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Integrated Water Flow Model and Modflow-Farm Process: A Comparison of Theory, Approaches, and Features of Two Integrated Hydrologic Models

Technical Information Record

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INTEGRATED WATER FLOW MODEL AND MODFLOW-FARM PROCESS: A COMPARISON OF THEORY, APPROACHES, AND FEATURES OF TWO INTEGRATED HYDROLOGIC MODELS

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

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Table of Contents

List of Figures

List of Tables

Abstract

Effective modeling of conjunctive use of surface and subsurface water resources requires simulation of land use-based root zone and surface flow processes as well as groundwater flows, streamflows, and their interactions. Recently, two computer models developed for this purpose, the Integrated Water Flow Model (IWFM) from the California Department of Water Resources and the MODFLOW with Farm Process (MF-FMP) from the US Geological Survey, have been applied to complex basins such as the Central Valley of California. As both IWFM and MF-FMP are publicly available for download and can be applied to other basins, there is a need to objectively compare the main approaches and features used in both models. This paper compares the concepts, as well as the method and simulation features of each hydrologic model pertaining to groundwater, surface water, and landscape processes. The comparison is focused on the integrated simulation of water demand and supply, water use, and the flow between coupled hydrologic processes. The differences in the capabilities and features of these two models could affect the outcome and types of water resource problems that can be simulated.

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Introduction

Groundwater is a crucial component of water-resources-management practices. It often serves as a supplementary source to surface water to meet urban and agricultural water demands; in arid regions it may be the only source of water. Groundwater interacts with streams, sometimes replenishing and pumping of groundwater can deplete in-stream flows. It can also be used as a “water bank,” to be tapped into as a supplemental source during drought periods. Groundwater is commonly used conjunctively with stream flows to meet urban and agricultural water needs. As the world's fresh water supplies diminish, accurate simulation of the conjunctive use of surface water and groundwater becomes an increasingly important component of water-resource-planning efforts.

In heavily inhabited and cultivated basins, the level of urban and agricultural water demands, and the water-resources-management practices implemented to meet these demands, affect all processes of the hydrologic cycle. Therefore, to model conjunctive use of surface and subsurface water effectively, it is necessary to integrate simulation methods for subsurface, surface, and urban and agricultural water-demand computations. These models need to simulate conjunctive use in cases where there is not enough water supply to meet the total water demand.

i) Integrated Hydrologic Model Development

Early groundwater models were constrained by static parameters defining stresses related to the rest of the hydrologic cycle (Prickett and Lonnquist, 1971; McDonald and Harbaugh, 1988). They used a priori external estimates of recharge, generated from precipitation and irrigation and pumping rates, to meet an externally computed demand. For instance, Williamson et al. (1989) used electric power records to estimate the groundwater pumping in the Central

Valley of California and Hanson et al. (2003) used land use acreages to estimate pumpage for various land use periods for the Santa Clara-Calleguas Basin of California. Since the inception of the first groundwater models, the need to dynamically simulate more components of the hydrologic cycle that are related to groundwater-flow dynamics has led to the development of more complex simulation models. Models were developed that coupled precipitation runoff with groundwater to route the water through all components of the hydrologic cycle and to simulate the interactions between them. For instance, GSFLOW (Markstrom et al., 2008) couples the Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983), with the three-dimensional multi-layer Modular Ground Water Flow Model (MODFLOW) (Harbaugh, 2005). WEHY (Kavvas et al., 2004) links a hydrologic watershed model to a two-dimensional Dupuit-Forchheimer-type single-layer groundwater model. A linkage of the frequently used Soil Water Assessment Tool (SWAT) to MODFLOW, also known as SWATMOD (Sophocleous et al., 1999; Sophocleous and Perkins, 2000), simulates a soil-water budget and “quasi root uptake” by aggregating cell-by-cell evapotranspiration (ET) calculated by the EVT package of MODFLOW from shallow aquifers over watershed sub-basins. However, this procedure can greatly overestimate root uptake from groundwater as a result of the conceptual simplicity of the EVT package of MODFLOW and, therefore, can underestimate the irrigation demand. In addition, the simplicity of applying a uniform capillary uptake over an entire sub-basin can result in additional estimation errors, since phreatophytic uptake often reflects local conditions.

Another limitation of SWATMOD is its inability to model the unsaturated zone beyond the root zone. Percolation is applied instantly to the groundwater table. SWATMOD returns basin-wide hydrologic balances but not economic or physical budgets for individual water accounting units, such as farms, irrigation districts, or urban areas. Recent improvements of exchanging the characteristics of SWAT hydrologic response units with MODFLOW cells (Kim et al., 2008) have not changed most of the limitations described above. The outer boundaries of models based on SWATMOD, which is now called SWAT-MODFLOW, are limited to watershed boundaries. Some constraints on surface- and groundwater supply are present in SWAT-MODFLOW, but a simulation of surface-water rights seniorities, or rate or head constraints on pumpage from multi-aquifer wells, are not present. Another limitation is that the recent improvements to the new SWAT-MODFLOW include head-dependent boundary flow. However, this condition is simulated only with the stage-invariable RIVER package instead of the stage-variable Streamflow Routing Package (SFR; Niswonger and Prudic, 2005). This limits the ability to realistically simulate stream-flow responses to stresses due to changing hydrologic conditions, such as diversions to meet the water demands and surface runoff into streams generated by precipitation and irrigation.

Another model that links surface and groundwater components is MIKE SHE (Systeme Hydrologique European), which is used to simulate flow and the transport of solutes and sediments in both surface water and groundwater (DHI 1999). However, Said et al. (2005) points out that MIKE SHE does not have the ability to handle variable grids and that its ability to simulate evapotranspiration and stream-aquifer interaction could be improved (Prucha, 2004). The stream-aquifer interaction is calculated using a conductance and the head difference between the river—considered a line source—and the aquifer (Illangasekare, 2001). This approach is similar to that used in the RIVER Package of MODFLOW, meaning stage is prescribed and not dynamically dependent on stream-aquifer leakage and other inflows and outflows. MIKE SHE is a physically based, fully distributed parameter model. It uses the 1-D Richards' equation for unsaturated flow, which requires an extensive set of physical parameters. Often, some of the soil-water constitutive parameters are not available, which makes it difficult to set up a fully coupled MIKE SHE model. Among the coupled surface and groundwater models described above, MIKE SHE is probably the most fully coupled hydrologic model; it includes an irrigation module, but its downsides are its lack of a fully dynamic stream-aquifer interaction between variable stages and variable heads, it does not return economic or physical mass balances for water-accounting units, and it suffers from extensive data and parameter requirements.

HydroGeoSphere (Therrien et al., 2007) and ParFlow-CLM (Maxwell and Miller, 2005; Kollet and Maxwell, 2008) are also among the integrated hydrologic models. These models solve the three-dimensional Richard's equation for the variably saturated subsurface flow simultaneously with the conservation equations for land surface flow processes. Simultaneous solution of surface and subsurface flow equations avoids the need to iterate between individual flow models and provides a robust simulation mechanism. Since both HydroGeoSphere and ParFlow-CLM solve Richard's equation for the subsurface flow, the simulation time steps are generally expressed in fractions of a second. For large basins with long simulation periods, such a small magnitude for the time step may lead to very long computer run times. Even though both models use fast matrix solvers, and ParFlow-CLM offers parallel processing features, the long computer run times make these models primarily research tools.

The models described above all include the simulation of the land use based runoff processes and the plant consumptive use, and their effects on groundwater dynamics. However, they do not simulate agricultural and urban water demands on the basis of water-accounting units and the conjunctive use of surface and subsurface water resources to meet these demands. Essentially, they are descriptive models; i.e., given all the stresses on the hydrologic system modeled, they describe where and how fast the water flows. Models like SIMETAW (Synder et al., 2005) or methods described by Allen et al. (1998), on the other hand, simulate the agricultural crop consumptive water requirements; however, they do this by separating the root zone from the rest of the hydrologic cycle, neglecting the uptake from groundwater, and assuming that the crop water requirement is met at every simulation time step without actual knowledge of the potential sources of water supply.

To effectively model conjunctive use of surface and subsurface water resources to meet a computed or pre-specified water demand, it is necessary to simulate two types of water balances in the system: i) the physical mass balance in the system, which the descriptive models mentioned above simulate, and ii) the economic balance between water demand and water supply, which models like SIMETAW (Synder et al., 2005) simulate with the assumption that supply is always available and is equal to demand. Additionally, for effective simulation of conjunctive use, it is necessary to develop a model that is both descriptive and prescriptive. For instance, in water resources planning studies, defining the sources of water (in terms of stream diversions and pumping) to meet a predicted water demand, while honoring water rights and environmental regulations, is as important as predicting the water demand itself.

ii) IWFM and MF-FMP Development

The California Department of Water Resources' (CADWR) Integrated Water Flow Model (IWFM) (Dogrul, 2009a, 2009b) and MODFLOW with the Farm Process (MF-FMP) of the U.S. Geological Survey (USGS) (Schmid et al., 2006; Schmid and Hanson, 2009a, 2009b) are two models that were developed to address the physical and economic water balance in a watershed. These models allow the user to simulate physical flow processes of the hydrologic system as well as simulate the water-resources-management practices in watersheds.

The roots of IWFM date back to a Ph.D. dissertation by Yoon (1976). IWFM's precursor was called the Integrated Groundwater Surface water Model (IGSM); after several modifications, it was documented by Montgomery & Watson (MW, 1993). In 1990, the latest version of Yoon's original model was released as part of the Programmatic Environmental Impact Statement for the Central Valley Project Improvement Act (CVPIA PEIS) funded by the U.S. Bureau of Reclamation, CADWR, California State Water Resources Control Board (SWRCB), and the Contra Costa Water District (CCWD). In 2001, after a thorough evaluation of IGSM, CADWR developed and released its own version of the model that incorporated major changes to both the theory and code of IGSM, called IGSM2, and later renamed IWFM (to distinguish it from other versions of IGSM still in use). IWFM is a comprehensive model that effectively balances the use of scientifically sound simulation methods with the ability to easily use readily available data in model development, and has a flexible input file structure that incorporates time tracking and other techniques to facilitate rapid revision of existing models for conducting feasibility and impact assessments. It has been used to model the conjunctive-use programs and scenario analysis in California's Central Valley (Brush et al., 2008; Miller et al., 2009), and other groundwater basins in California (BCDWRC, 2008a, 2008b) and Oregon (Jimenez, 2008).

MF-FMP uses MODFLOW-2000 (Harbaugh et al., 2000) and MODFLOW-2005 (Harbaugh, 2005). MODFLOW is a widely accepted, open-source, hydrologic model that has been in use since 1988. Over a period of decades, many people from academia, government agencies, and the private sector from all over the world have continuously contributed to its development and bug fixes. It is the most used and trusted groundwater model in the world and recently has been expanded to include more realistic coupling between surface and subsurface processes. MF-FMP has been applied to four productive agricultural regions of different scale in the states of California (Faunt et al., 2008, 2009a, 2009b, 2009c; Hanson et al., 2008) and New Mexico (Schmid, 2004) to assess the availability of water and the impacts of alternative management decisions.

Recently, both IWFM and MF-FMP have been used to model the water resources system of the California Central Valley (Brush et al., 2008; Faunt et al., 2008, 2009a, 2009b, 2009c). Both of these models were designed to assess the supply and demand components of the water-resources system in the Central Valley, which include water use and movement on the land surface, conjunctive use of surface and groundwater, and changes in groundwater storage and land subsidence due to groundwater pumping. The two applications cover virtually the same area, and the CADWR and USGS worked together during development of the two applications to incorporate the same historic precipitation, surface-water inflow, and surface-water diversion data to the extent that it was possible. Yet, even with similar input data, the two applications yield some results that are similar and some that are different, owing in part to differences in the conceptual framework of the two models, especially regarding the economic budgeting to match water supplies and demands. At the level of complexity of the two applications, it was difficult to track the sources of these differences. As part of an ongoing collaborative effort, the CADWR and USGS started a comparison of the models discussed in this paper and a comparison of the applications of the two models on a simple hypothetical problem (Schmid et al., 2011). This paper compares the relevant conceptualizations and features of each hydrologic model pertaining to groundwater, surface water and landscape processes, and the integrated simulation of water demand and supply, water use, and movement. The implementation of these features for a simple problem and comparison of results from the two models can be found in Schmid et al. (2011).

Governing Equations

Conservation equations for groundwater, stream, lake, root zone, and land-surface runoff processes are solved simultaneously in both models to simulate a large portion of the hydrologic cycle, and the agronomic and human effects on the cycle. Among the mass conservation equations, the groundwater-flow equation is the governing equation that is solved for groundwater heads. Both models solve the same conservation equation for groundwater; IWFM uses the finite-element approach, and MF-FMP uses the finite-difference approach. Conservation equations for the other surface water and landscape flow processes are also solved at each iteration until convergence of a groundwater-flow equation solver is reached. The solver is assumed to have converged when a user-specified closure criterion is met for the difference between results of successive iterations using the maximum absolute value of the change in groundwater hydraulic heads and, optionally in MF-FMP, also of residual groundwater flows at all nodes. With the coupled stream-groundwater conservation equations to simulate the stream-aquifer interactions, both models are powerful tools to efficiently address important issues, such as effects of conjunctive use programs, changes in irrigation methods, and implementation of urban and agricultural water conservation programs, etc. on the hydrologic system modeled.

Both IWFM and MF-FMP simulate the vertical interaction between surface- and groundwater across a vegetated root zone or non-vegetated unsaturated zone and across streambeds. Alternatively, MF-FMP can simulate the infiltration across unsaturated zones beneath stream beds (Niswonger and Prudic, 2005) and beneath large areas with unsaturated zones (Niswonger et al., 2006). In the horizontal direction, both models simulate stream diversions to agricultural and urban lands, and the surface runoff (i.e., rainfall runoff and irrigation return flow) into streams. The models also simulate the conjunctive use of surface water and groundwater to satisfy the consumptive use requirement of vegetation in excess of the effective precipitation as well as urban water demands.

Although both models simulate the interaction between surface water and groundwater across a root zone, the two models incorporate different conceptualizations of the conservation of mass for root zone processes. Even though MF-FMP can be considered a fully coupled surface and groundwater interactive hydrologic model, historically it originates from the groundwater model MODFLOW. While stress periods can be of any length, solution time steps of long-term regional MF-FMP models are commonly on the order of weeks or longer, as is typical for regional hydrologic models used to analyze conjunctive use over decades. At these time steps, and for medium root-zone depths, MF-FMP assumes all inflows into the root zone to be equal to all outflow, on the basis of numerous HYDRUS-2D (Simunek et al., 1999) simulations for various crop and soil types, root zone and capillary-fringe depths, water-table configurations, and levels of potential evapotranspiration (Schmid, 2004; Schmid et al., 2006). In MF-FMP, inflows that meet the crop evapotranspirative requirements are precipitation, irrigation, and root uptake from groundwater. Outflows are transpiration and evaporation, runoff, and deep percolation beneath the root zone.

