A GIS-based Management Tool to Quantify Riparian Vegetation Groundwater Use

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Abstract

Rapid population growth in semiarid regions of the southwestern United States is increasing the demand for water. In many cases, groundwater is mined from valley aquifers to meet this demand, which results in declining water levels in the aquifers. Riparian corridors are vulnerable to these declines since near-surface groundwater supports baseflow in the rivers and the abundant vegetation/habitat found therein. This is the case for the San Pedro River Basin in southeastern Arizona and northern Mexico. In such basins, effective management of water resources requires accurate measurements of water fluxes, including the evapotranspiration from the vegetation in the riparian corridor. This paper describes a management tool to help estimate groundwater demand from riparian vegetation along the San Pedro. The tool combines calibrated, process-based ecosystem models of riparian water use with a vegetation map to provide watershed-scale estimates of riparian vegetation groundwater use. This model is GIS-based to provide a user-friendly application that allows the user to change the vegetation cover in order to evaluate the effects of vegetation change (e.g., prescribed or accidental burns, rehabilitation of abandoned agricultural fields, shrub removal, etc.) on the groundwater demand.

Keywords: evapotranspiration, riparian vegetation water use, consumptive use

Introduction

Humans living in dryland regions increasingly rely on regional aquifers as a source of fresh water due to the limited availability of surface water sources and population increases. Without this groundwater resource, the further development and perhaps even the sustainability of these communities would not be possible. Similarly, the vegetation and enhanced biological productivity of oasis-like riparian areas in these regions are dependent upon the same groundwater source. Riparian regions are now recognized as biological "hotspots" and are extremely important for providing habitat for wildlife.

Groundwater pumping affects the dynamic balance between groundwater inputs (recharge) and outputs (discharge) within a watershed. The result is declining water levels until either recharge is increased (e.g., effluent injection) and/or discharge is reduced (e.g., decreasing stream flows, reduced groundwater use by vegetation) to balance the pumping demand. Since both the long-term sustainability of human habitation and riparian health are dependent upon the consequences of groundwater pumping, resource managers and scientists are making a significant effort to improve understanding of the water balance of these regional groundwater systems. An improved description and quantification of the key recharge and discharge processes will greatly support management decisions that will lead to sustainable human communities and the continued health of riparian ecosystems.

The Upper San Pedro River Basin in southeastern Arizona and northern Sonora, Mexico is an ideal area in which to investigate these poorly understood processes of regional aquifer water balance. Unlike many riparian systems that have been disrupted due to the lowering of the groundwater table by pumping, the basin has a lengthy reach of intact perennial flow, which sustains abundant riparian corridor vegetation. In 1988, the U.S. Congress recognized the importance and rarity of this ecosystem by establishing the San Pedro Riparian National Conservation Area (SPRNCA), which protects and enhances approximately 70 km of the river and its

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associated ecosystem. From previous observation and modeling studies, three dominant components of the basin's natural groundwater system have emerged. These three components--mountain front recharge, surface water discharge, and water uptake by riparian vegetation--are estimated to be of similar magnitude (Vionett and Maddock 1992, Corell et al. 1996).

It is widely believed that the presence of large-scale groundwater pumping in the nearby urban areas of Sierra Vista and Fort Huachuca has created a cone of depression which has, or will soon, diminish the baseflows in the river (e.g., Steinitz et al. 2003). The disruption of riparian corridor ecology due to groundwater depletion has been well documented throughout this region (Stromberg 1993, Grantham, 1996). Numerous groundwater modeling and conceptual studies have been performed for various sub-basins of the San Pedro. All of them include the "Sierra Vista sub-basin," the area of principal concern due to the larger amount of pumping therein (Freethey 1982, Vionnett and Maddock 1992, Corell et al. 1996, Steinitz et al. 2003).

In the San Pedro, an important component in the basin's groundwater budget is the amount of groundwater used by riparian vegetation. This flux was traditionally estimated by using groundwater models, where the riparian water use was the residual discharge that resulted from the model after it was calibrated against known inputs, groundwater levels, and discharges (e.g., Corell et al. 1996). Considerable improvements in these estimates have been made in recent studies with the use of actual measurements of riparian vegetation functioning/evapotranspiration (Goodrich et al. 2000, Scott et al. 2000, Schaeffer et al. 2000, Snyder and Williams 2000). Goodrich et al. (2000) combined these measurements with a vegetation map to derive observation-based estimates of riparian vegetation water use for different river reaches within the SPRNCA.

In this paper, we describe a prototype GIS-based tool designed to help management agencies determine the total riparian vegetation groundwater use in the San Pedro Basin and how the groundwater use will likely change with different management strategies. We also analyze how the incorporation of a new vegetation map and water use measurements will change the most the recent estimates of riparian vegetation water use made by Goodrich et al. (2000). One of the limitations of current estimates of vegetation groundwater use is that the amounts are fixed to a particular vegetation state. Our tool allows the user to change the vegetation cover within the riparian corridor. This flexibility allows us to understand how vegetation change due to natural (e.g., succession, wildfires) or human-induced (e.g., prescribed fires) causes might alter the vegetation water use. Additionally, the tool incorporates new, longer-term measurements of mesquite and cottonwood groundwater use that have been made over the last few years. These new estimates help us to better understand the variability of riparian water use and important factors that affect it.

Overview of GIS-Based Tool and Its Component Parts

The GIS-based tool is an accounting model that merges a vegetation map with component vegetation groundwater use models. This tool and its elements are described in the following subsections.

GIS-based tool

The GIS-based tool has a user-friendly interface that allows for easy manipulation of a vegetation map and projection of the seasonal demand of groundwater-using vegetation. The tool calculates the total amounts of different types of phreatophytic vegetation from a vegetation map of the riparian corridor of the Upper San Pedro River and, then, multiplies these amounts by the appropriate seasonal groundwater demand per unit area of vegetation to calculate the total groundwater use. ArcView GIS (ESRI, Redlands, CA) supplies the structure on which the tool is built, and easy to use menus with complete instructions are included. If desired, the user may select any area of a map or any type of vegetation to change. Out of the many different types of land cover in the San Pedro riparian corridor, we have identified the following as significant groundwater-using components: mesquite, cottonwood/willow, sacaton grass, and open water categories.

To modify the vegetation map, the user either supplies a polygon map of the area to be revised (i.e. a prescribed burn), or is prompted to draw a polygon of the area to be revised directly on the vegetation map. Upon starting the tool, the user is presented with a screen showing three choices of vegetation manipulation:

1) all vegetation within a user-defined polygon is changed to a new type of vegetation (e.g., sacaton);

2) one vegetation type within a user-defined polygon is changed to a new type of vegetation (e.g., change saltcedar to cottonwood);
3) simulate a burn, all vegetation within a user-supplied polygon map is changed to a new type of vegetation (e.g., change a prescribed burn area to bare soil).

To perform the vegetation manipulation the user first chooses which one of the above three types of vegetation change to perform. If option number 1 is selected, a new screen appears asking the user to select the grid to modify, the new vegetation type, and the name of the new map to create. If the user has chosen option number 2, the new screen also requests the type of vegetation to change from. If the user has selected the "simulate a burn" option, the user must specify the burn map, the new vegetation type, and name the new map to create. This option may also be used to analyze other types of vegetation manipulation where a polygon map of the area to be modified is available.

If either of the first two options is selected, the user is prompted to draw a polygon using the mouse of the area of interest. After the polygon is drawn, the tool performs the vegetation revisions, creates the new map, and calculates the new groundwater use values for the entire riparian corridor. When the last option is selected, the draw polygon step is skipped, the tool immediately calculates the change in groundwater use based on the user supplied polygon map, and presents the results. Using this option, the progression of vegetation re-growth after a prescribed burn or wildfire is shown. The results from all options are presented as a plot against the values calculated from the original, unaltered map. In all cases, the original vegetation map is not changed; a new map is created each time. The newly created maps may then be used for subsequent analyses.

