Groundwater

Methods Note/

Use of the MODFLOW 6 Water Mover Package to Represent Natural and Managed Hydrologic Connections

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Abstract

The latest release of MODFLOW 6, the current core version of the MODFLOW groundwater modeling software, debuted a new package dubbed the "mover" (MVR). Using a generalized approach, MVR facilitates the transfer of water among any arbitrary combination of simulated features (i.e., pumping wells, stream, drains, lakes, etc.) within a MODFLOW 6 simulation. Four "rules" controlling the amount of water transferred from a providing feature to a receiving feature are currently available. In this way, MVR can represent natural connections between features, for example, streams entering or exiting lakes, and perhaps more interestingly, it also can transfer water among simulated features to more accurately simulate water management. An example model representative of an agricultural setting demonstrates some of the available MVR connections. For example, an irrigation event that transfers surface water from an irrigation delivery ditch to multiple cropped areas demonstrates a "one-to-many" connection that is possible within MVR. Conversely, irrigation or precipitation runoff from multiple fields may be routed to a particular stream segment using "many-to-one" MVR connections. MVR supports many additional connection types, several of which are demonstrated by the included example problem.

Introduction

Increases in data availability, processing power, and complexity in the kinds of questions facing water managers and stakeholders alike have led to steady innovation in the modeling tools historically relied upon by groundwater modelers. Within the groundwater modeling discipline, the most widely used of these tools is MODFLOW (Hill et al. 2010; Langevin et al. 2017). Since its first release in 1984, MODFLOW (McDonald and Harbaugh 1984) was made available to the groundwater modeling community as an open-source, intuitive, and well-supported modeling platform. Thereafter, several core-version updates were released that modernized the code structure, streamlined input requirements, provided more robust solver options, or offered expanded simulation capabilities.

Within the MODFLOW modeling framework, new simulation capabilities were implemented as either new "processes," or, alternatively, as a new or updated "package". The "process" concept was introduced with the release of MODFLOW-2000 (Harbaugh et al. 2000) and describes a part of the code that solves a major equation or set of related equations (Langevin 2017); for example the groundwater flow equation. Additional processes, such as the groundwater solute transport process (Konikow et al. 1996), among many others listed in Langevin et al. (2017, 1–2), were added over time. Packages

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are narrower in scope than processes; they handle some specific aspect of a process. As such, they represent a boundary or stress on the groundwater flow process, such as the streamflow-routing (SFR; Prudic et al. 2004) or multi-node well (MNW; Halford and Hanson 2002) packages, respectively.

Prior to the release of MODFLOW 6 (Langevin et al. 2017; Hughes et al. 2017), a generalized approach for passing water among packages was not available. Packages were viewed as independent of one another, which required custom modifications for water to be passed between packages. In MODFLOW-2005 (Harbaugh 2005), the previous core version, some fairly obvious connection pathways were possible. For example, options available within the lake (LAK; Merritt and Konikow 2000) and SFR input files allowed users to transfer stream flow to a lake, and vice versa, wherever appropriate. Similarly, functionality for establishing overland runoff connections between the unsaturated zone flow (UZF; Niswonger et al. 2006) package and receiving surface water bodies (i.e., LAK and/or SFR) also was available through appropriate input specification. In another MODFLOW-2005-based example, the drain return package (DRT1; Banta 2000) allowed users to specify a fraction of drain water that returns to the groundwater flow process as recharge, but it did so directly without using the recharge (RCH) package. However, additional package-to-package transfer capabilities were lacking, and if needed, their implementation within the MODFLOW-2005 framework was not straightforward because packages were not designed with cross-package water transfers in mind. For example, the need to resolve the impacts of anthropogenic water management practices spurred the development of additional package-to-package connections that are possible in MODFLOW-FMP (Schmid et al. 2006), MODFLOW-OWHM (Hanson et al. 2014; Boyce et al. 2020), the Agricultural Water Use Package (AG; Niswonger 2020), and customized versions of MODFLOW described in Morway et al. (2016). However, in each of these codes, users are limited to a set of pre-determined package-to-package connection pathways with no options for mixing and matching as needs arise (or change).

Recognizing the need for a general methodology for passing water between packages, the new Water Mover (MVR) package was developed for MODFLOW 6. The basic premise of the MVR package is to transfer water from a feature in one package to a feature simulated by a different package. Packages with water available for transfer are termed "providers," while "receivers" accept the "moved" water. As such, the MVR Package facilitates simulation of water management operations in addition to its role in handling natural transfers (e.g., SFR to LAK) in a straightforward, generalized manner in which transfers are tracked and reported. Moreover, in anticipation of future development in MODFLOW 6, the generalized nature of the approach readily facilitates package-to-package transfer of dissolved mass in solute transport simulations. This text offers a brief description of the MVR package and its implementation within the MODFLOW 6 framework. We then demonstrate the use of MVR using a previously published hypothetical model patterned after an irrigated river valley. For the interested reader, the second demonstration of MVR applied to example 3 from Mehl and Hill (2013) can be found in the Supporting Information.

Approach

To better understand the role of MVR within the MODFLOW 6 framework, it is helpful to first describe two over-arching structural changes to MODFLOW 6 relative to its predecessors. Although the discussion that follows only focuses on two recent changes inside MODFLOW, we note that Langevin et al. (2017) offers a comprehensive list of many other important structural changes in the section titled "information for existing MODFLOW users."

The first and perhaps most foundational facet of the MODFLOW 6 re-design is that the groundwater flow process is modularized. As a result, multiple groundwater flow models may now be solved simultaneously in a single matrix solution. Motivation for this approach stems from the need to support additional processes as code development proceeds; for example, incorporation of the solute transport process. In MODFLOW 6 parlance, multiple models constitute a "simulation," though a single model is all that is required to run MODFLOW 6 and is a typical use case. Within a multi-model simulation, MVR not only facilitates the transfer of water between features residing in different packages within a single model, it also enables the transfer of water among features assigned to different models (that reside within the same simulation). For example, MVR could be used to transfer water between two SFR reaches, where each reach is contained in two distinct groundwater flow models of a single simulation.

The second important change pertinent to this discussion of the MODFLOW 6 framework is that multiple packages of the same type can be specified by the user, functionality that was introduced by Banta (2011) in MODFLOW-CDSS, an offspring of MODFLOW-2005. In MODFLOW-2005 and its variants, all features of the same type, lakes for example, must appear in one instance of a package (i.e., a single input file). In MODFLOW 6, however, users are free to organize features of the same type among an arbitrary number of instances of that package type. For example, a pump-and-treat system could be represented by multiple instances of the multi-aquifer well (MAW) package. Pumping and injection wells could be assigned to dedicated instances of the MAW package, respectively. In this example, MVR would transfer the pumped water from the provider wells to the receiving injection wells. Similarly, multiple instances of SFR could be used to organize the features associated with different sub-catchments in a large river network. For example, the stream networks associated with two sub-catchments that share a downstream confluence could be organized into two dedicated SFR packages. Moreover,

Table 1
A Complete List of Packages Available with MODFLOW 6 with an Accounting of Which Packages Are Used in this Work

Package Name	Abbreviation	Package Category	Available as MVR "Provider"	Available as MVR "Receiver"	Use in Example Models Included Herein: Demonstrated in Examples	Use in Example Models Included Herein: Simulated "Receiver"
Well	WEL	Hydrologic/Stress	✓		Main manuscript	UZF
River	RIV	Hydrologic/Stress	✓			
General-Head Boundary	GHB	Hydrologic/Stress	✓			
Drain	DRN	Hydrologic/Stress	✓		Main manuscript	SFR and LAK
Stream-Flow Routing	SFR	Hydrologic/Advanced Stress	✓	✓	Main manuscript and supplemental material	SFR, LAK, and UZF
Lake	LAK	Hydrologic/Advanced Stress	✓	✓	Main manuscript	SFR
Multi-Aquifer Well	MAW	Hydrologic/Advanced Stress	✓	✓		
Unsaturated Zone Flow	UZF	Hydrologic/Advanced Stress	✓	✓	Main manuscript	SFR and LAK
Mover	MVR	Hydrologic/Advanced Stress	NA	NA	Main manuscript and supplemental material	NA

Note: Packages not included in this list, for example, the recharge (RCH) package, are not eligible receivers because they do not solve their own continuity equation. NA, not applicable.

the receiving sub-catchment could be represented by a third instance of the SFR package. In such a setup, MVR would be required to route the outflow from the respective reaches of the two upstream sub-catchments to the appropriate upstream reach of the downstream sub-catchment. Without MVR, separate instances of SFR are incapable of communicating with each other on their own. Quantities of water passed between packages are tracked and reported in the standard MODFLOW 6 output file (i.e., the "listing" file) as with other components of the flow budget. This allows a user to inspect output for discrepancies in the reported flow budget and to ensure that moved quantities fit within expectations. Table 1 lists the specific MODFLOW 6 packages that may interact with the MVR package and in what capacity (as a provider, a receiver, or both). Owing to the requirement that a receiver solves its own continuity equation—that is, it balances inflows, outflows, and corresponding changes in storage—the list of potential receiver packages is restricted to the advanced packages listed in Table 1 (Langevin et al. 2017). Thus, the recharge package (RCH) is not eligible to receive water since it does not solve its own continuity equation but is instead taken into account as a source term in the groundwater flow equation. Table 2 lists some of the obvious use cases for the MVR package, though it is not exhaustive.

Activation of the MVR package in MODFLOW 6 initiates a sequence of events during the simulation. First, packages marked for water transfer allocate additional arrays for each feature. These supplemental arrays track the rate of available water that can be provided by each feature, the rate of water that is actually provided by the feature to the MVR package (not all of the available water is necessarily transferred), and the rate of water received for each feature from the MVR package. Receiving packages must account for MVR inflows and outflows in their respective continuity equations. When only a portion of the water made available by a provider is specified for transfer, the MVR package is responsible for calculating the exact fraction of the available water that is transferred to receivers. It is important to note that this calculation is performed as part of the outer nonlinear iteration loop in MODFLOW 6, which means that the MVR transfers are lagged by one outer iteration and that use of the MVR package may require additional nonlinear iterations to achieve convergence.

In general, the flexibility inherent in MODFLOW 6 requires that MVR not only handle different types of hydrologic connections (i.e., natural versus anthropogenic), but also that it facilitates "many to many" connections. That is, more than one feature type could provide water to a receiver, and, conversely, a provider can supply more than one receiver. A "many-to-one" example in an agricultural setting could include, for example, drainage from a subsurface tile drain represented by the drain package (DRN; Harbaugh 2005) and overland runoff simulated by the UZF package both contributing flow to an SFR stream reach. If, on the other hand, a "one-to-many" setup is needed, MVR is capable of distributing pumped

Table 2
Example Use Cases of MVR

Provider	Receiver (Limited to MODFLOW 6 "Advanced Packages") SFR	LAK	MAW	UZF
WEL	Pumped groundwater to lined ditch for delivery to irrigated field	Pumped groundwater to wetlands or temporary irrigation storage pond		Irrigation with groundwater
RIV	Wetland outflow to streams	Wetland outflow to lakes		
GHB				
DRN	Tile drainage dumping to open surface water drain (earthen ditch); spring discharge to stream feature	Tile drainage dumping to open surface water holding basin; spring discharge to lake or pond feature		
SFR	Cascading streamflow between instances of models or instances of SFR depending on how surface water network is organized	Streamflow entering a lake or reservoir	Diversion of streamflow for injection into wells for simulating aquifer storage and recovery	Irrigation, or land flooding for managed aquifer recharge
LAK	Streamflow exiting a lake or reservoir			
MAW	Pumped groundwater to lined ditch for delivery to irrigated field	Pumped groundwater to wetlands or temporary irrigation storage pond	Pump and treat systems	Irrigation with groundwater
UZF	Hortonian and Dunian runoff	Hortonian and Dunian runoff		Cascade runoff to downgradient cell

Note: Provider-receiver combinations left blank are still possible, but with no obvious use case.