In IWFM, the inflows are precipitation and irrigation, and the outflows are evapotranspiration, runoff, and deep percolation. MF-FMP simulates uptake from groundwater but does not simulate changes in the soil water storage. On the other hand, IWFM does not simulate groundwater uptake but simulates changes in soil water storage. Land use processes in both models are directly linked to the aquifer system, not only through deep percolation into the groundwater but also through pumping to satisfy the agricultural and urban demands that are not satisfied by surface water.

MF-FMP and IWFM have the option to neglect flow processes in the unsaturated zone beneath the root zone and to assume instant recharge from deep percolation. However, both models also feature an optional simulation of an unsaturated zone between the root zone and the saturated aquifer system. MF-FMP simulates delayed recharge through a deep vadose zone beneath root zones through a linkage to the Unsaturated Zone Flow package (Niswonger et al., 2006; Schmid and Hanson, 2009b). Through the same linkage, MF-FMP also simulates groundwater discharge to the surface and rejected infiltration from fully saturated conditions under conditions of shallow or above-surface groundwater levels. IWFM features its own unsaturated zone flow module that connects the root zone to the saturated groundwater system. This module simulates the attenuation of deep percolation before it recharges a deep water table or the rejection of infiltration in cases where the infiltration rates computed in the root zone module are too high. The interaction between the root zone and unsaturated zone modules is a one-way interaction, and no iterations between the two modules are performed. Vertical outflow from the root zone module becomes inflow into the unsaturated zone module. Any part of the inflow that is in excess of the available unsaturated zone storage or its conveyance capacity is converted into surface runoff.

Both models also simulate the interaction between streams and groundwater. For stream flow routing and stream-aquifer interaction across the streambed, MF-FMP uses the Streamflow Routing Package, SFR (SFR1, Prudic et al., 2004; SFR2, Niswonger and Prudic, 2005) and IWFM uses a method similar to that described in the SFR1 package. MF-FMP can also simulate delayed recharge from infiltration beneath streambeds through a deep vadose zone (Niswonger and Prudic, 2005). Although both models use similar approaches in stream-flow routing, the following conceptual and implementation differences may lead to differences in the results of both models:

i. The MF-FMP SFR package uses several options to define the relationship between the stream stage and the flow (e.g., Manning's equation with a rectangular channel or an irregular-shaped cross section, either a rating table or a power function relating both depth and width to stream flow). IWFM uses a user-specified rating table between flow and stage; Manning's equation can also be discretized through a rating table.

ii. Both models express the stream-aquifer interaction as

$$Q_{sg} = \frac{K_{st} w_s L_s}{d} \Delta h_{sg} \qquad (1)$$

where Q_{sg} is the flow rate between a stream section and the aquifer (L^3T^{-1}), K_{st} is the hydraulic conductivity of the stream bed material (LT^{-1}), w_s is the width of stream section (L), L_s is the length of stream section (L), d is the thickness of stream bed material (L), Δh_{sg} is the vertical head difference between stream and the aquifer (L). In both the SFR package and IWFM, Δh_{sg} is defined as the difference between the head in the stream and the aquifer head. However, the representation of stream-groundwater interaction when stream and aquifer are hydraulically disconnected is different in both models. To comply with Darcy's law in simulating flow through the streambed, the SFR package assumes that the streambed is saturated at all times with zero pressure at the bottom of the streambed. The SFR package represents the stream-aquifer interaction when they are hydraulically disconnected as

$$Q_{sg} = K_{st} w_s L_s \left(\frac{d+s}{d} \right) = K_{st} w_s L_s \left(1 + \frac{s}{d} \right) \qquad (2)$$

where s is the stream stage (L).

Equation (2) assumes that the stream bed is saturated at all times. However, following a prolonged drought the stream bed will be dry and it will require some time for re-wetting. If the stream stage compared to the thickness of the stream bed is small, such that s/d in equation (2) is much less than 1, most or all of the stream flow will likely be used in re-wetting the stream bed and no seepage will occur. However, using equation (2), a non-zero seepage rate will be computed that can be as large as the stream flow itself. In MF-FMP, the streambed is assumed to be saturated at all times, which, because of the large time steps used in most groundwater models, is tantamount to assuming that the time for rewetting is short enough to not significantly affect the modeled stream-aquifer water budget terms. IWFM, on the other hand, approximates (2) as

$$Q_{sg} \cong K_{st} w_s L_s \left(\frac{s}{d} \right) \qquad (3)$$

Although (3) is not an accurate representation of the Darcy equation, it does produce lower seepage rates when the stream stage is small. It should be noted that the offset between (2) and (3) is small in relation to Q_{sg} when s/d is sufficiently larger than 1, and that Q_{sg} is equal in both codes if the stream and aquifer are hydraulically connected. However both approaches used by SFR and IWFM assume instantaneous recharge from beneath the streambed to the underlying aquifer.

iii. In MF-FMP, the user has the option to simulate delayed recharge from infiltration beneath streambeds through a deep vadose zone (Niswonger and Prudic, 2005). First, using this option imposes a constraint for the Darcy-type stream seepage across the streambed as described above, which cannot exceed the vertical hydraulic conductivity of the underlying unsaturated zone. Second, the infiltration into the unsaturated zone between the streambed and the water table is converted to the water content of leading or trailing waves of wetting or drying fronts by assuming that the vertical flux is driven by gravitational forces only. The propagation of the waves is then simulated by a kinematic wave approximation of vertical seepage through the unsaturated zone. However, the water content cannot exceed the saturated water content when the infiltration rate exceeds the saturated vertical hydraulic conductivity.

Both models offer additional features for the simulation of other hydrologic processes (e.g., simulation of open waters such as lakes and reservoirs and their interaction with the aquifer system and the stream network). However, a comparison of these features is out of the scope of this paper, and the interested reader is referred to the documentation of each model (Dogrul, 2009a, 2009b; Schmid et al., 2006; Schmid and Hanson, 2009a, 2009b; Harbaugh et al., 2000; Harbaugh, 2005).

As well as vertical interactions between surface water and groundwater, lateral exchange of water between land use processes and the stream network is provided in both models. Land use processes in both models are directly linked to the stream network through direct runoff from precipitation and agricultural return flow, and stream diversions to meet the water demand for irrigated agriculture and irrigated urban landscape.

Comparison of Methods for Land Use and Root Zone Processes

Both IWFM and MF-FMP simulate most of the same flow processes of the hydrologic cycle. However, there are both similarities and differences in the way these processes and their interactions are conceptualized and simulated. In this section, a comparison of features and simulation methods adopted by both models is presented. For the purposes of this report, the comparison between these two models is generally limited to the flow processes that operate in the control volume defined by the land surface and the vadose zone that extends to the water table (Figs. 1 and 2). Furthermore, because of the complexity of both models, only the most important components will be explained and compared. The reader is encouraged to consult each model's documentation for more information (Dogrul, 2009a, 2009b; Schmid et al., 2006; Schmid and Hanson, 2009a, 2009b).

Both IWFM and MF-FMP consider two types of water budgeting for the control volume horizontally delineated by land surface areas, called "subregions" in IWFM and "farms" in MF-FMP. For both models, these water-accounting units can include irrigated and non-irrigated farms, native vegetation, and urban areas. Using the term "farm" in MF-FMP" has become somewhat of an anachronism as MF-FMP has advanced to types of water-accounting units other than just agricultural farms. The water-accounting units in IWFM include the land surface area and 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 (Figs. 1 and 2):

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.

In the real world, the physical water balance is always achieved (i.e. mass is not created or lost), whereas the economic balance may not be maintained. For instance, farmers may apply more water than the true crop irrigation requirements, an unforeseen drought may limit irrigation, non-irrigated lands that depend solely on precipitation may not get enough water in drought seasons and get too much water in wet seasons, or overall source of water may be a limiting factor.

The discussions below are centered on these two types of water budgeting. A summary of the following comparisons between IWFM and MF-FMP is also given in the synoptic Table 2 at the end of this report.

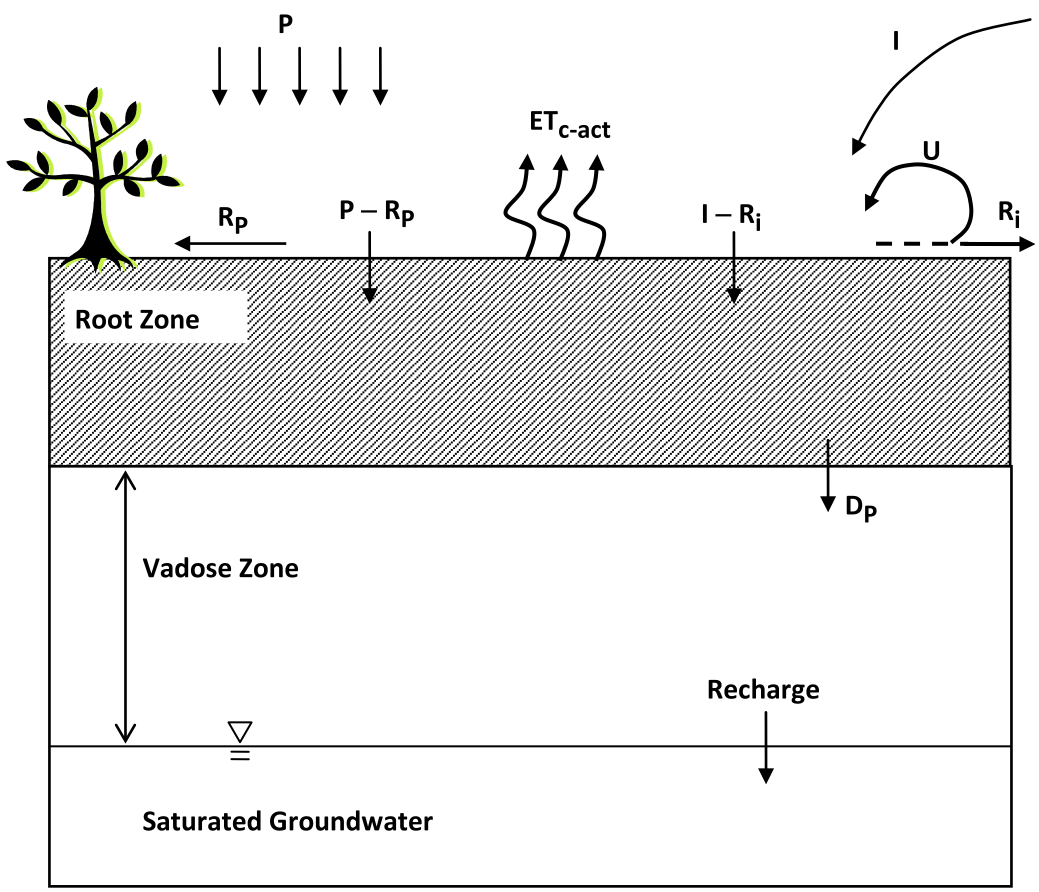
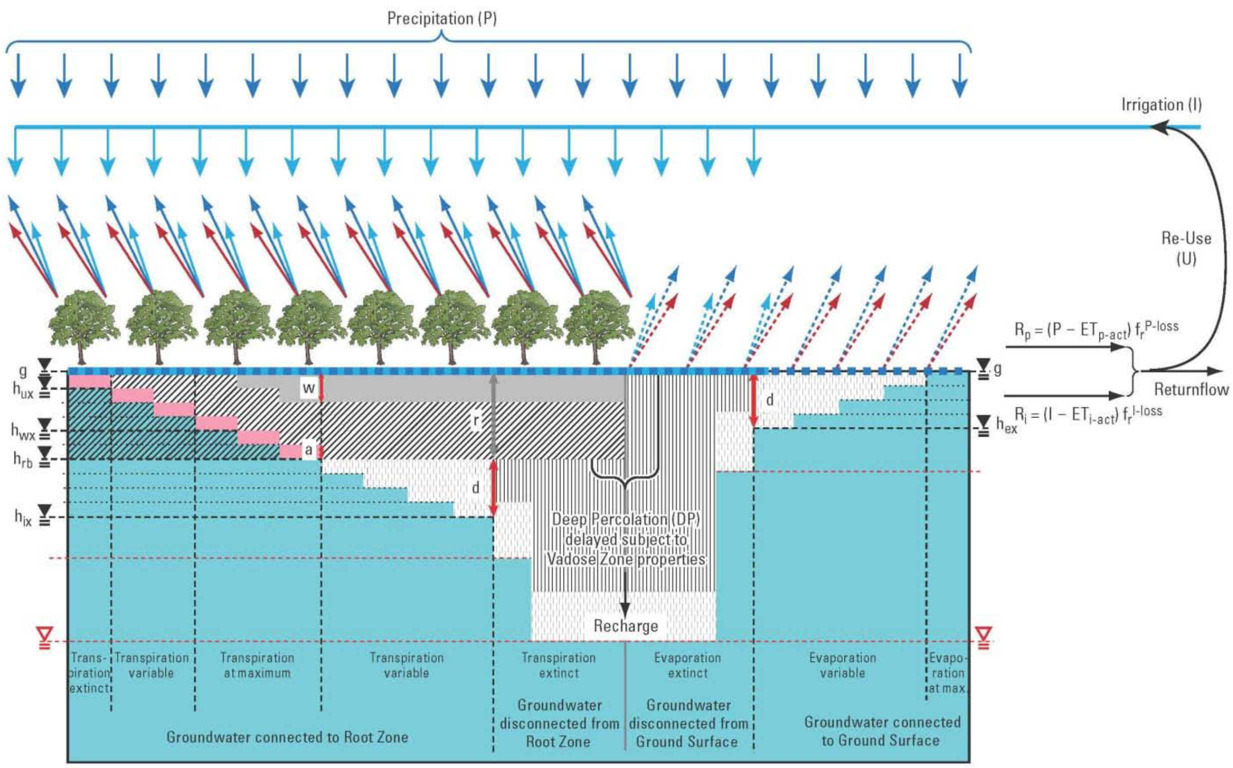
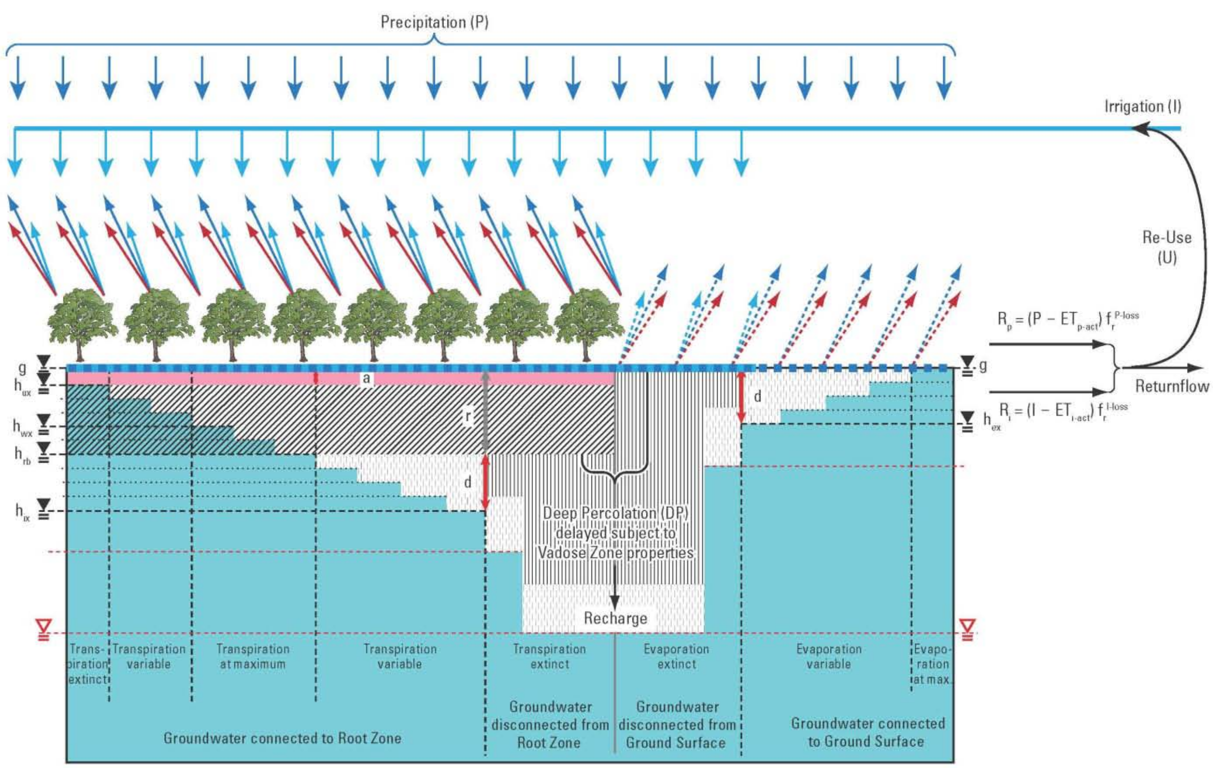


