THE SURFACE/VADOSE PACKAGE FOR COMPUTING RUNOFF, EVAPOTRANSPIRATION, AND NET RECHARGE IN MODFLOW

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Abstract. The newly developed Surface/Vadose (SV) Package is an open-source MODFLOW module that automatically calculates overland runoff, evapotranspiration (ET), and net groundwater recharge from given rainfall and anthropogenic inflows (e.g., irrigation, septic-tank discharge). The SV Package uses fairly simple empirical relationships to simulate the water-budget processes at the land surface and in the vadose zone.

The SV Package has been applied in northeastern Florida and is suitable for other coastal-plain areas. It is particularly useful where the water table is near land surface, where there are groundwater-fed wetlands, and where ET is a significant component of the hydrologic water budget.

INTRODUCTION

A new modeling package simulates the water budget of the surface and vadose zones within the popular groundwater modeling software, MODFLOW (Harbaugh et al., 2000). This new module, called the Surface/Vadose (SV) Package uses simple relationships to determine the portions of precipitation that become runoff, evapotranspiration (ET), and groundwater recharge. The SV Package significantly expands the capabilities of MODFLOW without the complexity of previously developed surface/vadose/saturated water flow simulators. The SV Package is freely available, including source code and user's manual.

This paper describes how calculations are made in the SV Package and presents an application of the package in northeastern Florida. The SV Package is especially useful where the water table is at or near land surface, including much of the southeastern US coastal plain.

BACKGROUND AND RELATED WORK

Groundwater flow models can help assess the likely environmental impacts of future development, evaluate alternative groundwater management strategies, aid the development of minimum flows and levels (MFLs), and support consumptive-use permit decisions. The U.S. Geological Survey's MODFLOW simulator (Harbaugh et al., 2000) is a public domain, widely used FORTRAN program.

While MODFLOW is easy to use and well tested, it is limited in its treatment of groundwater/surface-water interaction. This interaction is an important aspect of hydrology when the water table is near land surface, groundwater-fed wetlands are abundant, and evapotranspiration (ET) makes up a significant component of the water budget. In MODFLOW, the groundwater/surface-water interaction is treated very simply; estimates of net groundwater recharge are applied as a specified-flux boundary condition in the Recharge Package and an estimated groundwater ET vs. water-table depth function is applied as a boundary condition in the ET Package.

In recent years, more complex groundwater/surface-water simulators have been used. Examples include: MIKE-SHE (from DHI, Inc.), HMS-MODFLOW (from HydroGeologic, Inc.), ISGW (from SDI Environmental Services), and IHM (from Intera, Inc.). These simulators explicitly model groundwater flow, overland runoff, ET, wetland flow, river flow, and lake flow. However, these simulators are significantly more complex than MODFLOW and therefore more difficult to use. Additionally, some of these simulators (e.g., MIKE-SHE, HMS-MODFLOW) are proprietary software packages, which cannot be updated or tailored to a specific application without the aid of the software developers and distributors.

The new SV Package discussed here is a relatively simple, open-source MODFLOW module that automatically calculates overland runoff, ET, and net groundwater recharge from given rainfall and anthropogenic inflows (e.g., irrigation, septic-tank discharge). The module is called the Surface/Vadose Package because it simulates the water-budget processes at the land surface and in the vadose zone. This Package can be used in lieu of the Recharge Package and ET Package.

DESIGN OF THE SV PACKAGE

The SV Package consists of a set of FORTRAN routines added to the MODFLOW-2000 code (Harbaugh et al., 2000) to carry out the computations described here. Unlike more complex simulators, the SV Package does not apply partial-differential equations to simulate the processes of overland runoff and unsaturated flow. Rather, the SV Package uses accepted empirical relationships to estimate the components of the surface/vadose water budget. For instance, overland runoff at a grid cell is based on the Soil Conservation Service (SCS) Curve Number method. ET varies linearly from a minimum value when the water table is very deep to a maximum value (potential ET, or PET) when the water table is at or above land surface. Net recharge is calculated by applying a water-balance equation with negative net recharge indicating groundwater discharge. The SV Package does not simulate the overland (downhill) routing of surface water runoff from cell to cell. It is designed for transient simulations with daily time steps (stress periods may be longer).

