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Coupling groundwater and riparian vegetation models to assess effects of reservoir releases

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Abstract. Although riparian areas in the arid southwestern United States are critical for maintaining species diversity, their extent and health have been declining since Euro-American settlement. The purpose of this study was to develop a methodology to evaluate the potential for riparian vegetation restoration and groundwater recharge. A numerical groundwater flow model was coupled with a conceptual riparian vegetation model to predict hydrologic conditions favorable to maintaining riparian vegetation downstream of a reservoir. A Geographic Information System (GIS) was used for this one-way coupling. Constant and seasonally varying releases from the dam were simulated using volumes anticipated to be permitted by a regional water supplier. Simulations indicated that seasonally variable releases would produce surface flow 5.4–8.5 km below the dam in a previously dry reach. Using depth to groundwater simulations from the numerical flow model with conceptual models of depths to water necessary for maintenance of riparian vegetation, the GIS analysis predicted a 5- to 6.5-fold increase in the area capable of sustaining riparian vegetation.

1. Introduction

Much of the original riparian vegetation in the arid southwestern United States, essential for the diversity of species it supports, has been lost or substantially altered since Euro-American settlement [*Tellman et al.*, 1997]. In the southwestern United States, ~60% of all species are directly dependent on riparian areas, and another 10–20% use riparian areas for part of their life cycle [*Tellman et al.*, 1997]. Fremont cottonwood–Goodding willow forests were historically one of the most abundant community types along low-elevation, perennial, alluvial rivers of the southwestern United States but are now threatened throughout much of their range. Other community types, including riparian mesquite woodlands, have declined substantially in area. Hydrologic changes, including surface water diversions, groundwater pumping, and regulation of flows by dams, are the primary causes of riparian losses [*Busch and Smith*, 1995; *Rood et al.*, 1995; *Stromberg et al.*, 1996; *Scott et al.*, 1997, 1999]. Restoration of flow regimes is critical for successful restoration of degraded riparian ecosystems [*Poff et al.*, 1997].

Efforts to maintain, enhance, or create hydrologic conditions favorable for riparian vegetation through ecological restoration are increasing. In Arizona one opportunity to enhance riparian vegetation was created through the introduction of water imported via an open canal. The state of Arizona was allotted 3.4×10^9 m^3 yr^{-1} (2.8 million acre-feet yr^{-1}) of Colorado River water annually under the Colorado River Compact of 1944. Through water banking some of Arizona's allocation is recharged or "banked" in aquifers along the 530 km of the Central Arizona Project canal from Parker, Arizona, to Tucson. In this arid region, with open water evaporation rates >2.7 m yr^{-1}, aquifer recharge is considered a more viable and desirable method of water storage than storage in surface impoundments. Surface water infiltration through ephemeral streambeds is an important source of groundwater recharge in arid and semiarid regions. If such recharge results in groundwater levels which are shallow enough, conditions favorable for maintenance of riparian vegetation may be established.

The purpose of our research was to develop a methodology for coupling biotic and abiotic models in a GIS format to evaluate the potential for groundwater recharge and riparian vegetation restoration. Although there have been studies which have developed models to link riparian vegetation and hydrology [*Mahoney and Rood*, 1998; *Johnson et al.*, 1995; *Auble et al.*, 1994], these have focused on seedling establishment or community composition in relation to surface flows, not depth to groundwater. The presence of relatively high groundwater levels is not the only physical factor structuring riparian vegetation; however, it is critical for the maintenance of arid southwestern U.S. riparian communities [*Scott et al.*, 1999; *Stromberg et al.*, 1996]. The methodology developed in our study was applied to a reach of the Agua Fria River, Arizona, below Camp Dyer Diversion Dam to predict the impacts of a release on the hydrogeologic system and the potential to maintain riparian vegetation once it had been established. The objectives were to (1) simulate and analyze groundwater impacts of various reservoir release schedules and volumes, (2) couple the groundwater and riparian vegetation models within a GIS, (3) predict areas of riparian vegetation maintenance under various reservoir release schedules and volumes, and (4) compare water balances of the different scenarios.

2. Site Description

Our study reach along the Agua Fria is located within the Basin and Range Physiographic Province in the northern por-

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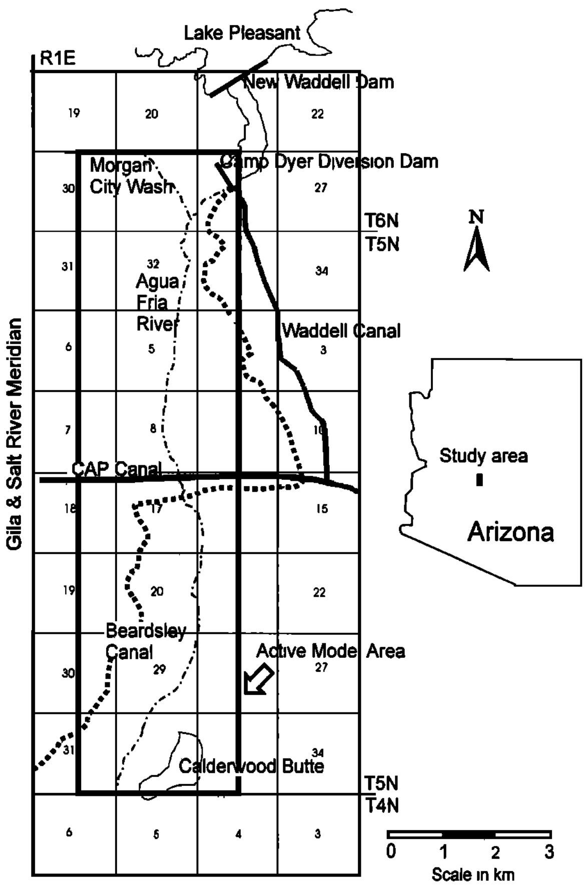

Figure 1. Map showing locations of the Agua Fria River, Arizona, study area, and active groundwater flow model area.

tion of the Desert Region [*Wilson*, 1962]. This region is semiarid Sonoran Desert, with annual precipitation of ~300 mm (Western Regional Climate Center, Map showing average annual precipitation in Arizona for the period 1961 to 1990, unpublished data, 1996, available on the World Wide Web at http://www.wrcc.dri.edu/index.html), >350 frost-free days per year, and summer temperatures that commonly exceed 40°C. The study reach extends 13.2 km downstream from Camp Dyer Diversion Dam south to Calderwood Butte (Figure 1), under a topographic gradient of 3.2 m km^{-1} at elevations between 380 and 425 m above sea level. Valley widths range from ~150 m near Camp Dyer Dam to >1 km near Calderwood Butte.

