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Linking Riparian Dynamics and Groundwater: An Ecohydrologic Approach to Modeling Groundwater and Riparian Vegetation

KATHRYN J. BAIRD*
Department of Hydrology and Water Resources
University of Arizona
P.O. Box 210011
Tucson, Arizona, 85721-0011

JULIET C. STROMBERG
School of Life Sciences
Arizona State University
P.O. Box 874501
Tempe, Arizona 85287-4501

THOMAS MADDOCK, III
Department of Hydrology and Water Resources
University of Arizona
P.O. Box 210011
Tucson, Arizona, 85721-0011

ABSTRACT / The growing use of global freshwater supplies is increasing the need for improved modeling of the linkage between groundwater and riparian vegetation. Traditional groundwater models such as MODFLOW have been used to predict changes in regional groundwater levels, and thus riparian vegetation potential attributable to anthropogenic water use. This article describes an approach that improves on these modeling techniques through several innovations. First, evapotranspiration from riparian/wetland systems is modeled in a manner that more realistically reflects plant ecophysiology and vegetation complexity. In the authors' model programs (RIP-ET and PRE-RIP-ET), the single, monotonically increasing evapotranspiration flux curve in traditional groundwater models is replaced with a set of ecophysiologically based curves, one for each plant functional group present. For each group, the curve simulates transpiration declines that occur both as water levels decline below rooting depths and as waters rise to levels that produce anoxic soil conditions. Accuracy is further improved by more effective spatial handling of vegetation distribution, which allows modeling of surface elevation and depth to water for multiple vegetation types within each large model cell. The use of RIP-ET in groundwater models can improve the accuracy of basin scale estimates of riparian evapotranspiration rates, riparian vegetation water requirements, and water budgets. Two case studies are used to demonstrate that RIP-ET produces significantly different evapotranspiration estimates than the traditional method. When combined with vegetation mapping and a supporting program (RIP-GIS), RIP-ET also enables predictions of riparian vegetation response to water use and development scenarios. The RIP-GIS program links the head distribution from MODFLOW with surface digital elevation models, producing moderate- to high-resolution depth-to-groundwater maps. Together with information on plant rooting depths, these can be used to predict vegetation response to water allocation decisions. The different evapotranspiration outcomes produced by traditional and RIP-ET approaches affect resulting interpretations of hydro-vegetation dynamics, including the effects of groundwater pumping stress on existing habitats, and thus affect subsequent policy decisions.

Riparian Ecosystems and Water Resources

Freshwater ecosystems play an integral role in human society, affecting fields as diverse as commerce, transportation, health, and recreation. For centuries, human populations have exploited freshwater ecosystems without understanding the basic environmental principles that allow these systems to maintain their inherent health and vitality (Naiman and others 2002). Consequently, overengineering, overabstraction of resources, pollution, and ineffective management practices have dramatically altered these ecosystems (Nienhuis and Leuven 2001). Many of the world's greatest rivers have been reduced from complex systems of floodplains and meandering, braided channels to single channels that support only a fraction of their original biodiversity and abundance (Kingsford 2000). Despite the mounting evidence of adverse effects and

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*Author to whom correspondence should be addressed; *email:* kbaird@hwr.arizona.edu

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lack of success, radical river regulation measures continue today (Nienhuis and Leuven 2001).

Global demands on water resources are increasing as populations and material needs grow. The pressure for water resource development is particularly acute in arid regions where water is already in short supply. In the arid western United States, irrigation needs still largely govern river management priorities and objectives, but urban population growth is increasing regional water demands. Surface water resources, diverted for urban and agricultural uses, often are entirely appropriated by existing state, interstate, and international compacts and treaties. Groundwater often is the only new or untapped water resource (Cooper and others 2003). Unsustainable groundwater development, although not always immediately obvious, threatens natural resource values and is becoming a major source of user conflict (Cooper and others 2003; Glennon and Maddock 1994; Steinitz and others 2003).

Riparian systems, the dominant freshwater ecosystem throughout the western United States, typically occur where groundwater is in close proximity to the soil surface or where a direct connection exits between groundwater and surface water. These groundwater–surface water interfaces support greater biomass and often greater species diversity than the surrounding landscape, and in semiarid and arid environments function as critical oases for plants, animals, and humans (Wurster and others 2003). Intricately coupled to both groundwater and surface water regimes, riparian ecosystems are sensitive to perturbations in either (Busch and others 1992; Grimm and others 1997; Stromberg 1993).

Riparian biota are dependent on the dynamic characteristics of the surface water regime, described in terms of magnitude, frequency, timing, duration, and rate of change (Naiman and others 2002; Poff and others 1997; Richter and Richter 2000). Surface water, however, forms only the visible part of a continuous hydrologic system. Water in the surface stream, vadose zone, and groundwater aquifer collectively sustains riparian ecosystems (Hancock 2002). Water from the capillary fringe of the alluvial groundwater table is the major water source for many riparian tree species in arid and semiarid regions (Shafroth and others 2000; Snyder and Williams 2000). Lowering groundwater tables can have widespread ecologic consequences, including the conversion of perennial stream flows to intermittent flows and the alteration of vegetation composition and cover. Even short-term declines in alluvial groundwater tables can change the distribution and abundance of riparian plant associations, leading to the decline of phreatophytes (Cooper and others 2003; Shafroth and others 2000). Identifying the vulnerability of riparian and wetland ecosystems to anthropogenic activities and climatic variation necessitates a thorough understanding of the groundwater–surface water interactions that maintain them (Winter and others 1998; Wurster and others 2003).

Role of Groundwater Models in Protecting Riparian Ecosystems

In regions where anthropogenic water use disrupts recharge and discharge processes, creating groundwater or surface water deficits, balancing the need for water against the conservation of natural ecosystems present a daunting challenge. To protect riparian ecosystems, special attention must be given to the protection of groundwater systems and to the effects of land use changes on the hydrologic cycle (Batelaan and others 2003). Consequently, conservation and regional water planners alike require tools that allow them to make informed decisions regarding the effects of land use development and water allocation on freshwater ecosystems (Richter and others 1997). Groundwater models that simulate regional groundwater behavior can be useful tools.