Figure 1. Schematic representation of root zone and land surface flow processes simulated by IWFM

Explanation: P – Precipitation**;** I – Irrigation**;** U – Re-use of irrigation water**;** DP – Deep percolation**;** R_p – Returnflow related to precipitation**;** R_i – Returnflow related to irrigation**;** $ET_{c\text{-}act}$ – Actual crop evapotranspiration**.**





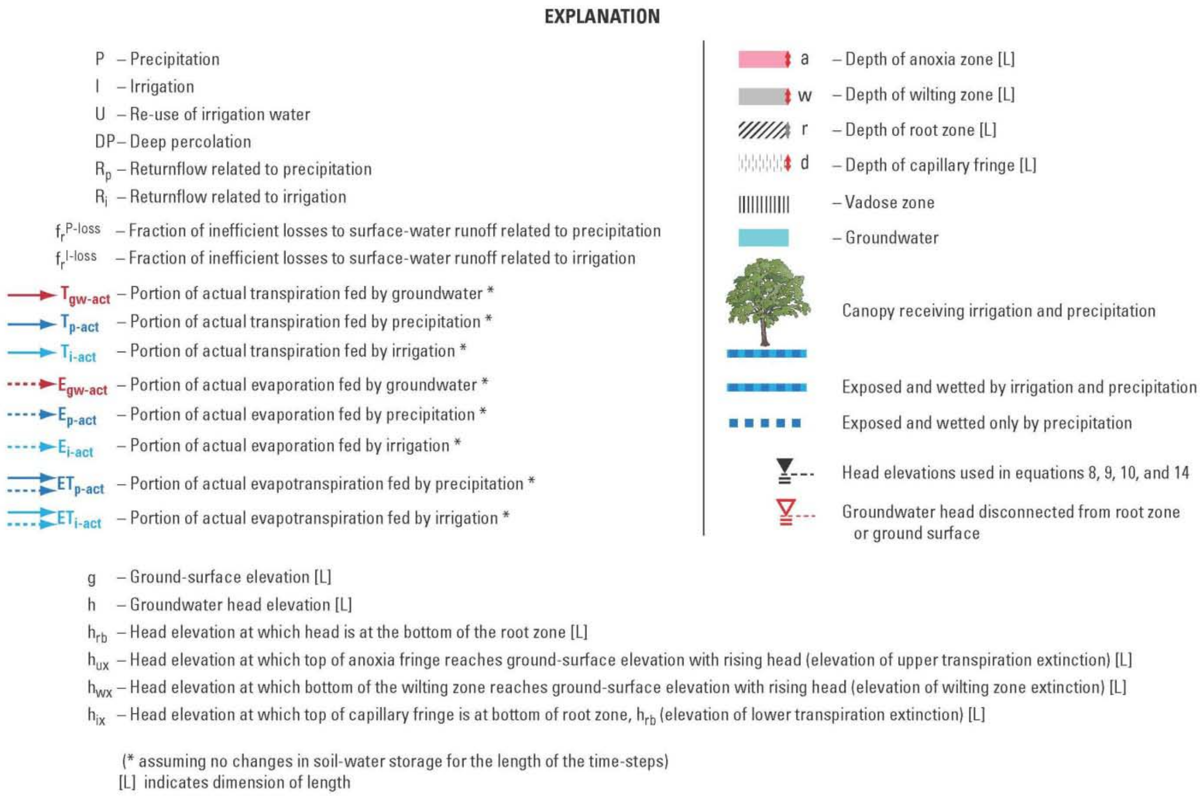


Figure 2. Schematic representation of root zone and land surface flow processes simulated by MF-FMP (modified from Hanson et al., 2010).

i) Framework and Distribution of Landscape Attributes

Both models adopt a land-use based approach to simulate the land surface and vadose zone flow processes as well as water demands. The mesh cells (finite element cells in IWFM and finite difference cells in MF-FMP) are grouped into “subregions” in IWFM and “farms” in MF-FMP. 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 are also 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. These include four integer values representing the basic characteristics of sands and gravels, fine and coarse textured soils, fine textured, and impervious clays based on the classification system developed by the National Resources Conservation Service (USDA, 1985), and basic soil-moisture properties such as a retention parameter, field capacity, and total porosity similar to the HELP model (Schroeder et al., 1994).

MF-FMP uses words for soil types, for which the MF-FMP code contains intrinsic soil-type specific coefficients. MF-FMP optionally allows the user to specify these coefficients. These coefficients describe soil-type specific analytical solutions derived from HYDRUS-2D soil-column models (Simunek et al., 1999; Schmid, 2004) that are 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 (Schmid et al., 2006; Schmid, 2004). These analytical solutions also depend on the potential transpiration and on the depth of the total root zone. The only other soil-type specific parameter in MF-FMP is the capillary fringe, which also contributes to the depth of evaporation below the land surface.

In IWFM, each cell area is allocated among four pre-specified land use types: agricultural, urban, native vegetation, and riparian vegetation. Agricultural lands are further divided into user-specified crop types whose acreages are defined as time series data at the subregional level. Physical and agricultural management properties for each crop are time-series data specified by the user (table 1; Dogrul, 2009a, 2009b; Schmid et al., 2006; Schmid and Hanson, 2009a, 2009b). Using the subregional crop acreages, IWFM computes area-weighted averages for physical and management properties, resulting in a representative agricultural crop for each subregion. Land surface and root zone flow processes are calculated for each of the four land use types in each subregion in an aggregate form. For the purpose of groundwater flow simulation, however, the root zone flow computed at the subregional level is distributed to the cell level using the land use specified for each cell. Optionally, each element can be designated as a separate subregion, making the areal resolution of the root zone in IWFM equivalent to that of the underlying groundwater module, and closer in resolution to individual cell values specified by that of MF-FMP.

In MF-FMP, each cell is assigned a user-defined crop-type ID, which may be constant or change by stress period to simulate temporal and areal changes in cropping patterns within the farm. The crop can be irrigated or non-irrigated. Irrigated crop types can also be “virtual crops” used, for instance, to simulate water deliveries to zero-transpiration “crops” that represent artificial recharge systems (Hanson et al., 2008, 2010). Non-irrigated crops can represent rain-fed agriculture (i.e. dry-land farming) or native vegetation. Physical properties for all crops and management practices (table 1) for agricultural crops are all user-defined on a cell-by-cell basis; thus, MF-FMP computes landscape processes at the cell level

Table 1. -- Summary of crop physical and management properties for IWFM and MF-FMP models (==== not included as a model input attribute).

Crop Properties (IWFM)	**Crop Properties (MF-FMP)**	**Management Properties (IWFM)**	**Management Properties (MF-FMP)**
Root-zone depth	Root-zone depth	Crop application Efficiency	Irrigation Efficiencies
====	Fraction of Transpiration	====	Fractions of inefficient losses as runoff from Precipitation
====	Fraction of Evaporation from Precipitation	====	Fractions of inefficient losses as runoff from Irrigation
====	Fraction of Evaporation from Irrigation	Fractions of inefficient losses as runoff from Irrigation re-used	====
Fraction of Field Capacity as Minimum Soil Moisture Requirement (i.e. wilting only) Volume-based properties	Stress-Response Function Values for Saturated and Unsaturated Root Zones (Zero uptake at Anoxia, Minimum pressure for full uptake, Maximum pressure for full uptake, and Wilting) Pressure-based properties		
	Potential Crop Evapotranspiration		
Potential Crop Evapotranspiration	Consumptive Use		
====	Crop Coefficients		
Acreage of irrigated crops	Irrigated or non-irrigated crop flag		

ii) Computation of Land Surface and Root-Zone Components

For a given computational unit (a particular land use area in a given subregion for IWFM, and a cell for MF-FMP), the general mass-balance equation that both models are based on for the root zone is the following:

$$P^{t+1} + I^{t+1} + ET^{t+1}_{gw-act} - ET^{t+1}_{c-act} - R^{t+1} - DP^{t+1} = \frac{\theta^{t+1} - \theta^{t}}{\Delta t} \qquad (4)$$

and

$$R^{t+1} = R^{t+1}_{p} + R^{t+1}_{i} \qquad (5)$$

where P is precipitation (LT^{-1}), I is irrigation water (LT^{-1}), $ET_{gw\text{-}act}$ is root uptake from groundwater (LT^{-1}), $ET_{c\text{-}act}$ is the total actual crop evapotranspiration (LT^{-1}), R is the runoff from precipitation and irrigation (LT^{-1}), R_p is the surface runoff from precipitation (LT^{-1}), R_i is the irrigation surface return flow (LT^{-1}), DP is the deep percolation that leaves the root zone as the moisture moves downward (LT^{-1}), θ^{t+1} is the soil moisture at the end of a time step (L), θ^{t} is the soil moisture at the beginning of a time step (L), Δt is the time step length (T), and t is the time step index (dimensionless).

In IWFM, equation (4) is solved for each subregion iteratively for each time step. IWFM does not consider uptake from groundwater and $ET_{gw\text{-}act}$ in equation (4) drops out:

$$P^{t+1} + I^{t+1} - ET^{t+1}_{c-act} - R^{t+1} - DP^{t+1} = \frac{\theta^{t+1} - \theta^{t}}{\Delta t} \qquad (6)$$

In MF-FMP, equation (4) is solved for each cell at each iteration (equation 7) because many of the terms depend directly or indirectly on the elevation of the groundwater head, h. $ET_{gw\text{-}act}$ and $ET_{c\text{-}act}$ vary with groundwater head where the water table is shallow enough to evaporate and(or) be transpired. Since applied irrigation (I) and returnflows from excess irrigation (R and DP) depend on ET(h) terms as part of the irrigation requirement calculation, these terms depend indirectly on groundwater head. The following sections (c through f) explain the dependencies of the actual ET components ($ET_{c\text{-}act}$(h) and $ET_{gw\text{-}act}$(h)) on the head from the irrigation delivery requirement (I(h)) and explain the dependencies of the crop irrigation requirement ($ET_{i\text{-}act}$(h)) on the actual ET, runoff returnflow (R(h)), deep percolation (DP(h)), and irrigation delivery requirement (I(h)) for MF-FMP.

MF-FMP does not consider changes in soil-water storage in the root zone (i.e., RHS in equation (7) = 0):

$$P^{k+1} + I^{k+1}\left(h^k\right) + ET^{k+1}_{gw-act}(h^k) - ET^{k+1}_{c-act}(h^k) - R^{k+1}(h^k) - DP^{k+1}(h^k) = 0 \qquad (7)$$

MF-FMP does simulate changes in storage in the deeper vadose zone below the root zone through a linkage to the Unsaturated Zone Flow package (Niswonger et al., 2006) by treating deep percolation out of the root zone as quasi-infiltration into the deeper vadose zone.

A comparison of how each term in equation (4) is computed in IWFM and MF-FMP is given in the following sections. Some flow terms depend on others; therefore, the description of these terms below is arranged accordingly. For simplicity, indices for time step (t) and iteration (k) are dropped in the expressions that follow. Variable names have been simplified for use in this document relative to those in the user guides (Dogrul 2009a, 2009b; Schmid et al., 2006; Schmid and Hanson 2009b).

a) Precipitation, P

In both models, precipitation is a user-specified time series for each cell. In IWFM, precipitation values are aggregated over four land use areas (agricultural, urban, native vegetation, and riparian vegetation) in each subregion. In MF-FMP there is only one land-use per model cell and the precipitation is used directly with that land use and associated attributes.

b) Rate of change of soil moisture, $\left(\dfrac{\theta^{t+1}-\theta^{t}}{\Delta t}\right)$

IWFM

IWFM simulates the rate of change in soil moisture by implicitly solving equation (6) for θ^{t+1}. Equation (6) is a non-linear conservation equation because both $ET_{c\text{-}act}$ and deep percolation, DP (as discussed below), are functions of θ^{t+1}. IWFM uses the Newton-Raphson method to linearize and iteratively solve equation (6) for θ^{t+1}. It should be noted that the iterative solution of equation (6) in IWFM is separate from the iterative solution of the linked groundwater and stream-flow equations. Since none of the terms in equation (6) are dependent on the groundwater head, there is no need to iterate between the root-zone and groundwater modules. Instead, for each iteration of the simultaneous solution of the groundwater and stream-flow equations, equation (6) is solved once (iteratively, since it is a non-linear equation) for the soil moisture and flow processes in the root zone. As the solution for the groundwater and stream flow equations converge so do the pumping and diversion rates that are used to compute I in (6), and other root zone flow terms that depend on I.

MF-FMP

Unlike IWFM, MF-FMP does not simulate the rate of change in soil moisture in the root zone. MF-FMP is currently limited to time steps of several days or longer, commonly used in groundwater modeling, and was not designed to simulate root-zone processes in deep root zones (on the order of several meters) with high soil-water storage potential that require simulation on the order of minutes to days. MF-FMP assumes quasi-steady state conditions in the root zone on the basis of findings from transient HYDRUS-2D soil-column models representing shallow- to medium-depth root zones (Schmid et al., 2006). Simulated inflows into the root zone converged to outflows after time intervals of several days, the minimum time step commonly used in groundwater modeling. Hence, for these conditions in MF-FMP, the rate of change in soil moisture is not tracked.

c) *Evapotranspiration, $ET_{c\text{-}act}$ and $ET_{gw\text{-}act}$*

Crop evapotranspiration (ET) is conceptualized differently in the two models. IWFM treats evaporation and transpiration as a combined flux; whereas, MF-FMP decomposes ET into three separate evaporation (E) and three transpiration (T) flux components from precipitation, irrigation, and groundwater uptake.

