DRAFT

RIPARIAN PROTECTION PROGRAM

LEGISLATIVE REPORT

VOLUME A

Arizona Department of Water Resources

15 S. 15th Avenue

Phoenix, Arizona 85007

February 1, 1994

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LEGISLATIVE REPORT

A report to the Governor, President of the Senate and Speaker of the House

Arizona Department of Water Resources

Rita Pearson
Director

Herb Dishlip
Deputy Director

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ARIZONA DEPARTMENT OF WATER RESOURCES
15 South 15th Avenue, Phoenix, Arizona 85007
Telephone (602) 542-1553
Fax (602) 542-3383

February 2, 1994

FIFE SYMINGTON
Governor

RITA P. PEARSON
Director

Honorable Fife Symington
Governor of Arizona

Honorable Speaker Mark Killian
Arizona House of Representatives

Honorable President John Greene
Arizona State Senate

Members of the Riparian Area Advisory Committee

On behalf of the Arizona Department of Water Resources (ADWR), I am pleased to submit to you the draft Riparian Protection Program Legislative Report. In 1992 the Arizona State Legislature passed Senate Bill 1030 requiring ADWR to: 1) study the effects of groundwater pumping and surface water diversions on riparian areas; and, 2) evaluate alternative regulatory programs that would enhance riparian protection.

This report addresses the studies required by S.B. 1030 and includes three actual case studies of riparian areas. Potential alternative regulatory programs were developed that look to balance the protection of riparian areas with existing and future groundwater pumping and new surface water diversions.

ADWR will be distributing this report to interested parties and members of the general public and will be seeking public input on the report's findings. After reviewing public comments, ADWR will publish a final report.

We believe that the findings contained in this report represent an important first step toward the protection of valuable riparian areas throughout the state. Arizona's existing riparian areas are of critical importance to the state and must be considered in future water management decisions.

Sincerely,

Rita P. Pearson

Rita P. Pearson
Director

RPP/gsw

Enclosure

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ARIZONA DEPARTMENT OF WATER RESOURCES

Main Contributing ADWR Hydrologists

Greg Bushner - Project Coordinator, Summary of Findings Report, Upper San Pedro Case Study
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CHAPTER 1
SUMMARY OF FINDINGS

CHAPTER I

SUMMARY OF FINDINGS

DRAFT

TABLE OF CONTENTS

INTRODUCTION AND BACKGROUND 1-1
RIPARIAN PROTECTION LEGISLATION 1-1
REPORT FORMAT 1-3

FINDINGS 1-5
HYDROLOGIC REPORT 1-5
ECOLOGIC REPORT 1-8
Groundwater 1-8
Surface Water 1-10
Flood Flows 1-12
Water Quality 1-12
REGULATORY STRATEGIES REPORT 1-13

RIPARIAN VEGETATION AND HYDROLOGIC INTERACTIONS . . 1-17
RIPARIAN VEGETATION/GROUNDWATER RELATIONSHIPS 1-17
RIPARIAN VEGETATION/SURFACE WATER RELATIONSHIPS 1-19
HYDROGEOLOGIC ANALYSIS OVERVIEW 1-20
Surface Water 1-21
Groundwater 1-23
Stream-Aquifer Systems 1-25
HYDROLOGIC EFFECT OF GROUNDWATER WITHDRAWALS 1-27
HYDROLOGIC EFFECT OF SURFACE WATER DIVERSIONS 1-33

ALTERNATIVE REGULATORY PROGRAMS DISCUSSION 1-37
TYPES OF PROTECTION PROGRAMS 1-38
Statutory non-permit system 1-38
Statutory-Permit System 1-39
Local Area Management 1-40
CURRENT EXAMPLES OF REGULATORY SYSTEMS 1-41
Statutory Non-permit System - Well Drilling Permit Example 1-41
Statutory Permit System - Surface Water Appropriations/Groundwater Withdrawal Permits 1-42
Local Area Management - Flood Control Districts/Active Management Areas 1-44
ECONOMIC IMPACTS OF A RIPARIAN AREA PROTECTION PROGRAM . 1-46
PLANNING AREA ECONOMIC AND WATER RIGHT TRADEOFFS 1-50

LIST OF FIGURES

Figure 1. Schematic of riparian floodplain 1-18
Figure 2. Diagram showing perennial, intermittent and ephemeral stream types 1-22
Figure 3. Diagram of regional alluvial aquifer system 1-24
Figure 4. Diagram of a cone of depression in an aquifer 1-29
Figure 5. Diagram showing direct and indirect well interference 1-30
Figure 6. Species change with increasing depth to groundwater in a sonoran riparian ecosystem. 1-32
Figure 7. Groundwater basins of Arizona by county and planning region . . 1-47
Figure 8. 1990 Arizona employment and water use 1-51
Figure 9. Statewide perennial stream reaches and landownership 1-55

INTRODUCTION AND BACKGROUND

On July 10, 1992, the Governor of Arizona signed into law an act providing for the collection of scientific and economic data to study the protection of riparian vegetation communities throughout the State. The act calls for a study of specific impacts to riparian communities, bringing to the forefront the increasing importance and awareness of these communities within the State of Arizona. As we seek to protect riparian vegetation communities from increased demands on both surface water and groundwater supplies, many inter-related issues must be addressed. These issues range from the development of new water supplies for growing communities and the impact this growth will have on the nearby riparian areas, to the need for inter-related surface water/groundwater laws that recognize that groundwater withdrawals from regional aquifers will eventually impact a perennial or intermittent stream. Projected future groundwater demands must be analyzed considering current impacts to hydrologic systems as riparian areas are inextricably tied to these systems. In order to effectively address these and other concerns it is necessary to collect valid scientific data on which to base credible and effective management programs whether regulatory or non-regulatory.

RIPARIAN PROTECTION LEGISLATION

The purpose of the riparian protection law is to provide the legislature with sufficient data that will allow it to make an informed decision regarding riparian area protection. This effort involved three State agencies including the Arizona Department of Water Resources (ADWR), Arizona Game and Fish Department (AGFD) and the Arizona Department of Environmental Quality (ADEQ). AGFD was tasked with identifying, mapping, and classifying riparian areas throughout the state. AGFD gave priority to areas associated with perennial waters. ADEQ was tasked with identifying activities, operations, and uses that occur in riparian areas located on federal, state, and private lands, that involve removing or depositing material, removing vegetation, or otherwise obstructing, altering or destroying riparian areas.

As outlined in the legislation, the three objectives of ADWR's studies were to evaluate:

1. The hydrologic effect of groundwater pumping on riparian areas.
2. The effect of new surface water appropriations and changes in the use or point of diversion of existing appropriations on riparian areas.
3. Alternative regulatory programs designed to balance the protection of riparian areas with:
   - existing and future groundwater pumping;
   - new surface water appropriations;
   - changes in the use or point of diversion of existing surface water appropriations.

The hydrologic studies focus on the first two objectives that directly require hydrologic and ecologic analyses. This in turn supports and provides the direction for the last objective, providing the foundation for a regulatory program. Additionally, to evaluate alternative regulatory programs, the law also required the Department to consider:

- The economic impacts on various classes of landowners, including federal, state, private, and Indian Tribes.
- The impacts on existing water rights, pending water right adjudications and negotiated water settlements.
- The availability of alternative water supplies for existing and future users.
- The environmental costs and benefits of the program.
- The costs to ADWR in implementing such a program.

The fourth component to this effort includes the formation of the Riparian Area Advisory Committee (RAAC). This committee is tasked with evaluating the results of the agencies' reports and making recommendations to the legislature with respect to the scope and parameters of potential regulatory and/or non-regulatory programs and additional statutory provisions.

REPORT FORMAT

The Riparian Area Protection Program Report consists of five chapters and is produced in three separate volumes. Volume (A) contains Chapters I through III including the Summary of Findings, Hydrologic and Ecologic Reports, and pertinent appendices. Volume (B) contains Chapter IV, the Case Studies Report, pertinent appendices and plates, and volume (C) contains Chapter V, the Regulatory Strategies Report. This chapter of the report, which serves as the executive summary, provides the summary and findings for the entire report. To adequately evaluate the effects that well pumping and surface water diversions have on riparian areas, it was necessary to provide a basic hydrologic and ecologic understanding of the physical processes that occur in riparian ecosystems. This information is presented in the Hydrologic and Ecologic Reports (Chapters II and III, respectively). Methods of analysis presented in these chapters were applied in the Case Studies Report (Chapter IV) to evaluate three site-specific riparian areas within the State. These areas are the Upper San Pedro River, the Upper Santa Cruz River, and the Verde Valley. Finally, Chapter V, the Regulatory Strategies Report, presents an overview of current Arizona state water law, an overview of protection strategies used by other States, potential strategies that could be used to protect riparian areas in Arizona, and a statewide economic analysis to determine potential impacts to these areas resulting from the implementation of different riparian protection strategies.

FINDINGS

The major conclusions and findings for the entire report, with the exception of the Case Studies Report (Chapter IV), are set forth below. The major findings for the Case Studies Report can be found in that chapter.

HYDROLOGIC REPORT

The following statements can be made based on the Hydrologic Report (Chapter II).

1. Groundwater and surface water were historically considered as separate and distinct resources in Arizona. Water laws were created to manage the water resources based on this concept. However, in reality, groundwater and surface water form an interconnected hydrologic system in which quantities of water are exchanged between a stream and an aquifer based on changing hydrologic conditions. It is critical to have an accurate representation or conceptualization of the interconnected surface water and groundwater system in order to quantify any impacts.

2. The effects of natural climatic variability on components of the hydrologic cycle are unevenly distributed through time, and therefore the magnitude of streamflow expressed in a particular stream reach and the volume of groundwater in storage within an aquifer naturally fluctuate through time. This natural climatic variability was not assessed in detail in this report, but it is important to keep in mind the impacts that could occur during drought cycles or periods of low runoff or streamflow.

3. The concept of an "interrupted-perennial" stream reach is important because: (1) this type of flow has been included as appropriable surface water by the Department in the adjudication process, and (2) even though a stream may not have been "mapped" as perennial flow by AGFD, subflow may still sustain a riparian ecosystem (e.g., the San Pedro River).

4. It is often difficult to determine streamflow characteristics for streams throughout the state other than at USGS streamgage locations. In addition, not all streams are gaged by the USGS. This in turn makes it difficult to accurately determine impacts to streamflow between gage locations. Furthermore, many gage records are fragmentary and discontinuous and the data do not reflect the entire range of streamflow conditions as they presently exist (e.g., many gages throughout the

state are used to measure flood flows and are not set up to monitor more prevalent low flow conditions).

5. Long-term groundwater withdrawals have created regional groundwater declines areas such as the Salt River Valley, Pinal County, and Santa Cruz Valley. In these areas, continuous groundwater pumping for agricultural, municipal, and industrial purposes has severely lowered water tables in the surrounding aquifers. Groundwater levels have been lowered to the point where they are no longer connected to surface water flows.

6. Undisturbed stream-aquifer systems achieve an equilibrium where long-term inflows equal long-term outflows. In this type of balanced system, streamflow reductions only occur during extended drought periods where below normal precipitation results in a corresponding reduction in runoff and aquifer recharge. In a developed watershed, direct streamflow diversions and groundwater pumping can have an appreciable affect on the hydrologic system depending on the timing and magnitude of depletions and the location of these diversions. Often, depletions occur in or near riparian areas, where surface water is available and groundwater is close to the land surface.

7. Extensive groundwater pumping results in depletion of streamflow by inducing infiltration of surface water through the streambed or interception of groundwater that would have discharged to the stream. If the volume of water pumped exceeds the amount of natural recharge to the groundwater system, a deficit will occur causing a reduction in groundwater storage and declining water levels. A continuous trend of declining water levels indicates overdevelopment of groundwater resources. The degree of this groundwater mining depends on the magnitude, duration, and distribution of withdrawals, as well as the hydraulic properties of the aquifer. Where multiple wells are clustered in close proximity to one another, the effect of pumping on the aquifer is compounded, as are impacts to any nearby stream.

8. A statewide network of observation wells (index wells) is monitored annually to assess changes in hydrologic conditions through time. There are approximately 1,160 index wells throughout the state. However, most of these wells are not ideally located to monitor groundwater levels in or near riparian areas. In addition, out of the total number of wells in the state, a very small percentage of them are monitored on a regular basis. Of the few that are, an inadequate number of monitor wells occur in the riparian areas being assessed, and many of the wells that are present in riparian zones may not be effective monitoring tools for the particular area, depending on well construction and purpose. Most of the wells throughout the state penetrate more than one aquifers. Water levels from

these wells reflect a regional, rather than a specific aquifer system. Usually, aquifer-specific data is not available, and when available, is spatially non-contiguous.

9. Direct well interference occurs when a cone of depression expands from the pumped well into the stream alluvium of a river creating a groundwater gradient away from the stream. Streamflow losses increase as additional surface water infiltrates into the permeable alluvium to fill the area dewatered by the well. Indirect interference occurs when groundwater flowing toward the stream is intercepted by a cone of depression. Indirect interference has the affect of reducing the amount of groundwater that would have eventually discharged to the stream, thereby reducing baseflow. In both instances the well is depleting streamflow, either by inducing additional infiltration of streamflow or by intercepting groundwater that would have discharged to the stream. In some areas, the impacts resulting from a pumping well adjacent to a stream are compounded by regional groundwater declines resulting from the combined affects of many pumping wells.

10. The effects of groundwater withdrawals on a stream do not occur the instant a well begins pumping and do not stop immediately after pumping ceases. A stream's response to pumping can lag considerably after pumping has ceased. Even if pumping is continuous, it can take decades for water levels to decline to the point where indirect interference becomes direct, perhaps changing perennial streamflow to intermittent or ephemeral. Once withdrawals have been discontinued, water will continue to fill the cone of depression created by the pumping, thereby continuing to deplete streamflow by either reducing the volume of water discharged to the stream or inducing streamflow infiltration.

11. There are several methods that can be used to assess the effects of groundwater withdrawals on an aquifer and an adjacent stream. Most methods depend on mathematical equations to describe the interaction between an aquifer and a pumping well. These methods require data regarding the storage and water yielding properties of an aquifer and the pumping parameters of a well. All of the methods have a common foundation in the fundamental theories of hydrology that describe groundwater flow through porous geologic material (e.g., silt, sand and gravels that comprise alluvial aquifers). Differences between the various methods are due to simplification of the limiting assumptions that may not always exist in nature. Selection of the appropriate method depends largely on the type of information being sought, the availability of accurate hydrologic data with sufficient coverage, and the level of detail required. Currently, these methods can be used to effectively evaluate hydrologic impacts and changes to riparian areas.

ECOLOGIC REPORT

The following conclusions and findings are drawn from the Ecologic Report (Chapter III).

Groundwater

1. In a regional aquifer, groundwater sustains riparian vegetation indirectly. However, in floodplain aquifers, groundwater directly sustains riparian vegetation. It is well established that the health, vigor, composition, structure and abundance of riparian vegetation varies with depth to water in the floodplain aquifer. The response of the riparian vegetation to groundwater declines can be quantified. A continuous and direct relationship exists between riparian vegetation health and depth to groundwater. Therefore, as groundwater levels decline, riparian vegetation becomes stressed, resulting in the sequential loss of shallow-rooted plants followed by deep-rooted plants, reduction in tree density and canopy development, and the eventual loss of the riparian area. Such degradation and loss has been documented along many of Arizona's rivers.

2. Although vegetation characteristics changes along a continuum, there are certain thresholds of change that can be recognized. General depth to water criteria were determined by this study for many plant associations of Sonoran riparian ecosystems and warm-temperate riparian zones found in southern Arizona. Some of the depth to water criteria that have been determined are as follows:

   - Cienegas/marshlands: water tables should remain at about 0.5 (½) ft above or below the floodplain surface.
   - Goodding willow and Freemont cottonwood: for established or well developed floodplain forests groundwater tables should at a minimum be no deeper than 10 feet.
   - Mesquite bosques: to maintain high structural development groundwater tables should be no deeper than 25 feet.

   There is need for additional study of vegetation-groundwater relationships, particularly for plant associations located in higher elevation riparian zones.

3. To maintain riparian plant associations over the long-term, conditions must be met for survivorship of adult plants and regeneration of new plants. A different set of water table requirements must be met to allow a new generation of riparian plants to establish. For example, to allow for establishment or continued regeneration of Fremont cottonwood and Goodding willow, portions of the floodplain must be seasonally saturated and water tables maintained within 2 to 3 ft below the water surface for several months at least once every several years. The establishment requirements for many other riparian plant species need to be determined.

4. Some riparian plant/groundwater relationships have been extensively studied. Results of these studies indicate that relationships are transferrable between like streams. For example, groundwater conditions associated with the establishment of Fremont cottonwood are very similar between rivers located in approximately the same elevation and climatic zones. Additional study is needed to determine whether this and other such relationships are "robust" in the sense that they are transferrable between streams located in different climatic zones (e.g., southern versus northern Arizona) or that differ in the floodplain's ability to hold and transmit water.

5. Although information gaps exist, adequate information is available on many vegetation groundwater relationships to determine when groundwater level changes become ecologically significant. Groundwater vegetation data can be used in conjunction with groundwater models and/or groundwater monitoring programs to identify vegetation-limiting groundwater conditions.

   Additional or predicted declines in water tables below thresholds for each riparian vegetation type or indicator species can serve as a "red-flag" that signals the need to modify pumping or diversion activities. This approach is similar to that currently being undertaken in Owens River Valley, California. Information on water requirements of vegetation, including data on rooting depths of riparian plants, can be used as a basis for modifying pumpage when unacceptable depths to groundwater are reached. This type of riparian protection approach necessitates the development of riparian monitoring programs.

6. It is recommended that riparian monitoring programs be established in Arizona to prevent groundwater decline from degrading riparian ecosystems. These programs should include groundwater and ecological monitoring components.

   For the groundwater component:

   Groundwater depths should be monitored at pumped sites and at control sites using continuous recording groundwater level instruments. Monitoring wells should be established within the floodplain alluvium that supports riparian ecosystems, as well as in regional aquifers that recharge that alluvium. Additionally, numerical groundwater models should be developed for streams of concern to enable prediction of long-term trends that may affect alluvial aquifers.

   For the ecological component:

   Vegetation parameters, including new recruitment and vegetation changes from baseline conditions, should be measured over time. Although ecologically stressful groundwater levels can be determined in advance for

some species, as described in no. 5 above, riparian ecosystems also should be monitored directly for changes in their ecological condition. Direct monitoring of riparian vegetation is particularly valuable for those associations and species for which relatively little is known about their groundwater relationships.

7. There is a need for systematic study of riparian zone water table conditions, including existing and impending threats. A monitoring program such as described in no. 6 above would help to identify "at-risk" aquatic and riparian habitats located throughout the state.

8. In addition to continued study of vegetation groundwater relationships, development of riparian monitoring programs and surveys for "at-risk" habitats should be established. This could be accomplished by establishing a series of "reference" watersheds that are managed for their natural values. Such watersheds should include a variety of riparian plant communities. Riparian zones in such watersheds provide an index of the species composition, plant abundance, and community structure that are expected for each type of riparian community under "natural" or unmodified hydrologic conditions.

Surface Water

9. Surface water reductions, like groundwater declines, cause loss and degradation of riparian plant communities. Although surface water declines have caused much riparian loss in Arizona, quantification of the instream flow needs of riparian vegetation has received comparatively little study in contrast to other types of instream flow studies (e.g., instream flow requirements for fish). Nonetheless, it is clear that abundant riparian vegetation changes along a continuum with changes in surface water flow volumes. In other words, the amount of riparian vegetation increases as surface flows increase, except in sites where other factors constrain riparian development. Conversely, riparian abundance declines continuously as the amount of diversion increases. Species composition also changes along a continuum depending on surface flow rates.

10. To minimize riparian loss and degradation, new diversions should be minimized, particularly during drought years and during the growing season. Seasonal and annual flow patterns should closely track historical hydrograph information (e.g., seasonal high flows should remain in spring and late summer, or otherwise follow the natural seasonal flow pattern, and the magnitude of flood flows relative to the low flow rate should not be altered). It also should be remembered that often the combination of surface flows and groundwater together sustain large, healthy riparian vegetation zones, and thus surface waters should be allowed to remain hydraulically connected to groundwater.

11. Riparian vegetation instream flow models such as those described in this report (see Verde River Case Study) can be used in conjunction with hydrologic models to predict some of the effects of flow diversion or groundwater pumping on Sonoran and warm-temperate riparian forests, including changes in overall riparian abundance (e.g., canopy foliage area) or abundance of particular species (e.g., Fremont cottonwood). The vegetation/surface flow models developed for this study can be used as a planning tool to predict riparian vegetation declines or identify flow requirements for riparian vegetation. The instream flow models are to some degree transferable between watersheds that do not greatly differ in elevation, climate, and stream and valley morphology. However, greatest accuracy would be obtained when using watershed-specific models.

    Instream flow models should be developed for cold-temperate riparian forest-types. When using such models to predict changes, it is important to be aware that surface water volume in Arizona highly variable due to climatic variation.

12. Other types of models could also be developed to predict the response of individual species to changes in flow in specific rivers. Instream flow models that relate tree growth to flow volume (using tree-ring studies) have been used to identify minimum annual flows needed to prevent cottonwood tree death and have documented flows necessary to maintain healthy cottonwood communities. Also, demographic studies of seedling establishment should be undertaken to refine our knowledge of flow requirements for riparian regeneration. Instream flow studies also should be undertaken on effluent-dominated streams to further knowledge of relationships between volume and timing of effluent flow release, and riparian stand size and composition.

13. It is also recommended that riparian monitoring programs be initiated on rivers of concern. Monitoring should include a physical and biological component. Discharge in many streams is monitored by USGS streamgages, although there is a need to expand and upgrade this streamgage network. In addition, other groups monitor instream flows through the use of streamgages, such as The Nature Conservancy along the Hassayampa River and other river preserves, and the BLM along the San Pedro River. Many high elevation streams, however, are not gaged, nor is there much quantification at any elevation of streamflow losses resulting from diversions. There is a need to obtain and analyze such flow data in terms of riparian vegetation requirements and to focus on flow reduction trends that impact these communities. Riparian vegetation health and status should also be directly monitored on streamflow potentially or actually affected by diversions or from groundwater pumping.

Flood Flows

14. Floods are a natural process in riparian zones. Native riparian plant communities are altered by changes in flood magnitude, frequency, and timing associated with river damming and diversion. For example, because diverted streams have less plant cover, flood velocities are often higher and more destructive. Watershed and floodplain management activities that reduce the natural resistance and resilience of riparian zones to flood events ultimately increase flood damage and reduced riparian ecosystem recovery ability.

15. For maximum ecological benefit, Arizona rivers could be managed so that their flow patterns closely resemble natural hydrographs. For example, diversion dams are a major factor modifying flood flows. Flow regimes of above-dam control sites are frequently monitored and could be used as templates for potential below-dam flow regimes. The results of the programs could be used to modify the pattern or rate of peak flows or baseflows released from a dam. If ecological stress is apparent, flow releases may need to be modified to benefit the downstream ecosystem. Determination of the release pattern will require site-specific study or review. Hydrologic studies can indicate which floodplains are inundated by flood flows of various magnitude and the rate water tables recede in response to flood flow reduction. Appropriate riparian management can be accomplished using hydrologic studies combined with biologic information on factors such as timing of tree seed dispersal, germination, and seedling requirement for various rates of water table recession.

16. The response of the vegetation in reference watersheds (see comment no. 8) can be used as an indication of the biological potential of riparian vegetation to resist and recover after floods. Riparian abundance and survivorship should be monitored at sites where floodplains or watersheds are impacted by varying types of land uses that may modify flood flow intensities or by diversions that reduce vegetation cover. If flood mortality is unnaturally high in comparison to the control or reference watershed, land and water uses in the impacted watershed and riparian zone should be investigated to determine possible factors causing riparian degradation.

Water Quality

17. Although water quantity is the primary determinant of riparian abundance and composition in semi-arid region riparian zones, water quality also plays an important role in influencing species composition. In many cases, water quality changes as water quantity changes. For example, soil salinity in riparian zones soil salinity often increases as a result of flow reduction or river damming. For some water quality parameters, sufficient information is available to identify ecological threshold levels (e.g., salinity levels) that are related to riparian

compositional changes and that warrant corrective measures (e.g., release of flushing flows from dams). Additional research is needed to determine the relationship of other water quality parameters (e.g., nutrients and heavy metals) to riparian vegetation and wildlife.

18. Water quality, particularly salinity, alkalinity, nutrient levels, and heavy metals, should be monitored in surface water, groundwater, and riparian zone soils in areas suspected of undergoing water quality changes, such as dammed rivers, effluent-dominated rivers, rivers receiving irrigation return flow or CAP water, or rivers undergoing other types of interbasin water transfers. Water quality is presently measured in several rivers (e.g., Colorado River, per the Colorado River Compact; rivers designated as "Unique Waters" pursuant to the Clean Water Act; and rivers monitored as part of the USGS stream monitoring program), however, this program could be expanded.

REGULATORY STRATEGIES REPORT

The following conclusions and summary statements were obtained from the Regulatory Strategies Report (Chapter V).

1. Current law in Arizona does not allow for administrative enforcement of surface water diversions. Surface water right disputes are adjudicated and administered by court decree.

2. Groundwater withdrawals are not regulated outside of Active Management Areas and indirect impacts of groundwater withdrawals on senior surface water right holders are allowed. Current law does not recognize direct, long-term impacts of groundwater depletions on streamflow.

3. Any landowner may apply for instream flow water rights to establish minimum flows for stream reaches appurtenant to their land if the water is put to beneficial use such as recreation or wildlife, including fish.

4. **Approximately 80% of perennial stream reaches are located adjacent to or on land managed by the federal government or owned by Indian Tribes.** The U.S. Forest Service (USFS) and the U.S. Bureau of Land Management (BLM) manage their lands through a 10 year planning process. In addition, their management actions are regulated by federal laws, such as the Endangered Species and National Environmental Protection Acts. Both agencies are actively seeking instream flow and other water rights to protect sensitive wildlife habitat areas and streams possessing wild and scenic values. State laws can assist

these agencies with their protection plans, but the federal government can also provide some riparian area protection through their own legislative authorities. Currently, both these agencies have withdrawn selected land from mining, timber harvesting, and/or grazing use. In addition, they can restrict a use or require mitigation for unavoidable resource impacts resulting from a permitted use. Many of these actions could affect current or planned land uses including mining, grazing, logging as well as permits for roads and utility distribution corridors.

5. Other states have enacted laws to protect minimum streamflows, wild and scenic values, and riparian restoration. The most comprehensive of these programs provide for strong state leadership coupled with local management. Oregon, Florida and Oklahoma have programs which provide protection and restoration of riparian areas. These programs include land use regulations, building structures (e.g., constructing fences, developing water resoureces away from riparian areas), and comprehensive planning to protect riparian areas.

6. **Riparian area protection regulations that depend solely on water rights legislation will not restore lost or degraded riparian areas or protect instream flow rights from senior appropriators exercising their water rights.**

7. Many potential changes to Arizona state water rights law could be used to protect riparian areas. Two of these are (1) to require well permit applicants to provide proof that proposed withdrawals would not affect groundwater levels in aquifers supporting riparian vegetation located on public or private land, unless written permission is obtained from the landowner(s) acknowledging potential impacts and permitting their occurrence; and (2) to set by statute and/or rule allowable decline rates and volumetric reductions for groundwater levels. These statutory changes would have the added benefit of protecting other surface water rights.

8. Several changes could also be made to surface water law. For example, the statutory definition for "beneficial use" could be expanded to include appropriation for maintenance or restoration of riparian vegetation. Instream flow water right applicants would be required to determine the amount of streamflow needed to support riparian vegetation located along a claimed stream reach and provide streamflow data that shows required flows would be available.

   Currently, sever and transfer of an existing consumptive use water right to fish, wildlife, and/or recreational use is limited to landowning state agencies or political subdivisions of the state. This law could be changed to include any water right holder which would allow individuals and other agencies to convert an existing diversionary right to an instream flow right and thereby allowing conversion of an older priority date.

9. Water rights management could be accomplished through a state management authority. The management structure of the authority could be similar to that established for groundwater Active Management Areas. The authority would be responsible for developing a water management plan with supporting rules and regulations designed to protect riparian resources from long-term groundwater depletion and new diversions, including changes in places-of-use and points-of-diversion. In addition, the authority could have regulatory enforcement capabilities.

   Another management strategy that would allow more local control and funding could be modeled after the states's county flood control districts. These districts are able to raise revenues through taxation, enter intergovernmental agreements with federal agencies, develop plans, own land, and obtain water rights.

10. Potential impacts resulting from statutory changes designed to protect riparian areas cannot be forecast without site specific studies. Further studies should address long-term water supplies and demand, including the development of alternative water supply strategies and water conservation plans.

11. Riparian protection laws may necessitate conversion of existing agricultural water rights to municipal and industrial uses to help support future growth and development. These conversions will probably result in a reduction in agricultural employment opportunities. However, the reduction would probably be nominal from a statewide perspective, with some job losses offset by job opportunities resulting from municipal and industrial development.

12. **Riparian protection legislation may preclude the development of new surface water diversions upstream of protected riparian areas. However, the probability of constructing new diversions, in most planning areas of the state is limited. This is because many remaining perennial or intermittent stream reaches are either located in remote headwater areas, or streamflow within these reaches are claimed by senior water right holders with diversions located downstream. In addition, some of these streamflows are controlled by existing court decrees.**

13. The projected growth of many cities and towns should not affect existing riparian areas with proper planning and management. However, growth of many other areas, including those in the Verde Valley and along Oak Creek, may continue to threaten existing riparian habitat unless water management strategies that require retirement and conversion of some agricultural water rights to residential and industrial uses and recycling of water back to the river are developed and implemented.

Riparian vegetation located along the San Pedro River may sustain some long-term impacts resulting from water withdrawals associated with growth and development in the Sierra Vista/Fort Huachuca area. Existing and future groundwater withdrawals may require management if riparian areas are to be protected from long-term groundwater depletion. Groundwater use can be minimized through effluent use, and development of other alternative water supplies.

Even if water withdrawals are prohibited to protect a critical stream reach, alternative water supplies may be available to meet all water demands, but at a potentially higher cost. A significant impact, resulting from riparian protection, would be predicted for an area if all of the following conditions were to occur: (1) alternative water supplies were not available; (2) the volume of water withdrawn supported many users; and, (3) the prohibition occurred immediately.

14. Efforts to maintain riparian areas could enhance rural lifestyles in many areas of the state with potential increased tourism and recreational activities providing additional employment opportunities. As metropolitan areas in Arizona continue to expand, these opportunities would increase as progressively more people look to rural locations for recreation.

15. