

One-Water Hydrologic Flow Model: A MODFLOW Based Conjunctive-Use Simulation Software

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Preface

This report presents a computer program for simulating the movement and conjunctive use of surface water and groundwater by the U.S. Geological Survey (USGS) hydrologic model, MODFLOW One-Water Hydrologic Model (MF-OWHM) version 2.

All MODFLOW code developed by the USGS is available to download on the Internet from a U.S. Geological Survey software repository. The repository is accessible on the World Wide Web from the USGS Water Resources information Web page at

<https://www.usgs.gov/software/modflow-owhm-one-water-hydrologic-flow-model>

and a git repository at

<https://code.usgs.gov/modflow/mf-owhm>

Although this program has been used by the USGS, no warranty, expressed or implied, is made by the authors, the USGS, or the United States Government as to the accuracy or functioning of the program and related program material, nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by the authors or the USGS in connection with it. Future applications might reveal errors that were not detected in the test simulations. Users are requested to notify the USGS of any errors found in this document or the computer program by using the email address available on the aforementioned Web site. When important updates are made either to the MF-OWHM program or to the documentation, these updates are uploaded to the USGS Web site. Users are encouraged to check the Web site periodically and read the `release.txt` document provided with the distribution of the software.

The computer program described here is based, in part, on copyrighted scientific methodologies originally obtained from the copyright holder (Schmid, 2004). The copyright holder has granted full permission to the USGS and to the public to quote, copy, use, and modify these methods, as well as publish modified methods. Whereas MF-OWHM includes all the features and core elements of MODFLOW-2005 (rev 1.12), we request that if you use MF-OWHM version 2, you also include proper citation to this document (Boyce and others, 2020) in any related reports, articles, or presentations.

In the download of this computer program is a `readme.txt`, `release.txt`, and supplemental documentation. The `.txt` files can be viewed in any ASCII/UNICODE text viewer. The `readme.txt` contains an overview of the release and describes the contents of the software download. The `release.txt` file describes any changes or bug fixes made since the initial release of MF-OWHM. The supplemental documentation provides background knowledge about the software and any features incorporated since the release of this report.

To provide a “living” reference to all input features from all the currently supported packages and processes, an online manual (guide) is available at

<https://ca.water.usgs.gov/modeling-software/one-water-hydrologic-model/users-manual/>

At the time of this report’s publication, the online guide is maintained by Richard Winston (rbwinst@usgs.gov).

A user-group email, MODFLOW_OWHM@usgs.gov, is available for users to electronically report potential software issues (bugs); users may also request to be on a mailing list that sends notices related to the MF-OWHM simulation-software distribution.

Specific correspondence regarding this report, its documented simulation program, notification of simulation issues or bugs, or future feature suggestions can be sent electronically to

MODFLOW_OWHM@usgs.gov

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Conversions, Datums, Abbreviations, Acronyms, and Definitions of Variables

Common Unit Conversions Between International System of Units and U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
Area		
square meter (m ²)	10.7639104	square feet (ft ²)
square meter (m ²)	0.0001	hectare (ha)
hectare (ha)	2.4710538	acre
acre	43560.0	square feet (ft ²)
Volume		
cubic meter (m ³)	35.3146667	cubic feet (ft ³)
cubic meter (m ³)	0.0008107	acre-foot (acre-ft)
acre-foot (acre-ft)	43560.0	cubic feet (ft ³)
Flow rate		
cubic meter per second (m ³ /sec)	70.0456199	acre-foot per day (acre-ft/d)

Acre-foot (acre-ft) is a unit of volume used commonly in water resources. Its volume equals one acre of surface area to a depth of one foot

decisiemens (dS) is a unit of electric conductance and is the inverse of electrical resistance.

Elevation, as used in this report, refers to distance above the vertical datum.

Parts per million (ppm), is a unit of concentration in water. It is the same quantity same as milligram per liter.

The symbols "L" and "T" represent any accepted unit for length and time, respectively.

For example, L³/T represents any volumetric flow rate (such as, m³/sec or acre-ft/d).

The symbol "M" represents any accepted unit for mass (such as, kilogram or pound-mass).

For example, M/LT² represents a pressure (such as, kilogram/meter-second²).

For variable and input definitions, the symbol "{-}" is used to indicate that the variable or input is unitless.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Stage, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

ASCII	American Standard Code for Information Interchange (basic text file file)
BAS	Basic Package
BCM	Basin Characterization Model
CFP	Conduit Flow Process
CFPM1	Conduit Flow Process Mode 1
CFPM2	Conduit Flow Process Mode 2
CIMIS	California Irrigation Management Information System
CIR	crop irrigation requirement
CU	consumptive use
$D_{\text{irrigation}}$	necessary irrigation to meet a land use's consumptive use (CIR/OFE)
DIS	Discretization Package
DRN	Drain Package
DRT	Drain return-flow package
DP	deep percolation, water that infiltrates beneath the root zone
ET	Evapotranspiration
ET_{ref}	Reference evapotranspiration flux [L/T]
FAO	Food and Agriculture Organization of the United Nations
FEI	Fraction of evaporation from irrigation
FIESWI	Fraction of inefficient losses from irrigation to surface water
FIESWP	Fraction of inefficient losses from precipitation to surface water
FMP1	Farm Process, version 1; from MODFLOW-FMP
FMP2	Farm Process, version 2; from MODFLOW-FMP2
FMP3	Farm Process, version 3; from MF-OWHM
FMP	Farm Process, version 4; from MF-OWHM2
FTR	Fraction of transpiration
GCM	Global Climate Model

GHB	General Head Boundary Package
GIS	Geographic Information System
HFB	Hydrologic Flow Barrier Package
HOB	Head Observation Process
HUF	Hydrogeologic-Unit Flow Package
HYDMOD	computer program for calculating hydrograph time series data for MODFLOW
IHM	integrated hydrologic model
IRR	amount of applied, irrigated water to crop
ISO	International Standard Organization
K_c	Crop coefficient for evapotranspiration
K_{cb}	Basal crop coefficient for transpiration
LAI	List-Array Input Style
LGR	Local Grid Refinement
LIST	Listing File, a transcript of all operations in a MODFLOW, MF-OWHM, and MF-OWHM2 simulation
LPF	Layer Property Flow Package
MF	MODFLOW
MF2005	MODFLOW-2005
MODFLOW-FMP	MODFLOW-2000 with the Farm Process version 1
MODFLOW-FMP2	MODFLOW-2005 with the Farm Process version 2
MF-OWHM	MODFLOW-One-Water Hydrologic Model Version 1
MF-OWHM2	MODFLOW-One-Water Hydrologic Model Version 2
MNW1	Multi-Node Well Package version 1 Package
MNW2	Multi-Node Well Package version 2 Package
MULT	Multiplier Package
NAME	MF-OWHM2 Name file
NFARM	number of FMP water-balance subregions
NWBS	number of FMP water-balance Subregions
NWT	Newton-Raphson Solver Package
OFE	on-farm efficiency
PCG	preconditioned conjugate gradient solver package
PVAL	Parameter Value Package
RES	Reservoir Package
RIV	River Package
SFAC	Scale Factor—keyword to indicate advanced scale factors are read

SFR	Streamflow Routing Package
SGMA	Sustainable Groundwater Management Act of California
SUB	Subsidence Package
SWI	Seawater Intrusion Package
SWO	Surface-Water Operations Process
SWR	Surface Water Routing Process
TFDR	total farm delivery requirement
TFR	Transient File Reader
$T_{\text{irrigation}}$	transpiration from irrigation
T_p	transpiration from precipitation
TSF	Time-Series File
T_{uptake}	transpiration from groundwater-root uptake
ULOAD	universal input-loading utility
UPW	Upstream weighting flow package
USGS	U.S. Geological Survey
UZF	Unsaturated Zone Flow Package
WBS	Water-Balance Subregions—previously called FMP "Farm"s
WEL	Well Package
ZON	Zone Array Package
ZONEBUDGET	computer program for calculating subregional water budgets for MODFLOW

One-Water Hydrologic Flow Model: A MODFLOW Based Conjunctive-Use Simulation Software

By Scott E. Boyce¹, Randall T. Hanson¹, Ian Ferguson², Wolfgang Schmid³, Wesley Henson¹, Thomas Reimann⁴, Steffen M. Mehl^{1,5}, and Marisa M. Earl¹

Executive Summary

The U.S. Geological Survey's (USGS) Modular Groundwater Flow Model (MODFLOW-2005) is a computer program that simulates groundwater flow by using finite differences. The MODFLOW-2005 framework uses a modular design that allows for the easy development and incorporation of new features called processes and packages that work with or modify inputs to the groundwater-flow equation. A process solves a flow equation or set of equations. For example, the central part of MODFLOW is the groundwater-flow process that solves the groundwater-flow equation; the surface-water routing process is an additional process that solves the surface-water flow equation. Packages are code related to the groundwater-flow process. For example, the subsidence package modifies the groundwater-flow process by including aquifer compaction effects on flow. With the development of new packages and processes, the MODFLOW-2005 base framework diverged into multiple independent versions designed for specific simulation needs. This divergence limited each independent MODFLOW release to its specific purpose, so that there was no longer a single, comprehensive, general-purpose hydraulic-simulation framework.

The MODFLOW One-Water Hydrologic Flow Model (MF-OWHM, also informally known as OneWater) is an integrated hydrologic flow model that combines multiple MODFLOW-2005 variants in one cohesive simulation software; changes were made to enable multiple capabilities in one code. This fusion of the MODFLOW-2005 versions resulted in a simulation software that can be used to address and analyze a wide class of conjunctive-use, water-management, water-food-security, and climate-crop-water scenarios. As a second core version of MODFLOW-2005, MF-OWHM maintains backward compatibility with existing

MODFLOW-2005 versions, with features that include the following:

- Process-based simulation.
 - ▶ Saturated groundwater flow (three-dimensional).
 - ▶ Surface-water flow (one- and two-dimensional).
 - ▷ Stream and river flow.
 - ▷ Lake and reservoir storage.
 - ▶ Landscape simulation and irrigated agriculture.
 - ▷ Land-use and crop simulation.
 - ▷ Root uptake of groundwater.
 - ▷ Precipitation.
 - ▷ Actual evapotranspiration.
 - ▷ Runoff.
 - ▷ Infiltration.
 - ▷ Estimated irrigation demand.
 - ▶ Reservoir operations.
 - ▶ Aquifer compaction and subsidence by vertical model-grid deformation.
 - ▶ Seawater intrusion by a sharp-interface assumption.
 - ▶ Karst-aquifer and fractured-bedrock flow.
 - ▶ Turbulent and laminar-pipe network flow.
 - ▶ Unsaturated groundwater flow (one-dimensional).
- Internal linkages among the processes that couple hydraulic head, flow, and deformation.
- Redesigned code for faster simulation, increased user-input options, easier model updates, and more robust error reporting than in previous models (approximately 75,000 new lines of Fortran code were added to MF-OWHM).

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2 One-Water Hydrologic Flow Model: A MODFLOW Based Conjunctive-Use Simulation Software

MF-OWHM is a MODFLOW-2005 based integrated hydrologic model that can simulate and analyze varying environmental conditions to allow for the evaluation of management options from many components of human and natural water movement through a physically based, supply and demand framework. The term “integrated,” in the context of this report, refers to the tight coupling of groundwater flow, surface-water flow, landscape processes, aquifer compaction and subsidence, reservoir operations, and conduit (karst) flow. Another benefit of this integrated hydrologic model is that models developed to run by MODFLOW-2005, MODFLOW-NWT, MODFLOW-CFP, or MODFLOW-FMP can also be simulated with MF-OWHM. At the time of this report’s publication, MF-OWHM version 2 (MF-OWHM2) does not include a direct internal simulation of snowmelt, advanced mountainous watershed rainfall-runoff simulation, detailed shallow soil-moisture accounting, or atmospheric moisture content. Atmospheric moisture may be accounted for indirectly by, optionally, specifying a pan-evaporation rate, reference evapotranspiration, and precipitation. These features are not included to ensure that simulation runtime remains short enough to enable the use of automated methods of calibrating model parameters to field observations, which typically require many simulation model runs. The MF-OWHM approach is to include as much detail as possible to simulate hydrological processes, providing the simulation runtimes remain reasonable enough to allow for robust parameter estimation and model calibration.

To represent both natural and human-influenced flow, MF-OWHM integrates physically based flow processes derived from MODFLOW-2005 in a supply and demand framework. From this integration, the physically based movement of groundwater, surface water, imported water, and precipitation serve as supply to meet consumptive demands associated with irrigated and non-irrigated agriculture, natural vegetation, and urban water uses. Water consumption is determined by balancing the available water supply with water demand, leading to the concept of a demand-driven, supply-constrained simulation.

The MF-OWHM Supply-and-Demand Framework is especially useful for the analysis of agricultural water use, where there are often few data available to describe changes in land-use through time, such as crop type and distribution, and the associated changes in groundwater pumpage. This framework attempts to satisfy each land-use water demand with available water supplies—that is, groundwater uptake, precipitation, and irrigation. An option provided in MF-OWHM2 is to automatically increase groundwater pumping for irrigation, which often is unknown, by the calculated residual between demand and the other available sources of supply. From large- to small-scale applications, the physically based supply and demand framework provides key capabilities for simulating and analyzing historical, current, and future conjunctive-use of surface water and groundwater.

To achieve the physically based supply and demand framework, the MODFLOW-2005 standard of no inter-package and -process communication was relaxed for MF-OWHM2. Traditional MODFLOW simulation models required that all packages and processes interact through the groundwater-flow equation or by removing the water flow from the simulation domain. For example, the MODFLOW-2005 representation of a groundwater well extracts water from the groundwater-flow equation (by subtraction) and removes it from the simulation domain. This feature is available in the MF-OWHM framework, but options have been added to allow the specification of a use or destination of pumped groundwater within the model domain, for example, it can be used for irrigation, managed aquifer recharge, or return-flow to streams.

This report documents the new features and capabilities associated with the second release of the One-Water Hydrologic Flow Framework (MF-OWHM2), which expands upon the features of the MF-OWHM by introducing new packages and processes, improving linkages between them, and updating the overall software. The major MF-OWHM2 enhancements include the following:

- Inclusion of a Conduit-Flow Process (CFP) for simulating karst aquifers, leaky pipe networks, and secondary porosity.
- Updates to the Farm Process (FMP).
 - ▶ The ability to specify multiple land-use types (crops) within a model cell.
 - ▶ The ability to specify additional demand types not associated with land use.
 - ▶ Calculation of additional irrigation for soil-salinity flushing.
 - ▶ A direct-recharge option to represent infiltration ponds.
 - ▶ A “sand” soil type and bare-soil or fallow land-use option.
 - ▶ Allow for enabling or disabling, by land-use category, root uptake of groundwater, crop anoxia, or crop-soil stress.
 - ▶ Updating of base code from FORTRAN 95 to FORTRAN 2008.
 - ▶ Complete redesign of the input structure for easy maintenance and calibration.
- Additions to General Head Boundary (GHB) that include head-dependent conductance and automatic calculation of conductance based on aquifer properties.
- Inclusion of a Calendar Date and Time format for model input and output by specifying a starting simulation date; the model then tracks when each time-step occurs on the calendar.

- Inclusion of alternative package input structures that facilitate easier model maintenance.
 - ▶ LineFeed—Stress-period-based input that is structured like a spreadsheet.
 - ▶ Time-Series Files— uses calendar dates to assign input by the start and ending dates of each model time step.
 - ▶ TabFiles—tabulated data input that have a time stamp and data.
 - ▶ Addition of a second well package with enhancements to its TabFile input.
 - ▶ New Warning Package (WARN)
 - ▶ The Listing file (LIST) is now optional.
 - ▶ Designation of multiple budget groups for select packages that are passed to the cell-by-cell output and volumetric budget information for advanced post-processing.
- Upgrades and modifications to the Basic (BAS), Discretization (DIS), Stream Flow Routing (SFR), Multi-Node Well v2 (MNV2), Reservoir (RES), Parameter Value (PVAL), Multiplier Array (MULT), Zone Array (ZONE), and Head Observation (HOB) to improve the execution speed and add features that support conjunctive-use simulation and analysis.
- Code-specific changes include buffering of input and output files for decreasing simulation runtimes, the ability to split output files into multiple files to prevent excessively large file sizes, an advanced program-stop utility that provides detailed information, a universal input-loading utility (ULOAD) that uses a transient file reader for more flexible input, and a generic block-input tool that loads block-style input automatically.

The MF-OWHM2 framework also is designed to support the concept of “self-updating” models. This was implemented by separating the MODFLOW input-file structure into spatial (or structural) and temporal components. This allows the input files to be easier to read and modify by model developers, users, and reviewers; thus, the models are easier to use and update. This separation also allows automated programs to query databases, websites, or spreadsheets for data to update the input files (for example, streamflow or specified pumping rates). This automation, or self-updating, of the input files allows for the simulation model to be readily used after its initial construction, thus increasing the longevity and value of the simulation model.

This report includes a hypothetical example using MF-OWHM2. The example problem illustrates how to answer typical conjunctive-use questions by addressing additional irrigation requirements due to salinity flushing. When needed, salinity flushing results in an additional irrigation demand that is met by increased groundwater pumpage.

Introduction

The Modular Ground-Water Flow Model (MODFLOW-2005) is a computer program that uses the finite difference method to simulate the groundwater-flow equation (Harbaugh, 2005). The MODFLOW-2005 framework used a modular design that allows for the easy development and incorporation of features called packages and processes that work with the groundwater-flow equation solver. Packages are features related to the groundwater-flow process (for example, the Well package, “WEL”), whereas a process solves flow equations and can represent an ancillary process that interacts with the groundwater-flow equation (for example, Farm Process, “FMP”). Typically, popular packages were incorporated into the base MODFLOW-2005 code, whereas processes were released as separate, independent versions of MODFLOW. The separate, independent versions resulted in a divergence of MODFLOW development, limiting each independent release to the specific purpose for its design. The simulation of conjunctive management of water resources using MODFLOW-2005 required unifying the various MODFLOW-2005 variants into a single general-purpose hydraulic-simulation framework. This core update to MODFLOW-2005 yielded the integrated hydrologic flow model software called the One-Water Hydrologic Flow Model (MF-OWHM). Beyond “integrating” the separate MODFLOW-2005 variants into one cohesive simulation software, MF-OWHM incorporated new capabilities to the unified code. This fusion of MODFLOW-2005 versions resulted in analysis and simulation software capable of addressing, and thereby advancing, the understanding of a broad class of water-use and sustainability problems, including conjunctive-use, water-management, water-food-security, and climate-crop-water scenarios. Another benefit of this fusion is that existing models developed using the various predecessors—MODFLOW-2005 (Harbaugh, 2005), MODFLOW-NWT (Niswonger and others, 2011), MODFLOW-CFP (Shoemaker and others, 2008), and MODFLOW-FMP (Schmid and others, 2006; Schmid and Hanson, 2009a)—can also be simulated using MF-OWHM and have access to features of other MODFLOW releases.

The improvements, new features, modifications to MODFLOW-2005, and newly developed processes described in this report continue the MF-OWHM goal of retaining and tracking as much water as is feasible in the simulation domain. This provides the scientific and engineering community with confidence in the water accounting and a technically sound foundation to address broad classes of problems for the public. Because complex questions are being asked about the sustainability of water resources and sophisticated tools are required to answer difficult conjunctive-use management questions, the Bureau of Reclamation (Reclamation) cooperated with the U.S. Geological Survey (USGS) to develop this updated version of MF-OWHM incorporating the new capabilities of software and availability of data.

Report Organization

This report is organized as a main text and set of appendixes. The main text of the report presents an overview of the MODFLOW-2005 based hydrologic modeling software and the features and concepts incorporated in MF-OWHM version 2 (MF-OWHM2). The concepts of integrated hydrologic modeling, the MF-OWHM2 supply and demand framework, and the self-updating model structure are introduced for users new to this approach to integrated conjunctive-use modeling. The main text of the report then describes improvements to MODFLOW specific to the MODFLOW-2005 base code and new landscape features, which include the updates and improvements to the Farm Process (FMP). Next, the report introduces the revised Conduit Flow Process (CFP), with emphasis on improvements to the original MODFLOW-CFP (Shoemaker and others, 2008). The report includes a hypothetical example problem to illustrate the application of a subset of the features of MF-OWHM2. The current limitations and future improvements to MF-OWHM2 are the final topics.

The report contains nine appendixes. The first appendix, appendix 0, discusses the meaning and types of syntax highlighting used throughout this report. The next two appendixes (appendix 1 and 2) introduce new utilities for input and temporal separation in MF-OWHM2. In particular, the input and output file utilities *Generic_Input*, *Generic_Output*, the *Universal Loader* utility (ULOAD), and how they relate to the new *List-Array Input* syntax (LAI) are described appendix 1. Appendix 2 provides details about the *LineFeed* input format, the *Time-Series File* input format, improvements to the *TabFiles*, and concludes with suggestions on how to effectively build a *Transient File Reader* (TFR). Appendix 3 describes specific updates and improvements to the MODFLOW-2005 part of MF-OWHM2—including improvements to the Basic (BAS), Discretization (DIS), General Head Boundary (GHB), and WEL packages. Appendixes 4 and 5 provide an overview of the theory behind the Farm Process and the data requirements for simulating land use and calculating consumptive use. Appendix 6 describes the new FMP input options and related upgrades. Lastly, appendixes 7 and 8 describe the addition of the Conduit Flow Process (MODFLOW-CFP) in MF-OWHM2 and new features incorporated in it.

MODFLOW-2005 Framework Descendants Relationship to MF-OWHM2

The MODFLOW-2005 modular framework facilitated the development of independent releases designed for specific applications. A diagram of the MODFLOW-2005 variant descendants (fig. 1) shows the relationship of each one to MF-OWHM2. Each of the major independent releases of MODFLOW-2005 variants are discussed in the remainder of this section as context for the development of the MF-OWHM2 software.

MODFLOW-FMP (Schmid and others, 2006; Schmid and Hanson, 2009) was one of the early attempts to develop the ability of MODFLOW-2005 to simulate conjunctive use by including landscape processes. It introduced the Farm Process (FMP1), which simulates crop growth, root uptake of groundwater, water deliveries, and runoff within a supply and demand framework. It also incorporated climate information in the form of reference evapotranspiration and precipitation; climate influences on water consumption by crops and the use of irrigation. MODFLOW-FMP resulted in the capability for dynamic estimation of surface-water diversions and groundwater pumpage, neither of which are necessarily known quantities.

MODFLOW-2005 is based on the concept of structured finite volumes, which are calculated by the finite difference method. Structured grids have the limitation that for a single model row, column, or layer, there must be a constant width, length, or height, respectively. This means that two rows may have different widths, but for any one row, all the columns and layers passing through it must have the same width. This limitation prompted the development of MODFLOW-LGR, Local Grid Refinement (Mehl and Hill, 2005, 2013). MODFLOW-LGR couples a coarse “parent” model grid with a refined “child” grid. The parent and child models both follow the structured finite-volume scheme, but flows at the parent–child boundary are dynamically coupled. The parent grid can, for example, be associated with a regional model that accounts for bulk flows, and a child model embedded within the regional domain can provide a more detailed simulation in a subarea of the regional model. The parent- and child-model coupling may be one-way, passing flows only from parent to child, or two-way, passing flows back and forth iteratively between the parent and child. This coupling allows for a detailed simulation of local areas in a model domain and provides hydrologically reasonable boundary conditions for problems on a local scale.

An assumption of MODFLOW-2005 was that groundwater flow is laminar, fully saturated, and follows Darcy’s law. This assumption is not valid for karst aquifers that are characterized by dual porosity and turbulent flow. This led to the development of the MODFLOW-CFP, Conduit Flow Process (Shoemaker and others, 2008), which can simulate short-circuit “conduits” in groundwater systems. These conduits represent fractures in porous media, karst topography, or a pipe-network distribution system, thereby enabling simulation of turbulent flow.

A MODFLOW-2005 simulation consists of a three-dimensional structured grid analogous to stacked cubes. Each cube has defined groundwater properties and may have flow into or out of the cube, either directly from its interior—such as groundwater pumping—or through any of its six faces. A single MODFLOW cube is called a model cell and is identified by model row, column, and layer. According to the model cell properties and location, the MODFLOW-2005 groundwater-flow equation is solved using the Picard method of successive approximations by integration

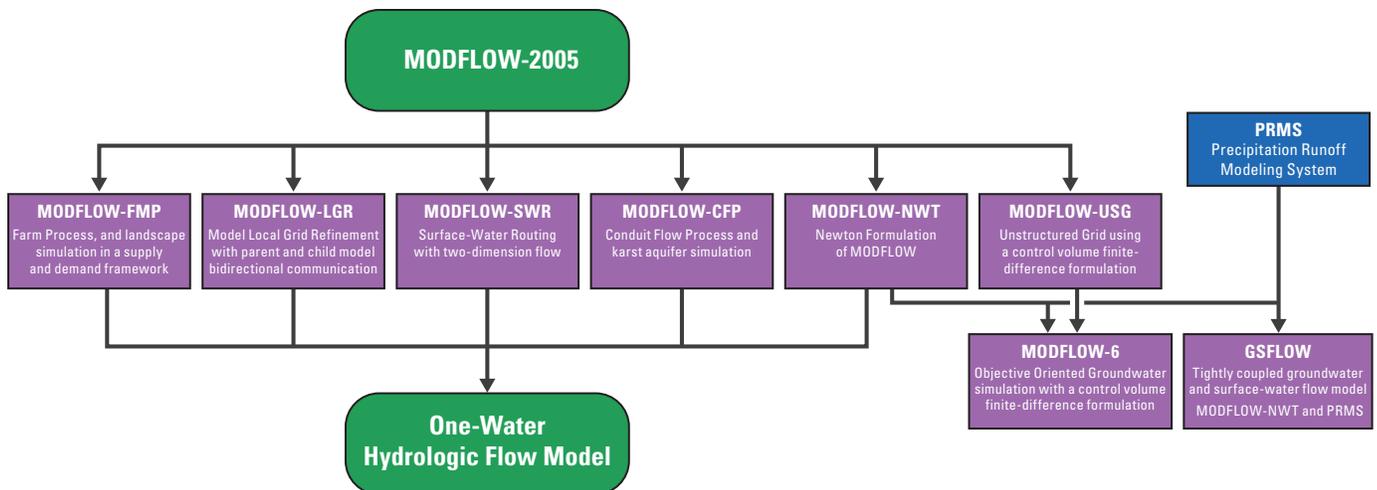


Figure 1. Overview of the MODFLOW-2005 framework and its descendants.

(Harbaugh, 2005). The Picard method iteratively solves the groundwater-flow equation by applying the head estimated in the previous iteration to all nonlinear features to linearize them. This procedure continues until the previous head value, used to linearize the groundwater-flow equation, converges to have the same value as the solution from linear groundwater equations. A limitation of this method is that when a water-level drops beneath the bottom of a cell, the cell is removed from the simulation. When a model cell is removed from the simulation, it is called a "dry" model cell; conversely, when it contains water (having a water level above its bottom) it is called a "wet" model cell. Under some certain circumstances, the Picard method can cause the solution for a model cell to oscillate between wet and dry, thereby preventing the groundwater-flow equation from converging to a final solution (Keating and Zyvoloski, 2009). This is referred to as the MODFLOW wet-dry problem. One of the early attempts to resolve this problem was the development of MODFLOW-NR (Painter and Başağaoğlu, 2007; Painter and others, 2008), which applied upstream weighting, well smoothing, and a Newton-Raphson formulation to MODFLOW, but was only applicable to single-layer models. The USGS generalized this formulation to develop MODFLOW-NWT (Niswonger and others, 2011), which solved the wet-dry problem for multi-layer systems. This variant recast the groundwater-flow equations in a Newton-Raphson framework and called the Newton-Raphson solver package (NWT) of MODFLOW. This formulation requires an asymmetric matrix solver that precludes the use previous default solver methods, so MODFLOW-NWT incorporated two alternative matrix solvers: generalized minimal residual method solver (GMRES) and a specialized solver called χ MD (Ibaraki, 2005). By eliminating the wet-dry issue, MODFLOW-NWT enabled a stable simulation of flow in unconfined and perched groundwater systems.

The Surface-Water Routing process (SWR) is an advanced surface-water flow simulator for the MODFLOW-2005 framework (Hughes and others, 2012). The SWR solves the continuity equation for one-dimensional and two-dimensional surface-water flow routing by a simple level- and tilted-pool reservoir routing and a diffusive-wave approximation of the Saint-Venant equations. At the time of writing this report, the SWR is available within MODFLOW-NWT, MODFLOW-2005, and MF-OWHM.

The MODFLOW unstructured grid (MODFLOW-USG; Panday and others, 2013) is a special, branched version of MODFLOW that relaxes the structured-grid requirement, allowing for a true finite-volume representation. This relaxation resulted in a control-volume finite-difference formulation that allows a model cell to be connected to an arbitrary number of adjacent cells—with its resulting cell shape, such as a cube, based on the number of connections. This unstructured feature allows for models to incorporate local grid refinements in areas that require more detailed groundwater-flow simulation by increasing the number of connections, such as a quadtree refinement. This method improves solution stability by using a "ghost-node correction" that interpolates the head value within a model cell to a location that is orthogonal to its adjacent cell. MODFLOW-USG included several of the key MODFLOW-2005 packages to provide a comprehensive groundwater-flow simulation platform without the structured-grid requirement. Building upon the concepts of MODFLOW-USG and MODFLOW-2005, a new groundwater-flow framework, called MODFLOW-6 (Langevin and others, 2017), was developed using an object-oriented programming paradigm. At the time of this publication, MF-OWHM2 does not include the unstructured-grid formulation, because of fundamental differences in how the groundwater-flow equation is solved. It is mentioned here because it provides a flexible model grid for groundwater-flow models that require refinement beyond the capabilities of MODFLOW-LGR.

To accurately represent hydrologic systems where groundwater flow is tightly coupled with surface-water flow and runoff modeling, the Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983, Markstrom and others, 2015) was merged with MODFLOW-2005 to form GSFLOW (Markstrom and others, 2008). GSFLOW is a variant of MODFLOW-2005 with a tight coupling between PRMS and MODFLOW-2005 that enables detailed simulation of watersheds holistically, linking streams, lakes, and groundwater flow. A subsequent release of GSFLOW included the advanced flow solvers of MODFLOW-NWT, allowing for a robust representation of unconfined flow. GSFLOW simulations use daily time steps and, optionally, include solar-radiation balances, snowmelt, and air temperature.

In comparison to MF-OWHM2, the GSFLOW incorporation of PRMS provides a more detailed runoff model at the expense of simulation runtime. MF-OWHM2, through the Farm Process, has a simpler runoff model and often faster simulation runtimes. MF-OWHM2 has no inherent limit to time-step length, but a time step greater than or equal to 1 day is recommended when using the FMP. GSFLOW is therefore more physically based for runoff calculations, but may be more challenging to calibrate owing to the confluence of two inherent features: its daily time step and its requirement for convergence of both solutions (PRMS's and MODFLOW's) for each time step. Conversely, MF-OWHM2's simpler runoff model results in models that may be easier to calibrate and verify in terms of runoff. This makes MF-OWHM2 suitable for simulating long historical periods (months to 1,000 plus years) and for short and long-term future projections for evaluating sustainability and conjunctive-use management scenarios, as well as land-use changes.

GSFLOW most accurately represents, and is recommended for, simulation of mountainous headwater regions or valleys that have strong interaction between groundwater and surface runoff. MF-OWHM2 is more appropriate for simulation of aquifer systems in valley settings, especially in arid and semi-arid regions, that do not require a detailed runoff simulation or snowmelt (radiation balance) calculations. MF-OWHM2 simulation domains typically have a lateral boundary at the base of a mountain (or foothill area) or other bedrock feature and may, optionally, use a larger regional rainfall-runoff model to estimate the stream inflows and mountain-block recharge along that boundary. For more details about rainfall-runoff models please see the "Optional Use of Separate Rainfall-Runoff and Hydraulic Models" section, which briefly describes potential companion simulation models. A rainfall-runoff model is not required by MF-OWHM2, and any model domain or aquifer system that can be simulated by MODFLOW-2005, MODFLOW-NWT, MODFLOW-CFP, or MODFLOW-FMP can also be simulated by MF-OWHM2.

Overview of MF-OWHM2

Like its MF-OWHM predecessor, the MF-OWHM2 software can be used to simulate and analyze a wide class of conjunctive-use, water management, water-food-security, sustainability, and climate-crop-water scenarios.

MF-OWHM2 uses a physically based simulation that is connected to a supply and demand framework (fig. 2). This framework starts with the landscape's demand for water consumption that originates from either an administrative requirement—such as urban consumption or managed aquifer recharge—or from the landscape surface's potential evaporation and transpiration. This "landscape water demand" is then satisfied from available supplies of water—such as precipitation, surface water, groundwater, and imported water. Water supply can be limited by physical constraints from the natural and engineered water systems. These constraints result from the physics of natural groundwater and surface-water flow and to physical limits of engineered systems, such as diversion canals or well-production capacity. The landscape water demand can affect both surface water and groundwater because of their interconnectivity. Further, the supply of groundwater and surface water can be controlled by water rights, managed through reservoir operations, or limited by regulations.

MF-OWHM2 is well suited for simulation of agricultural settings because it includes the dynamic estimation of agricultural water consumption and groundwater pumpage for irrigation, routing and management options for surface-water diversions, detailed water-budget output, and embedded functionality for reservoir operations. This dynamic estimation makes MF-OWHM2 a powerful tool for evaluation of present and future agricultural scenarios and assessing conjunctive-use sustainability.

MF-OWHM2 provides a simulation engine for assessing conjunctive use and groundwater sustainability, which may be part of a water agreement, transboundary compact or treaty, or legislation. For example, the California Sustainable Groundwater Management Act of 2014 (SGMA; State of California, 2014) requires that the management and use of groundwater is done without causing "undesirable results." The SGMA specified "undesirable results" are "(1) chronic lowering of groundwater levels that is independent of drought, indicating a significant and unreasonable depletion of supply, (2) significant and unreasonable reduction in groundwater storage, (3) significant and unreasonable seawater intrusion, (4) significant and unreasonable degraded water quality, (5) significant and unreasonable land subsidence, and (6) reduction in surface-water flow, due to groundwater use, that has significant and unreasonable adverse impacts on beneficial uses of the surface water" (http://leginfo.ca.gov/faces/codes_displayText.xhtml?lawCode=WAT&division=6.&title=&part=2.74.&chapter=2.&article=).