IWFM

IWFM treats ET as a single outflow component. $ET_{c\text{-}pot}$ is specified by the user as a time series data set for each crop in each subregion. Although these estimates can be taken as the crop ET under standard conditions, ET_c, described by Allen et al. (1998), they can also be taken as the crop ET under non-standard conditions, $ET_{c\text{-}adj}$, also described by Allen et al. (1998), to incorporate local conditions such as non-uniform irrigation, low soil fertility, salt toxicity, pests, diseases, etc. (except in cases where the plants are water-stressed because of lack of sufficient water; this situation is simulated dynamically in IWFM as discussed below). In essence, $ET_{c\text{-}pot}$ values specified as input data to IWFM represent crop evapotranspirative requirements for a target yield under known local soil, plant, and management conditions. Using user-specified crop $ET_{c\text{-}pot}$ values, an average $ET_{c\text{-}pot}$, weighted with respect to crop areas, is computed for each subregion. Averaging of $ET_{c\text{-}pot}$ values is performed only for agricultural crops. Values for urban lands, native vegetation and riparian vegetation in each subregion remain unchanged. IWFM computes an $ET_{c\text{-}act}$ as a function of the soil moisture in the root zone:

$$ET_{c-act} = \begin{cases} ET_{c-pot} & \text{if } \dfrac{\theta}{\theta_f} > 0.5 \\ \\ 2\dfrac{\theta}{\theta_f} ET_{c-pot} & \text{if } 0 \le \dfrac{\theta}{\theta_f} \le 0.5 \end{cases} \quad (8)$$

where θ_f is the field capacity (L) and θ in (8) refers to θ^{t+1} in (6).

Equation (8) suggests that if the soil moisture at a given time is greater than half of field capacity, ET_{c-act} will be equal to ET_{c-pot}. If the soil moisture falls below half of field capacity, plants will start experiencing water stress, and ET_{c-act} will be less than ET_{c-pot}. The method described by equation (8) is similar to the method described in Allen et al. (1998) to compute a non-standard crop ET under water-stress conditions. In Allen et al. (1998), a water stress parameter, p, is defined for each crop which represents the fraction of the total available water below which the crop starts experiencing water stress. In equation (8), p is assumed to always be half of field capacity regardless of the plant or soil type. In IWFM, ET_{c-act} will be equal to ET_{c-pot} as long as the soil moisture stays above half of field capacity.

MF-FMP

In MF-FMP, potential crop ET, ET_{c-pot}, can be specified for each crop or calculated internally as the product of specified reference ET, ET_r, and crop coefficients, K_c. Using a specified fraction of transpiration, K_t, ET_{c-pot} is separated into potential crop transpiration, $T_{c-pot} = K_t\, ET_{c-pot}$, and potential crop evaporation, $E_{c-pot} = (1-K_t)\, ET_{c-pot}$. Separating E and T data input is in line with multi-component ET models (Shuttleworth and Wallace, 1985; Kustas and Norman, 1997; Guan and Wilson, 2009), some variably-saturated-flow models (e.g., HYDRUS, Simunek et al, 1999; or SWAP, Kroes and van Dam, 2003), or with the use of transpirative (K_{cb}) and evaporative (K_e) crop coefficients (Allen et al., 1998). MF-FMP differs from the latter by not composing K_c by separate K_{cb} and K_e *coefficients* but by optionally making use of literature data on K_c and K_{cb} to preprocess *fractions* of transpiration as ratios of K_c and K_{cb}. However, preprocessing or estimating K_t fractions is required from the user and not part of MF-FMP.

MF-FMP optionally simulates conditions of wilting or anoxia, which is appropriate if $ET_{c\text{-}pot}$ input data are derived under ‘unstressed conditions’ as, for instance, stated by Allen et al. (1998) for ET_c listed therein. Using $ET_{c\text{-}act}$ as input data for this option would erroneously double-account for simulated stresses already inherent in the measurement. MF-FMP reduces $T_{c\text{-}pot}$ proportionally to the reduction of the active root zone by conditions under which root uptake ceases (Schmid et al., 2006). For a simple ‘Concept 2,’ a root zone is assumed to be inactive for anoxic conditions caused by saturation through groundwater but not for conditions of wilting. For a more complex ‘Concept 1,’ a root zone is assumed to be inactive for ranges of pressure heads under variably saturated conditions at which uptake ceases because of stresses of wilting or anoxia. The response of crops to stresses of wilting or anoxia is specified in MF-FMP as crop-specific pressure heads at which uptake is either zero, commonly called *wilting or anaerobiosis points* (Feddes et al., 1976), or at maximum analogous to *reduction functions* by Prasad (1988), or Mathur and Rao (1999), or *stress response functions* by Simunek et al. (1999).

Zones within the root zone where conditions of wilting or anoxia eliminate root uptake (in MF-FMP: *wilting or anoxia zones*) are found by matching ranges of zero-response pressure heads with a vertical steady-state pressure-head distribution. One approach would be to solve for vertical transient pressure head distributions using Richard’s-equation-based variable-saturation flow models; however, these require soil-water constitutive input parameters (ex. Schmid et al., 2006, eqn 2 and table 1) and may be computationally expensive when linked to regional groundwater models. Instead, MF-FMP uses analytical solutions of vertical steady-state pressure-head distributions derived from transient, Richard’s-equation-based, variably saturated soil-column models upon convergence of atmospheric and moving water-level boundary fluxes after time intervals of several days. Soil-column models were developed using HYDRUS-2D (Simunek et al., 1999) for various soil-specific soil-water constitutive parameters, crop-specific stress-response functions, root-zone depths, depths to groundwater, and rates of potential transpiration with groundwater as the only source for root uptake (Schmid, 2004). For groundwater rising above the root-zone bottom, a wilting zone in the upper part of the root zone decreased linearly, and an anoxia fringe above the water table remained constant until its top reached ground surface. For other HYDRUS-2D simulations, infiltration (e.g., from precipitation or irrigation) was added as an additional source for root uptake. However, the actual transpiration, $T_{c\text{-}act,}$ did not reach $T_{c\text{-}pot}$ because infiltration wetting-fronts also can contain pressure heads at which the crop's response to anoxia reduces transpiration (Drew, 1997). Hence, even for root zones not influenced by groundwater, $T_{c\text{-}act}$ cannot exceed an anoxia-constrained maximum possible $T_{c\text{-}act\text{-}max}$. Adding infiltration in excess of $T_{c\text{-}act\text{-}max}$ resulted in transpiration-inefficient losses. $T_{c\text{-}act\text{-}max}$ might further be diminished if pressure heads of a wetting front are higher than those of an anoxia fringe above a water table or where drainage takes place in lower parts of the root zone that causes wilting.

MF-FMP calculates a maximum actual transpiration ($T_{c\text{-}act}$; eq. (9)) and portions of transpiration fed by uptake from groundwater ($T_{gw\text{-}act}$; eq. (10)), precipitation ($T_{p\text{-}act}$; eq. (11)), and supplemental irrigation ($T_{i\text{-}act}$; eq. (12)), assuming no changes in soil-water storage over time steps, and equal spatial distribution of roots and potential transpiration over the root zone. The full development of these features is described by Schmid et al. (2006, figs 5-9) and Schmid and Hanson (2009b, eqns 7-9, figs. 4 and 5). In summary, the estimate of actual from potential transpiration in MF-FMP is formulated using the three components of groundwater, precipitation, and irrigation as:

$$T_{c-act} = \begin{cases} 0 & \text{if } h \geq h_{ux} \\ T_{c-pot}\dfrac{h_{ux}-h}{r} & \text{if } h_{ux} > h > h_{rb};\ \ h_{ux} = g - a \\ T_{c-pot}\left(1-\dfrac{a}{r}\right) = T_{c=act\text{-}max} & \text{if } h \leq h_{rb} \end{cases} \quad (9)$$

$$T_{gw-act} = \begin{cases} 0 & \text{if } h \geq h_{ux} \\ T_{c-pot}\dfrac{h_{ux}-h}{r} & \text{if } h_{ux} > h > h_{wx};\ h_{ux} = g-a,\ \ h_{wx} = g - r + w \\ T_{c-pot}\left(1-\dfrac{a+w}{r}\right) = T_{gw-act-max} & \text{if } h_{wx} \geq h > h_{rb} \\ T_{gw-act-max}\left(1-\dfrac{h_{rb}-h}{d}\right) & \text{if } h_{lx} < h \leq h_{rb};\ h_{lx} = g - r - d \\ 0 & \text{if } h \leq h_{lx} \end{cases} \quad (10)$$

$$T_{p-act} = \begin{cases} 0 & \text{if } h \geq h_{wx};\ h_{wx} = g - r + w \\ T_{c-act} - T_{gw-act} & \text{if } h < h_{wx},\ T_{p-pot} > T_{c-act} - T_{gw-act} \\ T_{p-pot} & \text{if } h < h_{wx},\ T_{p-pot} \leq T_{c-act} - T_{gw-act} \end{cases} \quad (11)$$

$$T_{i\text{-}act} = \quad T_{c\text{-}act} - T_{gw\text{-}act} - T_{p\text{-}act} \quad (12)$$

where (Fig. 2):

a = depth of the anoxia fringe (L), w = depth of wilting zone (L).

r = total depth of root zone (L), d = depth of capillary fringe (L),

g = ground-surface elevation (L), h = groundwater head elevation (L),

h_{rb} = groundwater head elevation at the bottom of the root zone (L),

h_{ux} = head elevation where top of anoxia fringe, a, above the water level is at ground-surface elevation, g (*elevation of upper transpiration extinction*) (L),

h_{wx} = head elevation at which bottom of the wilting zone, w, is at ground-surface elevation, g (*elevation of wilting zone extinction*) (L),

h_{lx} = head elevation at which top of capillary fringe, d, is at bottom of root zone, h_{rb} (*elevation of lower transpiration extinction*) (L).

For 'Concept 1,' $T_{c\text{-}act}$ varies linearly in eq. (9) between the elevation of upper transpiration extinction, h_{ux}, and the elevation of the root-zone bottom, h_{rb}. For heads below the root-zone bottom, $T_{c\text{-}act}$ is constant and reduced by the ratio between the anoxia fringe, a, and the total root zone, r. In eq. (10), $T_{gw\text{-}act}$ varies linearly between the elevation of upper transpiration extinction, h_{ux}, and the elevation of wilting zone extinction, h_{wx}. For heads between h_{wx} and root-zone bottom, $T_{gw\text{-}act}$ is constant and reduced from $T_{c\text{-}pot}$ to a maximum actual transpiration from groundwater, $T_{gw\text{-}act\text{-}max}$, by the ratio between the sum of anoxia and wilting zones, a + w, and the total root zone, r. $T_{gw\text{-}act}$ also varies linearly between the head elevations between the root-zone bottom and lower transpiration extinction, h_{lx}. In eq. (11), $T_{p\text{-}act}$ is equal to $T_{p\text{-}pot}$, except when limited to the remainder of $T_{c\text{-}act}$ that is not yet satisfied by transpiration fed by $T_{gw\text{-}act}$.

For 'Concept 2,' wilting and anoxia above the water level are not simulated (a = 0, w = 0 in eq. (9) and (10)), but $T_{c\text{-}pot}$ is still linearly reduced to $T_{c\text{-}act}$ (eq. (9)) or $T_{gw\text{-}act}$ (eq. (10)) as the active root zone is reduced by a rising water level. $T_{c\text{-}act}$ equals $T_{c\text{-}pot}$ for water levels below the root-zone bottom, and $T_{gw\text{-}act}$ reaches $T_{c\text{-}pot}$ for water levels located at the root-zone bottom.

The actual evaporation from precipitation, $E_{p\text{-}act}$, is equal to the potential evaporation from precipitation, $E_{p\text{-}pot}$, where precipitation in open areas exceeds $E_{p\text{-}pot}$, and equal to precipitation in open areas where $E_{p\text{-}pot}$ exceeds this precipitation. The potential evaporation from irrigation, $E_{i\text{-}pot}$, can be reduced in open and exposed areas if not fully wetted. Evaporation fractions of $ET_{c\text{-}pot}$ related to irrigation, K_e^i, can therefore be smaller than $(1\text{-}K_t)$. If ET input data reflect local wetting patterns of irrigation methods, and a reduction in evaporation is implicitly accounted for, then the user should keep $K_e^i = (1\text{-}K_t)$. In eq. (13), the actual evaporation from irrigation, $E_{i\text{-}act}$, accounts for evaporative losses of irrigation and varies proportionally to the transpirative irrigation requirement by a ratio of K_e^i and K_t:

$$E_{i\text{-}act} = T_{i\text{-}act}\,(K_e^i/K_t) \qquad (13)$$

The remaining saturation water-vapor pressure deficit over the exposed areas that is not yet satisfied by $E_{p\text{-}act}$ or $E_{i\text{-}act}$ is assumed to be met by evaporative capillary groundwater uptake as long as the groundwater level in a cell allows the capillary fringe to be partially above the extinction depth. The evaporation from groundwater, $E_{gw\text{-}act}$, varies linearly with the groundwater level (eq. (14)) between zero for groundwater heads below the elevation of evaporation extinction, h_{ex} (= surface elevation, g, minus capillary fringe, c) and a maximum for heads rising to or above ground surface, g:

$$E_{gw-act} = \begin{cases} E_{c-pot} - E_{p-act} & \text{if } h \geq g \\ \left(E_{c-pot} - E_{p-act}\right)\left(1 - \dfrac{g+h}{c}\right) & \text{if } g < h < h_{ex}, \quad \text{with: } h_{ex} = g - c \\ 0 & \text{if } h \leq h_{ex} \end{cases} \qquad (14)$$

MF-FMP computes runoff (eqs. (22), (23)) and deep percolation (eq. (30)) using actual ET from precipitation, $ET_{p\text{-}act}$, and actual ET from applied irrigation, $ET_{i\text{-}act} = E_{i\text{-}act} + T_{i\text{-}act}$. The crop irrigation requirement, CIR, and total irrigation requirement, I, are computed using $ET_{i\text{-}act}$ (eqs. (26), (27)). These flux terms and other parameters that these terms depend on will be discussed later in the document.