Table 3
A Description of the Four Options Controlling How Much Water to Move from a Provider to a Receiver

Rule (mvrtype)	Description
FACTOR	Moves only a portion of the available water from the provider to the receiver. The fraction of water to move is determined by *value*: $Q_R = Q_P \times value$
EXCESS	Water will be moved from the provider to the receiver only when the water made available by the provider is in excess of *value*. The amount of moved water is calculated as the provider water minus *value*: $Q_R = Q_P - value$ (if $Q_P >$ value)
THRESHOLD	Water is only moved from the provider to the receiver when the total amount of water made available by the provider is above a threshold amount given by *value*. Once the available water exceeds the threshold, then the receiver is supplied with a rate equal to *value*. $Q_R = 0$ (if $value > Q_P$), $Q_R = Q_P$ otherwise
UPTO	All of the water made available by the provider will be moved to the receiver up to *value*. When the total available water exceeds *value*, only *value* will be moved: $Q_R = value$ (if $Q_P >$ value), $Q_R = Q_P$ otherwise

Notes: The four options appearing under the column header "rule" are the character strings that must be used with the parameter mvrtype within the MVR input file. Q_P is the amount of water made available by the provider, Q_R is the total flow passed to the receiver, and value is a user-specified quantity, the meaning of which changes based on which option is selected. This list of rules was originally formulated in Prudic et al. (2004, 44).

groundwater (represented by either the well [WEL] or MAW packages) across multiple UZF objects representative of cropped fields for simulating separate-in-space but simultaneous-in-time irrigation events. Combinations of MVR connections may be used in series to represent more complex water management pathways. For example, a pumping well (represented by the WEL package) that discharges to a leaky earthen ditch (represented with SFR) for delivering irrigation water to a cropped field (represented by UZF) is readily represented with MVR: a WEL to SFR connection followed by an SFR to UZF connection.

In simulations that require one-to-many connections, MVR offers four options, hereafter referred to as "rules," for distributing the available water among an arbitrary number of connected receivers. Table 3 lists the four rules and gives a brief description of how each one works. Also, where one-to-many connections exist, their relative priority is established by the order in which they are entered in the input file. Thus, if a provider is connected to three receivers, for example, the available water supply is distributed to whichever of three receivers is listed first within the MVR input file, then to the second, and so on, using their respective rules to calculate the amount of water to transfer. In this prioritization scheme, it is possible that some receivers may not get water if the supply of water made available by a provider is exhausted by the first receiver. Conversely, in other situations, water made available by a provider may go unused (non-transferred) based on the selected rule type and specified amount of water to transfer. In this situation, unused water will be reported in the MVR budget within the standard MODFLOW "list" file and is removed from the MODFLOW 6 simulation. Finally, MVR is restricted to only transferring water that is made available by a provider. As a result, if the water table drops below the bottom elevation of a cell containing a WEL, for example, then MVR connections associated with that WEL are prevented from transferring water since none is available.

Within the MODFLOW 6 framework, each MVR connection is listed in a "period" block within the MVR input file. Period blocks correspond to MODFLOW stress periods and define intervals of time over which boundary conditions remain fixed at user-specified values (Langevin et al. 2017). Multiple period blocks may be used to alter some or all of the specified boundary conditions within the model, including different MVR connections and the rules associated with those connections.

Each feature-to-feature MVR connection appears on its own line inside the input file. Depending on whether multiple models are active within the MODFLOW 6 simulation, a line of MVR input may optionally start with the model name that hosts the provider depending on whether the MODFLOW 6 simulation contains multiple models. Regardless of whether multiple models are present within a simulation, a line of MVR input must, at a minimum, specify the package name and feature identifier of the provider. Similarly, the model name (optional), package name, and feature identifier of the receiver must be listed after the provider information to establish an MVR connection. The final two values listed on each line establishing an MVR connection are the mover type—a character string identifying which rule should be applied to a water transfer—and an associated value that is interpreted differently depending on the selected mover type (note the various implementations of value under the "description" column header of Table 3).

Demonstration of the MVR Package

As with all other packages, MVR is activated through its inclusion in the model name file. If activated, MODFLOW 6 reads the MVR input file(s) that establishes package-to-package, feature-to-feature connections for each stress period as described above. Two previously published models are used for demonstrating MVR: (1) example problem 3 from Mehl and Hill (2013) and (2) the hypothetical irrigated river valley in Morway et al. (2016). The first problem appears in the supplemental material provided with the online version of this paper and uses two MVR connections to pass water (1) from an SFR reach in a parent model to an SFR reach in a child model and (2) from an SFR reach in the child model back to an SFR reach in the parent model. The second example, appearing below, is more complex than the first, employing thousands of MVR connections across a mixture of packages to simulate an irrigation system. The Flopy library built for the Python programming language (Bakker et al. 2016) was used to construct both models. For the interested reader, the python script for recreating model 1 is available in the model archive that accompanies this manuscript. More information about the model archive is available in the section titled Supporting Information.

Demonstration of MVR: A Mock Irrigated River Valley

The second demonstration of MVR proceeds with a model that first appeared in Morway et al. (2016). The original purpose of the model was to demonstrate the importance of tightly integrating—rather than loosely coupling—river operation models with distributed-parameter hydrologic simulators like MODFLOW. In tightly integrated models the respective solutions synchronize before the integrated model advances to the next time step. River operation models help guide the distribution of water allocations in river reservoir systems where demand for water typically exceeds supply. Because this problem is patterned after an irrigated river valley located in a semi-arid region, annual evapotranspiration (ET) demand is roughly four to five times greater than the total annual precipitation supply, thereby requiring supplemental water from irrigation to meet crop water needs. Given the highly managed nature of irrigated river systems, exemplified in this model, it presents a more complex implementation of MVR.