Water use decisions often affect large geographic areas, making their impacts difficult to characterize. Regional models, which focus on broad landscape elements, allow us to understand and predict the effects of water management decisions and climate changes at relevant scales (Elmore and others 2003; Nilsson and Svedmark 2002). When coupled with mechanistic models of wetland or riparian ecology and with sufficient field monitoring, regional groundwater models can provide a tool for predicting both the vulnerability of wetland and riparian habitat to water table decline and the future status of created or restored ecosystems (Mitsch and Wilson 1996; Springer and others 1999). They also can aid in the quantification of basin or reach scale water requirements for key habitat types in the riparian landscape.

Regional groundwater models are used widely to estimate water budgets as part of the local water allocation decision-making process. The accuracy and applicability of these groundwater models is, of course, dependent on accurate representations of the processes they simulate. One of the most critical but poorly simulated processes is seasonal riparian evapotranspiration (ET) (Goodrich and others 2000). The narrow, heterogeneous nature of riparian zones, coupled with their complex hydrology, hinders our understanding and quantification of ET processes in these systems (Hipps and others 1998). Controlled by

the interaction of both abiotic and biotic factors, ET is strongly linked with such ecosystem parameters and processes as soil moisture content, nutrient flows, and vegetation productivity (Jarvis and McNaughton 1986; Wever and others 2002).

The method used to model ET affects the calculated water budget and simulated depths to groundwater, and thus the resulting interpretations regarding ecosystem dynamics. In the current state of groundwater modeling, ET is appropriately defined as a function of hydraulic head or groundwater depth in an alluvial aquifer. Unfortunately, the manner in which it is modeled does not accurately reflect the relationship between riparian or wetland plant transpiration and groundwater conditions.

To improve ability to calculate riparian and wetland ET, estimate vegetation water requirements, and aid in predicting vegetation response to changing water availability, we developed a new method for modeling riparian and wetland ET. This methodology is applied in a Riparian Evapotranspiration Package (RIP-ET) for MODFLOW-96 and MODFLOW 2000 (Maddock and Baird 2003). The RIP-ET package is designed to be coupled with MODFLOW (McDonald and Harbaugh 1988; 1996), one of the most widely used groundwater flow models in the fields of consulting and research (Romero and Maddock 2003). In addition, two preprocessing programs were developed to aid the user in RIP-ET data preparation. The first, RIP-GIS, is a geographic information system (GIS) pre- and postprocessor that automates the steps required to complete a riparian coverage file for those with ArcView capabilities (Dragoo and others 2004). The second preprocessor, PRE-RIP-ET (Baird and others 2004), sets up the desired ET curves, reads the fractional coverage information from RIP-GIS, assigns surface elevations (see following sections) and, using the MODFLOW grid, writes the riparian ET file required by MODFLOW.

The modeling and mathematical details of RIP-ET are described in Maddock and Baird (2003). The goal of this article is to bring the model to the attention of ecologists, conservationists, and land/water managers. The objectives are twofold: to describe the ways in which the new modeling method overcomes the limitations of traditional ET modeling approaches, and to demonstrate and discuss some conservation applications of the model.

Development of a New Modeling Methodology

Plant Functional Groups

The largest source of error in traditional approaches to ET modeling is the use of a single ET curve to represent both evaporation and transpiration regardless of the species assemblages present and their vigor and density. Not only is evaporation a unique physically based process and transpiration a biologic process, but ET rates also vary widely between plant species because of morphologic differences in root architecture, including rooting depth, and physiologic sensitivities to water availability (Horton and others 2001; Shafroth and others 2000). Our first steps were to decouple the process of evaporation from transpiration and then develop individual transpiration curves for the species or vegetation types being modeled.

Given the complexity of freshwater ecosystems, the creation of transpiration curves for all riparian and wetland species is not feasible. To address this issue, we incorporated the concept of plant functional groups (PFGs) into the ET model. Plant functional groups are defined as nonphylogenetic associations of plant species that exhibit similar responses to environmental conditions and have similar effects on the dominant ecosystem processes (Lavorel and others 1997). Typically, these are groups of species with similar morphologic, physiologic, or phenologic traits that vary predictably along environmental gradients. Using information on correlated traits in lieu of detailed species information simplifies the complex structure of plant communities and provides a framework for predicting ecosystem response to environmental change (Dyer and others 2001; Symstad and others 2000).

In the Riparian Evapotranspiration Package, PFGs are the units used to elucidate the interaction of plant ET with groundwater depth. We defined a set of PFGs relevant for semiarid environments on the basis of transpiration rates, rooting depths, and the upper and lower range of seasonal groundwater depth tolerance. These basic groups are obligate wetland, shallow-rooted riparian, deep-rooted riparian, and transitional riparian species. Working definitions are provided in Maddock and Baird (2003). To decouple evaporation from transpiration, we included a fifth group: bare ground/open water.

Evapotranspiration rates and the occupied range of groundwater elevations differ between PFGs. Because most riparian corridors comprise a mixture of PFGs, each with different hydrologic requirements and ET rates, total ET is determined from the combination of PFGs present and the ambient groundwater levels. To make the methodology, and thus the program, broadly applicable, users can develop the set of PFGs relevant to their geographic region and model area.

Plant population traits such as health and age can affect rooting depths, limits of water tolerance, and transpiration rates (Meinzer and others 1997). Com-

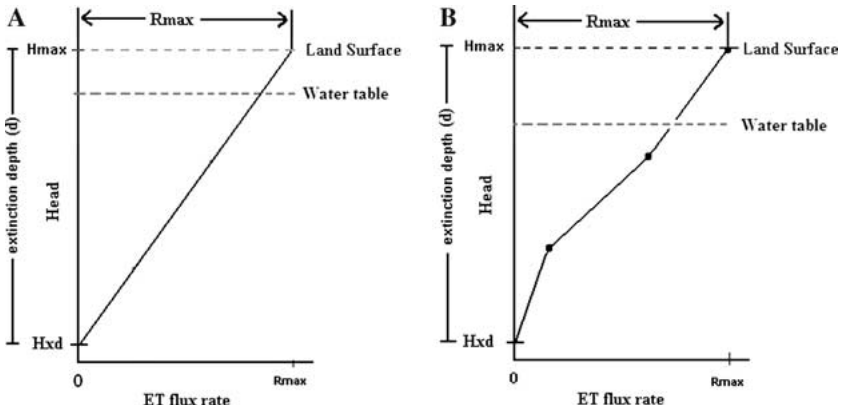

Figure 1. (a) Traditional linear (MODFLOW 96) and (b) segmented function (ETS1) package (MODFLOW 2000) evapotranspiration (ET) curves. Hxd, extinction depth elevation; d, extinction depth; Rmax, maximum ET rate; Hmax, maximum ET surface elevation.

munity traits such as plant density and cover also can affect transpiration rates, as can abiotic factors such as soil salinities. Any number of these or other such factors may be used as modifiers to create plant functional subgroups (PFSGs), and thus to refine further our ability to model plant ET in response to environmental conditions.