In summary, the discussion above addresses the following differences in the treatment of ET in both models:

i) IWFM calculates ET as a single term for a representative crop, computed by area-weighted averaging of ET for individual crops within a subregion. MF-FMP calculates six separate ET components of evaporation and transpiration from precipitation, irrigation, and groundwater on a cell-by-cell basis within the water accounting unit (i.e. a farm). The differences between the two models, due to differing approaches in this context, can be minimized if each mesh cell in IWFM is designated as an individual subregion.

ii) IWFM does not simulate ET from groundwater; whereas, MF-FMP does.

iii) IWFM does not simulate anoxic conditions but simulates wilting conditions by reducing $ET_{c\text{-}pot}$ to $ET_{c\text{-}act}$ when soil moisture falls below half of field capacity. MF-FMP always reduces $ET_{c\text{-}pot}$ to $ET_{c\text{-}act}$ to simulate the effects of conditions of anoxia and wilting

iv) IWFM uses the user-specified $ET_{c\text{-}pot}$ values as the target crop consumptive use to be met when calculating the irrigation water demand, while MF-FMP uses computed $ET_{c\text{-}act}$, for the same purpose.

d) Runoff, R

Overland runoff can be composed of several flow components, such as (a) direct runoff, (b) interflow from excess precipitation and irrigation, (c) runoff generated by infiltration in excess of the saturated hydraulic conductivity of the deeper unsaturated zone beneath the root zone, and (d) runoff from groundwater discharge and from rejected infiltration in areas of high groundwater levels. Neither IWFM nor MF-FMP capture all of these components. IWFM can simulate runoff components (a) and (c) through its own root zone and unsaturated zone modules. Historically, MF-FMP was developed to address flood and basin-level irrigation along the Rio

Grande of New Mexico, where slopes are small and direct runoff is negligible, but interflow runoff can matter in different intensities for irrigation and precipitation (Schmid et al. 2009c). Hence, MF-FMP simulates runoff component (b). Runoff components (c) and (d) are available in MF-FMP through a linkage to the Unsaturated Zone Flow Package (Schmid and Hanson, 2009b) but are not discussed further here as this linkage is optional for deeper vadose zones that extend below the root zone.

IWFM

For the calculation of runoff from precipitation, R_p, IWFM uses a modified version of SCS curve number (SCS-CN) method (USDA, 1985) described by Schroeder et al. (1994):

$$R_p = \frac{1}{\Delta t}\frac{(P\Delta t - 0.2S)}{(P\Delta t + 0.8S)} \tag{15}$$

$$S = \begin{cases} S_{max}\left[1 - \dfrac{\theta - \frac{\theta_f}{2}}{\eta_T - \frac{\theta_f}{2}}\right] & \text{for } \theta > \dfrac{\theta_f}{2} \\ S_{max} & \text{for } \theta \le \dfrac{\theta_f}{2} \end{cases} \tag{16}$$

$$S_{max} = \frac{1000}{CN} - 10 \tag{17}$$

where CN is the curve number specified for a combination of land use type, soil type, and management practice (dimensionless); S_{max} is the soil retention parameter for dry antecedent moisture conditions (L); S is the soil retention parameter at a given moisture content (L); θ_f is the field capacity (L) and η_T is the total porosity (L). Equations (15) - (17) state that when root zone moisture is below half of field capacity, R_p is at a minimum as computed by the SCS-CN method. As the soil moisture increases above half of field capacity, the retention capacity of the soil decreases and R_p increases.

In IWFM, the net return flow due to irrigation, R_i, is computed as

$$R_i = R_{i-ini} - U_i \tag{18}$$

where, $R_{i\text{-}ini}$ is the initial return flow before a portion of it is captured and re-used, and U_i is the re-used portion of the initial irrigation return flow. $R_{i\text{-}ini}$ and U_i are computed based on user-specified time series initial return flow and re-use factors, defined as a fraction of the prime irrigation water (i.e., irrigation water before re-use occurs), I:

$$R_{i-ini} = I \times f_r^{I-ini} \tag{19}$$

$$U_i = I \times f_u^{I} \tag{20}$$

Substituting (19) and (20) into(18), R_i is expressed as

$$R_i = I\left(f_r^{I-ini} - f_u^{I}\right) \qquad ; \qquad f_r^{I-ini} \geq f_u^{I} \tag{21}$$

In (19) - (21), f_r^{I-ini} and f_u^{I} are the ratios of the initial return flow, R_{i-ini}, and the re-used return flow, U_i, to the prime irrigation water, I, respectively. By explicitly modeling re-use with equation (20), IWFM can represent irrigation water recycling practices in a regional simulation where it would be impractical to model every single structure designed to capture the irrigation return flows. Furthermore, such an approach is in line with the available data and design practices for the return-flow-capturing structures (Schwankl et al., 2008). Both R_p and R_i are used as inflows to stream reaches specified by the user, and they become available for downstream diversions. This is equivalent to the method that can be used in MF-FMP to represent re-use; it offers a second way to represent re-use in IWFM.

MF-FMP

MF-FMP computes R as the portion of crop-inefficient losses from precipitation or irrigation that contribute to runoff:

$$R_p = (P - ET_{p-act})f_r^{P-loss} \quad (22)$$

$$R_i = (I - ET_{i-act})f_r^{I-loss} \quad (23)$$

where $ET_{p\text{-}act}$ and $ET_{i\text{-}act}$ are the portions of the $ET_{c\text{-}act}$ fed by precipitation or irrigation (LT^{-1}), respectively, and f_r^{P-loss} and f_r^{I-loss} are fractions of the respective crop-inefficient losses from precipitation or irrigation that go to runoff, given as time series data. Losses from precipitation or irrigation that do not contribute to runoff are assumed to be deep percolation. MF-FMP assumes that all precipitation or irrigation is initially available for crop evapotranspiration before any runoff in the form of crop-inefficient losses occurs. Instead of specifying f_r^{P-loss} and f_r^{I-loss} manually, MF-FMP also provides an alternative option to calculate these fractions based on the local (cell-by-cell) slope of the surface. In MF-FMP, irrigation return flow is routed to any user-specified stream reach or, alternatively, to let MF-FMP search for a stream reach nearest to the lowest elevation of the farm, where return flow is assumed to gather. The stream network is simulated by a linkage between FMP and the Stream flow Routing Package of MODFLOW. Re-use of irrigation return flow is not explicitly modeled in MF-FMP. However, the user has the option to return the entire runoff from both precipitation and irrigation losses to points of diversion either to the farm, from which the runoff originates, or to a downstream farm. This way, runoff becomes available for diversions and can be re-used.

Irrigation return flow in MF-FMP is related to losses from irrigation, while in IWFM it is related directly to the total irrigation. Assuming re-used return flow is zero and both MF-FMP and IWFM yield the same irrigation return flow, the respective “runoff fractions” can be translated into each other by equating (21) and (23):

$$(I - ET_{i-act})f_r^{I-loss} = I \times f_r^{I-ini} \qquad (24)$$

One important difference between the approaches of the two models is that IWFM subtracts surface runoff from precipitation and irrigation before the computation of $ET_{c\text{-}act}$, i.e., portions of precipitation and irrigation never contribute to crop evapotranspiration. MF-FMP, on the other hand, assumes all precipitation and irrigation are initially available for crop evapotranspiration and inefficient losses; runoff generated as portion of these inefficient losses is computed after $ET_{c\text{-}act}$ is calculated.

e) Irrigation water, I

Irrigation water in both models can be specified as time series input data (in terms of pumping, stream diversions, and water imported from outside the model domain), or dynamically computed to satisfy the unmet agricultural crop consumptive requirement. MF-FMP can also dynamically compute the irrigation water requirement for irrigated urban landscape, whereas, in IWFM, urban water demand (both for outdoors and indoors usage) is always user-specified as time series data. In MF-FMP, the unmet agricultural and irrigated urban water demand is the portion of that demand after the contributions of precipitation and uptake from groundwater to $ET_{c\text{-}act}$ are taken into account. In IWFM, it is the portion of the demand after contributions of precipitation and soil moisture stored in the root zone to meet this demand are taken into account. Both models distinguish between urban lands, agricultural crops, and native vegetation so that *I* is specified or computed only for irrigated agricultural or urban lands.

In both models, if *I* is specified by the user, it will either be equal to, less than, or more than the computed water demand. If the user chooses to let IWFM or MF-FMP compute *I* internally, then it will be equal to the unmet agricultural water demand (and urban water demand in the case of MF-FMP), given that there is no shortage of water (in terms of stream diversions, groundwater pumpage, and imported water) in the modeled system. In this section, the methods used by both models to compute the unmet water demand, and how *I* is related to it, will be discussed. The situations where *I* is different from the unmet water demand will be discussed later in this document.

IWFM

In IWFM, for agricultural lands, the user can choose to compute water demand dynamically or specify it as a time series. The latter option is used in planning studies where the demand is dictated by water rights and entitlements, rather than the actual crop evapotranspirative requirements. The physical routing of irrigation water through the root zone is still based on physical properties, such as $ET_{c\text{-}pot}$, soil moisture, etc. In this approach, it is possible that the water supply, to meet the water demand dictated by legal rights, will be different than the actual crop evapotranspirative demand. It should be noted that specifying water demands based on water rights or entitlements in IWFM does not imply that IWFM considers water rights hierarchy and preferential water delivery. By using this option, the user simply overrides water demands computed based on physical conditions (explained later in this document) by water delivery amounts defined by legal rights. Each diversion/delivery has equal priority in IWFM.

If the former option of dynamic water demand computation is chosen, IWFM uses an irrigation scheduling-type approach. For each crop in a subregion, time series data of maximum allowable depletion (MAD), defined as a fraction of the field capacity at which irrigation is triggered (Allen et al., 1998), as well as time series irrigation period flag (equals 0 or 1) that defines if it is irrigation season or not, are specified by the user. Similar to other crop properties, MAD is averaged using a crop-area-weighted approach to come up with a representative MAD for the subregion. In IWFM, crop-water demand is closely linked to the mass balance expressed in equation (6). At the beginning of each time step, equation (6) is solved for θ^{t+1} with I and the irrigation return flow, R_i, set to zero. If θ^{t+1} is computed to be greater than or equal to $MAD \times \theta_f$, then irrigation water demand is zero. Otherwise, an irrigation amount that is required to raise the soil moisture up to θ_f is computed by setting θ^{t+1} to θ_f, using user-specified $ET_{c\text{-}pot}$ for $ET_{c\text{-}act}$, rearranging equation (4) with $ET_{gw\text{-}act}$ set to zero, and utilizing equations (5) and (21):

$$I^{t+1} = \frac{\dfrac{\theta_f - \theta^t}{\Delta t} - \left(P^{t+1} - R_p^{t+1} - ET_{c-pot}^{t+1} - DP^{t+1}\right)}{1 - \left(f_r^{I-ini} - f_u^{I}\right)} \qquad (25)$$

Equation (25) is used to compute irrigation water demand only for agricultural lands and only for time steps where irrigation period flag is set to 1. Urban water demand is always a user-specified time series data in IWFM.

MF-FMP

In MF-FMP, the crop irrigation requirement, CIR, is equal to the actual evapotranspiration from irrigation, $ET_{i\text{-}act}$, and 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, as follows:

$$CIR = ET_{i\text{-}act} = T_{i\text{-}act} + E_{i\text{-}act} \qquad (26)$$

where $T_{i\text{-}act}$ is the portion of the actual transpiration supplied by irrigation (LT^{-1}), and $E_{i\text{-}act}$ is the actual evaporation loss from irrigation (LT^{-1}) proportional to $T_{i\text{-}act}$. The simulation of $T_{i\text{-}act}$ and $E_{i\text{-}act}$ is discussed in detail in the previous section and expressed in equations (12) and (13).

MF-FMP calculates a total irrigation delivery requirement, *I*, for each cell at each iteration of a particular time step as the evapotranspirative crop irrigation requirement that depends on the groundwater head at the previous iteration divided by the on-farm efficiency of a particular time step:

$$I^{t,k+1} = \frac{ET_{i-act}^{t,k+1}(h^{t,k})}{e^t} \tag{27}$$

where e is the on-farm efficiency defined as the fraction of the total irrigation water that is used beneficially in the farm. The total irrigation water demand for each 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.

Comparing (25) to (27), it can be seen that, in MF-FMP, I is calculated for each cell on an iterative level based on a dynamically updated groundwater head-dependent evaporative crop irrigation requirement, $ET_{i\text{-}act}$, while in IWFM, I is calculated for a subregion based on user-specified input data and independent of groundwater elevations.

Based on the discussion of irrigation water, I, and irrigation return flow, R_i, a correlation between initial return flow fraction, f_r^{I-ini}, in IWFM, and crop inefficiency losses due to irrigation, f_r^{I-loss}, in MF-FMP, can be obtained. After substituting equation (25) into (24) for $ET_{i\text{-}act}$ and rearranging the resulting equation, one can obtain

$$f_r^{I-ini} = \frac{(I - ET_{i-act})f_r^{I-loss}}{I} \Rightarrow f_r^{I-ini} = (1-e)f_r^{I-loss} \tag{28}$$

Hence, the initial return flow fraction, f_r^{I-ini}, in IWFM, is linearly related to the fraction of the crop inefficiency losses due to irrigation, f_r^{I-loss}, and in MF-FMP, by a proportionality factor of 1-e, with e being the on-farm efficiency for the entire farm or for a specific crop on that farm.

f) Deep percolation, DP

IWFM

IWFM computes DP with a one-dimensional physical routing approach to compute the deep percolation using Campbell's method (Campbell, 1974):

$$DP = K_u = K_s \left(\frac{\theta}{\eta_T} \right)^{\frac{2+3\lambda}{\lambda}} \quad (29)$$

where K_u is the unsaturated hydraulic conductivity (LT^{-1}), K_s is the saturated hydraulic conductivity (LT^{-1}), η_T is the total porosity (L), θ is soil moisture (L), and λ is the pore size distribution index (dimensionless). In (29), it is assumed that the vertical hydraulic gradient is unity and residual water content (i.e., specific retention) is negligible.

As defined in equation (29), deep percolation is a function of soil moisture; it is computed dynamically in IWFM. As shown in equation (25), it has a direct effect on computed water demand. As it depletes soil moisture, it increases the computed water demand. The irrigation water not only needs to meet the crop evapotranspirative requirements and bring the soil moisture to field capacity, but it needs to compensate for water lost from the root zone through deep percolation as well. As an example, growing a specified crop for a target yield on a sandy soil will require more water than growing the same crop on a clayey soil for the same target yield as a result of higher deep percolation rates. Recharge to groundwater in IWFM can be instantaneous or it can optionally be delayed with the use of IWFM's unsaturated zone component (Dogrul, 2009a).

MF-FMP

MF-FMP computes DP as the sum of deep percolation below the root zone from precipitation and irrigation, which can be instantaneous or delayed with linkage to the unsaturated zone infiltration package, UZF (Niswonger et al, 2006). It is the user-specified portion of losses of precipitation and irrigation that are not consumptively used by plants and not lost to surface water runoff:

$$DP = (P - ET_{p-act})\left(1 - f_r^{P-loss}\right) + (I - ET_{i-act})\left(1 - f_r^{I-loss}\right) \qquad (30)$$

iii) Water Demand and Supply

In today's world where fresh water sources are limited, questions that constantly arise in densely populated and cultivated watersheds are related to the magnitudes of future urban and agricultural water demands, i.e., if the available sources of water in terms of precipitation, stream diversions, and groundwater pumping are sufficient to meet these demands. The answers for these questions become harder to track with the presence of complicated surface water rights and environmental regulations in the watershed. Typically, the hydrologic runoff processes in a basin are controlled by the water-resources-management practices used to meet the water demand while honoring surface-water rights and environmental regulations on stream-flow quantities.

In the real world, computed or estimated water demands and available water supplies don't always balance. For instance, water agencies generally have surface-water rights defined by laws that may or may not equal their actual water demand. In severe drought years, farmers may not receive all the water they need for a target crop yield, creating a supply deficit. Conversely in wet years, farmers may have more water delivered than is needed for irrigation to sustain surface-water rights, sustain flushing of saline soils, or to enhance deep percolation for later groundwater pumpage. Non-irrigated areas with natural vegetation rely solely on precipitation, which may be more or less than the actual plant evapotranspirative requirement.