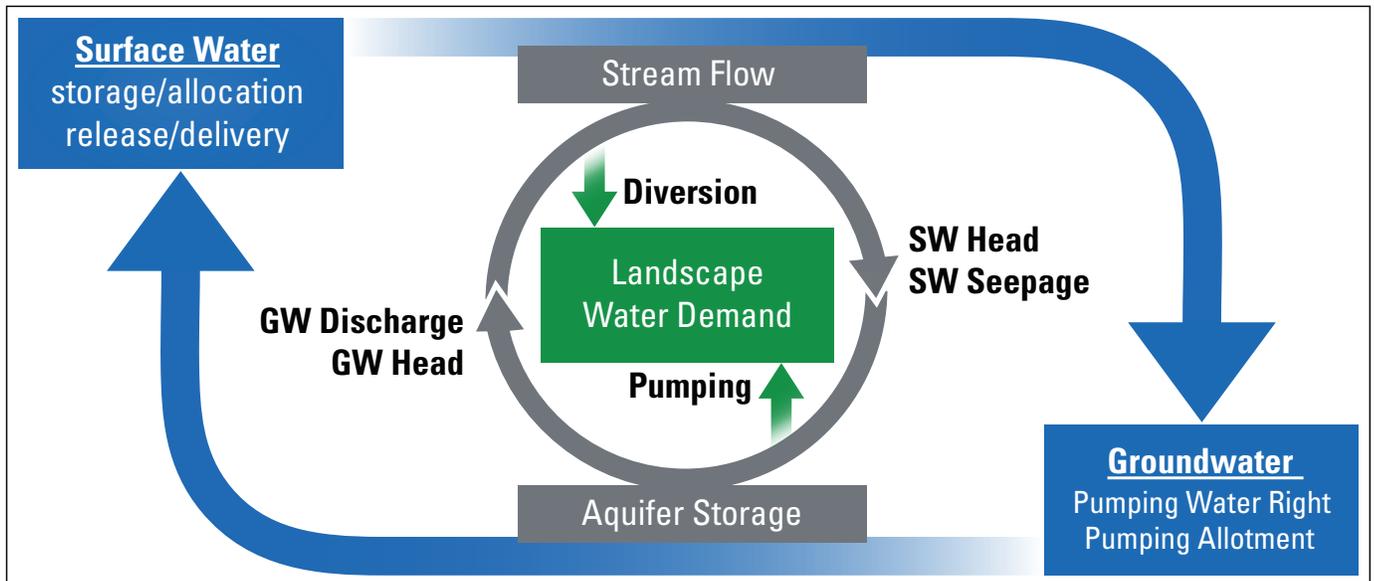


Figure 2. Water flow and use is interconnected through physically based processes and management processes. [SW stands for surface water and GW stands for groundwater; precipitation, not included in figure, is a source of water that could potentially reduce the landscape water demand and increase aquifer storage and stream flow.]

Five of the six SGMA “undesirable results” (1, 2, 3, 5, and 6) can be directly simulated in the MF-OWHM framework, and the sixth, degraded water quality (4), can be simulated indirectly. (1) *Chronic lowering of groundwater levels* can be evaluated through analyzing aquifer heads output with the Head-Observation Process (HOB) or HydMod (HYD). (2) *Significant and unreasonable reduction in groundwater storage* can be evaluated by using MF-OWHM2’s detailed water-budget outputs or using standard post-processing tools, such as Zonebudget (Harbaugh, 1990), that analyze the Cell-By-Cell (CBC) flow output. (3) *Significant and unreasonable seawater intrusion* can be evaluated with the Seawater Intrusion (SWI) Process (Bakker and others, 2013) using an equivalent freshwater head boundary condition or addressed indirectly by linking MF-OWHM2 to a mass transport simulation model. (4) *Significant and unreasonable degraded water quality* cannot be directly simulated in MF-OWHM2; however, using MF-OWHM2 with the Link-MT3DMS (LMT) Package can generate flow input for MT3DMS (Zheng and Wang, 1999), and MT3DMS-USGS (Bedekar and others, 2016) can be used to determine water-quality changes in groundwater and surface water. (5) *Significant and unreasonable land subsidence* can be evaluated with the Subsidence and Aquifer-System Compaction (SUB) Package (Hoffmann and others, 2003) or Subsidence for Water Table Aquifers (SWT) Package (Leake

and Galloway, 2007). (6) *Reduction in surface-water flow* is part of understanding conjunctive use and can be determined using water budgets from the Stream Flow Routing (SFR) Package (Prudic and others, 2004) or the Surface-Water Routing (SWR) Process (Hughes and others, 2012).

The first release of MF-OWHM (Hanson and others, 2014d) was selected by the World Bank Water Resource Software Review as one of three recommended simulation programs for “integrated surface and ground water simulations required for conjunctive management” (Borden and others, 2016). MF-OWHM incorporated and built on the features and source code of MODFLOW-2005 (Harbaugh, 2005), MODFLOW-FMP2 (Schmid and Hanson, 2009a), MODFLOW-NWT (Niswonger and others, 2011), MODFLOW-SWR (Hughes and others, 2012), MODFLOW-SWI (Bakker and others, 2013), and MODFLOW-LGR version 2 (Mehl and Hill, 2005, 2013) and included the Riparian Evapotranspiration (RIP-ET) package (Maddock and others, 2012). Visual development of MF-OWHM simulation models is possible through the USGS graphical user interface ModelMuse (Winston, 2009, 2014). MF-OWHM is also used as the primary simulation engine for FREEWAT, a European Union sponsored open-source water-management software environment and geographic information system (GIS) user interface (Rossetto and others, 2015; De Filippis and others, 2017).

The capabilities incorporated in MF-OWHM2 have been designed to maintain backward compatibility with the assimilated MODFLOW versions. Any existing model that runs with MODFLOW-2005 should run with MF-OWHM and MF-OWHM2 with little to no modification. There are two exceptions to this. The first is that the variants descended from MODFLOW-2005 automatically set the last input variable on a line to zero if it was not present. For example, if an input file contained a line expected have three integers (layer, row, column) and there were only two integers on the line, then MODFLOW would automatically set the third integer to zero (that is, column is equal to 0). In contrast, MF-OWHM2 raises an error stating that a required input variable is missing, and the user must include it for the simulation to continue. The second exception is that the default input for MODFLOW-2005 is fixed formatted, which required the Basic (BAS) package keyword, **FREE**, to use free formatted input. In practice it is not common, nor is it recommended, for any of the MODFLOW versions to use the fixed formatted input. Consequently, MF-OWHM2 reads all input with free format by default. MF-OWHM2 still accepts the BAS keyword **FREE**, but also offers the keyword **NOFREE** to use fix formatted input for legacy models.

MF-OWHM2 includes a conduit-flow process for karst aquifers and leaky pipe networks; a variety of improvements to all the MODFLOW packages, including head-dependent conductance for GHB cells; a new Well Package (WEL); and a complete redevelopment of the FMP. It also includes additional features to facilitate easier model updates, faster execution, better runtime-error messages and reporting, a new Warning package (WARN), and more cross-communication between the traditional MODFLOW packages.

MF-OWHM2 also includes a new “self-updating” structure. The self-updating aspect refers to conversion of the MODFLOW input-file structure to one that separates the spatial and structural input from the temporal input; for example, well location is separate from its pumping rate. This allows the input-file structure to be easier to read and modify by the model developers, users, and reviewers; thus, the temporal files are easier to use and update. This separation also was implemented to allow automated programs to query databases, websites, or spreadsheets for new data to update the input files (for example, streamflows or specified pumping rates). This automation, or self-updating, of the input files allows a simulation model to more readily be used after its initial construction, thus increasing the longevity and value of the simulation model.

To facilitate easy maintenance of models, three new types of input files were introduced. The first an alternate input-file type, called LineFeed (appendix 2) is now available for the WEL, GHB, and MNW2 packages. LineFeed separates a package’s spatial and construction information from its temporal information. This allows the user to predefine all the static model properties once and have a separate file of the transient stress-period properties that is easy to maintain. The

second type of input file is called a TabFile (time-tabulated input). TabFiles have been linked to an ExpressionParser to allow the tabulated values to be passed to a user-defined function (appendix 2). This function requires fewer TabFiles to describe a set of model features; for example, sea-level data can be applied to a user-defined equation that translates it to a freshwater equivalent boundary condition across an ocean boundary. Similar to TabFiles, the third new type of input file, called a Time-Series File (TSF), is introduced. The TSF is tied to calendar dates and offers more options to specify the handling of the time-series data (for example, interpolate, nearest value, time-weighted mean, or step function) than are available in TabFiles.

A new set of input and output utilities (appendix 1) offer a more general and user-friendly input structure called the List-Array Input (LAI). This input structure allows for keyword-based input that supports two-dimensional array input and record-based list inputs, including advanced scale-factor options. The LAI can either load input once or load data by stress period using the *Transient File Reader* (TFR), which is a pointer file that directs how the input is loaded every stress period. Additional new input and output file utilities, called *Generic_Input* and *Generic_Output*, provide standard methods of opening and handling input and output files, respectively. The *Generic_Input* is used by the Universal Loader utility (ULOAD) to read any style of input file. ULOAD also is used by LAI to provide a generic input-format framework. In MF-OWHM2, LAI is only available to the FMP and SWO. *Generic_Input* and *Generic_Output* files are used by the new input and output options for multiple packages.

The traditional input structure for MODFLOW-2005 was based on model-dependent coordinates—row, column, layer, and simulated time. Although this was convenient for coding purposes, simulation outputs required translation to real-world coordinates (that is, geographical and date-time coordinates). MF-OWHM2 includes the optional specification of a Cartesian coordinate system that is linked to the model-grid and calendar-date systems. This option lets the user specify a model feature—for example, WEL or GHB—by X, Y, and Z coordinates. If an initial calendar date is specified, then it is propagated forward with each time step, considering leap and non-leap years. For example, for an FMP supply well—Farm Well—the user can specify a starting and ending date to represent when it is available to supply irrigation water. In addition, when a starting calendar date is specified, the volumetric budget, hydraulic head observation package (HOB), and the FMP include the calendar date in the output. The HydMod package (HYD) now only uses the MF-OWHM2 Cartesian coordinate system to spatially position each time-series output for a point (XL and YL) in the model domain. If the MF-OWHM2 Cartesian coordinate system is not specified, then the origin of the model domain is automatically set to the lower-left corner—which is the HydMod coordinate system used in MF-OWHM.

MF-OWHM2 includes a set of new features that facilitate parameter estimation. The Basic Package (BAS) offers an option that cycles through the input files to check, before parameter estimation, if they loaded correctly. Also, the “FastForward” feature allows the input files to be cycled through to a specified starting stress period, which allows parameter estimation for a specified simulation window without having to rebuild an entirely new input dataset.

A variety of new features improve users’ control over simulation outputs. To reduce excessive writing to a hard drive, writing the CBC flow file can be turned off, all output files can be optionally buffered in RAM, and writing the Listing File (LIST) is optional (total suppression). Packages can use sub-budget groups for improved tracking and reporting of the volumetric budget. The HOB package allows head observations to be written at the end of each time step using null values for observations yet to be simulated.

MF-OWHM2 Package and Process Support

This section presents short descriptions of the packages and processes supported in MF-OWHM2 (table 1). Please check the Online Guide to MODFLOW-OWHM version 2 (<https://ca.water.usgs.gov/modeling-software/one-water-hydrologic-model/users-manual/>) for any other packages supported after the release of this report. The packages and processes have been grouped according to a common functionality. The following are the groups specified in table 1:

- Parameter
 - ▶ Packages associated with a MODFLOW Parameter Process. Parameter values, once loaded, can alter the properties of another package (for example, rescaling the hydraulic conductivity in a flow package).
- Flow Package
 - ▶ Packages that specify the aquifer flow properties. For example, hydraulic conductivity and specific storage.
 - ▶ Only one flow package may be used during a MF-OWHM simulation.
- Flow Modification
 - ▶ Packages that modify the flow package; they are not required for a simulation.
- Land Use
 - ▶ Farm Process related group.
- Karst/Pipe Flow
 - ▶ Conduit Flow Process related group.
- Transport
 - ▶ Group represents the package that produces the flow-link binary input file to MT3DMS (Zheng and Wang, 1999) and MT3DMS-USGS (Bedekar and others, 2016) for transport simulation.
- Fixed Boundary
 - ▶ Packages that represent constant hydraulic head or constant flux
 - ▶ The CHD package is not recommended for conjunctive use because of the lack of head-dependence.
- Head-Dependent Boundary
 - ▶ Packages that calculate boundary flows based on hydraulic head.
 - ▶ GHB is the most commonly used boundary condition. (Note that most head-dependent packages are variations of GHB.)
 - ▶ For a conjunctive-use simulation, the drain return-flow package (DRT) is recommended instead of the drain (DRN) package. The DRN package always removes water from the simulation domain, whereas the DRT package has the option to return runoff to the landscape or groundwater.
 - ▶ Caution is advised when simulating evapotranspiration using FMP, RIP, evapotranspiration (EVT), and evapotranspiration segments (ETS). Only one should be used in each model cell because they all simulate evapotranspiration, and there no internal check for double-accounting evapotranspiration.
- Subsidence
 - ▶ Packages that simulate interbed storage and aquifer compaction.
 - ▶ Only one Subsidence package may be used in a simulation.
- Surface Flow
 - ▶ Packages that simulate surface-water flow and storage.
 - ▶ Caution is advised when using the river package (RIV) for integrated or conjunctive-use simulations because it is more like GHB (Head-Dependent Boundary) than surface-water flow.
- Groundwater Well
 - ▶ Packages that represent groundwater well functionality through either extraction or injection.
 - ▶ Note that the WEL package is technically a Fixed Boundary package, but it is designed to represent groundwater pumping or injection. Models can use the WEL package to represent boundary recharge or inflow.
- Observation
 - ▶ Packages that support other packages by writing output in a convenient form for post-processing or calibration.

10 One-Water Hydrologic Flow Model: A MODFLOW Based Conjunctive-Use Simulation Software

- Solver
 - ▶ Packages that solve the groundwater flow equation.
 - ▶ Only one solver may be used during a simulation.
- HUF Extension
 - ▶ Specialized packages that only function when the HUF flow package is in use.

Table 1. MODFLOW One-Water Hydrologic Flow Model version 2 (MF-OWHM2) supported packages and processes grouped by common functionalities.

[LGR, Local Grid Refinement; MT3DMS, Modular Three-Dimensional Multispecies Transport Model Dimensional Multispecies Transport Mode; MT3D-USGS, U.S. Geological Survey update to MT3DMS; 1D, One-dimensional; 2D, Two-dimensional; —, not applicable]

Package	Package or process name	Short description
NAM	Name file that lists all packages in use	Not a package, but loaded at start of simulation to declare packages and processes used by user's model application.
LIST	Listing file	Contains transcript of package output, warnings, and errors.
WARN	Warning file	Contains a transcript of package warnings and errors that are raised and written to the listing file.
BAS	Basic	Defines global options, active model cells, and initial head.
DIS	Discretization	Specifies model time and space discretization.
OC	Output control	Specifies writing of output to list and cell-by-cell flow file.
Parameter		
ZONE	Zone file	Parameter process—specify parameter zones of application.
MULT	Multiplier file	Parameter process—specify parameter multiplication arrays.
PVAL	Parameter value file	Parameter process—specify global parameters.
Flow package		
BCF	Block-centered flow	Defines aquifer flow properties.
LPF	Layer-property flow	Defines aquifer flow properties.
UPW	Upstream weighting	Defines aquifer flow properties.
HUF	Hydrogeologic-unit flow	Defines aquifer flow properties.
Flow modification		
HFB	Horizontal flow barrier	Barriers to flow between model cells (for example, faultline or slurry walls).
UZF	Unsaturated-zone flow	Vertical flow of water through the unsaturated zone to water table.
SWI	Seawater intrusion	Vertically integrated, variable-density groundwater flow and seawater intrusion in coastal multi-aquifer systems.
Land use		
FMP	Farm Process	Dynamic simulation of land use, evapotranspiration, surface-water diversions, and estimation of unknown pumpage.
Karst/pipe flow		
CFP	Conduit Flow Process	Simulation of turbulent flow through karst conduits or pipe networks.
Transport		
LMT	Link-MT3DMS	Produces a binary flow file that is used for MT3DMS and MT3D-USGS for transport simulation.
Fixed Boundary		
BFH	Boundary flow and head	LGR child model only—couples parent model's flows and heads to child model.
CHD	Time-variant specified-head	Specifies model cells that have a constant head (not recommended for conjunctive use).
FHB	Flow and head boundary	Specifies model cells that have a constant head or constant flux in or out.
RCH	Recharge	Specified flux distributed over the top of the model domain.

Table 1. MODFLOW One-Water Hydrologic Flow Model version 2 (MF-OWHM2) supported packages and processes grouped by common functionalities.—Continued

[LGR, Local Grid Refinement; MT3DMS, Modular Three-Dimensional Multispecies Transport Model Dimensional Multispecies Transport Mode; MT3D-USGS, U.S. Geological Survey update to MT3DMS; 1D, One-dimensional; 2D, Two-dimensional; —, not applicable]

Package	Package or process name	Short description
Head-dependent boundary		
GHB	General head boundary	Simulates head-dependent flux boundaries.
DRN	Drain	Simulates head-dependent flux boundaries that remove water from domain if head is above a specified elevation.
DRT	Drain return	Simulates head-dependent flux boundaries that move water from model cell if head is above a specified elevation.
RIP	Riparian evapotranspiration	Simulates evapotranspiration separately for multiple plant functional groups in a single model cell.
EVT	Evapotranspiration	Simulate a head-dependent flux out of the model distributed over the top of the model domain.
ETS	Evapotranspiration segments	Simulates evapotranspiration with a user-defined relation between evapotranspiration rate and hydraulic head.
RES	Reservoir	Simulates leakage between a reservoir and the underlying groundwater.
Subsidence		
IBS	Interbed-storage	Simulates compaction of low-permeability interbeds within layers (legacy code—recommended to use SUB instead) (not recommended for conjunctive use).
SUB	Subsidence and aquifer-system compaction	Simulates drainage; changes in groundwater storage; and compaction of aquifers, interbeds, and confining units that constitute an aquifer system.
SWT	Subsidence for water table aquifers	Simulates compaction for changes in water table by including geostatic stresses as a function of water-table elevation.
Surface flow		
RIV	River	Simulates head-dependent flux boundaries by specifying a river stage (not recommended for conjunctive use).
LAK	Lake	Simulates lake storage and flow.
STR	Stream	Flow in a stream is routed instantaneously to downstream streams (legacy code—recommended to use SFR instead).
SFR	Streamflow-routing	Simulates streamflow either by instantaneously routing to downstream streams and lakes or routed using a kinematic wave equation.
SWR	Surface-Water Routing Process	Simulates surface-water routing in 1D and 2D surface-water features and surface-water and groundwater interactions.
Groundwater well		
WEL	Well (Version 2)	Specified flux to model cells in units; revised TABFILE input.
WEL1	Well (Version 1)	Specified flux to model cells in units; original TABFILE input.
MNW1	Multi-node, drawdown-limited well	Simulates wells that extend to more than one cell (legacy code—recommended to use MNW2 instead).
MNW2	Multi-node well	Simulates “long” wells that are connected to more than one model cell; calculates well head and well potential production.
Observation		
MNWI	Multi-node well information	Provides detailed output from MNW2 wells.
HYD	HydMod	Provides time series of observations from SFR, SUB, and Head.
GAGE	Stream gaging (monitoring) station	Provides output for specified SFR segments and LAK lakes.
HOB	Head-observation	Specifies observations of head in aquifer.
DROB	Drain (DRN) observation	Specifies observations of DRN related flows.
DRTOB	Drain Return (DRT) observation	Specifies observations of DRT related flows.
GBOB	GHB observation	Specifies observations of GHB related flows.

Table 1. MODFLOW One-Water Hydrologic Flow Model version 2 (MF-OWHM2) supported packages and processes grouped by common functionalities.—Continued

[LGR, Local Grid Refinement; MT3DMS, Modular Three-Dimensional Multispecies Transport Model Dimensional Multispecies Transport Mode; MT3D-USGS, U.S. Geological Survey update to MT3DMS; 1D, One-dimensional; 2D, Two-dimensional; —, not applicable]

Package	Package or process name	Short description
Observation—Continued		
CHOB	CHD observation	Specifies observations of CHD related flows.
RVOB	RIV observation	Specifies observations of RIV related flows.
Solver		
NWT	Newton-Raphson groundwater formulation	Solves groundwater-flow equation with Newton-Raphson method; requires UPW or LPF as flow package.
PCG	Preconditioned conjugate-gradient	Primary MODFLOW-2005 solver.
PCGN	PCG solver with improved nonlinear control	Solver with advanced dampening and relaxation for highly nonlinear groundwater models.
GMG	Geometric multigrid solver	Geometric multigrid preconditioner to conjugate gradient solver.
DE4	Direct solution solver	Use Gaussian elimination solver for the groundwater-flow equation.
SIP	Strongly implicit procedure	Legacy code—recommended to use PCG or PCGN.
HUF extension		
KDEP	Hydraulic-conductivity depth-dependence	HUF extension that allows for the automatic calculation of depth-dependent horizontal hydraulic conductivity.
LVDA	Variable-direction horizontal anisotropy	HUF extension that allows for the automatic variable-direction horizontal anisotropy.

Integrated Hydrologic Modeling

Simulation and mathematical representation of the hydrologic cycle often are based on the assumption that each process in the cycle is independent. The most common assumption is that groundwater flow is decoupled from surface-water flow, such that surface water is treated as a simple boundary condition for the groundwater system (for example, the river package, RIV). Similarly, some surface-water models treat groundwater inflow—called base flow—and outflow as a constant value. When it is important to understand the relationship between groundwater and surface water, such as for conjunctive-use management, the decoupling assumption breaks down.

The groups of physical systems represented in integrated hydrologic modeling (IHM) vary depending on the document describing the IHM. Typically, IHM involves the simulation of multiple hydrological processes across the hydrologic cycle. The term “integrated,” in the context of this report, refers to the tight coupling of groundwater flow, surface-water flow, landscape processes, subsidence and aquifer compaction, reservoir operations, and conduit or karst flow. To run MF-OWHM2, a groundwater flow package (LPF, UPW, HUF) must be specified; the rest of the integrated features are optional. For example, if there is neither subsidence nor conduit flow in an aquifer system, then there is no need to include them in the simulation.

The original MODFLOW-2005 had one flow process: groundwater flow. This necessitated that all packages in

MODFLOW-2005 communicated through the groundwater-flow equation as boundary conditions, such as specified hydraulic head or specified flows. This yielded what is called “head-dependent flow,” which is controlled by the hydraulic head in a model cell and in the cells adjacent to it. This approach prevented communication among packages and did not allow the transfer of water from one package to another, except through groundwater flow.

MODFLOW-FMP relaxed this requirement by allowing the transfer of water outside of the groundwater-flow process. MF-OWHM2 incorporated MODFLOW-FMP and extended this ability by allowing cross-communication among the other assimilated MODFLOW versions. The additional cross-communication introduced the potential for simulation capabilities associated with what is called “flow-dependent flow,” “consumption-dependent flow,” and “deformation-dependent flow” (Hanson and others, 2014d). Flow-dependent flows are calculated from flows that originated from other flow processes. For example, drain flow from the DRT package, which originated as a head-dependent flow, could move drained water to a SWR segment or SFR stream reach as a flow-dependent flow. Another example is surface-water runoff that originates from delivery losses from irrigation water. Consumption-dependent flows originate from the demand for water by irrigated and non-irrigated agriculture, natural vegetation, and urban water uses. The water demand is then satisfied by “flows” either from natural sources or from human sources. Examples of natural sources are root uptake from groundwater or precipitation that falls over the landscape.

Examples of human sources are groundwater pumping, surface water diverted for delivery, and reclaimed water. Deformation-dependent flows result from the vertical deformation associated with compaction of aquifer materials during subsidence. The user can configure the subsidence package (SUB) to adjust the simulation domain's vertical discretization in response to aquifer compaction. The change in vertical discretization alters the aquifer-flow properties (transmissivity and conductance terms). Lastly, the change in surface gradient and aquifer-flow properties may alter the surface-flow features (such as SFR streamflow).

Each of the previously described dependent flows can be interlinked. For example, surface-water diversions to meet irrigation requirements can decrease streamflow (consumption-dependent flow); conversely, irrigation surface runoff, which may include groundwater pumping, can increase streamflow (flow-dependent flow). Groundwater pumping could be characterized as a head-dependent flow (for example, MNW2 well) and might affect the groundwater hydraulic head. The associated change in head could cause subsidence, resulting in deformation of the vertical model grid; in turn, the change in slope of the deformed land surface could alter streamflow (deformation-dependent flow). In addition to being interlinked by their dependencies, flows can also be climate dependent. The climate dependence plays a dominant role because it typically affects major sources of water, specifically precipitation, and losses of water through evapotranspiration.

The subsections that follow provide an overview of the main processes represented in the MF-OWHM2 conceptual framework. The MF-OWHM2 framework builds upon the MODFLOW-2005 framework and incorporates the other processes and packages from other MODFLOW versions in one platform for the simulation of conjunctive use. MF-OWHM2 has incorporated major processes that can be selectively coupled to the fundamental groundwater-flow process combined with surface-water, landscape, reservoir, and conduit-flow processes. The MODFLOW framework defines a process as an operation that solves a major equation or set of equations (for example, groundwater flow, surface-water flow, on-farm water use), and a package is the part of the model addressing a single aspect of simulation (for example WEL, GHB). Overall, the suite of processes and potential couplings results in an integrated hydrologic modeling toolbox that allows the simulation of head-dependent flows and the associated boundary conditions, along with flow-dependent, consumption-dependent, and deformation-dependent flows.

The MF-OWHM2 simulation time frame is specified as a set of stress periods, which are composed of a set of time steps. A stress period is a length of time for which MF-OWHM2 simulates groundwater flow. At the start of each stress period, all model related stresses are specified and applied for the duration of the stress period. For example, at the start of each stress period, the WEL package declares all the wells in use for the stress period and their pumping rate.

The number of stress periods, and their associated length of time, determines the total simulation time frame. Typically, stress periods are in line with the months of the year; using the appropriate number of days for each month and take into account 29 days in February for a leap year. For example, a 3-month time frame in a non-leap year would have three stress periods of 31, 28, and 31 days, respectively, to represent January, February, and March. Within each stress period are a set of time steps that subdivide solving the MF-OWHM2 flow equations at a shorter interval of time. The concepts of the stress period and time step are a fundamental to MODFLOW; simplify the input to each stress period while solving the MODFLOW equations at shorter time length, the "time step." MF-OWHM2 does differ from MODFLOW in that some input can be specified at the time step level by using override keywords or defining input with TabFiles or Time-Series Files (TSF). Also, MF-OWHM2 does have packages that dynamically change at the time-step level based on user input at the stress-period level. For example, an FMP agricultural supply well's maximum pumping capacity is specified by stress period, but the actual pumping rate is determined every time step by agricultural demand. Another difference is that MF-OWHM2 allows for time-step lengths to be directly specified, rather than being a subdivision of a stress period. This modification was necessary to allow the user greater control over the time-step length and ensure that time steps are simulated using whole numbers, such as 5 days, instead of 3.1416 days.

Groundwater Flow

The fundamental component of head-dependent flow in MF-OWHM2 is the calculation of the groundwater flow through the main flow package. This package establishes the groundwater-flow equations for a given set of aquifer properties, which can then be modified by any additional packages. For a complete formulation of the MODFLOW-2005 groundwater-flow equation and how it is translated into a block-centered finite-difference scheme, please see Harbaugh (2005). This section provides a brief overview of hydraulic head and groundwater flow.

Hydraulic head, sometimes called piezometric head, total head or head, represents the mechanical energy per unit weight of fluid in the system, or simply is the potential for water flow through a porous media. Hydraulic head is measured as the elevation of freshwater above a datum that can be supported by the hydraulic pressure at a given point in a groundwater system. For consistency, head is typically referenced to a standard elevation datum, such as the North American Vertical Datum of 1988 (NAVD 88). Hydraulic head (Hemond and Fechner, 2015) is calculated as the sum of a pressure term ($P/\rho_{fw}g$), an elevation term (Z), and a kinetic energy term ($v^2/2g$):

$$h = \frac{P}{\rho_{fw} g} + Z + \frac{v^2}{2g} \quad (1)$$

where

- h is the hydraulic head for a given pressure (L),
- P is the gauge pressure measured at elevation Z (M/LT²),
- ρ_{fw} is the freshwater density (M/L³),
- Z is the elevation that the gauge pressure is measured at (L),
- v is the velocity of water at the referenced point (L/T), and
- g is the acceleration due to gravity (L/T²).

The pressure term in the context of MODFLOW assumes constant freshwater density and represents an equivalent gauge pressure at elevation Z within a column of fresh water. For a continuous, nonmoving body of water, the kinetic energy term can be assumed to be zero ($v = 0$). Because of the low flow rate of groundwater compared to the pressure and elevation terms, this simplifies equation 1:

$$h = \frac{P}{\rho_{fw} g} + Z \quad (2)$$

In MODFLOW, and consequently MF-OWHM, the change in hydraulic head across an aquifer determines where groundwater flows. Specifically, groundwater flows toward regions of the aquifer with a lower hydraulic head.

Groundwater flow in MODFLOW relies on the application of Darcy’s law to the conservation of mass (continuity) equation. Darcy’s law, originally formulated on the basis of empirical evidence by Henry Darcy (1856), can be derived from the Navier-Stokes equations (Whitaker, 1986). Darcy’s law is formally defined as follows:

$$q = -K \frac{\Delta h}{D} \quad (3)$$

where

- Δh is change in hydraulic head between two points (L),
- D is the distance between the two points (L),
- K is the hydraulic conductivity of the aquifer material along the distance D (L/T), and
- q is the specific discharge or Darcy flux (L/T).

The physical parameter of hydraulic conductivity, K, describes the resistance to flow in the porous medium that makes up the

groundwater system. Hydraulic conductivity is a function of the mean grain diameter, a shape constant of the soils called specific permeability, dynamic viscosity, and specific gravity (Willis and Yeh, 1987; Boyce, 2015).

The representation of hydraulic conductivity in a groundwater simulation model is hampered by the difficulty of direct measurements of K at scales applicable to regional hydrologic models. Hydraulic conductivity is a non-uniformly distributed property; direct measurements at the field scale do not capture all the spatial variability present at the larger scales; hence, uncertainty increases when extrapolating K to typical scales of a simulation domain. In addition, hydraulic conductivity stochastically varies in the subsurface. This stochastic variation can be described by the log-normal probability distribution (Freeze, 1975) or the gamma and log-gamma distributions (Loaiciga and others, 2006). Because of spatial variability in hydraulic conductivity, representative values in hydrologic models are often inferred by solving inverse problems, such as an aquifer test, or using optimization techniques, called parameter estimation. If hydraulic conductivity is treated as stochastic, then it can be solved with a Bayesian inverse problem (further discussion of this approach is beyond the scope of this report). For most situations, the estimated hydraulic conductivity is distributed over zones of model cells on the basis of available information and is calibrated to field observations.

In MODFLOW, groundwater flow between model cells is calculated using hydraulic properties, saturated thickness, and the associated hydraulic head. MODFLOW assumes that groundwater flow between model cells is primarily horizontal and laminar, which originates from a modified Dupuit-Forchheimer assumption. To account for vertical flow, MODFLOW specifies a vertical hydraulic conductivity and applies Darcy’s law in the vertical direction. This results in a full three-dimensional formulation of groundwater flow.

Because flow passes through each face of a model cell, it is advantageous to align the model grid in the primary direction of groundwater flow. This ensures that groundwater flow passes smoothly between model cells. This is illustrated in [figure 3](#), which has a model grid that is not aligned with the general groundwater flow and another grid that has been rotated to have the cell faces aligned with the general direction of groundwater flow.

The mathematical reason for aligning the model grid in the dominant-flow directions is that hydraulic conductivity (K) is a second-order, symmetric tensor (eq. 4). This tensor contains a set of off-diagonal terms (K_{xy} , K_{xz} , K_{yz}) that represent the rotational offset of the model grid (or model cell faces) from the principal directions of flow ([fig. 3A](#)).

$$K = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix} \quad (4)$$

where

- K_{xx} is hydraulic conductivity in the x-principal direction (L/T),
- K_{yy} is hydraulic conductivity in the y-principal direction (L/T),
- K_{zz} is hydraulic conductivity in the z-principal direction (L/T),
- K_{xy} is hydraulic conductivity in the x-principal direction due to the gradient in head in the y-direction (L/T),
- K_{xz} is hydraulic conductivity in the x-principal direction due to the gradient in head in the z-direction (L/T), and
- K_{yz} is hydraulic conductivity in the y-principal direction due to the gradient in head in the z-direction (L/T).