A New Transpiration Curve

A second source of error in traditional ET models involves the assumed shape of the curve relating ET rates to groundwater depths. The traditional approach to modeling ET in MODFLOW-96 (McDonald and Harbaugh 1988; 1996) assumes a quasilinear relationship between the ET flux rate and the hydraulic head or groundwater depth in an unconfined aquifer (Figure 1A). With this approach, if the water table is below the model extinction depth (Hxd) the ET rate is assumed to be zero. As the water table rises above this depth, the ET rate is assumed to increase linearly until it reaches a maximum rate (Rmax) at a user-defined maximum elevation (Hmax). The distance between Hxd and Hmax is called the extinction depth (d). Over this depth, the ET rate varies linearly with hydraulic head and is described by the slope of $\frac{R\max}{d}$.

In an ET package for MODFLOW 2000, Banta (2000) replaces the linear slope with a segmented function (ETS1) (Figure 1B). This function allows for limited flexibility, but assumes a constant Rmax above the maximum ET surface elevation, which in most modeling exercises is set equal to the land surface.

These quasilinear relationships may be useful for modeling evaporation, but do not accurately reflect the relationship between plant transpiration and groundwater conditions in that no allowance is made for the reduction in plant transpiration that occurs as the groundwater table approaches the upper horizons of the plant's rhizosphere. There is evidence that at high water table elevations, the root systems of plants other than obligate wetland species become oxygen deficient, causing transpiration rates to decline until the plants eventually die of anoxia (Hughes 1997).

With RIP-ET, we simulate transpiration from riparian/wetland systems in a manner that more realistically reflects the ecophysiology of the component plant species (Figure 2). For each user-defined PFSG, as in the traditional approach, there is an extinction depth elevation (Hxd) (i.e., water table elevation below which the roots are unable to obtain water) at which transpiration is zero. As water table levels increase above the extinction depth, water becomes increasingly available to the root system and transpiration rates increase to a maximum average transpiration flux (Rmax) at a water table depth some distance below land surface. (This maximum transpiration flux rate is designed to be a measured or estimated maximum average daily transpiration rate, not the peak daily transpiration flux rate.) As water table elevations increase further, the root zone of nonobligate wetland groups becomes saturated, and increasingly less of the root system is capable of water uptake. Consequently, transpiration rates decline. The water table elevation associated with plant death from anoxia is the saturated extinction depth elevation (Hsxd). The transpiration flux rates for both the extinction and saturated extinction depths are by definition zero. The distance between these points is the active root zone depth (Ard). The traditional ET curve, illustrated in Figure 2 for comparative purposes, is used exclusively to model evaporation from bare soil or open water.

In the Riparian Evapotranspiration Package, we approximate the continuous curve shape with a series of small linear segments. Figure 3 illustrates the resulting segmented ET flux rate curve. The curve segments (labeled 1 through 7), defined by the vertices *h(k)* and *R(k)*, determine the shape of the curve. The

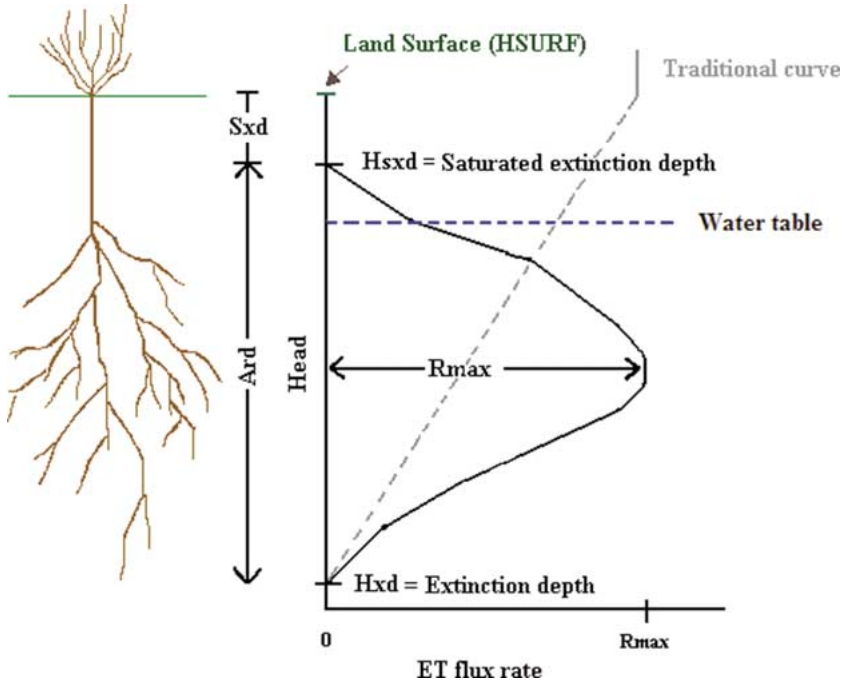

Figure 2. Generic evapotranspiration (ET) flux rate curve for a plant functional group in RIP-ET with associated plant schematic. Sxd, saturated extinction depth (L); Ard, active rooting depth (L); Hsxd, saturation extinction depth elevation; Hxd, extinction depth elevation; HSURF, land surface elevation; Rmax, maximum ET rate.