Figure 1 depicts, conceptually, the components simulated by the SV Package. The applicable domain, or control volume, for the package includes the land surface, the vadose zone, and the plants and trees (including roots that may be below the water table). The domain is discretized into rectangular cells following MODFLOW conventions. The modeler specifies inflows to the cells in this domain: precipitation, irrigation, and septic discharge. The SV Package computes the outflows: runoff, ET, and groundwater recharge (which can be an inflow, in which case it is called groundwater discharge). Some details are presented in the following paragraphs.

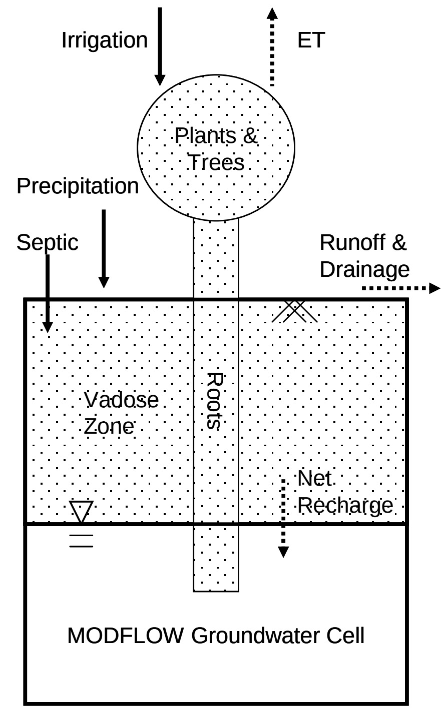

Figure 1. Conceptual diagram of a cell in the SV Package. The filled areas (vadose zone, plants/trees, roots) are part of the SV Package domain. Solid arrows indicate specified inflows. Dotted arrows indicate computed outflows.

Specified Inflows

The modeler may specify precipitation, irrigation, and septic inflows for each day (time step) and each cell in a simulation. Conceptually, irrigation is applied to plants while septic discharge is any inflow that occurs in the shallow subsurface (it may also include discharge from artificial recharge facilities). Precipitation, irrigation and septic inflows are treated differently in the calculation of runoff and ET (as explained in subsequent paragraphs).

Input protocols for these inflows (and other SV Package input data) follow MODFLOW conventions, with additional flexibility for data that are zoned (reduced spatial variability) and for data that vary less frequently than daily (reduced temporal variability).

Runoff Calculation

The SV Package calculates precipitation runoff by the Soil Conservation Service (SCS) runoff curve number (CN) method (USDA 1986). The user enters a CN value, ranging from 1 to 100, for each cell in the model. Higher CN numbers indicate conditions are more favorable for runoff. Standard methods are available for calculating CN from land-use and soil-type descriptions. The SV Package allows for CN adjustment due to antecedent moisture conditions (as specified by the modeler) following SCS (USDA 1986) guidelines.

Irrigation and septic discharge are generally not allowed to run off. However, if the water table (as estimated in MODFLOW for a particular cell) is near enough to land surface that inflows cause pooling at land surface, then the calculated runoff is adjusted upward, with the maximum runoff being the sum of precipitation and irrigation.

ET Calculation

The modeler may specify the minimum ET demand and maximum ET rate (also called potential ET, or PET) for each cell and each time step. The SV Package calculates two ET components at each cell and in each time step.

First, the SV Package calculates surface/vadose ET, which conceptually occurs above the modeled water table and is independent of water-table depth. By default, the surface/vadose ET is taken to be equal to the minimum ET demand. The surface/vadose ET is lower than the minimum ET if there is not enough precipitation and stored water (discussed in later paragraphs) available.

Also, if irrigation is applied, then the surface/vadose ET is augmented to include the irrigation amount up to the specified PET.

The SV Package then calculates the groundwater ET, which conceptually occurs below the water table. This amount varies linearly with (modeled) water table depth in the manner of the standard MODFLOW ET Package. The maximum groundwater ET (equal to PET minus surface/vadose ET) is applied when the water table is at or above land surface. A groundwater ET of zero is applied when the depth to water is greater than a specified ET extinction depth.

