ground water

Methods Note/

RIPGIS-NET: A GIS Tool for Riparian Groundwater Evapotranspiration in MODFLOW

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Abstract

RIPGIS-NET, an Environmental System Research Institute (ESRI's) ArcGIS 9.2/9.3 custom application, was developed to derive parameters and visualize results of spatially explicit riparian groundwater evapotranspiration (ETg), evapotranspiration from saturated zone, in groundwater flow models for ecohydrology, riparian ecosystem management, and stream restoration. Specifically RIPGIS-NET works with riparian evapotranspiration (RIP-ET), a modeling package that works with the MODFLOW groundwater flow model. RIP-ET improves ETg simulations by using a set of eco-physiologically based ETg curves for plant functional subgroups (PFSGs), and separates ground evaporation and plant transpiration processes from the water table. The RIPGIS-NET program was developed in Visual Basic 2005, .NET framework 2.0, and runs in ArcMap 9.2 and 9.3 applications. RIPGIS-NET, a pre- and post-processor for RIP-ET, incorporates spatial variability of riparian vegetation and land surface elevation into ETg estimation in MODFLOW groundwater models. RIPGIS-NET derives RIP-ET input parameters including PFSG evapotranspiration curve parameters, fractional coverage areas of each PFSG in a MODFLOW cell, and average surface elevation per riparian vegetation polygon using a digital elevation model. RIPGIS-NET also provides visualization tools for modelers to create head maps, depth to water table (DTWT) maps, and plot DTWT for a PFSG in a polygon in the Geographic Information System based on MODFLOW simulation results.

Introduction

Despite the importance of riparian ecosystems in providing a wide range of ecological, economic, recreational, and social values for humans, and habitats for a wide variety of plants and animals (Baker and Walford 1995; Stringham et al. 2001), global land cover changes have had a considerable impact on many types of river ecosystems (Dynesius and Nilsson 1994; Tockner and Stanford 2002). Furthermore, groundwater depletion has resulted in loss of riparian ecosystems throughout the world (Gremmen et al. 1990; Stromberg et al. 1996). The ecohydrological impact of riparian land cover change consists of large-scale effects on groundwater and surface water use by riparian species, and changes in basin-scale carbon and water budgets (Williams et al. 2006).

Riparian groundwater evapotranspiration (ETg) constitutes a major component of the water balance in many arid and semiarid environments (Scott et al. 2008; Lubczynski 2009). Spatial and temporal variability of riparian ETg are controlled by climate, vegetation structure, soil moisture, and depth to water table (DTWT). In groundwater modeling, DTWT is often considered the major factor controlling ETg rates (Cooper et al. 2006). This apparent relationship between ETg rate and DTWT has been applied in one of the most commonly used groundwater modeling programs, MODFLOW, to

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estimate ETg while the impact of unsaturated zone is ignored (McDonald and Harbaugh 1988; Harbaugh et al. 2000; Harbaugh 2005).

In the MODFLOW evapotranspiration package (EVT), a piecewise linear relationship between DTWT and ETg rates is considered. This relationship is later modified into a piecewise linear segmented relationship in the evapotranspiration segments (ETS1) package to include nonlinearity between DTWT and ETg rates (Banta 2000). Recently Baird and Maddock (2005) developed the riparian evapotranspiration (RIP-ET) package for MODFLOW to simulate riparian and wetland ETg using nonlinear ETg curves which incorporate reduction in ETg rates as a result of anoxic conditions (Figure S1 and Table S1, Supporting Information). Impact of soil moisture dynamics in unsaturated zone is not incorporated in RIP-ET. In RIP-ET, riparian vegetation is grouped as plant functional groups. Plant functional groups are non-phylogenic groupings of plant species with a similar response to environmental condition (Lavorel et al. 1997). Plant functional groups may be further subdivided to plant functional subgroups (PFSGs) based on their plant size and density (Baird and Maddock 2005).

Accurate estimates of riparian ETg and vegetation habitat modeling requires detailed spatial information about riparian ecosystem extent, community structure, and land surface elevation. Geographic Information System (GIS) provides a powerful tool for managing and storing spatial and non-spatial datasets, and modeling different environmental processes (Martin et al. 2005). The spatial analysis capability of GIS can be linked with RIP-ET package for enhanced parameterization of riparian ETg in regional groundwater models and visualize MODFLOW groundwater results.