Vegetation map

Goodrich et al. (2000) made the most recent estimates of riparian groundwater use along the San Pedro using estimates of vegetation area that were made from a 1997 *pixel-based* vegetation classification (hereafter referred to as VEG97). In the map, each 3 x 3 m pixel is classified as a particular vegetation cover. From aerial photography made in 2000 and field data collected in 2001, the U.S. Army Corp of Engineers produced a new *polygon-based*, GIS vegetation cover map (VEG00), where continuous stands of vegetation alliances were delineated and given various attributes like vegetation alliance, polygon area, total area of vegetation cover, area of dominant vegetation cover, etc. It includes 33 different vegetation communities, open water, and urban lands.

The conversion from a pixel- to a polygon-based coverage made the task of computing total vegetation areas for the relevant land cover types more difficult. For the new map, VEG00, both the polygon area and the percent area that is covered by the vegetation of interest were needed to estimate the total area of groundwater-using vegetation. The basic classification in VEG00 has five ranges for the vegetation percent cover. They are: 1 – 10, 11 – 25, 26 – 60, 61 – 80, 81 – 100 %. This range is quite course for calculating the total area covered by a specific vegetation type and induced uncertainty in the new estimates of vegetation groundwater use. To reduce this uncertainty, the map provides the vegetation percent cover estimated to the nearest 5 % for the mesquite or cottonwood polygons classified as a woodland or forest, defined as those patches dominated by mesquite or cottonwood/willow with greater than 60 % cover.

Unfortunately, there were still many polygons not classified as woodland or forest that contain vegetation that uses groundwater (e.g., mesquite patches with less than 60 % cover, sacaton grasslands, etc.). We incorporated this uncertainty into the GIS-tool by providing the user with a choice to calculate the minimum, median, and maximum amount of each functional vegetation group. Then, total vegetation area was calculated by summing up, over all polygons of a certain plant functional group, the product of the polygon area and the minimum, median, and maximum percent cover, or, if the more accurate percent cover was available, then this was used instead.

Evapotranspiration

We used a combination of micrometeorological and eco-physiological measurements to make evapotranspiration (ET) measurements of plant functional groups. Because sacaton and mesquite ecosystems along the San Pedro occupy more extensive and broad areas, we used long-term eddy covariance measurements to get the total ecosystem ET fluxes in these cover types. Scott et al. (2000) made measurements of mesquite and sacaton ET using Bowen ratio techniques. We used sap flow techniques to measure cottonwood transpiration in order to further test the measurements and model of cottonwood water use made previously (Goodrich et al. 2000, Schaeffer et al. 2000). The multiple years of growing season ET observations indicate that groundwater use is quite variable annually. The GIS-tool accounts for this variability by displaying a range for the total amount of groundwater used that has been shown in the observations.

We have made mesquite ET measurements since 2000 at a mature, dense mesquite woodland, while the measurements of cottonwood, sacaton, open water and seep willow water use began in 2003. In this paper, we concentrate on using the mesquite measurements of ET to estimate mesquite groundwater use.

Scott et al. (in review) report in detail on the mesquite ET measurements for the 2001 and 2002 growing seasons. In order to estimate a yearly groundwater use from these ET measurements, we employed a water balance computation for the entire growing season:

$$Q_t = ET - (P - \Delta S) \quad (1)$$

where Q_t is groundwater use, ET is evapotranspiration, P is precipitation, and ΔS is the change of soil moisture in the top 1 m of soil. At the site, runoff was negligible and there were only small changes in soil moisture deeper than 1 m. Thus, Q_t is the ET in excess of precipitation and soil moisture storage. We assumed that this excess soil moisture is derived from groundwater. Scott et al. (2003) and Scott et al. (in review) showed that the mesquites at the site used groundwater. Lastly, we computed the amount of groundwater used on a per unit *mesquite* area, $Q_{mesquite}$, (rather than per unit *ecosystem* area) by dividing Q_t by the percent cover of mesquite found at the site.

The GIS-tool requires daily estimates of groundwater use rather than ET. For the cottonwood and willows, we will use the sap flow measurements to calibrate a model to estimate the transpiration. We assume that this transpiration is derived mainly from groundwater as shown by Snyder et al. (2000). For the measurements of mesquite and sacaton ET, we plan to employ a simple understory ET model to compute the amount of ET derived from precipitation. Subtracting this from the eddy covariance ET measurements, the mesquite tree or sacaton grass transpiration component will be calculated. Until the results of on-going studies of mesquite or sacaton water sources are known, we will use the simplifying assumption that the tree/grass water source is groundwater. The details and results of this work will be reported in future publications.