2.1. Vegetation

Existing riparian vegetation along the study reach varies, depending largely on water availability, which generally diminishes as one moves downstream. A series of semipermanent pools exist for ~800 m immediately downstream of the dam, fed by spring flow from adjacent Morgan City Wash and by seepage around the dam. Associated with these pools and the adjacent elevated water table is a small area of relatively dense riparian vegetation. Stands of cattail (*Typha domingensis*) line the margins of the pools, while thickets of Goodding willow (*Salix gooddingii*), saltcedar (*Tamarix* sp.), seepwillow (*Baccharis salicifolia*), and an occasional Fremont cottonwood (*Populus fremontii*) grow on the adjacent floodplain. The existing riparian vegetation was estimated from aerial photography to be ~28 ha at ~67% coverage. A short distance orthogonal to this floodplain vegetation, sites are characterized by lower water availability and are dominated by more xeric riparian vegetation, including burro brush (*Hymenoclea monogyra*), Bebbia (*Bebbia juncea*), and mesquite (*Prosopis velutina*). A quasi-perennial reach exists for approximately the next kilometer downstream. The riparian vegetation assemblage persists through this reach, but there is an abundance of more xeric species, and the vegetation changes from riparian to desert scrub a short lateral distance away from the channel.

Two kilometers below the dam, the channels of the Agua Fria are generally dry, flowing only as a result of infrequent runoff from tributary washes. Kilometers 2.0–8.0 (measured from the dam) are almost completely dominated by xeric riparian species. The final 5.2 km of the study reach consist of a mix of the same xeric riparian species and species more characteristic of uplands, including paloverde (*Cercidium floridum*) and creosote bush (*Larrea tridentata*).

2.2. Hydrogeology

The study area is on the northern margin of the West Salt River Valley Basin [*Corkhill et al.*, 1993]. Rock units in the region include Precambrian gneiss and granite; Tertiary (Miocene) basalt, andesite, and rhyolite; Tertiary (Miocene) pebble/cobble conglomerate and sandstone interbedded with volcanics; unconsolidated to partly consolidated basin fill; and recent stream deposits [*Wahl et al.*, 1988; *Huckleberry*, 1995]. The conglomerate flanks the river on both sides in the upstream reaches and dips below basin fill farther downstream, persisting on the west side to almost kilometer 11. On the east side the conglomerate is exposed only within 6.5 km of the dam.

Before construction of the dam, this reach of the Agua Fria connected the Upper Agua Fria Basin with the West Salt River Basin. The dam, however, spans a portion of the river channel cut through rhyolite and conglomerate, partially blocking the conduit for surface water and groundwater flow between the two basins. Alluvial fill, the major water-bearing unit for this region, is <30 m thick throughout the study area but thickens considerably to the south and east (Figure 2). The regional groundwater flow direction is to the south-southwest [*Reeter and Remick*, 1983], as is the general direction of river flow (Figure 3).

Depth to the water table ranges from zero meters at the base of the dam to a maximum of ~20 m at the southern boundary of the model near Calderwood Butte (13 km downstream), based on recent water level measurements [*Mitchell and Putman*, 1987] (Figure 2). The slope of the water table increases dramatically south of the butte, dropping 67 m over just 1.5 km [*Camp Dresser and McKee*, 1988]. This precipitous change in the groundwater gradient near the volcanic outcrops of the butte has been attributed to a Basin and Range fault separating the Agua Fria Basin from the West Salt River Basin [*Integrated Water Technologies* (*IWT*), 1997].

2.3. Streamflow

The amount of water available for the Agua Fria project from the Central Arizona Project is estimated to be between 1.8×10^7 and 5.6×10^7 m^3 yr^{-1} (15,000–45,000 ac ft yr^{-1}). Flow regimes used in this study were based on streamflow records for the U.S. Geological Survey gaging station at Rock Springs (6.5 km upstream of Lake Pleasant) and the estimated flow that could be available for the project. Streamflow records for this seasonally intermittent river over the 24-year period from 1971 to 1997 reflect large interannual variations, consis-

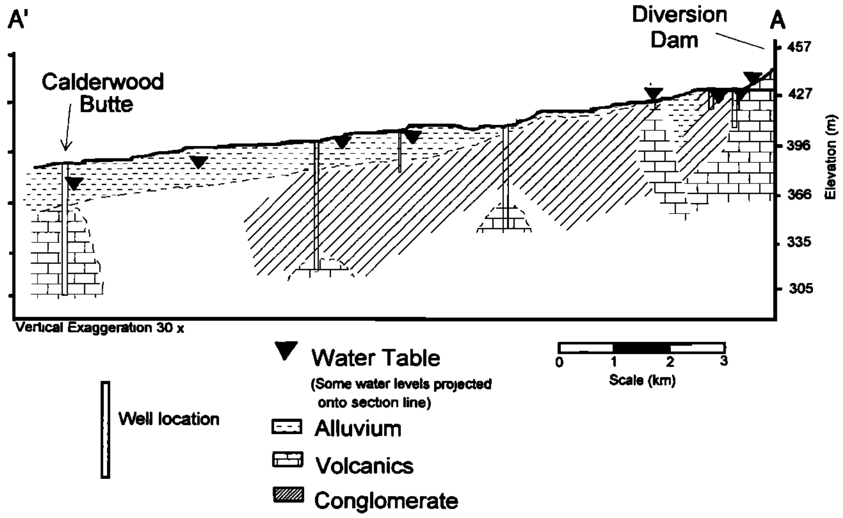

Figure 2. Longitudinal north-south hydrogeologic cross section along the Agua Fria River from Camp Dyer Diversion Dam to Calderwood Butte. Line of section shown on Figure 3.