In this article, we discuss the development of a GIS-based tool (RIPGIS-NET) to create data input files for the RIP-ET package (Baird and Maddock 2005) in MODFLOW-2000 (Harbaugh et al. 2000) or MODFLOW-2005 (Harbaugh 2005), and visualize MODFLOW results. Application of RIPGIS-NET program depends on the availability of a MODFLOW model of a riparian groundwater system. The combined application of RIP-ET in MODFLOW with the GIS capabilities of RIPGIS-NET provides a useful tool for calculating spatially explicit ETg estimates at multiple levels including ETg estimate for each PFSG in a model cell, total ETg estimate for each MODFLOW cell with riparian polygons, and finally overall ETg estimates for the entire region. As such, applications of RIPGIS-NET and RIP-ET include (1) assessing the impact of riparian vegetation change on groundwater resources in a MODFLOW groundwater model; (2) evaluating how riparian vegetation dynamics are influenced by change in groundwater levels because of pumping and recharge; (3) examining the impact of riparian management scenarios on groundwater budget; and (4) visualizing the status of water table. These capabilities make this package suitable for riparian ecosystem restoration planners and groundwater modelers to simulate the impact of different riparian vegetation scenarios and visualize model results (Baird et al. 2005) when application of integrated land surface-groundwater models is limited because of data requirements.

RIPGIS-NET: A GIS-Based Tool

RIPGIS-NET is developed in Visual Basic 2005 using ArcObjects technology. ArcObjects, which constitute ArcGIS framework, are common modular libraries of reuseable GIS software components written in C++, and developed by Environmental System Research Institute (ESRI). Therefore, it is possible to use any COM-compliant development language to customize ArcGIS applications (Chang 2004). Development of RIPGIS-NET in ArcGIS has several advantages; ArcGIS is a widely used software program, supports a variety of vector and raster data formats, and contains hundreds of built-in geoprocessing tools. The automated procedures in RIPGIS-NET reduce the amount of time required for creating input dataset and visualizing MODFLOW model results.

RIPGIS-NET user interface is made up of two components: the RIPGIS-NET main form and the standard ArcMap window. The RIPGIS-NET main entry form consists of a series of menus and tools for creating the RIP-ET ASCII input file (*.rip*), and visualizing MODFLOW simulation results (Figure 1). In addition, RIPGIS-NET has tools for adding fields and attributing riparian polygon shapefiles, modifying existing RIP-ET input files, and calculating average surface elevation for MODFLOW cells based on high-resolution digital elevation model (DEM).

To determine RIP-ET parameters, RIPGIS-NET requires riparian vegetation polygon boundaries, PFSG raw data table which has the ETg curve data for each PFSG in a project, DEM and MODFLOW Discretization (*.dis*) and Basic package (*.ba6*) files. For each PFSG, dimensionless curve segment data are derived from PFSG raw dataset in RIPGIS-NET. To compute ETg, PFSGs are arranged in a series of polygons with approximately uniform land surface elevation. Each polygon in a MODFLOW cell may have single or multiple PFSGs where percent cover for each PFSG is defined by the user using interactive tools in RIPGIS-NET. Multiple polygons can exist per MODFLOW cell. RIPGIS-NET creates a MODFLOW grid in a shapefile format and supports both regular and irregular grid. RIPGIS-NET calculates fractional coverage areas of each PFSG per model cell based on polygon areas and PFSG's percent cover in each riparian polygon and MODFLOW cell area. Furthermore, it automatically calculates average and standard deviation of surface elevation per riparian polygon using a DEM. In the absence of GIS data, input data can be entered using Excel files. The basic workflow of creating RIP-ET input file consists of five steps (Figure S2, Supporting Information).