By aligning the model grid—that is, aligning the Cartesian principal axes (x, y, z) with the general flow directions—the off-diagonal terms approach zero. If the model grid is rotated so that the cell faces align with the principal directions of flow (fig. 3B), then mathematically, K changes to equation 5:

$$K = \begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix} \quad (5)$$

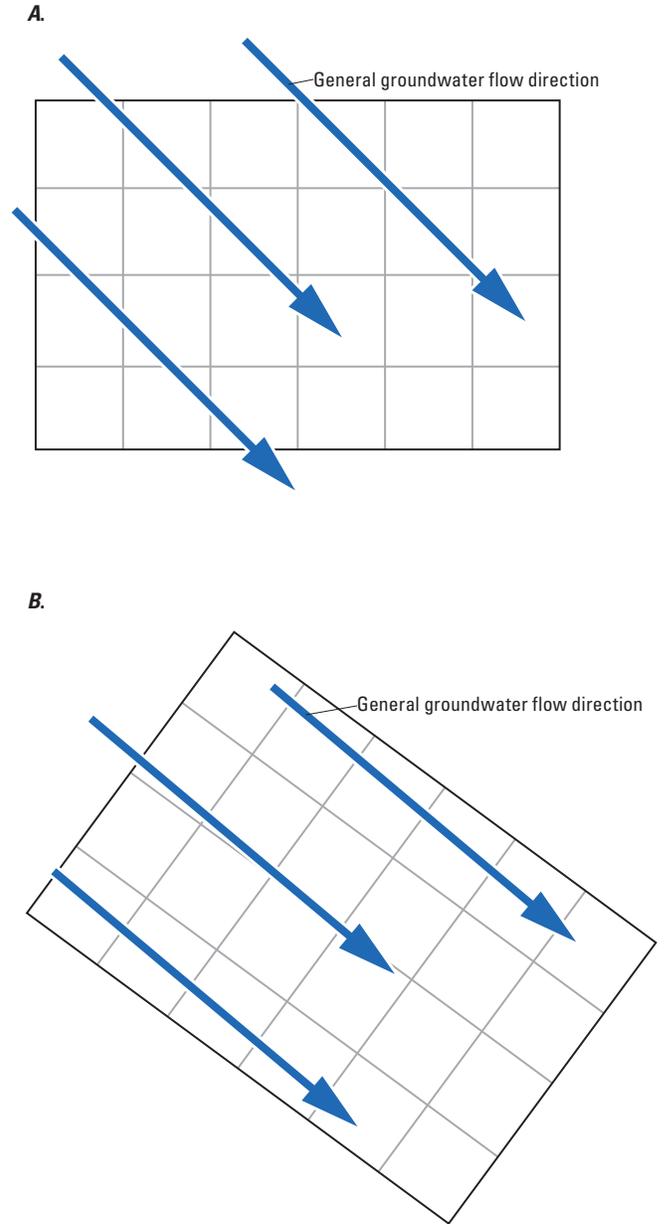


Figure 3. Example model grids that differ by orientation to groundwater-flow direction: *A*, not aligned with the general groundwater flow, and *B*, aligned with the general groundwater flow.

A single model cell is a representative elementary volume (REV) of a porous medium such as an aquifer, aquitard, or aquiclude. Model cells are grouped by model layer, and each layer is defined as confined or convertible. The difference between these two layer types is the way that aquifer properties are treated when the hydraulic head is less than the model cell's top elevation—specifically, how the model cell's saturated thickness is calculated. The saturated thickness is the vertical thickness of the model cell in which the pore spaces are filled (saturated) with water. Given that the cell's hydraulic head represents the saturated water level, if the head is at or above the top of a model cell, it is considered fully saturated and has a saturated thickness equal to the cell thickness. For a confined layer, the saturated thickness is independent of hydraulic head and always equal to the model cell's vertical thickness—that is, the model cell is always fully saturated. A convertible layer acts as a confined or unconfined aquifer. If the hydraulic head is above the model cell's top elevation, then the convertible cell functions identically to a confined cell—that is, the model cell is fully saturated. If the hydraulic head drops below the top of a convertible model cell, but is above the cell bottom, then the saturated thickness is equal to the head minus the elevation of the bottom of the cell (that is, vertical saturated distance within the cell). If the head drops below the model cell, then the cell becomes “dry” with zero saturated thickness and no longer contributes to groundwater flow. The confined or convertible designation of a model layer affects the flow properties that are dependent on transmissivity—which is equal to the hydraulic conductivity multiplied by the saturated thickness—and storativity—which is equal to the specific storage multiplied by the saturated thickness.

The storativity represents the volume of water released from storage per unit decline in hydraulic head in the model cell per unit area of the model cell. Confined layers require specifying a specific storage (S_s , sometimes called volumetric specific storage), which is the volume of water that a model cell releases from storage per volume of model cell per unit decline in hydraulic head. Specific storage represents water that can be removed from a model cell without changing the saturation—that is, the model cell remains fully saturated yet releases water.

Convertible layers require specifying a specific storage and specific yield (S_y). When a convertible layer is fully saturated, then specific storage is used as its storage property; if it becomes unsaturated, then specific yield is used. Specific yield is always substantially larger than specific storage. Specific yield represents the volume of water that can be drained by gravity from a fully saturated model cell relative to the volume of the model cell. For example, if the hydraulic head in a model cell changes from the cell's top elevation to the cell's bottom elevation, then the specific yield is the cell's gravity-drained volume of water divided by the volume of the model cell. Convertible layers can increase simulation runtime, so it is common to initially develop a model in

which all layers are defined as confined. For layers defined as confined that are known to always be partially saturated (that is, not fully saturated, unconfined conditions), then the specific yield can be approximated by specifying a specific storage equal to the specific yield divided by the cell thickness. This is a common modeling technique that takes advantage of the speed of the confined formulation but represents the unconfined storage response.

Groundwater flow in model layers designated as “confined” is solved using the confined, anisotropic, saturated groundwater-flow equation. This governing equation is developed by combining the continuity equation with Darcy's law, and it can be expressed by the following parabolic partial differential equation (Willis and Yeh, 1987; Boyce and Yeh, 2014):

$$\frac{\partial}{\partial t} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial t} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial t} \left(K_z \frac{\partial h}{\partial z} \right) \pm W = S_s \frac{\partial h}{\partial t} \quad (6)$$

where

- x, y, z are distances in the respective Cartesian coordinate directions (L);
- t is the time (T);
- h is the hydraulic head at locations x, y, and z (L);
- K_x, K_y, K_z is the hydraulic conductivity in the x, y, and z directions (L/T);
- W is a volumetric flux per unit volume in or out of the system (1/T); and
- S_s is the specific storage (1/T).

Groundwater flow in model layers designated as “convertible” is solved with the confined flow equation (eq. 6) or the unconfined flow equation (eq. 7), depending on whether the model cell is fully saturated. The confined flow equation is used when the hydraulic head is above the model cell's top (fully saturated), and the unconfined flow equation when the hydraulic head is below the model cell's top but above the cell's bottom (water table conditions, variable saturated thickness). Because unconfined flow has a variable saturated thickness, its governing saturated groundwater-flow equation requires a slight modification to its confined-flow counterpart. The key change is that the upper boundary condition is now a free surface, so it must be included in the governing equation by integrating across the z-direction using Leibniz's integral rule. This yields the following equation (Willis and Yeh, 1987; Boyce and others, 2015):

$$\frac{\partial}{\partial t} \left(K_x h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial t} \left(K_y h \frac{\partial h}{\partial y} \right) \pm W = S_y \frac{\partial h}{\partial t} \quad (7)$$

where

- S_y is the specific yield (-).

The way vertical flow is handled in MODFLOW between an unconfined model cell and a confined model cell depends on the flow package. Each of the packages use Darcy's law to calculate the flow in the vertical direction, but differ in how they calculate the distance, D , between the model cells. The two most commonly used flow packages are Layer Property Flow package (LPF, table 1) and Upstream Weighting (UPW, table 1). The LPF package varies the distance by the saturated thickness of the upper, unconfined cell; that is, vertical conductance varies with saturated thickness. The UPW package mimics confined, vertical flow by holding the distance constant; that is, vertical conductance remains constant. It is important to note that MF-OWHM2 allows using the Newton-Raphson Groundwater Formulation (NWT solver, table 1) with the LPF package. Because the NWT solver is designed to only work with UPW, if the NWT solver is selected, the LPF package input is translated to UPW, resulting in a constant vertical conductance for convertible layers despite using the LPF package—that is, LPF acts like UPW when the NWT solver is used. Conversely, the UPW package input is translated to LPF if a solver other than NWT is used.

A limitation of the MODFLOW-2005 framework is that water removed by a package is removed from the model domain rather than connected to another package or process. For example, the WEL package extracts by pumping water from groundwater storage, and that water is removed from the model domain. By contrast, in MF-OWHM2 the extracted water often is applied to the surface as irrigation, where it can become groundwater recharge, runoff to streams, or satisfy some of the potential evapotranspiration demand.

The groundwater flow equation in MODFLOW-2005 was advanced by including vertical, unsaturated flow in the unsaturated-zone flow package (UZF; Niswonger and others, 2006), which solves a one-dimensional approximation to the Richards equation using the method of characteristics for solving partial differential equations.

Improvements to these fundamental components and features of the basic MODFLOW-2005 groundwater-flow process and associated boundary-condition packages are summarized in the appendixes of MF-OWHM (Hanson and others, 2014d). New features that enhanced the MODFLOW-2005 flow process and its basic packages are documented in the section “Fundamental MODFLOW Enhancements” and the associated new input-data structures are summarized in appendixes 1, 2, and 3.

Seawater Boundary Representation— Equivalent Freshwater Head

Coastal groundwater basins with an ocean boundary generally contain a density related pressure difference between

seawater and freshwater. An ocean boundary can be simulated with the GHB Package by a boundary head (BHead) set to the equivalent freshwater head of the sea level. Because of additional dissolved solids, sea water has a higher density than freshwater. Consequently, seawater hydraulic head represents a larger pressure than freshwater hydraulic head. The difference in seawater density (and viscosity) also affects hydraulic conductivity (K) compared to freshwater, but it is assumed to be negligible.

Using the seawater pressure and density, equation 2 can be recast to represent the seawater hydraulic head (which is equal to the sea level):

$$h_{sw} = \frac{P_{sw}}{\rho_{sw}g} + Z \quad (8)$$

where

h_{sw}	is the seawater hydraulic head (L);
P_{sw}	is the gauge pressure, as a result of seawater, at elevation Z (M/LT^2);
ρ_{sw}	is the seawater density (M/L^3);
g	is the acceleration due to gravity (L/T^2); and
Z	is the elevation that the gauge pressure is measured at (L).

MODFLOW uses the change in freshwater hydraulic head in Darcy's law to determine groundwater flow. Because of this, an ocean boundary condition in MODFLOW requires the sea level (h_{sw}) be converted to an “equivalent freshwater head” (h_{fw}). To derive an equivalent freshwater head for seawater, MODFLOW recasts equation 8 in terms of seawater pressure (eq. 9):

$$P_{sw} = \rho_{sw}g(h_{sw} - Z) \quad (9)$$

The seawater pressure (eq. 9) is then substituted for pressure in the freshwater hydraulic head equation (eq. 2) to yield the following:

$$h_{fw} = \frac{P_{sw}}{\rho_{fw}g} + Z \quad (10)$$

$$h_{fw} = \frac{\rho_{sw}g(h_{sw} - Z)}{\rho_{fw}g} + Z \quad (11)$$

This is simplified to produce the equivalent freshwater head equation:

$$h_{fw} = \frac{\rho_{sw}}{\rho_{fw}} h_{sw} - \left(\frac{\rho_{sw} - \rho_{fw}}{\rho_{fw}} \right) Z \quad (12)$$

where

- h_{fw} is the seawater's equivalent freshwater hydraulic head at elevation Z (L),
- ρ_{sw} is the seawater density (M/L^3),
- ρ_{fw} is the freshwater density (M/L^3), and
- Z is the elevation point where the equivalent freshwater head is calculated (L).

To specify an ocean boundary condition with the GHB, the sea level is converted to an equivalent freshwater head at the model cell's center. The density of seawater is not constant and changes with depth, but is typically assumed to have an average value of $1,025 \text{ kg/m}^3$. Similarly, the density of freshwater is assumed to be $1,000 \text{ kg/m}^3$. An ocean boundary head can be determined using equation 12 and these two densities:

$$\text{BHead} = 1.025 \times h_{sw} - 0.025 \times Z_p \quad (13)$$

where

- BHead is the GHB ocean boundary head (L),
- h_{sw} is the ocean sea-level elevation (L), and
- Z_p is the elevation at the center of the model cell (L).

There are three methods to evaluate seawater intrusion using MF-OWHM2. The first is to assume purely advective seawater transport and use a freshwater equivalent for ocean boundary heads (eq. 11); the seawater intrusion flow pathways can then be determined using particle tracking with MODPATH (Pollock, 2016) or MODPATH-OBS (Hanson and others, 2013). The second method is to assume a sharp interface (no concentration mixing) between the seawater and freshwater flow and use the Seawater Intrusion (SWI) Process (Bakker and others, 2013) to simulate the location of the sharp interface. SWI requires that a GHB specify BHead as an equivalent freshwater head (eq. 11), but defines Z as the model cell's top elevation. The third option uses MF-OWHM2 with the Link-MT3DMS (LMT) Package to generate flow input for MT3DMS (Zheng and Wang, 1999) or MT3DMS-USGS (Bedekar and others, 2016) for a full seawater transport simulation.

Surface-Water Processes

Interactions between groundwater and surface water are common near surface-water bodies, such as streams, wetlands, and lakes, and also for irrigated landscapes. When groundwater elevations are below those of a surface-water system, surface water drains into the groundwater. When groundwater elevations are above those of a surface-water system, groundwater discharges to surface water. This coupling results in a unique set of dynamics between the groundwater and surface-water system that can be characterized through simulation. For example, groundwater pumping can lower the groundwater level enough that nearby streambed leakage reduces streamflow; conversely, recharge ponds can raise groundwater elevations, increasing streamflow. Surface-water flows can be controlled by an upstream reservoir, augmented by imported irrigation water, retained locally (for example, urban runoff basins and farm ponds), or exported for off-stream storage, which then could contribute to groundwater recharge, evaporative losses, or be released as local or transbasin-diverted streamflow. Simulation is a common approach for developing an understanding of these complex dynamics and associated temporal lags between stresses and responses.

In the MF-OWHM2 model, rainfall-runoff processes are considered in a conjunctive-use context. Surface-water flows are computed using the spatial and temporal distribution of precipitation, the excess irrigated water that becomes runoff, surface-water diversions and deliveries, subsurface drain flows, and groundwater discharge to the surface. Runoff is either directly delivered or prorated throughout a stream network, where it can be routed through stream channels and further interact with the groundwater system. Recharge that leaves the soil root zone either is passed to the Unsaturated-Zone Flow (UZF) package to become delayed recharge or is routed instantaneously to the water table (or uppermost simulated model cell).

Streamflow routing is represented as a head-dependent-flow boundary condition in MODFLOW; two packages are available to offer a range of routing options. These packages account for flows in channels, elevation of water in the streams (that is, stream stage), and two-way interactions between streams and groundwater. The greatest difference between these two packages is the manner in which each computes the stream stage. The SFR package (Niswonger and others, 2006) assumes the slope of the water surface is equal to the surface of the streambed (that is, kinematic assumption), whereas the SWR (Hughes and others, 2012) does not make this assumption. The simplifying assumption in the SFR provides a robust and computationally efficient representation of streamflow for most applications, but for complex systems where the kinematic assumption is invalid—such as tidal areas or otherwise inundated channels—the SWR package is more suitable.

Conceptually, the method of computing flow between streams and aquifers in SFR and SWR is the same as that used for the standard river package (RIV; McDonald and Harbaugh, 1988, chapter 6), but it is important to note that the RIV package is not recommended for a conjunctive-use simulation. Flow between streams and aquifers in the groundwater model is computed using Darcy's law and assuming uniform flow between a stream and aquifer over a given section of stream and corresponding volume of aquifer. This flow is computed as follows:

$$Q_L = \frac{K_{sb}wL}{m}(h_s - h_a) \quad (14)$$

where

- Q_L is a volumetric flow between a given section of stream and volume of aquifer (L^3/T),
- K_{sb} is the hydraulic conductivity of streambed sediments (L/T),
- w is a representative width of stream (L),
- L is the length of stream corresponding to a volume of aquifer (L),
- m is the thickness of the streambed deposits (L),
- h_s is the stream head computed as the stream depth plus elevation of streambed (L), and
- h_a is the aquifer hydraulic head beneath the streambed (L).

In this formulation, transient leakage across the streambed could change depending both on the stream head and on the aquifer head that is calculated during each time step. The volume of water that seeps from a stream is calculated by multiplying the infiltration rate by the wetted area of the stream. The wetted area of the stream may be held constant or determined on the basis of stream cross-sectional dimensions, discharge, and stage. The relation between stage and discharge is calculated using Manning's equation. The SFR and SWR packages have both been previously described for MF-OWHM (Hanson and others, 2014d); new and updated features in MF-OWHM2 are summarized in appendixes 1, 2, and 3.

Landscape Processes

Landscape processes in MF-OWHM2 involve the simulation of consumption, use, and unchannelized flow of water across the land surface and vertically from the bottom of the root zone of plants—or soil zone—to the top of agricultural or natural vegetation. The development of landscape processes was an important change from the traditional MODFLOW approach, in that processes such as evapotranspiration (ET) and other demands for water from various sources were driven by the estimation of the consumption, movement, and even reuse of water across the landscape. This was initially implemented through the FMP

(Schmid, 2004; Schmid and others, 2006; Schmid and Hanson, 2009a; Hanson and others, 2014d). The features of FMP and their connection with other features and processes broadened the couplings between landscape processes and related groundwater and surface-water processes. The fundamental advance contributing to the FMP was the capability to incorporate “flow-dependent” flows, whereby packages and processes can pass flows from one model feature to another on the basis of estimated or specified water demands and supplies. This also facilitated simulation of water management in a demand-driven and supply-constrained context throughout the entire model framework (Hanson and others, 2010; Hanson and Schmid, 2013). An overview of the core concepts for the landscape simulation in the FMP is provided in appendix 4 (“Consumptive Use and Evapotranspiration in the Farm Process”) and appendix 5 (“Landscape and Root-Zone Processes”).

Landscape modeling improves the understanding of landscape, groundwater, and surface-water interactions. The Landscape process couples irrigation-water losses, precipitation, imported water, and evapotranspiration to groundwater flow and surface-water flow. The Landscape process simulates surface-water diversions and estimates the unknown pumpage to meet irrigation demands, infiltration to groundwater, and runoff return to surface water. In cases where groundwater is shallow enough for crop-root uptake, the Landscape process accounts for this source, thereby reducing the demand for diverted surface water and groundwater pumping. Lastly, surface water is coupled indirectly to receive deep groundwater, representing runoff of irrigation water extracted from deep groundwater wells. Incorporating landscape processes provides understanding of the feedback and interrelations between the land surface, groundwater, and surface-water flows.

Land Subsidence

The process of aquifer-system compaction, and associated land subsidence, can have important effects on the surface-water and groundwater systems. Representing these processes in simulations can help to avoid misleading results. Land subsidence is an often-overlooked hazard and an environmental consequence of ground-water withdrawal (Hoffmann and others, 2003; Galloway and others, 1999). The arid and semi-arid regions that contain compressible, unconsolidated basin-fill deposits are especially vulnerable to subsidence because of a reliance on groundwater in dry climates with limited surface-water supplies. Coastal regions may also be at risk if they are underlain by unconsolidated, compressible coastal plain and shallow-marine sediments (Hoffmann and others, 2003). Land subsidence can result in environmental consequences that include damage to engineered structures, such as buildings, roadways, pipelines, aqueducts, sewerages, and groundwater well casings; earth fissures; increased coastal and riverine flooding; and loss of saltwater- and freshwater-marsh ecosystems.

With respect to the groundwater system, inelastic aquifer compaction yields a one-time, but often substantial, source of water. Simulation of the compaction process ensures that this contribution from groundwater storage is calculated appropriately; simulation of the same system without accounting for water released by compaction would result in the incorrect estimation of elastic storage properties. For example, without simulation of aquifer compaction, the water released from inelastic compaction would result in an overestimation of the aquifer-storage properties (specific storage and specific yield). Simulation of subsidence in MF-OWHM2 is limited to one-dimensional, vertical compaction. For MF-OWHM2 simulation, compaction refers to the change in vertical thickness that accompanies changing stresses on the aquifer system.

MF-OWHM2 has two packages, SUB and SUB-WT packages (Hoffmann and others, 2003; Leake and Galloway, 2007) that simulate aquifer compaction and subsidence. A limitation is that only one subsidence package may be used during a simulation. MF-OWHM2 SUB also includes the improvements that enable separate accounting of elastic and inelastic subsidence (Schmid and others, 2009), parameterization of selected subsidence parameters (Hanson and others, 2014d) and the option to simulate deformation-dependent flows using the SUB-link feature (Hanson and others, 2014d; Schmid and others, 2014). The SUB-link feature allows dynamic modification of the vertical model discretization in response to aquifer compaction and expansion, and it correspondingly adjusts any packages affected by land-surface elevation change or aquifer thickness. For example, the SUB-link alters the elevation of the stream beds in SWR, which can change the streamflow rate or reverse the flow direction.

Reservoir Operations

Reservoir operations represent human influence on natural river systems through retention and release of surface water for multiple downstream purposes. Storage reservoirs provide a buffer during dry periods, enabling release of water for irrigation, domestic consumption, other uses, and for environmental flows. Reservoir operations typically are based on a set of rules associated with downstream water uses and other considerations, including flood protection, environmental flows for fish passage or habitat maintenance, stream and reservoir habitats and recreation, and hydro-electric power production. At the time of this publication, MF-OWHM2 does not simulate reservoir power production directly (Ferguson and others, 2016).

The altered flow regime that results from reservoir operations influences the timing of interactions among surface water, groundwater, and the landscape. For example, if a reservoir releases water to meet irrigation demand during a

period when insufficient flow in a river is typical, then some of the released water can infiltrate to groundwater during transit to the irrigation point.

Recent work on methods for incorporating reservoir operations in the MODFLOW framework involved linking MODSIM software (Labadie and Larson, 2007) with MODFLOW-NWT to simulate reservoir operations using the SFR package (Morway and others, 2016). An iterative linking between the two simulators allowed MODSIM to adjust releases to groundwater and flow conditions simulated by MODFLOW-NWT. Iterative, in this case, refers to the adjustments of MODSIM and MODFLOW at every model solver iteration (called the outer iteration).

The ability to dynamically simulate reservoir operations directly in MODFLOW, such that operations are tightly coupled to streamflow gains and losses and downstream demand, has become increasingly important to reservoir managers. This led to joint development by the USGS and Reclamation of the Surface-Water Operations Process (Ferguson and Llewellyn, 2015; Ferguson and others, 2016). The Ferguson and others (2016) Surface-Water Operations Process simulated single-reservoir system operations that efficiently released water to meet downstream irrigation demand; this demand was either user specified or calculated by the FMP dynamically.

Conduit Flow

The Conduit Flow Process (CFP) simulates dual-porosity aquifers that can be mathematically approximated by coupling the traditional groundwater-flow equation with a discrete network of cylindrical pipes (CFPM1) or inserting a preferential-flow layer (CFPM2) that uses a hydraulic conductivity based on turbulent flow to simulate turbulent horizontal-flow conditions. The pipes can represent dissolution features or fractures and can be fully saturated or partially saturated under laminar or turbulent conditions. The preferential-flow layers may represent (1) a porous media through which flow is turbulent flow or (2) horizontal preferential-flow zones in an aquifer for which the explicit geometry of the secondary porosity is not well defined. The CFP simulates steady-state and transient hydraulics of the dual-porosity system (Shoemaker and others, 2008).

The CFP was initially developed as an individual variant of MODFLOW (MODFLOW-CFP; Shoemaker and others, 2008) to address the issues of preferential flow in karst aquifers; however, the coupling with the groundwater-flow process was limited. The concepts behind the new upgrades to CFP are summarized in appendix 7 (“Conduit Flow Process Updates and Upgrades”); the associated new input data structures are summarized in appendix 8 (“Conduit Flow Process Input Data”).

Optional Use of Separate Rainfall–Runoff and Hydraulic Models

It can be advantageous to develop, along with a MF-OWHM2 model, companion models that use other simulation approaches. Such companion models may be valuable for providing boundary conditions, improving the understanding of areas beyond the MF-OWHM2 domain, or providing calibration targets (such as streamflows in areas that are unaged).

The domain of MF-OWHM2 models typically represents aquifer systems in valley settings; thus, the domain boundaries are often near the foothills of a mountain range. A rainfall–runoff model that includes the MF-OWHM2 domain and extends into the upland watersheds can provide estimates of boundary inflow from the upland watersheds to the MF-OWHM2 simulation domain. In such a case, runoff from the rainfall–runoff model is applied as a boundary inflow to the MF-OWHM2 model at the stream reaches that intersect the model boundary. The intersection at which flows are passed from the upland watershed model to the MF-OWHM2 model is called a “pour point” and is typically where SFR intersects the model-domain boundary. The SFR, or other packages or processes, then simulates the streamflow in the MF-OWHM2 model domain.

A rainfall–runoff model may also provide potential or reference evapotranspiration estimates (ET_{ref}) and supply streamflows as calibration targets in regions of the MF-OWHM2 model where measurements are sparse (that is, unaged streams). If ET_{ref} is available, then it can be used as part of the FMP input to provide a more accurate calculation of actual evapotranspiration. Because the temporal resolution of rainfall–runoff models (hourly to daily) is finer than that of a MF-OWHM2 model (typically more than a day), the detailed streamflow in unaged regions of the model can be aggregated and used as a calibration target. Conversely, the MF-OWHM2 model can provide better estimates of baseflow to the rainfall–runoff model. This may be particularly important if the rainfall–runoff model is used for sediment transport and flood prediction.

Companion rainfall–runoff models that have been developed along with MF-OWHM2 models are the Basin Characterization Model (BCM; Flint and others, 2013; Flint and Flint, 2014), Hydrologic Simulation Program—Fortran (HSPF; Donigian and others, 1995; Bicknell and others, 2001), and the Precipitation-Runoff Modeling System (PRMS; Markstrom and others, 2015). The BCM simulates the interactions of climate (rainfall and temperature) with empirically measured landscape attributes, including topography, soils, and the underlying geology. It is a grid-based model that calculates the water balance in a given watershed. Some BCM-simulated datasets are publicly available for download (https://www.usgs.gov/centers/ca-water/science/basin-characterization-model-bcm?qt-science_center_objects=0#qt-science_center_objects). The HSPF simulates watershed-hydrology and water-quality processes on pervious and impervious land

surfaces and in streams and well-mixed impoundments. The U.S. Environmental Protection Agency (EPA) maintains HSPF and a variety of databases at its Basins webpage (U.S. Environmental Protection Agency, 2019, <https://www.epa.gov/ceam/basins-framework-and-features>). The PRMS is a deterministic, distributed-parameter modeling system that simulates streamflow and general watershed hydrology in response to climate and land use. USGS maintains this model and access to associated datasets at the Modeling of Watershed Systems (MoWS) webpage (U.S. Geological Survey, 2019, https://wwwbrr.cr.usgs.gov/projects/SW_MoWS/index.html).

Where MF-OWHM2 is applied to simulation of regions that require detailed river hydraulics beyond the capabilities of SFR and SWR, the use of an independent river hydraulics simulator could prove beneficial. MF-OWHM2 can, in turn, provide an accurate base-flow estimate for the hydraulic simulator, or a more formal two-way coupling can be developed. Examples of hydraulic flow software include the Sedimentation and River Hydraulics—Two-Dimensional model (SRH-2D; Lai, 2008, 2010) and Hydrologic Engineering Center, River Analysis System (HEC-RAS; U.S. Army Corps of Engineers, 2016). The SRH-2D is a two-dimensional hydraulic, sediment, temperature, and vegetation model for river systems. It is capable of simulating flows involving in-stream structures, bends, perched rivers, side-channel and agricultural returns, and braided-channel systems. Similarly, the HEC-RAS can simulate a network of channels, a dendritic system, or a single river reach.

Supply and Demand Framework

One of the core goals of MF-OWHM2 is representing water supply, management, and use in a demand-driven and supply-constrained framework. Water supply can include surface water, groundwater, precipitation, imported water (non-routed deliveries), reclaimed water, or a combination of these and other sources, such as desalinated water. Water demands can originate from irrigation needs; managed aquifer-recharge operations; environmental needs; water-supply needs for domestic, municipal, and industrial uses; power production; and other uses.

The demand-driven and supply-constrained framework provides a physically based context for simulating water management. The physical constraints of supply, such as maximum-capacity surface-water flows or groundwater elevations and well-production capacity, are combined with management constraints, such as allocations, water rights, and administrative pumpage restrictions. Similarly, drivers of demand define the amount of water needed, such as irrigation efficiency, soil and water salinity, and how the landscape is used. The demand-driven and supply-constrained framework allows for the dynamic simulation of the landscape demands that can be satisfied with supplies from precipitation, surface water, groundwater, and imported water.

The dynamic representation of management constraints is important for scenario analyses involving changes in climate and associated climate variability; land use; socioeconomic conditions; governance; and management actions. The dynamic representation of demand and supply necessitates that demand be estimated as part of the simulation. Previous simulation practices required pre-calculating demand externally from the simulation model (the so-called “spreadsheet method”) and then specifying those demands directly as surface-water diversions and groundwater pumping. Spreadsheet methods directly specify surface-water diversions and groundwater pumping, resulting in a loss of the dynamic response that real, managed systems have. These methods are unable to dynamically change surface-water diversions and groundwater pumping in response to changes in land usage, current groundwater and surface-water conditions, climate variability, reservoir operations, and availability of external water sources.

The ability to dynamically represent management constraints in an integrated hydrologic model is a unique feature of MF-OWHM2 that makes it well suited for analysis and planning of conjunctive-use systems. FMP, attempts to satisfy the demand with available water sources. Water sources (the supply) include natural sources (precipitation and groundwater uptake) as well as supplies of groundwater pumpage, surface water, imported and reused waters. The supply can be constrained by physical infrastructure (such as well- or diversion-capacities), and management constraints (such as allotments or water rights).

Local landscape demands are estimated by defining accounting regions in the model domain that are called a water-balance subregion (WBS). The WBS was originally called a Farm in the first release of the FMP, so the term WBS and “Farm” are used interchangeably in this report. For example, the number of WBSs are defined by the keyword **NWBS** or **NFARM**. For a given WBS, its total demand is balanced with the available water supplies. One or more types of native vegetation, natural vegetation, or agricultural crops can be simulated as a landscape type referred to as a “Crop.” A Crop can represent any land-use type for which consumptive use of water can be represented as the sum of evaporation and transpiration of any combination of groundwater uptake, precipitation, and irrigation (appendix 4 and 5). Crops generally have additional demands associated with runoff or infiltration of irrigation water (that is, the additional irrigation requirement resulting from inefficient irrigation practices). For this report, the term consumptive use (CU) is defined as the total water consumed by a land-use type (a defined “Crop”), including natural and anthropogenic sources. When CU is in reference to vegetation or agricultural crops, then it is synonymous with actual evapotranspiration. Additional irrigation water applied to meet the CU demand, needed

because of inefficiencies in land management and irrigation methods in an area, is part of the farm delivery requirement.

The name “Farm” is potentially misleading because a WBS does not necessarily refer to a specific agricultural farm, nor does a “Crop” strictly represent an agricultural crop. A WBS represents a region that has a common set of supply and demand calculations applied. This region does not have to be contiguous and can be defined for any surface model cell in the model grid (that is, it is not required to have active groundwater cells beneath it). A WBS can range from a municipality, to a large collection of agricultural fields, to a ranch within a single model cell—anything that has common sources of water supply. During a simulation, each WBS aggregates its associated surface model cells to compute a collective water demand that is then satisfied by common sources of water supply. These sources of water do not have to be in the WBS. For example, an MNW2 well that serves a WBS can be anywhere in the active simulation domain.

A Crop may represent any type of native or natural, agricultural, urban, industrial, or other land use that consumes water. Crops may also represent solely evaporative land-uses, such as a water body, rock quarries, or dairy farm (a dairy farm would use evaporation losses to represent general consumption from care of the herd, such as drinking and washing of cows). Another use for Crops is to represent a wastewater-treatment plant, which would have a specified water-delivery requirement, zero consumptive use (no evapotranspiration), and all delivered water that is discharged to a river set to become runoff.

Water-Balance Subregions

The design of the water-balance subregion (WBS) for a valley or project region is an important consideration for the analysis of conjunctive-use issues. [Figure 4](#) indicates that the questions to be addressed (step 1) and extent of the analysis region (step 2) guide the division of the region into WBSs (step 3a) on the basis of conjunctive-use issues and the present and future framework of supply. A WBS can represent virtually any type of water use (or uses) for any specified area; however, in order to serve the broader understanding of conjunctive use, it is recommended that WBSs are defined by areas that have consistent water supplies and uses ([fig. 4](#), steps 3b, c). The WBSs can also represent areas that have consistent local elements of policy, governance, or treaties ([fig. 4](#), step 3). To achieve this, the design of WBSs benefits from consultation with local water purveyors or governing bodies that administer or control surface water, groundwater, or water-dependent features such as riparian habitat. The delineation of WBSs is also linked to the design of the land-use categories to be used to represent demand in each WBS ([fig. 4](#), step 4).