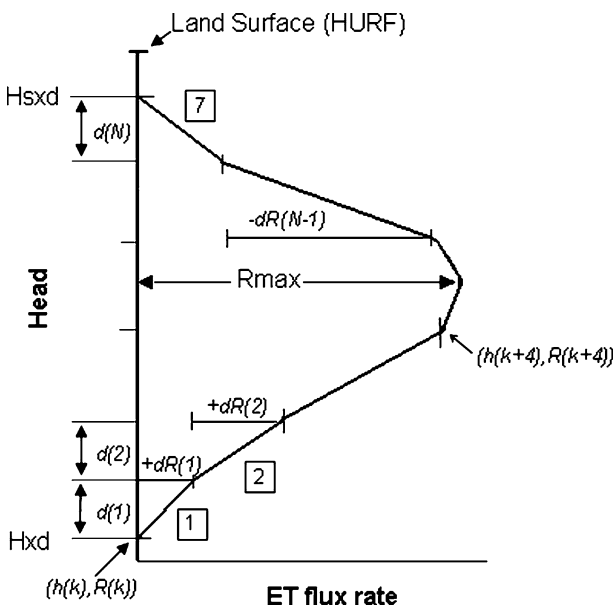

Figure 3. Segmented evapotranspiration flux curve illustrating linear interpolation using *d(N)*s and *dR(N)*s.

functions *d(1)...d(N)* represent the change in head over each segment (in length units), whereas *dR(1)...dR(N)* represent the change in flux over the segment (in flux rate units). The curve segments are specified as dimensionless and converted into units consistent with the other MODFLOW packages during the modeling simulation. The process for producing the dimensionless, segmented curves is conducted external to the RIP-ET package, and can be accomplished easily with PRE-RIP-ET. The following inputs are required for the development of an ET curve: extinction depth, saturation extinction depth, and preferably a minimum of three ET rates at specific groundwater depths.

Values of the extinction depth can be approximated by the maximum rooting depth of the species within each PFSG, as determined through field studies or literature research. Saturated extinction depth can be determined on the basis of experimental studies or correlations between plant species abundances and water table elevations. Between these extremes, the shape of the PFSG transpiration curves can be determined from measured or estimated transpiration rates associated with specific water table depths. For arid and semiarid riparian species, there are few estimates of the magnitude or the spatial and temporal heterogeneity of transpiration fluxes (Schaeffer and others 2000). However, even if available data are sparse, the use of an upper and lower water tolerance range for the species in question, combined with nonlinear curves (a more ecologically realistic scenario), provides for more realistic model outcomes.

Multiple Transpiration Curves

The third improvement in ET modeling methodology is the application of multiple transpiration curves within a single modeling cell. Traditional methods restrict the user to a single curve regardless of the com-

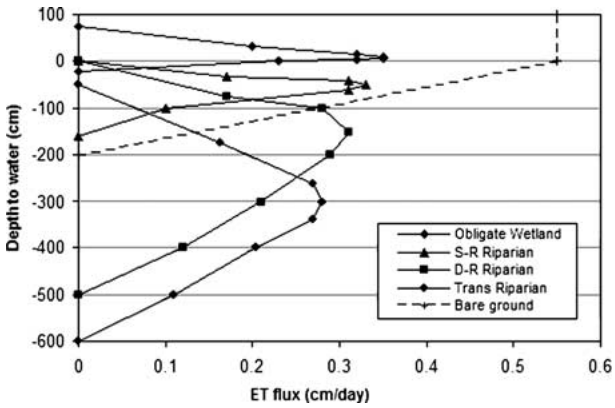

Figure 4. Mean daily evapotranspiration canopy flux (cm/day) curves for five plant functional groups. Positive numbers denote standing water.

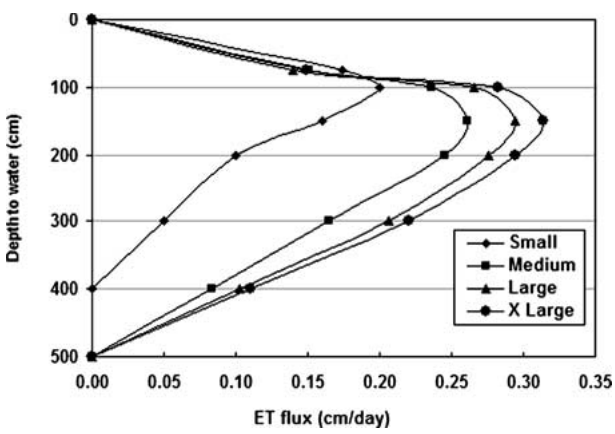

Figure 5. Mean daily canopy flux rates (cm/day) for four stem size classes of plants within the deep-rooted riparian plant functional group.

plexity of the system being modeled. With the traditional ET modeling approach, even when there is a range of plant species, age classes, and densities in the riparian landscape, the evaporation and transpiration rates must be averaged to a single value. With RIP-ET, the use of multiple ET curves, one for each PFSG, allows for a more realistic simulation of mixed plant assemblages and multistoried habitats.

On the basis of field ET measurements, literature review, and the expert opinion of researchers, preliminary transpiration–groundwater curves were developed for the riparian PFGs and evaporation curve (bare ground) presented in the RIP-ET package (Figure 4). Sap flow measurements were used to quantify transpiration in a set of willow (*Salix* spp.) and cottonwood (*Populus fremontii*) trees at the South Fork Kern River in central California and in the San Pedro River basin of southern Arizona. Simultaneous groundwater depths and meteorologic parameters were measured at both locations. At San Pedro, a controlled pumping experiment was performed specifically to measure the response of tree transpiration to declining water tables. Data from both sites formed the basis for the deep-rooted riparian canopy ET curves (Figure 5). We hope the preliminary curves we present serve to focus attention on the need for the development of ecophysiologically based ET curves. Refinement of these PFG curves and the development of additional curves will greatly benefit ET modeling efforts.

Fractional Coverages

Having modified the manner in which ET–groundwater relationships are defined, and having introduced habitat complexity into the model, we next focus on determining accurate aerial estimates of PFG cover. The fourth RIP-ET innovation is the incorporation of a process for accurate quantification of distinct ET areas from vegetationally complex mapping units. In regional groundwater models, model cells are generally quite large, often exceeding a square kilometer. Given the narrow linear nature of riparian zones, only a fraction of the cell is likely to contain riparian or wetland habitat. Furthermore, this fraction of a habitat is likely to comprise a mixture of PFGs (Figure 6).

