out, with an RSQ of merely 42% when aggregated over all farms. In contrast, the same parameter is well correlated per farm (table 2) with an RSQ of 84% when aggregated over all stress periods. Evapotranspiration in IWFM depends on storage changes, which occur in the non-irrigated area, Farm 6 (fig. 14). For all the irrigated farms, the actual evapotranspiration, Q-et-out, is consistently less in MF-FMP than IWFM (table 2). MF-FMP computes, on average, 72% of the total actual evapotranspiration calculated in IWFM, which propagates into 62% of supplied water (sum of Q-nrd-in, Q-srd-in, Q-wells-in) in MF-FMP versus IWFM. For irrigated farms only, evapotranspiration is highly correlated, with an RSQ of 98%, but MF-FMP computes, on average, only 61% of the IWFM ET-rates as a result of MF-FMP reducing the evapotranspirative requirement due to anoxia, or wilting, and irrigation non-uniformity, as opposed to IWFM trying to meet the evapotranspirative requirements specified by the user. Additional factors that may reduce evapotranspiration (such as known soil drainage problems, salinity, plant diseases, etc) related to the plants or cropping patterns are included in these user-specified values in IWFM, resulting in the need for the user to specify an adjusted ET and not a potential ET. Unlike MF-FMP, however, IWFM does not simulate a reduction of potential evapotranspiration or the effects of groundwater levels in meeting part of the evapotranspirative requirements on a cell-by-cell basis (i.e. localized conditions). When the amount of water in the system is not sufficient to meet the evapotranspirative requirements, such as Farm 6 in the current example, the correlation between the results of the two models becomes less predictable because the models compute reduced actual evapotranspiration using different assumptions and methods. Overall, if compared stress period by stress period, changes in soil moisture storage create significant differences that can be important, but compared farm by farm over the entire period of two years, the differences are not significant.

In the absence of irrigation, the IWFM simulated evapotranspiration rate equals the potential rate as long as there is sufficient soil moisture in the root zone but the rate is reduced when soil moisture is depleted beyond a certain point. . However, for Farm 6 as well as the rest of the farms where MAD is set to 0%, the net soil-water storage change in IWFM is close to zero for the entire period of two hydrologic years. In addition, the total evapotranspiration rate for Farm 6 simulated by IWFM and MF-FMP is almost equal (table 2; fig. 11b). Hence, the correlation of evapotranspiration accumulated over the entire simulation increases between the two models.

In IWFM, stresses on the plants due to lack of water are simulated by the method described by Allen et al. (1998). Evapotranspiration is reduced if soil moisture falls below one-half of field capacity (parameter *p* defined by Allen et al. (1998) is set to 0.5 for all crops). This situation occurs in the non-irrigated Farm 6. The sole source of water (other than moisture in storage) for Farm 6 is precipitation, which is not sufficient to meet plant evapotranspirative requirements as simulated by IWFM. In this situation, part of the evapotranspirative requirement is met by the moisture in storage, eventually reducing the moisture content below half of field capacity, stressing the plants, and thereby reducing evapotranspiration (ET). Thus, reduced ET in IWFM is driven by reduced soil moisture. For all farms, except Farm 6, the actual evapotranspiration, Q-et-out, is consistently less in MF-FMP than IWFM (table 2). MF-FMP computes, on average, 72% of the total actual evapotranspiration calculated in IWFM, which propagates into 62% of supplied water (sum of Q-nrd-in, Q-srd-in, Q-wells-in) in MF-FMP versus IWFM. For irrigated farms only, evapotranspiration is highly correlated, with an RSQ of 98%, but MF-FMP computes, on average, only 61% of the IWFM ET-rates as a result of MF-FMP reducing the evapotranspirative requirement due to anoxia, or wilting, and irrigation non-uniformity, as opposed to IWFM trying to meet the evapotranspirative requirements specified by the user. Additional factors that may reduce evapotranspiration (such as known soil drainage problems, salinity, plant diseases, etc) related to the plants or cropping patterns are included in these user-specified values in IWFM, resulting in the need for the user to specify an adjusted ET and not a potential ET. Unlike MF-FMP, however, IWFM does not simulate a reduction of potential evapotranspiration or the effects of groundwater levels in meeting part of the evapotranspirative requirements on a cell-by-cell basis (i.e. localized conditions). When the amount of water in the system is not sufficient to meet the evapotranspirative requirements, such as Farm 6 in the current example, the correlation between the results of the two models becomes less predictable because the models compute reduced actual evapotranspiration using different assumptions and methods. Overall, if compared stress period by stress period, changes in soil moisture storage create significant differences that can be important, but compared farm by farm over the entire period of two years, the differences are not significant.

Other output parameters of the two models correlate reasonably well for all stress periods (aggregated over all farms), but reveal a range of large discrepancies from stress period to stress period between the MF-FMP and IWFM models. For instance, for farm-well pumping, Q-wells-in, the range of discrepancies stretches from -189 to -41 % for stress periods 5 and 7, respectively, even though the overall RSQ for this parameter for all stress periods is 97%. Farm-well pumping per stress period accumulated over all farms correlates much better (RSQ = 97%) than farm-well pumping per farm accumulated over all stress periods (RSQ = 81%). The farm-well pumping occurs in wells associated with particular farms but often is located outside the domain of the respective farm and is heavily influenced by the groundwater flow field around those wells, which responds to sources and sinks related to other farms, the surface-water conveyance system, and the general head boundary condition. Therefore, during any stress period, one would not expect that the cumulative pumping effects of all farms would be proportionally correlated between the two models.

| | PER | Q-p-in | Q-nrd-in | Q-srd-in | Q-wells-in | Q-etgw-in | Q-tot-in | Q-et-out | Q-run-out | Q-dp-out | Q-tot-out | Q-storage-change | Q-in-minus-out | Discre-pancy [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MF2K | 1 | 3,139,500 | 844,500 | 1,555,070 | 0 | 36,938 | 5,576,008 | 4,401,377 | 666,671 | 507,959 | 5,576,008 | 0 | 0 | 0.00% |
| | 2 | 1,569,750 | 910,000 | 4,126,213 | 5,110,277 | 52,325 | 11,768,566 | 9,239,658 | 1,503,955 | 1,024,953 | 11,768,566 | 0 | 0 | 0.00% |
| | 3 | 4,186,000 | 910,000 | 3,594,219 | 6,014,124 | 124 | 14,704,467 | 12,253,587 | 1,479,382 | 971,498 | 14,704,467 | 0 | 0 | 0.00% |
| | 4 | 8,372,000 | 907,275 | 1,485,782 | 0 | 23 | 10,765,081 | 9,533,820 | 617,800 | 613,461 | 10,765,081 | 0 | 0 | 0.00% |
| | 5 | 3,139,500 | 1,092,000 | 2,260,914 | 59,670 | 893 | 6,552,978 | 4,403,462 | 1,250,964 | 898,552 | 6,552,978 | 0 | 0 | 0.00% |
| | 6 | 0 | 1,092,000 | 3,358,577 | 8,641,571 | 2,274 | 13,094,423 | 7,863,519 | 3,054,392 | 2,176,512 | 13,094,423 | 0 | 0 | 0.00% |
| | 7 | 4,186,000 | 1,092,000 | 2,670,217 | 7,924,831 | 0 | 15,873,048 | 12,253,463 | 2,167,998 | 1,451,587 | 15,873,048 | 0 | 0 | 0.00% |
| | 8 | 8,372,000 | 1,092,000 | 1,553,093 | 47,097 | 0 | 11,064,190 | 9,533,802 | 785,891 | 744,496 | 11,064,190 | 0 | 0 | 0.00% |
| IWFM | 1 | 3,081,078 | 910,000 | 3,488,707 | 1,016,383 | 0 | 8,496,168 | 5,086,724 | 1,183,596 | 987,168 | 7,257,488 | -1,238,680 | 1,238,680 | 0.00% |
| | 2 | 1,540,539 | 910,000 | 5,112,606 | 10,946,230 | 0 | 18,509,375 | 18,763,968 | 2,549,880 | 987,174 | 22,301,023 | 3,791,648 | -3,791,648 | 0.00% |
| | 3 | 4,108,104 | 910,000 | 4,848,167 | 10,575,243 | 0 | 20,441,514 | 16,645,049 | 2,480,756 | 987,162 | 20,112,966 | -328,548 | 328,548 | 0.00% |
| | 4 | 8,216,208 | 910,000 | 3,075,049 | 147,039 | 0 | 12,348,296 | 7,816,587 | 884,484 | 987,164 | 9,688,235 | -2,660,061 | 2,660,061 | 0.00% |
| | 5 | 3,081,078 | 1,092,000 | 3,106,093 | 2,114,619 | 0 | 9,393,790 | 5,213,059 | 2,081,219 | 987,197 | 8,281,475 | -1,112,316 | 1,112,316 | 0.00% |
| | 6 | 0 | 1,092,000 | 4,802,321 | 13,389,780 | 0 | 19,284,101 | 18,134,907 | 4,550,116 | 987,162 | 23,672,185 | 4,411,137 | -4,388,084 | 0.11% |
| | 7 | 4,108,104 | 1,092,000 | 4,183,981 | 11,978,524 | 0 | 21,362,610 | 16,353,670 | 3,401,851 | 987,162 | 20,742,683 | -619,927 | 619,927 | 0.00% |
| | 8 | 8,216,208 | 1,092,000 | 2,375,419 | 903,376 | 0 | 12,587,002 | 7,802,429 | 1,123,190 | 987,164 | 9,912,783 | -2,674,219 | 2,674,219 | 0.00% |
| MF2K minus IWFM | 1 | 58,422 | -65,500 | -1,933,637 | -1,016,383 | 36,938 | -2,920,160 | -685,346 | -516,925 | -479,209 | -1,681,481 | 1,238,680 | | |
| | 2 | 29,211 | 0 | -986,392 | -5,835,953 | 52,325 | -6,740,809 | -9,524,310 | -1,045,925 | 37,778 | -10,532,457 | -3,791,648 | | |
| | 3 | 77,896 | 0 | -1,253,948 | -4,561,120 | 124 | -5,737,048 | -4,391,462 | -1,001,374 | -15,663 | -5,408,499 | 328,548 | | |
| | 4 | 155,792 | -2,725 | -1,589,266 | -147,039 | 23 | -1,583,215 | 1,717,232 | -266,684 | -373,703 | 1,076,846 | 2,660,061 | | |
| | 5 | 58,422 | 0 | -845,179 | -2,054,949 | 893 | -2,840,813 | -809,597 | -830,255 | -88,646 | -1,728,497 | 1,112,316 | | |
| | 6 | 0 | 0 | -1,443,743 | -4,748,209 | 2,274 | -6,189,678 | -10,271,388 | -1,495,724 | 1,189,350 | -10,577,763 | -4,411,137 | | |
| | 7 | 77,896 | 0 | -1,513,765 | -4,053,693 | 0 | -5,489,561 | -4,100,207 | -1,233,852 | 464,425 | -4,869,635 | 619,927 | | |
| | 8 | 155,792 | 0 | -822,326 | -856,278 | 0 | -1,522,812 | 1,731,373 | -337,299 | -242,668 | 1,151,407 | 2,674,219 | | |
| Ratio: MF2K IWFM [%] | 1 | 101.90% | 92.80% | 44.57% | n/a | n/a | 65.63% | 86.53% | 56.33% | 51.46% | 76.83% | n/a | | |
| | 2 | 101.90% | 100.00% | 80.71% | 46.69% | n/a | 63.58% | 49.24% | 58.98% | 103.83% | 52.77% | n/a | | |
| | 3 | 101.90% | 100.00% | 74.14% | 56.87% | n/a | 71.93% | 73.62% | 59.63% | 98.41% | 73.11% | n/a | | |
| | 4 | 101.90% | 99.70% | 48.32% | n/a | n/a | 87.18% | 121.97% | 69.85% | 62.14% | 111.11% | n/a | | |
| | 5 | 101.90% | 100.00% | 72.79% | 2.82% | n/a | 69.76% | 84.47% | 60.11% | 91.02% | 79.13% | n/a | | |
| | 6 | n/a | 100.00% | 69.94% | 64.54% | n/a | 67.90% | 43.36% | 67.13% | 220.48% | 55.32% | n/a | | |
| | 7 | 101.90% | 100.00% | 63.82% | 66.16% | n/a | 74.30% | 74.93% | 63.73% | 147.05% | 76.52% | n/a | | |
| | 8 | 101.90% | 100.00% | 65.38% | 5.21% | n/a | 87.90% | 122.19% | 69.97% | 75.42% | 111.62% | n/a | | |
| Dis-crepancy [%] | 1 | 1.88% | -7.47% | -76.67% | n/a | n/a | -41.50% | -14.45% | -55.88% | -64.10% | -26.20% | n/a | | |
| | 2 | 1.88% | 0.00% | -21.35% | -72.69% | n/a | -44.53% | -68.02% | -51.60% | 3.76% | -61.83% | n/a | | |
| | 3 | 1.88% | 0.00% | -29.71% | -54.99% | n/a | -32.65% | -30.39% | -50.57% | -1.60% | -31.07% | n/a | | |
| | 4 | 1.88% | -0.30% | -69.69% | n/a | n/a | -13.70% | 19.79% | -35.50% | -46.69% | 10.53% | n/a | | |
| | 5 | 1.88% | -0.00% | -31.50% | -189.02% | n/a | -35.63% | -16.84% | -49.83% | -9.40% | -23.30% | n/a | | |
| | 6 | n/a | 0.00% | -35.38% | -43.10% | n/a | -38.23% | -79.02% | -39.34% | 75.19% | -57.54% | n/a | | |
| | 7 | 1.88% | 0.00% | -44.17% | -40.73% | n/a | -29.49% | -28.67% | -44.30% | 38.09% | -26.60% | n/a | | |
| | 8 | 1.88% | 0.00% | -41.86% | -180.18% | n/a | -12.88% | 19.97% | -35.34% | -28.03% | 10.98% | n/a | | |
| RSQ | | **1.00** | **0.96** | **0.86** | **0.97** | **n/a** | **0.89** | **0.42** | **0.99** | **0.06** | **0.65** | **n/a** | | |