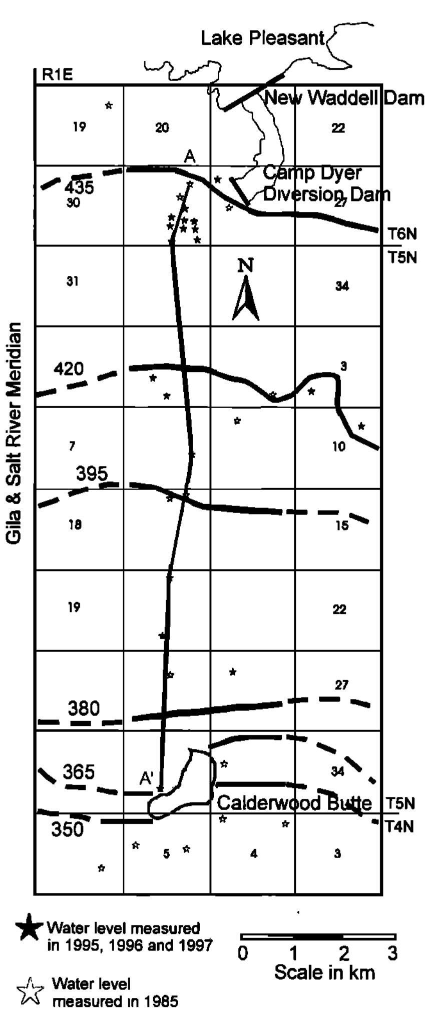

Figure 3. Map showing locations of wells in the Agua Fria River study area used for steady state water levels, steady state water table contours, and section line A-A′.

tent with many watersheds in the southwestern United States. Annual instantaneous peak discharge values were between 15.9 and 1680 $m^3 s^{-1}$.

On the basis of the hydrology of the Agua Fria, three separate flow scenarios were defined: constant flows, seasonally varying flows, and establishment flows. The constant release scenario, the least complicated from a logistical perspective, was included for comparison purposes. Seasonally varying flows, incorporating low flow rates for most of the year and a higher release rate during the late winter/spring, were included to more closely simulate unregulated patterns of discharge. Establishment flows, designed to inundate larger portions of the floodplain at higher elevations, would be planned every 5–10 years, given that this is an average rate for establishment frequency at a nearby reference river, the Hassayampa [*Stromberg et al.*, 1991; *Brinson and Rheinhardt*, 1996]. Only the constant and seasonally varying flow regimes were modeled and analyzed for their impacts on the hydrogeologic and riparian systems. Planning for higher-volume establishment flows would benefit more from the experience of an actual release and surface water modeling and thus was beyond the scope of this study. Constant and seasonally variable release volumes of 1.8×10^7, 3.7×10^7, and 5.6×10^7 $m^3 yr^{-1}$ (15,000, 30,000, and 45,000 ac ft yr, respectively) were simulated (Table 1).

3. Methods

Basic and theoretical data were compiled in conceptual and numerical models to describe how riparian vegetation could be maintained by a reservoir release. A conceptual groundwater model relied on (1) geologic data, including structural geology, geomorphology, and stratigraphy and (2) hydrogeologic data, such as elevation of the water table, hydraulic conductivity of the lithologies, and regional groundwater flow directions [*Wahl et al.*, 1988; *Huckleberry*, 1995]. From the conceptual hydrogeological model of the system, a preliminary numerical model was built using a modular, three-dimensional, finite difference groundwater flow model (MODFLOW) [*McDonald and Harbaugh*, 1988]. Interactions between groundwater and various

Table 1. Total Annual Volumes of Streamflow and Constant and Seasonally Varying Rates at Which the Flow Scenarios Were Simulated in the Groundwater Model

	Annual Release Volumes, m^3 yr^{-1}		
Flow Scenarios	1.8×10^7	3.7×10^7	5.6×10^7
Constant Release Rate, m^3 s^{-1}			
Oct.–Sept.	0.59	1.2	1.8
Seasonal Release Rates, m^3 s^{-1}			
Oct.–Dec. and April–Sept.	0.25	0.45	0.62
Jan.–March	1.6	3.4	5.0

surface water releases from Lake Pleasant were simulated with a stream routing procedure [*Prudic*, 1989]. Constant and seasonally variable flow scenario releases of 1.8×10^7, 3.7×10^7, and 5.6×10^7 m^3 yr^{-1} (15,000, 30,000, and 45,000 ac ft yr^{-1}, respectively) were simulated.

Arc/Info (Environmental Systems Research Institute, Arc/Info, Geographic Information System software, Redlands, California, 1991) was used as a basis for combining the numerical groundwater model results with empirical studies of evapotranspiration (ET) rates and depth to water requirements for riparian vegetation, using depth to water as the common link. A loose coupling of MODFLOW with Arc/Info was implemented for ease and maximum flexibility. The results were used to identify flow scenarios necessary to maintain riparian vegetation.

3.1. Conceptual Groundwater Model

From a cross-sectional profile (Figure 2), and utilizing a combination of published and field data, a conceptual model of the hydrogeologic system was constructed. The area's structural position on the margin of the basin reduced the lithologies to three hydrostratigraphic units: (1) rhyolite, andesite, and basalt interbedded with a pebble/cobble conglomerate; (2) basin fill; and (3) stream deposits (Figure 2). The basin fill is the main aquifer unit and is largely unconfined. Small perched aquifer systems may exist above volcanic layers in the region. Synoptic water level measurements in 1995 and 1996, in conjunction with historical water level records from the Ground Water Site Inventory database at the Arizona Department of Water Resources (Figure 3), were used to build, calibrate, and constrain a steady state model.

Inputs of water to this region include regional underflow, recharge from precipitation, infiltration of spring flow from Morgan City Wash, and seepage through rocks around the dam. Water leaves the region through groundwater pumping, ET, and regional groundwater underflow. The only direct impact on the immediate river area due to groundwater withdrawal is the seasonal pumping of two production wells for citrus groves. A steady state hydraulic head scenario was assumed for this subregion of the basin on the basis of water levels from two wells in the area that depict stable long-term well levels from 1981 to 1996.