Example Problem Design

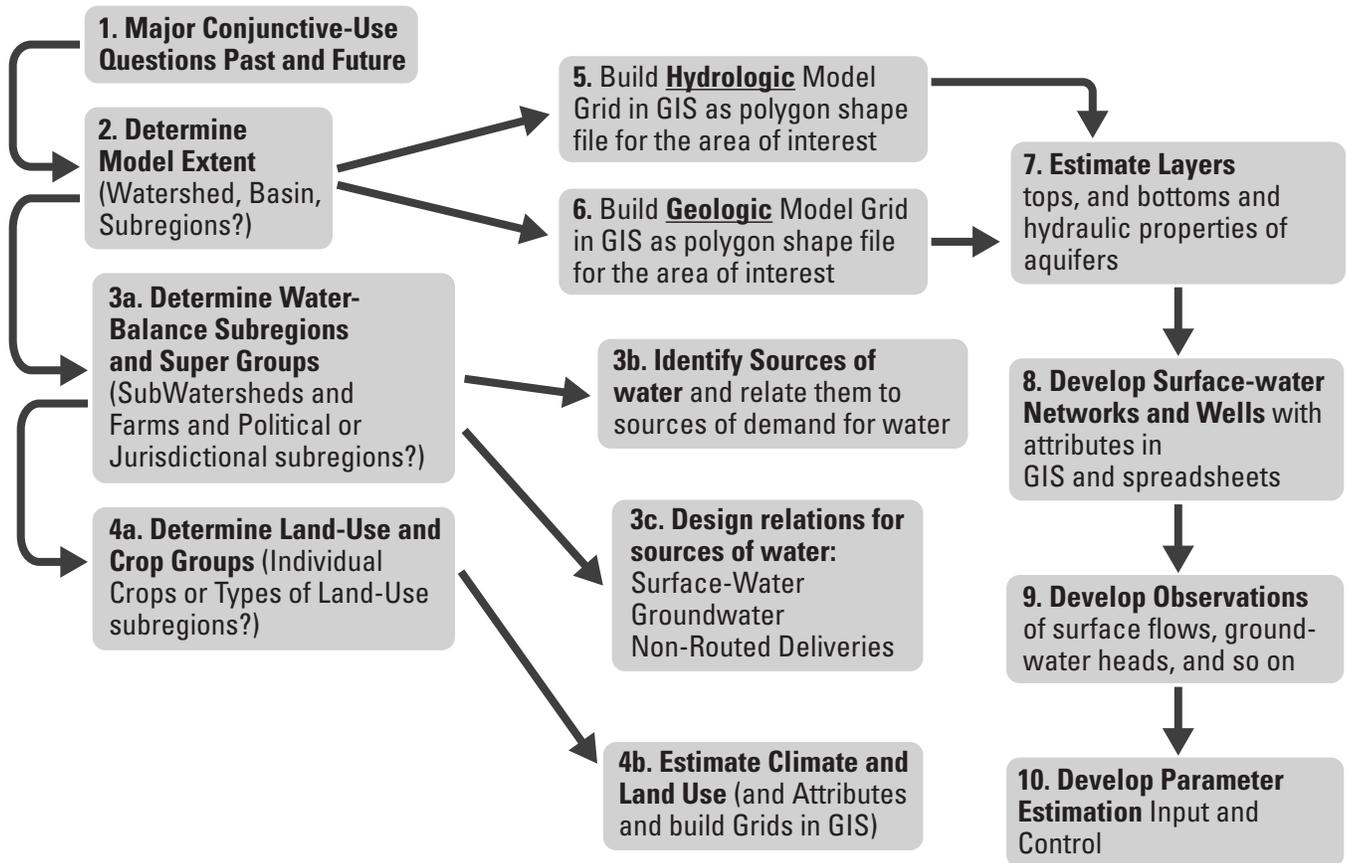


Figure 4. Example of the steps in a workflow process for developing a conjunctive-use model design.

A WBS can represent an individual spatial location (a single model cell) or a multi-cell area where water is consumed or intermittently stored from a common or shared supply or from any potential combination of water sources. Spatially contiguous and non-contiguous multi-cell subregions can be represented by WBSs. Examples of this were included in the USGS Central Valley (of California) Hydrologic Model (CVHM), in which the WBSs represent state-delineated depletion accounting units (DAUs) that each receive one or more surface-water diversions (Faunt, 2009; Faunt and others, 2009; Hanson and others, 2012). Similarly, WBSs can be grouped to represent all areas and beneficiaries that receive water from a common supply, such as a reservoir or groundwater basin. An example of this is an application of the FMP and SFR to the Rincon and Mesilla Valleys in southern New Mexico and western Texas, which includes parts of the federal Rio Grande Project (Hanson and others, 2019). Water supplies and demands for each irrigation district and for the Rio Grande Project as a whole were analyzed by aggregating fine-scale WBSs representing areas of the water-delivery service area. Alternatively, a WBS can represent a mixture of

parts of irrigation districts, municipalities, and subwatersheds, as was done for California applications in Pajaro Valley (Hanson and others, 2014a) and Borrego Springs (Faunt and others, 2015). The WBS can also represent individual locations where managed aquifer-recharge operations or supplemental or blended-groundwater wells are augmenting supply and demand; this was done for Pajaro Valley, California (Hanson and others, 2014a). A WBS can be oriented toward specific native, natural, or agricultural vegetation types as completely discontinuous sets of cells heterogeneously distributed across a region.

Finally, WBS subregions can change through time as administrative boundaries, land ownership, land use, and water-related infrastructure change and induce corresponding changes in water demands, water rights, and well and diversion locations. This can require adjusting the extent and shape of WBSs through the course of a model simulation. For example, for the simulation of the Cuyama Valley in California (CVIHM), it was necessary to represent the transition from about a dozen large ranches and native lands parcels in the 1940s to more than 80 smaller parcels by 2010 (Hanson and

others, 2014c). The change in the size and number of WBSs can be represented in several ways, including using results of land-use or economic models, known changes in land ownership or zoning, or projections of land use into the future. The latter method was applied to the Sonoma Valley (Andrew Rich, Sonoma County Water Agency, written commun., 2015) to assess the potential expansion of agricultural lands.

Ultimately, for purposes of jurisdiction, decision making, or physical infrastructure, groups of WBSs may be combined into larger subregions, or super groups of WBSs, that facilitate analyses appropriate to such scales. This allows the analyses of water demand and use scenarios for developing best management practices, sustainability, or adaptation plans. Examples of combining local-scale WBSs in large, regional-scale groups include applications for California's Central Valley, Pajaro Valley, and Cuyama Valley.

Land-Use Types

A fundamental function of FMP is the calculation of consumptive use for each type of land use. For MF-OWHM2, potential consumptive use (potential CU) is defined as the amount of water from any source needed to meet a land use's (or Crop's) water demand as evaporation and transpiration. It is synonymous with a crop's potential evapotranspiration (PET), and consumption can range from solely transpiration (potential transpiration) to only evaporation (potential evaporation). If a land use has access to irrigation, then after the consumption from natural sources (groundwater-root uptake and precipitation), any remaining CU is satisfied with the available irrigation water. Appendix 4 provides a detailed explanation of the consumptive-use calculations.

As described previously, the term "land use" in this report is synonymous with the word "Crop" and may represent different kinds of consumptive uses on the landscape. The term "Crop" can be used either to aggregate multiple crops into one group of similar properties or to split a crop type into multiple crops of differing properties. An example of aggregation would be to lump different sets of berries—such as blackberries, blueberries, and raspberries—together as one crop having a common set of properties. Crop classification is used to nest groups of input properties for a given land use. Crops typically have a common user-specified consumptive use or crop coefficient. Additional properties associated by Crop are whether it is irrigated, irrigation efficiency, fraction of delivery losses from irrigation and precipitation, and the ratio of a basal crop coefficient to crop coefficient. A Crop may also have a specified additional irrigation demand. The additional demand can be used to represent urban demand or additional irrigation for salinity flushing.

The geographic location and area that a Crop occupies affects its consumptive use because of the spatial variability in climate conditions, crop coefficients, and reference

evapotranspiration. A Crop may occupy an entire model cell and be specified as a two-dimensional array of Crop identities (IDs), or there can be multiple Crops in a single cell, the footprints of which can be specified as fractions of the model cell. The ability to simulate multiple Crops in a model cell provides a more accurate representation of the land use but has the additional computational expense of a more complex input dataset.

Virtual Crops can be used to represent a specific demand or non-plant-based consumption, such as urban demand, dairies, lumber mills, or rock quarries. Non-plant-based consumption requires that no root uptake of groundwater is included in the consumptive use—this is specified by setting the FMP keyword **GROUNDWATER_ROOT_INTERACTION** to 1 for the Virtual Crop. By removing groundwater-root uptake, the Virtual Crop's CU is only fulfilled by irrigation and precipitation. Typically, non-plant-based crops' CU are defined as either having solely transpiratory or only evaporative consumptive demand. Two examples of transpiratory Virtual Crops are irrigation demand for urban consumption or drinking water for a dairy. Examples of purely evaporative consuming Virtual Crops are rock quarries or animal agriculture, such as livestock feedlots, dairies, or poultry farms.

Any Crop may have a specified additional irrigation demand using the FMP keywords **ADDED_CROP_DEMAND** and **ADDED_DEMAND**. This additional irrigation water is not consumed by the crop, but instead becomes either runoff or deep percolation (infiltration). Additional irrigation demand requires that the Crop is irrigated with an irrigation type to incorporate the irrigation type's irrigation efficiency. The actual amount of additional irrigation water applied is equal to the specified additional irrigation demand divided by the irrigation efficiency. Additional irrigation could represent an urban demand that becomes discharge from a wastewater treatment plant—this is done by specifying that all of the additional irrigation water becomes runoff that flows to a stream network.

As described previously, the demand calculations are based on the location of the WBS and its associated land uses (Crops). The association between a WBS and Crop is made by collocation wherever the WBS locations are coincident with the Crop's location. The locations are ordered to proceed from demand to supply, however; that is, the demand for water is calculated by the Crop's location (given reference evapotranspiration, crop coefficient, precipitation, and groundwater levels). Each crop is designated as irrigated or not, and if irrigated, associated with an irrigation type. Crops that are irrigated rely on their coincident WBS to provide water to meet their deficit consumptive use (the irrigation demand after consumption of groundwater uptake and precipitation). This allows for a single Crop type to be reused across multiple WBSs.

To illustrate the relationship among a WBS, Crop, and irrigation, consider a model that has two surface cells, where Cell 1 is associated with WBS 1, Cell 2 is associated with WBS 2, and both cells contain Crop 1 that is irrigated. The potential consumptive use of Crop 1 in Cell 1 is satisfied by WBS 1 and that of Cell 2 is satisfied by WBS 2. The Crop first consumes the natural sources of water (groundwater and precipitation) in the cell. If the natural sources are less than the potential consumptive use, then the crop has an irrigation demand. If Crop 1 in Cell 1 has an irrigation demand, then WBS 1 uses its sources of irrigation water to attempt to meet the irrigation demand. Similarly, if Crop 1 in Cell 2 has an irrigation demand, then WBS 2 uses its sources of irrigation water to attempt to meet the irrigation demand.

Water-Balance Subregion Supply Wells— The Farm Well

The supply and demand framework includes water supplied from groundwater-extraction wells. For each WBS, the model attempts to fulfill the total aggregated demand by imported water, surface water, and groundwater uptake, in that order; any remaining demand is supplied by groundwater pumping. This is how an unknown pumping component is calculated as part of the FMP (appendixes 4 and 5). For simplicity, the groundwater-extraction wells are henceforth referred to as Farm Wells. Farm Wells either are defined in the FMP input or are linked to a well that is defined in the Multi-Node Well package, version 2 (MNW2). Farm Wells are associated with a WBS and have a specified maximum pumping capacity. The sum of maximum capacities for all Farm Wells serving a WBS represents the total potential pumping capacity that supplies groundwater to meet the WBS irrigation demand.

Farm Wells either can be represented as a direct-sink term to groundwater flow—as is the WEL package—or can be linked to MNW2 to more accurately represent the well’s construction and production potential. Farm Wells that mimic the WEL package extract or inject water at the FMP requested rate. This extraction rate can be curtailed if a saturated thickness smoothing function is applied. Smoothing decreases the pumping rate linearly as the head approaches the bottom of a model cell to represent the loss of production due to a cell going dry. This simulates the dewatering of the well and serves to minimize solution convergence issues associated with cells alternating between wet and dry. If a Farm Well is linked to MNW2, then the well’s location and construction are defined by the MNW2 input, and the MNW2 well’s maximum desired pumping rate (Q_{des}) is set by FMP (typically in response to demanded pumpage from a WBS). MNW2 determines the actual pumping rate on the basis of Q_{des} , the well construction and current aquifer conditions. If MNW2 cannot meet the FMP-specified Q_{des} to meet a WBS’s demand, then FMP

adjusts the WBS’s supplies accordingly. Specifically, if there is insufficient supply from a Farm Well, a WBS may shift its demanded pumping to another linked MNW2 well or direct-sink well or the WBS may end up in a deficit irrigation situation because of inadequate well production (water supply does not meet water demand). For more details about farm wells, see the “Supply Well (Farm Well) Redesign and Implementation” section.

Supply and Demand Hierarchy for Surface-Water Operations

When using the Surface-Water Operations Process (SWO; Ferguson and others, 2016), the concept of the water-balance subregion (WBS) is extended to a supply and demand hierarchy. This hierarchy, from highest to lowest, is composed of a Project, District, Unit, and Beneficiary, and a WBS is considered a type of Beneficiary.

A Beneficiary consists of an entity served by a surface-water delivery that is controlled by a set of surface-water operation rules to meet the entity’s water-consumption demand. That is, a Beneficiary is a water consumer that directly benefits from reservoir operations managing the surface-water delivery. Beneficiaries are nested in groups, called Units, that keep track of the water accounting. In particular, each Unit manages a diversion location that serves a group of Beneficiaries and keeps track of water consumption and bypassed flow. The Units are aggregated in groups, called Districts, that have a common water allocation to which the Unit water consumption is charged and, optionally, bypassed water is credited. Districts are aggregated in a water project that represents water storage from a single or set of reservoirs.

Figure 5 presents a conceptual example schematic of the supply and demand hierarchy. This example has a single reservoir that serves project water to three water districts. The reservoir releases water to a single main river channel that runs through the center of the figure. The first district served is District 1, which is on both sides of the main river channel. District 1 is composed of two units (Units 1 and 4), because the district is on both sides of the main river (each unit manages a diversion on either side of the main river). Within Units 1 and 4 are a set of Farmland beneficiaries that use the released project water for consumption. The second district, District 2, contains Unit 5, which manages the diversion that serves three beneficiaries (Municipal consumption, Farmland, and an Industrial Plant). Lastly, District 3 is composed of two units (Units 2 and 3). Unit 2 has the same main diversion location as Unit 1 from the main river system and receives water bypassed from Unit 1 to deliver water to two beneficiaries (Greenhouse and Farmland). Unit 3 from District 3 receives water from its own diversion, which delivers water to a single beneficiary (Farmland).

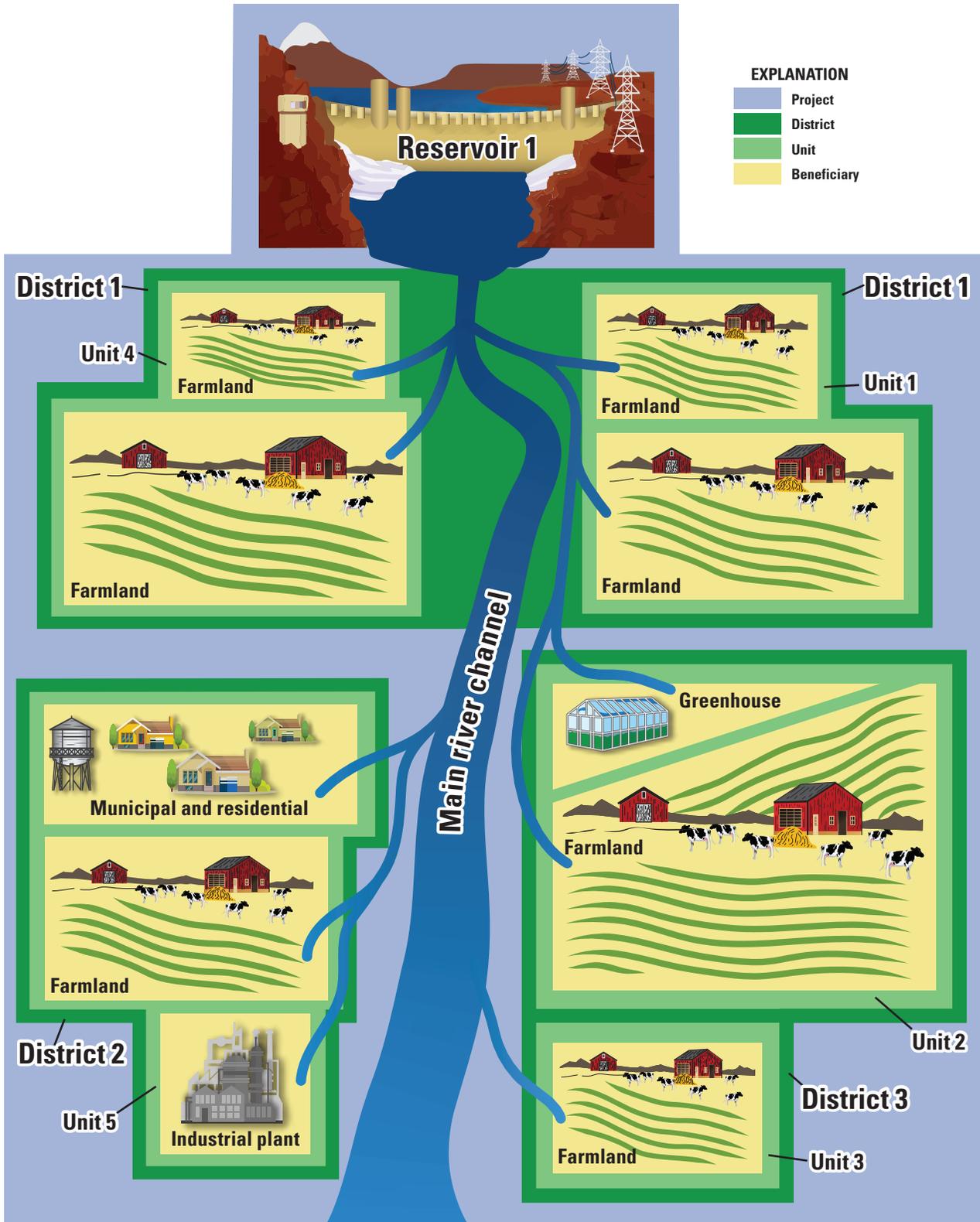


Figure 5. A conceptual example of the supply and demand hierarchy. The project area is served by a single reservoir that releases water to serve 3 districts, 5 units, and 10 beneficiaries (modified from Ferguson and others, 2016).

Self-Updating Model Structure

The MF-OWHM2 framework design implements the concept of “self-updating” models. The self-updating design refers to the conversion of the MODFLOW input-file structure to separates the spatial and structural input from the temporal input. This makes the input files clearer to the model developers, users, and reviewers; thus, the models are easier to use and update. This separation also allows automated programs to query databases, websites, or spreadsheets for new data to be downloaded and appended as updates to the model input files (for example, streamflows or specified pumping rates). This automated self-updating of the input files allows the simulation model to be re-used after its initial construction, thus increasing its potential longevity and value.

The construction of a self-updating model facilitates the use of data streams from land-based sensors and satellite-based imagery, which can provide estimates of properties that vary spatially and temporally. Examples of data streams that are temporally varying point measures are municipal pumping and gaged streamflow. Spatiotemporal varying examples are climate-related data (for example, temperature, precipitation, reference evapotranspiration) and sea-level gage extrapolation across an ocean boundary condition. Part of the MF-OWHM2 framework involved the progressive restructuring of the MODFLOW packages and processes—namely, SFR, FMP, GHB, DRT, MNW2, and WEL—to accommodate the variety of data streams as separate input files. This facilitates a more efficient transfer of these data streams into model input without having to restructure them.

Separation of Non-Spatial, Temporal Input (Point-Data Stream)

A point-based data stream is applied to a specific location or has its single value replicated to multiple points in space. Point-based data streams are applied to MF-OWHM2 using TabFiles, Time-Series Files (TSF), and LineFeed files. The fundamental difference in these types is that a LineFeed does not have a specific temporal component, but automatically loads the next input line for every stress period (or time step); conversely, TabFiles and TSFs contain a time stamp with the input data that determines when the data are applied.

The LineFeed input can load an arbitrary number of “FeedFiles” that structure the temporal input in a spreadsheet style. Each column of the FeedFile represents a data point, and each row represents one stress period (or time step) of data input. The columns can be separated by multiple blank spaces, multiple tabs, and single commas. The keyword “NaN” is used as a place holder for a missing point measurement (for example, an MNW2 well that has not been drilled or one that has been destroyed). The NaN value allows differentiation between stress periods in which a feature does not exist and

those in which the applied rate is equal to zero. For example, a zero-value specified for a well in the MNW2 package indicates intraborehole flow is possible, whereas a NaN means that the well does not exist during that stress period. The LineFeed input style is currently supported only for the SFR, WEL, GHB, and MNW2 packages. For the input structure details and package support of LineFeed, please see the “LineFeed—Alternative Temporal Input” section in appendix 2.

TabFiles (time-tabulated input) have been linked to an MF-OWHM2 ExpressionParser to allow their tabulated values to be passed to a user-defined function. A TabFile is a time-series-like text file that contains a date and associated datum point on each line that uses a simulation’s time-step date (or total simulation time) to set a model input property. By linking the TabFile result to the ExpressionParser, fewer text files are required to describe a set of model features. For example, a group of model cells that represent a GHB ocean boundary can be linked to a single TabFile composed of a time series from a sea-level gage, and use the ExpressionParser to translate the sea level to a freshwater equivalent for each ocean boundary GHB cell. As with TabFiles, a Time-Series File (TSF) has been introduced that is tied to calendar dates and offers more options to process the data (for example, interpolate, nearest value, time-weighted mean, step function). TabFiles are optimized for one file that is applied to many features (such as one TabFile linked to hundreds of GHB cells), whereas the Time-Series File is optimized for setting a property of a single feature (such as specifying a single SFR stream inflow or diversion). These new input structures facilitate integration into a self-updating structure of data streams, simulation, and analysis useful for evaluating changing water-resource management problems.

TabFiles and TSFs are similar in that both are single files that contain a time stamp and associated data input for each timestep. At the start of a simulation time step (not stress period) MF-OWHM2 uses the time step’s starting and ending dates to parse the appropriate input data from the TabFiles and TSF. TabFiles and TSF both support time stamps in the form of a decimal year or calendar dates (in International Standard Organization, ISO, or American style), and TabFiles also support the model simulated time (TOTIM).

TabFiles (described in appendix 2) are optimized for reuse across multiple model features—such as one TabFile applied to multiple wells—and can optionally pass the time-tabulated data point to a custom expression. Each model feature that the TabFile is linked to can have its own custom expression. For example, a single sea-level gage record can be used as a TabFile input that is applied to all model cells that represent the ocean boundary condition simulated with the GHB. The sea-level gage is then made unique to each model cell by including an expression that translates the sea level to its freshwater equivalent and incorporates the bathymetry of the location. Tabfiles’ data are parsed using the time interval from a time step’s starting and ending times.

The TSFs (described in appendix 2) are optimized for use by a single model feature, such as a TSF that specifies the inflow to a single SFR segment. As with TabFiles, the TSF uses the time step's starting and ending calendar dates to determine which input data are applied (note that it does not use the simulated time, TOTIM). Because a TSF uses a time step's starting and ending calendar date, its use requires that a starting calendar date is specified as a BAS package option (see appendix 3, **STARTDATE** keyword). In MF-OWHM2, the data in a TSF are processed on the basis of a time step's starting and ending calendar date and using either interpolation, averaging, or resampling (appendix 2). TSF files either contain a complete time record in which the current time step's calendar date window matches the appropriate data, or the TSF may specify a single annual time series that is parsed based on the day and month of the time step. The single annual time series is advantageous if there is a repeating annual input. As a TSF, this repeating annual input would only require specifying the month and day of the month, and the input automatically finds the appropriate part of the file on the basis of the time step's month and day.

Separation of Temporally Varying Spatial Input (Array or Raster Data Stream)

Separation of spatial data through time is most useful for compiling and managing input for features such as FMP that require large data streams of climate and land-use data. This is facilitated with the Transient File Reader (TFR, appendix 1 and 2), which is a pointer file that directs when and from where input is loaded. In a TFR input file, each uncommented row of text has a keyword that directs where to load input or to reuse previous input that is applied for the current stress period. The TFR allows the temporal input to be split among multiple files. This allows the specification of multiple arrays of climate or land-use attributes coincident with the stress-period intervals. For example, a set of monthly precipitation arrays can each be in a separate file that is loaded with the TFR for the appropriate stress period. This type of separation makes it easier to build and manage climate data for historical periods or for future climate change evaluations derived from downscaled Global Climate Model data. The TFR also supports multiple scale factors that provide flexibility to rescale the input data from simulation scenarios and model calibration. These scale factors also provide a method of altering raw input data without having to rebuild a package input. For details about the input structure of a TFR, see "Transient File Reader and Direct Data Files" in appendix 1. For input and calibration examples, see "Transient File Reader—Spatial-Temporal Input" in appendix 2.

Fundamental MODFLOW Improvements

MF-OWHM2 is based on MODFLOW-2005 and consequently can run any models developed for it. With each release of MF-OWHM2, the original MODFLOW base code is updated and improved. This section briefly introduces some of the updates, improvements, and new features of the MODFLOW part of MF-OWHM2. Although not specific to the MODFLOW-2005 packages, this section discusses how error messages have been altered to be more user friendly and how to interpret their meaning. The MODFLOW-2005 part includes notable code changes and improvements, which maintain backward compatibility, to the BAS, DIS, WEL, WEL1, MNW2, HydMod, and HOB packages; modifications and improvements to the rest of the MODFLOW base packages; additional spatial coordinate and temporal information; improved and advanced file operations, input and output (I/O) options, and budget features; and new clear and understandable warning and error message handling. Appendix 3 provides a detailed explanation of the new features for the MODFLOW-2005 part of MF-OWHM2.

Error Messages and How to Interpret Them

The MODFLOW base-read utilities (*U2DREL*, *U2DINT*, *UIDREL*, *URWORD*, and *ULSTRD*) were modified to provide user-friendly error information. Traditional MODFLOW errors would raise Fortran-style debug information that could be of limited value in determining the cause of the error. In MF-OWHM2, the error messages provide the user with clues to the reason the simulation stopped. Typical output includes the name of the input file that contains the error-producing input, the line of text that was processed, and the operation that was not executed (for example, failure to load a number or open a file). [Figure 6](#) shows an example of an error message for the GBH package where the expected input is three integers (model layer, row, column) and two floating point numbers (BHead, the boundary head, and Cond, the boundary conductance), but the last floating-point number—the boundary conductance—is missing.

This error is written to the command prompt, then the Listing file (LIST) file, and the WARN file. One important clue in the example ("FAILED TO CONVERT TEXT TO DOUBLE PRECISION NUMBER"; [fig. 6](#)) error message is that MF-OWHM2 was attempting to convert "#" to a number. If there was no number present and the end of the line was reached, then the message would convey failure attempting to convert " ", indicating that the number is missing. [Figure 7](#) shows an example error loading input that requires the user to specify a file to open and load data, but the path to the specified file is incorrect.

In rare situations, the user-friendly error messages are not able to identify the error, and Fortran debug information is written to the screen instead (fig. 8). MF-OWHM2 has been compiled so that the Fortran error debug messages provide the error type and the call stack to indicate where the problem is. The call stack is a list, which begins at the error, of Fortran routine names, source-code line numbers, and source-code file names. The call stack uses the word “Unknown” for routines that it cannot identify. In the call stack, the first source-code file name that is not written as “Unknown” is typically where the error is. Often the MF-OWHM2 package that raised the error is in the source-code file.

In figure 8, the first line indicates the error occurred while utilizing the file “D:\SFR_Input.sfr”. Ignoring rows with “Unknown”, the first readable Routine and Source are GWF2SFR7AR and gwf2sfr7_OWHM.f, respectively, which indicate that the error originated from SFR because the letters “sfr” are in the Source name. If the error cannot be determined from the SFR input, the number specified under “Line” represents the line number in the file gwf2sfr7_OWHM.f

where the error occurred. In the Fortran file around line 1194 (fig. 9), it can be discerned that the error is in the command `READ (In, *) ITMP, IRDFLG, IPTFLG` that has three input variables defined in the SFR manual (Niswonger and others, 2006). This indicates that the error must be caused by input file “D:\Model\input.sfr” while loading one or more of the input variables ITMP, IRDFLG, or IPTFLG. If this error cannot be determined from the previously described input variables, then the nearby code comments can help determine the source of the error. In Fortran, a comment begins with either an “!” or contains a letter in the first column (typically a C in the first column). For example, on line 1192, there is the following comment: “C14----READ SEGMENT INFORMATION FOR FIRST STRESS PERIOD.” that provides helpful information for identifying the error. The comment indicates that the subsequent code is designed to load the first stress-period segment input for SFR. This indicates that the error must have occurred at some point while loading the first stress period’s segment information.

```

                                ONE-WATER ERROR

                                THE FOLLOWING COMMENTS WERE PASSED TO THE ERROR ROUTINE

THIS ERROR IS BELIEVED TO HAVE ORIGINATED FROM WITHIN THE FOLLOWING FILE:
"D:\ExampleModel\GHB\GHB_Input.ghb"

THE GUESSED LINE THAT THE ERROR OCCURED ON IS:

"1  3  5   10.    # Layer Row Column Bhead  Cond"

THE DESRIPTION OF THE ERROR IS:

GET_NUMBER READ UTILITY ERROR: FAILED TO CONVERT TEXT TO DOUBLE PRECISION NUMBER.
THE FOLLOWING IS THE TEXT ATTEMPTED TO BE CONVERTED "#".

THE FOLLOWING IS AN ADDITIONAL COMMENT PASSED TO GET_NUMBER:

ULSTRDSTRUCT ERROR: FAILED TO LOAD FLOATING POINT NUMBER AFTER LAYER, ROW, COLUMN.
INPUT EXPECTS 2 FLOATING POINT NUMBERS AFTER LAYER, ROW, COLUMN,
BUT FAILED TO LOAD THE 2 FLOATING POINT NUMBER ON THE CURRENT INPUT LINE.

```

Figure 6. Example of a MF-OWHM2 error message for missing input in the general head boundary (GHB) package. In this example the input failed to supply the second floating point input (fifth input number of the line) and instead found a #, which is why the error message was raised.

```

FILE I/O ERROR:

FOR FILE UNIT 20

WHICH IS ASSOCIATED WITH FILE: D:\ExampleModel\FMP\FMP_Main.fmp

WHILE READING OR WRITING LINE
"SURFACE_ELEVATION  OPEN/CLOSE  ./ExampleModle/Land_Surface_Elevation.txt"

THE FOLLOWING IS AN ADDITIONAL COMMENT INCLUDED WITH ERROR:

FAILED TO OPEN FILE WITH GENERIC_INPUT_FILE_INTERFACE.

FOUND KEYWORD "OPEN/CLOSE",
BUT FAILED TO OPEN THE FOLLOWING FILE:

"./ExampleModle/Land_Surface_Elevation.txt"

PLEASE CHECK TO SEE IF THE PATH AND FILE NAME CORRECT.

***NOTE THAT THE "/" WORKS FOR BOTH WINDOWS AND LINUX,
    BUT THE "\" ONLY WORKS ON WINDOWS.

```

Figure 7. Example of error message for incorrect file path for input data specified by the user. This error is raised because the path to the file `./ExampleModle/Land_Surface_Elevation.txt` is invalid. This error results when the file does not exist or there is a mistake or spelling error in the directory path. In this example, the directory `ExampleModle` should have been spelled `ExampleModel`.

```
forrtl: severe (59): list-directed I/O syntax error, unit 4, file D:\SFR_Input.sfr
```

Image	PC	Routine	Line	Source
OneWater.exe	00007FF60FEABF87	Unknown	Unknown	Unknown
OneWater.exe	00007FF60FF06624	Unknown	Unknown	Unknown
OneWater.exe	00007FF60FF045A9	Unknown	Unknown	Unknown
OneWater.exe	00007FF60EAB3555	GWf2SFR7AR	1194	gwf2sfr7_OWHM.f
OneWater.exe	00007FF60F70C5FC	MAIN__	181	OWHM_Main.f90
KERNEL32.DLL	00007FFB80E71FE4	Unknown	Unknown	Unknown
ntdll.dll	00007FFB8132CB31	Unknown	Unknown	Unknown

Figure 8. Example of a crash of MF-OWHM2 that returns Fortran call stack information. In the call stack, the first source code line number (Line) and file name (Source) that is not written as “Unknown” is typically where the error is. In this example, the call stack indicates that the error is on line 1194 in the source file gwf2sfr7_OWHM.f.

```

1188
1189     CALL ERR%CHECK(HED='SFR FATAL ERRORS',
1190     +             INFILE=IN, OUTPUT=IOUT, KILL=TRUE)
1191 C
1192 C14-----READ SEGMENT INFORMATION FOR FIRST STRESS PERIOD.
1193     IF ( NSFRPAR.EQ.0 ) THEN
1194     READ (In, *) ITMP, IRDFLG, IPTFLG
1195     NP = 0
1196     nlst = NSS
1197     lb = 1
1198     ichk = 1
1199     CALL SGWF2SFR7RDSEG(nlst, lb, In, Iunitgwt, Iunituzf, NSEGCK,
1200     +             NSS, ichk, 1, Nsol)
1201     END IF

```

Figure 9. An example excerpt of Fortran code from gwf2sfr7_OWHM.f that includes the line numbers in gray. If there was a Fortran error that stated the error was on line number 1194, then it would indicate the error occurred while trying to load ITMP, IRDFLG, or IPTFLG.

Calendar Dates

MF-OWHM2 supports, for select packages, calendar dates both for input and for output. The input structure for calendar dates is very flexible, allowing for ISO 8601 format, American (United States) style structure, or a decimal year. If the year is specified, then it must be a four-digit Gregorian year, unless it represents a year before the 11th century.

The ISO 8601 format has the following input structures:

- yyyy-mm
- yyyy-mm-dd
- yyyy-mm-ddThh:MM:ss

The yyyy is the four-digit Gregorian year, mm is a two-digit month number, and dd is a two-digit day of the month. If the day (dd) is not specified, then it is automatically set to the first of the month (dd=1). The time separator T is used to initiate the start of the 24-hour clock time input, where hh is the hour in 24-hour format, MM is minutes, and SS is seconds. If the input only uses the calendar part (yyyy-mm-dd), then the assumed time is midnight (00:00:00). Note that the hyphen, -, is used as the delimiter between parts of the date for the ISO style. To use American date format, a forward slash is used instead, resulting in the following input formats:

- mm/yyyy
- mm/dd/yyyy
- mm/dd/yyyyThh:MM:ss

Several of the date-aware input structures allow for input of a month and day, but exclude the year. The input structure then automatically appends the year at a later time. Internally, the year is set to zero and then updated with the correct year when in use. Note that February 29th should be avoided in this input structure because it can become ambiguous by automatically becoming March 1st during non-leap years. The following are different methods of specifying a month and day, but not the year (note the use of a backslash is required if the month and day are specified as numbers):

- mm\dd
- mmm
- mmm-dd
- mmm/dd

The mmm represents either a three-letter representation of the month (for example, JAN) or the full month name (for example, January). If the day of the month is not specified, then it is automatically set to the first of the month. Note that the month-day input structure also supports a 24-hour clock if the T separator is present, but it is not recommended. If a starting calendar date is specified, then MF-OWHM2 keeps track of the date of each stress period and provides the

calendar date to the volumetric budget in the LIST file and for select package-output options. The following are examples of acceptable calendar date inputs:

- 1979-4-23
- 1979-4-23T16:20:01
- 4/23/1979
- 4/23/1979T16:20:01

Calendar date output is usually in the ISO 8601 standard format of yyyy-mm-ddThh:MM:ss, which some programs may not recognize. In particular, the spreadsheet program Microsoft Excel does not auto-recognize it as a date unless the letter T is removed. To fix this, “search and replace” the letter T with a blank space; Excel then auto-converts it to a date format.

