Managing Alamo Dam to Establish Woody Riparian Vegetation on the Bill Williams River, Arizona

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Abstract

A growing understanding of the importance of riparian ecosystems in the semiarid and arid west has sparked interest in the growth and distribution of riparian vegetation. Disturbances and stresses caused by changes in streamflow patterns from dams have profoundly affected riparian vegetation species composition and structure. In the Southwestern United States, riparian forests historically dominated by the native *Populus Fermontii* (Cottonwood) and *Salix Gooddingii* (Willow) have been inundated by the exotic species *Tamarix Ramosissima* (Salt Cedar). This study presents a method for reservoir release management to enhance downstream vegetation recruitment of native species. The focus is on the Bill Williams River (BWR) in Western Arizona which is regulated by Alamo Dam. Through literature review, expert knowledge, and computational modeling, more informed decisions can be made regarding recruitment strategies for riparian vegetation. Modeling in this study employs the U.S. Army Corps of Engineer Hydrologic Engineering Center's Ecosystems Functions Model (EFM) and River Analysis System (RAS), ESRI's ArcMap, and Applied Imagery's Quick Terrain Modeler. Vegetation recruitment of cottonwood, willow, and salt cedar for a 2006 experimental flood release from Alamo Dam is interpreted for use within the software. Finally, further research is presented regarding hypothetical flows and reservoir operations.

Introduction

Growing understanding of the importance of riparian ecosystems in the semiarid and arid west has raised interest in the growth and distribution of riparian vegetation (Busch et al. 1995, Glenn and Nagler 2005, Irvine and West 1979). The foremost disturbance influencing riparian vegetation in semiarid and arid regions is due to streamflow. Large flood disturbances influence the establishment, mortality, and distribution of riparian vegetation. Stresses from droughts influence plant survival, growth, and species composition (Shafroth 2002). Dams profoundly affect streamflows which change riparian disturbances and stresses. In semiarid and arid watersheds, dams have a larger effect by altering local variability in streamflow. Floodplain ecosystems depend naturally upon dynamic river flow patterns and occasional floods. The flood pulse concept (Poff et al. 1997) emphasizes the importance of floods as disturbances that drive geomorphic change and rejuvenate riparian and aquatic communities (Rood et al. 2005). In a dry climate, annual or seasonal reductions in streamflow from flow regulation can reduce the areal extent of riparian vegetation (Stromberg and Patten 1992). Alternatively, flow increases from reservoirs during normally dry seasons can increase riparian vegetation. Alternating disturbance and stress regimes influences the species composition of plant communities (Shafroth et al. 1998, Lite and Stromberg 2005, Dixon et al. 2002).

In the Southwestern United States, riparian forests historically dominated by the native *Populus Fermontii* (Cottonwood) and *salix gooddingii* (Willow) have been inundated by the exotic species *Tamarix Ramosissima* (Salt Cedar). The *Tamarix* genus was introduced to the American Southwest a century ago. *Tamarix* can form dense monocultures and dramatically change vegetation structure, animal species diversity, soil salinity, and hydrology of sites where it becomes dominant (Sher et al. 2002).

The stems and leaves of mature *Tamarix* plants secrete salt and consume an enormous amount of water. A single large plant can absorb 200 gallons of water a day (Hoddenbach 1987), although evapotranspiration rates vary based on water availability, stand density, and weather conditions (Davenport et al. 1982). The exotic *Tamarix* can extract water from unsaturated soil when groundwater is deeper and temporally more variable in depth (Horton et al. 2003). Elimination of riparian vegetation can occur where high ground-water use lowers the water table below the rooting depth of riparian species, where base flow is completely diverted, or both (Webb and Leake 2006). During dry summer months the high water consumption can dry up marshes, springs, and low-flow rivers as well as choke out shallow root species such as the *salix gooddingii*. Paradoxically, *Tamarix* infestations can also lead to flooding, as its extensive root system can choke stream beds (Rush 1994). The *Tamarix*'s extensive root system can create ineffective flow areas which can warm the water and in many cases allows invasive species to move upstream. Since the 1960s, biological control methods for *Tamarix* have been used such as the Saltcedar Leaf Beetle and the Middle-Eastern Mealy Bug but with limited success (Dudley and Deloach 2004). Root poisoning of *Tamarix* gives reasonable results but is difficult to implement for basin scale control.

The issue of species distributions is especially significant in the context of detrimental plant invasions, due to their potentially severe economic, ecological, and aesthetic impacts. The widespread establishment of *Tamarix* in western North American riparian ecosystems has been attributed, in part, to flow regulation (Everitt 1998, Smith et al. 1998). The connection between the addition of dams and the establishment of *Tamarix* is evident. When overbank flooding occurs, the seedlings can establish in high densities along the riverbank. Seeds of the *Populus*, *Salix*, and *Tamarix* genus are dispersed by wind and water. Competition experiments on seedlings suggest that *Tamarix* may not be a good competitor at the seedling stage (Sher et al. 2000, Glenn and Nagler 2005). Management plans to restore historical disturbance regimes to stimulate natives will only be successful if these native trees can reestablish in the presence of the invasive species.

The link between dams and the establishment of the invasive *Tamarix* suggests three decision options for improving native ecosystem health:

- continue operations as usual,
- dam removal,
- and manage reservoir discharge with native ecosystem health in mind.

Continuing reservoir operations as usual will accentuate the problem of invasive species. Conversely, continuing reservoir operations as usual will solidify water availability for human use. Dam removal will restore the natural flow regime to a river system. But may greatly increase flood damages downstream, have unforeseen economic costs, and have negative downstream environmental effects (Stanley and Doyle 2003). The best option might be managing reservoir discharge with ecosystems in mind. Indeed, managing reservoirs to simulate a more natural hydrograph has been a subject of both implementation and study (Poff et al. 1997, Stevens et al. 2001, Magilligan and Nislow 2005, Rood et al. 2005, Shafroth et al. 2002, Richter and Thomas 2007).

The objective of this study is to review a method to better understand vegetation recruitment for more informed management of dam releases. The focus will be on the Bill Williams River (BWR) in Western Nevada which is regulated by the Alamo Dam. By incorporating methods used in this study, a better understanding of timing and amount of spring releases can be incorporated into management practices.

Using computational simulation and geographical information systems (GIS), a 2006 experimental flood pulse will be simulated to predict where greater amounts of riparian vegetation should establish along the channel. For the hydraulic modeling, the USACE Hydrologic Engineering Center's River Analysis Tool (HEC-RAS) and HEC-GeoRAS will be used. HEC-RAS is used for one-dimensional steady flow, unsteady flow, sediment transport/mobile bed computations, and water temperature modeling. HEC-GeoRAS is used for processing geospatial data in ESRI's ArcGIS using a graphical user interface (GUI). The interface aids preparation of geometric data for import into HEC-RAS and processes simulation results from HEC-RAS. To find links between the riparian vegetation and hydrology, the Hydrologic Engineering Center's Ecosystem Functions Model (HEC-EFM) will be used. HEC-EFM is designed to help study teams assess ecosystem responses to changes in the flow regime of a river or connected wetland. Processing LIDAR data for digital terrain models (DTMs) and triangulated irregular networks (TINs) will be done using Applied Imagery's Quick Terrain Modeler (QTM) and ESRI's ArcMap. The results of this study will offer better management practice capabilities for riparian vegetation recruitment through more effective reservoir releases and timing of those discharges.

Study Area

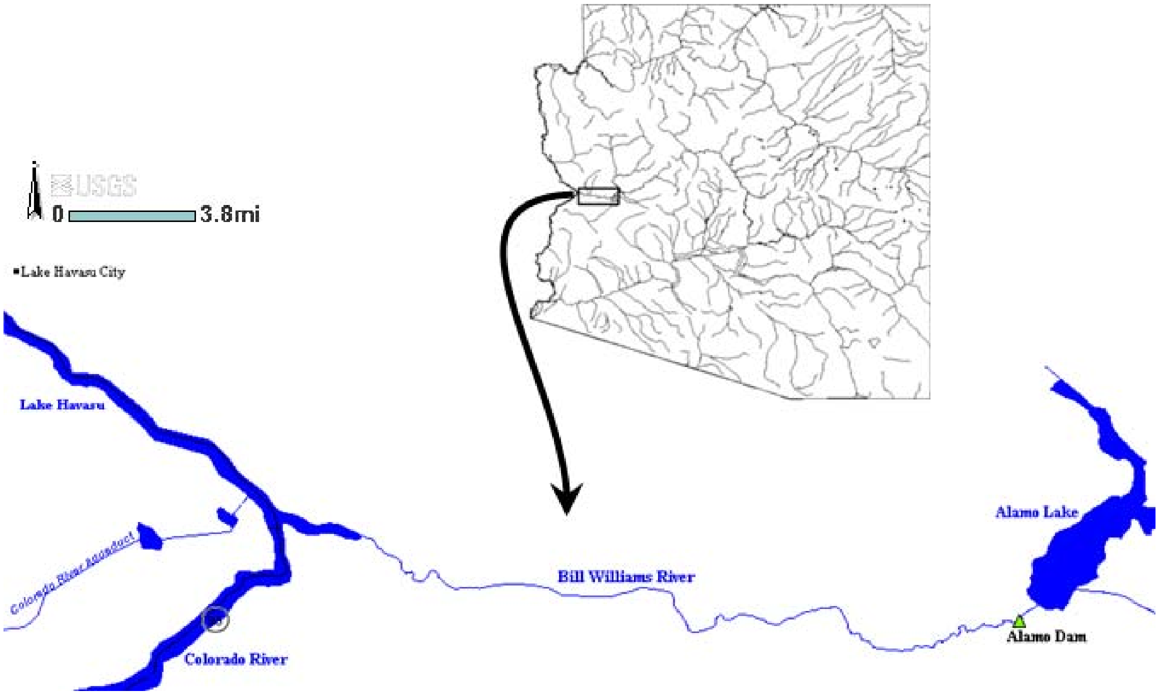

Figure 1. Map of the Bill Williams River study area in Western Arizona.

Named after an early explorer to the region, the Bill Williams River is approximately 45 river miles long which flows from Alamo Reservoir through the wild Buckskin Mountains in the west central part of Arizona and joins the Colorado River at Lake Havasu, just above Parker Dam. It is the largest tributary of the Colorado River between the Virgin and Gila rivers. Over the entire 45 mile reach, the Bill Williams River drops from an elevation of approximately 1,110 feet down to an elevation of 449 feet, with an average gradient of 0.003 (slope ranges between 0.001-0.009). The BWR passes through canyons interspersed with alluvial basins. The most notable alluvial basin is the roughly 8 mile long Planet Ranch, located 14.5 miles upstream of the confluence with the Colorado River, which acts as a sponge to upstream flow greatly affecting downstream hydraulics.

No perennial tributaries enter the Bill Williams River downstream of Alamo Dam. Channel bed and floodplain sediments are dominated by coarse particles (81%), primarily sand (67%), and are generally low in electrical conductivity, 1.0 dS/m (Shafroth 1999). Flood flows of 35.1 cms and larger readily transport the poorly consolidated sand. Average annual precipitation in the watershed ranges from 22 cm near Alamo Dam (National Climatic Data Center station Alamo Dam 6ESE and Alamo Dam) to 13 cm near the Colorado River (National Climatic Data Center station Parker 6NE). Historically, the Bill Williams River is prone to flash flooding. Records indicate pre-dam flood flows reaching up to 5,663 cms (200,000 cfs).

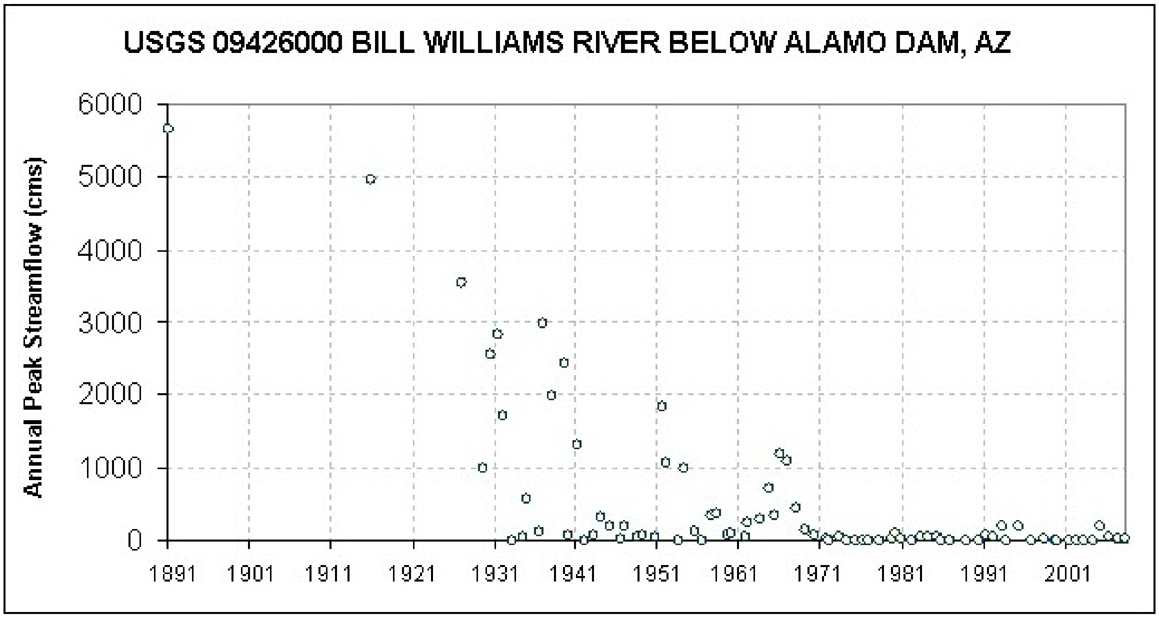

Figure 2. Annual peak flood flows for the Bill Williams River, AZ.