Table 3. Farm-Budget components for each stress period aggregated over all farms

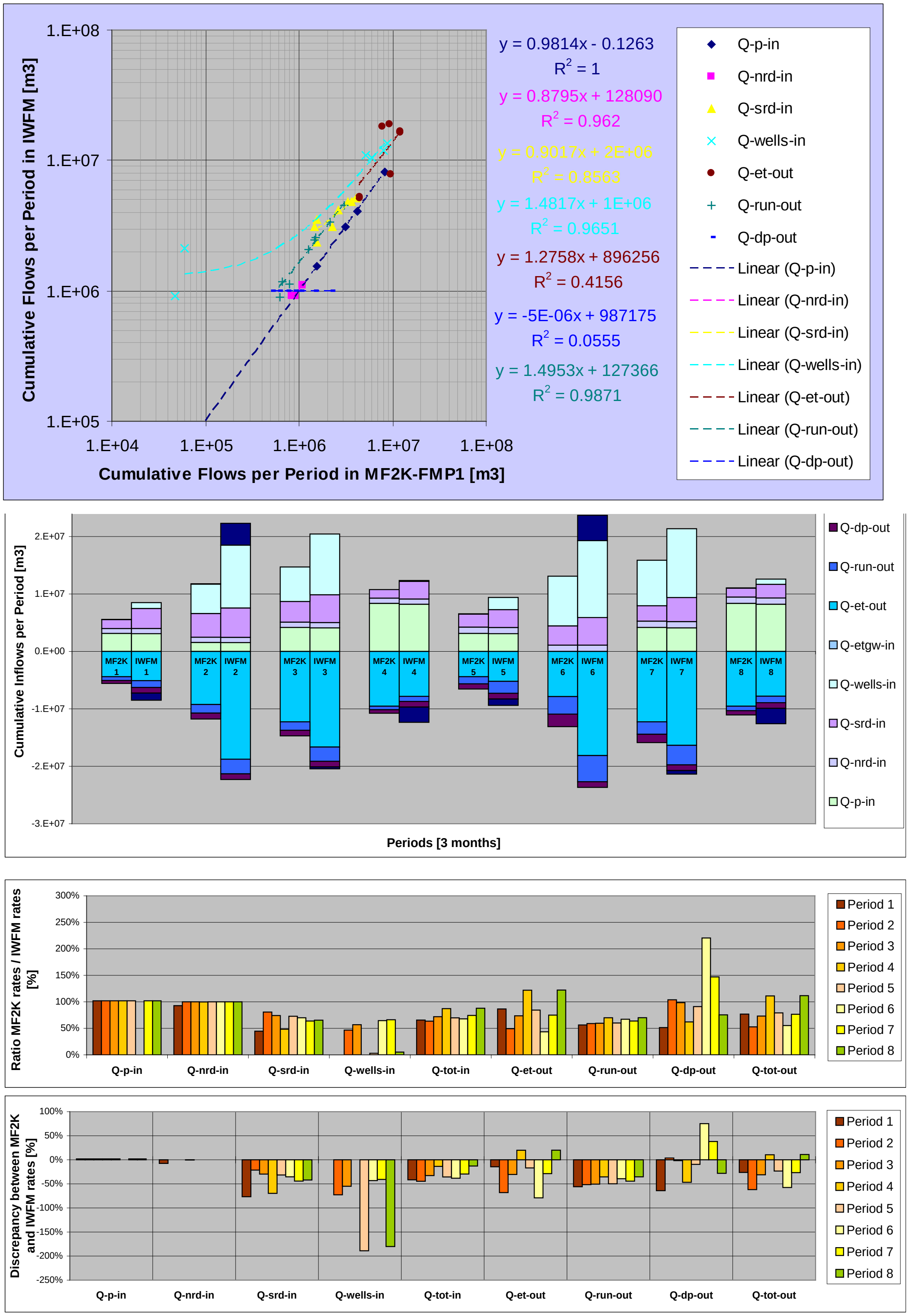



**Figure 12**. a, b, c, d: Farm-Budget components for each stress period aggregated over all farms ((a) linear regressions for input and output components of the landscape for the entire model region, (b) cumulative inflow and outflows, (c) ratios between MF-FMP and IWFM rates, (d) discrepancies between MF-FMP and IWFM rates).

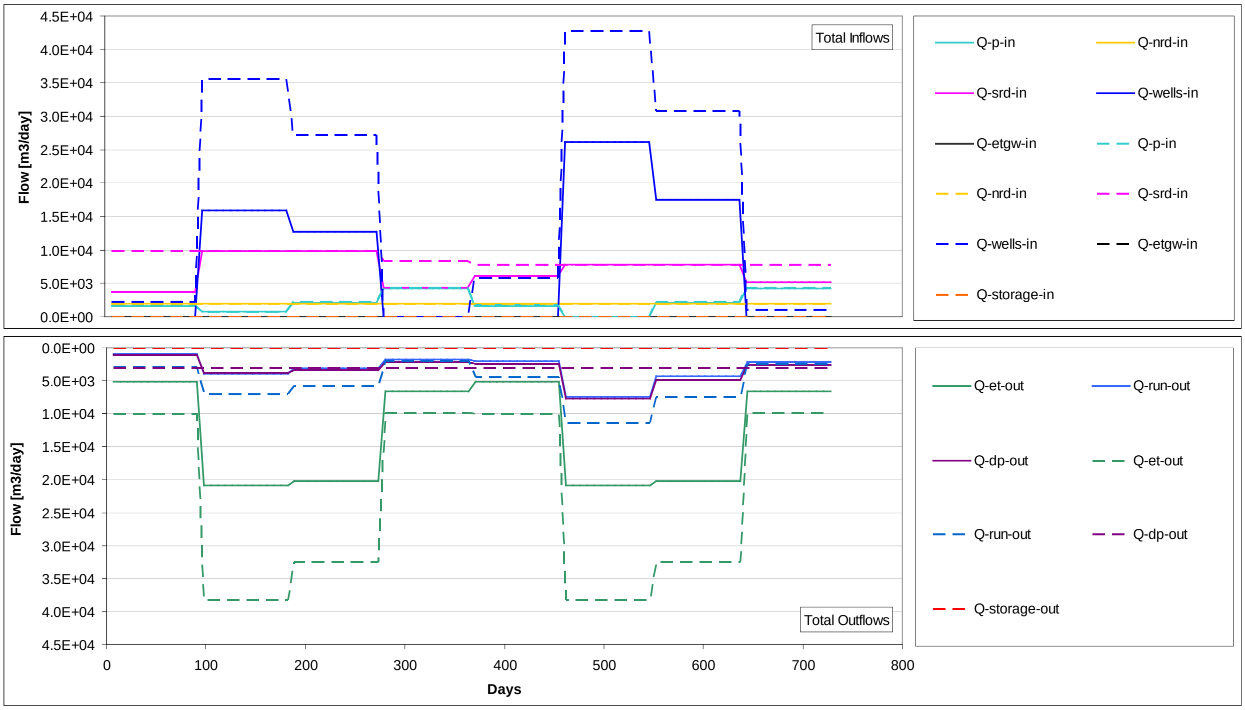



**Figure 13**: Time series of Farm-Budget components for Farm 1 simulated by MF-FMP (solid lines) and IWFM (dotted lines).

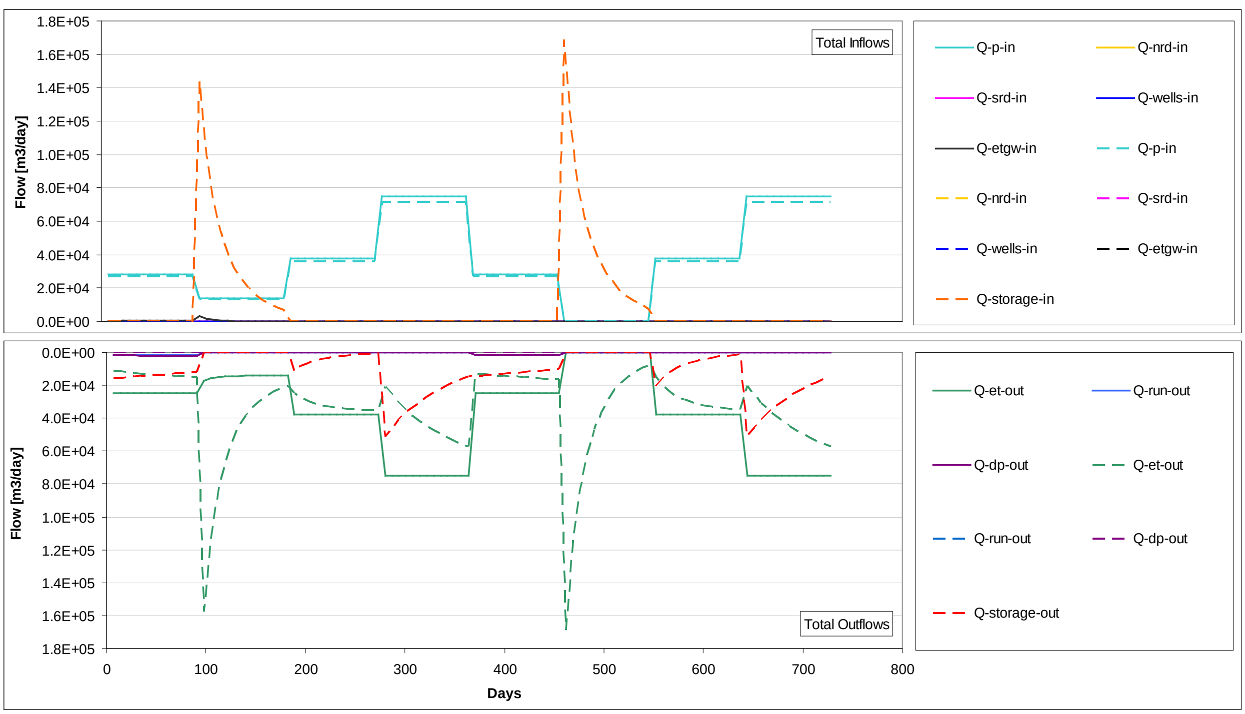



**Figure 14**: Time series of Farm-Budget components for Farm 6 (native and riparian) simulated by MF-FMP (solid lines) and IWFM (dotted lines).