The simulated region was a small portion of the West Salt River Basin, with model boundaries established to represent interactions with the regional aquifer system. Regional groundwater flow to the south-southwest indicates that the western and eastern boundaries of the model have little impact on groundwater flow. The northern and southern boundaries, simulating the regional underflow, are most influential. Surface water flow and spread of the groundwater mound beneath the riverbed are partially constrained by the conglomerate and volcanics that flank this narrow river valley.

3.2. Numerical Groundwater Model

The purpose of the numerical groundwater model was to predict how various dam releases would influence depth to groundwater under the channel of the Agua Fria River below Camp Dyer Diversion Dam. MODFLOW [*McDonald and Harbaugh*, 1988] was used to simulate hydraulic heads and to calculate water budgets. MODFLOW is a widely used, well documented, and verified model for simulating groundwater flow systems. It was used in conjunction with Visual MODFLOW [*Guiguer and Franz*, 1995], a preprocessor and postprocessor. A streamflow routing package [*Prudic*, 1989], developed specifically for the alluvial basins of the arid southwestern United States, was used to simulate the interaction between the surface water and groundwater systems.

The active model area (Figure 3) was positioned to minimize any boundary effects on surface water–groundwater interaction in the streambed. The active model area was 3230 m wide by 11,887 m long, with over 20,000 30-m-wide by 61-m-long grid cells. Boundaries of the study area were used to simulate interactions with the regional aquifer. Constant hydraulic head boundaries were used on the western and eastern edges of the model area. Underflow from north to south through the region was simulated with specified flux boundaries.

Vertically, lithologies were discretized into three separate hydrogeologic units. Two units represented bedrock and basin fill, with the stream routing package containing the stream deposits overlaid as the third layer. Unit 1 was stream alluvium, defined as recent deposits within the current channel system. Unit 2 was unconsolidated basin fill, comprised of clay- to boulder-sized materials in the form of floodplain, terrace, and abandoned channel deposits. Unit 3 was the basement unit, composed of a pebble/cobble conglomerate and interbedded volcanics. To simulate natural topography, an overlay of topographic contours derived from aerial photographs [*Jerry R. Jones and Associates*, 1990; Cooper Aerial, Phoenix, digital map data, 1987] was used for the top surface of the model.

Measurements of aquifer parameters were compiled from previous investigations and field work and were used to constrain the numerical model [*Wright*, 1997]. Final hydraulic conductivity k values for the steady state model were determined through calibration: 2.8×10^{-4} m s^{-1} for volcanics/conglomerate, 1.7×10^{-3} m s^{-1} for basin fill, and 1.7×10^{-3} m s^{-1} for stream alluvium. The vertical hydraulic conductivity of stream alluvium controlled the degree of surface water–groundwater interaction. Vertical conductivity values of the streambed were between 1.4×10^{-6} m s^{-1} for clay-rich or bedrock reaches and 9.4×10^{-6} m s^{-1} for coarse sand and cobble reaches and were constrained by field measurements [*Wright*, 1997] and results from long-term infiltration testing in the region [*IWT*, 1997].

A storage coefficient for the aquifer materials was estimated to be 0.0005. An estimate of specific yield for this region was 0.15 [*Mitchell and Putman*, 1987]. Recharge to the aquifer is only ~2% or 6.0 mm yr^{-1} of the 300 mm of precipitation per year.

Different ET rates were employed on the basis of whether the upper layer was dominantly riparian or nonriparian vegetation. Maximum ET rates of 0.08 mm d^{-1} for nonriparian areas and 4.9 mm d^{-1} for riparian areas were simulated. The

Table 2. Evapotranspiration (ET) Estimates for Dominant Vegetation in the Depth to Water Categories up to a Maximum of 6 m

Depth to Water, m	Dominant Vegetation	ET, m yr^{-1}	Average ET, m yr^{-1}	Source
Ponded	Open pan evaporation		2.8	this study
0–0.3	cattail (*Typha*)		2.8	*Young and Blaney* [1942]
0.3–0.9	seepwillow (*Baccharis*)	1.4–3.2	2.3	*Gatewood et al.* [1950]
0.9–1.8	juvenile cottonwood (*Populus*)	1.2–2.9	2.0	this study
1.8–3.0	mature cottonwood (*Populus*)	1.1–2.6	1.8	*Bowie and Kam* [1968] *Gatewood et al.* [1950]
3.0–6.0	juvenile mesquite	0.58		*Sammis and Gay* [1972]
	mature mesquite	1.3	0.94	*Qashu and Evans* [1967]
	saltbush	0.98		*McDonald and Hughes* [1968]

extinction depth (depth of ET equal to zero) was estimated to be 4.5 m below land surface, a reasonable value for vegetation of the region [*Stromberg et al.*, 1991].

Time was discretized into 3-month periods, to correspond to the germination period of representative woody riparian communities. Total simulation time for each run was 2 years.

The model was considered to be calibrated when it (1) simulated the extent of the quasi-perennial reach of the Agua Fria River and Morgan City Wash and (2) had a mean absolute error (MAE) for well levels within the model area of <3.8 m (<5% of the total head change across the region). A sensitivity analysis was used to examine the sensitivity of the model to cell size, topography, boundary conditions (location and type), streambed conductance, hydraulic conductivity, recharge, evapotranspiration, and extinction depth [*Wright*, 1997].

3.3. Conceptual Riparian Vegetation Model

A conceptual riparian vegetation model was used to enhance the predictive abilities of the groundwater model. The conceptual model provided a basis for more accurate calculations of ET, predictions on the potential woody riparian vegetation area, and refining the flow regimes. MODFLOW simulations of ET were based on a simple riparian–nonriparian classification of model cells. Use of representative vegetation type by depth to water zones allowed ET estimates to more closely approach the actual system than was possible with the ET components of MODFLOW (Table 2).