Completion of Alamo dam in 1968 drastically reduced the system's natural tendency for flash flooding (figure 2). Consequently, the exotic *Tamarix ramosissima* has become the dominant tree species along the Bill Williams River. The lack of river power to flush the Bill Williams River has also caused heavy buildup of sediment deposits from alluvial fans.

Alamo Dam

Alamo Dam was constructed between 1963 and 1968 by the Corps of Engineers as a multipurpose project under authorization of the Flood Control Act of 1937. Congress authorized the dam with specific storage allocations for flood control, water conservation, and recreation (Appendix VII). The outlet works include three large slide gates, which allow a maximum gated release of 198 cms (7,000 cfs). Although the outlet rating curves show a maximum release of 198 cms (Appendix I), the releases rarely reach that value.

The following description of management objectives for Alamo Dam was addressed by the Bill Williams River Corridor Technical Committee in 1994 (USACE 1998). The main purpose of authorizing Alamo Dam by Congress was flood control for lower Colorado River communities and properties along the Bill Williams River. Alamo Dam is operated in conjunction with the U.S. Bureau of Reclamation dams on the Colorado River to reduce flood related damage. The water in the Bill Williams River belongs to the state of Arizona. To date, the Corps has not contracted with a user for water supply storage. The conservation pool has been used only for short-term storage of water. The Arizona Game and Fish Department holds water rights for 25,000 acre-feet in the recreation pool. The Arizona State Parks Department operates and maintains boat launching ramps, campgrounds, and appurtenant structures. The Arizona Game and Fish Department also has established a productive lake bass fishery. Federally listed Southern Bald Eagles have nested around Alamo Lake since the early 1980's. In 1988, the U.S.

Fish and Wildlife Service requested that the Corps maintain a minimum water surface elevation of 1,100 feet at Alamo Lake to ensure sufficient forage area for the eagles. Reservoir operations have been modified to prevent nest inundation along the lake's periphery. A National Wildlife Refuge is downstream of Alamo Dam near the mouth of the Bill Williams River. The U.S. Fish and Wildlife Service suggested that a significant portion of the cottonwood trees have been destroyed due to the pattern of past Alamo Dam releases.

In the 1980's there were intensified conflicts over the operation of Alamo Reservoir. Among the problems were fluctuating water levels that interfered with boat ramps and other activities, such as largemouth bass spawning season, bald eagle nesting sites, and requirements to inspect the dam's outlet works once every five years (Pulokas 1996).

Recent management decisions of Alamo Dam have been made to emulate aspects of a more natural hydrograph. In the early 1990's, a group of interested parties recognized that conflicts between stakeholders were likely regarding Alamo Dam operations, and that any approach to re-operating Alamo Dam had to provide a means to resolve these likely disagreements. This effort culminated in the 1994 endorsement of a new approach to managing Alamo Dam and the issuance of a new Water Control Manual by the US Army Corps of Engineers (USACE) in December of 2003 (USACE 2003). Since issuing the new Water Control Manual, experimental releases from Alamo have occurred in the spring to emulate a more natural hydrograph with the hope of increasing recruitment of riparian vegetation, namely the native *Populus fremontii* (cottonwood) and *Salix gooddingii* (willow) species.

GIS

Geographic information systems are technologies to store, manage, edit, analyze, and display data that are spatially referenced. GIS in this study allows for pre and post processing of Bill Williams River data. In this study, ESRI's ArcGIS allows for the analysis of the HEC-RAS and coinciding GeoRAS data layers as well as any external data sets that have ecological significance. Datasets of significance to this study are vegetation maps, elevation data, inundation depth grids, and orthographic imagery. Computationally, ArcGIS's raster calculator was used to calculate inundation coverage areas. ArcGIS was also used to re-project all datasets to a horizontal datum of North American Datum 1983, projected in zone 12, vertical datum of North American Vertical Datum 1988, and Metric units (meters).

The second GIS used in this study is Applied Imagery's Quick Terrain Modeler to evaluate and filter Light Detection and Ranging (LIDAR) data. LIDAR data for the Bill Williams River below Alamo Dam were collected by Airborne 1 Corporation on February 6 and 7, 2006. Airborne was a subcontractor for Tetra Tech, Inc., who was performing a broad hydrographic survey (LIDAR, surveyed cross sections, bed materials, etc) of the Bill Williams for the Los Angeles District (SPL) of the U.S. Army Corps of Engineers.

LIDAR data were collected during low flow conditions (surface water flow rates varied spatially between 0 and 0.8 cms). Spacing to closest neighboring point varied between 1.2 and 1.5 m. Comparisons with points of known elevations showed minimum, maximum, and mean differences of -16.2, 14.6, and -3.5 cm, respectively (Airborne 1 Corporation 2006a,b).

Tetra Tech delivered data to SPL for ground last return, all shots first return, all shots last return, and a set of bare earth TINs. All data used a horizontal datum of North American Datum 1927, projected in Arizona State Plane West, vertical datum of National Geodetic Vertical Datum of 1929, and English units (feet).

Initial vegetation filtration was done by Airborne using MicroStation and Terra Scan software. The resulting TINs were delivered to SPL in five sections spanning the Bill Williams River from Alamo Dam to its confluence with the Colorado River.

SPL provided the five TINs to HEC in August 2006. Inspection of the TINs, in comparison with orthographic photos taken in September 2005, revealed that the elevation data was not truly bare earth. Vegetation missed during initial filtering was still distinctive and widespread enough to cause irregularities in the overall topography. This was a serious concern for the proposed simulation modeling that relied on the bare earth TINs as a fundamental and required data set.

Additional vegetation filtering was performed using a bare earth extraction tool developed by the National Geospatial-Intelligence Agency, which is functionally just a plug-in to a software tool called Quick Terrain Modeler (QTM).

QTM is a 3-D modeling package originally developed at the Johns Hopkins Applied Science Laboratory. It is now a stand-alone software tool available from a company called Applied Imagery. QTM was designed for 3D visualization and exploitation of various digital elevation model formats. Specifically designed for LIDAR and 3D terrain visualization, the software efficiently handles large file sizes (up to 200 million vertices). QTM was the primary GIS tool used for vegetation filtration. The next section of this document describes work done to produce a more truly "bare earth" set of TINs for the Bill Williams River.

Data Filtration

Per guidance from USGS, the 5 TINs were split into 12 pieces, each representing a study reach providing a spatial framework for future science and engineering work on the Bill Williams River. ArcGIS was used to convert the 12 TINs into node features and then into ASCII xyz text format. The bare earth extraction plug-in classifies those ASCII xyz points as surface or foliage based on a set of user-defined parameters for: Minimum resolution, maximum surface slope, maximum surface delta, and maximum surface variation (JHU/APL 2006).

<u>Minimum resolution</u> defines the highest resolution at which bare earth processing computes surface statistics. This value should be set based on the nominal point spacing of the data and the size of the objects to be classified as foliage. In general, the smaller the value, the better the surface fit, but too small a value will result in foliage being classified as ground surface.

<u>Maximum surface slope</u> should be set to match the maximum expected slope in the terrain being analyzed. A lower value will do better at rejecting trees, shrubs, and

buildings, but if the terrain is expected to have surface slopes exceeding this value, then it should be increased to match the maximum expected terrain slope.

Maximum surface delta is used as the final filter for determining whether a point should be included in the surface. This value is dynamically adjusted based on local surface variance and the user-specified value for Minimum Resolution. With thick foliage (i.e., fewer returns off "real" ground) you may want to increase this value to prevent large voids in the surface file. In urban areas with lots of smooth, level surfaces (parking lots, roads, grass yards) this value could be decreased to better distinguish small objects on the surface.

Maximum surface variation defines the amount of variation the filter will allow. If too much "real" surface is being excluded because it is very rough, then increase this value. If too much “foliage” is being marked as surface and there is good high resolution coverage, then you can reduce this value to try to improve the discrimination.

To keep the original topography of features such as canyons and ridges, the valley floor of each reach was cropped from the rest of the data prior to filtering. The bare earth extraction plug-in was then applied to the valley area to remove vegetation. Each section went through 2-3 iterations of filtration with minimum resolution ranging from 1-2 meters, maximum surface slope ranging from 35-65 degrees, and maximum surface variation ranging from 0.1-0.3. The maximum surface delta was left as the system default value of 0.3 meters. The parameter values varied depending on the nature of the valley floor topography. When complete, the cropped and filtered area was added back to the parent data.

A final visual pass was made to manually remove any points deemed as vegetation in accordance with the September 2005 aerial photography. Figure 3 shows portions of the TINs during the vegetation removal process.

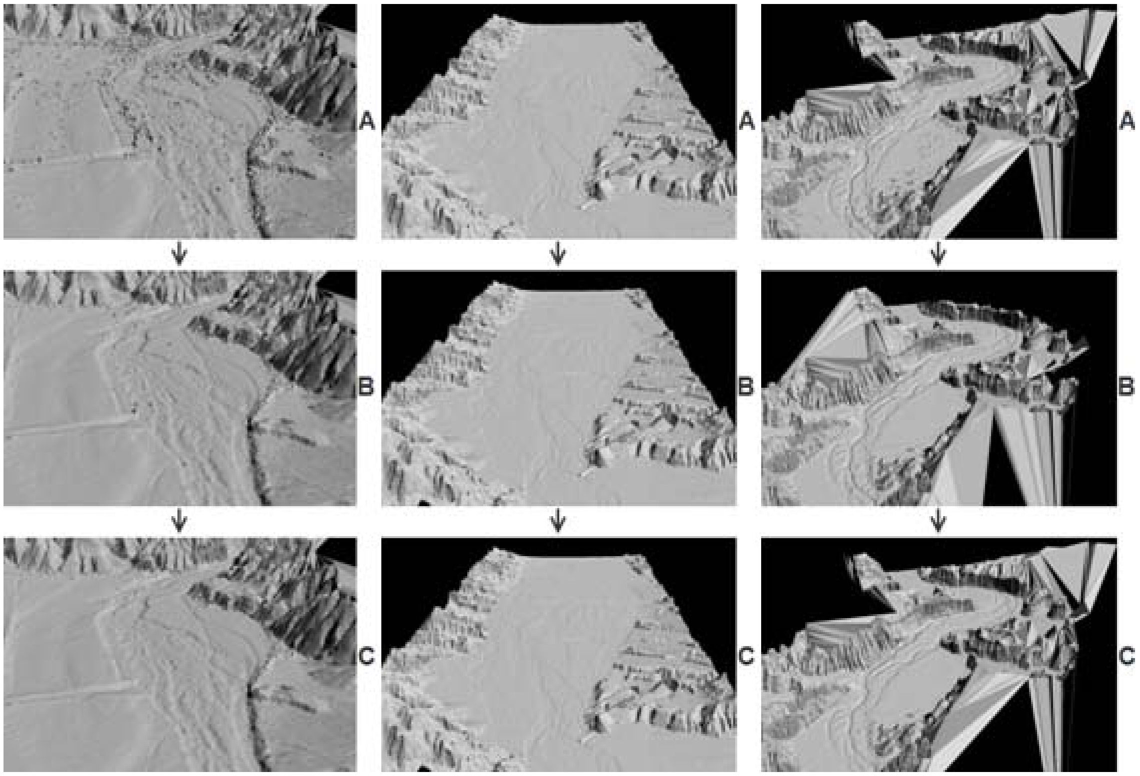

Figure 3. Vegetation filtration process for Reach 2 (Lincoln Ranch), 8 (Planet Ranch), and 10 (Mineral Wash) of the Bill Williams River LIDAR data. (A) is as received by HEC from SPL, (B) is after filtration using the bare-earth extraction plug-in, and (C) is after manual editing.