Simulation Starting Date and Variable Time Steps

Two improvements to the temporal features of MF-OWHM2 are the ability to specify a starting calendar date and define custom time-step lengths. Defining a starting date is required when using inputs that only support calendar dates or decimal years, such as a TSF. Custom time-step lengths allow the user to predefine each time step’s length so that they can be aligned with observations or ensure that time-step lengths are in whole numbers (such as a 11-day stress period with time step lengths as 5 and 6, instead of 5.5 and 5.5).

Starting Date

In MF-OWHM, dates were included by specifying a starting decimal year using the DIS package keyword **STARTIME**. The problem with this input is that it assumed a 365.2425-day year and did not support common and leap years (365- and 366-day years, respectively). To overcome this limitation, calendar dates were introduced in MF-OWHM2. Calendar dates are initiated by specifying the keyword **STARTDATE** (appendix 3, BAS package options) followed by the starting calendar date of the model.

When **STARTDATE** is included, MF-OWHM2 uses the starting calendar date to keep track of every time step’s starting and ending calendar date and the corresponding decimal year. A decimal year in this case has its decimal part (the numbers to the right of the decimal point) representing the fraction of a 365-day or 366-day year, depending on if it is a common or leap year, respectively. For example, the calendar date April 23, 1979, equals decimal year 1979.306849, where 0.306849 represents $(113 - 1) / 365$, whereas April 23, 1980, equals decimal year 1980.308743, where 0.308743 represents $(114 - 1) / 366$.

If **STARTDATE** is specified, then MF-OWHM2 provides the calendar date to the volumetric budget in the LIST file and for select package-output options. In particular, when using the HOB package and specifying calendar dates, the HOB output file includes the decimal year and the calendar dates with each observation.

Specifying Time-Step Lengths

The DIS package was modified to allow the user to specify the exact time-step length. The time-step lengths are loaded on the same line as the stress-period information (PERLEN NSTP TSMULT SS/TR). This feature is initiated when the time step count (NSTP) is specified as a negative number and the multiplier is set to 1. The absolute value of the time step count represents the number of time-step lengths read to the right of the stress-period type (SS/TR), and the sum of the time-step lengths is the stress-period length (over-writes PERLEN). This allows the user to customize time-step lengths to match observation times or to create an acceleration factor that uses simpler-integer numbers (for example, 1, 2, 7, 10, 80 to accelerate to a total of 100 days). The compact numbering can be used to prevent simulation times with decimal parts by specifying time-step lengths to be whole numbers.

The capability for user-specified time-step lengths is particularly advantageous when the stress periods mimic calendar months and the month can be broken into different counts of days. For example, a month with 31 days can be represented by a stress period with four time steps with lengths defined as 7, 8, 8, and 8 days.

Improved Coordinate System

Previous MODFLOW simulation models did not provide a link between spatial coordinates and the model grid. This lack of explicit connection caused the user to rely on a separate GIS, graphical user interface (GUI), or comments in the input files to keep track of where spatially the model resided. This limitation was partially overcome with the release of MF-OWHM2 by allowing the user to specify a Cartesian coordinate system for the model grid.

In MF-OWHM2, the Cartesian coordinate system is connected to a new input format, called LineFeed (see appendix 2), that, for the GHB and WEL packages, accepts either the traditional layer, row, and column input or the Cartesian (X, Y, and Z) coordinates. If coordinates are specified, then MF-OWHM2 automatically determines the layer, row, and column in which the coordinate resides. The coordinate system is also connected to HydMod, such that the hydrograph location's point coordinates (XL and YL) use the specified coordinate system to determine the model row-and-column location of the hydrograph (note that if a coordinate system is not defined, then it defaults to the same coordinate system as HydMod).

Basic Packages Improvements

Modifications were made to most of the MODFLOW core packages to advance the supported input styles toward the self-updating concept, extend the features, and reduce simulation runtimes. One important improvement is that the BAS package has the new option, **INPUT_CHECK**. When this option is activated, MF-OWHM2 cycles through the simulation's input files—that is, the simulation is run, but without the solver, to check all input. Any problems with the input files result in MF-OWHM2 either crashing or recognizing erroneous input and writing a message to the LIST file. This option is especially useful to quickly check the input files for long-running simulations that could have an input error toward the end.

The WEL package source code was entirely rewritten to restructure the location of the TabFiles in the input file. The new WEL package also expands the optional smoothing of the pumping rate as the pumping cell goes dry by providing this option to all the solver packages (previously only available when using the NWT solver). The original WEL package remains, allowing the user to have two separate WEL packages during a simulation (declared as WEL for the new version and WEL1 for original).

An improvement to the GHB package provides the option to automatically build its boundary conductance (BCOND) from the hydraulic conductivity used by the flow package (LPF or UPW packages). This avoids having to specify BCOND as part of the input and allows the GHB to implicitly use the aquifer properties when determining boundary flow. The GHB package also can vary a GHB cell's BCOND with saturated thickness, which can be applied to the user specified BCOND or the flow package calculated version. Lastly, the inputs to PVAL, MULT, and ZON packages offer automatic counting of the number of parameters, multiplier arrays, and zone arrays, respectively, by setting their count variable to -1, and all these packages may include text comments anywhere, preceded by a “#” character.

File Operation Improvement

The file operations of MODFLOW can be challenging for new users, especially those without a background in Fortran programming languages. One of the limitations of Fortran 95, used for MODFLOW-2005, is requiring an identification number, called a unit number, to be assigned to all files opened by the program. Consequently, MODFLOW-2005 requires, as part of its NAME file input, a unit number that is assigned to each package-input file opened by it. Part of the MODFLOW base code was modified to make use of Fortran 2003 and 2008 features, which include automatic unit-number assignment. This modification allows the unit numbers in the MF-OWHM2 Name file (NAME file) to be optional for packages. If the NAME file only has the package name followed by a file

name, it auto-assigns a unit number that will not conflict with another. It is still required to use a unit number in the NAME file for the keywords DATA and DATA(BINARY) because the unit number is used for identification by other packages, such as the CBC number or input that uses the keyword EXTERNAL to load input (see appendixes 1 and 3 for more information).

A transcript of all operations is written to the Listing file in a MODFLOW and MF-OWHM2 simulation. This file is called LIST in the NAME file and was previously required to run a MODFLOW simulation. For large simulation models the LIST file can become very large. The large file size may affect hard-drive performance, slowing down the overall simulation runtime. This is particularly important during calibration, when multiple copies of the listing file can occupy a large amount of hard drive space. In MF-OWHM2, the LIST file is now optional. If LIST is not specified in the NAME file, then it is not used in the simulation. LIST suppression was included in MF-OWHM with the LSTLVL feature, but this feature has been removed from MF-OWHM2 now that the LIST file is optional.

The NAME file itself was modified to include a set of new optional keywords that alter how the file is opened and processed. To maintain backward compatibility, the keywords are specified to the right of the file name in the NAME file. Another useful option is the ability to buffer the files opened for input and output in random access memory (RAM; appendix 1). The buffered file is either preloaded in RAM if it is an input file or, for an output file, written to RAM until the buffer is full and then written to the hard drive. This is initiated by the keyword BUFFER, followed by the buffer size in kilobytes (KB). By default, all files in the MF-OWHM2 NAME file are opened with a buffer of 0 KB for the listing file, for immediate writing; 128 KB for all packages; and 32 KB for all files opened with DATA and DATA(BINARY). There are two limitations to buffering for output files. The first is that the file is not written until the buffer is full, causing results to be written in chunks equal to the buffer size, which delays the actual writing. This can be a problem if the user wants to view results during runtime. The second is that if there is a power interruption to the computer, then the information stored in the buffer is lost and never written to the file. For this reason, the LIST file has a default buffer of 0 KB, but if this is not an issue, it is recommended to have the LIST buffer set to 1024 KB to buffer the file in one-megabyte chunks.

For the LIST file and DATA and DATA(BINARY) files that are used for output, there is an option to split the file into a set of smaller files. This is done with the optional keyword SPLIT, followed by a split size in megabytes (MB). This is advantageous when output files become too large to be opened in a text editor. If a file is specified by including the keyword SPLIT and its file size exceeds the split size limit, a new file is created with the same name, but has a number appended to

the name to make it unique. This new file has the same header on the first line as the original file. The new file is used until the new file size exceeds the split limit; then, another file is created.

New Budget Features

MF-OWHM2 includes a set of new budget options for certain packages that allow the user to analyze and understand model results better or to make the connection to calibration software simpler. These modifications include the ability to define multiple budget groups and to write detailed budget information to a separate file. Traditional MODFLOW-2005 Volumetric Budgets and CBC file outputs only write the total flowrate in and out of the groundwater flow equations as simulated by each package. Lumping all the rates for an entire package does not allow the user to see how different parts of the package may interact with groundwater flow.

One common example of this problem is FMP linked MNW2 wells. In this case, FMP determines the desired pumping rate MNW2 wells should have, and MNW2 determines the actual pumping rate and includes this rate in its budget terms. To single out the FMP linked wells would require using the MNWI package and reconstructing its output information.

The new feature allows two budget groups to be defined for output in the MODFLOW Volumetric Budget from the CBC. Having two distinct groups in the CBC allows for programs such as the ZoneBudget post-processor (Harbaugh, 1990) to tabulate water budgets that represent each group. This feature is available for the MNW2, RIP-ET, WEL, GHB, DRN, DRT, and RIV packages.

MODFLOW-2005 simulations only write budget information to the LIST file (or WBGT file) if requested by the Output Control (OC) package. This led to two potential issues. The first is that the mass balance errors and cumulative mass balance errors were only calculated when the budget information is requested in the OC. This could result in underestimates of cumulative mass errors, because only the time steps specifically requested by the OC for a budget calculation are summed. The second issue is that time steps that reached convergence may have a large mass error that is unknown to the user. This occurs when the convergence criteria are not strict enough (specifically, the solver's HCLOSE and RCLOSE are too large). In MF-OWHM2, the BAS package was modified to always calculate the Volumetric Budget for every time step and raise a warning if the mass rate balance error ever exceeds 5 percent. The BAS package also includes an external output file that contains detailed budget information for every time step. The budget information is specified as a time-step number, calendar date, simulated time, time-step length, and then the rates of groundwater inflow and outflow for all packages in use during the specified time-step. The

format of this file is tabular (columns of rate values for each package and rows of time-step records), in which the first row contains a header and subsequent rows contain the data. This format can easily be loaded to a spreadsheet or database software for post-processing.

For the packages SFR, GHB and FMP, there is a new option similar to the column-based volumetric budget output, which prints properties specific to each package for each time step and includes a calendar date, the rate information, and head-dependent properties. For SFR, the output is identical to the file created by using the flag “`ISTCB2>0`” (the input keyword used in MODFLOW-2005), with the addition of two columns—the date and the streambed elevation at the start of the reach. The GHB package output provides the conductance used in the simulation, which in MF-OWHM2 can be a function of the water-table height or of the flow-package hydraulic conductivity. FMP has multiple output options that provide detailed information about Crops and Farm Wells. The Crop output provides detailed information for actual transpiration, actual evaporation, anoxia losses, fallowed-land evaporation, and, optionally, the crop root pressures. The Farm Wells output gives detailed information for demanded pumpage; final simulated pumpage; and the reason for reduced pumping capacity of wells, such as scale factors or seepage faces in MNW2 wells.

Warning Package (WARN)

MODFLOW-2005 writes all errors and warnings to the LIST file. Because of the length of the LIST file, it can be difficult to find important warnings that various packages might raise. The Warning Package is an optional output package that presents all package warnings in one location. To initiate the Warning Package, it must be declared in the NAME file by the keyword `WARN`, followed by a unit number, and the filename to which to write the warnings. If the warning package is used, then warnings are written to the LIST and WARN files.

Landscape Features— Farm Process (FMP)

In MF-OWHM2, the Farm Process, version 4 (FMP), has important upgrades that include modification to some of the structural relationships of selected features. The concepts and features that are the foundation for simulating the use and movement of water through the landscape by

FMP (Schmid, 2004; Schmid and others, 2006; Schmid and Hanson, 2009a; and Hanson and others, 2014d) are summarized in appendixes 4 and 5 (“Consumptive Use and Evapotranspiration in the Farm Process” and “Landscape and Root-Zone Processes”). Upgrades to FMP improve simulation runtimes, simplify the input structure, remove features that are seldom used, add features that represent newly modeled relationships between selected features, and make the addition of other features easier to incorporate. The following sections briefly summarize the newly added concepts and features. Features that were removed from FMP are also listed. Appendix 6 describes the input structure for FMP in detail.

Concepts New to the Farm Process

A variety of concepts have been added or modified in FMP. These include options for additional demand related to leaching requirements for salinity (salinity demand) and urban consumption; capability to specify multiple land-use (crop) types in a model cell; revised crop consumptive-use concepts; options for defining how each crop type’s roots interact with groundwater; a redefined irrigation efficiency and deficit irrigation framework; revised methods to define how pumpage in a WBS is distributed; and new options for simulating managed aquifer recharge for water-banking operations.

Crops can have an additional irrigation demand (leaching requirement) for flushing salts out of the soil zone based on the salinity of the irrigation water. The MF-OWHM2 implementation of a leaching requirement, called a salinity demand, is described in the “Salinity Irrigation Demand” section.

The deficit irrigation “deficiency scenario” now has two options for how irrigation efficiency is handled when there is insufficient water supply. Previously, irrigation efficiency increased up to perfect efficiency to ensure supply met the demand. This assumes that during water shortages agricultural entities became more efficient with their irrigations. This previous option is still available, but now, by default, irrigation efficiencies are held constant during deficit irrigation. This assumes that irrigation equipment does not change or improve during a water shortage. The implementation of deficit irrigation is described in the “Implementation of Deficit Irrigation” section. The “Non-Irrigation Flag” has been redefined as an irrigation type with an associated efficiency, rather than being specified by land use (Crop). It should be noted that in FMP a crop is not irrigated when the “Irrigation Flag” is set to zero, and if set to a positive integer, the flag refers to the irrigation type. The irrigation types—such as flood, sprinkler, soaker hose, or drip irrigation—can be

associated with specific crops or crop groups to indicate that the crop is irrigated and has the irrigation type's efficiency.

Deliveries of water for managed aquifer recharge were newly implemented into FMP. This is described in the "Direct Recharge Options" section.

As part of the FMP upgrades, a revised input format and related set of input read utilities were developed. The FMP input now utilizes a template file structured as block-style input using keywords that indicate the property to load or feature to enable. The input blocks simplify the user's choice of FMP options. Active features are grouped into the following named blocks in the template (appendix 6):

1. **GLOBAL_DIMENSION:** Global properties used by other FMP blocks
2. **WATER_BALANCE_SUBREGION:** Properties that pertain to defining WBS
3. **OUTPUT:** Ancillary output files
4. **OPTIONS:** Global modifier options
5. **SOIL:** Soil-specific properties
6. **CLIMATE:** Climate-related properties
7. **SURFACE_WATER:** Surface-water deliveries and runoff properties
8. **SUPPLY_WELL:** Groundwater-supply well properties
9. **ALLOTMENT:** Apply a limit to different water supplies
10. **LAND_USE:** Crop or land-use specific properties
11. **SALINITY_FLUSH_IRRIGATION:** Addition irrigation demand for salinity leaching

There is no requirement for the order of the blocks in the FMP input file, but the numbered list order provided here is recommended for consistency with different model applications. The only blocks required to run the FMP simulation are the **GLOBAL_DIMENSION** and **WATER_BALANCE_SUBREGION** blocks. The remaining blocks can be retained as needed to specify the input data and the desired FMP simulation.

Water-Balance Subregion (Farm) Water Sources

To increase simulation speed, each water-balance subregion (WBS) can have its water sources specified. These water sources represent the available sources of water used for irrigation of crops. The available sources are non-routed deliveries (NRD) that represent imported water, semi-routed deliveries (SRD) that represent surface water delivered from an SFR diversion, and groundwater pumping. The input is

specified in the **WATER_BALANCE_SUBREGION** block by the **WATERSOURCE** keyword (see appendix 6). Use of the water-balance block is advantageous if a WBS does not have any imported or surface-water sources. The block essentially declares this as a groundwater-only WBS, which prevents FMP from using any of the surface-water routines when determining the available water supplies for the WBS.

Supply-Constraint Options (Allotments)

Supply constraints are applied by WBSs in FMP and can be specified as a surface-water or groundwater allotment (if not defined, then the allotments are set to infinity for all WBS). Allotments are useful for representing water rights, operating agreements, legislation, adjudication, or analyzing sustainability. A surface-water allotment imposes a limit for a WBS on the amount of surface water that can be delivered. This limit only restricts water delivered as a semi-routed delivery (SRD) from SFR. Surface-water allotments must be specified as a maximum volume of water that can be delivered in a stress period or a maximum height per stress period (the height is converted to a volume by multiplying it by the associated WBS's irrigated area). The volume per stress period becomes a rate limit by dividing it by the stress period duration. This volumetric flow rate (L^3/T) becomes the maximum delivery rate that is allowed. A groundwater allotment is a volume per stress period limit imposed on a WBS's collective pumping. As with the surface-water allotment, the groundwater allotment is divided by the stress period to obtain a maximum allowed total WBS groundwater pumping flow rate (L^3/T).

Salinity Flush Irrigation Demand

Managing soil salinity is essential to avoid salt accumulation in the soil zone and loss of arable lands for agriculture. Dissolved salts in irrigated water remain in the soil after the water is removed through evapotranspiration. For example, applying 1 acre-foot of water with a total dissolved salt concentration of 735 parts per million could increase the soil-salinity mass by one ton of salt (Cahn and Bali, 2015). The increase in soil salinity reduces potential transpiration of the crops and lowers potential yields. The crop yield is the quantity of crop, by mass, that is harvested per unit area of land cultivated. A maximum yield can be determined for a unit of cropped area by assuming ideal water supply, climate, and soil salinity. Morway and Gates (2012) estimated the reduction in yield due to salinity for agricultural lands of the Lower Arkansas River Valley, Colorado, ranged from 6 to 17 percent over a 9-year period. In addition to the loss of productivity and irrigable lands, the supplemental water required for salt flushing as part of irrigation with saline waters can also greatly

increase water demand. Salinity-flush demand was added to FMP to account for the additional applied water necessary to flush salts out of the soil zone.

The Food and Agriculture Organization of the United Nations (FAO) includes detailed information about soil salinity, crop salt tolerances, and guidelines for increasing crop yields (Tanji and Kielen, 2002). Soil salinity can be measured using the average electrical conductivity (EC) of a soil sample in units of decisiemens per meter (dS/m). Within the range of 0.1 to 5 dS/m, an EC of 1 dS/m represents 640 milligrams per liter (mg/L) of total dissolved solids (TDS). For measurements greater than 5 dS/m, 1 dS/m represents approximately 800 mg/L of TDS. Table 2 presents a set of thresholds for various crops that represent the average soil salinity tolerated by the crop, as measured in a saturated soil-paste extract (EC_e), without a loss in potential yield (Tanji and Kielen, 2002). These values are guides, and the actual value can vary depending upon climate, soil conditions, agricultural practices, and the stage during a life cycle of a crop. For example, if a crop is grown in a soil rich in gypsum, then the crop-salinity tolerance threshold (EC_e) can be increased by 2 dS/m (Tanji and Kielen, 2002).

To account for the reduction in yields due to soil salinity, the FAO designated crops as sensitive, moderately sensitive, moderately tolerant, and tolerant to salt build up. Figure 10 presents the EC_e ranges of these designations for different values of relative crop yield. For example, 80-percent relative yield indicates that for the EC_e ranges indicated, there is a 20-percent reduction from the potential yield. The crop-specific soil-salinity tolerances in table 2 represent a relative yield of 100 percent in figure 10.

The most common method for determining the necessary irrigation for salinity flushing is the Rhoades equation (Rhoades, 1972, 1977, 2012; Rhoades and Merrill, 1976; Ayers and Wescott, 1985; Cahn and Bali, 2015), which is composed of two parts. The first part involves determining the fraction of total irrigation (applied) water that must pass through the soil to prevent the soil salinity from reaching the tolerance of the crop. This is a unitless fraction called the leaching requirement (LR). The LR is determined from the salinity concentration of irrigation water (EC_w) and the crop tolerance to soil salinity (EC_e). The EC_w and EC_e are both measured as electrical conductivity (dS/m). From Ayers and Wescott (1985), the leaching requirement can be calculated as follows:

$$LR = \frac{EC_w}{(5 \times EC_e) - EC_w} \quad \forall (5 \times EC_e) > EC_w \quad (15)$$

where

LR is minimum leaching requirement needed to control salts, with $0 \leq LR < 1$ (-);

EC_w is salinity of the applied irrigation water (dS/m); and
 EC_e is average soil salinity (dS/m) tolerated by the crop as measured in a saturated soil-paste extract, and it can be viewed as the desired soil salinity after additional irrigation is applied.

The leaching requirement must be less than 1, so salinity flushing is possible only when EC_w is less than 5 times the EC_e. The choice of EC_e is based on the desired, or obtainable, relative yields of the crop. For example, table 2 represents EC_e values that calculate a leaching requirement to obtain 100 percent relative yield. Once the leaching requirement is determined, the Rhoades equation uses the crop irrigation requirement (the irrigation necessary to satisfy evapotranspiration for a crop) and specifies the total irrigation necessary for salinity flushing as follows:

$$AW = \frac{CIR}{1 - LR} \quad (16)$$

$$D_{\text{irrigation}} = AW / OFE \quad (17)$$

where

CIR is crop-irrigation requirement under perfect irrigation efficiency (L³/T);
 AW is applied water necessary for salinity flushing under perfect irrigation efficiency (L³/T);
 OFE is the irrigation efficiency, with $0 < OFE \leq 1$ (-); and
 D_{irrigation} is the irrigation necessary to satisfy evapotranspiration for a crop and also sufficiently provide salinity flushing (L³/T).

MF-OWHM2, using FMP, can calculate the crop-irrigation requirement and determine the additional irrigation necessary, given a set of crop-salinity tolerances (EC_e) and the salinity of each of the sources of irrigation (EC_w). With this information, the FMP determines the leaching requirement from a composite EC_w (calculated from the mixture of available irrigation sources) and the corresponding additional irrigation to prevent salt build up. The determination can either be made through the Rhoades equation or through user-supplied expressions that calculate the additional irrigation. Additional details and examples for using salinity-demand input options are summarized in appendix 6 in the SALINITY_FLUSH_IRRIGATION block input option.

Table 2. List of common agricultural crops and their soil salinity (EC_e) threshold (Tanji and Kielen, 2002).

[The threshold value represents the point when the potential crop yield is decreased because of soil salinity. **Abbreviations:** dS/m, decisiemens per meter, a unit measurement of electrical conductivity; EC_e , mean electrical conductivity of a saturated soil paste taken from the crop’s root zone]

Crop common name	Soil salinity threshold, EC_e (dS/m)	Crop common name	Soil salinity threshold, EC_e (dS/m)
Alfalfa	2.0	Garlic	3.9
Almond	1.5	Lemon	1.5
Barley	8.0	Lettuce	1.3
Broccoli	2.8	Peach	1.7
Cabbage	1.8	Potato	1.7
Carrot	1.0	Spinach	2.0
Celery	1.8	Strawberry	1.0
Corn	1.7	Tomato	2.5
		Wheat, durum	5.9

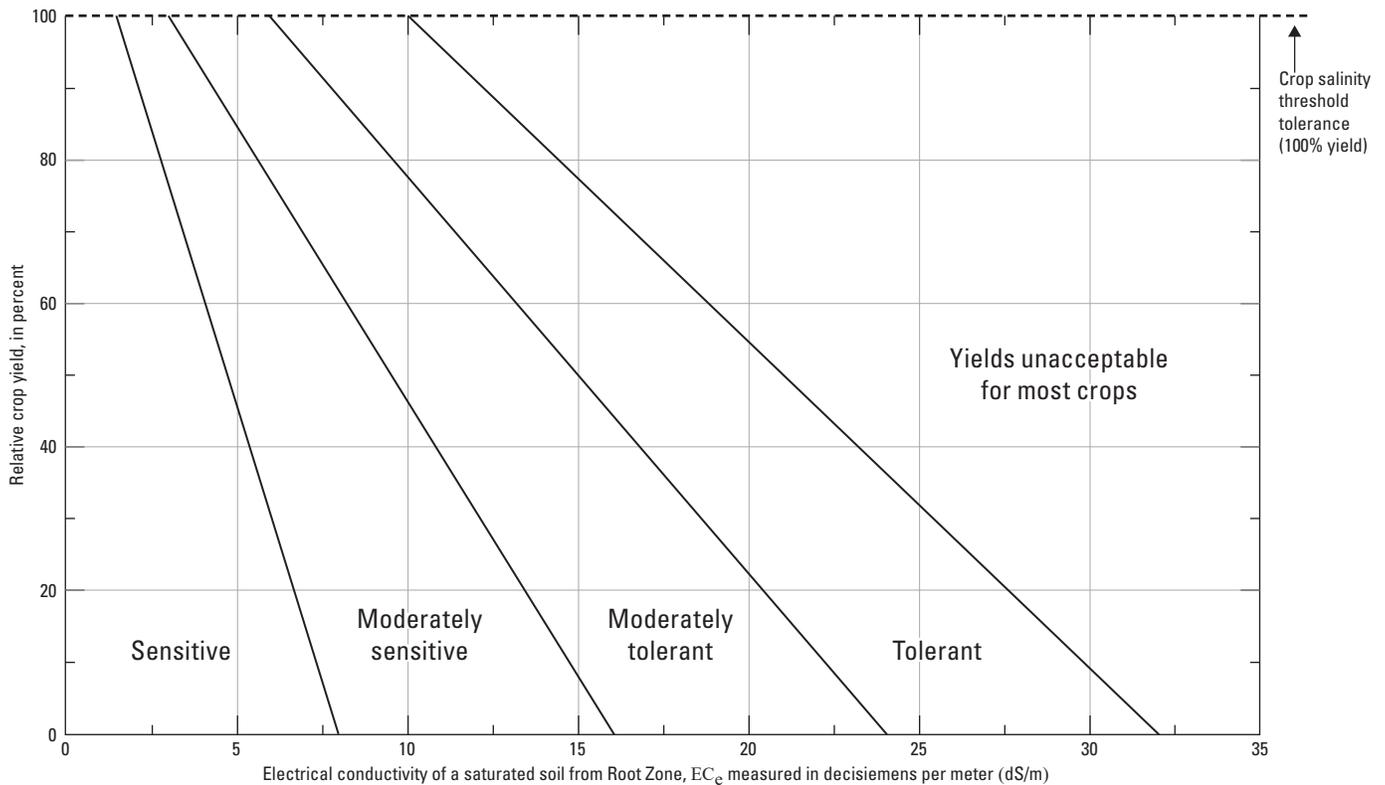


Figure 10. The United Nations Food and Agriculture Organization classification of crop tolerance to salinity (modified from Tanji and Kielen, 2002). The crop specific soil-salinity-threshold value, EC_e , represents 100-percent yield, and larger salinities result in decreases in the percentage yield.

Land-Use Grouping and Spatial Definition

Land use is an important aspect of an integrated hydrologic model. Along with climate, land use influences changes in water demand, use, and movement as well as sources of water supply and reuse. Each land use or “Crop” is specified using a numeric identifier (land-use ID). A land-use ID serves as a pointer to a set of common land-use properties (such as crop coefficient or potential consumptive use), and the ID is used to designate the land use’s location in the surface model grid. The maximum number of land-use ID’s must be declared at the start of a simulation (keyword **NCROP**), but the use of any land-use ID during a simulation is optional. That is, not all land-use IDs are required to be used during a single “stress period.”

The land-use’s available water for consumption and runoff calculations are determined by the WBS that a land-use is associated with. The association of the land-use ID with a WBS is by collocation, that is, where the land-use ID is spatially coincident with the WBS. For example, land use 1 (wheat) may be specified in WBS 1 and WBS 2, but only the wheat in WBS 1 contributes to WBS 1’s total demand and the wheat in WBS 2 contributes to WBS 2’s total demand. Additionally, if the wheat is irrigated, then WBS 1 only provides irrigation water to wheat in its domain; similarly, WBS 2 is for wheat in its own domain. The runoff calculations for wheat in WBS 1 are determined by WBS 1 and similarly for the wheat areas in WBS 2.

Allowing the user to define a set of land-use ID’s that have a set of associated properties and spatial location provides better flexibility in model development. Although it could be preferable to some modelers if FMP used a pre-defined set of crop identification and properties, such as having a “wheat” category with preloaded properties or links to existing databases, it provides less flexibility and limits the applicability of MF-OWHM2. For example, agricultural catalogues such as CropScape (Mueller and others, 2011) do not include natural or urban categories of land use and related vegetation and only provide selected recent years of annual agricultural land use. As a result, each modeled region typically requires its own catalogue of land use that includes the vegetation and crop types specifically growing in that region. For example, a model can declare wheat, fruit trees, natural vegetation, urban irrigation, and strawberries as land-use IDs 1, 2, 3, 4, and 5, respectively. Although the same land-use ID can be used in any WBS in a model, the user may have reasons to segregate the same crop to different IDs that represent different plant varieties, agricultural practices, landscapes, or hydrologic conditions. For example, strawberries can be broken into two regional groups to capture different climate and growing condition effects, such that the new land-use IDs are 5 and 6 to represent coastal strawberries and inland strawberries, respectively.

Multiple Land Uses (Crops) in a Model Cell (New Feature)

The input for the spatial distribution of a land use ID in FMP is very flexible, ranging from a single model cell to every model cell in the entire model domain. The spatial location of land use in FMP can be specified using one or two possible methods. The first method, FMP keyword **SINGLE_LAND_USE_PER_CELL**, limits the spatial resolution to one land-use location of each land use to one per surface model cell. This is how previous versions of FMP declared the location of each land use (Crop). This method is still supported and is the recommended method for specifying the spatial location of the land uses because of its simple input structure. A new feature in FMP is an adjustment fraction, keyword **LAND_USE_AREA_FRACTION**, that reduces the surface area of a land use in a model cell. For example, an almond tree farm that covers half the surface area of a model cell would have a land-use fraction of 0.50—previous versions of FMP required that the almond tree land use cover the entire model cell. It should be noted that the land-use fraction is based on the farmed area and not the almond tree covered area—that is, the fraction includes tree canopy-covered area and the open space between the trees.

The second method for specifying the spatial location of land uses, FMP keyword **MULTIPLE_LAND_USE_PER_CELL**, allows for more than one land use to be defined per surface model cell. This option is useful when the land uses in a surface model cell are too different to be combined in a composite land use. The method that FMP uses to define multiple land uses per model cell is similar to the mixed riparian vegetation method in the RIP-ET package (Maddock and others, 2012; Hanson and others, 2014d). The input structure for multiple land uses per surface cell requires defining an area fraction array for each land-use type. The fraction represents the part of the model cell’s surface area covered by the land use. For example, if a surface model cell is 30-percent wheat farm and 60-percent almond tree farm, then the fraction for wheat and almond trees for that that model cell would be 0.30 and 0.60, respectively. If the fractions of all crops defined for a model cell do not sum to 1, then the remaining area is assumed to be fallowed land (bare soil). In the previous example, 10 percent is assumed to be bare soil.

The choice of the appropriate input, one land use per model cell or multiple lands uses per cell, should be based on the spatial and temporal resolution of available land-use data, the objectives of model application, and the potential benefit of using multiple land uses compared to composite land use. Selecting land uses as **MULTIPLE_LAND_USE_PER_CELL** increases the complexity of input and total simulation run time, but this option may be essential for regions with mixed cropping and vegetation or complex topologies of land use.

To have multiple land uses (Crops) in a model cell, the user must specify a two-dimensional array of fractions, in a domain from zero to one, for each Crop instead of a Crop ID array (appendix 6). It is not required to have Crop fractions sum to 1 per model cell; if the Crop fractions do not sum to 1, then the unspecified part of the model cell follows the bare soil calculations (appendix 4). Therefore, if fractions are used, it is required to specify either a bare-soil evaporation rate or reference evapotranspiration rate. Additional details for using Crop-input options are summarized in appendix 6 in the **LAND_USE** block input.

Land-Use Grouping

Potential considerations for developing land-use categories include appropriately balancing loss of detail for the model's scale or generality, allowing flexibility for future land-use categories, and reducing the amount of model input and number of land-use categories. A useful approach to developing land-use IDs is to determine (1) the important land uses in the model domain, (2) how land use varies spatially and temporally during the simulation period, and (3) the relationship of land uses to the hydrologic budgets needed from the model. Equally important can be whether certain crops or vegetation types need to be simulated as separate entities, or whether groups of crops that have similar planting dates, harvest dates, growth cycles, crop attributes, and methods of irrigation can be grouped together into "virtual crops." Consequently, if specific land uses are integral to the desired model analysis, it is best to aggregate them in groups for analysis. For example, land uses can be grouped in stable land uses that are relatively permanent, such as natural or urban vegetation; land uses that can change on multi-year time frames, such as orchards and vineyards; land uses that are annual or seasonal, such as wheat-corn-fallow rotation; land uses with high-frequency multi-cropping, such as spinach; or land uses that represent non-traditional growing techniques, such as indoor nurseries. Grouping of more detailed land uses allows a simpler input structure and reduces the data input needs. Furthermore, representing the water demands of a group of similar land uses in the model can result in more efficient model execution. If it is found that a more detailed representation of a specific land use within a group is needed, it can be removed and made into its own group.