Empirical studies of the riparian vegetation of the San Pedro and Hassayampa Rivers of Arizona [*Stromberg et al.*, 1991, 1996], deemed analogous to the Agua Fria River system, formed a basis for the species component of our predictive analysis. The most influential factors for the establishment and maintenance of Sonoran riparian vegetation are (1) depth to water, floodplain elevation, and inundation frequency; (2) soil texture and moisture holding capacity; (3) light availability; and (4) site elevation [*Stromberg et al.*, 1996]. One factor, the functional depth to water ranges observed for juvenile (under 5–10 years) and mature tree species and shrubs along the San Pedro River, provided a conceptual model that we combined with results of the predictive numerical flow model [*Stromberg et al.*, 1996]. Depth to water ranges were used in a GIS to assess the potential of the Agua Fria River to maintain woody riparian vegetation (Table 3).

The seasonal flow regime developed for modeling relied on historical streamflow records and seed dispersal behavior of Fremont cottonwood and Goodding willow. Compared to *Tamarix chinensis* (tamarisk or saltcedar), an invasive, nonnative species that disperses seed from May to October, the seed dispersal period of cottonwood and willow is short, extending only from March through May [*Stromberg et al.*, 1991]. Streamflows were designed to enhance cottonwood/willow recruitment from March to May to favor site occupation by cottonwood (March–April) and by willow (April–May) before tamarisk seed is dispersed.

3.4. Coupling of Models in a GIS

Because GIS technology does not have the algorithmic capabilities to build process-based models internally and is not yet capable of space-time representations [*Corwin and Wagenet*, 1996], there has been a need to couple environmental models with GIS. The various levels of sophistication in the strategy to link these technologies define a continuum from loose coupling, an interchange of data files between the model and the GIS, up through complete integration, embedding the model inside the GIS [*Tim*, 1996]. The loose coupling of MODFLOW and the riparian vegetation model with Arc/Info in our study was a one-way link. Model results were imported into the GIS and combined with the vegetation model. This involved three major tasks: (1) designing a database system to contain the groundwater and riparian model data, (2) converting the groundwater model output to a format useable by Arc/Info, and (3) developing the database.

The application definition approach to database design was used. The types of analyses required of the finished database were defined, and the specific data types and structures required to support those analyses were identified. The desired outputs were (1) maps of potential riparian vegetation types based on depth to water, (2) area and ET associated with a vegetation type, (3) area and ET associated with depth to water zones, (4) time series study of a monotypic stand, (5) variations in ET volumes over time, (6) variations in riparian vegetation

Table 3. Depth to Water Ranges Observed for Willow and Cottonwood on the San Pedro River, Arizona and Used in the Geographic Information System

Species	Age	Min DTW,* m	Max DTW,† m
Salix goodingii	juvenile	0.091	2.0
(Goodding willow)	mature	0.091	3.2
Populus fremontii	juvenile	0.21	2.0
(Fremont cottonwood)	mature	0.091	5.1

Depth to water ranges are taken from *Stromberg et al.* [1996].
*Min DTW is the minimum depth to water observed for species.
†Max DTW is the maximum depth to water observed for species.

Table 4. Assumptions and Inputs Used to Calculate Evapotranspiration in the Geographic Information System for Depth to Water Zones Used in the Agua Fria River Project

Depth to Water, m	Representative Species	Average ET Rate, m yr^{-1}	Percent Vegetation Coverage Assumed
Ponded water	open pan evaporation	2.8	100% of 12-m-wide river channel*
	generic riparian value	1.8	50% of 18-m-wide cell
0–0.3	cattail	2.8	50
0.3–0.9	seepwillow	2.3	50
0.9–1.8	juvenile cottonwood	2.1	50
1.8–3.0	mature cottonwood	1.8	50
3.0–6.0	juvenile mesquite		
	mature mesquite	0.94	50
	saltbush		
>6.0	desert vegetation	0.003	40

*It was assumed that the river channel would only cover 12 m of the 30-m cell width.

area (depth to water less than or equal to ~6 m) over time, and (7) an expandable database capable of supporting queries and analyses based on multiple species and multiple environmental factors. On the basis of these outputs it was determined that the most versatile raw data file would contain depth to water in 0.03-m increments for each cell in the model.

The main output from MODFLOW simulations is the average hydraulic head for a model cell. Hydraulic head at 3-month intervals was exported from MODFLOW for a total of 12 files for each 2-year simulation. Depth to water for each cell in the model was calculated by subtracting hydraulic head from the surface elevation. Cell size was converted to 30-m squares (a square grid is required by Arc/Info), and the data files were imported into the GIS GRID module utilizing a conversion program written in Arc/Info's Macro Language (AML). All analyses in Arc/Info were performed either within the GRID module or on GRID files using the TABLES or INFO modules. The data files were then modified to calculate ET, using what is termed a remap table, to regroup cells into the depth to water zones shown in Table 3. ET was calculated using values for representative species for particular depth to water zones, assuming ~50% vegetative cover (Table 4). This process converted the raw data files to a database over time, in which all files for a particular flow scenario could be combined as needed.

Three separate analyses utilizing the GIS database were performed. These included a time series study based on the ET model (Table 2), an establishment scenario to track the changes in depths to water over the crucial period between germination and seedling development for cottonwood, and a sustenance study through time on juvenile cottonwood.

4. Results

4.1. Groundwater Model

Figure 4 depicts the extent of surface flow (measured in kilometers from the dam) for the various quarterly release rates simulated in constant and seasonal flow scenarios. Extent of surface flow ranged from ~4 to 10 km. Under a seasonally variable flow regime each 1.7×10^7 m^3 (15,000 ac ft) addition to yearly flow volume resulted in an increase in surface flow of ~800 m. Similar flow patterns for all simulations were observed in the 4.5 km immediately downstream of the dam, which is attributed to lithologic constraints on flow. This is shown on Figure 5, the time series study of depth to water zones for the 3.7×10^7 m^3 yr^{-1} seasonally varying flow scenario. South of kilometer 4.5, a lateral spreading component is introduced as the floodplain widens and the riverbed materials become relatively more coarse.