When first published, this model used native functionality in MODFLOW-NWT (Niswonger et al. 2011) to pass water between the LAK and SFR packages and UZF to SFR (tail-water runoff from over-irrigation) packages; however, some custom modifications allowed water to pass from SFR to UZF (surface water irrigation) and WEL to UZF (groundwater irrigation). Having updated the model to MODFLOW 6 for demonstrating MVR functionality, all the SFR-LAK connections and custom package-to-package connections made inside the MODFLOW-NWT source code are replaced by the MVR package. Specifics for each of the connection pathways are offered in the sections that follow. First, however, we note some important changes between this model and its original setup.

While many features of the current model—the grid, land-surface elevation, surface water network, and aquifer properties (Table 4)—remain largely unchanged from their original description in Morway et al. (2016), four important changes were implemented. The first is for simplicity; the reservoir release and four main diversions are not calculated by MODSIM (Labadie 2010) in this application of the model. Instead, operational decisions, like how much water to release from the reservoir, or how

Table 4
Specified Aquifer Properties and Boundary Conditions in the MODFLOW 6 Model

Model Parameter	Value
Saturated zone parameters	
Horizontal hydraulic conductivity	10 m/d
Ratio of vertical to horizontal hydraulic conductivity	0.1
Specific yield	0.28–0.34
Unsaturated-zone parameters	
Saturated hydraulic conductivity of unsaturated zone	0.18 m/d
Brooks-Corey epsilon	7.1
Saturated water content	0.42
Extinction water content	0.08

much water to divert from the main-stem river are either fixed, as in the case of the reservoir release, or calculated at model runtime by one of the four rules available within the SFR package that mirror the four rules available within the MVR package (Table 3). All four rules are exercised by this example and are adequate for diverting water into the four main diversions for subsequent transfers of water from the SFR package to the UZF package by MVR for simulating surface water irrigation events.

The second important change is that the simulation period was shortened from 17 years to 1, though it still uses daily stress periods. The third noteworthy alteration pertains to how pumps are activated and is described in the section "WEL to UZF" below. The fourth and final significant change is the inclusion of the drain package for keeping rejected infiltration distinct from groundwater discharge in the model water budget.

Reservoir Inflows and Reservoir Releases (SFR to LAK and LAK to SFR)

Among all possible connections available with MVR (Table 1), streamflow entering and exiting lakes is likely among the most common use case. In this example problem, the reservoir is represented using the LAK Package. An individual lake can be designated as a receiver as is the case when a stream flows into a lake. Lakes can also be designated as providers. If a lake is used as a provider, then one or more outlets must be assigned to the lake. Lake outlets are the mechanisms by which water is removed from the LAK package and provided to MVR. Also, users must assign a type to each lake outlet. Outlet types include SPECIFIED, MANNING, and WEIR. Outlet flow, whether specified or calculated, is made available to MVR. Additional information explaining the nuances of each outlet type is described in the input instructions available with the software (Langevin et al. 2017).

In this example problem, there is one SFR to LAK connection and two LAK to SFR connections (Figure 1A and 1B, Table 5). To represent streamflow into the reservoir, the last reach of the uppermost stream is a provider of water to the reservoir. This connection is implemented in the simulation through the MVR by sending 100% of this streamflow (the last reach of the upper segment) to the receiver (the reservoir, which is represented with LAK). Streamflow out of the reservoir is represented by designating the reservoir as the provider and the first stream reach below the reservoir as the receiver. The first lake outlet is low on the dam and represents a location where managed releases occur. As such, the assigned outlet type is SPECIFIED. At the start of the simulation, the specified reservoir release was set equal to 10 cubic feet per second (cfs; 24,456 cubic meters per day [cmd]) and was raised to 350 cfs (856,293 cmd) at the start of the irrigation season (stress period 184 within the model) to provide ample flow in the river for the downstream diversions. The model will continue to release water from the reservoir at the specified rate until the simulated reservoir stage falls below the sill elevation of the outlet, at which point the outflow is limited to the inflow plus or minus any additional gains and losses within the reservoir (e.g., evaporation, groundwater reservoir exchange, etc.). The second outlet is a spillway of type WEIR with a sill elevation equal to the maximum elevation of the reservoir. In this configuration, the spillway keeps the reservoir stage from rising above a maximum stage if the managed release rate is set too low or if inflows cause the lake stage to rise above the maximum level. Both LAK outlets are listed in the appropriate LAK package input block—in this case the "OUTLETS" block. MVR transfers 100% of the water provided at the outlets (managed release, or spillway as needed) to the first SFR reach downstream of the reservoir using the "FACTOR" rule with "value" (Table 3) set equal to 1.0.

Irrigation with Surface Water (SFR to UZF)

This simulation represents a variety of surface water features that includes the mainstem river above and below the reservoir, irrigation delivery ditches (diversions), natural tributaries, and man-made open-ditches. All surface water features are represented with a single instance of the SFR package. Figure 1A depicts the layout of the surface water network. Downstream of the reservoir, a total of four primary irrigation ditches divert water out of the mainstem river for delivery to irrigated fields and are specified in the "DIVERSIONS" block of the SFR input file. Two of the four main diversions are located north of the river, the remaining two are south of the river. A single natural tributary with user-specified inflow enters the model domain on the southern boundary of the model (Figure 1A). Additional tributaries shown in Figure 1A represent open drains.

Representation of large irrigation canals with SFR is important in agricultural settings for adequate simulation of seepage, both in terms of its contribution to groundwater recharge and accurate accounting of reduced delivery to irrigators (a consequence of seepage). Most large-scale irrigation systems use secondary diversions, commonly referred to as laterals, to convey irrigation water from