When calculated in this manner, the total ET is a simple function of water-table depth: at a depth of zero or less the total ET is equal to PET, at a depth greater than the extinction depth the total ET is equal to the surface/vadose ET, and in between the total ET varies linearly between PET and the calculated surface/vadose ET.

Groundwater Drainage

When the modeled water table rises above land surface (as in groundwater-fed wetlands), groundwater can drain off. The SV Package calculates the amount of drainage by multiplying an input soil leakance (hydraulic conductivity divided by thickness) by the potential difference between the modeled head and land surface elevation. This formulation is equivalent to the formulation used in the standard MODFLOW Drain Package. Conceptually, groundwater drainage is additional surface runoff, though the SV Package treats it as a budget component separate from precipitation-derived runoff.

Stored Infiltration

The SV Package has a simple algorithm that can be used to hold infiltration in the vadose zone for release in a subsequent time step. To implement this, the modeler specifies an empirical depth vs. delay function. For instance, the modeler may specify an infiltration delay of one day for every three feet in (modeled) water table depth. The water that is stored in this manner is considered to be in the vadose zone and may be used to meet the minimum ET demand in subsequent time steps.

Note that vertical unsaturated flow is not modeled with the SV Package. The stored infiltration function is just a simple water-budget method for holding water in storage when the water table is deep.

Net Recharge

The SV Package calculates net recharge to (or discharge from) groundwater by applying a water-budget calculation. When there is no infiltration delay, the net recharge at a surface/vadose cell (see Figure 1) is equal to the sum of inflows to the cell (precipitation, irrigation, septic discharge) minus the sum of outflows from the cell (runoff, ET, groundwater drainage).

When stored infiltration is applicable, the amount of stored infiltration is calculated as precipitation plus irrigation minus the sum of runoff, surface/vadose ET, and groundwater drainage. In this case, the net recharge is equal to the amount of released infiltration (stored in a prior time step) plus septic discharge minus the calculated groundwater ET.

APPLICATION IN NORTHEASTERN FLORIDA

A MODFLOW model of groundwater flow in the Pierson area of Volusia County, Florida is used to demonstrate the features and utility of the SV Package. This model was originally constructed without benefit of the SV Package and has since been updated to utilize the SV Package.

Model Description

The original Pierson model includes simulation of groundwater flow and lake stage at five lakes of interest using a Lake Package (Council, 1997, 1999) in MODFLOW. The 5-layer, 360-row, 375-column model uses monthly stress periods and daily time steps for a five-year calibration period. That means that model boundary conditions such as pumping rates are updated each month in the model. In the original model, the recharge and maximum evapotranspiration (ET) rates also change monthly. A complicated preprocessing procedure was originally used to calculate the groundwater recharge and maximum (saturated-zone) ET at each grid cell montly. The procedure uses precipitation, irrigation, runoff (SCS) curve number, and minimum/maximum ET data. Drain Package boundary cells simulate discharge at wetlands (when the water table is above land surface) in the original model.

With the SV Package, the net recharge (or discharge) rates are recomputed in each time step (day) using the same types of data input (precipitation, runoff curve number, irrigation rates, minimum and maximum ET rates). The Recharge and ET Packages are not needed. The SV Package method provides a better resolution for model boundary conditions (conditions change daily rather than monthly) without requiring the complicated preprocessing procedure of the original model. The SV package automatically handles drainage when the water table is above land surface (obviating the use of wetland drains) and it automatically routes runoff in identified watershed cells to lakes modeled with the Lake Package.

Many of the inputs used to preprocess for recharge, runoff, and ET in the original model are used as direct inputs to the SV package in the updated model. The inputs include daily precipitation (assumed spatially uniform), minimum and maximum (potential) ET (also spatially uniform), runoff curve numbers (spatially variable, constant in time), and monthly irrigation rates (spatially and temporally variable; calculated from water-use permit information).

An ArcView™ pre-processor for the SV Package facilitates creation of the SV-Package input dataset for this model. The ArcView™ pre-processor uses mapped data (e.g., a map of CN at each model cell) to define model input and has easy-to-use dialogs that are used to define all of the SV Package input variables.