### *Groundwater Budgets*

Cumulative groundwater pumpage simulated with MF-FMP amounts to about 54 percent of the pumpage generated by IWFM (table 4). This difference results from (1) different conceptualizations and techniques used in both models for the simulation of water demands, root zone, and overland-runoff processes, (2) differences in streamflow routing methods, and (3) from different availability of higher-priority delivery components, such as semi-routed deliveries. These reasons are discussed in other sections. This section illustrates how the groundwater budget is perturbed by the different groundwater pumpage in IWFM and MF-FMP.

For the entire model domain, the IWFM-simulated groundwater pumpage intercepts much of the groundwater flow toward the downgradient general-head boundary; the outflow at that boundary only is 14 percent of that simulated by MF-FMP (table 4). In contrast, the inflows along the upgradient general-head compare better; IWFM inflow is 70 percent of MF-FMP inflow (table 4). The pumpage of individual zones below each farm is counterbalanced by water released from groundwater storage, inflows from neighboring zones, and farm net recharge into groundwater (fig. 15). Recharge from stream seepage is relatively small in the IWFM model, representing 31% of that generated by MF-FMP (table 4). This is expected, as IWFM conceptualizes stream seepage for aquifer-disconnected streams differently from MF-FMP (section ‘streamflow comparison’ below or Dogrul et al., 2011).

Previous sections elaborated on IWFM generating more pumpage as a result of different evapotranspiration and root zone concepts. Similarly, differences in the formulation of the streamflow leakage also are contributing to differences in the performance of the two models. The groundwater budget comparison reveals that differences in formulation of seepage result in reduced stream seepage, which also contributes to higher depletion of groundwater storage in IWFM.

| | Farm | IN | | | | | | OUT | | | | | | | IN - OUT | Percent Dis-crepancy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Storage (in) | From other zones (in) | Head dep. boundary (in) | Stream leakage (in) | Farm net recharge (in) | Total in | Storage (out) | To other zones (out) | Head dep. Boundary (out) | Stream leakage (out) | Farm well pumping (out) | Farm net recharge (out) | Total out | | |
| MF-FMP [1000 m$^3$] | 1 | 698 | 5,016 | | 0 | 2,551 | 8,265 | 335 | 3,549 | | 0 | 4,381 | 0 | 8,265 | 0 | 0.00% |
| | 2 | 364 | 2,589 | | 0 | 947 | 3,900 | 170 | 1,613 | | 0 | 2,117 | 0 | 3,900 | 0 | 0.00% |
| | 3 | 362 | 1,124 | | 0 | 1,412 | 2,897 | 139 | 2,758 | | 0 | 0 | 0 | 2,897 | 0 | 0.00% |
| | 4 | 389 | 2,234 | | 0 | 1,515 | 4,139 | 214 | 3,924 | | 0 | 0 | 0 | 4,138 | 0 | 0.01% |
| | 5 | 1,344 | 5,177 | | 0 | 1,628 | 8,149 | 719 | 3,675 | | 0 | 3,756 | 0 | 8,150 | 0 | 0.00% |
| | 6 | 12,958 | 13,103 | 5,370 | 14,178 | 295 | 45,904 | 6,315 | 13,725 | 8,138 | 152 | 17,523 | 52 | 45,903 | 1 | 0.00% |
| | Domain | 16,114 | | 5,370 | 14,178 | 8,349 | 44,010 | 7,891 | | 8,138 | 152 | 27,776 | 52 | 44,010 | 1 | 0.00% |
| IWFM [1000 m$^3$] | 1 | 2,301 | 5,145 | | 0 | 2,169 | 9,614 | 465 | 322 | | 0 | 8,828 | 0 | 9,614 | 0 | 0.00% |
| | 2 | 1,113 | 3,388 | | 0 | 1,078 | 5,579 | 196 | 0 | | 0 | 5,383 | 0 | 5,579 | 0 | 0.00% |
| | 3 | 1,344 | 0 | | 0 | 1,591 | 2,935 | 29 | 2,906 | | 0 | 0 | 0 | 2,935 | 0 | 0.00% |
| | 4 | 1,181 | 0 | | 0 | 1,166 | 2,347 | 11 | 2,337 | | 0 | 0 | 0 | 2,347 | 0 | 0.00% |
| | 5 | 3,086 | 1,355 | | 0 | 1,894 | 6,335 | 779 | 491 | | 0 | 5,065 | 0 | 6,335 | 0 | 0.00% |
| | 6 | 31,140 | 1,338 | 3,746 | 4,439 | 0 | 40,663 | 2,580 | 5,171 | 1,116 | 0 | 31,795 | 0 | 40,663 | 0 | 0.00% |
| | Domain | 39,731 | | 3,746 | 4,439 | 7,897 | 55,813 | 3,626 | | 1,116 | 0 | 51,071 | 0 | 55,813 | 0 | 0.00% |
| Ratio: IWFM MF-FMP | 1 | 330% | 103% | n/a | n/a | 85% | 116% | 139% | 9% | n/a | n/a | 202% | n/a | 116% | | |
| | 2 | 306% | 131% | n/a | n/a | 114% | 143% | 116% | n/a | n/a | n/a | 254% | n/a | 143% | | |
| | 3 | 372% | n/a | n/a | n/a | 113% | 101% | 21% | 105% | n/a | n/a | n/a | n/a | 101% | | |
| | 4 | 304% | n/a | n/a | n/a | 77% | 57% | 5% | 60% | n/a | n/a | n/a | n/a | 57% | | |
| | 5 | 230% | 26% | n/a | n/a | 116% | 78% | 108% | 13% | n/a | n/a | 135% | n/a | 78% | | |
| | 6 | 240% | 10% | 70% | 31% | 0% | 89% | 41% | 38% | 14% | n/a | 181% | n/a | 89% | | |
| | Domain | 247% | n/a | 70% | 31% | 95% | 127% | 46% | n/a | 14% | n/a | 184% | n/a | 127% | | |
| Ratio: MF-FMP IWFM | 1 | 30% | 98% | n/a | n/a | 118% | 86% | 72% | 1102% | n/a | n/a | 50% | n/a | 86% | | |
| | 2 | 33% | 76% | n/a | n/a | 88% | 70% | 86% | n/a | n/a | n/a | 39% | n/a | 70% | | |
| | 3 | 27% | n/a | n/a | n/a | 89% | 99% | 474% | 95% | n/a | n/a | n/a | n/a | 99% | | |
| | 4 | 33% | n/a | n/a | n/a | 130% | 176% | 1952% | 168% | n/a | n/a | n/a | n/a | 176% | | |
| | 5 | 44% | 382% | n/a | n/a | 86% | 129% | 92% | 749% | n/a | n/a | 74% | n/a | 129% | | |
| | 6 | 42% | 979% | 143% | 319% | 629884% | 113% | 245% | 265% | 729% | n/a | 55% | n/a | 113% | | |
| | Domain | 41% | n/a | 143% | 319% | 106% | 79% | 218% | n/a | 729% | n/a | 54% | n/a | 79% | | |
| Dis-crepancy [%] | 1 | -107% | -3% | n/a | n/a | 16% | -15% | -32% | 167% | n/a | n/a | -67% | n/a | -15% | | |
| | 2 | -101% | -27% | n/a | n/a | -13% | -35% | -15% | n/a | n/a | n/a | -87% | n/a | -35% | | |
| | 3 | -115% | n/a | n/a | n/a | -12% | -1% | 130% | -5% | n/a | n/a | n/a | n/a | -1% | | |
| | 4 | -101% | n/a | n/a | n/a | 26% | 55% | 181% | 51% | n/a | n/a | n/a | n/a | 55% | | |
| | 5 | -79% | 117% | n/a | n/a | -15% | 25% | -8% | 153% | n/a | n/a | -30% | n/a | 25% | | |
| | 6 | -82% | 163% | 36% | 105% | 200% | 12% | 84% | 91% | 152% | n/a | -58% | n/a | 12% | | |
| | Domain | -85% | n/a | 36% | 105% | 6% | -24% | 74% | n/a | 152% | n/a | -59% | n/a | -24% | | |
| RSQ | | **1.00** | **0.01** | **n/a** | **1.00** | **0.85** | **0.99** | **0.95** | **0.68** | **n/a** | **n/a** | **0.99** | **n/a** | **0.99** | | |

Table 4: Cumulative volumetric groundwater budgets for zones below each farm and for entire domain over the entire simulation period [1000 m$^3$].

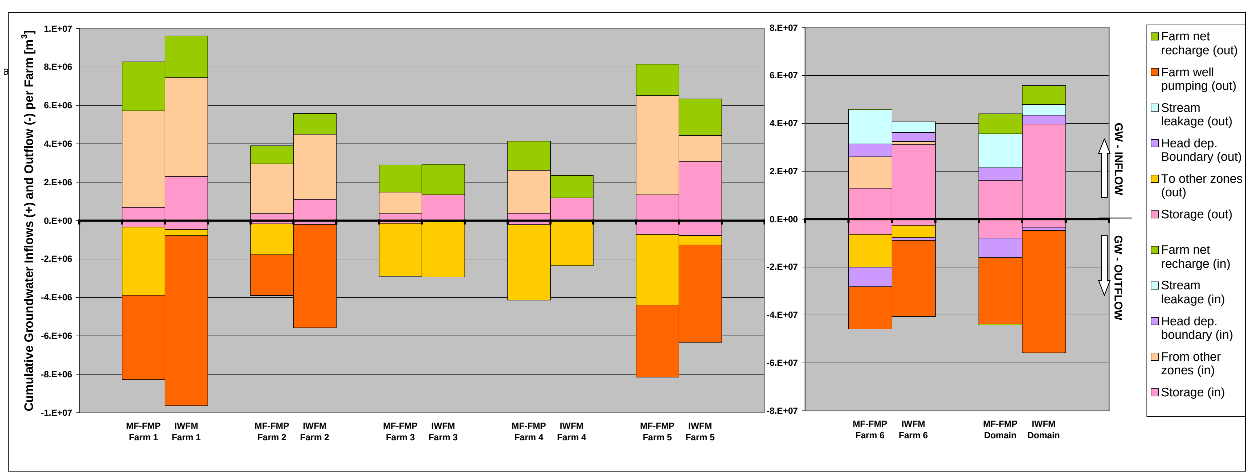



**Figure 15**: Groundwater budget inflow and outflow components for each farm and the entire model domain accumulated over all stress periods.

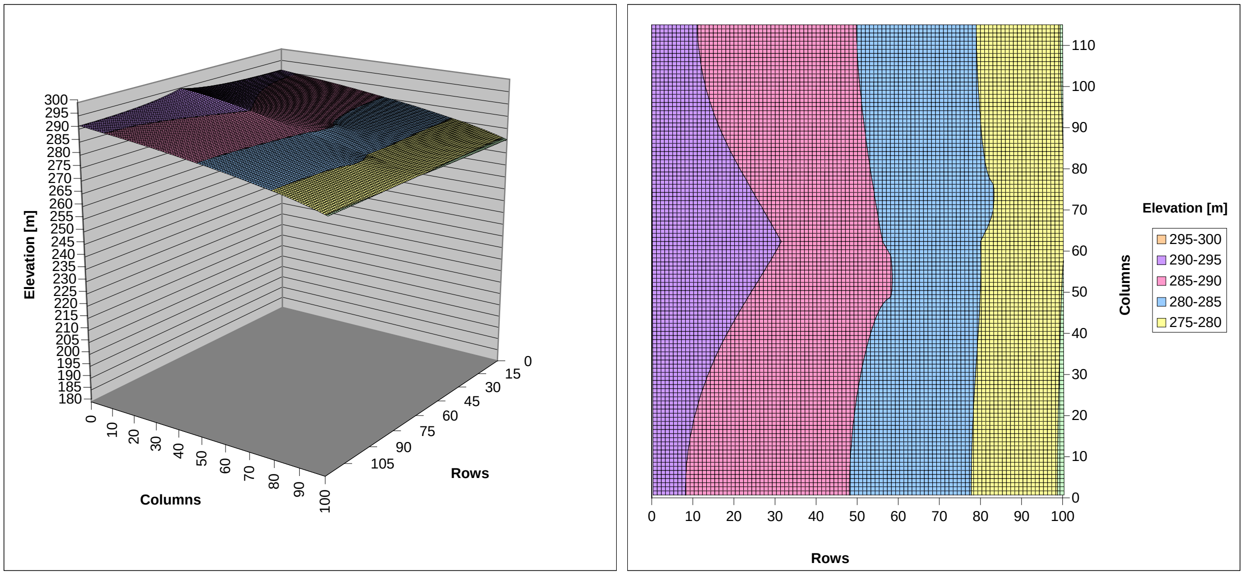
## Water-level Comparisons

Comparison of the MF-FMP simulated layer 1 water-level contours from steady-state conditions (fig. 16) to peak growing season conditions during year 2 (stress period 7, time step 13; fig. 17) reveals three major developments. First, the eastern half of the river system is converted from a slightly gaining system to a losing system. Second, the average water level of the unconfined aquifer drops about 10 meters, and the standard deviation of water levels rises from about 5 to 7.4 meters. Third, large regional cones of depression develop in the alluvial aquifer in layer 1 in the northeastern and southeastern corners of the model domain (fig. 17).

