MODELING FLOW AT THE STREAM-AQUIFER INTERFACE
A REVIEW OF THIS FEATURE IN TOOLS OF THE TRADE

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ABSTRACT: Interest in modeling the stream-aquifer interface has increased in recent years due to heightened concern over in-stream flows, riparian conditions, TMDL limits, and interstate compacts; and, due to interest in conjunctive management to optimize water availability. Many integrated or linked models are available to quantify the stream-aquifer water exchanges. The first step in identifying the most appropriate model for a particular application is identifying the physical process represented in the model, the mathematical description of the physical process, and the implementation of the mathematical formulation by the numerical code. If the process modeled is analogous to the problem of interest, the mathematical formulation adequately represents the key physical variables, and the numerical handling doesn't introduce unacceptable error, then, a model feature may be judged adequate for the problem at hand. This paper focuses on a single feature of the integrated surface water-groundwater models: exchanges at the stream-aquifer interface. This review characterizes the physical process, the mathematical formulation, and the code implementation of flow exchanges at the stream-aquifer interface in several "tools of the trade". Included in this review are MODFLOW-Prudic, MODBRANCH, IGSM, and InHM.

Key Terms: interface, models, review, groundwater, surface water

INTRODUCTION

Water resource evaluations often involve an integrated analysis of groundwater and stream conditions. Examples of questions generating a need for a modeling evaluation of surface water-groundwater interactions include:

- How will a transfer or new use of groundwater affect existing water uses on a stream system? (or, how will transfer of surface water uses impact present groundwater conditions?)
- How re-engineering of the stream hydrograph impact groundwater elevations in the riparian zone?
- How will channel restoration activities change stream gains/losses and resulting shallow groundwater conditions?
- How will scheduling of groundwater use under a drought management plan impact baseflows in a stream at present, and into future years, as lagged impacts?

Questions such as the above often are evaluated with the aid of modeling tools. When groundwater stresses or responses are a key element of the analysis, a numerical groundwater flow model is appropriately selected to characterize changes to the groundwater environment. Available groundwater models offer a variety of approaches for handling the groundwater/surface water interface. This review paper describes the stream-aquifer interaction component of several commonly used groundwater models. Other model features are presented only as needed for understanding the stream-aquifer interaction. This review is not intended to be exhaustive or judgmental. Rather, the descriptions are summarized simply for the convenience of practitioners considering application of a numerical groundwater model to handle groundwater /surface water interactions.

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All of the models reviewed in this paper are capable of transient simulations. Most of them were originally designed for groundwater flow. Subsequent surface water modules were added for more accurate simulation of the interaction between surface and groundwater. Some of the models represent the stream channel in a simple rectilinear shape with vertical seepage occurring through a flat streambed. In this situation, a specified general head, or constant head in the stream is used to drive stream-aquifer interaction. Other models are designed to simulate flow in the streams using channel geometry and rating curves to compute head in the stream. Some can represent manmade channel diversions, surface water return flows (such as treated wastewater discharge), and priority water rights accounting based on available water in the stream.

The models referenced in this paper include the following:

- MODFLOW-Prudic – The non-proprietary MODFLOW code used in conjunction with the Prudic stream package, both developed by the USGS (Harbaugh et. al., 1996)
- MODBRANCH - The MODFLOW code linked with BRANCH, both non-proprietary and developed by the USGS (Swain et al, 1996),
- IGSM (Integrated Groundwater and Surface Water Model) - A finite element surface water-groundwater simulation model originally developed in the private sector (Montgomery Watson, 1993).
- InHM (Integrated Hydrology Model) - Code for a finite element hydrological–response model extending across the surface-subsurface interface (VanderKwaak, 1999)

MODFLOW - PRUDIC

The Prudic stream package (Prudic, 1989) was initially written as an extension to MODFLOW, the USGS' modular, finite difference groundwater modeling program, and was designed as an option to the River package module. The new package was soon incorporated into the updated MODFLOW documentation report (Harbaugh et al, 1996).

Physical Process

The MODFLOW stream package "is not a true surface-water flow model but rather is an accounting program that tracks the flow in one or more streams which interact with groundwater" (Prudic, 1989). Leakage is calculated based on the head difference between the stream and the aquifer and the conductance of the streambed. The stream is represented as a rectilinear feature with the wetted perimeter representing the streambed. Leakage through the streambed is subtracted or added to the amount of streamflow into each reach of a user-defined channel network. Leakage from the stream is assumed to reach the aquifer within the span of the model timestep, effectively assuming steady-state moisture conditions within the unsaturated zone (if the head in the aquifer is below the stream bottom elevation). Streambed conductance values are a constant for each stress period, and the river head is calculated at the node. Since there is no vadose zone simulation, if the aquifer cell underlying the stream cell dries out, leakage is not possible. The timestep for surface water accounting must be the same as a groundwater time step.