Crop Consumptive-Use (CU) Concepts

The potential consumptive use (CU) of a land use (crop) is defined as the consumption of water necessary to meet the land use's potential evapotranspiration (PET). In the context of MF-OWHM2, it can be assumed that CU is the same as PET, which is satisfied from water that originates directly from groundwater, precipitation, and applied irrigation

under perfect irrigation efficiency. The necessary irrigation to meet the CU under perfect efficiency is called the crop irrigation requirement (CIR). After the CIR is determined, the additional water demand caused by inefficient irrigation can be determined from the irrigation type's irrigation efficiency.

Previously, FMP specified two consumptive-use flags as part of its input, **ICUFL** and **ICCFL**. The first flag, **ICUFL**, defines how the consumptive use input is specified. In FMP, if a crop's CU is to be directly specified, **ICUFL** is set to 1 or 2. If CU is to be calculated using a crop coefficient (K_c) and reference evapotranspiration (ET_{ref}), such that $CU = K_c \times ET_{ref}$, **ICUFL** is set to -1. Appendix 4 provides a detailed explanation of the consumptive use concepts used in FMP.

The second flag, **ICFFL**, defines two consumptive use concepts previously called Concept 1 and Concept 2. These "Concepts" define how a crop's anoxia- or wilting-related pressure heads are calculated, the potential quantity of groundwater that a crop can consume directly, and whether deep percolation is simulated by UZF for delayed recharge. In this report, to identify these two concepts, the concept formerly called Concept 1 (**ICCFL** set to 1 or 3) is referred to as the *analytical root response* for root uptake of groundwater and anoxia, and Concept 2 (**ICCFL** set to 2 or 4) is referred to as the *linear root response* for root uptake of groundwater and anoxia. For a detailed explanation of the concepts, please see "Consumptive Use and Evapotranspiration in the Farm Process" (appendix 4) and "Concepts of Landscape and Root Zone Processes" (appendix 5).

The FMP can determine which of the two concepts is applied for simulating consumptive use of a given crop on the basis of amount of input provided. The consumptive-use concepts are no longer global properties (**ICUFL** and **ICCFL**) applied to all crops, but instead are specified on a crop-by-crop basis. The optional linkage to the UZF package—that is, FMP deep percolation becomes infiltration to UZF for delayed recharge—is still a global option that is specified with the keyword **UZF_LINK** in the **GLOBAL DIMENSION** block (appendix 6). If the **UZF_LINK** is enabled, it is important that the UZF package's ET option is disabled to prevent double accounting from FMP and UZF.

All consumptive-use concepts in the new input structure require, at a minimum, specifying the soil capillary fringe in the **SOIL** block. The *linear root response* concept (formally Concept 2 with **ICCFL** = 2 or 4) requires specifying the root depth (ROOT), fraction of transpiration (FTR), fraction of evaporation from irrigation (FEI), and fractions of delivery losses to surface water from precipitation and irrigation in the **LAND_USE** block for each crop. The *analytical root response* concept additionally requires a soil-type coefficient (silt, silty clay, sandy loam, or sand) in the **SOIL** block, four root pressures that define the threshold for anoxia, the range of optimal root uptake of groundwater, and the threshold for wilting in the **LAND_USE** block.

If there are crops that receive applied water or irrigation, then the **WATER_BALANCE_SUBREGION** block must specify each irrigation type's OFE, and the **LAND_USE** block must include an irrigation flag (zero to indicate no irrigation and non-zero to indicate the specific irrigation type being used). FMP defines the number of irrigation types with the keyword **NIRRIGATE**. Consequently, if a crop is irrigated it should be specified with an irrigation flag from 1 to **NIRRIGATE** to indicate irrigation type used. It should be noted that earlier FMP versions specified a “non-irrigation flag,” where 0 (zero) indicated the crop was irrigated and 1 (one) meant it was not. This feature is no longer supported; instead, the “non-irrigation flag” is replaced with an “irrigation flag” that is set to 0 (zero) for no irrigation and greater than zero for irrigation and to identify the irrigation type. Irrigation types are discussed in more detail in the “Redefinition of Irrigation Efficiency” section.

Any combination of consumptive-use concepts is valid as long as all the necessary input information is provided. For example, a user may elect to directly specify the consumptive use of crop 1 and simulate crop uptake using the *linear root response* concept, but for crop 2, to use crop coefficients and the *analytical root response* concept. FMP distinguishes among the different combinations of concepts applied by the user setting flags to zero in the input to signify features not wanted. For example, if one crop has all its soil-water pressures (ψ) set to zero, then FMP uses the *linear root response* concepts rather than the *analytical root response* concepts.

Redefinition of Irrigation Efficiency

Irrigation efficiency is required to determine the irrigation water demand for a given crop irrigation requirement. The irrigation water demand (D) is determined as the crop irrigation requirement divided by the irrigation efficiency ($D = CIR/OFE$). In the previous versions of FMP, the irrigation demand is referred as the farm delivery requirement (FDR). The specification of irrigation efficiency (OFE) has changed in FMP. The OFE input for FMP was an array-based input specifying a set of efficiencies for each crop in each WBS, resulting in the input-array dimensions NFARM by NCROP. This definition and input structure of OFE limited crops to one irrigation style based on the crop's irrigation efficiency—that is, one OFE per crop. To provide a more realistic way to represent OFE, it has been redefined to allow specification of OFE by irrigation types (number of types, with the keyword **NIRRIGATE**) for each WBS. The number of irrigation types is specified along with the other global dimensions, NWBS, NCROP, and NSOIL, and represents the number of irrigation types that are specified for each WBS. This changes the OFE input from defining NCROP efficiencies for each WBS to NIRRIGATE efficiencies for each the WBS, thereby changing the input-array dimensions to NWBS by NIRRIGATE. For example, if the user specifies three irrigation

types representing drip, sprinkler, and flood irrigation, then an OFE can be specified for each irrigation type in each WBS. Actual irrigation-efficiency values are dependent on the local practices, but previous publications (Hanson and others, 2014a) have set irrigation efficiencies within the range of 0.8 to 0.9 for drip, 0.6 to 0.7 for sprinkler, and 0.5 to 0.6 for flood. If desired, users may specify temporal changes in efficiencies in the model input—that is, the OFE can change by stress period.

The redefinition of irrigation efficiency necessitated changing the meaning of the irrigation option in FMP. Previously, it was referred to as “non-irrigation,” for which a value of 0 indicated the crop was irrigated and 1 indicated no irrigation. In this version, the irrigation flag of 0 indicates no irrigation, and greater than zero indicates the type of irrigation used for the crop. For example, if there are three irrigation types and the third type is used for a crop, then its irrigation flag would be set to “3” to indicate that it is irrigated using the efficiency defined for irrigation type number 3.

The irrigation efficiency is included as part of several outputs, including the output files that result from the keywords **FARM_BUDGET** (FB_Details.out) and **FARM_DEMAND_SUPPLY_SUMMARY** (FDS.out). For output files that summarize the efficiency by WBS, the output efficiency is an aggregate of the total efficiency in the WBS (dividing the sum of all requirements, $\Sigma CIRs$, by the sum of the irrigation demands, ΣD). It should be noted that when a simulation includes deficit irrigation, OFE can either remain constant under deficit irrigation (default in FMP) or if the keyword **EFFICIENCY_IMPROVEMENT** is included, then OFE can increase to represent farmers being more efficient under water shortages. The “Irrigation Efficiency under Deficit Irrigation” section includes a detailed description of efficiency improvement.

Groundwater–Root Interaction Options

A crop simulated in FMP has a specified root depth that interacts with the water table. This interaction is dependent on the distance between the water table with its associated overlying capillary fringe and the bottom of the roots, and it can result in root groundwater uptake or an anoxic reduction in transpiration. Previously, root groundwater uptake, anoxia, and soil-moisture stress were calculated and applied to the crop's final consumptive use. This feature is applied using keyword **GROUNDWATER_ROOT_INTERACTION** and is now optional on a crop-by-crop basis. There are five levels of groundwater–root interaction. There is also a zero-level to indicate the crop is dead and, consequently, has no consumption. Table 3 presents each of the crop root–groundwater interaction levels and indicates whether FMP is applying root groundwater uptake, anoxia, and soil stress for each one. See appendix 6 for a detailed overview and explanation of **GROUNDWATER_ROOT_INTERACTION** and how it is applied in the FMP input **LAND_USE** block.

Table 3. Crop root–groundwater interaction levels.

[—, not applicable]

Level	Groundwater root uptake	Anoxia reduction	Soil stress reduction
0	—	—	—
1	No	No	No
2	No	Yes	Yes
3	Yes	No	No
4	Yes	No	Yes
5	Yes	Yes	Yes

At the first level of groundwater–root interaction, there is no interaction between the groundwater and the crop roots. This prevents any reduction in consumptive use due to anoxia or soil stress conditions and does not allow the crop to consume any groundwater directly (it can be indirectly satisfied through precipitation and applied irrigation). This method is most appropriate for crops that are always disconnected from groundwater or do not suffer from anoxia, such as rice.

At the second level, anoxia and soil stress can reduce transpiration by the crop and, consequently, the consumptive use. Root groundwater uptake is not allowed; thus, all water consumption is from precipitation and irrigation. This option is the least useful, and not recommended, because it allows for high groundwater conditions to affect the crop while disconnecting any actual consumption. This option is most appropriate if most of the crop’s consumption is supplied primarily from precipitation and irrigation, but the root groundwater uptake is negligible. This allows FMP to determine the anoxia and soil-stress the crop is experiencing, but not any consumption of groundwater.

The third level is the opposite of the second; root groundwater uptake is allowed, but transpiration is not decreased by anoxia or from soil stresses. To achieve this, the anoxia and soil-stress quantities are calculated; then, any root groundwater uptake is added to the uptake amount rather than deducted from the consumptive use. If there is no root groundwater uptake, then the anoxia and soil-stress quantities are added to the water demand from surface sources of precipitation and irrigation.

At the fourth level, root groundwater uptake and soil-stress losses are allowed, but anoxia is not. This is similar to the third level, except that soil stress is deducted from the total consumptive use, but anoxia is not added either to the root groundwater uptake or to the water needed from surface sources.

At the fifth level, full interaction between groundwater and the crop root is allowed. If anoxia and soil stress are present, then the crop’s reduced transpiration consumes only groundwater by root uptake (not precipitation or irrigation consumption). In previous releases of FMP, this fifth level was the only option; now it is the default interaction for all crops if the groundwater–root interaction flag is missing from the FMP input.

Implementation of Deficit Irrigation

If FMP does not have enough water supply to meet the water demand for a WBS, one of two options is taken: water from an external source is used to meet the supply shortfall, or deficit irrigation is implemented. External source water is called the Zero-Scenario and indicates that a WBS can obtain an unlimited supply of water from outside the simulation domain to meet an irrigation-supply shortfall. Conversely, deficit irrigation allows for a deficit between the demanded irrigation and the available water supply (actual applied water). The supply shortfall then results in a reduction in crop transpiration. The reduced transpiration is accompanied by reduced water uptake, which can result in wilting conditions and a reduction in crop yield.

When a WBS has a supply shortfall and is under deficit irrigation, FMP must determine how water is distributed among the crops. In previous versions of FMP, water was distributed by an average supply flow for each irrigated-crop area (WBS supply divided by the irrigated area). Crops that had a demand below this average received no reduction in water. The remaining water supply was then evenly distributed among the remaining crops. The formal equations for this method of deficit irrigation for all crops (N) in a WBS are as follows:

$$QAVF = \frac{\text{Supply}}{\sum_{i=1}^N \text{Area}_i} \tag{18}$$

$$QDEF = \sum_{i=1}^N QAVF \times \text{Area}_i - D_i \quad \forall i \text{ with } D_i \leq QAVF \times \text{Area}_i \tag{19}$$

$$QEXC = \sum_{i=1}^N D_i - QAVF \times \text{Area}_i \quad \forall i \text{ with } D_i > QAVF \times \text{Area}_i$$

$$\begin{aligned} \tilde{D}_i &= D_i && \forall i \text{ with } D_i \leq QAVF \times \text{Area}_i \\ \tilde{D}_i &= QAVF \times \text{Area}_i + \frac{QDEF}{QEXC} \times (D_i - QAVF \times \text{Area}_i) && \forall i \text{ with } D_i > QAVF \times \text{Area}_i \end{aligned} \tag{20}$$

where

- QAVF is average supply flow for each irrigated-crop area for a WBS (L/T),
- Supply is total water supply available to the WBS (L³/T),
- i is the crop ID (-),
- N is the number of crops (-),
- Area_i is Crop i’s area (L²),
- D_i is Crop i’s initial irrigation demand (L³/T),

- QDEF is sum of area-weighted supply less demand when demand is less than the area-weighted supply (L^3/T),
- QEXC is sum of demand less area-weighted supply when demand is greater than the area-weighted supply (L^3/T), and
- \tilde{D}_i is Crop i 's deficit irrigation demand that was satisfied by supply (L^3/T).

This method of prorating irrigation supply to simulated crops tends to shift the available irrigation water to crops that have lower irrigation demand and causes a larger deficit (supply shortfall) for the high-irrigation demand crops. This method is most suitable if it is preferable to fully satisfy the demand of low-irrigation demand crops at the expense of high-irrigation demand crops. To distinguish this method, it is referred to as ByAverage Deficit Irrigation.

A new deficit irrigation option is the ByDemand Deficit Irrigation, which is now the default option in FMP. ByDemand Deficit Irrigation prorates each crop's irrigation demand by the ratio of the total water supply divided by the WBS irrigation demand. This causes all crops to have an equal percentage reduction in transpiration, allowing for a smaller deficit for high-irrigation demand crops. This can spread the wilting evenly among all the crops. Equations 21 and 22 describe how the ByDemand deficit demand is calculated.

$$DEF_{ratio} = \frac{Supply}{\sum_{i=1}^N D_i} \quad (21)$$

$$\tilde{D}_i = D_i \times DEF_{ratio} \quad \forall i \quad (22)$$

where

DEF_{ratio} is deficit ratio used to reduce all the demands equally (-).

To illustrate the difference between ByAverage and ByDemand Deficit Irrigation, table 4 presents a hypothetical set of demands from four crops and the resulting deficit demand. In this example, the crop area and initial demand are given, and the necessary components for the deficit demand were calculated using equations 18–22.

In this example, crops 1 and 2 have low demand per unit area (both are 0.5), so they receive their full demand when the ByAverage method is used, at the expense of crops 3 and 4. Conversely, the ByDemand method reduces all the crop irrigation demands by half, satisfying a larger fraction of the initial demand for crops 3 and 4. ByAverage and ByDemand Deficit Irrigation are specified in the WATER_BALANCE_SUBREGION block by the keyword PRORATE_DEFICIENCY followed by the keyword "ByAverage" or "ByDemand." If PRORATE_DEFICIENCY is not specified, then the FMP defaults to the ByDemand Deficit Irrigation option.

Table 4. Example of the difference in final irrigation demand using ByAverage and ByDemand Deficit-Irrigation simulation methods.

[Note that "ByAverage" deficit demands are rounded to the nearest integer. **Abbreviations:** L^2 , area in model units; L^3/T , volume per time in model units; D_i , irrigation demand (L^3/T); i , designates the i th crop out of N total specified land use types; ID, identification number]

Crop ID	Area _{<i>i</i>} (L ²)	Initial demand (D _{<i>i</i>})	Deficit demand (\tilde{D}_i)	
			ByAverage	ByDemand
1	100	50	50	25
2	200	100	100	50
3	100	200	73	100
4	100	250	77	125

Supply	300
QAVF	0.6
DEF _{ratio}	0.5
QEXC	330
QDEF	30

Crop ID	QAVF × Area
1	60
2	120
3	60
4	60

Irrigation Efficiency Under Deficit Irrigation

Previous versions of FMP assumed when deficit irrigation was enabled and a WBS did not have enough supply to meet its demand, the irrigation efficiency would increase linearly to unity. Increasing the efficiency assumed that irrigation practices improve when there is less water available for irrigation—that is, a farmer is more conservative with his water use during a shortage. For a detailed discussion about this, please see appendix 4, “Satisfying the Potential Transpiration Component.” The original method calculated the increase in efficiency by holding the crop irrigation requirement (CIR) constant and setting the total water demand (D_i) equal to the total available water supply for irrigation (\tilde{D}_i). The efficiency is recalculated by dividing the CIR by the available supply for irrigation:

$$OFE_i = CIR_i / D_i \quad (23)$$

$$O\tilde{F}E_i = CIR_i / \tilde{D}_i \quad (24)$$

where

- i is any one crop (-),
- OFE_i is crop i 's initial irrigation efficiency (-),
- $O\tilde{F}E_i$ is crop i 's improved irrigation efficiency (-),
- CIR_i is crop i 's crop irrigation requirement (L^3/T),
- D_i is crop i 's initial irrigation demand (L^3/T), and
- \tilde{D}_i is crop i 's deficit irrigation demand that is equal to the available supply (L^3/T).

If the adjusted efficiency was greater than 1.0, then it was changed to 1.0, resulting in a deficit irrigation—that is, the crop is irrigated with the available water at perfect efficiency ($OFE = 1.0$). This method is appropriate when it is known that the agricultural irrigation implementation in a WBS becomes more efficient under deficit irrigation.

Typically, it is not easy to change existing irrigation infrastructures or to modify irrigation practices to improve efficiency. Consequently, FMP now has the option to hold irrigation efficiency constant irrespective of water supply. By holding OFE constant, the applied water is either equal to the demanded water (D_i) or to the available irrigation that can be applied to the crop (IRR) taking into account irrigation efficiency (IRR = Supply). To keep the math consistent, when $D_i > IRR$, a new CIR is calculated based on the available irrigation water ($\tilde{C}IR$). The new $\tilde{C}IR$ then would result in a reduction in the crop transpiration due to wilting (eq. 14).

$$\begin{aligned} \text{If } D_i > IRR_i \\ \text{then } \tilde{C}IR_i &= OFE_i \times IRR_i \\ \text{and } \tilde{D}_i &= IRR_i \end{aligned} \quad (25)$$

$$T_{\text{irrigation}} = \frac{\tilde{C}IR_i}{1 + FEI / FTR} \quad (26)$$

$$W_i = \frac{CIR_i - \tilde{C}IR_i}{1 + FEI / FTR} \quad (27)$$

where

- IRR_i is the amount of irrigation water available to crop i (L^3/T);
- OFE_i is crop i 's initial irrigation efficiency (-);
- CIR_i is crop i 's initial crop irrigation requirement (L^3/T);
- $\tilde{C}IR_i$ is crop i 's deficit irrigation requirement (L^3/T);
- FEI is the fraction of evaporation from irrigation, which is the fraction of total cropped area where irrigated water is applied to bare soil (-);
- FTR is the fraction of transpiration, which is the ratio of the basal crop coefficient divided by full crop coefficient that represents the fraction of total cropped area covered by the crop canopy (-);
- $T_{\text{irrigation}}$ is the proportion of crop transpiration that originated from irrigation, reduced by the available water supply (L^3/T); and
- W_i is the deficit in a crop's potential transpiration resulting from insufficient water supply (L^3/T).

Holding the efficiency constant simulates irrigation practices that do not become more efficient under deficit irrigation. This is more representative of irrigation practices that have a relatively low efficiency, such as flood or sprinkler irrigation.

To account for different irrigation practices for each WBS and irrigation type, the method of increased efficiency remains available as an option in FMP. The method can be specified in the FMP input in the **WATER_BALANCE_SUBREGION** block. This requires including the keyword **EFFICIENCY_IMPROVEMENT** and specifying a flag for each WBS and each irrigation type. If the keyword is not present, then FMP defaults to holding efficiency constant and reducing transpiration if there is deficit irrigation.

Supply Well (Farm Well) Redesign and Implementation

A water-balance subregion’s water demand is determined by the total consumptive use of all the land uses in it. This water demand is first satisfied by natural sources of water, which are direct uptake from groundwater and precipitation. If the water demand is not fully satisfied from the natural sources, then the remaining demand is met with irrigation water that originates from imported sources (non-routed delivery, NRD), from surface-water sources (semi-routed delivery, SRD), and from supply wells that pump groundwater (Q_{WBS}), in that order. A WBS can be associated with a set of irrigation supply wells. These wells were called “Farm Wells” in previous publications, but have been renamed in this release as WBS Supply Wells (Q_{WBS}).

The implementation of FMP supply wells was redeveloped to increase speed, simplify user-input, and include new features and output options. Supply wells are defined in the FMP input’s **SUPPLY_WELL** block. The supply wells have two possible methods for extracting water from groundwater and three potential input configurations.

Traditional FMP Supply Well

The first method by which a WBS supply well can extract water functions identically to the WEL package. This method sets a demanded pumping rate to a model cell. The demanded extraction rate is always satisfied unless the model cell becomes “dry” or if the FMP well-capacity smoothing option is enabled. Capacity smoothing reduces a supply well’s capacity (Q_{cap}) if the cell’s saturated thickness (eq. 28) is less than a user specified threshold (MT). When the saturated thickness is less than the specified threshold, then Q_{cap} is multiplied by a smoothing factor (Q_{smf} , eq. 29) to determine the supply well’s smoothed pumping capacity. This mimics the loss of well production and improves the stability of the groundwater simulation. The threshold can be specified as a fraction of the cell thickness or as a length above the cell bottom:

$$\begin{aligned} \text{If } h_{cell} > TOP_{cell} & \quad b_{cell} = 1.0 \\ \text{else-if } h_{cell} > BOT_{cell} & \quad b_{cell} = h_{cell} - BOT_{cell} \\ \text{else} & \quad b_{cell} = 0.0 \end{aligned} \quad (28)$$

where

- cell is a model cell at a model layer, row, and column (-);
- h_{cell} is the simulated hydraulic head of the model cell (-);
- TOP_{cell} is the top elevation of the model cell (-); and
- b_{cell} is the model cell’s saturated thickness (L).

$$Q_{smf} = b_{cell}^2 \times \left(\frac{3}{MT^2} - \frac{2b_{cell}}{MT^3} \right) \quad \forall b_{cell} \in 0 \leq b_{cell} \leq MT \quad (29)$$

where

- MT is saturated thickness threshold that enables smoothing (L), and
- Q_{smf} is smoothing factor multiplied by the supply well capacity and is only applied if b_{cell} is in the range of $0 \leq b_{cell} \leq MT$ (-).

To enable well-capacity smoothing, the **SUPPLY_WELL** block must include the keyword **SMOOTH** followed by the secondary keyword **ByFraction** or **ByThick**. The saturated thickness threshold (MT) can be set as a minimum cell thickness (**ByThick**) or as a minimum cell fraction (**ByFraction**). If the input is specified as a fraction, then it is converted to a cell thickness for each model cell. The threshold can also be specified as a single number applied to all wells, by WBS, or by model layer. For more details on the usage of the keyword **SMOOTH**, see appendix 6.

FMP-MNW2 Linked Supply Well

The second method by which a WBS supply well can extract water uses the MNW2 package to simulate the actual pumping. If a supply well is linked to MNW2, the well’s spatial location and construction are defined by MNW2, but the MNW2 well’s desired pumping rate (Q_{des}) is set by FMP (typically in response to demanded pumpage from a WBS). MNW2 determines the actual pumping rate on the basis of Q_{des} from FMP, the well construction, and aquifer conditions (such as hydraulic head and horizontal hydraulic conductivity). If MNW2 cannot meet the FMP specified Q_{des} , then FMP adjusts the WBS’s supplies accordingly. Specifically, if there is insufficient supply from an FMP-MNW2 linked well, then a WBS may shift its demanded pumping to a different supply well or the WBS may end up in a deficit irrigation situation due to insufficient water supply.

Supply Well QMAXRESET and NOCIRNIQ Options

The Farm Well keywords **QMAXRESET** and **NOCIRNIQ**—previously included in the “flags for auxiliary variables”—are now specified in the **SUPPLY_WELL** block as a global option by WBS rather than by a supply well. Supply wells with **QMAXRESET** flag indicate that if they are linked to MNW2, then the supply well’s maximum production capacity (Q_{cap}) is reset to the value specified in the input at the start of each time step instead of at the start of each stress period. MNW2

can reduce Q_{cap} when calculating the production potential of the WBS supply well. The advantage of not resetting Q_{cap} is that typically subsequent time steps have the same production potential, resulting in an improvement on simulation execution time. In practice, this improvement was negligible; consequently, **QMAXRESET** is enabled by default for all WBS. The keyword **QMAXRESET** is only necessary if it is desired to specify it for only certain WBS—or, optionally, the keyword **NO_QMAXRESET** can be specified to entirely disable it.

NO CIRNOQ indicates that a supply well contributes groundwater to meet a WBS demand—through pumping—only if the model cell that it resides in has a crop irrigation requirement (CIR). This is advantageous for representing local deliveries of groundwater when every cell that has an irrigated crop in a WBS also contains a supply well. By default, **NO CIRNOQ** is disabled.

Prorating Farm Supply Well Pumpage

A new option is the ability to define how WBS demanded pumpage is spread across its Farm Wells if the total demand for groundwater pumping is less than the total summed pumping capacity. It is defined for each WBS as follows:

$$QTOTcap_j = \sum_{i=1}^N Qcap_i \quad (30)$$

where

- $QTOTcap_j$ is the total pumping capacity of the j th WBS (L^3/T),
- j is the WBS index ($1 \leq j \leq NWBS$),
- N is the number of wells associated with the WBS (-),
- i is the index for one of the wells associated with the WBS ($1 \leq i \leq N$), and
- $Qcap_i$ is maximum pumping capacity of well i , (L^3/T).

This option is initiated by including the keyword **PRORATE_DEMAND** in the **SUPPLY_WELL** block, followed by a method keyword—either **ByAverage** or **ByCapacity**. This proration functions similarly to the way deficit irrigation is applied to crops, as described in appendix 6.

The **ByAverage** option is the way that previous releases of FMP spread pumpage and is the default option if **PRORATE_DEMAND** is not specified. The formal equations for **ByAverage** proration for all wells associated with one WBS are as follows:

$$QAVF = DMD_j / N \quad (31)$$

$$QDEF = \sum_{i=1}^N QAVF - QCAP_i \quad \forall i \text{ with } QCAP_i \leq QAVF \quad (32)$$

$$QEXC = \sum_{i=1}^N QCAP_i - QAVF \quad \forall i \text{ with } QCAP_i > QAVF$$

$$Q_i = QCAP_i \quad \forall i \text{ with } QCAP_i \leq QAVF$$

$$Q_i = QAVF + \frac{QDEF}{QEXC} \times (QCAP_i - QAVF) \quad \forall i \text{ with } QCAP_i > QAVF \quad (33)$$

where

- $QAVF$ is average demanded pumping rate (L^3/T),
- DMD_j is the j th WBS total pumping demand (L^3/T),
- N is the number of wells associated with the WBS (-),
- i is the index for one of the wells associated with the WBS ($1 \leq i \leq N$),
- $QCAP_i$ is maximum pumping capacity of well i (L^3/T),
- $QEXC$ is total excess pumping relative to $QAVF$ (L^3/T),
- $QDEF$ is total deficit pumping relative to $QAVF$ (L^3/T), and
- Q_i is the final pumping rate assigned to the well i (L^3/T).

This proration tends to keep the pumping rate even for all wells, but may under-utilize the large production wells that can be operated at higher pumping rates.

The **ByCapacity** option uses the ratio of the demanded pumping rate (DMD_j) to the total pumping capacity of a WBS to prorate the pumpage across wells. Equations 34 and 35 describe the way the **ByDemand** deficit demand is calculated.

$$QPRO_j = \frac{DMD_j}{QTOTcap_j} \quad (34)$$

$$Q_i = QCAP_i \times QPRO_j \quad \forall i \quad (35)$$

where

- $QPRO_j$ is ratio used to prorate equally the well capacities for the j th WBS (-).

To illustrate the difference between **ByAverage** and **ByCapacity** methods of distributing pumpage, [table 5](#) presents a hypothetical total pumpage demanded from four Farm Wells that have varied capacities and lists the resulting pumping rates. It should be reiterated that this algorithm is only applied if a WBS-demanded pumping rate is less than the WBS summed maximum pumping capacity ($DMD_j < QTOTcap_j$); otherwise, all the wells in the WBS pump at the maximum rate.

Direct Recharge Option

In FMP, water not consumed by the land-use type (crop), as evaporation and transpiration, becomes either surface-water runoff or deep percolation to groundwater. The deep percolation can be handled by the Unsaturated Zone Flow Package (UZF), to simulate delayed recharge and rejected infiltration, or flow directly to the water table as recharge. A previous limitation was having no way to specify additional deep percolation beyond what was calculated to result from efficiency losses from precipitation and irrigation water. Additional deep percolation could be specified with the Recharge Package (RCH), but this recharge was not included in the WBS budget information and did not offer the option of delayed recharge. Another limitation was that if FMP was linked to UZF, then the UZF input FINF (infiltration rate at land surface) is set to zero; subsequently, FINF is set to the FMP-calculated deep percolation.

To overcome such limitations in FMP, an input called Direct Recharge is now available. Direct Recharge may be

used to represent a set of infiltration ponds that obtain their water from external sources or it could represent natural recharge to the groundwater system that is not consumed by the land use. This option is useful for simulating water banking of managed aquifer recharge (MAR).

Direct Recharge is specified as part of the **CLIMATE** block and is composed of a two-dimensional array (NROW by NCOL) that represents water intended to be directly recharged, bypassing crop consumption (transpiration) and bare soil evaporation. This recharge is simulated similarly to the methods used in the Recharge Package, but differs in that the Recharge Package is a user-specified flux that becomes a volumetric rate across the entire model grid, whereas the FMP Direct Recharge array can be either specified as a flux or volumetric rate. The resulting recharge is passed to deep percolation. From there, it is sent to the UZF or directly recharges the water table. This recharge is not a source of demand, but it could be a source of supply through root groundwater uptake. Because Direct Recharge is a source of water—that is, it enters the landscape budget—it is included as a new column in the FB_Details.out file and has the heading Q-drch-in. Direct Recharge leaves the landscape through deep percolation, so it is included in the column Q-dp-out. For separate accounting of deep percolation from crops, this can be calculated as Q-dp-out minus Q-drch-in.

Farm Process Features Removed

Several seldom used features were removed from FMP. These features included **FLAG_BLOCKS** input data structure (the new input for FMP is not backward compatible with previous versions), the prior appropriation scheme for ranked appropriation by farms that represented a water rights hierarchy of preferred deliveries, deficit irrigation options for acreage optimization, conservation pool, water stacking, and the LGR “P” flag that automatically translated farm and crop properties from a parent LGR grid to its associated child-model’s farms and crops. Functions equivalent to many of these features can be more effectively performed through external optimization wrappers and preprocessing of child-model data. For example, acreage optimization, formerly initialized by `IDEFFL>0`, is no longer included as an option. Instead, it is recommended to use an external optimizer for determining optimal crop placement. This type of crop optimization has been successfully used by Fowler and others (2014 and 2016). Another important change is that the prior appropriation system between FMP and SFR, formerly initialized by `IALLOTSW>0`, is no longer included. If the removed features are desired, the user can use MF-OWHM (Hanson and others, 2014d). The removed features are summarized in appendix 6.

Table 5. Example illustrating the difference in final pumping rate, in L³/T, between calculations using **ByAverage** and **ByDemand** proration methods.

[ID, identification; QCAP, maximum pumping capacity rate of a well; L³/T, volume per time in model units]

Well ID	QCAP	Well pumping rate	
		ByAverage	ByCapacity
WELL_1	100	100	60
WELL_2	175	175	105
WELL_3	325	160	195
WELL_4	400	165	240
DMD _j	600		
QAVF	150		
QPRO _j	0.6		
QEXC	425		
QDEF	25		

Several relatively minor features also were removed. Farm Well Parameters (NPFWL) have been removed and replaced with an entirely different input structure for Farm Wells (appendix 6). This new input structure supports a variety of scale factors that can provide the same benefit that was included with NPFWL. The daily crop coefficient and root-depth time series for an entire simulation (ICUFL=3 and IRTFL=3) have been removed. An alternative to this setup is to develop equivalent crop coefficients by upscaling the daily values to the length of stress period (or time step). Additionally, crop properties can be specified by time step or stress period. The efficiency behavior flag (IEBFL) options have been removed; efficiency is now held constant until a new efficiency value is loaded. Declaring a non-irrigation season (IROTFL>0) is no longer an option; this can now be set directly with irrigation flags or fallowing cropland. Lastly, the fraction of evaporation from precipitation (FEP) is no longer required input. Its definition required that its sum with the fraction of transpiration (FTR) was always equal to one. Instead of requiring the user to specify it, it is automatically calculated as $FEP = 1 - FTR$.

Conduit Flow Process (CFP)

Dual-porosity aquifers consist of a primary interstitial porosity of the aquifer or soil and a secondary porosity that may be due to secondary solution, regional fracturing, or both (Freeze and Cherry, 1979). If there are relatively large interconnected voids or fractures, there can be rapid laminar or turbulent groundwater flow through the aquifer. Dual-porosity aquifers are often associated with karst aquifer systems, but could also include volcanic aquifers or anthropogenic settings, such as a system of mine shafts and tunnels. Approximately 10 to 20 percent of the Earth's surface is underlain by karst carbonate aquifers that supply about 25 percent of the world's population with drinking water (Ford and Williams, 1989). The rapid flow in dual porosity aquifers makes them vulnerable to contamination. The contaminants can be rapidly transported through the aquifer through the larger voids of the secondary porosity (that is, conduits; Ewers, 2006). For example, in the Floridan aquifer of the southeastern United States, karst windows and sinks provide direct connections between the surface and aquifer, resulting in increased aquifer vulnerability. Quantification of local to regional porous media flow and preferential flow in conduits is essential to quantifying this vulnerability. This setting provides an ideal example of how quantitative simulation of flow and exchanges between both porosity domains in hydrologic decision models could improve water- and land-management strategies.

Adequate quantification of dual-porosity flow in hydrologic models requires developing a mathematical formulation based on a physical representation of flow in both domains. Traditional groundwater-flow models using the groundwater flow equation to simulate flow through porous media cannot effectively account for the potentially rapid transport of water and solutes. The Conduit Flow Process (CFP; Shoemaker and others, 2008) can simulate turbulent groundwater-flow conditions of dual porosity aquifers. In systems that are strongly influenced by karst conduit flow or fracture flow, the CFP provides a means to represent these embedded flow systems through a porous media, resulting in a more complete representation of flow.