The IWFM simulated layer 1water-level contour map for the peak growing season in year 2 (fig. 18) is similar to the MF-FMP simulated water-level contour map (fig. 17), with two major differences. First, unlike the MF-FMP steady-state condition, the eastern half of the river system was a slightly loosing system in IWFM. These differences are explained in later sections. Over the course of the transient simulation, the eastern river system continues to lose more water to the unconfined alluvial aquifer. Second, the average water level of the unconfined aquifer drops about 27 meters compared to about 10 meters in MF-FMP.

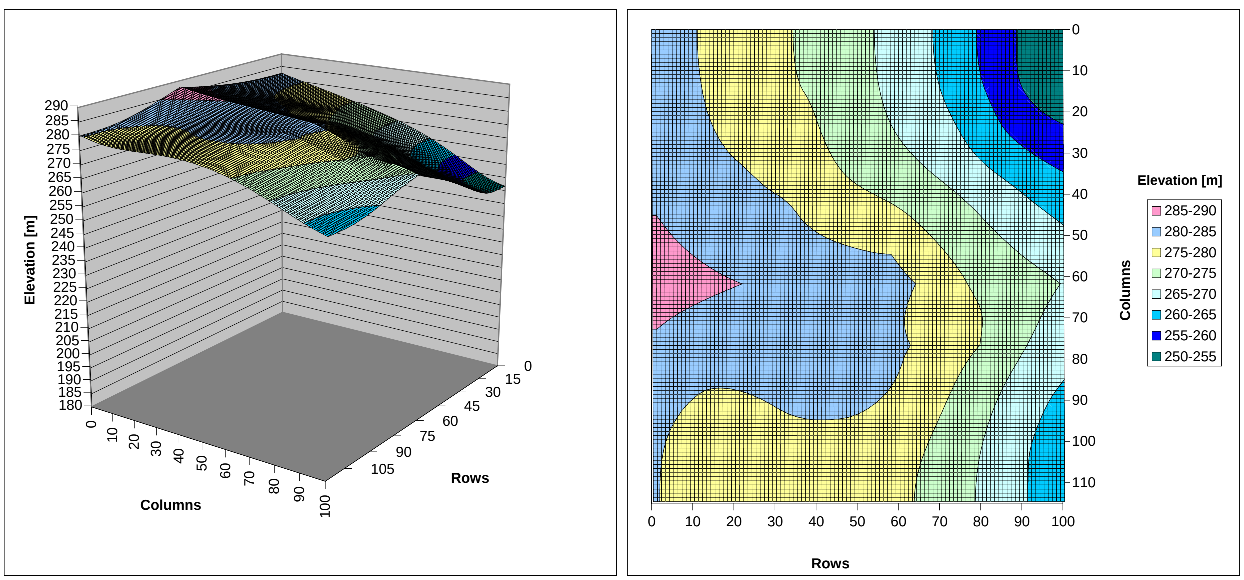
For both IWFM and MF-FMP, pumping from the confined aquifer (layer 2) for Farms 1–5 causes groundwater levels in layer 2 (figs. 19 and 20) to below simulated water levels in layer 1 (figs. 17 and 18), which results in downward leakage through the confining unit between layers 1 and 2. The simulated drawdown in layer 2 in IWFM is much greater than in MF-FMP, which was due to higher delivery requirements simulated. For Farms 1–4, the higher supplemental groundwater pumping in IWFM is a result of higher demands with similar non-routed, and only slightly higher routed surface-water deliveries (table 2). Reasons for higher delivery demands in IWFM were discussed in previous sections.

No water-rights allotments are used in the models and the farms located downstream of the diversion canals (Farms 2 and 4) fall short on surface-water deliveries. The upstream Farms 1 and 3 have priority over such deliveries without water-rights allotments. Deliveries to Farm 5 depend on the river flow near Farm 5 and, therefore, on the total diversions minus return flows that take place for farms upstream of Farm 5. When comparing the available streamflow in both models during year 2 (figs. 22, 23), a much higher flow rate is available for diversions to Farm 5 in IWFM than in MF-FMP. In MF-FMP, excessive pumping for Farm 5 indicates that this region mainly relies on pumping from the confined aquifer as a result of prioritizing the availability of surface water to upstream agricultural deliveries. Because there were larger rates of applied water in IWFM, more return flow from the upstream agricultural area re-enters the river than in MF-FMP (table 2). Consequently, more stream flow is available for diversion to Farm 5, which, unlike Farms 1–4, allows Farm 5 to pump slightly more groundwater than in MF-FMP, owing to the higher demand simulated in IWFM.



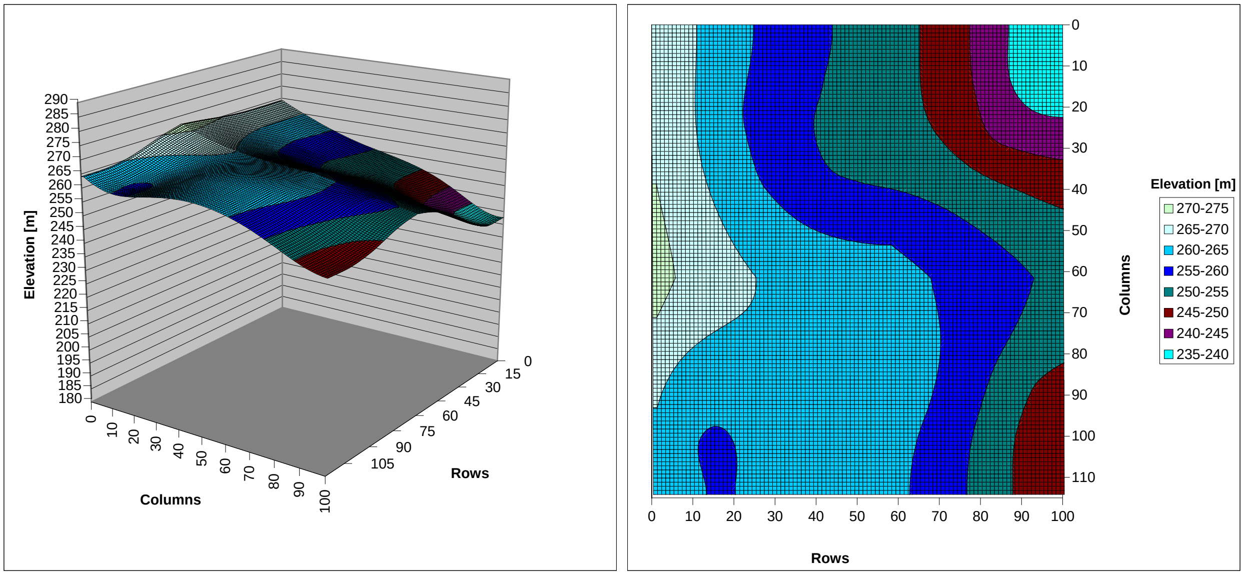

| minimum | maximum | average | stand-dev. |
|---|---|---|---|
| 274.49 | 294.80 | 284.72 | 4.93 |

**Figure 16:** Head distribution of alluvial aquifer in layer 1 during the steady state simulation period (initial conditions for the transient simulations in MF-FMP and IWFM)



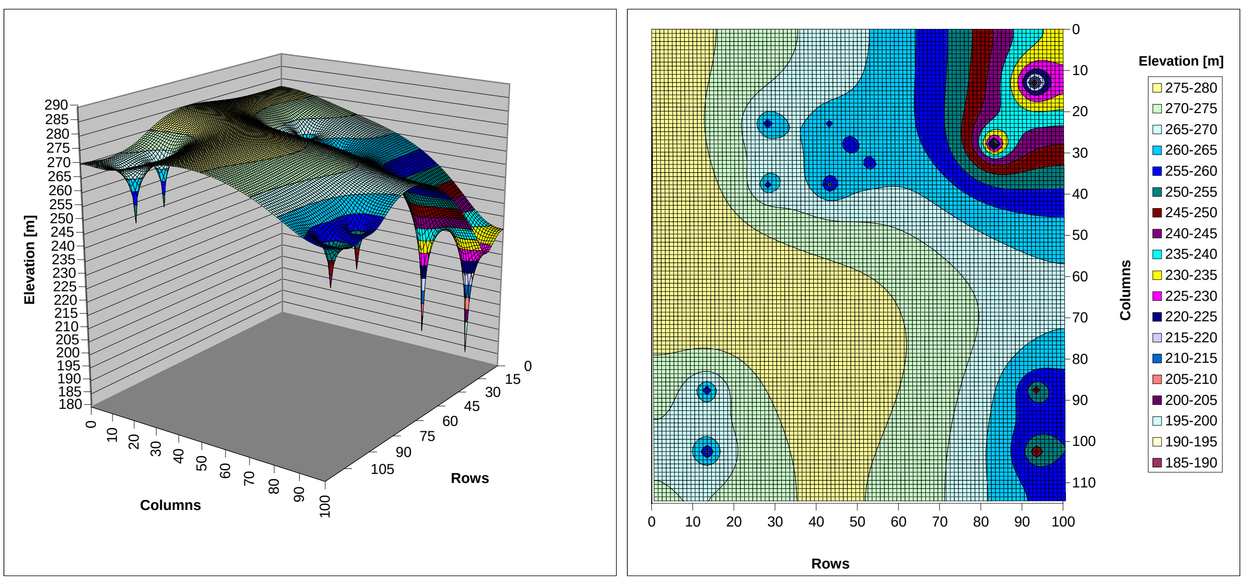

| minimum | maximum | average | stand-dev. |
|---|---|---|---|
| 251.14 | 287.63 | 275.04 | 7.42 |

**Figure 17.** Head distribution of alluvial aquifer in layer 1 during peak growing season in year 2 (stress period 7, time step 13 of MF-FMP simulation)



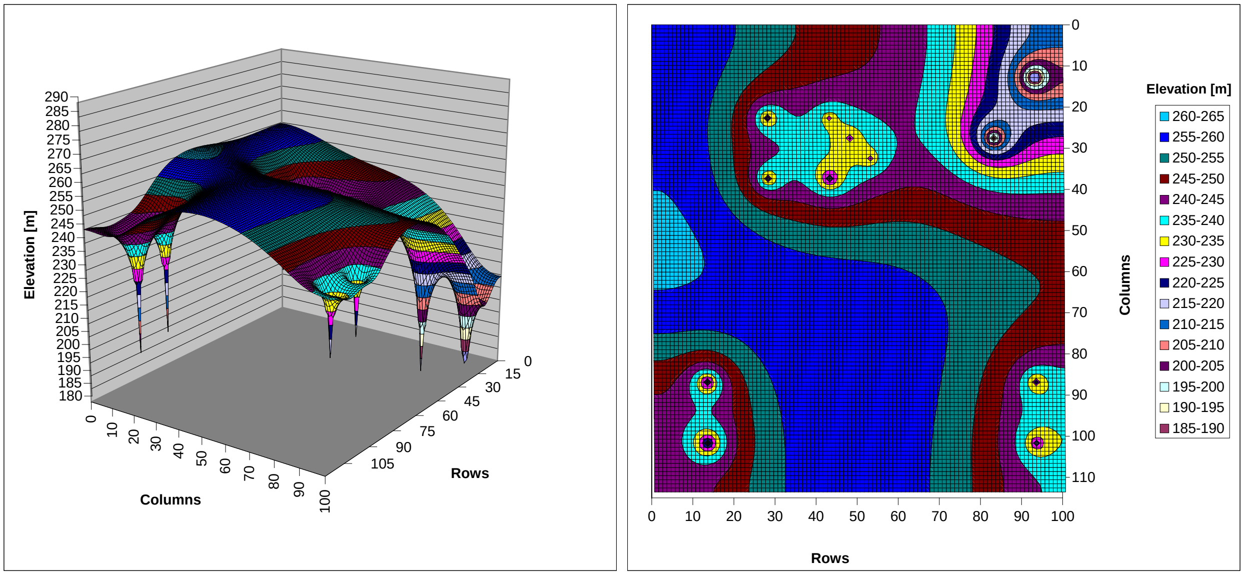

| minimum | maximum | average | stand-dev. |
|---|---|---|---|
| 236.17 | 271.85 | 257.72 | 7.03 |