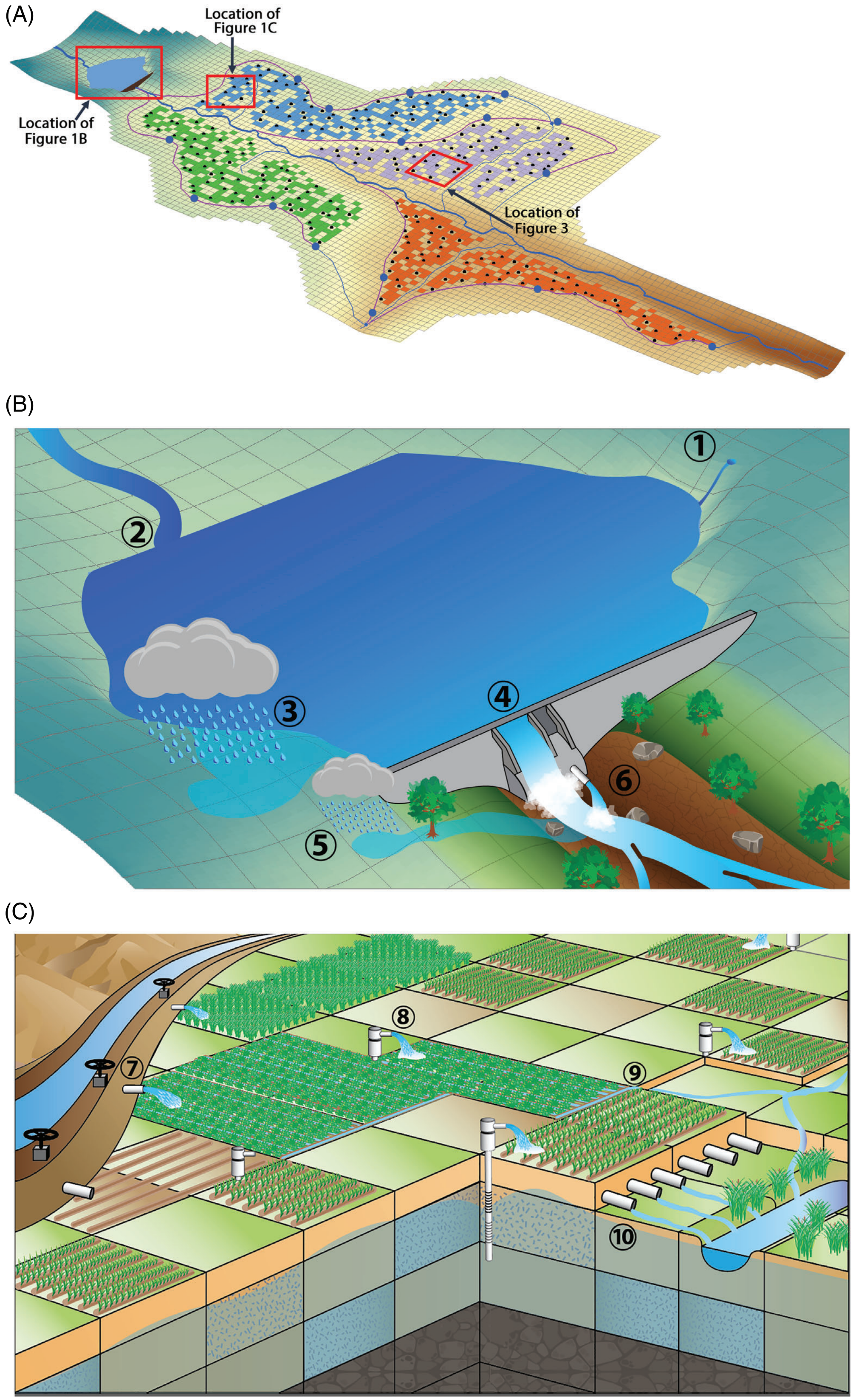

Figure 1. (A) Layout of the demonstration model, which includes four of the five "advanced packages" listed in Table 1. Direction of the river flow is left to right. Solid-but-distinctly colored grid cells give the location of irrigated grid cells served by one of four irrigation ditches, the location of which is given by the magenta colored lines. Black circles show the locations of pumping wells. (B, C) Two "callouts", the locations of which are given in (A), depict select use cases of the MVR package for this problem. Not all potential uses of the MVR package are illustrated. Number labels shown in (B) and (C) are described in Table 5.

Table 5
A Description of MVR Connection Labels Identified in Figure 1

Identifying # on Figure 1B and 1C	Package Connection	Description
1	DRN → LAK	Spring discharge to a lake
2	SFR → LAK	Stream-lake confluence
3	UZF → LAK	Rejected infiltration due to infiltration excess or saturation excess overland flow
4	LAK → SFR	Spillway
5	UZF → SFR	Rejected infiltration due to infiltration excess or saturation excess overland flow
6	LAK → SFR	Managed reservoir release
7	SFR → UZF	Headgate along an irrigation ditch
8	WEL → UZF	Irrigation pumping well
9	UZF → SFR	Irrigation tail-water runoff
10	DRN → SFR	Tile drainage

the main irrigation canals to a cropped field. Because SFR accommodates any number of arbitrary diversions, this hypothetical simulation uses four additional lateral-like diversions along each primary ditch to transfer water from SFR to UZF (Figure 1A and 1C). Locations of the four subsequent diversions along each of the four diversion ditches are identified by the blue circles placed along the magenta color lines highlighting the irrigation ditches (Figure 1A). At each of these locations, a portion of the flow (approximately one-quarter) in each primary irrigation ditch is diverted out of the ditch and provided to the MVR package where it is then distributed among select irrigated fields listed in the MVR package input file (more on this to follow in the next paragraph). An important goal of limiting the lateral diversions to only four per primary ditch is to reduce the complexity of the SFR input file to a reasonable level. However, MODFLOW 6 supports as many laterals and/or headgates (Figure 1; Table 5) as required by the application. To summarize the current example, there are four primary diversions from the main-stem river with an additional four diversions (laterals) per primary ditch resulting in 20 total diversions (4 diversions along river $+$ 4 ditches $\times$ 4 laterals $=$ 20), all specified within the "DIVERSIONS" block of SFR package.

Water that is provided to MVR by the 16 laterals is then distributed among a subset of UZF receivers. In this example, a select set of grid cells represent irrigated fields that are approximately 40 acres (16 ha) each (Figure 1A). For any given time step, each lateral diversion provides enough water to irrigate approximately three fields a day. In this way, MVR delivers surface water irrigation to about 12 fields per day per ditch. Because each ditch serves approximately 250 fields, a full irrigation rotation takes roughly 21 days (250 divided by 12) to complete.

Irrigation with Groundwater (WEL to UZF)

As in the previous section, WEL to UZF connections established with MVR provide water for irrigation, but use groundwater pumps as the providers (Figure 1C; Table 5). In the original model, supplemental pumping occurred when surface water supplies fell short of maintaining "well-watered" growing conditions (i.e., crop-water stress is avoided). In this updated version of the model, groundwater irrigation events for any given field occur roughly 3 weeks apart regardless of the availability of surface water or soil-moisture conditions. Surface water irrigation also occurs on a roughly three-week rotating schedule, resulting in fields (grid cells) receiving irrigation sourced from groundwater, then surface water, then groundwater, and so on, every week-and-a-half. Although arbitrary, the pumping schedule (i.e., pump activation) used in this model is primarily focused on demonstrating the use of MVR to simulate managed connections using the MODFLOW 6 modeling framework. As such, the selected pumping schedule may be more or less frequent than its real-world counterparts.

Runoff to Surface Water Features (UZF to SFR and UZF to LAK)

MVR connections from UZF to SFR and to LAK replace the IRUNBND array functionality included in UZF1 (Niswonger et al. 2006). In this model, the use of these two pathways ensures that runoff derived from infiltration excess or saturation excess is routed back to a surface water feature (Figure 1B and 1C; Table 5). All UZF objects (cells), irrigated or otherwise, are connected to whichever surface water feature is first encountered when taking the steepest topographical path of decent. With this methodology, overland runoff is not cascaded from one cell to its downhill neighbor, as in Daoud (2020), but is instead instantaneously routed to the identified stream reach or lake, regardless of how many cells are between these two features. For the present model, this simplifying assumption is supported by the relatively quick travel times associated with surface water relative to groundwater, though in a spatially extensive system a more sophisticated approach may be required.

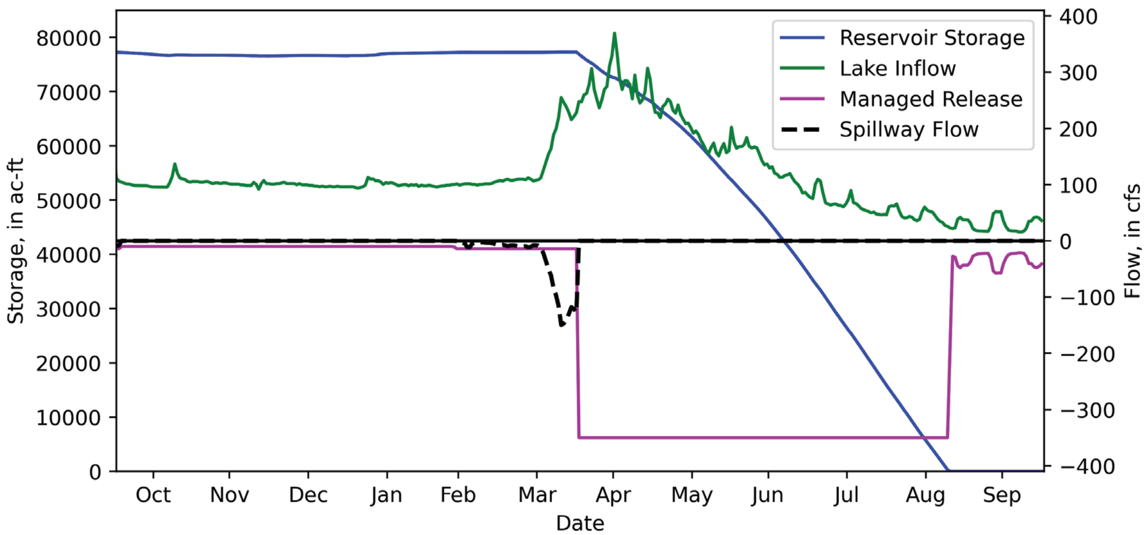

Figure 2. Lake inflow and outflow are transferred between the LAK and SFR packages using MVR. Positive and negative values on the right *y* axis denote reservoir inflow and outflow, respectively. At the start of the irrigation seasons (April 1), water is released from the reservoir at a constant rate of 350 cfs (856,293 cmd) until the reservoir storage is depleted (late August). After the reservoir is evacuated, the outflow roughly mirrors the inflow that is passed through the reservoir to satisfy downstream irrigation demand. Owing to the magnitude of the stored volume, the relatively small changes in inflow from the start of the irrigation season to when the reservoir is drained do not register on the stored volume curve.

Springs (DRN to LAK and DRN to SFR)

The DRN package did not appear in the original formulation of the model and was added for routing groundwater discharge—as opposed to rejected infiltration—to a nearby surface water feature (Figure 1B and 1C; Table 5). In MODFLOW-NWT, it was not possible to connect the DRN package to surface water features. By plumbing the model in this way, rejected infiltration is kept separate from groundwater discharge, resulting in two important benefits. First, the model now offers a more detailed accounting of the specific sources of water transferred between features (i.e., further disaggregation of flows reported in the budget listing file). Second, this approach is better suited for supporting a solute transport simulation. Because the concentrations associated with rejected infiltration versus groundwater discharge may be as different as their respective flow characteristics (e.g., flashy versus steady), there may be important implications for modeled outcomes.

Results

The total amount of water moved by the SFR-to-LAK and LAK-to-SFR connections is shown in Figure 2. Also depicted on the left *y* axis of the plot is the total reservoir storage for helping make sense of the three lines showing reservoir inflow and outflow. A small background managed release persists from the beginning of the simulation to the start of the irrigation season (April 1). When the natural inflow ramps up in mid-March, indicative of the beginning of a snowmelt pulse, the reservoir begins to spill with a shape that mirrors the inflow (black dashed line). With the beginning of the irrigation season, the managed release increases to 350 cfs until the reservoir storage is depleted in late August. While the releases are controlled by the LAK input file, MVR is the mechanism by which flows are transferred between the reservoir and main-stem river features.