Results

When the SV Package is used in place of the Recharge, ET, and Drain Packages, the changes in modeled head are noticeable at certain locations. Figure 2 shows the effect at a modeled lake and at selected model cells that correspond to monitoring well locations.

Two main effects are noted when the SV Package is used in the Pierson model, as compared to the original model. Firstly and most importantly, simulated water levels are generally higher with the SV Package. This results primarily from higher net recharge to groundwater (analogous to recharge minus ET and drainage in the original model). The main cause for this increase in net recharge is that total vadose-zone ET is decreased. In the original model, the vadose-zone ET – generally taken to be the minimum ET – is accounted for in the preprocessor on a monthly basis. With the SV Package, there is no vadose-zone ET on days with no precipitation or irrigation since stored infiltration is not used in this example. This increases net recharge over the course of the simulation.

Simulations that include stored infiltration (results not presented here) result in the somewhat lower heads, but there is still no vadose-zone ET during long periods of no rainfall or where the water table is shallow.

A secondary cause for water-level increases, particularly for the lakes, is the fact that the SV Package adds groundwater drainage within a lake watershed to the lake's runoff inflow, which was not done in the original model.

The other noticeable effect with the SV-Package simulations is more transient fluctuation in simulated hydrographs. This happens because recharge and maximum groundwater ET rates are no longer averaged by month, but are calculated daily using daily precipitation data.

Note that no attempt has been made to recalibrate the model to observed heads and flows (the observed heads at monitoring wells are omitted in Figure 2). The purpose of this exercise is simply to show an example of the effect of using the SV Package on model results when similar data and assumptions are applied.

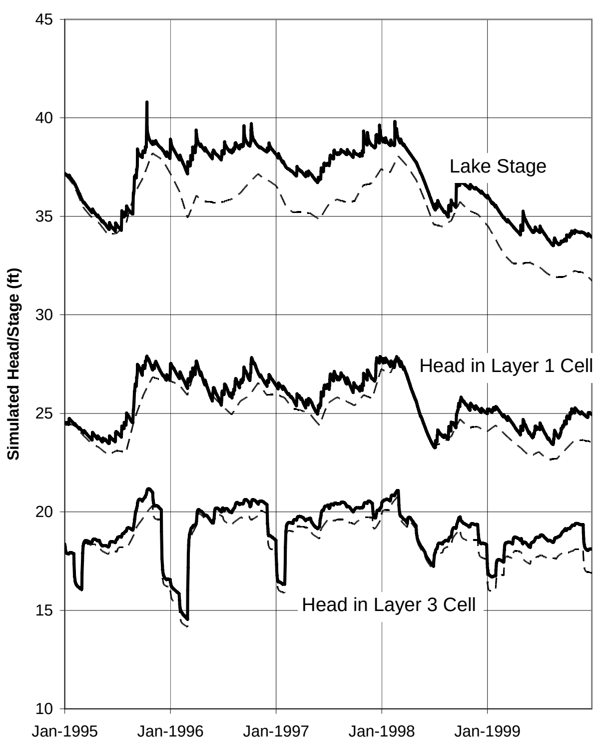

Figure 2. Simulated lake stage and groundwater head at selected model locations with the SV Package (solid lines) and without the SV Package (dashed lines).

RECOMMENDATIONS

The SV Package is well-suited for groundwater flow models where surface-water/groundwater interaction is important, including much of the southeastern U.S. coastal plain. It provides a relatively simple way to translate daily precipitation data into reasonable recharge, ET, and runoff rates, alleviating the need for some of the time-consuming pre-processing that is sometimes done to generate model input. While some applications may require complex hydrologic simulators (such as MIKE-SHE, HMS-MODFLOW, or IHM), many only require a relatively simple, realistic method for determining how rainfall (with other inflows) is distributed among runoff, ET, and groundwater recharge. The SV Package is ideal for this – more capable than standard MODFLOW but not as complex or computationally burdensome as other simulators.

In addition, unlike some other simulators, the SV Package source code is freely available and completely open to the public. This allows open discussion on the procedures, critical review of the methods, and future updating by others. Also, the ArcView™ processor for the SV Package allows for easy creation of datasets from digital maps and databases.

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