Mathematical Formulation

The calculation of leakage (Q) is based on Darcy's Law:

$$Q = CSTR\left(Z - H_a\right) \tag{1}$$

where CSTR is the conductance of the streambed (hydraulic conductivity of the streambed times the product of the width of the streambed and its length, divided by the thickness of the streambed), Z is the stream stage, and H_a is the head in the aquifer. If materials are unsaturated, the elevation of the bottom of the streambed is used for the head in the aquifer.

Numerical Code Implementation

In the first iteration leakage terms are calculated based on computed stream stage (based on specified inflow), streambed conductance, and the initial (starting) head in the model cell. A new head is then calculated. For subsequent iterations, leakage calculated in the previous iteration is added or subtracted from stream flow prior to calculating a new stream stage and new leakage terms are computed on the basis of the head in the corresponding model cell. Information from the previous iteration is used to determine stream stage, stream flow and leakage terms.

MODBRANCH

Physical processes

This model combines the USGS models MODFLOW and BRANCH (Swain, et al, 1996), where BRANCH uses the St. Venant equations to model unsteady non-uniform flow. As in the stream package, terms that describe leakage between stream and aquifer are a function of streambed conductance and differences in aquifer and stream stage. During the simulation, seepage between the surface and groundwater flow systems can be computed separately by BRANCH and MODFLOW. Alternately, seepage calculated in the BRANCH simulation can be imported into and utilized by MODFLOW. Because time increments required to represent surface water systems are generally much smaller than for groundwater systems, there can be many BRANCH time steps for each MODFLOW time step. Time-variant flows, backwater conditions, river junctions with varying flows in and out and non-rectangular cross-sections are some of the system characteristics that can be represented in the surface water component of this model.

Mathematical Formulation

MODFLOW calculates leakage as described above for the Prudic package (Equation 1). In order to accommodate leakage in BRANCH, the original continuity equation in BRANCH is modified to include a leakage term, *q*:

$$B\frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial L} + q = 0 \qquad (2)$$

where B is channel topwidth, Z is stage in the channel, t is time, Q is flow rate in the channel, L is longitudinal distance down the channel, and q is the outflow per unit length of channel, i.e., leakage. The leakage term is calculated in similar fashion to that employed in the Prudic Package, utilizing a function based on Darcy's Law.

Numerical Code Implementation

For each time interval, the BRANCH model computes stream stage, discharge and leakage based upon boundary conditions, stream characteristics and aquifer head in the corresponding MODFLOW cell. If, as is often the case, BRANCH model time steps are smaller than MODFLOW time steps, the aquifer head used in the BRANCH simulation is linearly interpolated from aquifer heads at the beginning and end of the MODLFOW time step. The leakage in each BRANCH time step is simultaneously calculated and the average of these leakage rates is then applied for the entire time step of the MODLFOW simulation. MODFLOW uses this average leakage rate to estimate aquifer head at the end of the groundwater simulation time step. Streamflow is recalculated with the new value of groundwater heads, and the process is repeated until the user defined convergence criteria are met for head and stage, after which the model advances to the next MODFLOW time step. This process usually needs only 4 to 9 iterations.

The BRANCH component is called during the formulation of the continuity equation. The average channel topwidth from the previous time step is used. MODBRANCH does not recalculate conductance. When the saturated groundwater level in an aquifer node below a stream node falls below the bottom of that aquifer layer (i.e. the node “dries out”), then the stream and aquifer are disconnected and no stream seepage to the aquifer is simulated. An option is available for handling channel drying and rewetting.

IGSM – INTEGRATED GROUNDWATER AND SURFACE WATER MODEL

Physical Process

Three separate equations are applied depending on the stream-aquifer condition. The two saturated conditions include (1) flow out of the stream into the subsurface and (2) flow from the subsurface into the stream. Each of these iterates the head in the aquifer with head in the stream until closure. With unsaturated conditions, where the stream and aquifer are not in direct hydraulic connection, a separate equation is used which passes the flux term to an unsaturated flow subroutine which delays the saturated aquifer recharge.