After filtering, ArcGIS was used to convert the ASCII xyz files back into node features. Node features were reviewed, edited to remove excess overlap between the 12 reaches, saved to a geodatabase, and loaded into a terrain. ArcGIS's terrain feature allows for massive amounts of node data to be viewed in an on-the-fly TIN format at multiple resolutions. 12 new reach TINs were extracted from the bare earth terrain for use in hydraulic modeling. The quality of the bare earth representation is directly related to the density of the vegetation at the time of the LIDAR flights. Table 1 contains a qualitative description of the new bare earth TINs for each reach

Reach	Rating	Comments
1	Fair	Canyonized region of the Bill Williams River. Point density acceptable after vegetation filtration. Some issues with lack of original data along the river channel. Lack of bathymetric data may be a cause of concern in some sections.
2	Fair	After filtration and spot checking, a few areas had low point density due to heavy vegetation filtration. Vast improvement over the original data.
3	Good	After filtration there was still a decent point density. Vegetation was sufficiently removed.
4	Good	After filtration there was still a decent point density. Vegetation was sufficiently removed.
5	Good	After filtration there was still a decent point density. Vegetation was sufficiently removed.
6	Fair	Heavy vegetation caused point density to decrease significantly. Some areas lacked data. Floodplain topography was maintained and improvement over original data was achieved.
7	Good	Very long reach with relatively high point density. Vast improvement over original data regarding bare earth topology. Minor concern regarding riverbank surface point removal.
8	Very Good	Little vegetation needed to be removed. A very high density of points. Very little change to existing data was needed.
9	Fair	High density on the upstream side of reach was maintained. Lower side of reach is highly vegetated and consequently the point density was greatly reduced.
10	Poor	Original point density was low and after filtration the point density was even lower. Heavily vegetated area produced low amounts of ground surface data points.
11	Poor	Original point density was low and after filtration the point density was even lower. Heavily vegetated area produced low amounts of ground surface data points.
12	Poor	Original point density was low and after filtration the point density was even lower. Heavily vegetated area produced low amounts of ground surface data points. This reach contains a wildlife refuge which is highly vegetated.

Table 1. Summary of reach-based vegetation filtration results for the Bill Williams River.

Hydraulics

For hydraulic analysis of the Bill Williams River, this study used the river analysis system HEC-RAS. HEC-RAS performs one-dimensional hydraulic calculations for a network of natural and constructed channels. This study employed a steady flow analysis.

The steady flow component of the modeling system is for calculating water surface profiles for gradually varied flow. The system can handle a network of channels, a dendritic system, or a single river reach. The steady flow component can model subcritical, supercritical, and mixed flow regime water surface profiles (USACE 2008). The basic computational procedure is based on solving the one-dimensional energy equation. Energy losses are from friction (Manning’s equation) and contraction/expansion. The momentum equation is used where the water surface profile is rapidly varied. These situations include mixed flow regime calculations, hydraulics of bridges, and profiles at river confluences.

Various obstructions such as bridges, culverts, dams, weirs, and other structures in the flood plain may be considered in the computations. The steady flow system is designed for use in flood plain management and flood insurance studies. Also, capabilities are available for assessing the change in water surface profiles due to channel modifications, and levees.

Steps in developing a HEC-RAS project include (USACE 2008):

- Starting a new project
- Entering geometric data
- Entering flow data and boundary conditions
- Performing the hydraulic computations
- Analyzing results

The hydraulic computations are the only thing strictly done in HEC-RAS for this project. Flow data are taken from the analysis with HEC-EFM. The boundary conditions are from a combination of field and GIS data. The geometric data and analysis of results are done using HEC-GeoRAS in ESRI's ArcGIS.

HEC-GeoRAS is a set of ArcGIS tools for processing geospatial data from HEC-RAS. The extension allows users with limited GIS experience to create an HEC-RAS import file containing geometric data from an existing DTM and complementary data sets. Results exported from HEC-RAS analysis also may be processed.

Geometric data can be created in HEC-GeoRAS containing river, reach and station identifiers; cross-sectional cut lines; cross-sectional surface lines; cross-sectional bank stations; downstream reach lengths for the left overbank, main channel, and right overbank; and cross-sectional roughness coefficients. Additional geometric data defining levee alignments, ineffective flow areas, blocked obstructions, and storage areas may be written to the HEC-RAS GIS import file (USACE 2005). Once the geometric data has been created in HEC-GeoRAS, it can then be exported in .sdf file format and imported to HEC-RAS. Once HEC-RAS has been used to create water surface profiles, results can be exported in .sdf format. HEC-GeoRAS can then convert the HEC-RAS results file to .xml file format and create depth grids based on the HEC-RAS input and DTMs or TINs. For this study, HEC-RAS version 4.0.1 Beta was used which has the capability of producing depth grids in .flt format internally. Production of depth grids was done in HEC-RAS for this study because of improvements over the HEC-GeoRAS version. HEC-RAS 4.0.1 Beta improves on interpolating water surface elevations between cross sections and produces depth grids based on connected grid cells. Therefore, the HEC-RAS method of producing depth grids is hydraulically more accurate than the HEC-GeoRAS method.

A previous HEC-RAS model developed by the USACE Los Angeles District (SPL) (USACE 2006) was obtained for the study. The SPL HEC-RAS model has 154 cross sections representing the Bill Williams River. The SPL HEC-RAS model was found to be inadequate for floodplain mapping purposes. The cross sections do not accurately map floodplain boundaries and channel morphology. Without sufficient coverage of the floodplain, mapping vegetation recruitment areas in GIS would be ineffective. Therefore, a new HEC-RAS model had to be created and calibrated to accurately depict the flood plain.

GIS Pre-processing

HEC-GeoRAS with the aid of Lidar based elevation data along with ortho-rectified imagery taken March 2005 and September 2005 assisted in creating the river, reach and station identifiers; cross-sectional cut lines; cross-sectional surface lines; cross-sectional bank stations; downstream reach lengths for the left overbank, main channel, and right overbank; and cross-sectional roughness coefficients. 341 cross sections were produced along the 45 mile stretch. Cross section locations were chosen to best represent channel geometry. With no perennial streams, the Bill Williams River was modeled as a single river reach with no tributaries, Appendix II.

Roughness of the river and corresponding floodplain are highly variable due to dense vegetation. Roughness values were generated from a vegetation map produced from orthographic photos taken on the 5th of September 2005 during a mean daily discharge of 5 cms at USGS gage 09426000. The vegetation map is a polygon shapefile which assigns a code for different vegetation types and densities. Manning's n values were assigned to each code (Fasken 1963, Barnes 1967, Arcement and Schneider 1984, Hicks and Mason 1991, Phillips and Ingersoll 1998). Below is a table of the vegetation codes and the relative roughness values attached to those codes. A detailed table of various roughness value scenarios is presented in Appendix IV.

LU-CODE	SHORT_DESCRIPTION	RELATIVE ROUGHNESS
1	Sparse flood plain - Populus and/or Salix	0.044
2	Dense flood plain - Populus and/or Salix	0.085
3	Sparse flood plain - Tamarix	0.052
4	Dense flood plain - Tamarix	0.094
5	Sparse terrace, mesquite dominant	0.046
6	Dense terrace, mesquite dominant	0.088
7	Sparse terrace, low shrub dominant	0.049
8	Dense terrace, low shrub dominant	0.092
9	Sparsely vegetated flood plain	0.040
10	Low flow channel	0.030
11	Deltaic marshland	0.090
12	Bare sand bars	0.022
13	Bare terrace	0.023
14	Cultivated land	0.029
55	Channel margins and islands	0.032
99	Rock outcrop	0.035

Table 2. Vegetation codes and relative roughness values for the vegetation map of the Bill Williams River, AZ.

The stream centerline, flow paths, bank stations, cross sections, and Manning's n values were exported from HEC-GeoRAS in .sdf format and imported to HEC-RAS through the Geometric Data Editor. Elevation data was based on the adjusted bare earth

TINs. Once imported, a visual inspection of the data was done to assess model integrity. Bank stations were adjusted to better match channel edges.

Flow Data

For the Bill Williams River, it is assumed that the flow is subcritical throughout the river system. Therefore, it is only necessary to enter a boundary condition at the downstream end of the river. The normal depth boundary condition was chosen for this study with an energy slope of 0.0028. The energy slope was approximated as the average slope of the channel bottom. The contraction/expansion coefficients were left as the default 0.1 and 0.3 in transition energy losses between two adjacent cross sections. A large range of flow values were used to produce rating curves at each cross section. Flows from the ecosystem analysis were also used to produce water surface elevations.

Calibration

To calibrate the HEC-RAS model, observed water surface elevations were matched with simulated water surfaces by adjusting the Manning's n values based on a vegetative cover map. By making global adjustments to the n values, the vegetation map's merit is not degraded. A detailed explanation of the calibration process for the hydraulics model can be found in Appendix III.

Ecosystem functions and requirements

To analyze the relationship between ecosystem functions and hydrology, this study will use the ecosystem functions model HEC-EFM. The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers is developing HEC-EFM to enable project teams to visualize existing ecologic conditions, highlight promising restoration sites, and assess and rank alternatives according to the relative change in ecosystem aspects (USACE 2008). Central to HEC-EFM are "functional relationships" that link characteristics of hydrologic and hydraulic time series (flow and stage) to elements of the ecosystem through a combination of four basic criteria:

- season,
- flow frequency,
- duration,
- and rate of change.

Season is defined as the time period in which the relationship occurs. Flow frequency is the frequency of ideal hydrologic conditions, usually defined in years. Duration is the amount of time that the relationship requires a defined flow. Rate of change defines a change in water level over a length of time required for the relationship. The criteria defined above are typically developed by teams of scientists and engineers using a combination of expert knowledge and scientific literature.

Once the relationships are developed, HEC-EFM performs statistical computations to analyze flow and stage time series for the specified criteria and produces a single flow value for each relationship. This process can then be repeated on alternative flow regimes to compare different project scenarios and indicate the directions of change for the ecosystem.

In addition to the statistical computations, HEC-EFM analyses typically involve hydraulic modeling, which can translate statistical results to water surface profiles and spatial layers of water depth, velocity, and inundation areas. Geographic Information Systems (GIS) can then display these generated layers and other relevant spatial data.

Data requirements of HEC-EFM are related to the level of detail desired by the modeler. If only statistical results are desired, then required data consists only of the flow regimes to be analyzed and the eco-hydro relationships. If the user intends to visualize statistical results spatially, data and software requirements increase significantly and include flow and stage time series, eco-hydro relationships, digital topography, a geo-referenced hydraulic model, and any other spatial data relevant to the ecosystem investigations. This study uses the more detailed method.

Interpretation

The riparian tree species considered in this study are the native *Populus fremontii*, *Salix gooddingii*, and the invasive *Tamarix ramosissima*. For implementation into HEC-EFM, flow regime data for the Bill Williams River and an understanding of the eco-hydro relationships to the tree species in this system must be known or assumed. For flow inputs, daily mean flow data dating from 1939 to 2009 were used from USGS gage station 09426000 located below Alamo Dam. For stage values, flow-stage rating curves were acquired for each cross section from the HEC-RAS model. Each cross section has a unique rating curve based on channel topography. 341 flow regimes were then added in HEC-EFM to represent the 341 cross sections of the Bill Williams River.

The ecological relationship to be addressed is seedling recruitment for each species. Establishment has been tied to high flows that occur and recede during germination periods. If inundated, seedlings are prone to drowning and, conversely, if water levels recede too rapidly, roots desiccate and seedlings are lost. For the three species in this study, three distinct eco-hydro relationships are needed.

Each of the three species has a unique period of seed dispersal, though they may overlap at times. *Salix gooddingii* disperses seeds later than the *Populus fremontii* on the BWR and thus tends to germinate either in response to later floods or to a later period of the flood recession limb. Seed dispersal of the non-native *Tamarix* species begins later than that of *Populus fremontii* on the BWR (Shafroth et al. 1998), though not all rivers in Western North America follow this trend (Cooper et al. 1999), and continues throughout the growing season and into fall months. Thus, *Tamarix ramosissima* is not nearly as dependent as *Populus* or *Salix* on precisely timed floods for establishment. Previous studies have shown that under conditions favorable for native species establishment, there is open substrate with spring flooding and native species will not be competitively excluded at the seedling stage by colonizing *Tamarix* seedlings or vegetative sprouts (Sher et al. 2002, Stromberg 1998).

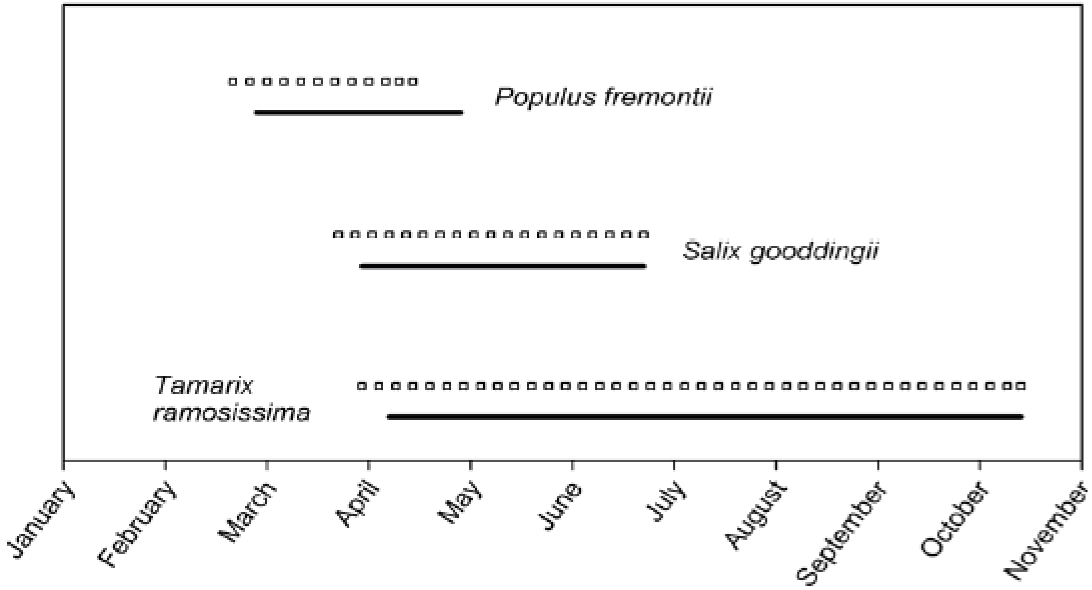

Figure 4. Seed release periods of three woody riparian pioneer species at upstream and downstream areas of the Bill Williams River, Ariz. Dispersal at the downstream site (459 ft above sea level) is represented by a solid line and dispersal at the upstream site (755 ft above sea level) is represented by open squares (modified from Shafroth and Beauchamp 2006).