Overview

The CFP was developed in response to the need for the simulation of karst and dual porosity aquifers (Shoemaker and others, 2008). Incorporation of the CFP into MF-OWHM2 allows the simulation of flow processes in highly conductive structures, like pipe networks. The CFP simulates one-dimensional laminar and turbulent steady flow in discrete pipes according to the Darcy-Weisbach equation. Flow in discrete pipes is iteratively solved in the CFP. Discrete pipes are coupled to the matrix continuum through a head-dependent transfer function. In this way, the CFP allows the consideration of karst systems (for example, Saller and others, 2013; Xu and others, 2015a, b; Xu and Hu, 2017) or other highly conductive discrete elements, such as drainage systems or abandoned mines.

There are three modes of operation for the CFP to simulate karst and dual-porosity aquifers (Shoemaker and others, 2008). The CFP mode 1 allows simulation of relevant discrete flow structures, like karst conduits, drainage systems, or abandoned mining shafts. Conduit flow pipes can represent dissolution or biological burrowing features in carbonate aquifers, voids in fractured rock, or lava tubes in basaltic aquifers. These pipes can also be fully or partially saturated under laminar or turbulent flow conditions. Mode 1 couples the traditional groundwater-flow equation with the formulation for a discrete network of cylindrical pipes. Mode 2 may be used to represent any of the three feature types: a porous media in which turbulent flow is suspected under the observed hydraulic gradients; a single secondary-porosity subsurface feature, such as a well-defined, laterally extensive underground cave; or a horizontal preferential flow layer consisting of many interconnected voids. Mode 3 can simultaneously simulate modes 1 and 2 by coupling the discrete pipe-network formulation with a high-conductivity flow layer.

Mode 2 simulates a high-conductivity flow layer that can switch between laminar and turbulent flow and allows the representation of a dual-porosity system without definition of the individual conduit elements. This can be especially useful if knowledge of the distribution and location of karst conduits is limited and there is a regional aquifer that may represent non-discrete conduits as a secondary porosity. In addition, this mode can be useful to represent other types of secondary porosity settings, such as fractured igneous or volcanic rocks or unknown distributions of conduits in anthropogenic settings, such as networks of mine shafts and addits, water or sewer transmission tunnels, or even fractures from land subsidence or tensional faulting.

Previously, the CFP was only available in a separate release of MODFLOW-2005 called MODFLOW-CFP (Shoemaker and others, 2008). A modified CFP code has been integrated in MF-OWHM2 to allow for the simulation of dual porosity. This integrated approach increases flexibility for the application of MF-OWHM2 to a variety of hydrologic settings. Furthermore, the ability to simulate single- and dual-porosity flow using one code allows the evaluation of the importance of conduit-flow processes to model objectives. The CFP is not linked to any of the advanced packages, such as the MNW2, UZF, SFR, HFB, or to other processes such as FMP and SWR.

Improvements

The revised CFP includes selected upgrades and modifications to the original CFP (Shoemaker and others, 2008), including additional boundary conditions, input, storage, and linkages for the modular, three-dimensional, multispecies transport modeling (MT3D):

- Additional mixed boundary conditions (Cauchy, combined Dirichlet-Neumann).
- Time series as input files (for example, for boundaries—important because of highly conductive pipes).
- Additional direct storage for discrete pipe structures (CADS).
- Water release through dewatering discrete elements considered by partially filled pipe storage.
- Improved input routines (conduit height, exchange).
- New linkage between the CFP and post-processing transport routines (modified version of MT3D).

The CFP input routines and data structures are described by Shoemaker and others (2008), and the revised and upgraded features are summarized in more detail in appendix 7. Slight modifications of selected input files are described in appendix 8. Although additional examples are available in the release package of MF-OWHM2, the use of CFP is not included in the example problem presented in this report.

MF-OWHM2 Example Problem

To demonstrate the functionality of MF-OWHM2, an example problem is presented that uses the SUB, FMP, SFR2, UZF1, NWT/UPF, and MNW2 packages to demonstrate the new linkages and flow interdependencies. This example model was originally distributed with MODFLOW-FMP2 (Schmid and Hanson, 2009a), was later modified to demonstrate the effects of deformation-dependent flows (Hanson and others, 2014d), and here is further modified to show the additional linkage between FMP3 with NWT and MNW2. The problem is used to compare results with and without the new Salinity Demand function now available in FMP. Although not all features of these processes and packages are included in this example, it illustrates many of the fundamental features needed in regional hydrologic models to simulate and analyze water movement and conjunctive use by irrigated agriculture, natural vegetation, and urban areas in a supply and demand framework. A full suite of example problems that can be tested using MF-OWHM2 are included in the distribution package. This includes the LGR2 example (Mehl and Hill, 2013) with the boundary flow and head package (Mehl and Hill, 2013) and the SWR1 and Sublink example (Schmid and others, 2014; Hanson and others, 2014b). Selected input and output datasets are shown in appendix 6, and the complete datasets are included with the distribution package of MF-OWHM2. Additional example problems for CFP applications are also included in the release package for MF-OWHM2. All previous examples from all other packages are also included in the release package, including the example problems from the previous versions of FMP.

Model Structure and Input

The spatial discretization, boundary conditions, and structure of wells, rivers, canals, drains, farms, and other landscape features are summarized in [figure 11](#). The GHB at the upgradient and downgradient edge of the model domain were from the example problem accompanying the MODFLOW-FMP2 user guide (Schmid and Hanson, 2009a); these head boundaries were used for an initial steady-state stress period to develop the predevelopment boundary inflows and outflows. The steady-state stress period was followed by 10 years of the transient simulation that had monthly stress periods. The model grid consisted of 23 rows and 20 columns in a uniform, horizontal spacing of 500 meters (m) and of 7 layers having thicknesses ranging from 60 m to 94 m. The original version of this example problem (Schmid and Hanson, 2009a) used the Layer Property Flow package (LPF) and the Preconditioned Conjugate Gradient Solver package (PCG) for simulating the aquifers and solving the equations of surface-water, landscape, and groundwater flow. For this example, the combination of LPF and PCG was replaced with the Upstream Weighting package (UPW) used in concert with the Newton-Raphson solver package (NWT; Niswonger and others, 2011).

The movement and use of water across the landscape simulated by FMP were represented by eight “virtual farms” or WBSs. These WBSs included five irrigated agricultural areas, an urban area, a non-irrigated riparian wetland, and a region of natural vegetation that represented a largely undeveloped landscape surrounding the other seven WBSs (fig. 11A). It should be noted that this example problem section uses the terms “virtual farm,” Farm, and WBS synonymously. The landscape was covered by six vegetation types that represented vegetable row crops, orchards, winter grains, urban lawns and gardens, natural vegetation, and riparian vegetation. The remaining features used to simulate consumption, recharge, and runoff were summarized by Schmid and Hanson (2009a).

The model (Hanson and others, 2014d) included three model soil types (fig. 12B) and seven hydrostratigraphic layers representing four aquifers and three intercalated confining-bed layers (fig. 11B). The streambed elevations of diversion segments followed the slope of a variable ground surface at defined depths (Schmid and others, 2006; Schmid and Hanson, 2009a, p. 93), which allowed local variation in size and slope of streambeds and changes in slope resulting from land subsidence. Using the default interpolation of the SFR between streambed elevations at up- and downstream ends of diversion segments would create streambed elevations that either cut through variable morphological relief or were above the land surface. In addition, linear interpolation between different elevations would create relatively steep slopes that do not allow detection of code limitations that arise for minimal slopes using Manning’s equation (slope in the denominator leads to overestimation of stream stages). FMP was also linked to MNW2 by multi-node wells screened across several layers that supply water to Farm 5 (UZF Farm) and Farm 6 (urban area; fig. 11A). The MNW1 wells that were in the original version of this example (Schmid and Hanson, 2009a) were replaced with MNW2 wells. FMP was also linked to UZF to simulate unsaturated-zone processes under farm 5 and farm 8 to include the effects of rejected infiltration and groundwater discharge to the surface in Farm 8 (riparian area; fig. 11A).

Although all model cells did not necessarily need to be assigned to specific model farms in FMP, in this example, all model cells of the model domain were assigned to eight “virtual farms” that represent water-accounting regions. Six of these “virtual farms” were associated with Farm Wells (supply wells) for the potential delivery of groundwater, if needed (fig. 11A). There were two additional non-irrigated, rain-fed water-accounting regions that represented a riparian wetland on the eastern boundary surrounding the river outflow (virtual farm 8) and the natural vegetation in the remainder of the model (virtual farm 7). The SWR canal that was in the MF-OWHM example (Hanson and others, 2014d) was removed from this example.

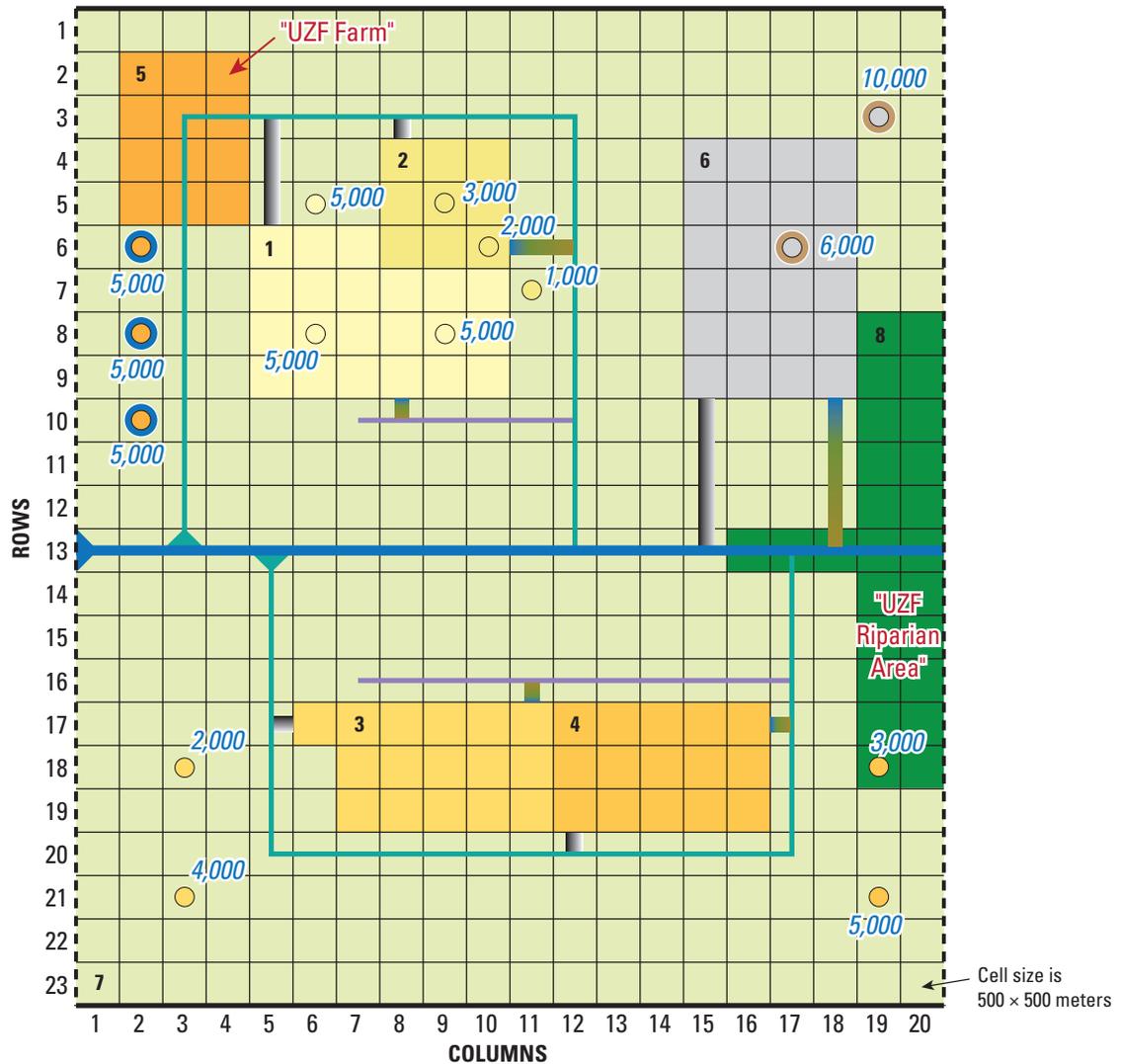
The example model included six virtual crop types that represented groups of crops aggregated by similar crop coefficients and growth-stage lengths (fig. 13). Although FMP provides the option to change the spatial distribution of crop types from stress period to stress period (representing crop rotation), in this example, the distribution of crop types did not

change through time. Crop-type 1 represented vegetable row crops consisting of 20-percent cabbage, 50-percent lettuce, and 30-percent green beans. Crop-type 2 represented apple, cherry, and walnut orchards. Crop-type 3 represented winter grains, such as barley, wheat, and oats. The landscaping of the urban area, crop-type 4, represented lawns and gardens, which were simulated with crop coefficients for turf. Crop-type 5 represented natural vegetation comprising equal areas of grazed pasture, grass and clover, a wildlife area, and non-agricultural trees and vines. Crop-type 6 represented a riparian area of willows, which can take up water under variably saturated conditions.

For each crop group, weighted averages of individual crop coefficients and growth-stage periods were computed using the percentage contribution of each individual crop. The individual values for initial-, mid-, and end-season crop coefficients as well as the periods for initial, mid, and late growth stages were compiled from published databases in various sources of literature (Allen and others, 1998, 2005; Food and Agriculture Organization, 2007). For each crop group represented by its average growth and harvest attributes, a daily time series (365 days) of crop coefficients was calculated using the “composite” crop coefficients and “composite” growth-stage periods. Finally, crop coefficients were calculated for each month of the year using the daily time series, and the 12 average monthly crop coefficients were applied to the 10-year simulation period for stress periods 1 through 12 and 13 through 24 of the example model. The monthly crop coefficients allowed the different types of vegetation to be active at different times of the year as they each cycled through their seasonal growth stages (fig. 13A). The virtual crop coefficients for the virtual crop types (crop groups) described previously were preprocessed for the example model prior to assembling the FMP data input. The technique and algorithms applied were formulated in Excel spreadsheets that also contained a compilation of crop coefficients and growth-stage time spans obtained from published sources. These Excel spreadsheets are provided in the release package of MF-OWHM2. Other approaches to preprocess crop coefficients for each model stress period are possible.

Crop-specific parameters required by the FMP include fractions of transpiration (FTR) and fractions of evaporation (FEI) related to precipitation and irrigation for the six crop groups. The separate simulation of transpiration and evaporation is an essential difference between FMP and many other hydrologic models, which assume a common extinction depth for a composite evapotranspiration term. In FMP, evaporation from groundwater is extinct at a depth to water equal to a specified capillary fringe, and transpiration from groundwater is extinct at a depth to water equal to the root zone plus the capillary fringe. The example problem simulated crop transpiration under unsaturated conditions (crop-types 1 through 5) as well as saturated conditions (for example, crop-type 6 simulated as riparian willows) by analytical solutions. Fractions of transpiration and evaporation were varied by month (figs. 13B–C).

A



Farms—Number and activity

Irrigated		Non-irrigated	
1	Agriculture	7	Native vegetation
2	Agriculture	8	Riparian vegetation
3	Agriculture		
4	Agriculture		
5	Agriculture		
6	Urban landscape		

Streamflow routing network (SFR)

- Inflow into stream, Odd years: 100,000 cubic meters per day Even years: 50,000 cubic meters per day
- Diversion into canals, Odd years: 10,000 cubic meters per day Even years: 8,000 cubic meters per day

EXPLANATION

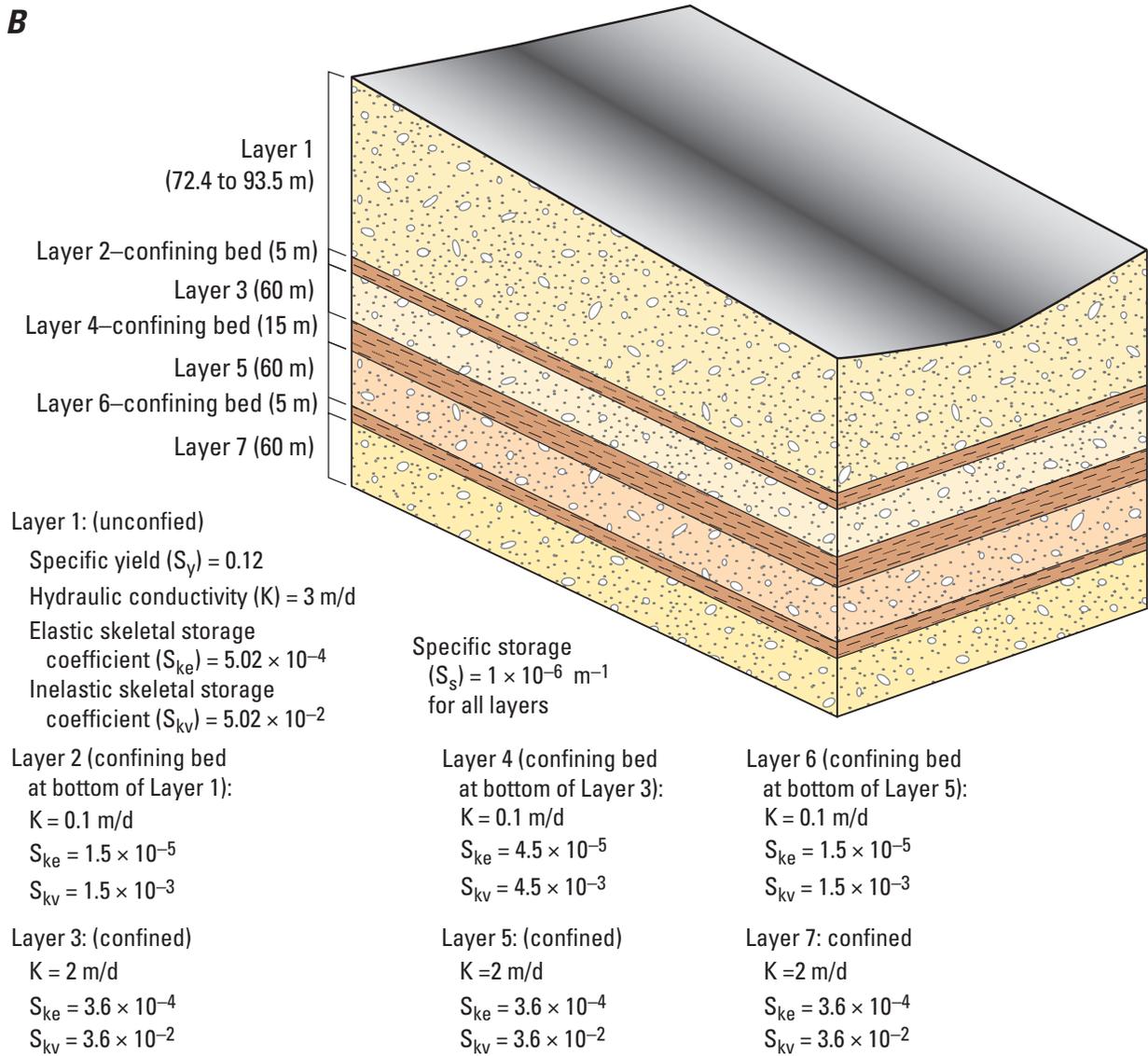
- Semi-routed deliveries
 - Semi-routed remote return-flow locations
 - No-flow boundary
 - General-head boundary
 - Stream (6-meter width), $K_v = 0.2$ meter per day
 - Canal (3-meter width), $K_v = 0.01$ meter per day
 - Drain (3-meter width), $K_v = 1$ meter per day
- K_v is vertical hydraulic conductivity

Wells (pumping from layer 1 unless multi-node)—Supply to

- Farm 1
- Farm 2
- Farm 3
- Farm 4
- Farm 5
- Farm 6
- Multi-node farm well screened in layers 1, 3, 5, and 7
- Multi-node farm well screened in layers 3, 5, and 7
- 5,000 Maximum pumping capacity, in cubic meters per day

Figure 11. Example model structure and features: A, plan view of model domain, grid resolution, boundary conditions, distribution of farms and Farm Wells (supply wells), and streamflow-routing network with points of diversion to farms, points of return flow from farms, and surface-water canal traversing an urban area; B, block view of model layering; and C, simulated land subsidence (from Schmid and others, 2014; Hanson and others, 2014d).

B



C

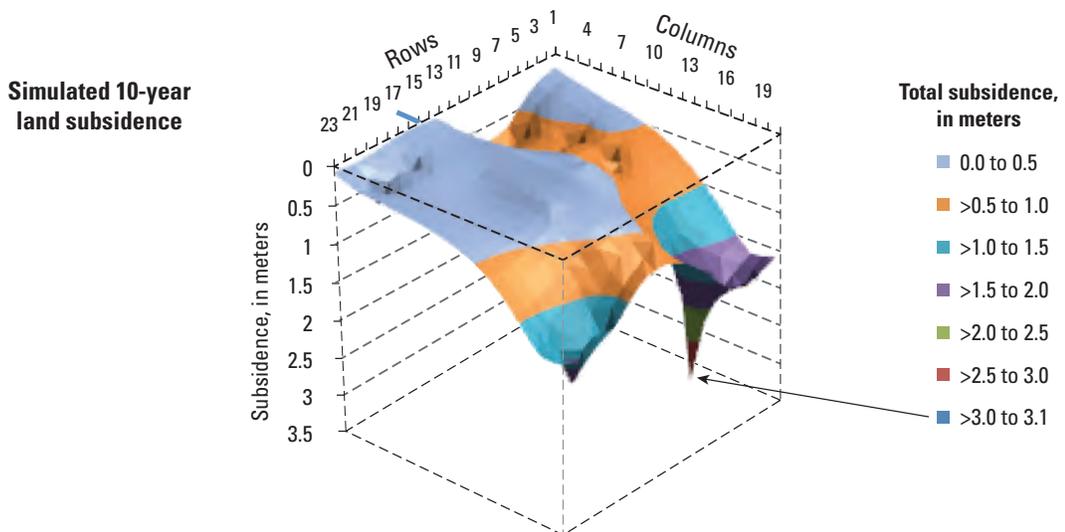
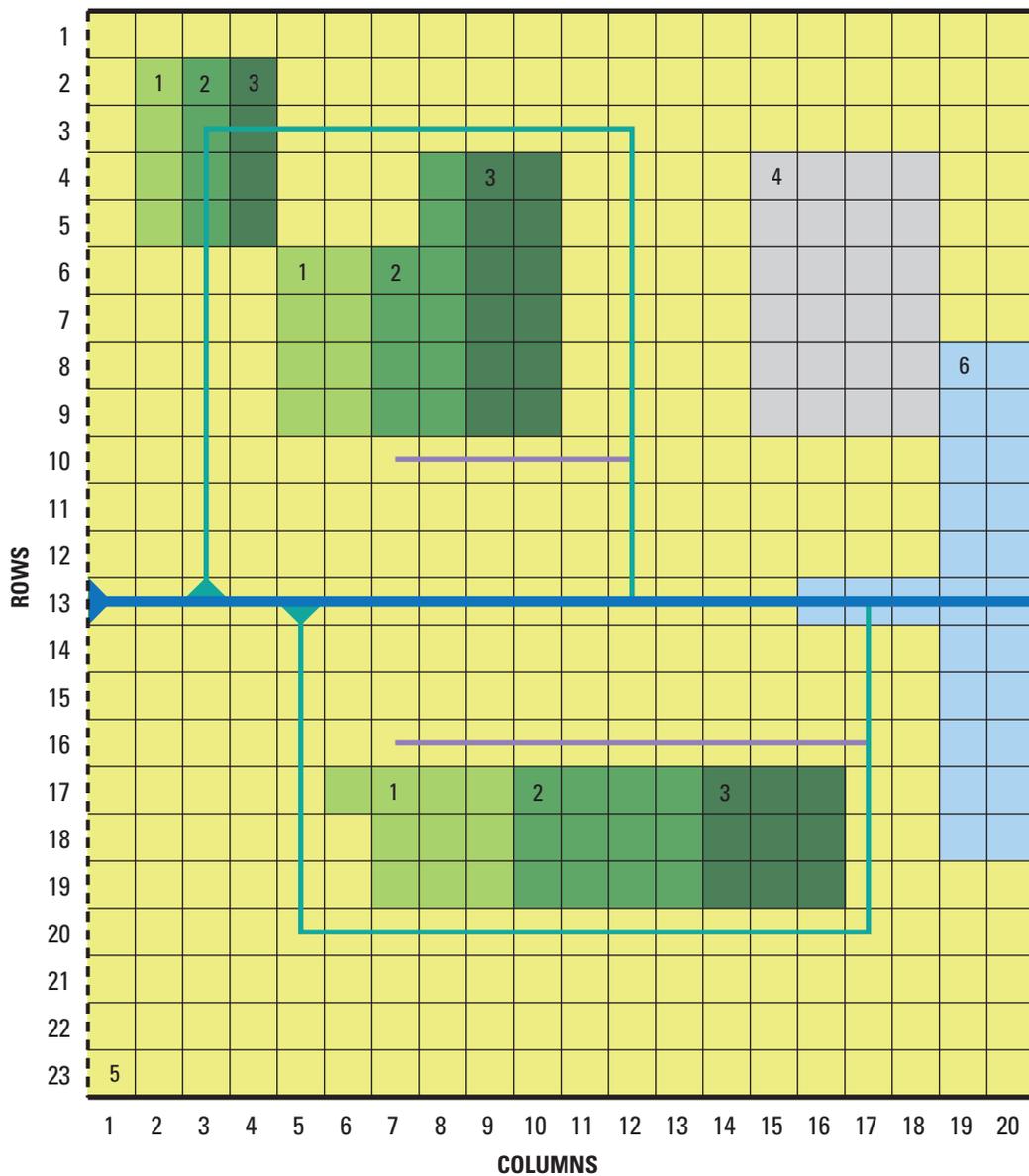


Figure 11. —Continued

A



EXPLANATION

Crop or vegetation type—

- 1** Vegetable row crops
(20% cabbage, 50% lettuce,
30% green beans)
- 2** Orchards
(33% apples, 33% cherries,
33% walnuts)
- 3** Winter grains
(33% barley, 33% wheat,
33% oats)

- 4** Irrigated urban
(lawns and gardens
simulated as turf)
- 5** Native
(25% pasture-grazed, 25% grass-clover,
25% wildlife area, 25% nonbearing trees
and vines)
- 6** Riparian
(willows)

- Inflow to stream
- Diversion to canals
- No-flow boundary
- General-head boundary
- Stream (6-meter width)
- Canal (3-meter width)
- Drain (3-meter width)

Figure 12. Model grid of MF-OWHM2 example problem showing A, crop and other vegetation distribution, and B, distribution of soils (Schmid and Hanson, 2009a).

B

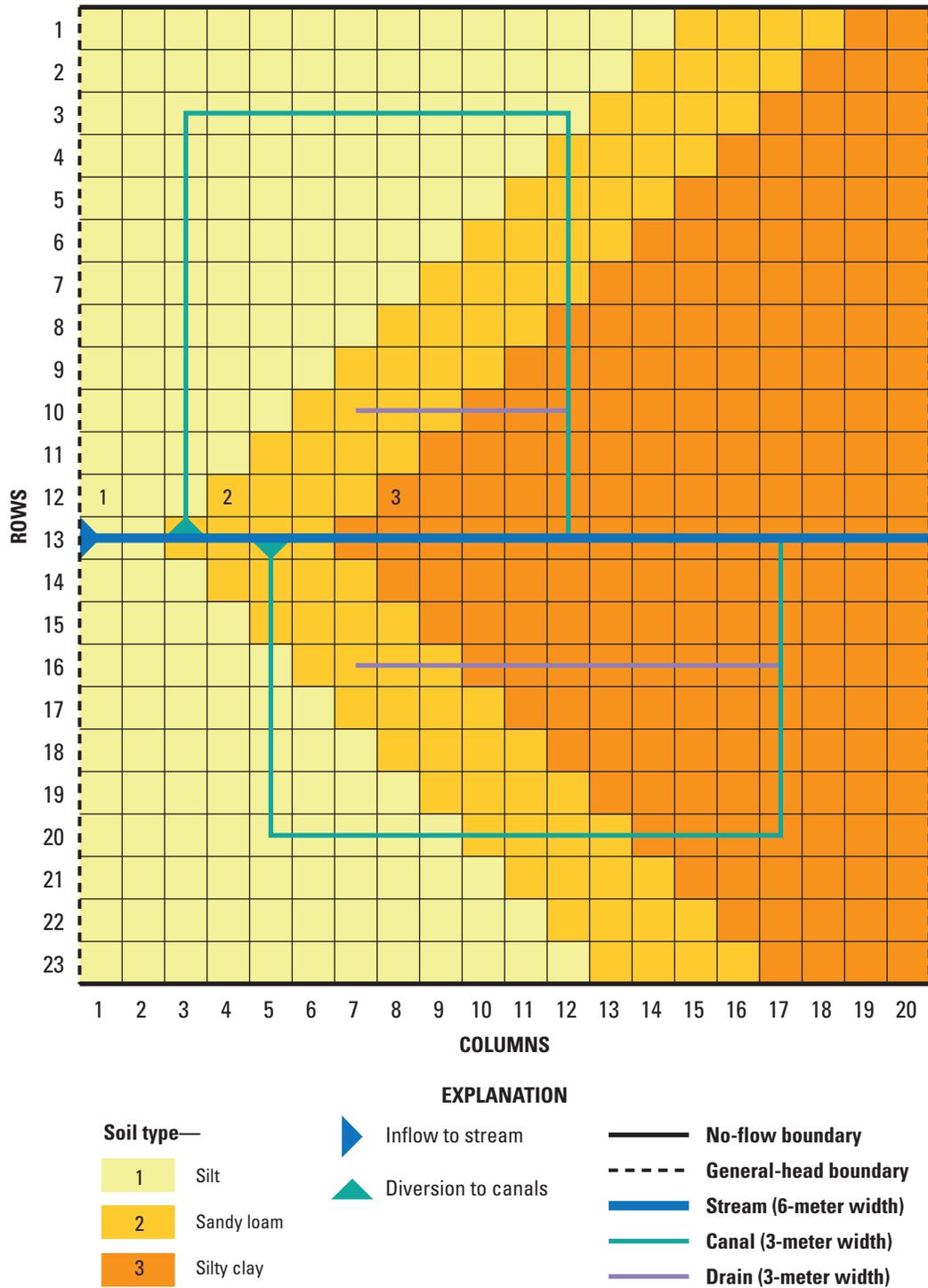


Figure 12. —Continued

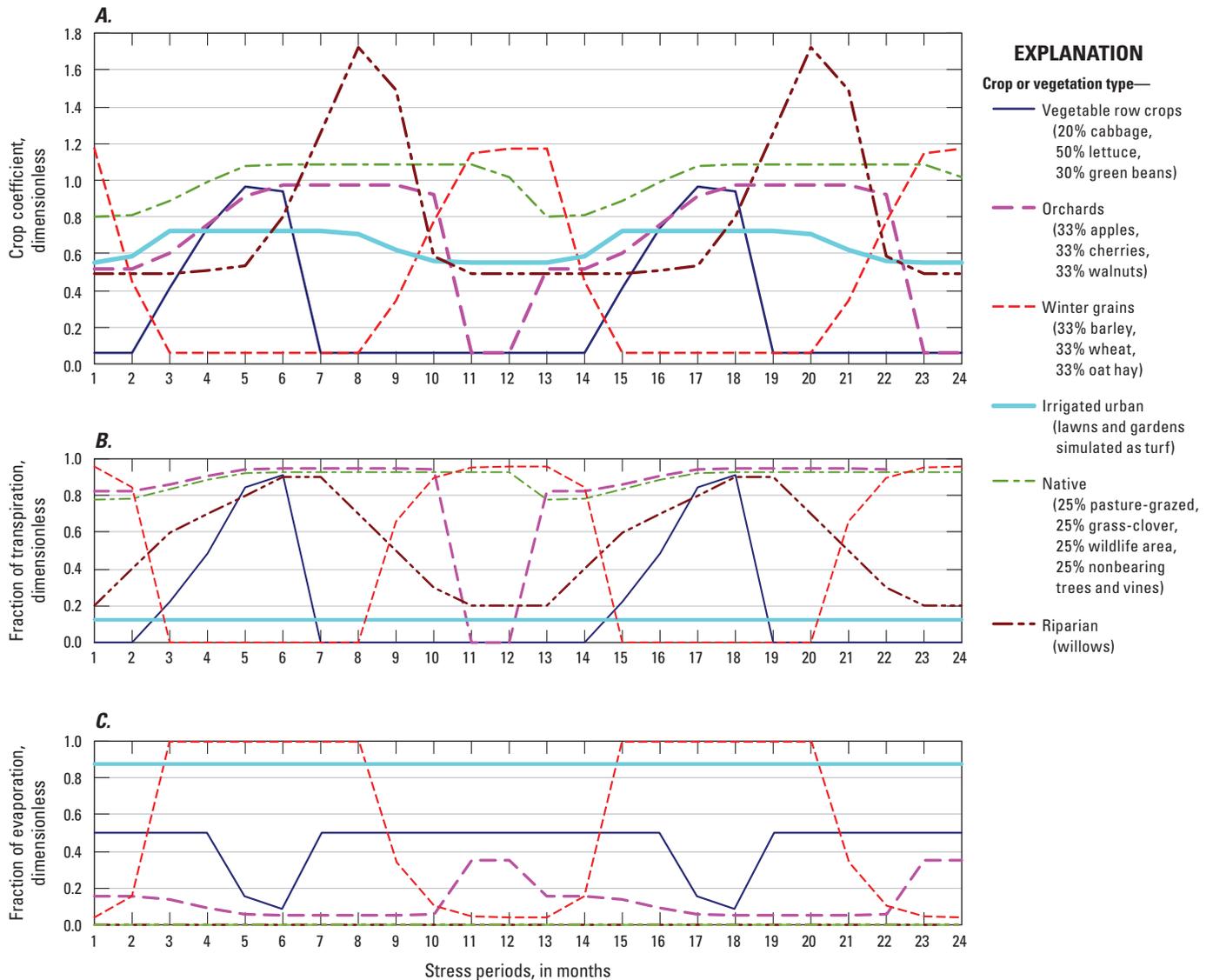


Figure 13. Results for the six virtual-crop types as monthly time series for the MF-OWHM2 model problem (Schmid and Hanson, 2009a): *A*, crop coefficients, K_c ; *B*, fractions of transpiration, FTR ; and *C*, fractions of evaporation related to irrigation, FEI .