4.2. Evapotranspiration

ET totals from the groundwater model corresponded to a conservative estimate of initial ET expected in the first year of a release from the dam. ET calculated with the GIS corresponded to a maximum volume associated with a mature system after 20–30 years of flow. The combination of these two estimates gives an initial and mature system ET value for the three different flow regimes (Table 5). We considered the GIS calculations of ET to be a vast improvement over the MODFLOW calculations of ET and a potentially useful tool for water managers.

ET volumes did not significantly increase in direct relationship to increases in discharge; in fact, ET volume as a percent of the total release volume actually decreased from 11% of the 1.8×10^7 m^3 yr^{-1} to 5% of the 5.6×10^7 m^3 yr^{-1} (Table 5). If the lake evaporation rate is 9.5% per year, then ~1.3×10^8 m^3 yr^{-1} of water would be evaporated from the reservoir. For seasonal flows >1.8×10^7 m^3 yr^{-1}, calculations indicate that less water would be lost to ET of riparian vegetation than would be lost by surface water evaporation if stored in the lake.

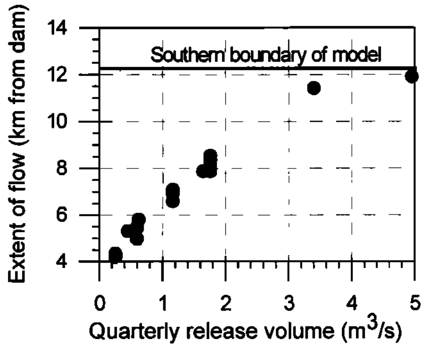

Figure 4. Extent of surface flow in the Agua Fria River (measured in kilometers from Camp Dyer Diversion Dam) for quarterly release rates (m^3 s^{-1}) simulated with the numerical groundwater flow model in constant and seasonal flow scenarios.

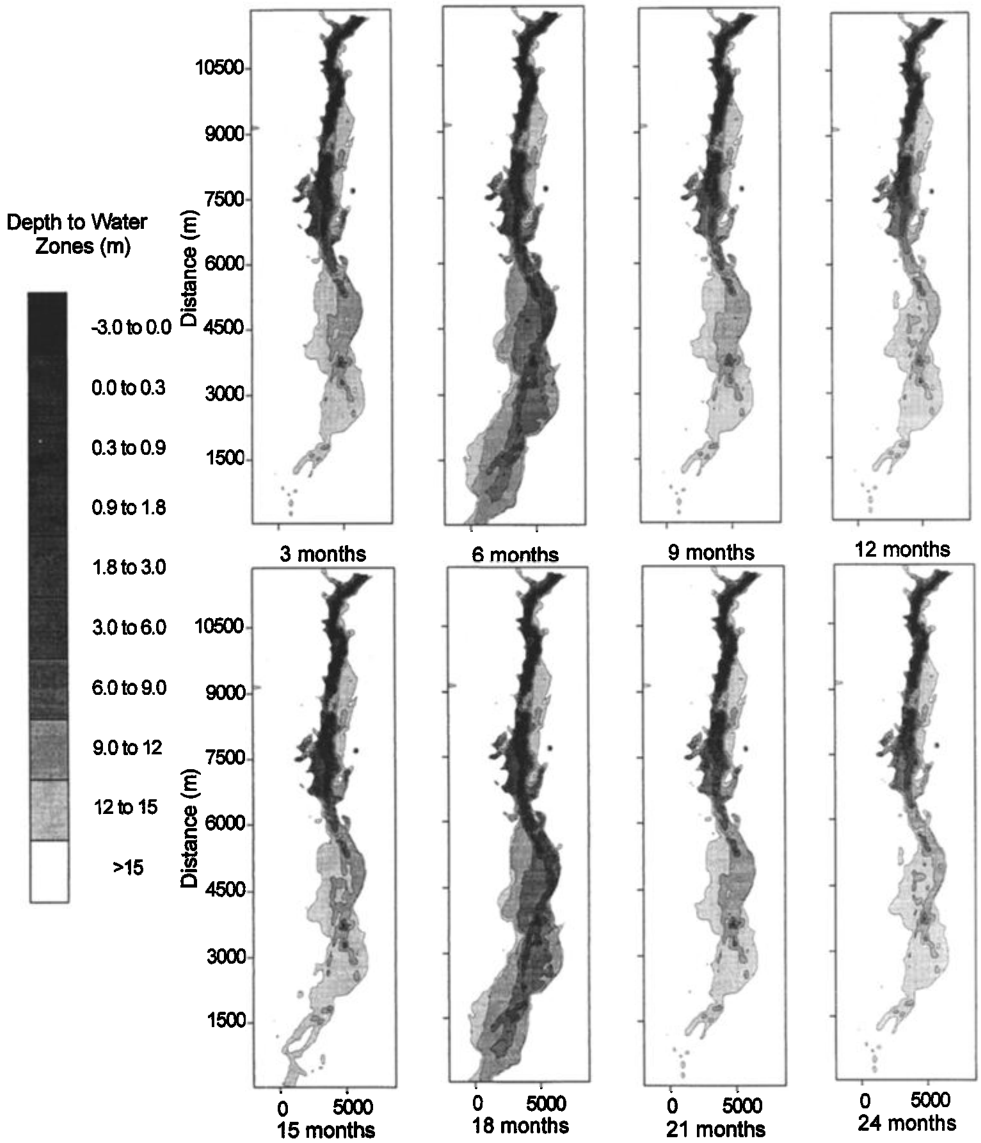

Figure 5. Time series study by 3-month intervals of depth to water zones for the 3.7×10^7 m^3 yr^{-1} seasonally varying flow scenario calculated with the Geographic Information System using depth to water calculated with the numerical groundwater flow model.

4.3. Time Series Study

The productivity and composition of riparian vegetation stands vary along a continuum with depth to groundwater, with some species and communities (e.g., mesquite bosques) occurring at depths of >6 m. The majority of the riparian vegetation in rivers such as the Agua Fria, however, occurs on sites with depths to groundwater of <6 m, which was used as a threshold range in our study. The area of the zones with depth to water ≤6 m for each 3-month period of the seasonal 1.8×10^7 m^3 yr^{-1} flow regime is shown in Table 6 and on Figure 5.