MODFLOW simulation results can be visualized using the MODFLOW visualization tool. The MODFLOW visualization tool in RIPGIS-NET requires the MODFLOW head file, DEM, and PFSG raw data to visualize MODFLOW model output results such as hydraulic

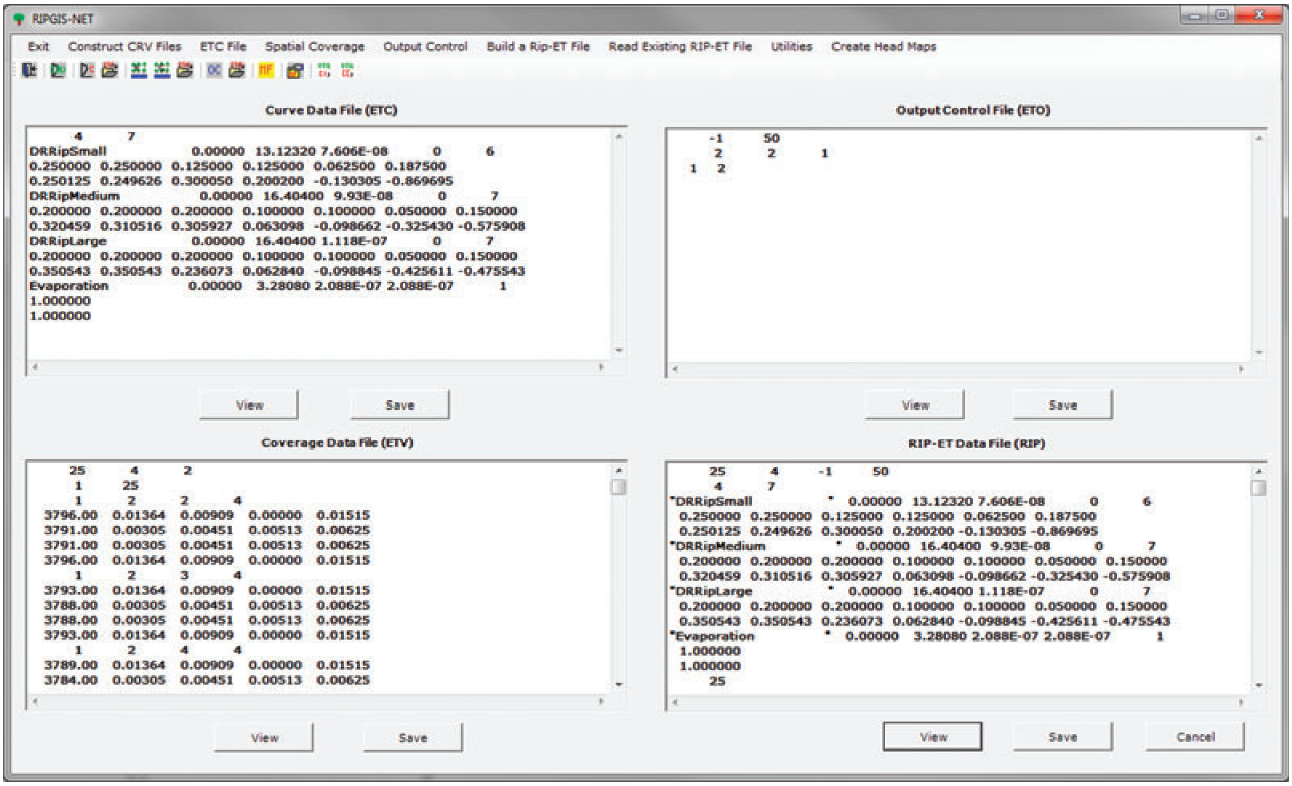

Figure 1. Main RIPGIS-NET form shown in ArcMap application. List boxes present steps in generating a RIP-ET input file. Curve Data File (ETC) shows ETg curve parameters for four PFSGs in a project. The ETV file shows average surface elevation and fractional coverage area for each riparian polygon in a MODFLOW cell.

head and DTWT maps and DTWT for a PFSG in a polygon (Table S2, Supporting Information). If the MODFLOW visualization tool was used independent of RIP-ET, PFSG raw data is not required. The *Plot Depth to Water Table for PFSG Polygons* command plots the DTWT for a given PFSG in a selected polygon relative to a given PFSG curve (Figure 2).

Why RIPGIS-NET?