After germination, seedling survival is a function of the rate of stage recession. Maximum rates of recession for the BWR were found to range from 4 cm per day to 6 cm per day for *Salix* and *Populus* vegetation. *Tamarix* rates were found to be between 2.3 cm to 6 cm per day (Shafroth et al. 1998). It is important to note that not all rivers in Western North America follow this trend (Rood et al. 2005) which demonstrates the importance of local basin data when dealing with riparian vegetation.

To link the rate of stage recession to a hydrograph, a riparian "Recruitment Box Model" that describes the seasonal streamflow pattern, associated river stage (elevation), and flow ramping that will enable successful seedling establishment is often used (Amlin and Rood 2002, Shafroth et al. 1998, Mahoney and Rood 1998).

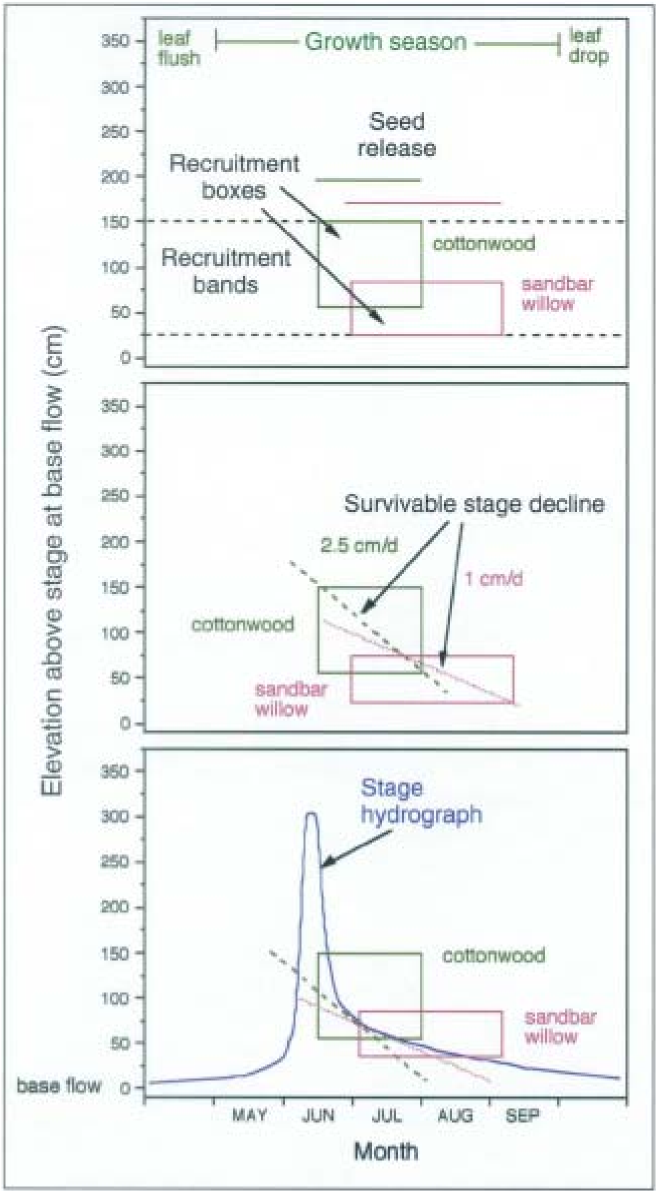

Figure 5. Riparian "Recruitment Box Model" that describes the seasonal streamflow pattern, associated river stage (elevation), and flow ramping that will enable successful seedling establishment of cottonwoods and willows. (Rood et. al. 2005)

In this model, the recruitment band represents the elevation along the riverbank at which seedlings would be low enough to draw from the receding moisture zone, but high enough to avoid subsequent scour. The recruitment box represents the overlap of the recruitment band with the appropriate timing relative to seed release and viability. If the river stage drops through the recruitment box, seedlings should be established at appropriate elevations. The subsequent survival of these seedlings relies on gradual river recession, since the adjacent riparian water table is closely coordinated with the river stage.

Along low elevation rivers in the Southwestern United States, young *Salix gooddingii* trees of this size 5 to 15 cm are typically 4 to 10 years old, while *Tamarix Ramosissima* are slightly older (7 to 20 years old). Thus, every 5 to 10 years, sufficiently large flood flows with a recession limb, the tail-end of which is timed to coincide with *Salix* and *Tamarix* seed dispersal (April through May on the BWR; figure 3), should allow for establishment of new cohorts (Shafroth and Beauchamp 2006). *Populus fremontii* recruitment is naturally episodic, occurring in only about 1 year of every 3 to 10, with medium or high spring flows (Rood et al. 2003).

From the information found in the literature, relationships were formed for the HEC-EFM application. The table below recaps the functional relationship criteria:

Species	Season	Rate of Change	Flow Frequency	Duration
Salix gooddingii	03/22 - 06/20	4 cm/day to 6 cm/day	Every 5-10 yrs	N/A
Populus fremontii	02/19 – 04/13	4 cm/day to 6 cm/day	Every 3-10 yrs	N/A
Tamarix ramosissima	03/29 – 10/09	2.3 cm/day to 6 cm/day	Every 5-10 yrs	N/A

Table 3. Table of the functional relationships to be used in HEC-EFM based off of literature review.

Six functional relationships were produced in HEC-EFM based on table 3. For each tree species, the lower and upper bound for maximum rate of change was used.

Following recruitment, survival is then a function of inundation. 8 and 10 week old *Tamarix* species have been reported to be completely killed if inundated for 4 weeks (Horton et al. 1960). 5 to 7 week old *Tamarix* were reported to have > 99% mortality when submerged during fall for 25 days (Gladwin and Roelle 1998). *Salix gooddingii* has been found to be the most tolerant to inundation of the three species in this study (Vandersande et al. 2001). Hosner (1958) found the black willow, *Salix Nigra*, to be able to survive more than 32 days of inundation. However, cottonwoods are least resistant to flooding of the three species. Eastern Cottonwood, *Populus deltoides*, seedlings die following 16-32 days of complete submergence (Hosner 1958). Galdwin and Roelle (1998) reported a 21% survival of 9 to 10 week old plains cottonwoods partially inundated for 25 days. Using inundation to control growth may be undesirable since submergence of preferred species also occurs (Sprenger et al. 2001, Tallent-Halsell and Walker 2002).

HEC-EFM relationships were then produced for the three tree species for inundation mortality following the 2006 flood event. The season used for the three tree species is 03/30/2006 – 12/31/2006. The functional relationships for each species are as follows:

- *Tamarix Ramosissima* seedlings fail at a sustained high flow of 25 days,
- *Populus fremontii* seedlings fail at a sustained high flow of 20 days,
- and *Salix gooddingii* seedlings fail at a sustained high flow of 32 days.

The recruitment results coupled with the post-flood inundation results will yield corridors of recruitment potential and subsequent growth area expected for each tree species from the 2006 flood event.

Results

With the flow regimes and ecological relationships defined, HEC-EFM was implemented. A range of cross section dependent results was produced for the recruitment relationships. A plot of the recruitment results is shown below for the 2006 experimental release:

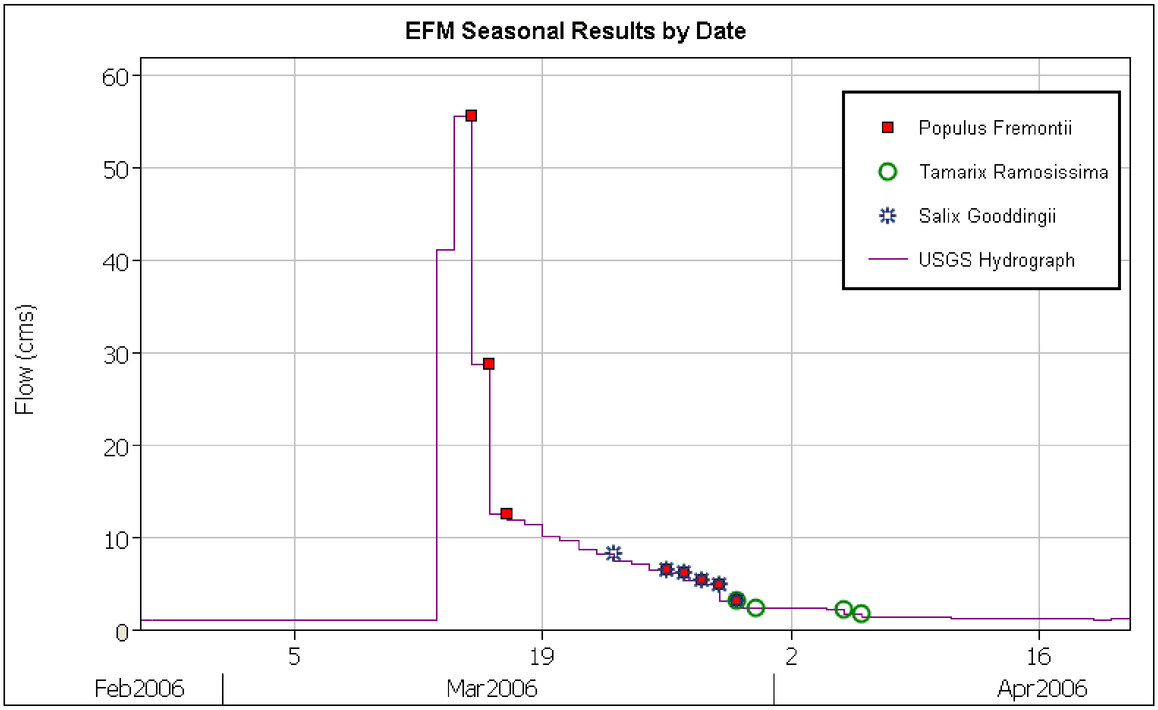

Figure 6. EFM results for 2006, results are based on 4cm and 6cm stage recession rates for *Populus* and *Salix* and 2.3cm and 6cm recession rates for *Tamarix* species.

The HEC-EFM results show more instances of high flows for the *Populus fremontii*. This can be attributed to the timing of the experimental flood release. If the same release had occurred one month later *Populus* would have little to no establishment since the release occurred after the seed dispersal season. Due its later start of season, *Tamarix* results show the lowest range of flows, 1.1 cms to 3.2 cms. Also, since the *Salix* dispersal season begins between the other two species seasons, the results lie in between the other two species on the hydrograph.

To get a spatial representation of the HEC-EFM results, the output for each species was transferred to an excel spreadsheet and plotted at each cross section from upstream to downstream. The spatial results for *Populus fremontii* are shown below.

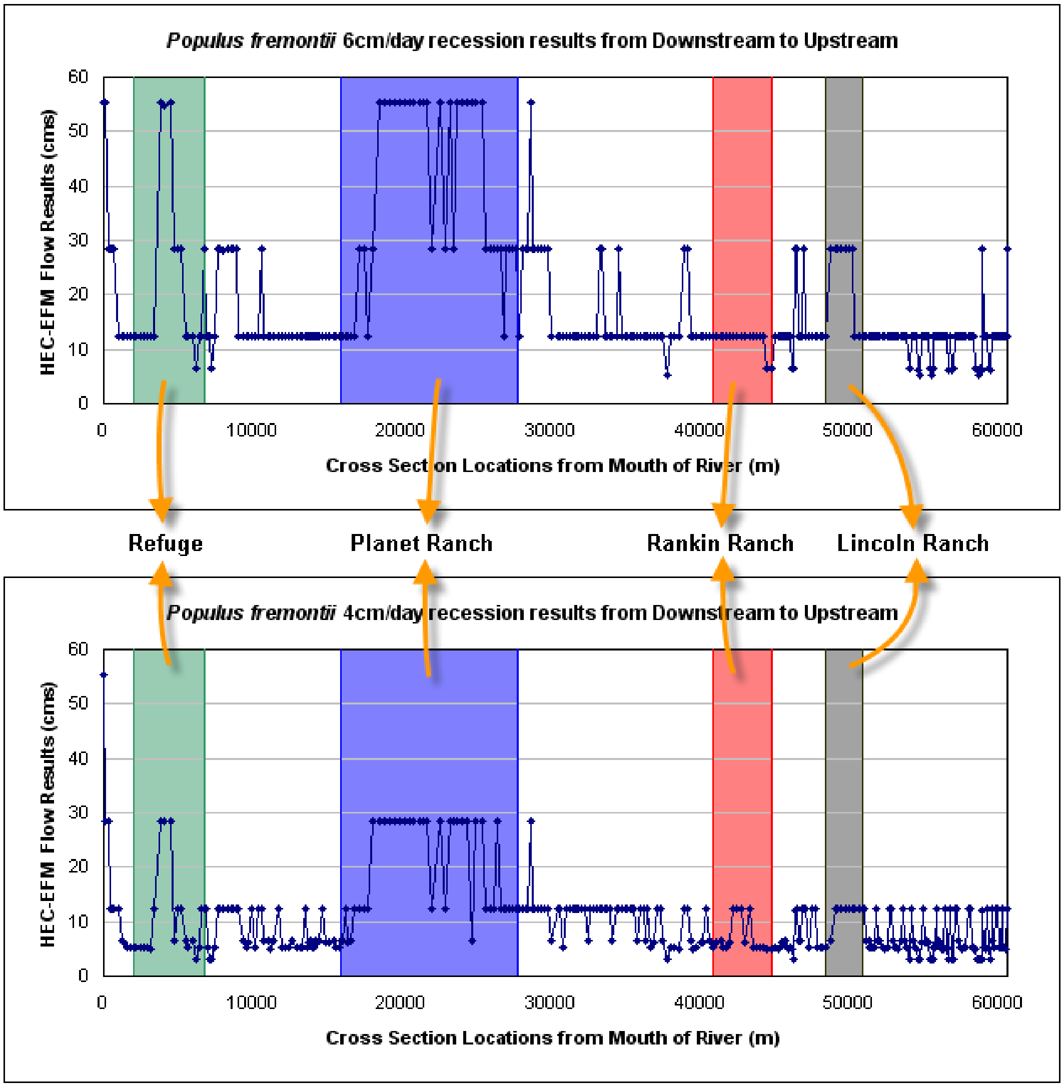

Figure 7. HEC-EFM results for the *Populus fremontii* tree at all cross sections of the Bill Williams River for a 4 and 6 cm/day stage recession from mouth of river to Alamo Dam.