**Figure 18.** Head distribution of alluvial aquifer in layer 1 during peak growing season in year 2 (stress period 7, time step 13 of IWFM simulation)




| minimum | maximum | average | stand-dev. |
|---|---|---|---|
| 187.91 | 279.86 | 267.48 | 10.55 |

**Figure 19.** Head distribution of confined aquifer in layer 2 during peak growing season in year 2 (stress period 7, time step 13 of MF-FMP simulation)




| minimum | maximum | average | stand-dev. |
|---|---|---|---|
| 127.94 | 261.19 | 247.38 | 11.67 |

**Figure 20.** Head distribution of confined aquifer in layer 2 during peak growing season in year 2 (stress period 7, time step 13 of IWFM simulation)

Hydrographs of observation wells located in the southwestern corner of Farm 2 and north of Farm 4 demonstrate the drawdown in these wells that results from heavy pumping during the midyear peak growing seasons (fig. 21 a, b). The difference between the piezometric head of the confined aquifer and the water level in the unconfined aquifer increases during peak growing seasons as a result of maximum irrigation, but also over the entire period of two years. This indicates an increase in vertical downward leakage between the alluvial aquifer and the underlying confined aquifer driven, in part, by the 20 percent reduction in stream inflow and related diversions that cause an increase in pumpage from the lower confined aquifers. While the drawdowns in IWFM are significantly greater than in MF-FMP as a result of higher demand and groundwater pumping simulated in the IWFM model, the general pattern of a steep cone of depression in the area of Farm 2, and a lesser drawdown north of Farm 4, is similar in both models.

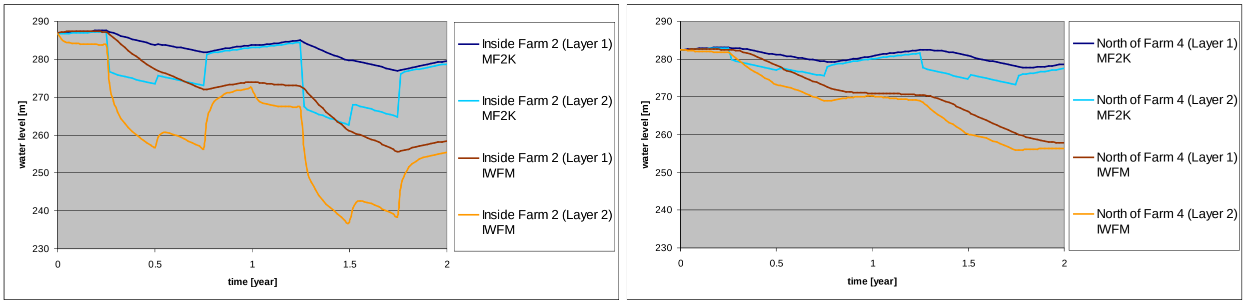



**Figure 21.** Hydrographs of observation wells in layers 1 and 2 inside Farm 2 (figure 21a, left) and north of Farm 4 (figure 21b, right) for the MF-FMP and IWFM simulations

## Streamflow Comparison

The rate of streamflow entering and exiting the farm diversion reaches (fig. 22, 23) depends mainly on the location of each farm's diversion. Ignoring small amounts of stream leakage, the streamflow that reaches the diversions to Farms 1 and 3 in both models is approximately equal to the main diversion from the river into each farm's canal (10,000 and 8,000 $m^3$/day for year 1 and year 2, respectively). During months that are outside the growing season in year 1 (e.g., first and fourth quarters), Farms 1 and 3 divert no surface water in the MF-FMP model, but divert significant amounts in the IWFM model. Therefore, in MF-FMP, the outflow from the diversion reach is equal to the inflow and is made available as inflow downstream to Farms 2 and 4 for potential diversion. Similar to Farms 1 and 3, Farm 2 receives non-routed water transfers by first priority during year 1. Likewise, in both models, Farm 2 diverts very little or no water from the canal outside the growing season in year 1. Contrary to Farm 2, Farm 4 receives no non-routed water transfers. Therefore, even though the off-season demand is relatively small compared to the peak growing season, Farm 4 uses the diverted semi-routed delivery to satisfy its demand and, hence, the outflow out of the diversion reach of Farm 4 is diminished. During the peak growing seasons of both years, the non-routed deliveries to Farms 1 and 3 are not sufficient to meet their demand, and all inflow is diverted, leaving no outflow available for downstream Farms 2 and 4, which must rely more on groundwater supplies.

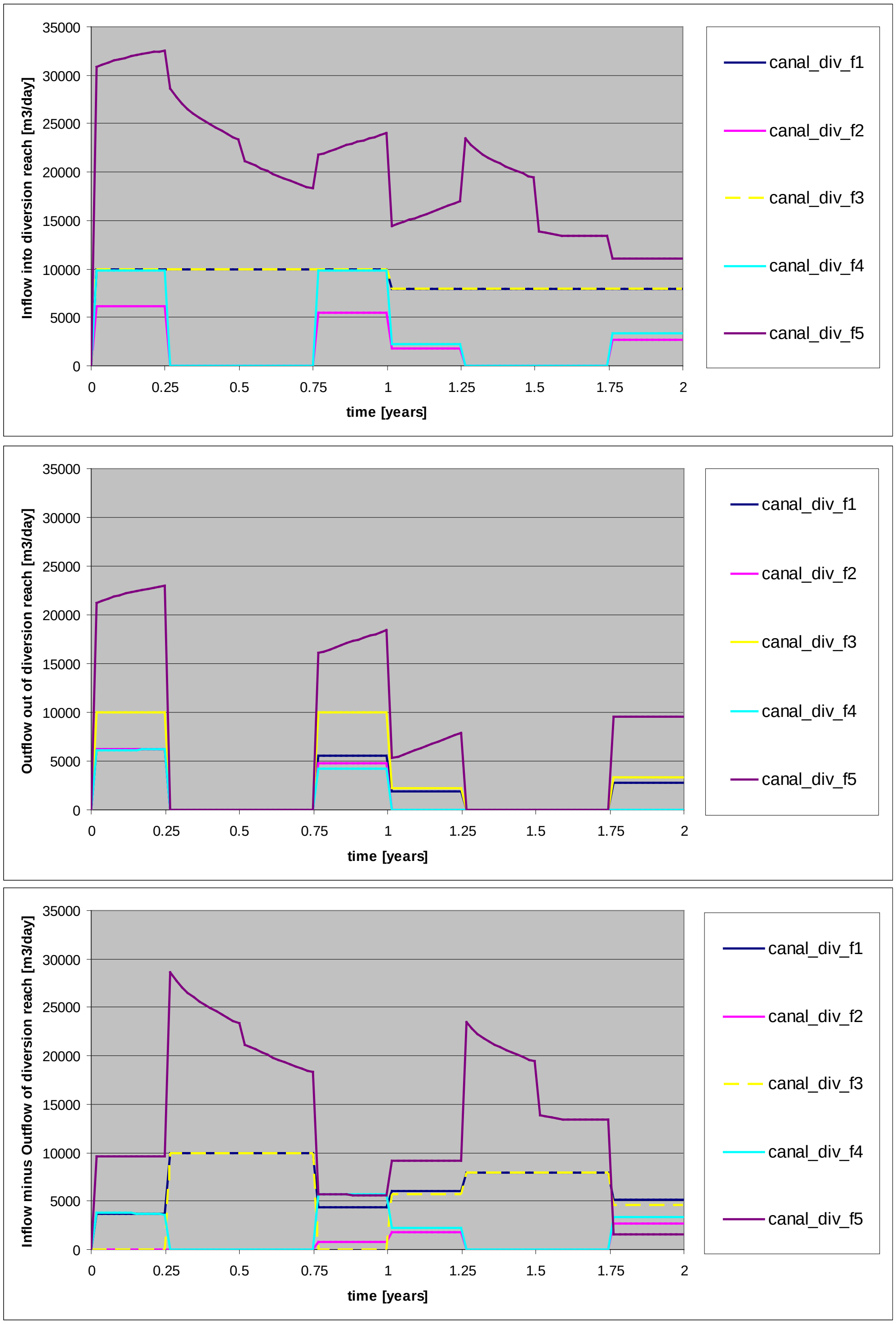



**Figure 22.** Inflows to and Outflows from farm diversion reaches (MF-FMP)

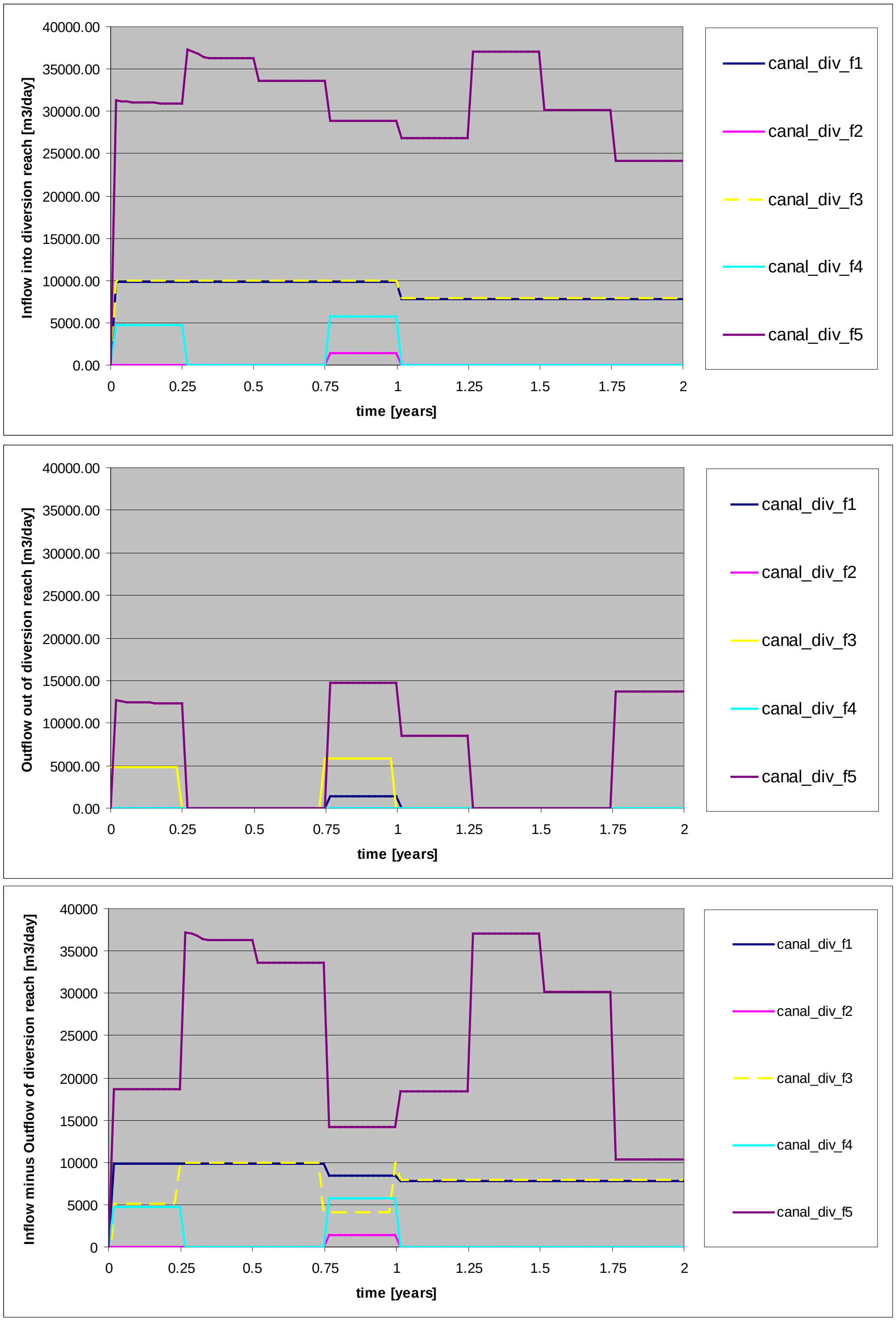



**Figure 23.** Inflows to and Outflows from farm diversion reaches (IWFM)

The rate of streamflow entering and exiting a return flow reach, into which the farms' return flow is recharged, depends mainly on the stream losses of formerly draining tributary segments and of the inefficiency losses to surface-water runoff from each farm (fig. 24, 25). In MF-FMP, the return-flow reach of Farm 4 receives a little inflow only during stress period 6 as a result of upstream return flows from Farm 3 (fig. 23). In contrast, in IWFM, the return-flow reach of Farm 4 receives significant inflow throughout the simulation period (fig. 25). Because the demands and, accordingly, applied water are higher in IWFM, return flows also are higher. The combined return flow of Farms 1–4 determines the majority of streamflow that is returned via the bypass canals to the river. The largest difference between inflows and outflows can be observed at the main-stem river reach that receives the return flow from Farm 5. Compared to the agricultural Farms 1–4, the urban area of Farm 5 has the highest return flow to the river in both models. This causes the river flow to increase tremendously, especially during the peak growing seasons. The river streamflow rate further downstream (blue dotted line in figs. 24, 25) is nearly equivalent to the rate of streamflow leaving the upstream reach where the return flows from Farm 5 enter.

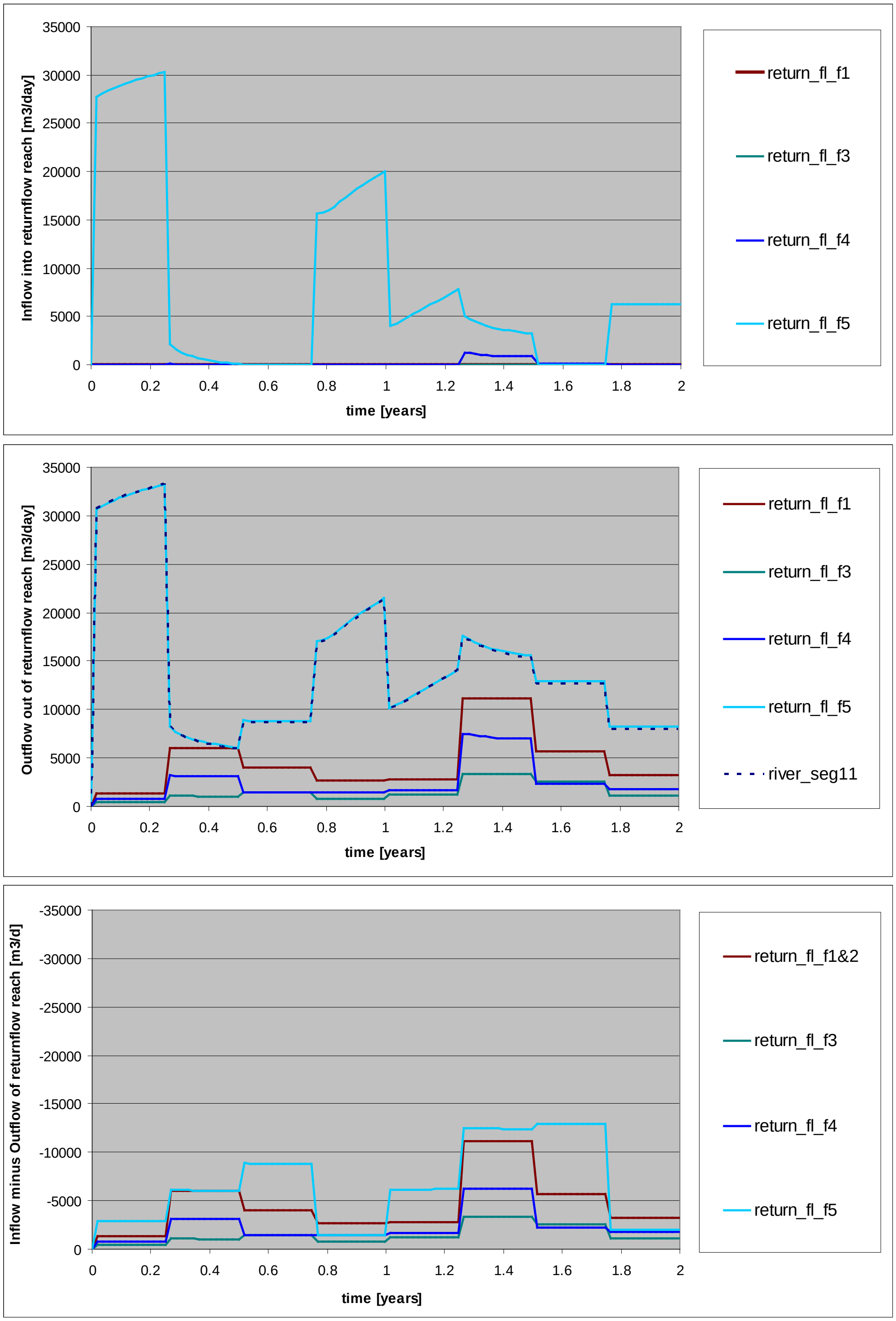



**Figure 24.** Inflows in and Outflows from farm return flow reaches (MF-FMP)

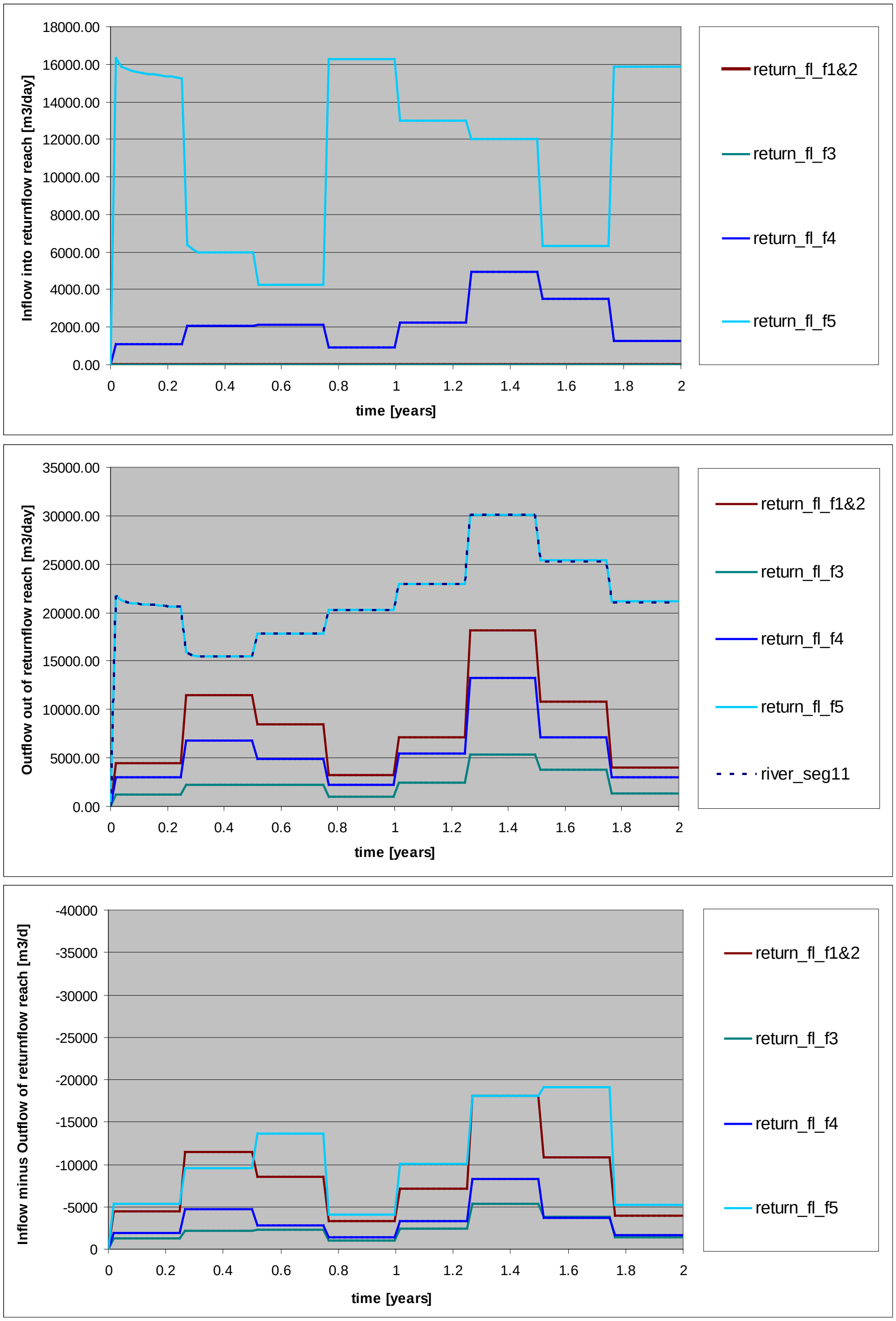



**Figure 25.** Inflows to and Outflows from farm return flow reaches (IWFM)

In both models, the inflow reaching the diversion to Farm 5 (urban) depends on the overall water use of the upstream agricultural area. Though both years have a prescribed inflow into the river from the western boundary and prescribed main diversions from the river into the two canals, the streamflow is quite variable over time within each model's hydrograph and between the two hydrographs of each model. The streamflow during peak growing seasons (stress periods 2, 3, 6, 7) is controlled mainly by the return flows from the agricultural areas, which, in IWFM, are higher than in MF-FMP (table 3). The overall decreasing trend of inflows over both years in the MF-FMP model clearly depends on reduced return flow from the agricultural areas (Farms 1 to 4) and on the seepage from a losing stream. At the main-stem river between the returnflow reach of Farm 5 and the eastern model boundary (fig. 2) at reach 10 of segment 11 (table 1), IWFM does not simulate as much stream seepage as MF-FMP (fig. 26). There are three main reasons for this:

i) The hydrographs are taken at a downstream location of the stream network. They reflect all the differences between the root zone and land surface flow processes as well as the resulting differences in the stream-aquifer interaction that are occurring in the entire model area. These differences are due to the different conceptualization and numerical implementation of root zone and land-surface processes in the models.

ii) The representation of stream/groundwater interaction, when stream and aquifer are hydraulically disconnected, differs in the models. In MF-FMP, the head difference of the Darcy head gradient is assumed to be equal to the stream head minus the elevation at the streambed bottom; in IWFM, head difference is assumed to equal the stream stage. A more detailed comparison of this model feature is in Dogrul et al. (2011).

iii) In the example considered in this report, the small depth of water in the stream compared to the stream-bed thickness amplifies the differences in how the models simulate stream/groundwater interactions. Generally, IWFM simulates less stream seepage into the alluvial aquifer than MF-FMP (fig. 26).