In this example, the SFR laterals provide surface water for irrigating approximately 60 fields via MVR connections using the rotating schedule described above. In this way, MVR connects one SFR feature to many UZF features. Given that there are roughly 1000 irrigated fields within the model, each one served by 1 of the 16 different lateral diversions, the generalized structure of MVR makes it easy to rotate active connections as necessary. Similarly, each pumping well listed within the WEL package provides irrigation water for up to five fields (there are approximately 250 wells in the simulation), thus requiring another set of one-to-many connections using MVR—or one WEL to many UZF objects. While connections have so far been described as one-to-many, note that each irrigated field represented by UZF can receive water from either SFR or WEL, thereby demonstrating a many-to-one setup established with MVR. Figure 3 shows the total delivered surface and groundwater by SFR and WEL, respectively, to a subset of model cells over the simulation period. The lower plane within the three-dimensional plot corresponds to a subset of cells identified in Figure 1A. Irrigated fields (cells) are identified by whether they received supplemental irrigation water and not just precipitation. The height of the bars shows the total depth of transferred irrigation water delivered by MVR. We also note that the precipitation component of each bar is specified directly within the UZF input file.

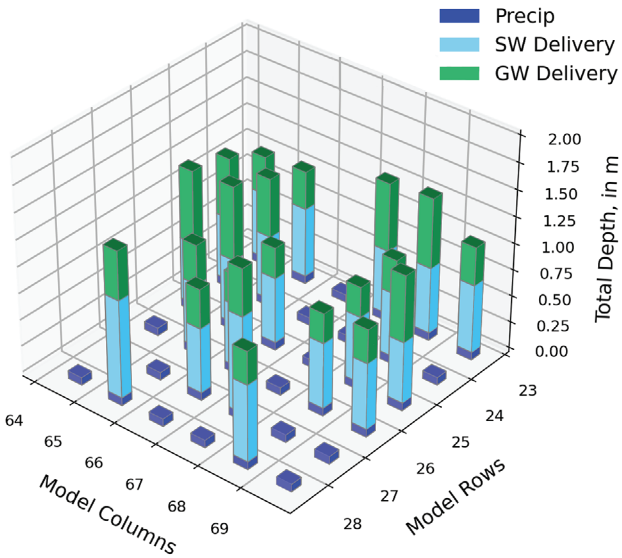

Figure 3. Total annual water deliveries for a subset of cells between rows 23–28 and columns 64–69 for the 1 year simulation period. Bar color shows the relative contribution of water to each irrigated cell by source. Both surface water and groundwater are transferred from SFR and WEL, respectively, to UZF by MVR. Precipitation is specified within the UZF input file and does not require MVR. The relative location of these cells within the broader model is shown in Figure 1A. Cells that only receive precipitation are representative of non-irrigated lands.

Discussion and Conclusions

The MVR package replaces functionality found in previous versions of the MODFLOW that handled natural connections among features assigned to different packages; for example, lake to stream or stream to lake connections. However, MVR goes further by leveraging its generalized structure to facilitate any natural or anthropogenic connection that can be represented by the packages listed in Table 1. In this way, MVR facilitates common management practices previously handled by specialized versions of MODFLOW (e.g., Schmid et al. 2006). Of the two example problems demonstrating the use of MVR, the first example problem included as supplemental information transfers water between two groundwater flow models within a MODFLOW 6 simulation while the second example, appearing in the main manuscript, uses MVR to transfer water among multiple package combinations within a MODFLOW 6 simulation containing a single groundwater flow model. Whereas the example model shown in the supporting information is relatively simple, that is it uses MVR to connect features one-to-one (SFR reach to SFR reach), the more complex example demonstrated in the main body of the report demonstrates numerous "one-to-many" and "many-to-one" MVR connections. Model input files associated with the two example models described in this manuscript and in the Supporting Information are provided at the following location: https://doi.org/10.5066/P9GQETP9.

An important limitation when applying MVR to a MODFLOW 6 simulation is that the list of eligible receivers is restricted to packages that solve their own continuity equation. Thus, one cannot specify a feature listed in a WEL package as a receiver since it does not solve its own continuity equation, though a MAW feature could be used instead.

The design and implementation of MVR facilitates some important MODFLOW 6 enhancements. Implementation of a tightly integrated groundwater transport process was released with version 6.2 of MODFLOW 6. In this updated version, a Mover-Transport package (MVT) working in concert with MVR will transfer dissolved mass from a provider to a receiver using the calculated concentration of the provider water. In this way, MODFLOW 6 is able to more accurately represent generalized solute transport when water is transferred between packages or models, as in the case of highly managed irrigation systems, for example.

A recent refactoring of MODFLOW 6 allows users to incorporate MODFLOW 6 as a dynamic-link library (DLL) in other modeling applications. As such, internal MODFLOW 6 variables can now be altered by external software, including variables related to MVR. Thus, if an externally determined water-management action, for example, a surface water irrigation delivery amount, is updated by the external software, then implementation of that change would take place through manipulation of MVR-related variables to explore the resulting impacts of that change.

In summary, MVR codifies capabilities that were incorporated into a number of MODFLOW variants. In so doing, MVR offers a significant expansion of simulation capabilities within the latest core version of MODFLOW and supports a number of ongoing and planned enhancements in future releases.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Figure S1. Model layout for first example problem originally appearing in Mehl and Hill (2013) as example 3. The direction of streamflow is from left to right. Red numbers indicate parent model stream reaches that are connected to child model stream reaches (green numbers). The integer value of the identified stream reaches corresponds to the feature ID within the model input (e.g., "1" indicates the first stream reach listed in the SFR input file of the child model. The format of the accompanying MVR package input file for this setup is shown in Figure 2.

Figure S2. Contents of the MVR input file for establishing the connections shown in Figure 1. Note that "gwf_lgr_ex3_parent" and "gwf_lgr_ex3_child" are the names of the parent and child models, respectively, within the MODFLOW 6 simulation. Similarly, "SFR-parent" and "SFR-child" are the names assigned to the SFR packages within the respective models. An assignment of 1.0 using the "FACTOR" rule transfers 100% of the streamflow leaving the upstream "provider" reach to the downstream "receiver" reach.