For the *Populus fremontii*, higher HEC-EFM flow results tended to occur at Planet Ranch and the wildlife refuge. This is likely due to the large flat floodplain attributed to these areas. There is also a central tendency of the system to a flow of 12.5 cms. This central tendency generally occurs in the canyonized regions between the ranches and refuge. To more accurately portray the system in the GIS analysis, using the flow results for each cross section instead of a single flow value was done.

Inundation flow results for the three species occurred later in the season from June 27th to July 4th. The HEC-EFM inundation flow results ranged from 1.36 cms for *Salix* to 1.44 cms for the *Populus*. Spatially, the HEC-EFM recruitment flow results would not survive in the inundated flow areas.

GIS Analysis

From the HEC-EFM analysis, flow results were simulated in HEC-RAS to produce water surface profiles. Cross sections with similar flow results, < 0.3 cms difference, were assigned a single flow value to reduce the number of water surface profiles to be simulated. For example, *Populus* at a recession rate of 4 cm/day was reduced from 18 to 6 flow results. A water surface profile was simulated in HEC-RAS for each flow result. The number of water surface profiles varied depending on the functional relationship. 3 meter cell size depth grids were then produced for each flow value using HEC-RAS 4.0.1 Beta. The depth grids were taken from the LIDAR based DTM. The depth grids were then converted to raster files in ArcMap for analysis.

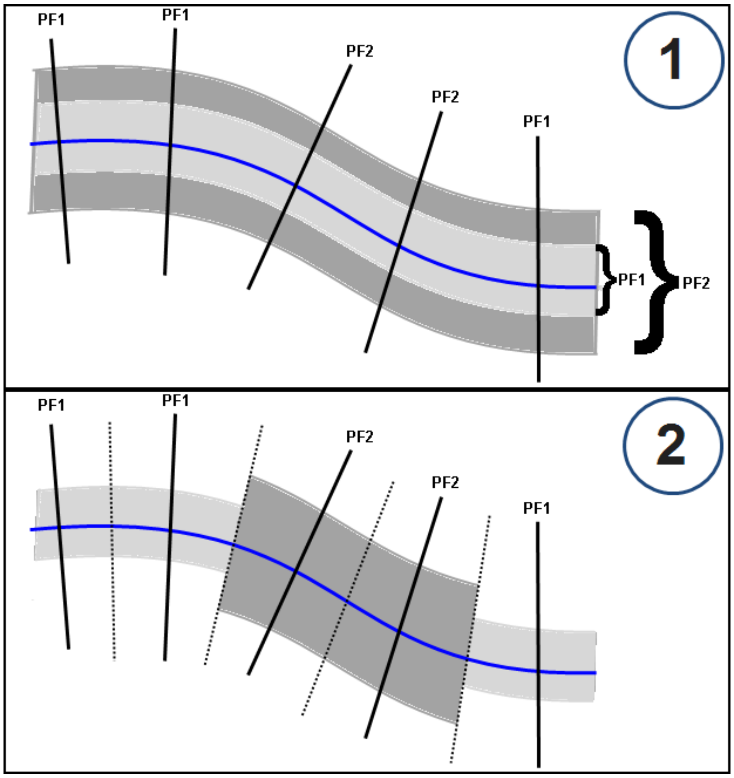

Figure 8. ArcMap depth grid editing process.

To use the flow results for all cross sections, each depth grid was cropped at the mid-point between corresponding cross sections and then spliced back into a final depth grid. Using this method, the resulting depth grids have a better representative coverage area than using a single flow value. This process was done for each of the six HEC-EFM functional relationships. An example of the process is shown in figure 8. In figure 8, PF1 and PF2 represent two depth grids based on different flow values. Each cross section has a flow value dependent on the HEC-EFM results.

Once the depth grid editing process was completed, analysis of the potential recruitment areas for the 2006 flood event could be done. The potential recruitment area is simply the recruitment minus the inundation. Figure 9 shows the potential recruitment area for a small stretch of the BWR just before Rankin Ranch for the *Populus* 6cm/day functional relationship.

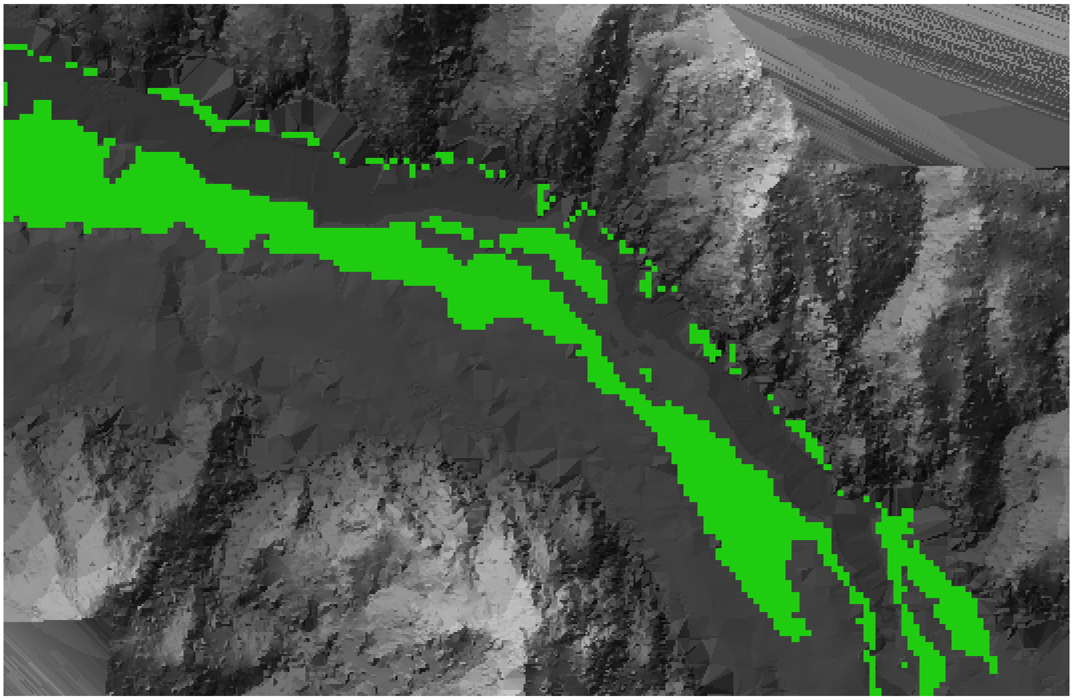

Figure 9. Recruitment area in a small section of the Bill Williams River just before Rankin Ranch for the *Populus fremontii* 6cm/day functional relationship.

Coverage area was calculated by multiplying the total number of grid cells by the area of a single grid cell, 9 m^2. The inundated area was removed from the recruitment area to obtain the total potential establishment area for each functional relationship.

Functional Relationship	Potential Establishment Area (Hectares)
Populus Fremontii 4cm/day	279.62
Populus Fremontii 6cm/day	480.97
Tamarix Ramosissima 2.3cm/day	58.89
Tamarix Ramosissima 6cm/day	59.62
Salix Gooddingii 4cm/day	173.97
Salix Gooddingii 6cm/day	188.30

Table 4. Potential recruitment area for each functional relationship.

Populus fremontii had the greatest potential recruitment area for the 2006 experimental flood release with a range of 279.6 - 481 hectares. *Salix Gooddingii* had the second greatest potential recruitment area with a range of 174 – 188.3 hectares. *Tamarix Ramosissima* had the lowest potential recruitment area with a range of 59 – 59.6 hectares. These results indicate the importance of flood event timing in species specific growth area potential. Field research will be needed to verify these results.

Release Hydrograph Analysis

Larger spring releases from Alamo dam will cover more of the downstream floodplain and therefore support increased seedling establishment. So the effects of flood events larger than the 2006 experimental release should be analyzed. If seedling establishment was the only concern, it would make sense to release the maximum flow of 198 cms during *Populus* and *Salix* seed dispersal seasons and draw down the flow according to the maximum allowable rate of stage recession to a base flow at end of season. This operation would maximize the coverage for establishing seedlings of the *Populus* and *Salix* species and minimize the coverage of *Tamarix*. However, this operation does not consider other uses of the water such as reservoir recreation. If enough water is released to significantly lower Alamo Lake levels, recreationalists would be dissatisfied over the boat ramps and fisherman would be dissatisfied over reduced bass spawning. These purposes encourage maintaining water in reservoir storage when deciding how much water to release for seedling establishment. Weather forecasts are another factor in deciding how much water to release. Precipitation runoff will replenish some released water aiding in the decision of how much water to release.

Using the stage recession rates from Shafroth et al. 1998, the 341 cross section profiles from the HEC-RAS model, and rating curves at those cross sections, a growth area potential plot can be produced for any given release volume. The release volume is calculated by integrating the flood hydrograph, figure 9. It can be assumed that the rising limb of the release hydrograph is going to be as steep as the outlet works at Alamo Dam will allow. According to the Alamo Dam Reservoir operation schedule, Appendix VI, the maximum rate of release increase is from 0.0 cms to 198 cms in nine hours. Historical USGS gage data shows releases from Alamo Dam reaching 198 cms from 5.7 cms in two days. The recession limb of the hydrograph will be the maximum acceptable flow release rate to meet the species stage recession requirements. Since the rising and falling limb of the hydrograph is constant for each cross section, the release volume is simply a function of peak flow, Qp.

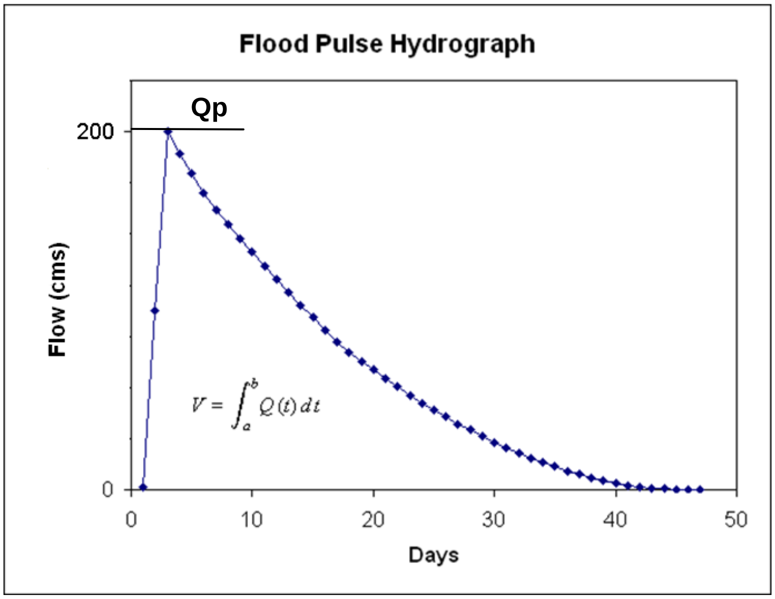

Figure 10. Example flood pulse release hydrograph from Alamo Dam, AZ.

The flow-stage rating curve defines the flow at various stages. This relationship generates a unique flood pulse recession limb for each cross section. The recession limb is created by reducing the stage at max flow, Qp, by the stage recession rate to get the required next day flow. This process is continued until the flow is less than or equal to a base flow. A wetted perimeter is then calculated from each flow value obtained. The representative width of the cross section being analyzed multiplied by the wetted perimeter gives the potential plant establishment area at that cross section. Below is an example of the potential establishment area for a single cross section of the Bill Williams River and its corresponding drawdown curve.