Mathematical Formulation

A water balance equation of inflows and outflows is applied to each stream node in each stream reach. A full stream flow simulation in this model tracks transient stream flow conditions as well as aquifer conditions. Head in the stream is computed from a rating curve, representing a function of flow rate and stream channel geometry. The wetted perimeter of the streambed is based on channel width, general channel morphology, and flow in the stream.

a) Flow out of stream into the subsurface with saturated flow is specified as

$$Q_s = K \cdot \left(W + aD_s\right) \qquad (3)$$

where Q_s is seepage from the stream per unit length, (L^3/T/L), K is estimated hydraulic conductivity of the stream bed material, (L/T), W is width of water in the stream, (L), D_s is depth of water in the stream, (L); and α is the stream channel coefficient.

b) Flow out of stream into subsurface with unsaturated flow is specified as

$$Q_s = K \cdot W\left(D_s + b_s\right)/\, b_s \qquad (4)$$

b_s is the thickness of streambed material, (L).

c) Flow from the subsurface back into the stream is specified as

$$Q_s = K \cdot P_w \cdot G \qquad (5)$$

where a negative value of Q_s indicates groundwater seepage to the stream; P_w = wetted perimeter of the channel (L) corresponding to the elevation of the stream water surface or the groundwater table, whichever is greater; G = gradient (L/L) between stream stage and groundwater table calculated as $(h_g\text{-}h_s)/b_s$, but limited to 1; h_s = elevation of the stream stage, (L); h_g = elevation of the groundwater table, (L); and b_s = thickness of stream bed material, (L).

Numerical Code Implementation

The solution methodology for stream-aquifer interactions is semi-explicit with time. The flux term from the previous timestep is applied at the current timestep. Therefore the stream-boundary flux values are one step behind. Timesteps for stream-aquifer interaction are computed on the groundwater timestep, which is fixed at a monthly value.

INHM – INTEGRATED HYDROLOGIC MODEL

Physical Processes

Surface flow interacts with porous medium and macropores through a thin soil layer at the land surface interface. The thickness of the layer is assumed to be proportional to the permeability of the underlying porous medium. Water exchange is described by one-dimensional Darcy equation. The Richards equation is used to describe flow in the variably saturated porous media. Flow coupling coefficients are defined as functions of characteristic length scales of interaction and fluid properties, and system parameters such as saturation or permeability. Channels are not defined within fixed locations, but result as a function of topographic controls and water elevations and availability. The InHM code also handles solute conditions and fluxes; this element of the code is not described here.

Mathematical Formulation

Surface-subsurface water exchange rates, q^e (T^{-1}), are approximated as

$$q^e = a^e \left(y_p - y_s \right) \tag{6}$$

where y_p is the subsurface pressure head (L), y_s is the depth of water (L) on the land surface; and, where the non-linear water exchange coefficient, a^e ($L^{-1}T^{-1}$), is given by

$$a^e = k_{rw}^e \frac{r_w g}{m_w} \frac{k_p^{zz}}{a_s^2} \tag{7}$$

where r_w is the density of water, g is the gravitational acceleration (LT-2), k_p^{zz} references the intrinsic permeability (L2), m_w is the viscosity of water (ML-1T-1) and a_s is the thickness of the thin soil layer (L). The interface relative permeability, k_{rw}^e (–), which ensures that the discretized solution is monotone, is defined in the upgradient continuum

$$k_{rw}^e = \begin{cases} k_{rw_p} : y_p \geq y_s \\ k_{rw_s} : y_s > y_p \end{cases} \tag{8}$$

where k_{rw_p} is the relative permeability of the porous medium, and k_{rw_s} is the pseudo-relative permeability of the surface continuum. The surface pseudo-relative permeability is defined by a depth-based function that reduces the area utilized in coupling the surface and subsurface flow continuum, resulting in restricted infiltration from concentrated ponding in rills. Equation (8) describes both rates of surface water infiltration

$$\left(y_p - y_s \right) < 0 \Rightarrow q_{sp}^e \leq 0;\ q_{ps}^e \geq 0 \tag{9}$$

and groundwater seepage (or exfiltration)

$$\left(y_p - y_s \right) > 0 \Rightarrow q_{sp}^e \geq 0;\ q_{ps}^e \leq 0 \tag{10}$$

Numerical Code Implementation

InHM employs a control volume finite element numerical approach. The user may assume continuity of pressure or specify a first order flux relationship between continua. Each system of coupled nonlinear equations is solved simultaneously using Newton iteration and numerical derivatives are employed in a Jacobian assembly. “Full coupling of the surface and sub-surface flow regimes is achieved by assembling and solving one system of discrete algebraic equations such that overland flow rates and water depths, streamflow rates, subsurface pressure heads, saturations and velocities, as well as water fluxes between continua are determined simultaneously” (VanderKwaak, 1999).

DISCUSSION

The rationale for selection of one of these or any other model is a function of the application and the model’s suitability for modeling key aspects of the problem at hand. The discussion above only profiles one feature of the models. Other elements (i.e., handling of recharge, evapotranspiration or boundaries) may be equally important to the hydrologist.

A more complex and detailed process model does not necessarily make a better model. Additional complexity is only justified if sufficient data are available for characterization of parameters, and if the problem requires the greater detail provided by additional complexity. It is the hydrologist’s responsibility to select a model that is best suited to the question of interest.

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