Because volumetric ET (L^3/T) is determined by multiplying the ET flux rate (L/T) by the cell area (L^2), estimations of the area covered by each habitat type or PFSG within a cell are required for accurate ET estimates. With RIP-ET, the contribution of each PFSG to a cell's ET is determined as follows. The areal extent of the ith subgroup within a cell or the fraction of the ith subgroup ($fSG_{(i)}$) is defined as $fSG_{(i)} = \frac{area\ of\ PFSG_{(i)}}{total\ cell\ area}$. The fraction of this area associated with the scaling factor ($fPC_{(i)}$) is defined as $fPC_{(i)} = \frac{canopy\ area_{(i)}}{area\ of\ PFSG_{(i)}}$. Therefore, the area of the i PFSG contributing to ET within a cell or $fCov_{(i)}$ equals $fCov_{(i)} = fSG_{(i)}\ x\ fPC_{(i)}$. Numerically, total plant coverage within a cell can exceed 100% to allow for multistoried habitats.

To deal with the discrepancy between cell size and riparian habitat area with the traditional approach, the percentage of the area within each cell contributing to ET can be estimated manually, and the ET rate adjusted accordingly. This process is external to the model, laborious, and too often neglected. Because volumetric ET is calculated as cell area multiplied by the head-dependent transpiration rate, the error associated with using the entire cell as ET area can be

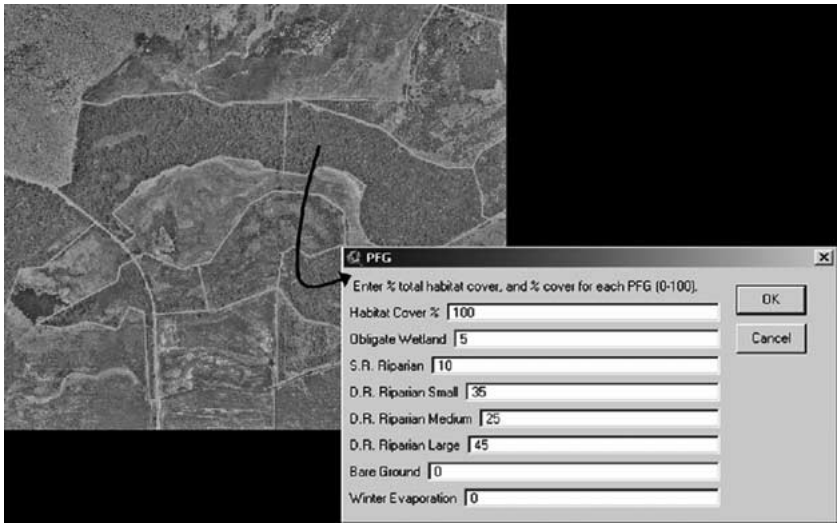

Figure 6. Digitized riparian polygons with RIP-GIS attribute table.

Table 1. Comparisons of groundwater model spatial information and areas of actively transpiring riparian habitat determined from the traditional-ET and RIP-ET modeling approaches[a]

	Basin size (mi^2)	Cell size (m^2)	No. of cells	ET area traditional (m^2)	ET area RIP-ET (m^2)	% Difference
Unnamed AZ basin	13.5	150 × 150	1554	8,550,000	5,630,910	−34
South Fork Kern	22.6	150 × 150	2604	6,286,772	3,060,425	−51
Lower San Pedro	424.7	550 × 540	7363	171,922,038	57,684,161	−66

ET, evapotranspiration; RIP-ET, Riparian Evapotranspiration Package; AZ, Arizona
[a]Values are shown for three semiarid basins.

substantial. Table 1 illustrates basin and cell dimensions for three groundwater model basins and the ET areas calculated using both methods.

Fractional coverage calculations must be performed for all active ET cells in the model. Hand calculation of values for the hundreds of cells that typify a MODFLOW model would be time consuming and error prone. Therefore, RIP-GIS, a GIS module, was developed. This GIS module is used to manage data while automating the fractional coverage section of PRE-RIP-ET. The standard in GIS desktop software is ArcView GIS from the Environmental Systems Research Institute. Riparian areas must be defined spatially within ArcView as polygons. Riparian polygons are most often identified and digitized using aerial photography, satellite images, topography maps such as digital elevation models, field surveys, or a combination of these sources. Once a new riparian polygon theme (shape file) is created, the required attribute fields are populated, and RIP-GIS prepares a text file that is then read by PRE-RIP-ET. Figure 6 illustrates a digitized riparian polygon containing multiple functional groups and the associated attribute table within RIP-GIS.

Depending on the plant community and terrain being studied, different measurement techniques may be used to estimate ET fluxes. Ultimately, most measuring techniques yield a specific flux (L/T: e.g., cm/sec) per specified unit area (L^2: e.g., xylem area, basal area, canopy area, or ground area). To accommodate the various measurement techniques, we use a scaling factor to represent the unit area being measured. The units associated with the ET–flux curves must match the specified unit area or scaling factor.

Riparian ecosystems are dynamic, with plant cover and composition changing seasonally and annually. Over longer time scales, climate and atmospheric carbon dioxide concentration changes may alter the groundwater–transpiration relationship, requiring that a new set of ET curves be developed. Temporal changes in plant coverage or changes in transpiration–groundwater relationships are handled as separate time steps within MODFLOW. Each time step requires a separate fractional coverage or shape file. The PRE-RIP-ET program makes the preparation of seasonal coverages relatively easy. Historically, most groundwater models were based on annual time steps. However,

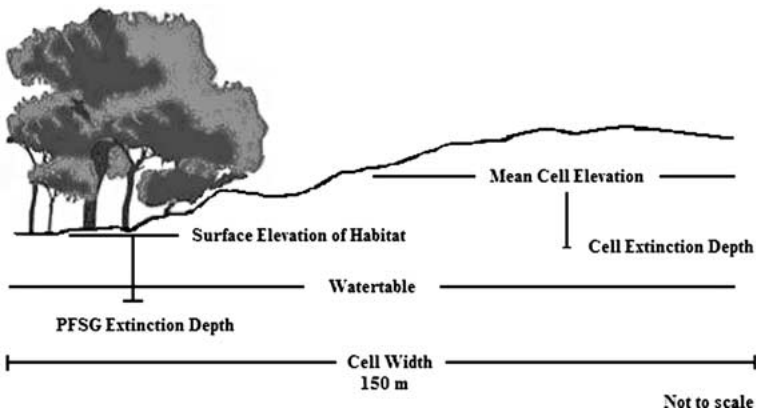

Figure 7. Schematic of a model cell showing the size of the cell, as compared with the riparian corridor width, and the effect of surface elevation variability on extinction depth.

seasonal models are strongly recommended if accurate groundwater–vegetation dynamics or estimates of ET are desired.