The relatively high spring discharge rates (second 3-month period) greatly increase the surface flow and the area within

Table 5. Minimum (After 1 Year of Flow) and Maximum (After 20–30 Years of Flow) ET Volumes Calculated by the Three Methods Used in This Study and Compared to Lake Evaporation

Seasonal Flow Regime, m^3 yr^{-1}	Minimum ET Volume After First Year of Flow,* m^3 yr^{-1}	Maximum ET Volume After Many Years of Flow,* m^3 yr^{-1}	ET Range After 30 Years of Flow, m^3 yr^{-1}	Estimated Annual Lake Evaporation, m^3 yr^{-1}
1.8×10^7	5.6×10^5 (3)	1.9×10^6 (11)	1.0×10^6–1.7×10^6	1.8×10^6
3.7×10^7	6.3×10^5 (2)	2.3×10^6 (6)	1.2×10^6–2.0×10^6	3.5×10^6
5.6×10^7	6.6×10^5 (1)	2.5×10^6 (5)	1.3×10^6–2.2×10^6	5.3×10^7
Calculation source	MODFLOW model	GIS analysis of models	ET and MODFLOW models	lake evaporation rate

*Percent of total release volume is given in parentheses.

Table 6. Area of Riparian (Depth to Water ≤6 m) Zones and Volumes of Evapotranspiration in Each Zone for Each Phase of the 1.8×10^7 m^3 yr^{-1} Seasonal Flow Regime Calculated by the Geographic Information System

Seasonal Flow Time, months	Discharge, m^3 s^{-1}	ET Volume, $m^3 \times 10^5$	Riparian DTW Zone, ha
0–3	0.51	5.2	166
3–6	3.4	7.1	301
6–9	0.51	5.4	174
9–12	0.51	5.2	167
12–15	0.51	5.2	163
15–18	3.4	7.4	286
18–21	0.51	5.3	174
21–24	0.51	5.2	167

the zone of groundwater <6 m, but the major impact of this increase was longitudinal, related to increased surface flow in the stream. The longitudinal cross section (Figure 2) shows the steadily dropping water table profile from north to south. Although larger spring discharges raised the water table in the southern reaches, it was still between roughly 6 and 12 m from the surface (see Figure 5 after 6 months for each seasonal scenario), which is not close enough to support a wide riparian corridor. In addition, the effects of larger discharges were short lived; the ≥6-m category dropped back to the base flow levels within the next 3-month period with no appreciable increase in area. This was true for all three flow scenarios.

The greatest influence to the system was within ~5–6 km of the dam. Although the extent of surface flow increased substantially with spring discharge rates, the return to base flow did not capture additional area for riparian vegetation nor did it cause a significant lateral spread of water in areas that could support vegetation. The major difference was the volume of groundwater which was recharged. There is not a substantial, quantifiable advantage to the high-volume flow regime of 5.6×10^7 m^3 yr^{-1}, apart from an increase in surface flow of ~1600 m, producing a reach that would support only a narrow riparian system within the stream channel and immediate bank area.

4.4. Cottonwood Establishment

An analysis of the potential sites available for establishment of cottonwood seedlings was conducted by evaluating the depth to water in each cell of the grid through time to determine potential for germination and assess the ability of the site to support the seedling through a subsequent 1-year period. This analysis only used depth to water as a requirement for establishment and did not consider any other factors discussed previously. Although willow was not included in the analysis, it has similar establishment and sustenance characteristics [*Shafroth et al.*, 1998]. Depth to water must be within 0.1 m of the surface during high spring flows to provide a moist substrate for germination, either through capillary action or direct contact with the water table. This condition may be created in a regulated river by controlling the hydrograph with a gradual recession [*Scott et al.*, 1993; *Rood et al.*, 1998]. During the subsequent year a depth to water between 0.2 and 2.0 m is necessary to sustain the juvenile cottonwoods (Table 3).

Under the 3.7×10^7 m^3 yr^{-1} flow regime a very small zone of <2 ha was identified as a potential establishment site, near the downstream extent of flow. These results could be attributed to model construction. The relatively coarse, 30-by-61-m grid cells used in the numerical groundwater flow model (reduced to 30 by 30 m in Arc/Info) are not conducive to such a small-scale phenomenon because establishment sites are often within 30 to 61 m of the stream [*Stromberg et al.*, 1991]. The depth to water values are averaged over the cell area and do not describe variation within a cell. Although the sensitivity analysis showed that smaller cell size did not significantly improve the resolution of the groundwater model in the stream, an analysis of the channel vegetation profile requires a model at the scale of the channel. Another reason for these results could be related to the abrupt return to base flow after spring discharge or to the lack of a substantial flood flow. A slower rampdown period, higher base flows, or much higher spring discharges could produce a quite different outcome.

4.5. Cottonwood Sustenance

The required depth to water zones for juvenile Fremont cottonwood plants was evaluated through time to examine the potential for sustaining established cottonwood seedlings. Raw data files were remapped to pinpoint depth to water zones observed for juvenile cottonwood, a range between 0.2 and 2.0 m (Figure 6).

The relatively large increases in flow volume resulted in very small increases in area suitable for juvenile cottonwood (Table 7). Comparing the changes in area with the 1.8×10^7 m^3 increases for this species, there appears to be a maximum attainable area of somewhere between 1.8×10^7 and 2.7×10^7 m^3, with a limited downstream extent of ~4.8 km. The 1.8×10^7 m^3 yr^{-1} increases in discharge had little impact on either the total area or downstream extent suitable for cottonwood maintenance.

High spring discharges did not produce any lateral increases in necessary depths to water; increases were only in the downstream direction. Once base flow was reestablished, the cottonwood maintenance area shrank back to the prespring discharge size. Seedlings established in the downstream reaches would not see flows after the return to base flow and would perish before the monsoons in late July/August.