Both IWFM and MF-FMP are designed to address (i) most of the issues regarding the computation of water demand, (ii) configuration of different sources of water supply to meet this demand, and (iii) computation of the hydrologic effects of unbalanced demand and supply. The next section discusses features in each model representing total water demand, water supply components, and the balance between supply and demand components.

a) Total water demand

In addition to irrigation water demand, both IWFM and MF-FMP also allow non-irrigation demand, such as urban, municipal, and industrial water demand, to contribute to the total requested demand that needs to be met with surface water and groundwater supply components.

IWFM

Urban-water demand is always represented by user-specified time series data in IWFM. This approach is in line with available data and methods for the prediction of urban-water demand. Although a similar approach as in equation (25) can be used for computing urban-water demand for parks, residential yards, etc., urban-water demand is often described as a function of population and expressed in terms of water use per capita per day (e.g., CADWR, 1998). By requiring urban-water demand as input data, IWFM allows the user to utilize standard methods for urban-water demand predictions. The fraction of the total urban-water demand that is used for municipal and industrial needs is specified by the user as time series data. It should also be noted that agricultural and urban demands in a subregion are not lumped in IWFM. Instead, IWFM attempts to meet both demands separately.

MF-FMP

In MF-FMP, other non-crop urban-water demand can be factored into the data input for so-called non-routed deliveries. That is, if non-routed external water transfers are known, then the municipal and industrial water demand needs to be subtracted first. The result is then the input in MF-FMP for non-routed deliveries. This may mean that more urban-water demand is subtracted than water transfers available. A negative non-routed delivery indicates a shortage that needs to be satisfied along with water demand for urban irrigated landscape by other second and third-level delivery components, that is, routed surface water and pumped groundwater.

Another non-agricultural water demand can be the target percolation rate of a percolation pond or of a set of injection wells of an Aquifer-Storage-and-Recovery System (ASR). This demand can be simulated as a “design” irrigation demand of a “virtual zero-transpiration crop” that is based on the known maximum infiltration rate of the ASR pond or injection wells (Hanson et al., 2008). These and other non-routed deliveries are accounted for separately for each farm.

b) Water-supply components

The initial sources of water to meet the total water demand come from precipitation in both models, soil moisture stored in root zone in IWFM, and root uptake from groundwater in MF-FMP. Any unmet demand in both models is satisfied by water imported from outside the model area, stream diversions, and groundwater pumping; referred to as water-supply components in this report.

IWFM

In IWFM water can be imported into the modeled system from outside sources that are not simulated. Diversions and pumping that occur in the modeled area also can be used as water supply to meet the demand. IWFM offers two types of pumping: well pumping and element pumping. Well pumping can be used when pumping from individual wells is simulated. Each well is defined with its coordinates, radius and screening depths. User-specified time series pumping rates are also assigned to each well. In cases where the screened interval of a well intersects with multiple aquifer layers, the Kozeny equation (Driscoll, 1986; Dogrul, 2009a) is used to distribute the pumping rate to individual aquifer layers. Element pumping can be used in regional modeling studies where simulation of individual wells is not practical, or the necessary information for all wells is not available. Element pumping allows the user to specify time series pumping rates at specific mesh elements based on the estimated agricultural water demand within that element. In essence, this option represents pumping from a cluster of wells that are located in a mesh element. Pumping defined at an element is distributed to the surrounding nodes using the fractions of element area associated with each node. These fractions are computed as part of the implementation of the finite element method. The distribution of pumping rate to individual aquifer layers is specified by the user. In a single model study, both well pumping and element pumping can be utilized.

IWFM associates each source of water supply with a target subregion and a time series irrigation fraction that allocates a portion of the supply to meet the agricultural demand. The rest of the supply is used to meet the urban demand in the subregion. Any water supply that is in excess of irrigation water requirement will either increase the soil moisture, or become deep percolation or irrigation return flow, based on the solution of the conservation equation (6).

IWFM allows both recoverable and non-recoverable losses specified for each water supply as a user-defined fraction of the total supply amount. The recoverable losses represent seepage from the conveyance system that ultimately becomes recharge to groundwater. The non-recoverable losses represent evapotranspirative losses from the conveyance system. This feature can also be used to simulate artificial recharge operations by designating a fraction or the entire amount of the diversion or pumpage as recoverable loss and identifying the mesh elements where these losses will be used as recharge to groundwater. The recoverable losses are completely head-independent and recharge groundwater instantaneously. Alternatively, IWFM allows part or all of a diversion to be diverted into a lake. Conservation equations for lakes are solved simultaneously with groundwater and stream flow equations, and this feature can be used for a head-dependent simulation of artificial recharge operations, such as spreading basins.

MF-FMP

MF-FMP simulates three types of water deliveries into farms that originate as stream diversions: non-routed deliveries (NRD), semi-routed deliveries (SRD), or fully-routed deliveries (RD). NRDs are deliveries that originate from any source outside the model domain; i.e., they represent water imported into the modeled area. SRDs and RDs originate from streams within the model domain. Multiple types of NRDs can be specified and are given farm identifiers (IDs) they serve, maximum volumes, ranks in which sequence they are used, and information whether to recharge potential excess from NRDs into the stream network or into injection wells. Locations within the stream network from where SRDs are taken are specified by the user at modeled stream reaches. RDs are automatically diverted to a farm from the uppermost stream reach of either segments that are used for diversion only, or from any type of river segment that is located within the domain of the respective farm. The last source of water, groundwater pumping, comes from farm wells located at user-specified cells with specified maximum pumping rates and farm IDs they serve.

MF-FMP first uses NRD types in sequence of their ranking to meet irrigation water demand. This can indirectly include the pumpage, delivery, and reuse of stored groundwater through ASR operations. Any unmet demand is then served by SRDs and finally by groundwater pumping. The maximum rates specified for each source of water generally represent legal or structural constraints on that source. NRDs are limited by the maximum rates specified for each of them. SRDs (or alternatively RDs) are limited by the available stream flow or by legal constraints such as equal appropriation allotment heights or prior appropriation calls. Diversion rates specified for a diversion from a main stem river into a diversion segment are possible through data input in the SFR Package. These “river-to-canal” diversions can be specified along a segment near, or further upstream, from which the SDRs or RDs. as “canal-to-farm” diversions, occur. Subject to any canal water losses or gains in between the “river-to-canal” and “canal-to-farm” diversion, this mechanism can be used to construct a demand-driven and supply-constrained surface-water delivery system that is implicitly linked to the potential amount of water that is simulated to be conveyed in the stream to the point of diversion and delivery.

In MF-FMP, water is derived first from natural crop water-supply components such as precipitation and uptake from groundwater and second from delivery requirement-driven supply components (such as NRDs) and surface-water deliveries. All farm wells in MF-FMP are associated with a farm through the Farm-ID and can thus be located inside or outside the farm. The groundwater pumping of each farm equals the residual delivery requirement or the cumulative maximum pumping capacity, whichever is less. The farm wells in MF-FMP can be single-aquifer wells that pump from the center of the finite-difference cell or multi-node wells which can represent non-uniform wellbore inflow from vertical multi-aquifer wells through a linkage with the multi-node well package (MNW; Halford and Hanson 2002) that is both head-and transmissivity-dependent. MNW allows for wellbore flow between model layers or aquifers typical of large irrigation-supply wells that occur during periods of pumpage and non-pumpage. This feature also allows for additional constraints on farm well pumpage through the head and drawdown features of the MNW package, which also are affected by the radius of each MNW farm well and the entrance losses of water flowing into these wells. The WELLFIELD option of MF-FMP allows for a re-distribution of stored groundwater, by recovery wells or well fields of an Aquifer-Storage-and-Recovery system (ASR), to receiving farms related to the cumulative demand of these farms. This pumpage is, in the case of the recovery wells of an ASR, recovered and reused water that originally was diverted from the stream network and percolated to groundwater by the ASR pond. The pumpage of any well field is distributed as simulated NRDs to receiving farms and given priority over local farm well pumpage. Farms can receive simulated NRDs from any number of well fields in sequence of user-specified priority ranks designated in the input data (Schmid and Hanson, 2009b). Whenever one well field's pumpage is limited by rate, head, or drawdown constraints, the well field next in priority will contribute to the simulated demand of the NRDs. These ASR and multi-aquifer farm-well features provide a wide range of linkages to the use and reuse of water resources in the supply and demand water balance (Hanson et al., 2008).

c) Balance between water supply and demand

IWFM

IWFM allows two approaches to address the balance between water demand and supply: (i) allow an imbalance between demand and supply and (ii) enforce a balance between the demand and supply. The first approach is appropriate when simulating a historical condition where diversions and pumpage are known but where they may or may not be equal to the demand. In this supply-driven approach, IWFM assumes that, in a historical simulation, the diversions and pumpage may not reflect the exact irrigation requirements and may be in deficit or excess of supply. The latter, demand driven approach is useful when simulating a future condition such as in planning studies to quantify the amount of diversions and pumpage needed to meet a computed or specified water demand. In this case, it is appropriate to enforce a balance between demand and supply. Even in historical simulations, where one or more of the sources of supply (e.g., groundwater pumping) are unknown, this approach can be used to estimate the amount of supply.

If a balance between supply and demand is forced, IWFM requires the user to specify individual sources of supply (in terms of imported water, pumping or diversions) to match the demand. In this case, each source of supply can be associated with a time series supply adjustment flag that IWFM uses to either adjust a supply to meet only the urban demand, only the agricultural demand, or both demands. This flag also can be used to completely suppress the adjustment of a particular supply source. This way, at a given time step, only a selected set of water sources can be adjusted to meet urban, agricultural, or both demands. If both surface-water diversions and pumping are adjusted to meet the demand, diversions are adjusted first. Then, any unmet demand is satisfied by adjusting the pumping. If water sources are imported into the model area from outside the model domain, they will be adjusted last. It should be noted that this supply adjustment process does not incorporate water-rights hierarchies. That is, all adjusted supplies are assumed to have equal priority. Water supplies that are adjusted to meet water demand are treated only as requirements, and they may or may not be met depending on the availability of actual simulated water in the system. At the end, diversions from modeled streams and pumping that occur in the modeled area are limited by the amount of flow in the streams and the available aquifer storage at the pumping locations, respectively. Adjusted imports have no upper limit and they will be increased until the full demand is met if there are any shortages in terms of simulated diversions and pumping. Maximum rates representing legal or structural constraints cannot be set in IWFM.

IWFM addresses the situations where an imbalance between supply and demand is allowed, i.e., when the supply is in deficit or excess of demand, by solving equation (6) and tracking changes in the soil moisture. If supply is in excess of demand, soil moisture increases accordingly, and can serve as an additional source of water to meet the demand in later times. If supply is less than the demand, soil moisture decreases accordingly, increasing the required irrigation amount to bring the moisture up to field capacity in later time steps.

In IWFM, deep percolation, DP, and evapotranspiration, $ET_{c\text{-}act}$, deplete the soil moisture, whereas infiltration due to precipitation and irrigation increase the soil moisture in the root zone. If the soil moisture is above half of field capacity, $ET_{c\text{-}act}$ will be equal to $ET_{c\text{-}pot}$. If, at a given time step, the soil moisture falls below a threshold level specified by the user, an irrigation demand will be computed to meet the crop evapotranspiration requirements, deep percolation and irrigation-return flow at that time step, and to bring the soil moisture up to field capacity. This irrigation amount may or may not be supplied, depending on the available water in the streams and storage at pumping locations. If there is a lack of water to meet this computed demand, soil moisture will fall below the threshold. In the next time step, the irrigation-water demand computed to meet the crop evapotranspirative needs, DP and irrigation return flow, and to bring the soil moisture to field capacity will be higher. Over a period of extended supply deficiency, the soil moisture will continue to drop below half of field capacity, the $ET_{c\text{-}act}$ will be less than $ET_{c\text{-}pot}$ (see equation (8)), and DP will be reduced along with reduced soil moisture. At the extreme case where soil moisture is completely depleted, DP and $ET_{c\text{-}act}$ will be zero and the irrigation demand will be at its maximum, i.e., an irrigation amount that will raise the soil moisture from zero to field capacity while meeting deep percolation, crop evapotranspiration requirement, and irrigation return flow. In the real world, prolonged moisture deficiency will kill the crops and set $ET_{c\text{-}pot}$ to zero. Such a case is not addressed by IWFM, and $ET_{c\text{-}pot}$ is never set to zero dynamically.

In the other extreme case, where the water supply is in excess of water demand, soil moisture increases beyond field capacity and towards full saturation (such as in an extreme flooding event), IWFM operates normally. For instance, IWFM does not consider the effects of anoxia due to high moisture contents. Deep percolation is computed as a function of the soil moisture, and $ET_{c\text{-}act}$ will still be equal to $ET_{c\text{-}pot}$.

MF-FMP

In MF-FMP, the total simulated water supply accounts for inefficient losses and meets crop irrigation requirements. Water supply in excess of the crop-water demand will be converted into irrigation return flow and deep percolation using equations (23) and (30), respectively. Water supply in excess of the total demand only can occur for excess imported water (NRDs) by user specification to either discharge the excess back into the conveyance network or into injection wells.

MF-FMP does not simulate changes in soil-moisture storage; therefore, no depletion in soil moisture contributes toward satisfying the crop water demand. It is assumed that for most modeling applications, and based on most irrigation practices, this distinction has minor consequences because most irrigation is performed on a regular basis during the growing season. Hence, an imbalance between irrigation demand and irrigation-supply components is not buffered by a soil-water reservoir. This becomes apparent at the first iteration of an MF-FMP time step. In case of supply deficit, MF-FMP requires that at each time step a solution to a deficit problem must be found according to the user's choice. The user has the choice to assume that (a) the necessary water supply must be guaranteed and that the deficiency will be made up by alternative sources external to the model domain; (b) the available supply will be used, but that after improving the efficiency and minimizing inefficient losses, the actual evapotranspiration will be further reduced, indicating that the crops' yield responds negatively to the deficit irrigation; or (c) profitability of a particular cropping pattern within a farm must be guaranteed by optimizing the profit subject to crop market benefits and water costs associated with a particular water type. The latter option may lead to a reduction of each cropped cell's area. Once MF-FMP detects a deficiency at the first iteration of a time step, the response to the deficit problem is dynamically applied according to the user's choice in the succeeding iterations of the same time step. These features of deficit response are unique to MF-FMP and provide a broad context of response to deficits in the entire supply and demand components of the entire hydrologic budget that spans all the farms within a watershed or groundwater basin.

Discussion and Conclusions

Both IWFM and MF-FMP are designed as integrated hydrologic modeling systems to address some of the most crucial issues in water-resources-planning studies for either micro- or macro-agricultural settings. IWFM and its predecessor, while limited in application, have been going through major developments for the past two decades to develop a practical tool to use the best available field data. Both models have been mentioned in various circles as possible modeling tools (CWEMF, 2008; Hanson et al, 2010) and are continuing to be developed with additional features through ongoing applications. MF-FMP uses the widely used MODFLOW (Harbaugh et al., 2000; Harbaugh, 2005) model as its groundwater and surface-water routing simulation engine. With the addition of the Farm Process and other packages, MODFLOW has become a more complete and fully coupled three-dimensional hydrologic model that can simulate a wide range of supply-demand and hydrologic scenarios.

Recently, IWFM and MF-FMP have been used to model the Central Valley of California, a critical area in the water-resources system of California (Brush et al., 2008; Faunt et al., 2008, 2009a, 2009b, 2009c). However, even with similar input data, both models can produce different results for selected hydrological components. It is difficult to track the sources of these differences with models at that scale and complexity. This document lists the similarities and differences in the relevant features and conceptualization in both models regarding the land-surface and root-zone runoff processes and their interactions with the stream-groundwater system.

An important difference between the two models is that IWFM treats ET as a single flow component; whereas, MF-FMP simulates the E and T components of ET separately. MF-FMP also identifies the individual contributions of precipitation, irrigation, and groundwater into simulated E and T. MF-FMP’s approach is applicable particularly when the effects of different irrigation systems are studied, since it is generally the E component that changes with changing irrigation systems. By simulating E and T separately, it is possible to represent more accurately the efficiencies of different irrigation systems, i.e., not to call for more irrigation water than what realistically can be evaporated and transpired. Even though Allen et al. (1998) list basal transpiration crop coefficients and provide techniques to account for the evaporative component, it is recognized that at this time there is a scarcity of field observed data for E and T separately, which limits the ability to constrain the calibration of these components of ET separately. As such data become available IWFM will migrate towards a similar approach.

MF-FMP simulates root uptake from groundwater as a source of water to meet crop ET requirements. This is a valuable feature, especially when non-irrigated areas with deep-rooted native plants are included in the model, or shallow groundwater makes a significant contribution and can affect irrigation scheduling. For example, it was estimated that about 10 percent of all ET can be attributed to uptake from groundwater from the simulation of ET for the Central Valley (Faunt et al., 2009a, 2009b, 2009c). Although observed data for this process is difficult to obtain, it is recognized that IWFM would benefit from including a similar feature.

The representation of pumpage from multi-aquifer wells is different in IWFM than in MF-FMP. IWFM simulates multi-aquifer pumping through the use of the Kozeny equation (Driscoll, 1986; Dogrul, 2009a) and static fractions in the case of well pumping and element pumping, respectively, to distribute pumping to multiple layers. Wellbore flow is not simulated in IWFM. MF-FMP uses the MNW package to simulate transmissivity-dependent pumping from multiple aquifer layers and wellbore flow (Halford and Hanson, 2002).

Another difference between the models is how they simulate water demand. IWFM uses area-weighted averages for crop properties in a given subregion to compute water demands as well as root zone and surface flow processes. MF-FMP, on the other hand, uses actual crop properties at each model cell. Depending on the crop types in a subregion, the average crop properties may not truly represent some of the crops and water-management practices in that subregion. The resulting differences between the two models in this context can be minimized if individual mesh elements in IWFM are designated as individual subregions. Another possibility is to define subregions in IWFM and farms in MF-FMP based on the location of similar crops so that average crop properties in IWFM will be similar to individual crop properties in MF-FMP. However, to efficiently use available data, IWFM is currently being modified to perform simulation of root zone and surface-flow processes at the cell level, even if subregions composed of more than one cell are defined.

Slightly different representations of stream-groundwater interaction can be another source of differences between the simulated results of the two models. As discussed earlier in the document, the representations are different only when stream and aquifer are hydraulically disconnected and the stream depth is much less then the streambed thickness. However, this difference is expected to minimal in a real-world application when the two models are properly calibrated to replicate the observed stream flows and groundwater heads.

A major difference between the two models is the simulation of soil moisture in the root zone. IWFM keeps track of changing soil moisture in the root zone whereas MF-FMP assumes steady-state conditions. This conceptual difference can cause substantial differences between the two model results. The importance of this feature becomes apparent when modeling (a) root zone and surface-low processes in non-irrigated natural areas that rely entirely on precipitation; (b) effects of drought conditions where soil moisture is depleted to the wilting point; (c) cases of irrigated agriculture where soil moisture is an important supply component, such as for very deep root zone or very short time steps; and (d) effects of pre-irrigation for field preparation. The differences between the two models emerge when MF-FMP meets the steady-state assumption at a particular time step by either importing additional water in a drought condition or by discarding excess water through return flow and deep percolation. In the case of irrigation deficit, the MF-FMP user also is allowed to use other optimization options described earlier in the document that reflect a general shortfall of supply relative to the demand driven by ET. Future versions of MF-

FMP will provide options for additional forms of water capacitance aside from the existing nodal groundwater storage, for instance, soil-moisture storage and on-farm water storage. Soil-moisture storage is relevant for areas susceptible to soil-moisture depletion, such as non-irrigated native vegetation or dry-land farming, or soil moisture replenishment by pre-wetting fields prior to the growing season. On-farm surface storage can be used for the purpose of water re-use as additional supply component. The combined use of soil moisture storage and on-farm surface storage becomes important for irrigated agriculture under conditions of extended drought.

Finally, one of the most prominent differences between the two models is how they conceptualize and simulate the crop evapotranspirative requirements. When comparing simulations of the same example, it has been observed that with similar $ET_{c\text{-}pot}$, precipitation, and irrigation efficiency values as input to both models, the $ET_{c\text{-}act}$ computed by MF-FMP was 72 percent, on average, of that calculated by IWFM. This difference, along with other conceptual differences between the two models, led to total irrigation water computed by MF-FMP to be 62 percent, on average, of that computed by IWFM (Schmid et al., 2011). The reason for this difference is that MF-FMP reduces $ET_{c\text{-}pot}$ to $ET_{c\text{-}act}$ based on analytical solutions of previous HYDRUS-2D soil-column simulations for anoxia and wilting and based on spatial patterns of wetting in open and exposed areas. Under simulated local conditions, this $ET_{c\text{-}act}$ poses a maximum possible evapotranspiration, and, hence, MF-FMP uses the resulting simulated $ET_{c\text{-}act}$, instead of $ET_{c\text{-}pot}$, as the target crop ET requirement to meet. IWFM, on the other hand, uses $ET_{c\text{-}pot}$ values as the target crop ET requirement.

Both models are able to handle ET input data that represent some form of stress underlying the measurement. Effects of anoxia and a reduction of evaporation due to spatial patterns of wetting are not calculated in IWFM, whereas MF-FMP can address these situations.

In order to be more compatible, MF-FMP does have the option to turn the anoxia simulation off or not to reduce evaporation if the input ET values already account for the effects of anoxia and local wetting pattern with some certainty. However, especially in areas of the world where measurements of actual ET are not available, one may have no other option than to use input potential ET values from databases that are assumed to represent unstressed conditions and to simulate local stresses.

It is expected that as both models find uses among hydrologists, their best features and worst shortcomings will be identified, and IWFM and MF-FMP will converge in their conceptualization of root zone, land surface flow processes, and their interaction with the groundwater system and stream network. They also will converge in their methods that address conjunctive-use issues in regions where water supply is not enough to meet the water demand. In the meantime, the goal of this document is to provide a guide for the current differences between the two models so that their results can be better interpreted.

Component	IWFM	MF-FMP
Physical water budgeting unit	Individual land use areas (agricultural, urban, native vegetation, riparian vegetation) in each subregion (defined by one or more cells)	Individual cell and cells aggregated over a farm or virtual farm (water-accounting units) for supply and demand components and for all inflow and outflow components (rates and cumulative volumes)
Economic water budgeting unit	Individual land use areas in each subregion	Same as above
Land use types	• Four pre-specified land use types (agricultural, urban, native vegetation, riparian vegetation) • Agricultural type is further divided into user-specified crops • User-specified time series data for areas of four land use types for each cell • User-specified land use and crop properties • Land use properties are weighted-averaged by land use area for each subregion	• User-specified crop types (irrigated agriculture, irrigated urban landscape, non-irrigated dry-land farming, native and riparian vegetation) • User-specified time series data for crop type for each cell • User-specified crop properties • Urban demand (specified as negative supply) • Aquifer-Storage-and-Recovery Units
Soil types	• Each cell is assigned a soil type • User-specified soil properties • Soil properties are weighted-averages by land use area for each subregion	• Each cell is assigned a soil type • Pre-specified or user-specified soil properties including capillary fringes to account for evaporation extinction.
Soil moisture	• Simulated soil moisture storage computed by solving conservation equation in the root zone implicitly every time step • User-defined depletion limit to trigger irrigation for agricultural lands • Unsaturated zone module to simulate flow between root zone and groundwater table	• Changes in soil moisture not computed for root zone (sources for and sinks of consumptive use are assumed to be at steady state with no net change in soil moisture over simulated time steps) • Storage changes are computed for deeper vadose zone between root zone and water table by link to UZF package, which simulates delayed recharge between root zone and groundwater table.
Precipitation, P	Time series input for each cell	Time series input for each cell
Direct runoff from precipitation, R_p	Modified SCS curve number method (Schroeder et al., 1994)	User-specified fraction of total losses from precipitation or based on local slope of each cell

Table 2 Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MF-FMP
Irrigation water, *I*	• Used only for urban and agricultural areas • User-specified or calculated for a subregion based on input data for precipitation, $ET_{c\text{-}pot}$, return flow and re-use fractions, and dynamically updated soil moisture in the root zone.	• Used only for urban and agricultural areas • Calculated for each cell, on an iterative level, and based on a dynamically updated groundwater head-dependent evapotranspirative crop irrigation requirement
Irrigation efficiency, *e*	• Not specified explicitly; instead specified in terms of return flow and re-use factors as a fraction of total irrigation water	• User-defined for each farm and crop • Dynamic efficiency based on conservation water use
Irrigation return flow, R_i	• Initial return flow is computed as a fraction of irrigation water • Net return flow is computed as initial return flow less re-use of irrigation water	• User-specified fraction of total losses from irrigation • User-specified fate of return flow of excess imported water to stream network or injection into farm wells • Semi-routed return flows to stream network facilitate the simulation of extensive drain networks and lined canals
Surface water deliveries	• Deliveries can be imported from outside the model area • Specified or computed deliveries originating from user-specified stream segments • Some or all deliveries can be dynamically adjusted to meet the water demand; however, deliveries originating from modeled stream nodes are limited by available in-stream flows	• Non-routed Deliveries (unlimited number of ranked water market components) • Semi-routed Deliveries (linkage to SFR package stream network and simulated diversion points) with no simulation of routed conveyance between diversion points and farm. • Fully-Routed Deliveries (linkage to SFR package) with simulation of routed conveyance to the farm. • All deliveries are demand-driven but supply constrained
Surface water appropriations	• All deliveries have equal priority	• User-defined equal appropriation or prior appropriation • Prior appropriation ranked by farm number for priority of surface water right deliveries
Groundwater pumpage	• Well pumping (individual wells are simulated) or element pumping (cluster of wells are simulated) • Lumped pumping can be distributed to individual wells/elements based on user-specified fractions • Pumping at a well and element is distributed to aquifer layers using Kozeny equation and user-specified fractions, respectively • Pumping can be exported outside a subregion • Pumping is limited by the amount of groundwater storage at the well location	• Single-aquifer farm wells pumpage based on fraction of total pumping capacity of all wells associated with a farm • Multi-aquifer farm wells linked to MNW package • Wells associated with Farm but not limited to Farm domain • Series of ranked well fields can export water to individual farms, which import this water as simulated non-routed deliveries (WELLFIELD option)

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MF-FMP
Re-use of irrigation water, *U*	• Computed as a fraction of the total irrigation water • Irrigation return flow can be directed to user-specified stream segments which can be re-used by downstream diversions	• Redirected inefficient losses as runoff from both precipitation and irrigation losses can be returned to point of diversion to augment stream flow available for diversion. • Re-use of artificially recharged water (ASR operation) through recovery wells (WELLFIELD option)
Deep percolation, *DP*	• Computed using physically-based approach assuming unit vertical hydraulic gradient and negligible residual water content • Unsaturated zone module to simulate flow between root zone and groundwater table • Contributes to water demand	• Computed as the sum of user-specified fractions of total losses from precipitation and irrigation for individual crop types • Simulated unsaturated infiltration between root zone and water table through linkage with UZF package • Simulated unsaturated infiltration below rivers and lakes with SFR and LAK package
Evapotranspiration, *ET*	• Computed as a single term on an element or subregional basis • Time series of $ET_{c\text{-}pot}$ for each crop is user-specified • Contributions from P and I are not tracked • ET from groundwater uptake is not simulated • Input $ET_{c\text{-}pot}$ is crop-area-weighted averaged for an $ET_{c\text{-}pot}$ of a representative crop in each subregion • Actual ET, $ET_{c\text{-}act}$, is computed as a function of soil moisture and field capacity • Anoxic conditions are not simulated • Wilting conditions are simulated: computed $ET_{c\text{-}act}$ is less than $ET_{c\text{-}pot}$ if soil moisture falls below half of field capacity	• Computed as a summation of evaporation, E, and transpiration, T, on a cell-by-cell basis • ET reduction from land use fractions, crop-stress coefficients, and anoxia and/or wilting • Time series of $ET_{c\text{-}pot}$ or reference ET_r and crop coefficients K_c for each crop are user-specified; time variable fractions are used to separate $ET_{c\text{-}pot}$ into $E_{c\text{-}pot}$ and $T_{c\text{-}pot}$ • Contributions from P and I to E and T are tracked separately as E_p, E_i, T_p, and T_i, • E and T from groundwater uptake are simulated • "Concept 1:" $ET_{c\text{-}act}$ is always less than $ET_{c\text{-}pot}$ for variably saturated conditions. Vertical steady-state pressure-head distributions are matched with defined ranges of negative or positive pressure heads at which stresses of anoxia or wilting eliminate uptake. Positive pressure heads can be set to allow or eliminate transpiration under fully saturated conditions, e.g., for rice or riparian vegetation. • "Concept 2:", $ET_{c\text{-}act}$ is only less than $ET_{c\text{-}pot}$ for water levels rising above the bottom of the root zone. Anoxia is assumed only to occur for fully saturated conditions: $ET_{c\text{-}act}$ is linearly reduced proportional to reduction of active unsaturated root zone due to anoxia by rising water level.