Land Surface Elevation

The fifth and final limitation we address deals with errors arising from the disparity between the variations in ground surface elevation and the assigned average cell elevation. Within the model domain, land surface elevation (HSURF) varies from cell to cell and within a cell. Because HSURF is one of the parameters used to calculate extinction depths for the PFGs, the magnitude of the within-cell variability of HSURF will have an important influence on ET. If the within-cell variation in land surface elevation is of the same magnitude as the extinction depths, it produces highly inaccurate ET calculations (Figure 7). There are two possible ways to avoid this problem: (1) make the model cell small enough to represent the variation in surface elevation or (2) allow for multiple surface elevations per cell. In most cases, option 1 in not feasible due to the large number of modeling cells this would require. Given the limitation on the number of cells in a model and the elevation changes inherent in many riparian ecosystems, the single average cell elevation used with the traditional method is not likely to produce meaningful estimates of riparian ET.

The RIP-ET program allows for multiple surface elevations per cell by providing the modeler with the option of assigning unique elevation values for each PFG or individual polygon within a cell. With RIP-GIS, a weighted-average elevation is calculated for each PFSG polygon using data from any type of digital elevation grid such as a digital elevation model. In many locations, fine-resolution digital elevation models (10 m or smaller) are now available. The extinction depths for the PFSGs are calculated according to the elevation of their associated polygons rather than the average elevation for the entire cell. The accuracy of HSURF and thus the extinction depths are now controlled by the user-determined polygon size and the resolution of the elevation data rather than by the model cell size.

Computational and convergence limitations are the major reasons why most basins or watersheds cannot be modeled with cell sizes small enough to capture accurately the variability of vegetation type and surface elevations in riparian systems. Groundwater flow models are represented by a partial differential equation. Cell size and number are dictated largely by the numeric approximation of this partial differential equation. In a groundwater flow simulation, the replacement of the continuous partial differential equation for ground water flow into a set of discrete cells is not straightforward process. Determining the number of model cells involves a trade-off between the costs (data preparation and ability to run the model and solve the matrix) and the benefits (accuracy). Sufficient detail is required to represent the hydraulic properties (Ks), hydraulic stresses (i.e., pumping, ET), and complexities of the flow field for the objectives of the study. However, this must be balanced by limitation in central processing unit (CPU) time and memory. For most solvers, the CPU time required for convergence is a function of n^3, where n is the number of nodes (cells). Increasing the number of nodes incurs a large penalty on the solver and convergence rates as instability develops. Convergence and instability are further exacerbated as the K field becomes more heterogeneous (Reilly and Harbaugh 2004).

Model Results

Are the results of this new method for estimating and predicting ET different from traditional methods? And are these differences substantial enough to alter interpretations of ecosystem dynamics and plant group distributions? As one test, we calculated model results

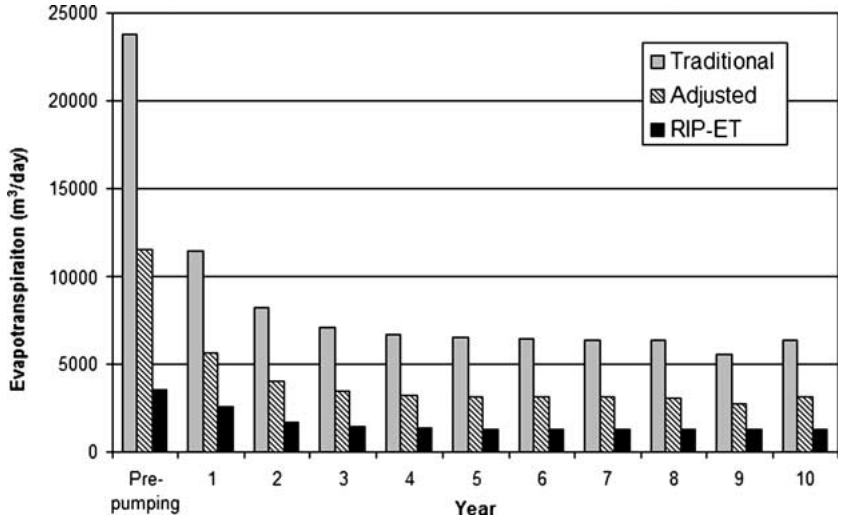

Figure 8. Estimated basin scale evapotranspiration (ET) rates from (a) the traditional MODFLOW ET package, (b) the area-adjusted MODFLOW package, and (c) the RIP-ET package.

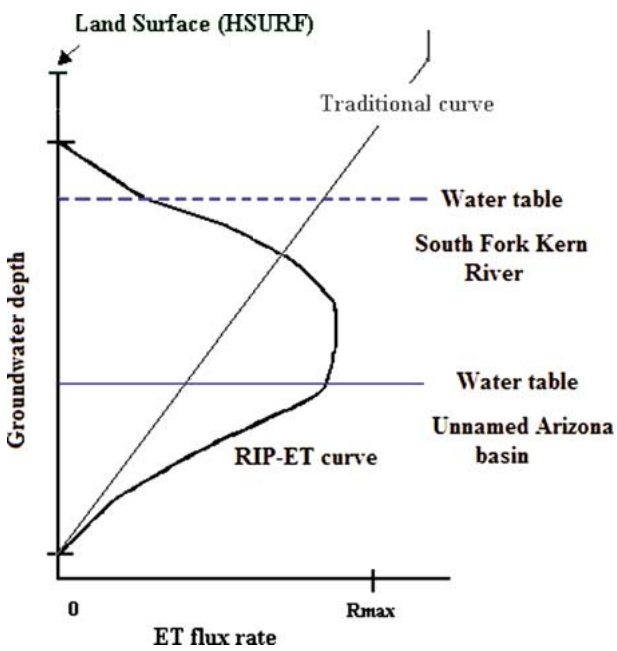

Figure 9. Average groundwater depths for South Fork Kern and no name basin in relation to the evapotranspiration curve for the dominant plant functional group.

from traditional and RIP-ET packages for two rivers. The first of these was the South Fork Kern River basin (California). Within this semiarid basin, wet sedge and marsh areas (obligate wetland and shallow rooted riparian PFGs) were intermixed with cottonwood-willow (deep-rooted riparian PFG) forest habitat along the length of the small river. Using physical modeling parameters developed for a regional groundwater model of the South Fork Kern River valley, we simulated conditions using a two-season (summer and winter) steady-oscillatory state model (Maddock and Vionnet 1998). To make the comparisons as equitable as possible, ET estimates within the traditional method were based on a weighted average of the ET flux rates for the PFGs present.