Figure S3. Simulated streamflow and groundwater surface water exchange for each stream reach in the first example problem. The transfer of water between adjacent stream reaches in the parent and child models occurs at locations identified on the plot. Bar widths are indicative of the relative stream reach lengths within the host grid cell. Large disparities in the amount of groundwater surface water exchange in the parent versus child grids at the model interfaces is related to the significantly longer stream reaches in the parent grid.

References

Bakker, M., V. Post, C.D. Langevin, J.D. Hughes, J.T. White, J.J. Starn, and M.N. Fienen. 2016. Scripting MODFLOW model development using Python and FloPy. *Groundwater* 54, no. 5: 733–739. https://doi.org/10.1111/gwat.12413

Banta, E.R. 2011. MODFLOW-CDSS, a version of MODFLOW-2005 with modifications for Colorado Decision Support Systems. U.S. Geological Survey Open-File Report 2011–1213, 19. https://pubs.usgs.gov/of/2011/1213/.

Banta, E.R. 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model; documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1). U.S. Geological Survey Open File Report 2000–466, 127. https://doi.org/10.3133/ofr00466.

Boyce, S.E., R.T. Hanson, I. Ferguson, W. Schmid, W.R. Henson, T. Reimann, S.W. Mehl, and M.M. Earll. 2020. One-water hydrologic flow model: A MODFLOW based conjunctive-use simulation software. U.S. Geological Survey Techniques and Methods, book 6, chap. A60, 435. https://doi.org/10.3133/tm6a60.

Daoud, M.G.M. 2020. Integrated hydrological model to study surface-groundwater interaction in hard rock systems using an unstructured grid approach, the Sardon Catchment, Spain. M.S. thesis, Geo-Information Science and Earth Observation Department, University of Twente, Netherlands.

Halford, K.J., and R.T. Hanson. 2002. User guide for the drawdown-limited, multi-node well (MNW) package for the US Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000. U.S. Geological Survey Open-File Report 02–293, 33. https://doi.org/10.3133/ofr02293.

Hanson, R.T., S.E. Boyce, W. Schmid, J.D. Hughes, S.W. Mehl, S.A. Leake, T. Maddock III, and R.G. Niswonger. 2014. One-water hydrologic flow model (MODFLOW-OWHM). U.S. Geological Survey Techniques and Methods, book 6, chap. A51, 120. https://doi.org/10.3133/tm6A51.

Harbaugh, A.W. 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model: the ground-water flow process. U.S. Geological Survey Techniques and Methods 6-A16.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. User guide to modularization concepts and the ground-water flow process, MODFLOW-2000 the U.S. Geological Survey modular ground-water model. U.S. Geological Survey Open-File Report 00–92, 121. https://pubs.er.usgs.gov/publication/ofr200092

Hill, M.C., E. Poeter, and C. Zheng. 2010. Foreword: Groundwater modeling and public policy. *Ground water* 48, no. 5: 625.

Hughes, J.D., C.D. Langevin, and E.R. Banta. 2017. Documentation for the MODFLOW 6 framework: U.S. Geological Survey Techniques and Methods, book 6, chap. A57, 40 p., https://doi.org/10.3133/tm6A57.

Konikow, L.F., D.J. Goode, and G.Z. Hornberger. 1996. A three-dimensional method-of-characteristics solute-transport model (MOC3D). U.S. Geological Survey Water-Resources Investigations Report 96–4267, 87. https://pubs.er.usgs.gov/publication/wri964267.

Labadie, J.W. 2010. *MODSIM 8.1: River Basin Management Decision Support System: User Manual and Documentation*. Fort Collins, CO: Colorado State University.

Langevin, C.D., J.D. Hughes, E.R. Banta, R.G. Niswonger, S. Panday, and A.M. Provost. 2017. Documentation for the MODFLOW 6 groundwater flow model. U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197. https://doi.org/10.3133/tm6A55

McDonald, M.C., and A.W. Harbaugh. 1984. A modular three-dimensional finite difference groundwater flow model. U.S. Geological Survey Open-File Report 83-875, 528. https://pubs.er.usgs.gov/publication/ofr83875.

Mehl, S.W., and M.C. Hill. 2013. MODFLOW-LGR-documentation of ghost node local grid refinement (LGR2) for multiple areas and the boundary flow and head (BFH2) package. U.S. Geological Survey, Techniques and Methods 6-A44, 43. https://doi.org/10.3133/tm6A44

Merritt, M.L., and L.F. Konikow. 2000. Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model. U.S. Geological Survey Water-Resources Investigations Report 00–4167, 146. https://pubs.er.usgs.gov/publication/wri004167.

Morway, E.D., R.G. Niswonger, and E. Triana. 2016. Toward improved simulation of river operations through integration with a hydrologic model. *Environmental Modelling & Software* 82: 255–274. https://doi.org/10.1016/j.envsoft.2016.04.018

Niswonger, R.G., S. Panday, and M. Ibaraki. 2011. MODFLOW-NWT, a Newton formulation for MODFLOW-2005. U.S. Geological Survey Techniques and Methods 6–A37, 44. https://pubs.er.usgs.gov/publication/tm6A37.

Niswonger, R.G., D.E. Prudic, and R.S. Regan. 2006. Documentation of the unsaturated-zone flow (UZF1) package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005. U. S. Geological

Survey Techniques and Methods 6-A19, 62. https://doi.org/10.3133/tm6A19.

Niswonger, R.G. 2020. An agricultural water use package for MODFLOW and GSFLOW. *Environmental Modelling & Software* 125: 104617. https://doi.org/10.1016/j.envsoft.2019.104617

Prudic, D.E., L.F. Konikow, and E.R. Banta. 2004. A new streamflow-routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000. U.S. Geological Survey Open File Report 2004–1042, 104. https://pubs.er.usgs.gov/publication/ofr20041042.

Schmid, W., R.T. Hanson, T. Maddock, and S.A. Leake. 2006. User guide for the farm process (FMP1) for the US Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW-2000. U.S. Geological Survey Techniques and Methods 6-A17, 127. https://doi.org/10.3133/tm6A17.