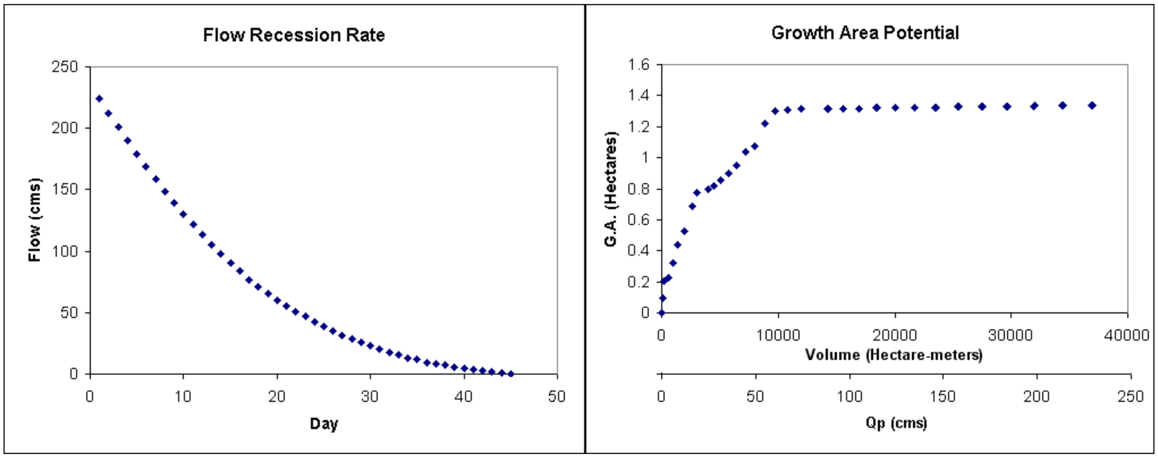

Figure 11. Flow recession limb and seedling establishment area potential curve at a cross section of the Bill Williams River, AZ.

Changes in release volume for the cross section represented in figure 11 have the greatest effect on growth area between a volume of 0.0 – 4,000 hectare-meters and 5,000 – 10,000 hectare-meters. These ranges represent the highest trade-off for growth area at this particular cross section. Small changes in volume released within these ranges have a greater effect on growth area potential than small changes in other volume ranges. For this particular example, releasing a peak flow exceeding 80 cms (10,000 hectare-meters) has little effect on total seedling establishment area.

The potential establishment areas calculated in this section will likely be higher than the potential establishment calculated in the GIS. Unlike an HEC-RAS produced depth grid, which populates grid cells based on connectivity, the potential establishment areas are computed from the cross section profile elevations and water surface elevations which does not distinguish a main channel from a dry side channel. Therefore, all areas of a cross section covered by water will be included in the wetted perimeter and resulting establishment area computations. The methods used here are similar to the HEC-GeoRAS method of producing depth grids. While HEC-RAS depth grids are more hydraulically accurate, they do not include pooled water leftover from recent high flows.

The establishment area potential and flow drawdown data were calculated for all 341 cross sections for a 4 and 6 cm/day maximum stage recession rate. The results of these calculations are shown below.

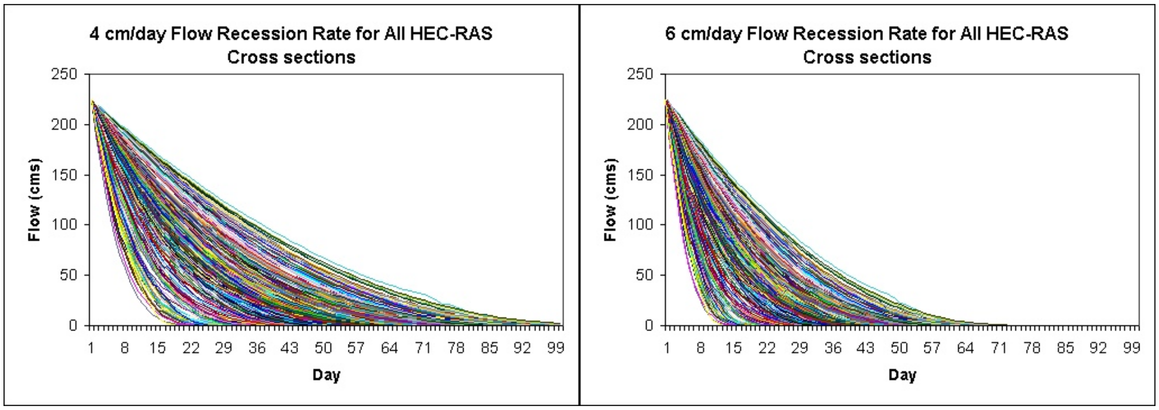

Figure 12. Flood pulse recession limbs for all cross sections on the Bill Williams River, AZ.

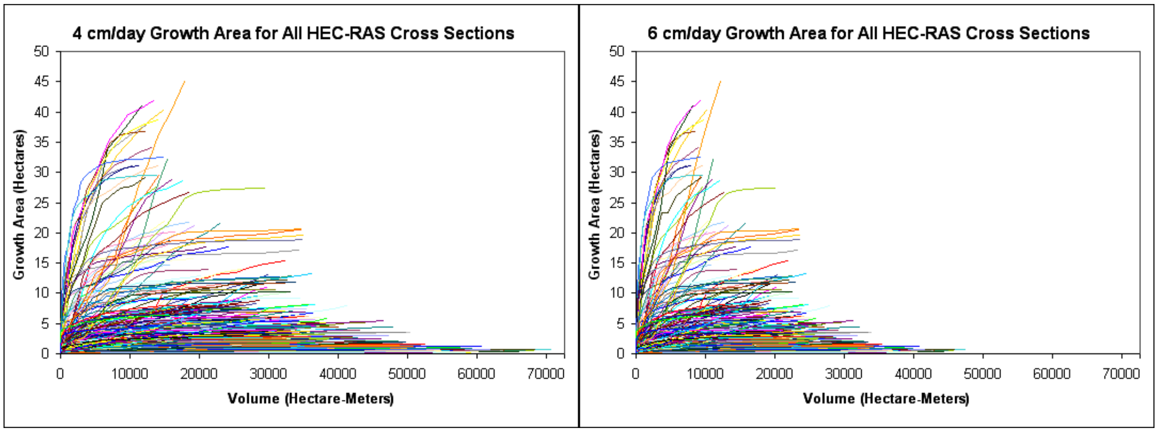

Figure 13. Potential growth area plot for all cross sections on the Bill Williams River, AZ.

Figure 12 presents the range of flow recession limbs for all cross sections. Using the upper bound of the range will ensure that all cross sections and their representative areas have full growth potential. If the recession limb falls below the upper bound of this range then the water will be receding too quickly at some cross sections to allow seedling recruitment. The drawdown curves for the 4 cm/day stage recession extend beyond the 6 cm/day drawdown curves. A recession limb which lasts for 60 plus days will end after *Populus* and *Salix* seedling dispersal periods and during the *Tamarix* seedling dispersal season. Therefore, it may be advantageous to also consider potential growth area when deciding when and how much water to release. Figure 13 is a plot of establishment area for all cross sections. This plot gives an upper bound on growth area potential at all cross sections for various release volumes. It also shows the large variation in potential growth area for all cross sections. To take advantage of the potential growth area plots, the growth areas will need to be summed to produce a single overall establishment area – release volume curve.

Each flood peak has a distinct volume at each cross section due to the unique drawdown curve. Summing the potential recruitment areas at each cross section for an array of peak flows, which are not unique, will yield equal results for a range of stage recession requirements since growth area is a function of peak flow. Therefore, the total potential growth area was calculated for release volumes using a single drawdown curve for the 4 cm/day and 6cm/day stage recession requirements. Using a drawdown curve which lies below the upper bound will yield deceiving results since stage may decline too fast in some river sections. The upper bound drawdown curve was then used to compute total potential growth for a range of release volumes on the Bill Williams River.

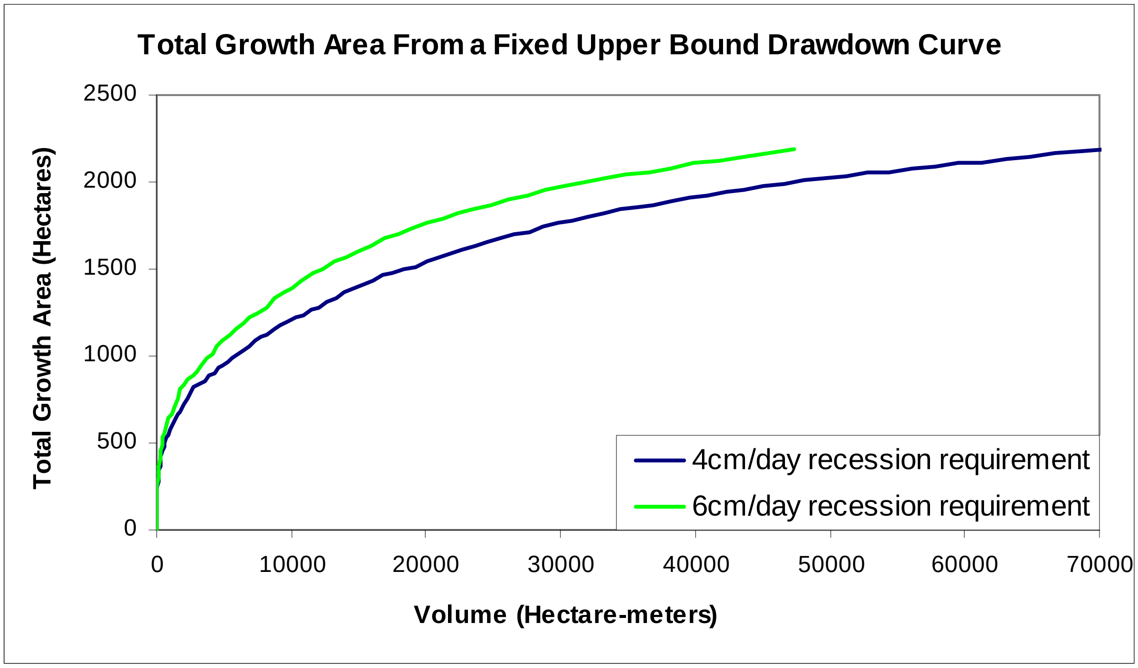

Figure 14. Total Growth Potential Area for the Bill Williams River, AZ.

The total potential growth area curve for specific release volumes gives the operations manager insights to potential growth area sacrifices with changes in release volume. From figure 14, the potential growth for the 6 cm/day recession requirement is larger than the 4 cm/day for all release volumes. Although potential growth area varies with each cross section, system-wide the 6 cm/day recession rate yields higher potential growth area at lower release volumes. If the goal is to reach 1,500 hectares of total potential growth in a season 18,400 hectare-meters of water would be required using a 4 cm/day recession rate, whereas 12,400 hectare-meters would be required with a 6 cm/day recession rate. However, the 4 cm/day recession rate offers seedlings improved establishment opportunity since the roots do not have to grow as quickly to keep up with the receding water. So if there is ample water available in the reservoir for release then the 4 cm/day recession rate should be used. Therefore, if the operations manager has more than 70,000 hectare-meters of release volume available, then the 4 cm/day release curve should be used; otherwise the 6 cm/day release curve should be used.

The upper bound drawdown curve (figure 12) requires the largest release volume. It may be more advantageous to follow a release hydrograph that augments potential growth for select sites along the river, e.g. the National Wildlife Refuge. For this scenario, the mean drawdown curve within select eco-regions may be used. This would reduce the upper bound drawdown curve lowering the required release volume while sustaining seedling flow requirements in key eco-regions.

From such an analysis, flood pulse recommendations can be made. Using the 6 cm/day upper bound drawdown curve (figure 12) and the seedling dispersal periods (figure 3), flood pulse hydrographs can be placed over the seedling dispersal periods to examine effects of reservoir release timing.