5. Summary and Conclusions

The methodology proposed in this study for coupling groundwater and riparian vegetation models in a GIS system was successfully applied to a reach of an arid region river below a reservoir. Results indicated that the Agua Fria River Site is a suitable candidate for riparian restoration and groundwater recharge. Extent of surface flow for discharge rates over a 3-month period ranged from ~4 to 10 km. A comparison of three separate seasonal flow scenarios showed that each 1.8×10^7 m^3 yr^{-1} (15,000 ac ft yr^{-1}) increase in discharge yielded ~800 m of additional surface flow. Major influences on riparian vegetation were concentrated in the first 5–6 km downstream of the dam, regardless of the release volume. Existing riparian area in the study area was estimated to be 28 ha. Under a dam release scenario, potential riparian area (defined as zones with depth to water ≤6 m) would increase by a factor of 5–6 to between 140 and 180 ha. On the basis of the analysis of area with depth to water ≤6 m the best seasonal release was $<3.7 \times 10^7$ m^3 yr^{-1} (30,000 ac ft yr^{-1}). Under this scenario, less water would be lost to ET of riparian vegetation than would be lost by ET if stored in a surface impoundment.

An assessment of establishment and sustenance of Fremont cottonwood plants was conducted using the combined models. A small zone of <2 ha was identified as potential cottonwood

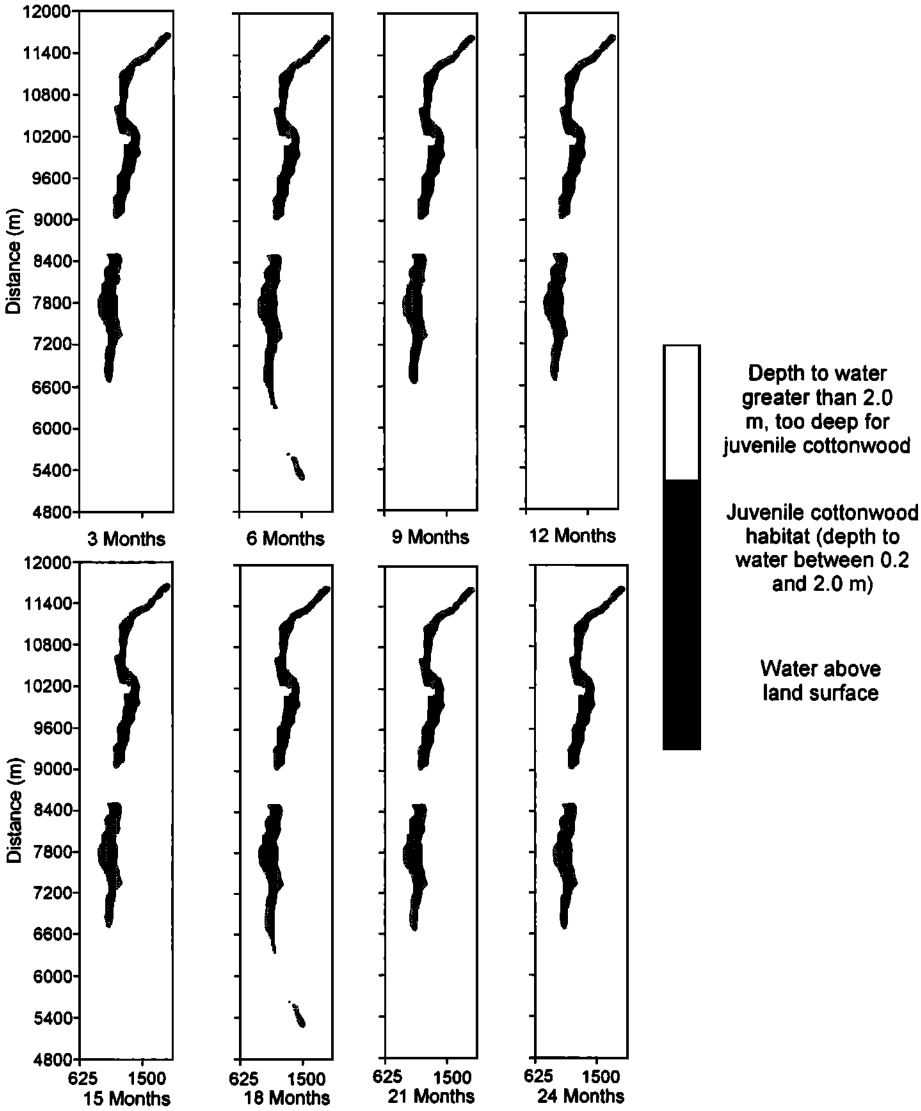

Figure 6. Potential juvenile cottonwood habitats over a 2-year period under the 3.7×10^7 m^3 yr^{-1} seasonally varying flow scenario.

establishment sites. Large increases in flow volume resulted in very small increases in areas capable of sustaining juvenile cottonwood. In addition, high spring discharges did not produce any lateral increases in the range of depths to water; increases were only in the downstream direction. These results could be attributed to physical constraints imposed by geology, topography, or the flow regime but could also be a function of scale differences between the groundwater and riparian vegetation models.

Table 7. Total Potential Juvenile Cottonwood Habitat and Predicted Extent of Habitat for Each of Three Seasonal Flow Regimes

Seasonal Release Scenario	Total Potential Juvenile Cottonwood Habitat, ha	Predicted Extent of Juvenile Cottonwood Habitat (Measured From the Dam), Km
1.8×10^7 m^3 yr^{-1}	41	4.5
3.7×10^7 m^3 yr^{-1}	49	5.1[a]
5.6×10^7 m^3 yr^{-1}	49	5.3[b]

Total potential juvenile cottonwood habitat is defined as the area with depth to water ranges between 0.2 and 2 m.

[a]A 14% increase over the 1.8×10^7 m^3 release.

[b]A 3% increase over the 3.7×10^7 m^3 release.

The coupling of models described in this study is useful for assessing similar sites, and the flexibility of the database design allows expansion to include multiple species and multiple factors impacting riparian vegetation establishment and sustenance. Careful consideration to scale compatibility between the models is necessary in the design stages, and a major expansion would benefit from a tighter coupling of the models within the GIS to automate the conversion steps. In addition, it is important to recognize that this was a virtual exercise. These models will be more robust in the future if they are calibrated to actual releases.

Novel approaches, such as this one, are necessary to assess the complex impacts of water management decisions, given that conflicts over allocation of water resources will only increase as human populations continue to grow.

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