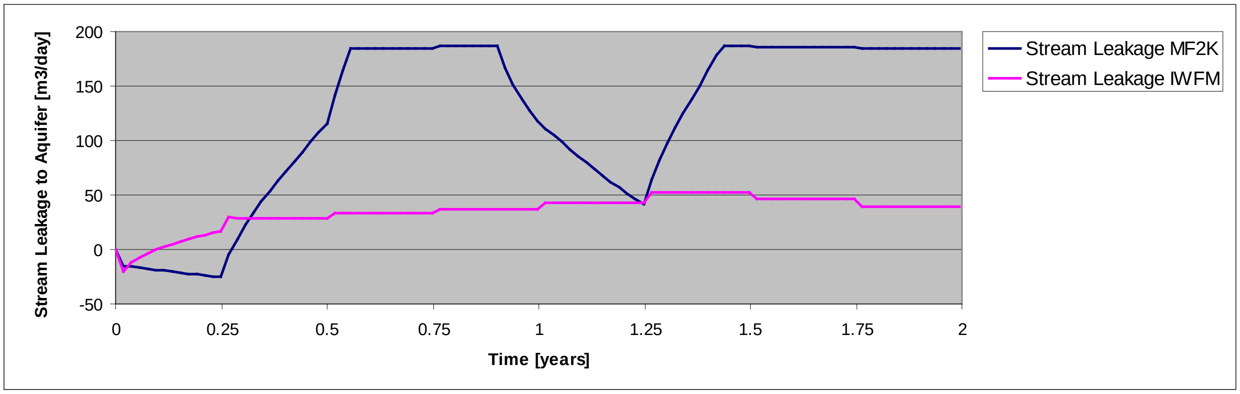



**Figure 26.** Stream Leakages of both models at the main-stem river (reach 10 of segment 11; row 62, column 92)

## Discussion of Results

MF-FMP and IWFM simulate the consumption of water by natural vegetation and irrigated crops. Irrigation demands, surface-water and groundwater supplies, and return flows are simulated for irrigated crops. Disabling or minimizing the use of some model features that are strictly only available in one code allows potentially different model results to be interpreted as a result of the common model features available in both codes that are conceptualized and formulated differently. Features common to both codes, but implemented using different concepts, include evapotranspiration and inherently linked irrigation requirements, deliveries, return flows, and stream seepage. For MF-FMP, head-dependent root water uptake of shallow groundwater was minimized by specifying initial water-level conditions below the root zone and capillary fringe. Also, pumping is simulated from a single aquifer, and MF-FMP's ability for multi-aquifer pumping is not used. For IWFM, the dynamic simulation of soil-moisture changes is restricted for irrigated farms by holding the soil moisture at field capacity and by minimizing the soil-moisture depletion (MAD set to zero). However, the capability to simulate depletion in soil-moisture storage was retained for non-irrigated areas.

In general, IWFM simulates higher demands from estimated ET, which lead to higher simulated deliveries and associated surface-water return flows. That is, return flows from the upstream agricultural area (Farms 1–4) determine how much surface water is available for diversion to the downstream urban area (Farm 5). The overall decreasing trend of flow available for diversion to Farm 5 over both years in MF-FMP is related to reduced return flow from the upstream agricultural areas and, also, to much higher stream seepage compared to IWFM.

In general, the correlation between MF-FMP and IWFM flow rates of farm budget components is greater for individual farm rates accumulated over all stress periods than for individual stress periods accumulated over all farms. While correlation for some output parameters is high, there are significant discrepancies between the MF-FMP and IWFM results. These discrepancies mostly result from differences in the conceptualization of evapotranspiration but, also of runoff, and deep percolation. This leads generally to higher irrigation demands in IWFM compared to MF-FMP. However, even though the associated diversions and deliveries differ, the dynamics of determining them are similar. For instance, a higher demand in IWFM (compared to MF-FMP) leads to more surface-water diversion in upstream farms and, accordingly, less available for diversion to downstream farms. Nevertheless, both models simulate the dynamics of higher-priority delivery of surface water to upstream farms, the resulting effect on downstream farms, and the non-linearly affected supplemental groundwater pumping.

The models start from inherently different assumptions. MF-FMP assumes the user-specified consumptive use represents potential crop evapotranspiration (Schmid et al. 2006a) under non-stressed, well-managed conditions (meaning not stressed by conditions of anoxia or wilting). In the present example, root zones are not influenced by groundwater because there are deep groundwater levels, and anoxia in MF-FMP is assumed to be related to an infiltration wetting front. Potential evapotranspiration is further reduced in MF-FMP by a reduction of evaporation that results from the fact that, for some irrigation methods, not all open and exposed areas between crop canopies are actually wetted, and therefore subject to evaporation, and not all the area within a model cell is covered by vegetation and subject to transpiration.

For IWFM, the user specifies estimates for the crop evapotranspiration requirements, which explicitly account for local conditions that influence the crops’ ability to extract water from soil. Reduction of evapotranspiration is simulated only when the soil moisture falls below half of field capacity. In the present example, this is the case only in deficit situations for non-irrigated areas, represented by Farm 6. Although the estimates of crop evapotranspiration requirements can be taken as the crop evapotranspiration under standard, non stressed, well-managed conditions, $ET_c$, as described by Allen et al. (1998), they also can be taken as the crop evapotranspiration under non-standard conditions, $ET_{c\text{-}adj}$, also described by Allen et al. (1998), to incorporate conditions such as non-uniform irrigation, low soil fertility, salt toxicity, pests, diseases, etc. (except in the case where the plants are water-stressed because of insufficient water; this situation is simulated dynamically in IWFM as discussed throughout the paper). IWFM makes no assumptions about input crop evapotranspiration requirements, and attempts to meet these requirements by adjusting user-specified stream diversions and groundwater pumping (if run in the “water resources planning” mode). Unlike MF-FMP, IWFM does not simulate reduced evapotranspiration caused explicitly by anoxia. If sufficient sources of water are available in the hydrologic system, the computed actual evapotranspiration equals the user-specified crop evapotranspirative requirement. In the case of insufficient sources of available water, IWFM uses the methods described by Allen et al. (1998) to compute the decrease in actual evapotranspiration due to water stress, which can lead to wilting. However, wilting is not simulated explicitly because no adjustments are made to the specified ET within IWFM owing to changing hydrologic conditions. In all simulation modes, IWFM accounts for soil moisture in the root zone as it is affected by deep percolation, evapotranspiration, and infiltration from precipitation and irrigation. If insufficient water is available to meet crop evapotranspiration requirements, the actual evapotranspiration is reduced when the soil moisture content falls below one-half the field capacity. In this case, computed actual evapotranspiration is less than the user-specified crop evapotranspiration requirement. In the present example, this situation occurs only in Farm 6, the non-irrigated area.

Even in the absence of groundwater uptake, which MF-FMP simulates and IWFM does not, the difference in the conceptualization of evapotranspiration leads to higher values of simulated evapotranspiration and, generally in irrigated areas, to higher total farm delivery requirements in IWFM than in MF-FMP. The opposite happens only periodically, in times of water deficiency when the crop evapotranspiration requirement is mainly fed by soil moisture, such as in the non-irrigated Farm 6 (fig. 14).

Based on the discussion above, the fundamental differences between the two models can be summarized:

i) MF-FMP can use potential or adjusted evapotranspiration as input. If potential ET is specified, MF-FMP reduces it by landscape and crop-growing factors to actual evapotranspiration that dynamically changes through time and is implicitly calculated and linked to other head-dependent features such as groundwater uptake, anoxia, and wilting. IWFM requires the user to estimate evapotranspiration *a priori* for a target crop yield under foreseeable local conditions such as non-uniform irrigation, low soil fertility, salt toxicity, pests, diseases, etc.

ii) In MF-FMP, a reduced actual evapotranspiration is computed from potential evapotranspiration and used in computing the irrigation requirement in irrigated areas. In IWFM, the irrigation requirement is computed based on user-specified evapotranspiration rates, regardless of changes in conditions that would reduce evapotranspiration. However, the additional requirement to replenish soil moisture deficits, or reductions in soil moisture toward the wilting point, can further reduce the actual evapotranspiration.

iii) Factors that influence the different levels of demand are not limited to the conceptualization of evapotranspiration. Deep percolation in IWFM is simulated as a function of soil-moisture storage and, accordingly, the replenishment of depleted soil moisture that is added to the demand includes deep percolation. The resupply of soil moisture occurs before deep percolation is allocated in IWFM. In contrast, deep percolation in MF-FMP depends on the inefficiency losses from irrigation and precipitation and is approximated for selected soil types based on a nonlinear approximation to steady-state infiltration from HYDRUS-2D approximations for each soil type.

iv) When comparing the farm-budget parameters by individual stress period accumulated over all farms, changes in soil-moisture storage occurring in non-irrigated or deficit-irrigated farms in IWFM result in low correlations of the evapotranspiration fluxes with MF-FMP, which does not simulate changes in soil-moisture storage. However, when comparing the evapotranspiration flux by individual farm accumulated over all stress periods, the net soil-moisture change becomes zero and, for a particular farm, the net evapotranspiration flux is similar between the two models.

v) When the stream and aquifer are hydraulically disconnected, the lower rate of stream seepage in IWFM contributes to a higher depletion of groundwater storage compared to MF-FMP.

vi) Finally, from a computational standpoint, the IWFM and MF-FMP execution times differed for the example hypothetical model. The hypothetical model was run in three steps with MF-FMP that represent the MF-FMP model run and post processing with ZONEBUDGET (Harbaugh, 1990) and HYDMOD (Hanson and Leake, 1998), and took about 4 minutes. The hypothetical model was run in three steps with IWFM that include preprocessor, simulation, and budget steps, and took about 58 minutes to complete.

## Conclusions (Water-Management Implications)

The results of this case study indicate that there are significant differences between the evaporation rates simulated by MF-FMP and IWFM. In general, IWFM simulated evapotranspiration rates were about 60 percent higher than MF-FMP rates for irrigated farms. In MF-FMP, a reduced actual evapotranspiration is computed from potential evapotranspiration and used in computing the irrigation requirement in irrigated areas. In IWFM, the irrigation requirement is computed based on user-specified evapotranspiration rates, regardless of changes in conditions that would reduce evapotranspiration. User-input evapotranspiration rates utilized by IWFM are adjusted only if soil moisture falls below a specified moisture content. IWFM does not simulate any further reduction of evapotranspiration related to local conditions of anoxia or limited wetting of open and exposed areas that are accounted for within MF-FMP. Other factors that can reduce evapotranspiration, such as salinity, plant diseases, etc., are assumed to be included in the evapotranspiration rates used as input and are not explicitly simulated based on changing conditions during simulation. These types of reductions in evapotranspiration are potential enhancements of both codes.

Measured evapotranspiration data may not always be available to estimate actual evapotranspiration rates, and reductions in consumptive use and related farm delivery requirements from groundwater uptake are difficult to measure. In modeling studies where these are the case, the calibration phase generally leads to water-balance problems (e.g., measured groundwater elevations, streamflows, and surface-water diversions not matching the simulated counterparts) that require the user to correct the initial estimates of actual evapotranspiration rates during model calibration. In addition to potential evapotranspiration, actual evapotranspiration also can be used as input in IWFM in areas where data of local evaporation under stressed conditions have been measured and are readily available. However, in many areas of the world, particularly in developing countries, localized data of actual evapotranspiration are not measured and only potential evapotranspiration or, at most, potential crop evapotranspiration data are available. Under such conditions, MF-FMP allows the use of potential evapotranspiration estimates derived from climate data, and the reduction to anoxia is implicitly computed by MF-FMP. In MF-FMP, potential consumptive use or crop coefficients representing non-stressed conditions can be associated with a particular crop or group of crop types and utilized to simulate unknown or unmetered historic surface-water and/or groundwater allocations.

For predictive models, both IWFM and MF-FMP have strengths and weaknesses. Because future climate and land-use only can be estimated, evapotranspiration estimates representing expected local stresses are unavailable. MF-FMP is able to use potential evapotranspiration estimates from global or regional climate and land-use models to calculate the reduction of evapotranspiration resulting from simulated stresses. IWFM does not calculate stresses due to anoxia and spatial patterns of area wetting, but it does simulate the effect of soil moisture depletion on the transpiratory uptake of plants over periods of extended drought. In the example model presented here, MF-FMP's inability to simulate soil-moisture storage is of minor importance when assessing a particular farm's budget components over a year or two. It also is of minor relevance for sufficiently irrigated farms that do not experience long-term depletions of soil moisture. However, severe changes in temperature and precipitation patterns may lead to changes in soil moisture over one to several hydrologic years.

For the simulation of the hypothetical model, evapotranspiration is well correlated, though offset in magnitude, even though the models have differences in conceptual processes and simulation methods. IWFM simulates higher evapotranspiration rates and return flows and less streamflow infiltration than MF-FMP. This results in larger surface-water diversions upstream in IWFM, and less water available to downstream farms than in MF-FMP. The simulated changes in soil moisture in IWFM vary each stress period but are small over the entire two-year period of simulation. The changes in soil moisture are relatively more important in the non-irrigated natural vegetation regions and are less important in irrigated regions over the entire period of simulation. The constant soil moisture requirement imposed in IWFM, for the sake of comparison of the two models, results in a constant deep percolation rate that compares poorly to the variable percolation rates in MF-FMP. Similarly, higher evapotranspiration rates are mainly responsible for larger groundwater pumpage demands and related lower groundwater levels in IWFM relative to MF-FMP.