At South Fork Kern River, there is concern over the potential loss of the endangered species riparian habitat attributable to changes in groundwater depths from increased agricultural pumping and proposed residential development. To impose development conditions, pumping was activated from a series of agricultural and domestic wells throughout the valley, and the model was run for a period of 10 years. All changes in ET are the result of changing groundwater elevations. No change in vegetation cover was simulated for these years. The resulting basin-scale summer ET estimates from both models (RIP-ET and traditional) are illustrated in Figure 8. The traditional modeling approach estimated 489% more ET than predicted by the RIP-ET approach. Much of this discrepancy was attributable to cell size effects (RIP-ET improvement number 4). The traditional model overestimated the riparian transpirational area by 51%. Although the South Fork Kern riparian habitat is extensive for a small river, few model cells were completely covered by riparian habitat. Most cells contained a mixture of riparian habitat, agricultural fields, and fallow pasture lands.

After adjustment for this discrepancy, the traditional ET model still overestimated riparian and wetland ET by 238% relative to the new approach. Factors contributing to the overestimation of ET included a high water table over much of the area that created water stress in the trees and reduced ET rates below the maximum. Field observations confirmed that this was

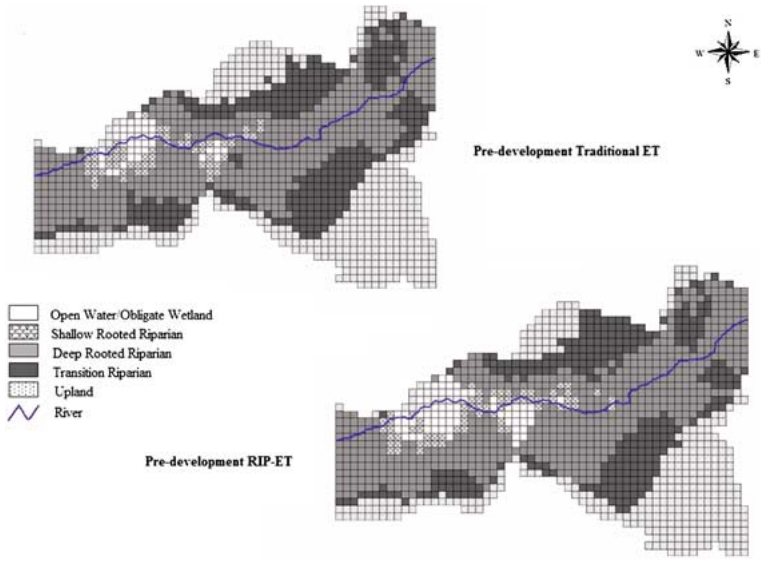

Figure 10. Predevelopment habitat distribution (based on modeled groundwater depths) as predicted using traditional evapotranspiration and RIP-ET methods.

in fact what the vegetation was experiencing, because the area is immediately upstream of a reservoir and experiences prolonged flooding for portions of the growing season. The traditional curve placed maximum ET rates at the upper part of the curve, whereas the maximum rates for most of the PFSG were at greater depths (Figure 9).

In addition to producing estimates of riparian ET and water needs that are more realistic and thus likely to be more accurate, RIP-GIS produces moderate to high resolution depth-to-groundwater maps based on the improved surface–groundwater modeling methods in RIP-ET. The postprocessor portion of RIP-GIS links the resulting head distribution from the MODFLOW simulation with surface elevations taken from a surface digital elevation model to determine depth to groundwater throughout the basin. These results then can be mapped at the resolution required to identify potential PFSG distribution based on user-defined water tolerance ranges. By relating PFSG rooting depths, ET rates, and groundwater levels within a spatially based model, it is possible to predict vegetation and habitat response to changes in land or water use, or to ascertain the level of plant stress that may arise from projected groundwater changes within the ecosystem.

In the South Fork Kern River example, the two methods of simulating ET resulted in substantially different habitat distribution maps. In the predevelopment phase, RIP-ET, with smaller ET losses, predicted higher water table elevations and consequently a much larger wetland area and more areas suitable for shallow-rooted and small deep-rooted trees than the traditional ET method (Figure 10). Postdevelopment predictions continue to show a significant difference in the models. After only 3 years of pumping, the traditional model predicts the loss of riparian forest over a much larger portion of the valley. Ultimately, both models predict significant habitat loss, but the timing and location of losses differ. The resulting groundwater budgets can be used to estimate water requirements for riparian vegetation and water availability for human needs.

The RIP-ET program will not always predict lower ET quantities, as evidenced by our second case study river. In this case, a small basin (13.51 square miles) in southern Arizona was modeled using both methods. Measured water table depths were at the lower portion of the traditional ET flux curve, and closer to the maximum rates for the species present, as modeled by RIP-ET (Figure 9). Consequently, ET estimates using RIP-ET were 37% higher than the estimates derived with the traditional method.

Discussion

Use of RIP-ET in Restoration and Conservation

Techniques such as RIP-ET, which incorporate plant-functional-group-specific transpiration curves, can aid in conservation and restoration efforts by increasing the accuracy with which we model plant–hydrology interactions. The incorporation of PFGs based on water tolerance ranges and rooting depths into the RIP-ET package provides an explicit link between groundwater and riparian/wetland habitat conditions and allows the effects of land use decisions or

increased water development on freshwater habitats to be ascertained. When this is combined with a probabilistic vegetation model, such as that developed by Rains and others (2004), changes in community types attributable to changes in groundwater/surface water regimes can be simulated.