In RIPGIS-NET, the functionality of the earlier RIP-ET pre-processors including PRE-RIP-ET written with Winteracter, a windows-based GUI for FORTRAN 90/95 interaction, and RIPGIS, an ArcView 3.x interface (Dragoo 2004), are combined to develop a comprehensive GIS package for modeling riparian ETg in MODFLOW models. Moreover, RIPGIS-NET refined the conceptual representation of riparian polygons in the RIP-ET package by including (1) multiple riparian polygons per model cell (Figure 2); (2) detailed surface elevation calculations per model cell for each polygon by including all DEM cells instead of a single DEM value at the polygon centroid; (3) accurate calculation of DTWT to estimate ETg; and (4) a MODFLOW visualization component to provide multiple ways for visualizing MODFLOW and RIP-ET results.

RIPGIS-NET spatial parameter derivation is enhanced compared to other MODFLOW GIS-based processors because of an improved conceptual presentation of riparian polygons in a MODFLOW cell. The method involves redefining riparian polygon boundaries per model cell by intersecting a riparian layer with a MODFLOW grid (Figure S3, Supporting Information). As a result, this approach preserves the areal distribution of riparian polygons compared to other methods, where inclusion of a riparian polygon in a model cell is defined by proximity of a polygon to the cell centroid.

Calculating fractional coverage areas of PFSGs per model cell as an ETg flux area instead of including total MODFLOW cell area provides a more accurate estimate of ETg using RIPGIS-NET. Moreover, calculating surface elevation per riparian polygon per MODFLOW cell instead of the overall cell average elevation provides more realistic changes in land surface elevation and calculated DTWT.

Conclusions

In RIPGIS-NET, enhanced conceptual representation of riparian ETg in RIP-ET through PFSG ETg curves is merged with the spatial data analysis of GIS, to improve riparian ETg estimation in a MODFLOW groundwater model. This improvement is achieved by incorporating the spatial distribution of plants and the water table, calculating fractional coverage areas of PFSGs per model cell instead of using the entire cell as ETg flux area, and calculating average surface elevation based on a DEM for each riparian polygon per cell as a substitute

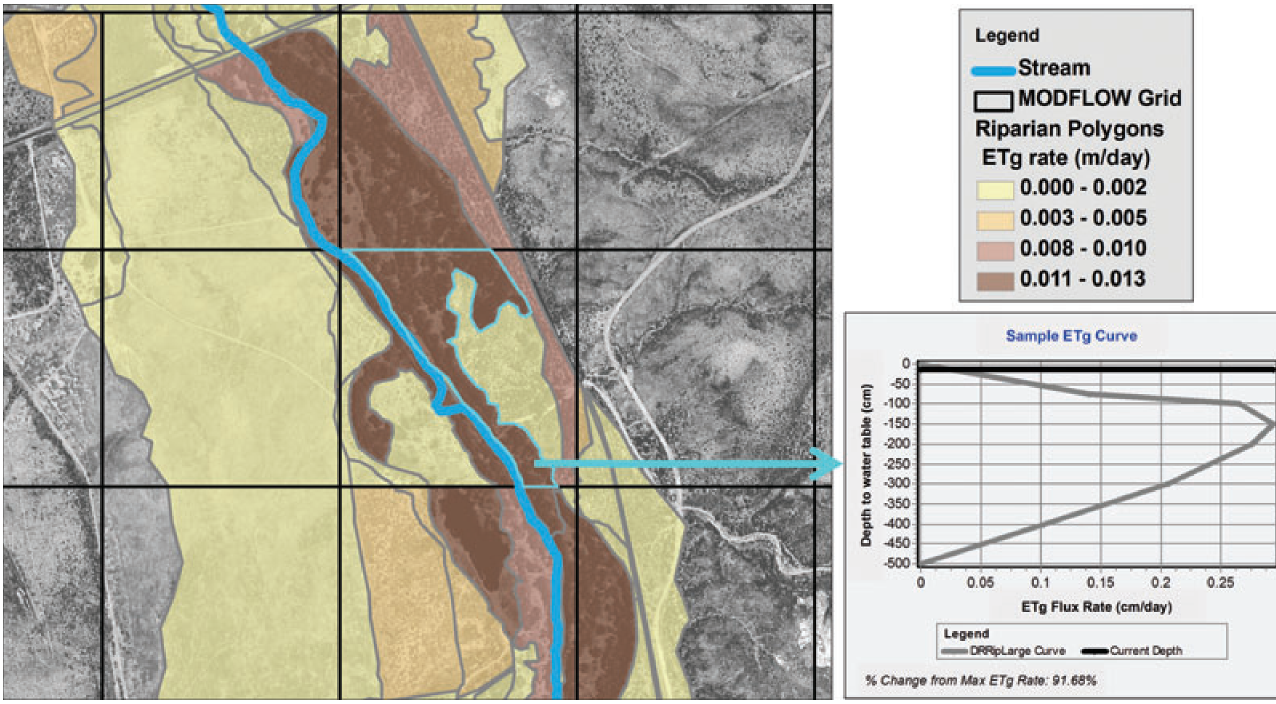

Figure 2. Spatial variability of riparian ETg estimated at a polygon level in a MODFLOW model using RIPGIS-NET. Sample ETg curve is created in RIPGIS-NET for deep rooted large riparian vegetations in a semiarid basin.

to one elevation value per cell. The MODFLOW visualization tool component of RIPGIS-NET provides a series of tools for visualizing any MODFLOW groundwater model's results making it a suitable tool for hydrologic assessment.

Simulation results demonstrated the power of the program and its impact on ETg and groundwater budget compared to the traditional MODFLOW modeling approaches. Results of these factors will be discussed in a forthcoming study. Potential application of the program consists of assessing the impact of riparian vegetation change on groundwater resources in a MODFLOW model and riparian ecosystem restoration.

Software Availability

RIPGIS-NET program is a public domain software. Users required installing ArcGIS version 9.2 or 9.3 with Spatial Analyst extension, and MODFLOW 2000/2005 prior to installing RIPGIS-NET. The program is accompanied by a detailed user's guide (Ajami and Maddock 2009) and can be obtained from H.A.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Generic ETg flux rate in RIP-ET compared with traditional MODFLOW ETg curve. Sxd, saturated extinction depth (L) measured with respect to the land surface elevation; Ard, active rooting depth (L); HSURF, land surface elevation; Rmax, maximum ETg rate (L/T); Hxd, extinction depth elevation (L); Hsxd, saturated extinction depth elevation (L) (adopted from Baird et al. 2005).

Figure S2. RIPGIS-NET basic workflow structure. The basic workflow of creating RIP-ET input file consists of five steps: (1) construct curve file (*.crv*) from the PFSG raw data; (2) construct ETC file (*.etc*) that has the RIP-ET curve segments information for all PFSGs in the project; (3) construct ETV file (*.etv*) that has the information about MODFLOW cell location (layer, row, and column number), number of polygons in a MODFLOW cell, fractional coverage area of a PFSG in a MODFLOW cell, and average surface elevation per riparian polygon; (4) construct MODFLOW output control file (*.eto*); and (5) construct RIP-ET input file (*.rip*). Moreover, RIPGIS-NET has utilities to import an existing MODFLOW RIP-ET file, and produces a PFSG Data File (*.etc*), a fractional coverage file (*.etv*), and an output control file (*.eto*). The benefit of this module is that it allows modifying contents of an existing (*.rip*) file, and it makes a new RIP-ET file.

Figure S3. Process of creating the ETV file parameters. The sample file shown here has 25 MODFLOW cells with riparian polygons, maximum number of polygons in each cell is 4, and there are two riparian coverage files in a MODFLOW model to define two seasons (parameters in line 1). For each cell, the cell location (layer, row, column number, number of polygons) is specified, and for each polygon in a cell, average surface elevation and fractional coverage area are reported. In RIPGIS-NET, a riparian layer is intersected with a MODLFOW grid to define number of riparian polygons in each MODFLOW cell. Later, average surface elevation is calculated for each polygon based on a high-resolution DEM. The use of this intersection method in RIPGIS-NET avoids losing information about the spatial distribution of riparian vegetation especially in larger cells.

Table S1. Parameter comparison between RIP-ET and traditional MODFLOW ETg packages

Table S2. RIPGIS-NET MODFLOW visualization tool commands

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