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MODFLOW
Water demand	• Uses input ET_{c-pot} as the target crop consumptive use to meet • Defined as the amount of water to bring the soil moisture from a threshold level (equivalent to maximum allowable depletion) to field capacity, increased by net irrigation return flow and deep percolation • Agricultural water demand can be either computed or specified as time series data by the user • Urban water demand is user-specified time series data • Agricultural and urban water demands are tracked separately in each subregion	• Uses iteratively updated ET_{c-act} as the target crop consumptive use to meet • Defined as the portion of ET_{c-act} that is not met by precipitation and uptake from groundwater, increased by the inefficiency losses from irrigation • Irrigation water demand of irrigated agriculture or irrigated urban landscapes is always computed • Municipal and industrial urban water demand is user-specified as negative supplies • Agricultural and urban water demands are tracked separately in separate "virtual farms"
Water supply	• Precipitation, stream diversions, pumping, soil moisture in storage and imported water from outside the model area are the water supply to meet demand • Supply for agricultural and urban water demand is simulated separately in a subregion • Stream diversions and/or pumping can be adjusted or kept at user-specified values through time series "supply adjustment flags" to meet the demand; if both diversions and pumping are to be adjusted, diversions are adjusted first • Diversions and pumping are limited only by the available storage in the stream or aquifer	• Precipitation, stream diversions, pumping, root uptake from groundwater and imported water from outside the model area are the water supply to meet demand • A single supply amount is simulated to meet the lumped agricultural and urban water demand in a farm • Non-routed deliveries are the first source of supply, then semi-routed deliveries and finally pumping is used as source of water • Diversions and pumping are limited to user-specified maximums or available storage in the stream/aquifer, whichever is smaller
Balance between water supply and demand	• Unmet demand or moisture in excess of meeting the demand in a time step can be carried forward to effect the demand in the next time step(s); maximum demand is field capacity increased by net irrigation return flow and deep percolation • Choice to enforce a balance between supply and demand or not • When supply-demand balance is enforced, user-specified sources of supply are adjusted to meet the agricultural demand, urban demand or both (all adjusted sources of supply are assumed to have equal priority) • When supply-demand balance is not enforced, change in soil moisture due to supply in excess or deficit of demand affects demand in following time step(s)	• Unmet demand is simulated by drought response scenarios that optimize deficit irrigation within the same time step in which deficiency occurs • Drought scenario option with acreage optimization based on cost and maximum profit • Drought scenario option with deficit irrigation • Drought scenario option with water stacking onto priority crops • Supply in excess of crop water demand in a time step is discarded as either deep percolation or return flow in the same time step • Supply of imported water in excess of total demand (delivery requirement) is discharged either back into the conveyance network or into injection wells

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Appendix A: Notation

The following symbols are used in this report:

a = anoxia fringe;

c = capillary fringe;

CIR = crop irrigation requirement;

CN = curve number;

d = thickness of stream bed material;

DP = deep perco0lation that leaves the root zone as the moisture moves downward;

e = on-farm efficiency defined as the fraction of the total irrigation water that is used beneficially in the farm;

E_{c-act} = actual evaporation;

E_{c-pot} = potential crop evaporation;

E_{i-act} = actual evaporation from irrigation;

E_{i-pot} = potential evaporation from irrigation;

E_{p-pot} = potential evaporation from precipitation;

ET_c = crop evapotranspiration under standard conditions;

ET_{c-act} = total actual crop evapotranspiration;

ET_{c-adj} = crop evapotranspiration under non-standard conditions;

ET_{c-pot} = potential crop evapotranspiration;

ET_{gw-act} = root uptake from groundwater;

ET_{i-act} = portion of actual evapotranspiration fed by irrigation;

ET_{p-act} = portion of actual evapotranspiration fed by precipitation;

ET_r = reference crop evapotranspiration;

$f_r^{I\text{-}ini}$ = ratio of the initial return flow to the prime irrigation water;

$f_r^{I\text{-}loss}$ = fraction of crop-inefficient losses from irrigation that go to runoff;

$f_r^{P\text{-}loss}$ = fraction of crop-inefficient losses from precipitation that go to runoff;

f_u^{I} = ratio of the re-used return flow to the prime irrigation water;

g = ground surface elevation;

h = saturated groundwater head;

h_{lx} = elevation of lower transpiration extinction;

h_{rb} = elevation of the bottom of the root zone;

h_{ux} = elevation of upper transpiration extinction;

h_{wx} = elevation of wilting zone extinction;

I = rate of irrigation water;

k = iteration number;

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;

L_s = length of a stream section;

MAD = maximum allowable depletion;

P = precipitation rate;

p = water stress parameter;

Q_{sg} = flow rate between a stream section and the aquifer;

r = root zone depth;

R = total surface runoff from precipitation and irrigation;

R_i = runoff from irrigation;

$R_{i\text{-}ini}$ = initial return flow before a portion of it is captured and re-used;

R_p = runoff from precipitation;

s = depth of stream flow;

S = soil retention parameter at a given soil moisture content;

S_{max} = soil retention parameter for dry antecedent moisture conditions;

t = time step index;

$T_{c\text{-}act}$ = 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;

w = wilting zone;

w_s = width of a stream section;

Δh_{sg} = vertical head difference between the stream and the aquifer;

Δt = time step length;

η_T = total porosity;

λ = pore size distribution index;

θ = soil moisture in the root zone;

θ_f = field capacity.

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.

[BCDWRC]. Butte County Department of Water and Resource Conservation. 2008a. Butte Basin groundwater model update: Phase II report. **[Internet].** Butte County Department of Water and Resource Conservation. variously paged. Technical memorandum, March 2008. [cited: 2008 Dec 18]. Available at: http://www.buttecounty.net/waterandresource/GWModelupdate/BCDWRC%20Model%20TM2%20FINAL.pdf

[BCDWRC]. Butte County Department of Water and Resource Conservation. 2008b. Butte Basin groundwater model update: base case and water management scenerio simulations. **[Internet].** Butte County Department of Water and Resource Conservation. variously paged. Technical memorandum, April 2008. [cited: 2008 Dec 18]. Available at: http://www.buttecounty.net/waterandresource/GWModelupdate/TM3%20Base%20Case%20-%20Scenario%2020080424.pdf

[CADWR]. California Department of Water Resources. 1998. California Water Plan. Sacramento (CA): California Department of Water Resources. Bulletin 160.

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

CWEMF, 2008, Central Valley Groundwater Modeling Workshop, California Water Environmental Modeling Forum, **[Internet].** [cited: 2008 Sept 11]. Available at: http://www.cwemf.org/workshops/GWWorkshop/

[DHI]. Danish Hydraulic Institute. 1999. MIKE SHE Pre- and Post-Processing User Manual. Hørsholm, Denmark: DHI Software.

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.

Drew, MC. 1997, Oxygen deficiency and root metabolism. Injury and acclimation under hypoxia and anoxia. Annual Rev. Plant Physiol. Plant Mol. Biol. 1997. 48:223–250.

Driscoll, FG. 1986. Groundwater and wells. 2nd ed. St. Paul (MN): Johnson Division. 1089 p.

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. Applying MODFLOW's Farm Process to California's Central Valley. **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. 78-80.

Feddes, R.A., Kowalik, P., Kolinska-Malinka, K. and H. Zaradny, 1976, Simulation of field water uptake by plants using a soil water dependent root extraction function, Journal of Hydrolology 31 (1976), pp. 13–26.

Guan, H. and J.L. Wilson, 2009, A hybrid dual-source model for potential evaporation and transpiration partitioning, Journal of Hydrology 377 (2009) 405–416.

Halford, KJ; Hanson, RT. 2002. User's guide for the drawdown-limited, multi-node well (MNW) package for the U. S. Geologic Survey's modular three-dimensional finite-difference groundwater flow model, versions MODFLOW-96 and MODFLOW-2000. Sacramento (CA): US Geological Survey. 33 p. Open-File Report 02-293.

Available at: http://pubs.usgs.gov/of/2002/ofr02293/text.html

Hanson, RT; Martin, P; Koczot, KM. 2003. Simulation of groundwater/surface water flow in the Santa Clara - Calleguas basin, California. Sacramento (CA): US Geological Survey. 214 p. Water Resources Investigations Report 02-4136. Available at: http://water.usgs.gov/pubs/wri/wri024136/text.html

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 Ground-water 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 ground-water model-User guide to modularization concepts and the Groundwater Flow Process. Reston (VA): US Geological Survey. 121 p. Open-File Report 00-92.

Illangasekare, T. 2001. MIKE SHE code verification and validation for RFETS site-wide water balance model. **[Internet].** Prepared by Colorado School of Mines, Golden, Colorado in collaboration with Robert Prucha, RMC Consultants and DHI-Water and Environment for Kaiser-Hill Company, L.L.C. 28 p. September 28, 2001. [cited: 2008 Oct 4]. Available at: http://www.integratedhydro.com/MSHEVerification_summary.pdf

Jimenez, ACP. 2008. Modeling surface water and groundwater interactions near Milton-Freewater, Oregon. [master's thesis]. [Corvalis (OR)]: Department of BioResource Engineering, Oregon State University. 105 p.

Kavvas, ML; Chen, ZQ; Dogrul, C; Yoon, JY; Ohara, N; Liang, L; Aksoy, H; Anderson, ML; Yoshitani, J; Fukami, K; Matsuura, T. 2004. Watershed Environmental Hydrology (WEHY) model based on upscaled conservation equations: hydrologic module. J. Hydrol. Engrng. 9(6):450-464.

Kim, NW; Chung, IM; Won, YS; Arnold, JG. 2008. Development and application of the integrated SWAT–MODFLOW model. J. Hydrol. 356(1-2):1-16.

Kollet, SJ; Maxwell, RM. 2008. Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. Water Resour. Res. 44: W02402.

Kroes, J.G. and J.C. van Dam (eds), 2003. Reference Manual SWAP version 3.0.4. Wageningen, Alterra, Green World Research.. Alterra-report 773. Reference Manual SWAP version 3.0.4.doc. 211 pp

Kustas, W.P., Norman, J.M., 1997. A two-source approach for estimating turbulent fluxes using multiple angle thermal infrared observations. Water Resources Research 33 (6), 1495–1508.

Leavesley, GH; Lichty, RW; Troutman, BM; Saindon, LG. 1983. Precipitation-Runoff Modeling System: User's Manual. Denver (CO): US Geological Survey. 207 p. Water Resources Investigations Report 83-4238.

Markstrom, SL; Niswonger, RG; Regan, RS; Prudic, DE; Barlow, PM. 2008. GSFLOW--Coupled Groundwater and Surface water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Groundwater Flow Model (MODFLOW-2005). Reston (VA): US Geological Survey. 240 p. Techniques and Methods 6-D1.

Mathur, S. and S. Rao, 1999, Modeling Water Uptake by Plant Roots, Journal of Irrigation and Drainage Engineering, Vol. 125, No. 3, May/June 1999, pp. 159-165.

Maxwell, RM; Miller, NL. 2005. Development of a coupled land surface and groundwater model. J. Hydrometeorol. 6(3): 233-247.

McDonald, MG; Harbaugh, AW. 1988. A modular three-dimensional finite-difference groundwater flow model. (US Geologic Survey Technical Water Resources Investigation; Book 6). Reston (VA): US Geological Survey. Ch. A1. Techniques of Water-Resource Investigation 6-A1.

Miller, NL; Dale, LL; Brush, CF; Vicuna, SD; Kadir, TN; Dogrul, EC; Chung, FI. 2009. Drought resilience of the California Central Valley surface-groundwater-conveyance system. J. Am. Water Resour. Assn. 45(4):857-866.

[MW]. Montgomery Watson. 1993. Documentation and user’s manual for integrated groundwater and surface water model. Sacramento (CA): Montgomery Watson. variously paged.

Niswonger, RG; Prudic, DE. 2005. Documentation of the Stream flow-Routing (SFR2) Package to include unsaturated flow beneath streams-A modification to SFR1. Reston (VA): US Geological Survey. 57 p. Techniques and Methods 6-A13.

Niswonger, RG; Prudic, DE; Regan, RS. 2006. Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005. Reston (VA): US Geological Survey. 62 p. Techniques and Methods 6-A19.

Prasad, R. 1988. ‘‘A linear root water uptake model.’’ Journal of Hydrology, 99, 297–306.

Prickett, TA; Lonnquist, CG. 1971. Selected Digital Computer Techniques for Groundwater Resource Evaluation. Urbana (IL): Illinois State Water Survey. 62 p. Bulletin 55. Available at: http://www.isws.illinois.edu/pubdoc/B/ISWSB-55.pdf

Prucha, RH. 2004. Review of MIKESHE. Southwest Hydrology. January/February:37.

Prudic, DE; Konikow, LF; Banta, ER. 2004. A new stream-flow routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000. Carson City (NV): US Geological Survey. 104 p. Open-File Report 2004-1042.

Said, A; Steven, DK; Sehlke, G. 2005. Estimating water budget in a regional aquifer using HSPF-MODFLOW Integrated Model. J. Am. Water Resour. As. 41(1):55-66.

Schmid, W. 2004. A Farm Package for MODFLOW-2000: Simulation of Irrigation Demand and Conjunctively Managed Surface water and Groundwater Supply. [dissertation]. [Tucson (AZ)]: Department of Hydrology and Water Resources, The University of Arizona. 278 p.

Schmid, W; Dogrul, EC; Hanson, RT; Kadir, T; Chung, F. 2011. Comparison of simulations of land-use specific water demand and irrigation water supply by MF-FMP and IWFM, California Department of Water Resources Technical Information Report No. xx, xxxp.

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. (Book 6). Reston (VA): US Geological Survey. 102 p. Techniques and Methods 6-A32.

Schmid, W., J.P. King, and T.M. Maddock III. 2009c. Conjunctive Surface-water/groundwater model in the southern Rincon Valley using MODFLOW-2005 with the Farm Process: New Mexico Water Resources Research Institute Completion Report No. 350.

Schmid, W; Hanson, RT; Maddock III, T; Leake, SA. 2006. 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.

Schwankl, LJ; Prichard, TL; Hanson, BR. 2008. Reducing runoff from irrigated lands, tailwater return systems. **[Internet].** University of California, Division of Agricultural and Natural Resources. Publication 8225. [cited: 2008 Aug 27]. Available at: http://anrcatalog.ucdavis.edu/pdf/8225.pdf

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops – an energy combination theory. Quarterly Journal of the Royal Meteorological Society 111.

Simunek, J; Sejna, M; van Genuchten, MT. 1999. HYDRUS-2D/MESHGEN-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. Golden (CO): Colorado School of Mines. 227 p. Handbook, International Groundwater Modeling Center – TPS 53C, Version 2.0.

Sophocleous, MA; Koelliker, JK; Govindaraju, RS; Birdie, T; Ramireddygari, SR; Perkins, SP. 1999. Integrated numerical modeling for basin-wide water management – The case of the Rattlesnake Creek Bain in South-central Kansas. J. Hydrol. 214(1-4):179-196.

Sophocleous, MA; Perkins, SP. 2000. Methodology and application of combined watershed and groundwater models in Kansas. J. Hydrol. 236(3-4):185-201.

Synder, R; Orang, M; Geng, S; Matyac, S; Sarreshteh, S. 2005. SIMETAW (Simulation of Evapotranspiration of Applied Water). (California Water Plan Update 2005; vol. 4: reference guide). Sacramento (CA): California Department of Water Resources.

Therrien, R.; McLaren, R.G., Sudicky, E.A. 2007. HydroGeoSphere—a three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport (Draft). Groundwater Simulations Group, University of Waterloo.

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

Williamson, AK; Prudic, DP; Swain, LW. 1989. Ground-water flow in the Central

Valley, California. Washington (DC): US Geological Survey. variously paged. Professional Paper 1401-D.

Yoon, YS. 1976. Identification of aquifer parameters in a large unconfined system: with finite elements and constrained nonlinear least squares optimization. [dissertation]. [Los Angeles]: Department of Civil and Environmental Engineering, University of California.