Results

We proceed here with a comparison of the vegetation maps and a summary of the mesquite water use estimates. These two issues will greatly influence the water use amounts that the tool will compute.

The change from the grid-based vegetation map, VEG97, to the polygon-based GIS coverage, VEG00, results in dramatic changes in computed vegetation area. As an example of this shift, Table 1 presents the total amount of area covered by each of four groundwater-using groups for the riparian area within Sierra Vista Sub-basin (defined as the San Pedro reach between the Palominas and Tombstone USGS gages.) The range given for the VEG00 map represents the minimum and maximum amounts. Recall that many of the vegetation polygons have an assigned range instead of an exact percent cover. For the reach in Table 1, all the cottonwood and open water polygons have an exact area given to them; hence, there is no range given for these functional groups. This is not the case for the sacaton and mesquite amounts.

Table 1. Sierra-Vista Sub-Basin Riparian Vegetation Areas (ha).

	Vegetation Map	
Vegetation Type	**Veg97**	**Veg00**
Mesquite	1166	721 - 967
Cottonwood/Willow	526	300
Sacaton	382	363 - 513
Open Water	5	42

The GIS-tool accounts for the uncertainty in the vegetation amounts by computing a range of water use for each plant functional type. The range in water use is computed by using the minimum, median and maximum vegetation areas and multiplying each by the appropriate water use amounts. Nonetheless, the change in amount of vegetation between maps will clearly result in a large change in the water use calculations. The magnitude of this change will far outweigh the changes due to the refinement of plant groundwater use amounts. While there have been some vegetation cover changes, mainly due to fires, from 1997 to 2000, it is unlikely that all this change is natural. A further check in the accuracy of the maps is warranted.

Goodrich et al. (2000) identified mesquite water use as the most uncertain and, likely, the most significant component of the total vegetation groundwater use. The three reasons for this uncertainty were: 1) mesquites cover the largest area within the SPRNCA, 2) previous measurements were made from a relatively immature mesquite site probably not representative of denser, more mature woodlands, 3) mesquites can use both precipitation and groundwater as a water source.

Table 2 lists the components of the 2001 and 2002 mesquite water balance and compares them to measurements made in 1997 (Scott et al. 2000). The aerial cover of mesquite at these sites was 0.5 and 0.7 for 1997 and 2001-2002, respectively. While the 1997 measurements were at a site that was considerably less dense, these differences are not sufficient to explain the much greater groundwater use in 2001-2002. The 2001-2002 site, was composed of much larger and more mature trees. The trees at the 1997 site, being less developed, were arguably less adept at tapping the deep groundwater source. (The water-table depth at both sites was ~ 9 m).

Table 2. Mesquite Growing Season Water Balance (May 1 – Nov 30). Units are in millimeters. See Methods Section for term definitions.

	1997	2001	2002
ET	330	694	638
$P - \Delta S$	173	206	244
Q_t	157	488	394
$Q_{mesquite}$	314	697	563

The new 2001 and 2002 mesquite measurements also show that the mesquite groundwater use varied considerably between the years. In 2002, much drier and hotter conditions prevailed in the first two months of the growing season prior to the onset of the summer rains. The trees showed considerably more stress (Scott et al. in review). It is possible that this stress caused some loss of conductivity in the stems and led to a decreased tree water use throughout the rest of the season. Measurements at this site continue and hopefully will allow us to better quantify and explain this seasonal variability. In the meantime, groundwater use by mesquites in the GIS-tool will reflect the mean seasonal behavior and the variability will be represented by uncertainty estimates in the final groundwater use calculations.

Conclusions

In the San Pedro Basin, the amount of groundwater used by phreatophytic plants is a substantial, yet difficult to estimate, component of the water budget. A combination of improved vegetation maps and understanding of plant groundwater use now makes it possible to better quantify this use in the San Pedro Basin. An easy-to-use GIS-tool will make it possible to communicate these results to management agencies and the public more readily, and it will allow them to better understand how natural and human-induced change will alter groundwater use in the future.