Because of the differences in features and conceptual approaches between MF-FMP and IWFM, the user may find that one model is better suited for a certain hydrologic setting than the other. It should also be noted that the performances of MF-FMP and IWFM on this particular test case with fixed framework and parameter values does not necessarily predict their performance in real-world situations. These differences may affect the evaluation of policies, projects, or water-balance analysis for some hydrologic settings.

Overall, the principal strength of both models is that they address a connected land surface, root zone, stream, and aquifer system through different levels of linkages. This approach allows many checks and balances in a modeling study, which were previously unavailable for the simulation of a broad range of hydrologic settings. For both models, discrepancies between simulated and real-world evapotranspiration rates will translate into different rates of recharge, groundwater-level elevations, stream-aquifer interactions and streamflows, which may not be indentified during model calibration and cannot be identified for predictive models. Therefore, it is expected that when both models are applied to the same area independently, the simulated differences will be dependent on the hydrologic setting and the types of issues that are being addressed in the water-resource management analysis. For some settings, such as those represented by this hypothetical case, both models produce reasonable estimates with similar variations but somewhat different magnitudes of the estimates for most of the components of the hydrologic cycle they simulate for the entire period of simulation.

# Appendix A: Notation

The following symbols are used in this report:

CIR = crop irrigation requirement;
$E_{c\text{-}act}$ = actual evaporation;
$E_{c\text{-}pot}$ = potential crop evaporation;
$E_{i\text{-}act}$ = actual evaporation from irrigation;
$E_{i\text{-}pot}$ = potential evaporation from irrigation;
$E_{p\text{-}pot}$ = potential evaporation from precipitation;
$ET_c$ = crop evapotranspiration under standard conditions;
$ET_{c\text{-}act}$ = total actual crop evapotranspiration;
$ET_{c\text{-}adj}$ = crop evapotranspiration under non-standard conditions;
$ET_{c\text{-}pot}$ = potential crop evapotranspiration;
$ET_{gw\text{-}act}$ = root uptake from groundwater;
$ET_{i\text{-}act}$ = portion of actual evapotranspiration fed by irrigation;
$ET_{p\text{-}act}$ = portion of actual evapotranspiration fed by precipitation;
$ET_r$ = reference crop evapotranspiration;
FID = Farm Identification Number;
I = rate of irrigation water;
$IE^{I}_{swFMP}$ Fraction of inefficiency loss to surface runoff from irrigation as defined by MF-FMP
$IE^{I}_{swIWFM}$ Ratio of surface runoff from irrigation to total irrigation amount as required by IWFM
$K_c$ = crop coefficient (FAO);
$K_{cb}$ = basal (transpirative) crop coefficient (FAO);
$K_e$ = evaporative crop coefficient (FAO);
$K_e^{\,i}$ = evaporation fraction of potential crop evapotranspiration related to irrigation;
$K_s$ = saturated hydraulic conductivity of the root zone;
$K_{st}$ = hydraulic conductivity of the stream bed material;
$K_t$ = transpiration fraction of potential crop evapotranspiration;
$K_u$ = unsaturated hydraulic conductivity of the root zone;
MAD = maximum allowable depletion;
Q-p-in = Rate of precipitation inflow to a water-balance subregion [L/T] for MF-FMP;
Q-nrd-in = Rate of non-routed delivery inflow to a water-balance subregion [L/T] for MF-FMP;
Q-srd-in = Rate of semi-routed delivery inflow to a water-balance subregion [L/T] for MF-FMP;
Q-wells-in = Rate of well pumpage inflow to a water-balance subregion [L/T] for MF-FMP;
Q-etgw-in = Rate of ET from groundwater inflow to a water-balance subregion [L/T] for MF-FMP;
Q-tot-in = Rate of total inflow to a water-balance subregion [L/T] for MF-FMP;
Q-et-out = Rate of total ET outflow to a water-balance subregion [L/T] for MF-FMP;
Q-run-out = Rate of total runoff outflow to a water-balance subregion [L/T] for MF-FMP;
Q-dp-out = Rate of total runoff outflow to a water-balance subregion [L/T] for MF-FMP;
Q-tot-out = Rate of total inflow to a water-balance subregion [L/T] for MF-FMP;
Q-storage-change = Rate of total change in storage in a water-balance subregion [L/T] for MF-FMP;
Q-in-minus-out = Rate of flow (inflow minus outflow) in a water-balance subregion [L/T] for MF-FMP;
P = precipitation rate;
$T_{c\text{-}act}$ = actual transpiration;
$T_{c\text{-}pot}$ = potential crop transpiration;
$T_{gw\text{-}act}$ = portion of transpiration fed by uptake from groundwater;
$T_{i\text{-}act}$ = portion of transpiration fed by irrigation;
$T_{p\text{-}act}$ = portion of transpiration fed by precipitation;
$T_{p\text{-}pot}$ = potential transpiration fed by precipitation;
$U_i$ = re-used portion of the initial return flow;

# References

Allen, RG; Pereira, LS; Raes, D; Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. Rome: Food and Agriculture Organization of the United Nations. 300 p. Irrigation and Drainage Paper 56.

Brush, CF; Dogrul, EC; Moncrief, M; Galef, J; Shultz, S; Tonkin, M; Wendell, D; Kadir, T; Chung, F. 2008. Estimating hydrologic flow components of the Central Valley hydrologic flow system with the California Central Valley Groundwater-Surface water Model. **In:** Brush, CF; Miller, NL, editors. Proceedings of the California Central Valley Groundwater Modeling Workshop. July 10-11, 2008; Lawrence Berkeley National Laboratory, Berkeley, (CA). Sacramento (CA): California Water and Environmental Modeling Forum. p. 80-88.

Campbell, GS. 1974. A simple method for determining unsaturated hydraulic conductivity from moisture retention data. Soil Sci. 117(6):311-314.

Dogrul, EC. 2007. Z-Budget: Sub-Domain Water Budgeting Post-Processor for IWFM Theoretical Documentation and User's Manual: Integrated Hydrological Models Development Unit, Modeling Support Branch, Bay-Delta Office, California Department of Water Resources. variously paged.

Dogrul, EC. 2009a. Integrated Water Flow Model (IWFM v3.1): Theoretical documentation. Sacramento (CA): Integrated Hydrological Models Development Unit, Modeling Support Branch, Bay-Delta Office, California Department of Water Resources. variously paged.

Dogrul, EC. 2009b. Integrated Water Flow Model (IWFM v3.1): User's manual. Sacramento (CA): Integrated Hydrological Models Development Unit, Modeling Support Branch, Bay-Delta Office, California Department of Water Resources. variously paged.

Dogrul, EC; Schmid, W; Hanson, RT; Kadir, T; Chung, F. 2011, Integrated Water Flow Model and MODFLOW-Farm Process: A comparison of theory, approaches and features of two integrated hydrologic model, California Department of Water Resources Technical Information Report No. xx, xxxp.

Faunt, CC; Belitz, K; Hanson, RT. 2009b. Chapter B: Groundwater availability in California's Central Valley. (Faunt, CC, editor. Groundwater availability of the Central Valley aquifer of California). Reston (VA): US Geological Survey. 225 p. Professional Paper 1766.

Faunt, CC; Hanson, RT; Belitz, K. 2009a. Chapter A: Introduction, overview of hydrology, and textural model of California's Central Valley. (Faunt, CC, editor. Groundwater availability of the Central Valley aquifer of California). Reston (VA): US Geological Survey. 225 p. Professional Paper 1766.

Faunt, CC; Hanson, RT; Belitz, K; Schmid, W; Predmore, SP; Rewis, D L; McPherson, K. 2009c. Chapter C: Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley. (Faunt, CC, editor. Groundwater availability of the Central Valley aquifer of California). Reston (VA): US Geological Survey. 225 p. Professional Paper 1766.

Faunt, CC; Hanson, RT; Schmid, W; Belitz, K. 2008. Application of MODFLOW's Farm Process to California's Central Valley. **In:** Poeter, E; Hill, M; Zheng, C, editors. Modflow and More 2008: Groundwater and Public Policy. May 18-21, 2008; International Groundwater Modeling Center. Golden (CO): Colorado School of Mines. p. 596-500.

Hanson, RT; Leake, SA. 1998. Documentation for HYDMOD, A program for time-series data from the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model. **[Internet].** US Geological Survey. 57 p. US Geological Survey Open-File Report 98-564. [cited: 2009 Apr 17]. Available at: http://pubs.er.usgs.gov/usgspubs/ofr/ofr98564

Hanson, RT; Schmid, W; Lear, WJ; Faunt, CC. 2008. Simulation of an Aquifer-Storage-and-Recovery (ASR) System using the Farm Process in MODFLOW for the Pajaro Valley, Monterey Bay, California. **In:** Poeter, E; Hill, M; Zheng, C, editors. Modflow and More 2008: Groundwater and Public Policy. May 18-21, 2008; International Groundwater Modeling Center. Golden (CO): Colorado School of Mines. p. 501-505.

Hanson, R.T., Schmid, Wolfgang, Faunt, C.C., and Lockwood, B., 2010, Simulation and Analysis of Conjunctive Use with MODFLOW's Farm Process: Ground Water Vol. 48, No. 5, pp. 674 - 689.( DOI: 10.1111/j.1745-6584.2010.00730.x)

Harbaugh, AW. 2005. MODFLOW-2005, the US Geological Survey modular groundwater model-the Groundwater Flow Process. Reston (VA): US Geological Survey. variously paged. Techniques and Methods 6-A16.

Harbaugh, AW; Banta, E R; Hill, MC; McDonald, MG. 2000. MODFLOW-2000, the US Geological Survey modular groundwater model-User guide to modularization concepts and the Groundwater Flow Process. Reston (VA): US Geological Survey. 121 p. Open-File Report 00-92.

Harbaugh, A.W. 1990. A computer program for calculating subregional water budgets using results from the U.S. Geological Survey Modular Three-dimensional Finite-difference Ground-water Flow Model. Reston (VA): US Geological Survey. 24 p. US Geological Survey Open-File Report 90-392.

Schmid, W; Hanson, RT. 2007. Simulation of Intra- or trans-boundary water rights hierarchies using the Farm Process for MODFLOW-2000. ASCE Journal of Water Resources Planning and Management. 133(2):166-178. Available at: DOI: 10.1061/(ASCE)0733-9496(2007)133:2(166)

Schmid, W; Hanson, RT. 2009a. Appendix 1: Supplemental Information – Modifications to MODFLOW-2000 packages and processes. (Faunt, CC, editor. Groundwater availability of the Central Valley aquifer of California). Reston (VA): US Geological Survey. 225 p. US Geological Survey Professional Paper 1766.

Schmid, W; Hanson, RT. 2009b The Farm Process Version 2 (FMP2) for MODFLOW-2005 - modifications and upgrades of FMP1 and inclusion into MODFLOW-2005. Located at: US Geological Survey. (Book 6). Reston (VA): US Geological Survey. 102 p. Techniques and Methods 6-A32.

Schmid, W; Hanson, RT; Maddock III, T. 2006b. Overview and advances of the Farm Process for MODFLOW-2000: managing groundwater systems. **In:** Poeter, E; Hill, M; Zheng, C, editors. Modflow and More 2006 – Managing Groundwater Systems. May 21-24, 2006; International Groundwater Modeling Center. Golden (CO): Colorado School of Mines. p. 23-27.

Schmid, W; Hanson, RT; Maddock III, T; Leake, SA. 2006a. User guide for the farm process (FMP1) for the US Geological Survey's modular three-dimensional finite-difference groundwater flow model, MODFLOW-2000. (Book 6). Reston (VA): US Geological Survey. 127 p. Techniques and Methods 6-A17. Available at: http://pubs.usgs.gov/tm/2006/tm6A17/

Schroeder, PR; Dozier, TS; Zappi, PA; McEnroe, BM; Sjostrom, JW; Peton, RL. 1994. The hydrologic evaluation of landfill performance (HELP) model: engineering documentation for version 3. Washington (DC): US Environmental Protection Agency, Office of Research and Development. 84 p. EPA/600/R-94/168b.

USDA, Soil Conservation Service. 1985. National engineering handbook. Washington (DC): US Department of Agriculture. Section 4, Hydrology, Chapters 9 and 10.