The fraction of transpiration, FTR , can be derived as $FTR = K_{cb}/K_c$ if, in addition to the total crop coefficient, K_c , a “basal” crop-transpiration coefficient, K_{cb} , is available (Allen and others, 1998, 2005; Food and Agriculture Organization, 2007). The fraction of evaporation for exposed areas wetted by precipitation, FEP , depends on the exposed bare-soil surface wetted by precipitation. Even though transpiration and evaporation may be related nonlinearly, for the virtual crop-types 1 through 3 and 5 in this example model, we simplified the fraction of evaporation to be equal to the complement of the fraction of transpiration—that is, $FEP = 1 - FTR$. The fraction of evaporation related to irrigation (FEI) depends on the fraction of the bare-soil surface wetted by irrigation. Unlike the soil surface wetted by precipitation, the exposed areas wetted by irrigation may not be entirely wetted. The extent to which the exposed area is wetted depends on the irrigation method used, which commonly is related to the

specific crop type. For the virtual crop-types 1 through 3 in the example model, the fraction of transpiration related to irrigation was assumed to be constrained by the lesser of complement of the fraction of transpiration or the wetted fraction, fw , for certain irrigation methods (Allen and others, 1998; Allen and others 2005; Food and Agriculture Organization, 2007). That is, $FEI = \min[1 - FTR, fw]$. Fractions of transpiration and evaporation are FMP parameters that often are uncertain, and MF-OWHM2 models are sensitive to these parameters (Schmid and others, 2008). The demonstrated approach is one of many ways the fraction of transpiration and evaporation can be either physically based or based on published data. Rough initial estimates of these fractions may be specified, but the user is advised to refine these parameters using estimates derived during the model-calibration process.

For the urban area (crop-type 4), the fraction of transpiration was assumed to be equal to the fraction of the entire area in which there is transpiration (for example, turf and gardens). In many cases, land-use surveys specify the percentage of irrigated land in urban areas. In the example model, an average value of percentage range (for example, 12.5 percent as the average of 0 to 25 percent) was used to represent the fraction of the area (that is, 0.125) in which there was transpiration. The fraction of evaporation was then assumed to be equal to the fraction of the entire urban area that was open and exposed (such as housing and other buildings, parking lots, industrial sites, airports). For the natural vegetation (crop-type 5), the fraction of evaporation related to irrigation was specified using placeholder zero values because no irrigation was applied. For riparian vegetation (crop-type 6), the fractions of transpiration and of evaporation related to precipitation were assumptions. No basal crop coefficients, K_{cb} , were found in published sources that could be applied. The fractions of evaporation related to irrigation were also placeholder zero values because no irrigation was applied.

The model represented three soil types that are internally defined by the FMP as silt, sandy loam, and silty clay (fig. 12B). Root depths were specified for all crop types for every stress period (IRTF1 = 2); the depths were varied for some of the crop types, such as vegetable row crops and winter grains, but were held constant for the others. For the example model, the maximum rooting depth used was the average of values available from Allen and others (1998, table 22) and Brush and others (2006). For perennial crops such as orchards and turf or for natural and riparian vegetation, the rooting depth was assumed to be constant through time. For annuals like vegetable row crops and winter grains, the root-zone depth was assumed to vary proportionally to the crop coefficient of each stress period using a proportionality factor equal to the ratio of maximum rooting depth to maximum crop coefficient. This algorithm is used when the crop coefficient increases or remains constant at its maximum or minimum.

$$\begin{aligned} RZ^t &= \left(\frac{RZ_{\max}}{K_{c-\max}} \right) \times K_c^t, \text{ if } K_c^t \geq K_c^{t-1} \text{ or } K_c^t = K_{c-\min} \\ RZ^t &= RZ^{t-1}, \text{ if } K_c^t < K_c^{t-1} \text{ and } K_c^t \neq K_{c-\min} \end{aligned} \quad (36)$$

where

t	is the time index,
RZ^t	is the root-zone depth at time t (L),
K_c^t	is the crop coefficient at time t (-),
$K_{c-\max}$	is the maximum crop coefficient (-), and
$K_{c-\min}$	is the minimum crop coefficient (-).

During the final stress period of the growing season, the crop coefficient declined until harvest. Nevertheless, the maximum root zone reached during the growth mid-period was assumed to remain at the maximum until the

crop coefficient dropped to the off-season minimum value corresponding to harvest or senescence.

Fractions of inefficient losses (delivery losses) to surface-water runoff were specified for each virtual crop type in each stress period. In the FMP, surface-water runoff is assumed to depend on irrigation methods, which in turn may depend, in part, on the crop type. Because rainfall intensity and irrigation application methods also influence runoff, the FMP requires input of two separate fractions of inefficient losses to surface-water runoff—one related to precipitation (FIESWP) and another related to irrigation (FIESWI)—which may be omitted or set to placeholder zero values for non-irrigated crop types, such as natural (crop-type 5) and riparian vegetation (crop-type 6). In the example model, FIESWP and FIESWI were held constant through time for crop-types 1 through 4. The FIESWP increases for natural (crop-type 5) and riparian vegetation (crop-type 6) during the winter–spring months, however, indicating an increased fraction of inefficient losses to runoff during the heavy winter–spring precipitation typical of the climate in Davis, California. Additional runoff components were calculated by the UZF-FMP link for farm 5 and the riparian area (farm 8) stemming from infiltration in excess of the saturated hydraulic conductivity, the groundwater discharge to land surface, and rejected infiltration for high groundwater levels. In the FMP, two flags indicate the design of the runoff return-flow routing system (see later). In the UZF1, a two-dimensional integer array, IRUNBD, specifies the SFR streamflow segment in which the potential runoff is returned to the river for each UZF-active cell (Schmid and Hanson, 2009a, appendix A).

Crop-specific parameters, such as crop coefficients, root-zone depths, fractions of transpiration and evaporation, and fractions of inefficient losses to surface-water runoff, can vary by stress period. In contrast, pressure heads that define stress-response function coefficients are the only crop-related set of parameters specified for the entire simulation. Notably, in the FMP, a stress-response function (appendix 5) can define unsaturated and saturated conditions by specifying negative and positive pressure heads, respectively. In the example model simulation, the stress response of riparian willow trees (crop-type 6) to water uptake was described by a stress-response function, in which the optimal uptake was in unsaturated conditions, but reduced uptake was still possible in saturated conditions, until the pressure head reached 20 centimeters and uptake became zero (Schmid and Hanson, 2009a, appendix A, file PSI.IN).

Reference evapotranspiration and precipitation were set to be constant within each monthly stress period, but to vary from stress period to stress period. The input data were derived from the California Irrigation Management Information System (CIMIS) data from the weather station at the University of California, Davis (<http://www.cimis.water.ca.gov/cimis/data.jsp>, accessed April 20, 2009). For each month of the year, a median was determined from the monthly values from water year 1982 to 2008.

Surface-water deliveries to irrigated farms included non-routed water transfers from outside the model domain and equally appropriated semi-routed deliveries along a streamflow-routing network simulated using the SFR2 Package. Non-routed deliveries (NRDs) were assumed to be known volumes of deliverable water for each stress period (Schmid and Hanson, 2009a, appendix A, file NRDV.IN). The NRDs were supplied to all but the natural vegetation and riparian areas using a variable monthly scale factor that changed the volume of the NRDs through the course of each model year (Schmid and Hanson, 2009a, appendix A, file NRDFAC.IN). Semi-routed surface-water deliveries to irrigated farms were diverted from specified stream reaches (Schmid and Hanson, 2009a, appendix A, file SRD.IN) outside the farm domain. The term “semi” is used to describe the routing for two reasons:

- A. Deliveries are routed along the stream network to a user-specified point of diversion.
- B. Deliveries are non-routed (for example, pipe flow) from the user-specified point of diversion (perceived as ‘remote head-gate’) to the farm.

Semi-routed runoff was returned to the stream network (simulated by SFR2) at a specified location only for virtual farm 1 (Schmid and Hanson, 2009a, appendix A, file SRR.IN). For all virtual farms other than virtual farm 1 (that is all WBS other than 1), FMP automatically prorates runoff to all SFR stream reaches within the WBS. For three farms, virtual-farm 5, the natural vegetation (virtual-farm 7), and the riparian area (virtual-farm 8), stream segments were found within the domain of each farm, and each farm’s return flow was prorated to those reaches accordingly. An output file, ROUT.OUT, was written that informs the user about the system of routing deliveries to, and runoff away from, each virtual farm (Schmid and Hanson, 2009a, of which appendix A contains the part of the file that pertains to stress-period 1, time-step 1).

The data input for linked packages is included with the model distribution package, and the reader is referred to the NWT, SFR2, UZF1, SWR1, and MNW2 input instructions for more complete explanations of the NWT, SFR2, UZF1, SWR1, and MNW2 data input used in the example model (Niswonger and Prudic, 2005; Niswonger and others, 2006, 2011; Hughes and others, 2012; Konikow and others, 2009). The streamflow network and its hydraulic properties are summarized in [figure 11](#) along with the location and screening of multi-node wells.

The FMP input features for this example model included temporally distributed precipitation as a specified-flux boundary condition typical of the rainfall for Davis, California, in the Sacramento and San Joaquin Valleys (also known as the Central Valley). This helps facilitate delayed recharge following time-varying supplies from precipitation and irrigation to crops, urban areas, and natural vegetation. The FMP also used semi-routed deliveries and return flows to connect agriculture with surface water derived from the river ([fig. 13A](#)). The distribution of crops demonstrates the

combined use of precipitation and irrigation for winter wheat as opposed to surface and groundwater supplies for irrigation of orchard and vegetable crops grown during the spring and summer.

The SUB Package used steady-state heads from the previous version of the example model as critical heads to enable simulation of subsidence with the onset of pumping. This implies the system is assumed to be normally consolidated at the beginning of the simulation. To ensure that the pumping provided sufficient drawdowns to drive subsidence, the transient model was extended to a 10-year model by repeating the 2 years of monthly stress periods from the FMP model five times. The subsidence package input dataset contains elastic and inelastic specific-storage coefficients (S_{ske} and S_{skv}) of 6×10^{-6} and 6×10^{-4} per meter, respectively, for fine-grained interbeds of all aquifer layers and of 3×10^{-6} and 3×10^{-4} per meter, respectively, for all confining bed layers ([fig. 11B](#)). Subsidence was assumed to be instantaneous, with no-delay interbeds or confining beds, and was active in all cells of all model layers. Land subsidence ranged from 0 to 3.1 m and was greatest under the city, near the urban supply wells, after the 10 years ([fig. 11C](#)).

Salinity Demand

This example demonstrates the simulation of additional demand for irrigation required for leaching salts from the soil zone. The salinity demand can be selectively applied to specific crops and to specific virtual farms (WBSs). In this example, the salinity demands were applied to the five agricultural virtual farms (WBS 1–5) for all the crop types (vegetable row crops, orchards, and winter wheat) and to the urban farm (WBS 6) for the urban landscape (turf grass). The RHOADES option was used in the salinity block to estimate the leaching requirement and the applied water. The crop salinity tolerances were specified from previously published values (Cahn and Bali, 2015; Ayers and Wescott, 1985), and vegetable row crops were represented by strawberries (640 mg/L), orchards represented by grapes and almonds (960 mg/L), grains represented by winter wheat (3,840 mg/L), and urban landscape represented by turf grass (704 mg/L). The salinity of the water sources was set to values typical of some of the coastal California basins with user-specified constant salinities for surface-water (309 mg/L), groundwater (216–340 mg/L), and nonrouted deliveries (510 mg/L for agriculture and 610 mg/L for the urban farm receiving recycled water). The irrigation uniformity represents how uniformly the irrigation is applied with respect to a crop’s root depth, where a value of 1 indicates perfectly uniform, and 0.5 is 50 percent of uniform. The irrigation uniformity with respect to depth in the root-zone varied by irrigation type and was set to 0.80 for sprinkler-soaker hose, 0.85 for drip, 0.75 for pivot irrigation, and 0.9 for urban sprinkler.

Unsaturated Flow

The linkage to the UZF1 package facilitated delayed recharge through the unsaturated zone in the upgradient (western) part of the example model domain, such as at virtual farm 5 (fig. 11A). This linkage also allowed simulation of rejected infiltration in the riparian areas in the discharge region along the river outflow at the eastern part of the model domain (virtual farm 8; fig. 11A). The areas where this linkage was active (specified through the UZF Package input in the IUZFBND array) were coincident only with virtual farm 5 and the riparian area (virtual farm 8). The additional unsaturated-zone properties specified included a Brooks-Corey epsilon of 0.35, a saturated water content of 0.2, an initial water content of 0.16, and a saturated vertical hydraulic conductivity in the unsaturated zone of 0.001 meters per day. The relationship between the land surface and the initial water table at the peak of growing season when water demand caused the water table to lower in model-layer 1 for the unsaturated zone beneath virtual farm 5 is shown in figure 14.

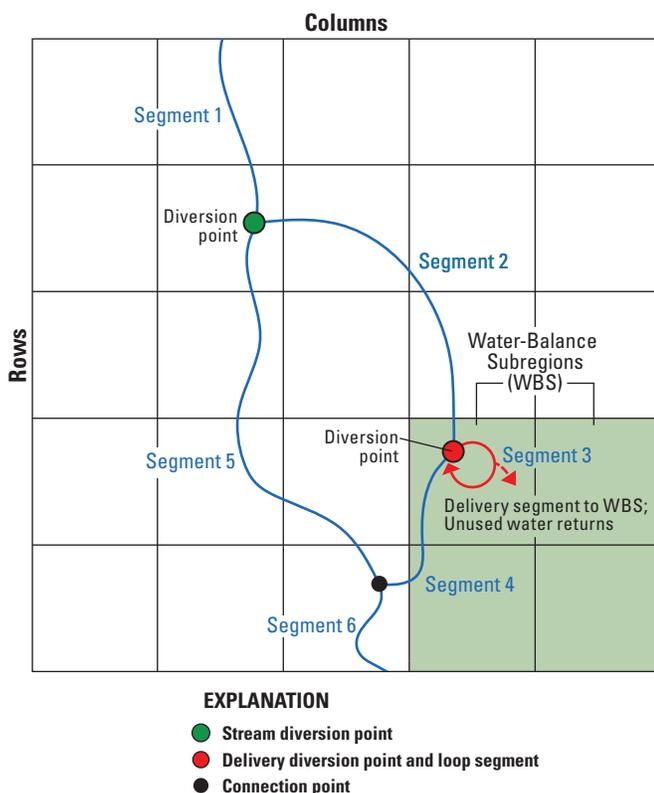


Figure 14. Relation between the land surface and the water table in an unsaturated zone from the MF-OWHM example (modified from Schmid and Hanson, 2009a).

Model Results

Results from the example model are used here to demonstrate how salinity demand, surface-water operations, and unsaturated-zone flow (or rejection) of infiltration were represented by the model.

Salinity Demand

The effects of salinity demand resulted in a large increase in irrigation demand for all the different landscapes and WBSs (fig. 15). The increases in irrigation demand to account for salinity leaching ranged from 22 to 38 percent and varied among the farms. Farms with more vegetable row crops had greater leaching requirements, with the most additional irrigation required for virtual farms 3 and 5 and least for the urban landscape of virtual farm 6. These different farms also required greater percentages of additional irrigation for leaching during the spring and fall (fig. 15A). Because each of these WBS received different amounts of surface-water and non-routed deliveries, the additional portions of groundwater needed to accommodate salinity leaching also varied among the WBS and from month to month (fig. 15B). The additional leaching demand can also result in variably increased irrigation among crops (fig. 15C). In this example, the increase was 22 to 43 percent for vegetable row crops in farms 1, 3, and 5, which have a lower salinity tolerance, whereas the increase was 24 to 34 percent for orchards in farms 2 and 4. Winter grain crops, which made up more than 60 percent of the land use for farms 2 and 4 and received winter precipitation to supplement irrigation, still required a 36-percent increase in irrigation for leaching. This additional irrigation demand can trigger adverse effects, such as reduced surface-water deliveries, land subsidence, and reduced streamflow, any of which can be an important consideration for management of conjunctive use. Such considerations are becoming increasingly relevant with the passage of groundwater laws, such as the Sustainable Groundwater Management Act (State of California, 2014). Other types of water demand for uses like dust control, frost protection, and pest control could also be simulated with this feature and user-specified equations that represent when those additional applications would be needed.

Unsaturated Flow

The effects of unsaturated flow are demonstrated in the example model beneath virtual farm 5 in the northwestern part of the model grid and the beneath the riparian area (virtual farm 8) where the UZF package was activated and beneath these water-balance subregions. Beneath virtual farm 5, there was a relatively large unsaturated zone that delayed recharge about 153 days in the middle of 2004 (fig. 16A). Similarly, the effects of rejected infiltration were apparent beneath the riparian area (virtual farm 8) for about a month during the same time (fig. 16B).

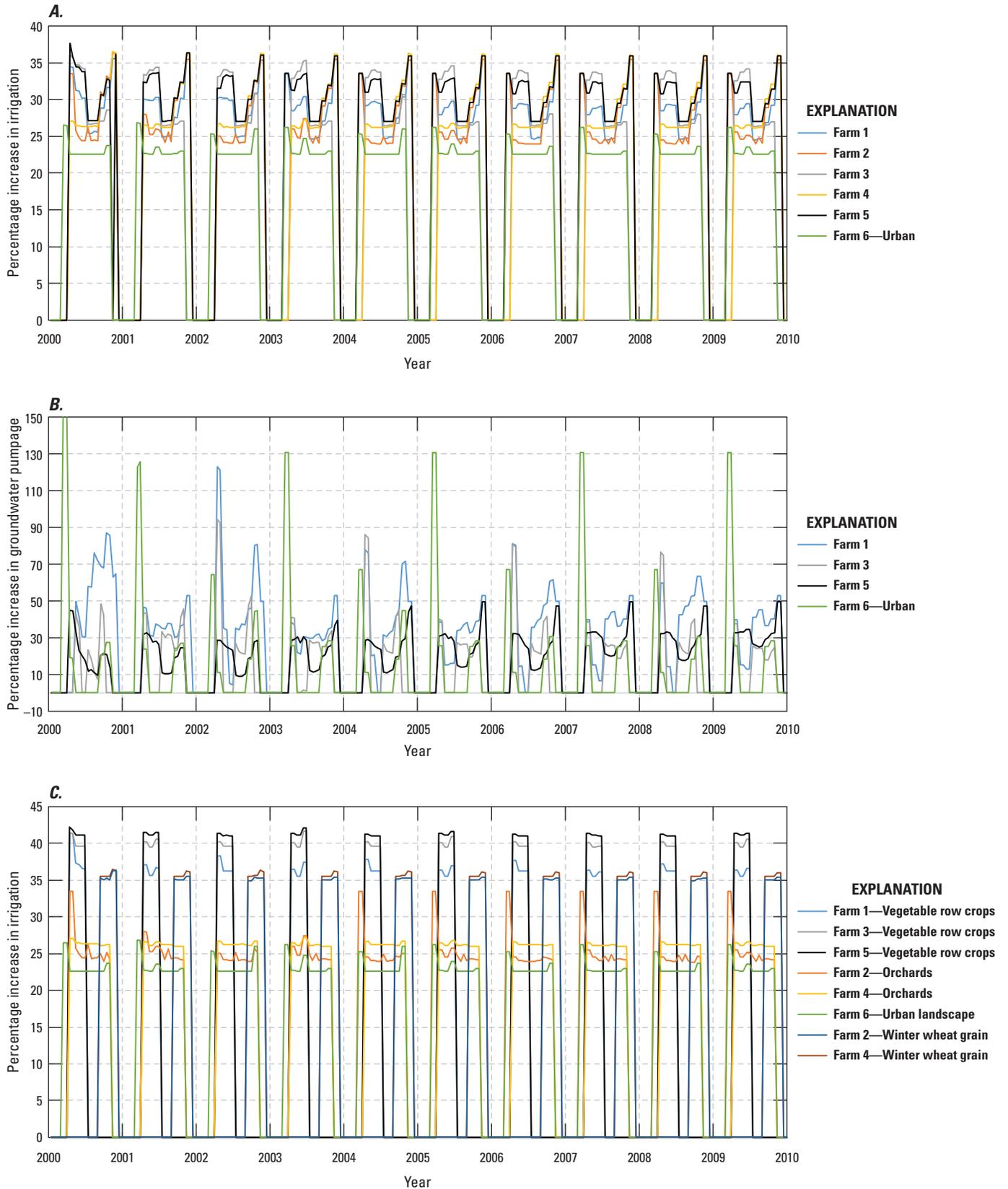


Figure 15. Relative increase with leaching among simulations from the example model with and without the salinity demand option: *A*, irrigation, *B*, groundwater pumpage, and *C*, additional irrigation for selected crops and farms.

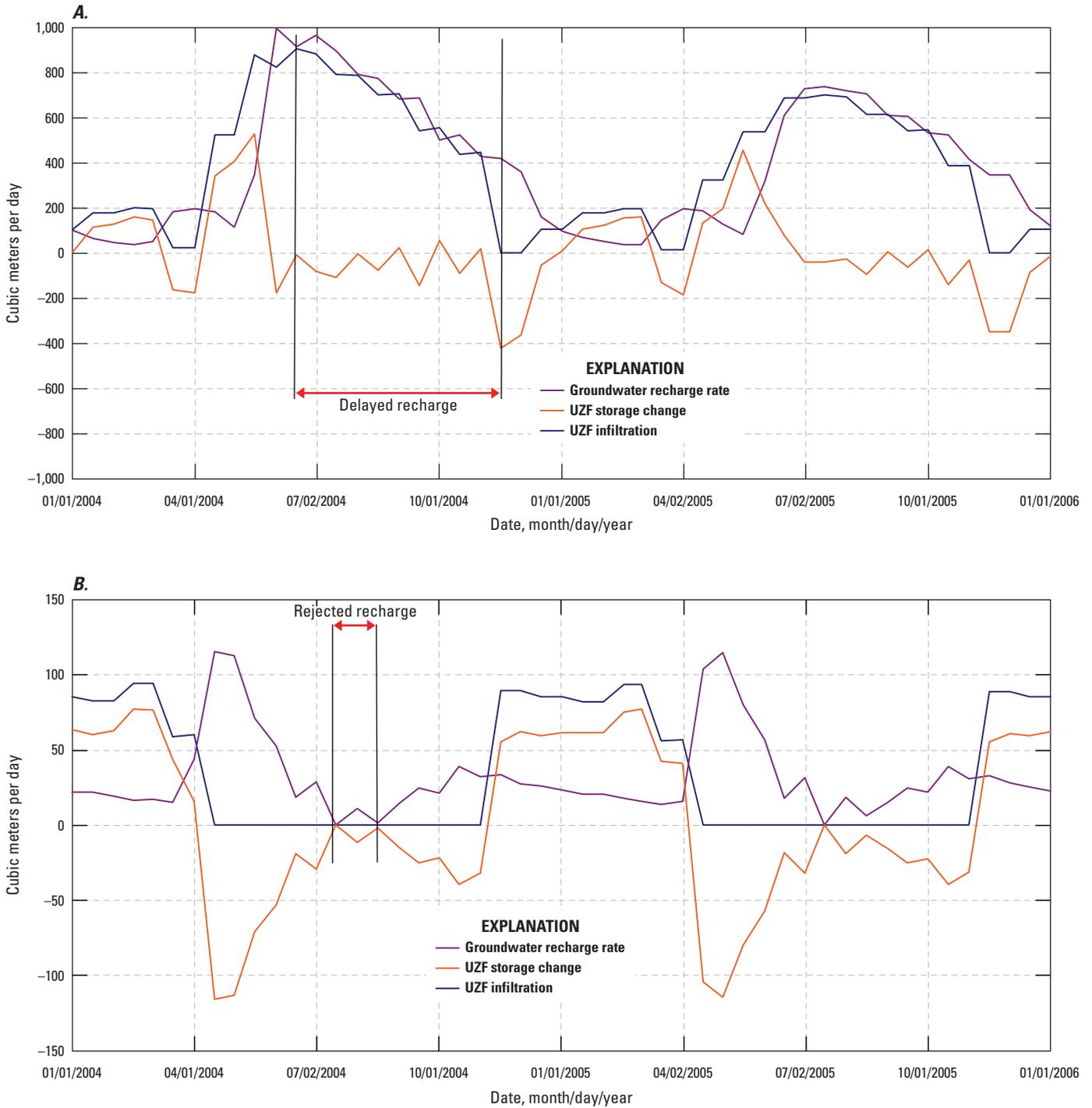


Figure 16. Results from the example model of the effects of unsaturated zone (UZ) on *A*, delayed recharge beneath farm 5, and *B*, rejected recharge beneath the riparian area (farm 8).

Limitations and Future Improvements

In MF-OWHM2, if the natural water supply—root groundwater uptake and precipitation—is not enough to satisfy demand, the remaining water is obtained from supplies in a specific order that cannot be changed. The order is always as follows: non-routed deliveries, that is water delivered without simulating its conveyance; surface-water delivery, that is, water diverted from a surface-water network; any remaining demand is supplied by groundwater pumping. This order of water-supply consumption is typical for the western United States, but it may not be applicable to other parts of the world or areas that give preference to groundwater pumping over surface-water deliveries. In a potential update to MF-OWHM2, a user-specified order for sources of supply would be possible.

Soil moisture is assumed to reach steady-state flow within a single time-step; unsaturated flow can be simulated with the unsaturated-zone flow package (UZF). Soil-moisture studies completed as part of the initial release of the farm process (FMP1; Schmid, 2004) indicated that this assumption is valid for time steps equal to or greater than 1 day (24 hours). It is recommended that time-step period be greater than 1 day for the FMP to simulate land use and the related soil moisture conditions. A separate software module which could be subsequently included in MF-OWHM2 is an approximation of the Richards equation for a more accurate simulation of soil-moisture dynamics.

This release of MF-OWHM2 does not simulate small scale on-farm storage (small ponds/storage tanks). This practice typically is used on farms to reuse water multiple times or capture runoff from precipitation events.

As of 2020, MF-OWHM2 does not include a direct, internal simulation of snowmelt, permafrost simulation, mountainous-watershed rainfall-runoff process, or atmospheric moisture-content effects. Snowmelt is treated as an inflow boundary condition that is calculated outside of the model. If detailed rainfall-runoff information is required, then a companion watershed model can be developed. Such a companion model may also serve to generate the inflow of the stream network along the model domain boundary. Atmospheric moisture may be accounted for indirectly by optionally specifying a pan evaporation rate, reference evapotranspiration, and precipitation. These features are not included in order to ensure that simulation runtime remains short enough to enable automated methods of calibrating model parameters to field observations, which typically

require a large number of model runs. The MF-OWHM2 development approach is to include as much detail in hydrological processes as possible, while simulation runtimes remain reasonable enough to allow for robust model validation, verification, and predictability.

Some additional limitations and abilities have been summarized in several model comparisons of selected integrated hydrologic model (IHM) codes, such as MODFLOW-FMP and the Integrated Water Flow Model (IWFM; Dogrul and others, 2011; Schmid and others, 2011; Dogrul, 2009a, b) and MF-FMP, IWFM, and Hydrogeosphere (Therrien and others, 2010; Harter and Morel-Seytoux, 2013). Other fine-scaled comparisons of the MF-FMP simulated groundwater uptake as ET to empirical methods have also been done (Liu and Luo, 2012).

Water quality is only included with the LMT link to MT3DMS and MT3DMS-USGS. This link supports only groundwater and surface-water flow through the streamflow routing package (SFR). At this point, there is no link to soil-moisture transport, transport that results from evapotranspiration and its effect on actual evapotranspiration, or from applied water that has a different chemistry than the groundwater in the area where it is applied.

Although several versions of MODFLOW have been integrated in MF-OWHM2, there are some compatibility issues that remain between packages. The Sea Water Intrusion package (SWI) does not support groundwater wells represented by the MNW1 or MNW2 packages. Combining the NWT formulation and LGR can present difficulties for convergence of flows across parent and child model boundaries given the way that conductance in rows and columns is specified in the upstream weighting package. The HFB2 package flow-routing feature in MF-OWHM2 is incompatible with other post-processing programs, such as MODPATH and ZoneBudget. Note that compatibility issues with other packages have been fixed in MF-OWHM2. For instance, the NWT can operate properly with the subsidence packages SUB and SUB-WT. Because of potential linkages between packages and processes, certain program structures and programming features and protocols need to be followed if developers want to add other features to MF-OWHM2. For example, the addition of a landscape-based feature to MF-OWHM2 requires careful implementation to be connected to the subsidence-linkage option. A description of ways modifications can be made to MF-OWHM2 for specific applications is beyond the scope of this document.

Summary and Conclusions

The One-Water Hydrologic Model (MF-OWHM2) is an integrated hydrologic model (IHM). It is a nearly complete version of the MODFLOW family of hydrologic simulators. It includes comprehensive functionality for the analysis of a broad range of conjunctive water-use issues. MF-OWHM2 simulates and can aid analyses to improve management of multiple components of human and natural water movement and use in a physically based supply and demand framework. MF-OWHM2 is based on the farm process of MODFLOW-2005 (MF-FMP3) combined with local grid refinement to allow use of the Farm process (FMP) and streamflow routing (SFR) in embedded grids. The ability to use embedded models allows for the use and linkage of models developed by local water agencies in the framework of regional models that simulate the entire watershed.

MF-OWHM2 combines several existing capabilities, including the surface-water routing process (SWR) and riparian evapotranspiration (RIP-ET); a broad range of solvers, such as Newton-Raphson (NWT) and nonlinear preconditioned conjugate gradient (PCGN); and simulates reservoir operations through linkage to SWO (Ferguson and others, 2016). MF-OWHM2 can simulate deformation-, flow-, and head-dependent flows, and also includes an upgrade for the salinity demand for additional irrigation. Deformation-dependent flows are simulated through the optional linkage to simulate land subsidence by a vertically deforming mesh. Flow-dependent flows include linkages between the updated SWR with SFR and the FMP, as well as connection to embedded models for the SFR and FMP through the LGR and DRT (drain return flows). Head-dependent flow processes include a modified Hydrologic Flow Barrier Package that allows optional transient HFB capabilities and flow between any two layers adjacent along a depositional or erosional boundary or displaced along a fault. The expansion of the subsidence package allows easier parameterization and separation of the elastic and inelastic deformation, which enables better representation and estimation of land subsidence. Additional features include an ExpressionParser in the multiplier package, as well as a more systematic time-series input for SFR, GHB, SWR, WEL, and MNW packages. The salinity demand option is embedded in the FMP and allows for flow-dependent application of additional water to prevent salt accumulation. Finally, support for SWO allows for flow-dependent linkage between allocation of water from a reservoir-based project and the conveyance and demands at multiple levels on and off the model grid. These added features facilitate a more physically based parameterization and the

fundamental input structures needed to build self-updating models for operational and forecasting analysis.

MF-OWHM2 represents a complete hydrologic model that fully links the use and movement of groundwater, surface water, and imported water for consumption by irrigated agriculture, as well as water used in urban areas and by natural vegetation. Supply and demand components of water use are analyzed under demand-driven and supply-constrained relationship. From large- to small-scale settings, MF-OWHM2 has capabilities to simulate and analyze historical, present day, and future conjunctive-use conditions. MF-OWHM2 is especially useful for the analysis of agricultural water use for which few data are available for pumpage, land use, or agricultural practices. MF-OWHM2 characteristically keeps water in the simulation and reduces the water not accounted for by the simulation. This facilitates a more comprehensive simulation and analysis of the conjunctive use and movement of precipitation, surface water, and groundwater, as well as water reuse. This allows a more complete representation of the hydrosphere and its potential connections to humanity, habitat, climate, agriculture, land use, and other related socioeconomic or physical elements that are affected by the distribution of water.

In addition to groundwater, surface-water, and landscape budgets, MF-OWHM2 provides additional options for observations of land subsidence, hydraulic properties, and evapotranspiration (ET). Detailed landscape budgets combined with output of estimates of actual evapotranspiration facilitate a linkage to remotely sensed observations as input or as additional observations for parameter estimation or water-use analysis. The features of the FMP have been extended to allow for temporally variable WBSs (farms) that can be linked to land-use models, defined surface-water and groundwater allotments to facilitate sustainability analysis, linked simulation-optimization that maximizes crop yield (for example, Fowler and others, 2014, 2016), and support for linking surface-water operations with FMP and SFR to analyze the complete reservoir-dependent project schemes for surface-water allotments.

The example model demonstrated the application of MF-OWHM2 in conjunction with land subsidence by a vertically deforming mesh, delayed recharge through an unsaturated zone, rejected infiltration in a riparian area, changes in demand due to deficiency in supply, changes in multi-aquifer pumping due to constraints imposed through the FMP and the MNW2 package, the simulation of unsaturated conditions by a combination of the NWT and UZF Packages, and changes in surface water such as runoff and streamflow. The example model was also used to show how the salinity demand can be represented in the FMP to simulate the potential reduction of salt accumulation in irrigated lands.

The effects of feedback to the land surface and aquifers from salinity demand in MF-OWHM2 were found to be relatively important with respect to simulations not using these linkages and additional demands. The inclusion of salinity demand in the simulation resulted in an even larger difference in flow terms relative to simulations that did not consider this additional demand and also resulted in additional secondary effects, such as increased pumping, storage depletion, streamflow infiltration, and land subsidence. Such linkages can be critical to a complete analysis of selected supply and demand components for conjunctive water use compared to simulations that do not consider these feedbacks, including simulations of the sustained agricultural and urban demands driving secondary effects, such as land subsidence, that can become the limiting factors for sustainability and further resource development. Therefore, these linkages are well suited for evaluating conjunctive water use where the vertical displacements or differential displacements can affect the availability of sources of water, the proportions of multiple sources of water, and the flow to and from aquifers.

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