Distinct transpiration curves for the various PFGs and the use of detailed spatial information on their distribution and elevation should improve estimates of basin-scale ET, water budgets, and environmental water needs. Ideally, incorporation of riparian ecosystem water needs into the modeling process will help to ensure that decision makers include riparian water demands as a vital component of the water budget. These estimates can then be incorporated into regional planning and conservation plans.

River rehabilitation or restoration has become a hot topic for water authorities, river managers, governmental regulators, and nature conservation groups throughout the world. In developed nations, ecosystem restoration has become (for better or worse) a major enterprise (Stromberg 2001). If restoration or conservation is to be successful, the natural hydrologic processes that govern ecosystem dynamics must operate effectively (Henry and others 2002). Knowledge of hydrology–vegetation interactions and the comparative water use characteristics of the target plant species as well as their effect on the local water balance is fundamental to the success of wetland and riparian restoration (Kolka and others 2000; Nagler and others 2003).

The RIP-ET and PRE-RIP-ET programs can help guide restoration when used as interactive tools during the planning stage. Existing or initial conditions can be used to calibrate a MODFLOW model of the area to be restored. Groundwater maps can be used to identify areas suitable initially for the target species. The groundwater levels produced by a restoration action and the effects on the proposed habitat or habitats then can be simulated using RIP-ET. If groundwater elevations do not stay within the required ranges of the desired plant groups, the plan can be altered and the model run until the simulated groundwater levels stay within appropriate ranges. The RIP-ET program also will show locations of areas that lack sufficient water resources for restoration, helping to avoid costly restoration failures.

Conservation efforts benefit by identifying and protecting key plant regeneration zones. The ability of riparian or wetland species to regenerate is imperative for ecosystem sustainability (Springer and others 1999). Regeneration of numerous riparian species requires spring floods of a characteristic intensity combined with high water tables during the early summer months (Mahoney and Rood 1998; Stromberg 2001). Areas with the appropriate groundwater conditions for tree establishment (e.g., the areas mapped as small deep-rooted PFG in Figure 10) can be thought of as potential regeneration areas. To identify riparian recruitment zones, river-specific regenerative flood intensity needs to be determined and the results from a surface water model overlain on the groundwater map. These data can be coupled with models such as the ''recruitment box model (Mahoney and Rood 1998) for further enhancement of our ability to predict recruitment success and area.

The RIP-ET program also can enlighten managers regarding the potential for phreatophyte control projects to increase downstream stream flow rates. In western United States, particularly in the 1950s and 1960s, cottonwoods, willows, and other phreatophytes suspected of having very high ET rates were cleared from waterways under the guise of water salvage. Although water savings did not always materialize, water salvage efforts continue today. The primary target is tamarisk, a riparian tree/shrub species that has become a dominant species in the West since its introduction to the United States in the late 1800s. Large-scale federal efforts are underway to eliminate tamarisk stands, partly under the assumption that such efforts will enable more water to be available for direct human use (Shafroth and others 2005). Models such as RIP-ET may prove valuable in providing accurate estimates of current and projected ET rates under various scenarios of vegetation replacement, and thus in determining whether alleged water salvage benefits are realistic or have been overstated.

Conclusion

Groundwater models traditionally have been used to characterize or simulate regional groundwater systems and predict changes in groundwater attributable to anthropogenic water use. The method used to model ET rates in these groundwater models can affect the calculated water budget, the simulated depths to groundwater, and the resulting interpretations regarding riparian ecosystem dynamics. We describe an approach that should increase the accuracy of these models, primarily by incorporating more realistic plant–hydrology interaction terms into the models. When combined with vegetation mapping and GIS, these ecohydrology models further increase our ability to understand and effectively manage riparian and wetland ecosystem responses, a matter of vital concern given the present milieu of increasing societal de-

mands for freshwater. This combined approach not only increases our understanding of ecohydrologic relationships, but also helps set the framework for more detailed research on the functioning of specific systems (Batelaan and others 2003).

The Riparian Evapotranspiration Package improves on traditional groundwater modeling techniques through numerous innovations. First, it uses a modeling approach that simulates ET from riparian/wetland systems in a manner that more accurately reflects both the ecophysiology of the component plant species and habitat complexity. The single, monotonically increasing ET flux curve used in traditional modeling packages is replaced with a set of ecophysiologically based curves. Each of the multiple transpiration curves reflects a particular PFG, thus capturing the inherent variability in the vegetation. For each PFG, the transpiration curve not only reflects transpiration declines at deep water levels, but also reflects declines that occur when shallow water levels produce anoxic soil conditions throughout the root zone. Furthermore, the package provides for separate representation of evaporation and transpiration, with retention of the traditional linear curve to model the evaporation process from bare soil or open water.

The Riparian Evapotranspiration Package also improves accuracy by more effectively dealing with spatial issues of plant and water table distribution. It replaces the single-cell, single ET value approach with multiple ET curves and associated fractional coverage. In other words, ET rates can now be calculated by determining the area of all plant assemblages (or habitat types) present and then applying multiple ET curves to a single model cell. When this is accompanied with RIP-GIS or PRE-RIP-ET, detailed information can be incorporated on the distribution of PFGs across land surface elevations. This effectively captures the range of ET responses across the topographic–hydrologic gradients.

The use of RIP-ET in groundwater models should result in more accurate determinations of riparian ET rates and thus of basin scale water budgets, which is of great value for water planning purposes. Depending on the attributes of the riparian ecosystem, RIP-ET may produce higher or lower ET values than traditional methods, as demonstrated through two case studies. By allowing for the quantification of riparian vegetation water requirements within a river segment, RIP-ET enables determination of environmental water needs. It also allows for predictions of riparian vegetation response to water use and development scenarios. For example, RIP-GIS links the head distribution from MODFLOW with surface digital elevation models to produce moderate- to high-resolution depth-to-groundwater maps. These maps then can be used, together with known plant rooting depths and tolerance ranges, to predict habitat response to changes in land use or water allocation decisions. Used as an interactive tool, RIP-ET can increase the success rate of restoration projects and help avoid costly restoration failures by identifying areas with insufficient water resources to recruit or sustain target plant communities. Finally, the models can be used to simulate water budget changes expected from phreatophyte control projects, thus helping managers to determine the legitimacy of such projects.

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