We consider this GIS-tool as a prototype since it is designed to be applied only in the San Pedro Basin and, thus, assumes a certain climate and riparian vegetation functioning for the basin. Future work will entail the development of a more general and flexible tool that can be applied elsewhere. This will be done by allowing the user to specify their own vegetation map, climate data, and vegetation water use models.

Acknowledgments

We acknowledge the following work of USDA-ARS staff: C. Unkrich and S. Miller created the initial prototype of the GIS-tool, and S. Scott significantly helped to improve it. Financial support for this work was provided to USDA-ARS from the Upper San Pedro Partnership, a consortium of local, state, and federal entities that have united together to look at water resource issues in the San Pedro Basin. This work is also supported by SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) under the STC Program of the National Science Foundation, Agreement No. EAR-9876800. We would also like to thank the Fort Huachuca Meteorological Support team and the US Bureau of Land Management. The authors would also like to acknowledge J. Stone and C. Holifield, who provided valuable reviews of this paper.

References

Corell, S.W., F. Corkhill, D. Lovvik, and F. Putnam. 1996. A groundwater flow model of the Sierra Vista subwatershed of the Upper San Pedro Basin – southeastern Arizona. Arizona Department of Water Resources, Hydrology Division. Modeling Report 10. Phoenix, AZ.

Freethey, G.W. 1982. Hydrologic analysis of the Upper San Pedro basin from the Mexico U.S. boundary to Fairbank, Arizona. U.S. Geological Survey Open-file Report 82-752.

Goodrich, D.C., R.L. Scott, J. Qi, B. Goff, C. L. Unkrich, M.S. Moran, D. Williams, S. Schaeffer, K. Snyder, R. MacNish, T. Maddock, D. Pool, A. Chehbouni, D.I. Cooper, W.E. Eichinger, W.J. Shuttleworth, Y. Kerr, R. Marsett, and W. Ni. 2000. Seasonal estimates of riparian evapotranspiration using remote and in-situ measurements. Journal of Agriculture and Forest Meteorology 105:281-309.

Grantham, C. 1996. An assessment of the ecological impacts of ground water overdraft on wetlands and riparian areas in the United States. United States Environmental Protection Agency, EPA 813-S-96-001.

Schaeffer, S.M., D.G. Williams, and D.C. Goodrich, 2000. Transpiration of cottonwood/willow forest estimated from sap flux. Journal of Agricultural and Forest Meteorology 105:257-270.

Scott, R.L., W.J. Shuttleworth, D.C. Goodrich, and T. Maddock III. 2000. The water use of two dominant vegetation communities in a semiarid riparian ecosystem. Journal of Agriculture and Forest Meteorology 105:241 –256.

Scott, R.L., E.A. Edwards, W.J. Shuttleworth, T.E. Huxman, C. Watts, and D.C. Goodrich. Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. Journal of Agriculture and Forest Meteorology (in review).

Scott, R.L., C. Watts, J. Garatuza, E. Edwards, D.C. Goodrich, D.G. Williams, and W.J. Shuttleworth. 2003. The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland. Journal of Agriculture and Forest Meteorology 114:127- 139.

Snyder, K.A., and D.G. Williams. 2000. Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. Journal of Agricultural and Forest Meteorology 105:227-240.

Steinitz, C., H.M. Arias Rojo, S. Bassett, M. Flaxman, T. Goode, T. Maddock III, D. Mouat, R. Peiser, and A. Shearer. 2003. Alternative Futures for Changing Landscapes: The Upper San Pedro River Basin in Arizona and Sonora. Island Press, Washington DC.

Stromberg, J.C. 1993. Riparian mesquite forests: A review of their ecology, threats, and recovery potential. Journal of the Arizona – Nevada Academy of Science 27: 111-124.

Vionnet, L.B., and T. Maddock. 1992. Modeling of groundwater flow and surface water/groundwater interactions in the San Pedro River Basin- Part I – Cananea, Mexico to Fairbank, Arizona. University of Arizona, Department of Hydrology and Water Resources, HWR No. 92-010.