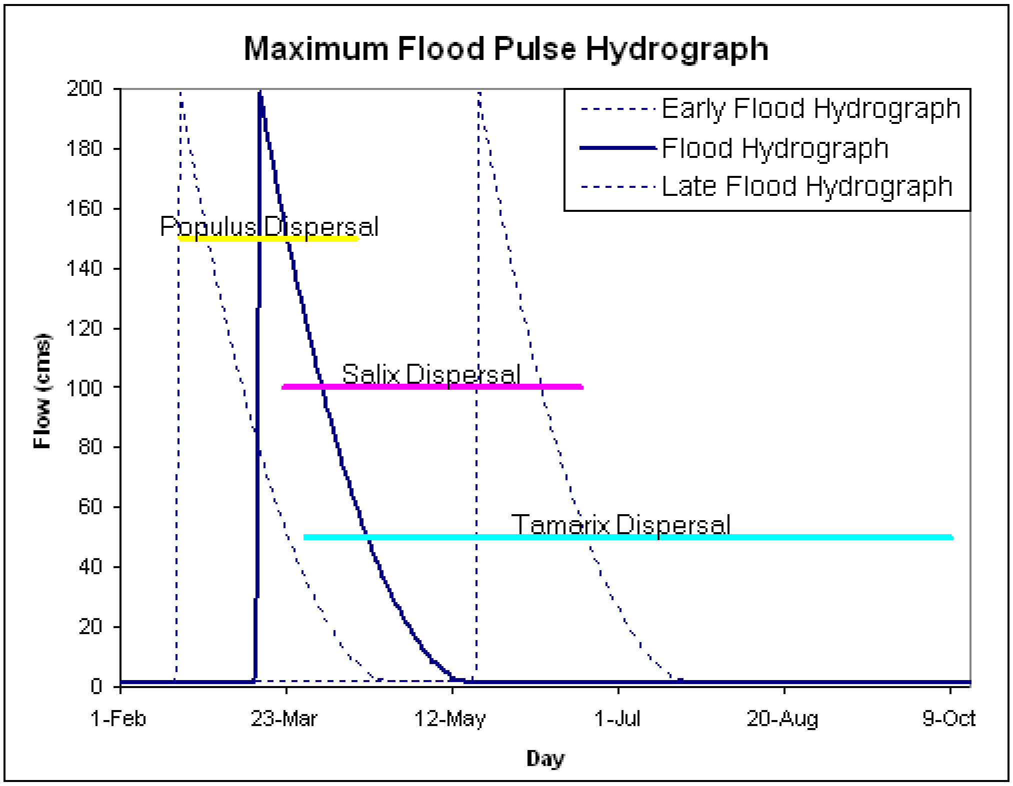

Figure 15. Example flood pulse hydrograph and seedling dispersal periods on the Bill Williams River, AZ

Figure 15 shows theoretical maximum flood pulse hydrographs during the seed dispersal season. If the flood pulse is released too early, *Salix* seedlings start dispersing lower on the recession limb greatly reducing their potential growth area. If the flood pulse is released too late, *Populus* seedlings will have already dispersed will have missed the flood pulse altogether. Therefore, releasing the flood pulse late enough in the *Populus* dispersal period to allow high flows for *Salix* to start dispersing is promising. However, this method still allows for a significant amount of *Tamarix* recruitment potential. Since *Populus* and *Salix* are competitive with *Tamarix* at the seedling stage (Sher et al. 2000, Glenn and Nagler 2005), as long as the flood pulse begins during the *Populus* dispersal season and ends before the *Salix* dispersal season ends, *Tamarix* species recruitment should not dominate the floodplain.

Releasing a 40,000 hectare-meter flood pulse, 198 cms peak flow with a 6 cm/day recession rate, once every 5 to 10 years may not be possible. The reservoir may have inadequate reserves to release such a volume. The reservoir has only exceeded 40,000 hectare-meters of storage in 8 years since its construction in 1968 (figure 16).

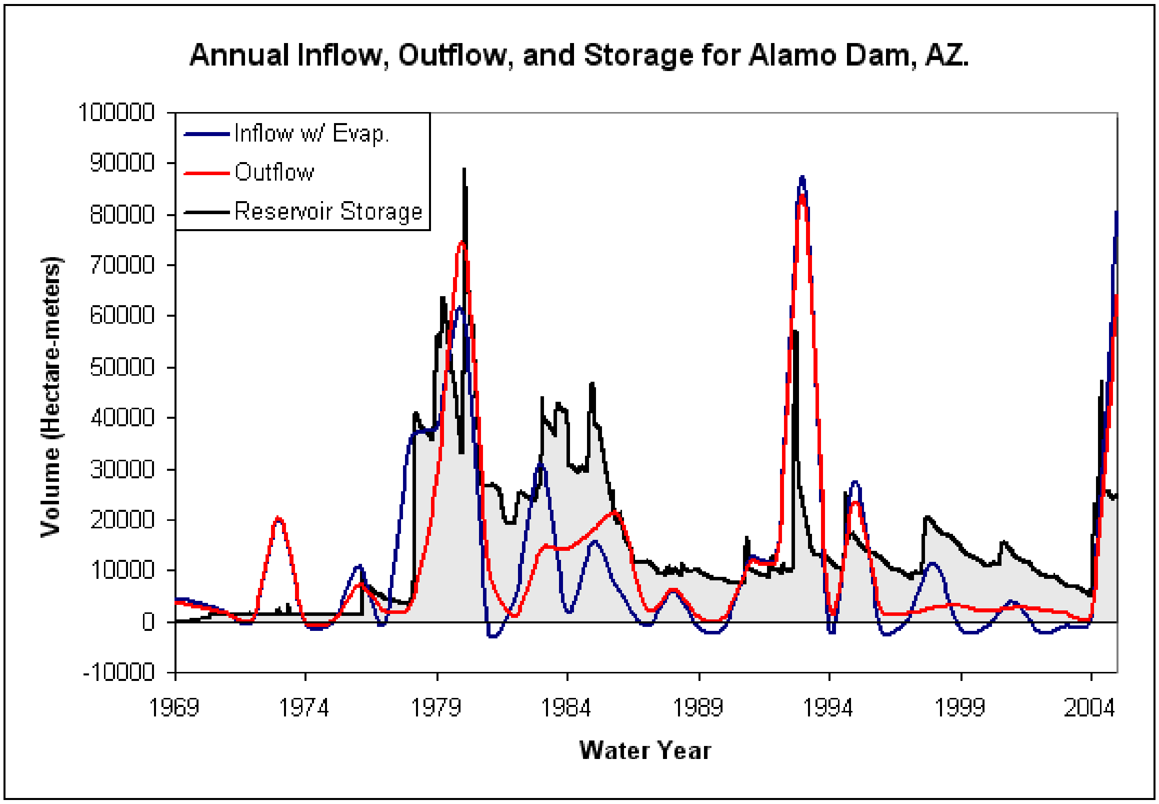

Figure 16. Annual inflow with evaporation, outflow, and storage for Alamo Dam, AZ.

Other storage allocations, such as recreation, also must be met (Appendix VII). Considering the other storage allocation requirements, the maximum allowable flood pulse could be attained every 10-15 years, which is beyond the 5-10 year seedling requirements. Therefore, the maximum volume available for release needs to be known in low storage seasons. With a known volume available for release and the known drawdown curve, a flood pulse hydrograph can be computed. The flood pulse lookup plot for a given release volume is shown below.

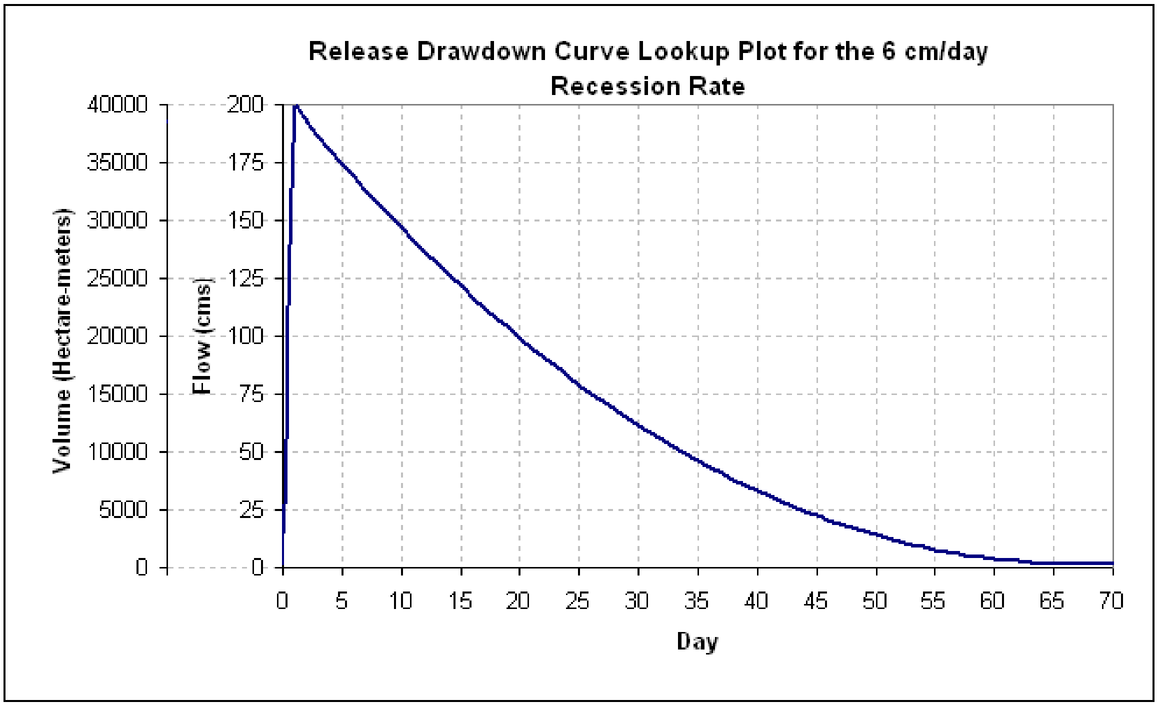

Figure 17. Flood pulse lookup plot for specific release volumes for the Bill Williams River, AZ.

With a lookup plot (figure 17), the reservoir operations manager can follow specific drawdown curves to maximize potential growth area for a given volume of water. For example, if the maximum available volume for release is 15,000 hectare-meters then a peak flow of 75 cms should be released. The drawdown curve then simply starts at the peak flow, figure 18.

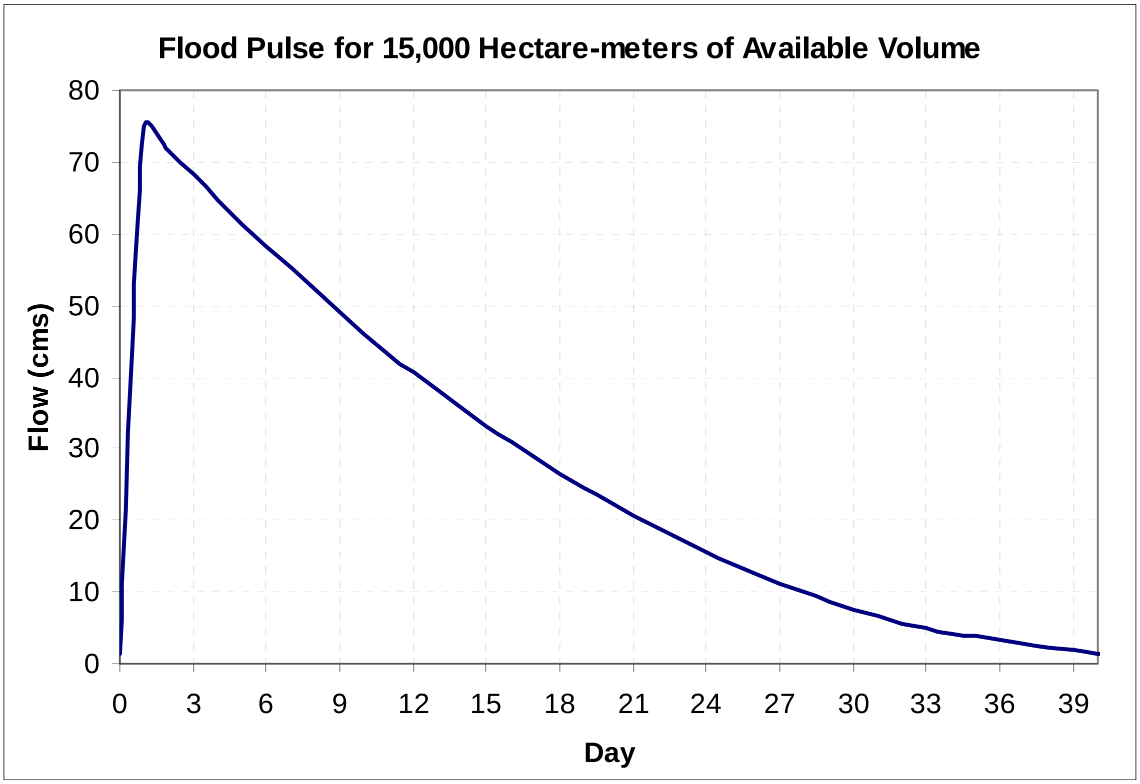

Figure 18. Example flood pulse with 15,000 hectare-meters of reservoir volume available for release from Alamo Dam, AZ.

Study Limitations

Limitations of this study arose in data and hydraulic modeling. Through comparison with field data from Tetra Tech, Inc. in cooperation with the USACE, the LIDAR dataset had inaccurate height values of up to 1.5 m. In many locations this seems to be a systematic difference, but not always. Elevation differences could be caused by channel morphology changes that occurred between LIDAR and field data acquisition. Also, in heavily wooded regions much of the ground cover was lost due to lack of LIDAR penetration. With point spacing of about 1.22 m, it is difficult to catch sufficient bare earth points in heavily wooded areas.

USGS gage 09426000 below Alamo Dam was unsuitable for calibration. Although using a range of flows would have been preferred for calibration, single high flow events were used. This leads to uncertainty in the rating curve at lower flows. Further work should require an unsteady hydraulics model. Steady flow, which was the method used in this paper, does not consider lag and attenuation downstream. Knowledge of the lag and attenuation at each cross section is critical to portray potential seedling establishment area at a given cross section.

In the theoretical analysis of this paper, a representative cross section width was used to compute growth area; this is a weakness. Using a representative width may not accurately reflect the real topography surrounding the cross section. Although producing depth grids is better for calculating growth area potential, it is labor intensive and has other flaws. While the HEC-RAS computed depth grids are more hydraulically correct, they may not represent coverage area for flows on the recession limb. Also, computing the coverage area by cropping depth grids along the midpoint between cross sections may not accurately depict the land surface. For example, if a cross section is placed just before a canyonized region, it would be appropriate to crop the depth grid for that cross section at the point where the canyon begins. This method, although better, is subjective and was not used here.

The results of this study give insights to potential growth area of three tree species based on land surface characteristics and hydrology. Other factors in seedling establishment such as sediment type, predation, and presence of currently established vegetation are not considered. For example, seedlings will not establish in a thick stand of well established *Populus Fremontii* trees due to shade intolerance. Therefore, the results presented must be viewed as a potential establishment and not the realized seedling establishment.

Conclusions

Greater understanding of how reservoir releases will affect the downstream ecosystem is critical to implementing more informed environmental constraints for management optimization. With an understanding of riparian vegetation links to hydrology and the simulation software to model these links, scenarios can be presented which help make more informed management decisions. For the Bill Williams River, this paper presents methods for making more informed decisions on vegetation recruitment using spring releases from Alamo Dam. *Populus* and *Salix* are competitive with *Tamarix* at the seedling stage. For this reason, the timing of Alamo Dam spring flood pulses is important.

This study provides methods for examining riparian vegetation restoration on dammed rivers. Vegetation recruitment flow patterns may be achieved without sacrificing other water commitments, because the restoration efforts for vegetation recruitment are particularly targeted for high-flow years. During these wet years, sufficient water would generally be available for other commitments. Each river basin is unique, the importance of knowledge with any river basin through literature review, local wisdom, or field studies should never be undermined. There is no plug and play model for these systems, each system is unique and its characteristics different. As too little water released can degrade the downstream ecosystem, too much water and timing of release can also have degrading effects.

Further Research and Application

Further research into the Bill Williams River will compare field data taken before and after the 2006 experimental flood. The comparison to field data will hopefully support the simulated results making the theoretical release hydrographs a viable tool for managers of Alamo Dam. The end result of this particular study will be the incorporation of a spring flood release drawdown lookup curve to the Alamo Dam Water Control Manual. Although this study focused on Alamo Dam and the Bill Williams River, these methods could be applied to any system.

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References

Airborne 1 Corporation. 2006a. QAQC Project Review.

Airborne 1 Corporation. 2006b. Approval Doc A06-TETR-002(Arizona).

Amlin, N. M. and S. B. Rood. "Comparative tolerances of riparian willows and cottonwoods to water-table decline" Wetlands Vol. 22, (2002): pp. 338-346.

Arcement, G. J. and V. R. Schneider 1984. "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains": U.S. Department of Transportation Federal Highway Administration Report No. FHWA-TS-84-204, 62 p.

Barnes, H. H. 1967. "Roughness Characteristics of Natural Channels": U.S. Geological Survey Water-Supply Paper-1849, 213 p.

Busch, D. E. and S. D. Smith. "Mechanisms Associated With Decline of Woody Species in Riparian Ecosystems of the Southwestern U.S." Ecological Monographs Vol. 65, No. 3 (Aug., 1995): pp. 347-370.

Cooper, D.J., D.M. Merritt, D.C. Andersen, and , R.A. Chimner. "Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA" Regulated Rivers-Research & Management Vol. 15, (1999): pp. 419–440.

Davenport, D.C., P.E. Martin, and R.M. Hagan. "Evapotranspiration from riparian vegetation: Conserving water by reducing saltcedar transpiration." Journal of Soil and Water Conservation Vol. 37 (1982): pp. 237-239.

Dixon, M. D., M. G. Turner, and C. Jin. "Riparian Tree Seedling Distribution on Wisconsin River Sandbars: Controls at Different Spatial Scales." Ecological Monographs Vol. 72, No. 4 (Nov., 2002): pp. 465-485.

Dudley, T. L. and C. J. Deloach. "Saltcedar (Tamarix spp.), Endangered Species, and Biological Weed Control-Can They Mix?" Weed Technology Vol. 18, Invasive Weed Symposium (2004): pp. 1542-1551.

Everitt, B. L. "Chronology of the Spread of Tamarisk in the Central Rio Grande." Wetlands Vol. 18, (1998): pp. 658-668.

Fasken, G. B. 1963. "Guide for Selecting Roughness Coefficient n Values for Channels": U.S.D.A. Soil Conservation Service, 24 p.

Gladwin, D. N. and J. E. Roelle. "Survival of plains cottonwood (Populus deltoides subsp. monilifera) and saltcedar (Tamarix ramosissima) seedlings in response to flooding" Wetlands Vol. 18, (1998): pp. 669–574.

Glenn, E. P., and P. L. Nagler. "Comparative ecophysiology of Tamarix ramosissima and native trees in western U.S. riparian zones." Journal of Arid Environments Vol. 61, No. 3 (May 2005): pp. 419-446.

Hicks, D. M., and P. D. Mason 1991. "Roughness Characteristics of New Zealand Rivers": New Zealand Dept. of Scientific and Industrial Research, Marine and Freshwater, Water Resources Survey, 329 p.

Hoddenbach, G. "Tamarisk control in southwestern United States." Cooperative National Park Resources Studies Unit, Special Report No. 9 (1987): pp. 116-125.

Horton, J. L., S. C. Hart, and T. E. Kolb. "Physiological condition and water source use of Sonoran Desert riparian trees at the Bill Williams River, Arizona, USA." Isotopes in environmental and health studies, Vol. 39, No. 1 (Mar., 2003): pp.69-82.

Horton, J. S., F. C. Mounts, and J. M. Kraft. "Seed germination and seedling establishment of phreatophyte species." United States Department of Agriculture, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO, USA. 1960. Paper No. 48.

Hosner, J. F. “The effects of complete inundation upon seedlings of six bottomland tree species” Ecology Vol. 39, (1958): pp. 371–373.

Irvine, J. R. and N. E. West. “Riparian Tree Species Distribution and Succession along the Lower Escalante River, Utah.” The Southwestern Naturalist Vol. 24, No. 2 (Jul. 31, 1979): pp. 331-346.

Johns Hopkins University / Applied Physics Laboratory (JHU/APL). 2006. “ILAP Bare Earth Extraction Plug-In Version 1.0 Operator’s Manual.”

Lite, S.J., and J.C. Stromberg. “Surface water and ground-water thresholds for maintaining Populus–Salix forests, San Pedro River, Arizona.” Biological Conservation Vol. 125, No. 2 (Sept., 2005): pp. 153-167.

Magilligan, F. J., and K. H. Nislow. “Changes in hydrologic regime by dams.” Geomorphology Vol. 71, No. 1-2 (1 Oct., 2005): pp. 61-78.

Mahoney, J. M. and S. B. Rood. “Streamflow requirements for cottonwood seedling recruitment - an integrative model” Wetlands Vol. 18, No. 4 (1998): pp. 634-645.

Phillips, J. V., and T. L. Ingersoll 1998. “Verification of Roughness Coefficients for Selected Natural and Constructed Stream Channels in Arizona”: U.S. Geological Survey Professional Paper-1584, 77 p.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. “The Natural Flow Regime.” BioScience Vol. 47, No. 11 (Dec., 1997): pp. 769-784.

Pulokas, A. P. “Analyzing risk in a reservoir system with applications to riparian vegetation and maintenance drawdowns” Thesis. UC Davis, Davis, California 1996.

Richter, B. D., and G. A. Thomas. “Restoring environmental flows by modifying dam operations” Ecology and Society Vol. 12, No. 1 (2007): 12. [online] URL: http://ecologyandsociety.org/vol12/iss1/art12.

Rood, S. B., G. M. Samuelson, J. H. Braatne, C. R. Gourley, J. M. Mahoney, and F. M. R. Hughes. “Managing River Flows to Restore Floodplain Forests.” Frontiers in Ecology and the Environment Vol. 3, No. 4 (May, 2005): pp. 193-201.

Rood, S.B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppettone, S. Swanson, and P. L. Wagner. “Flows for Floodplain Forests: A Successful Riparian Restoration.” BioScience Vol. 53, No. 7 (July, 2003): pp. 647-656.

Rush, E. “Strangers in the wilderness.” Pacific Horticulture Vol. 55 (1994): pp. 20-23.

Shafroth, P. B., G. T. Auble, J. C. Stromberg, and D. T. Pattern. “Establishment of Woody Riparian Vegetation in Relation to Annual Patterns of Streamflow, Bill Williams River, Arizona.” Wetlands Vol. 18, No. 4 (Dec., 1998): pp. 577-590.

Shafroth, P. B. “Downstream effects of dams on riparian vegetation: Bill Williams River, Arizona.” Dissertation. Arizona State University, Tempe, Arizona, USA 1999.

Shafroth, P. B., J. C. Stromberg, and D. T. Patten. “Riparian Vegetation Response to Altered Disturbance and Stress Regimes.” Ecological Applications Vol. 12, No. 1 (Feb., 2002): pp. 107-123.

Shafroth, P.B., and V.B. Beauchamp 2006, “Defining ecosystem flow requirements for the Bill Williams River, Arizona”: U.S. Geological Survey Open File Report 2006-

1314, 135 p. Also available online at: http://www.fort.usgs.gov/products/publications/21745/21745.pdf

Sher, A. A., D. L. Marshall, and S. A. Gilbert. “Competition between native *Populus deltoides* and invasive *Tamarix ramosissima* and the implications of reestablishing flooding disturbance.” Conservation Biology Vol. 14, (2000): pp.1744- 1754.

Sher, A. A., D. L. Marshall, and J. P. Taylor. “Establishment Patterns of Native Populus and Salix in the Presence of Invasive Nonnative Tamarix.” Ecological Applications Vol. 12, No. 3 (Jun., 2002): pp. 760-772.

Smith, S. D., D. A. Devitt, A. Sala, J. R. Cleverly, and D. E. Busch. “Water relations of riparian plants from warm desert regions.” Wetlands Vol. 18, (1998): pp. 687-696.

Sprenger, M. D., L. M. Smith, and J. P. Taylor. “Testing control of Saltcedar seedlings using fall flooding” Wetlands Vol. 21, No. 3 (2001): pp. 437-441.

Stanley, E. H. and M. W. Doyle. “Trading off: The Ecological Effects of Dam Removal.” Frontiers in Ecology and the Environment Vol. 1, No. 1 (Feb., 2003): pp. 15-22.

Stevens, L. E., T. J. Ayers, J. B. Bennett, K. Christensen, M. J. C. Kearsley, V. J. Meretsky, A. M. Phillips III, R. A. Parnell, J. Spence, M. K. Sogge, A. E. Springer, and D. L. Wegner. “Planned Flooding and Colorado River Riparian Trade-Offs Downstream from Glen Canyon Dam, Arizona.” Ecological Applications Vol. 11, No. 3 (Jun., 2001): pp. 701-710.

Stromberg, J. C., and D. T. Patten. “Mortality and age of black cottonwood stands along diverted and undiverted streams in the eastern Sierra Nevada, California.” Madroño Vol. 39, (1992): pp. 205-223.

Stromberg, J. C. “Dynamics of Fremont cottonwood (Populus fremontii) and saltcedar (Tamarix chinensis) populations along the San Pedro River, Arizona.” Journal of Arid Environments Vol. 40, (1998): pp. 133-155.

Tallent-Halsell, N. G., and L. R. Walker. “Responses of Salix Goodinggii and Tamarix Ramosissima to flooding” Wetlands Vol. 22, No. 4 (2002): pp. 776-785.

U.S. Army Corps of Engineers, HEC. 1998. “Technical Considerations for Alamo Lake Operation”: PR-37, IWR-HEC, 94 p. Also Available online at: http://www.hec.usace.army.mil/publications/ProjectReports/PR-37.pdf

U.S. Army Corps of Engineers, HEC. 2008. “HEC-EFM Ecosystem Functions Model”: CPD-80a, IWR-HEC, 42 p. Also Available online at: http://www.hec.usace.army.mil/software/hec-efm/documentation/HEC-EFM_Quick_Start_Guide.pdf

U.S. Army Corps of Engineers, HEC. 2008. “HEC-RAS River Analysis System”: CPD-68, IWR-HEC, 747 p. Also Available online at: http://www.hec.usace.army.mil/software/hec-ras/documents/HEC-RAS_4.0_Users_Manual.pdf

U.S. Army Corps of Engineers, HEC. 2005. “HEC-GeoRAS River GIS Tools for support of HEC-RAS using ArcGIS”: CPD-83, IWR-HEC, 204 p. Also Available online at: http://www.hec.usace.army.mil/software/hec-ras/documents/HEC-GeoRAS4_UsersManual.pdf

U.S. Army Corps of Engineers, Los Angeles District. 2003. “Alamo Dam Water Control Manual,” Los Angeles, California.

U.S. Army Corps of Engineers, Los Angeles District. 2006. “DRAFT Bill Williams River HEC-RAS Hydraulic Model,” Los Angeles, California.

U.S. Army Corps of Engineers, Los Angeles District. 2006. “Field Data Collection Report Bill Williams River February 2005 to June 2006,” Los Angeles, California.

Vandersande, M. W., E. P. Glenn, and J. L. Walworth. “Tolerance of five riparian plants from the lower Colorado River to salinity drought and inundation” Journal of Arid Environments Vol. 49, (2001): pp. 147-159.

Webb, R. H., and S. A. Leake. “Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States.” Journal of Hydrology Vol. 320, No. 3-4 (15 April 2006): pp. 302-323.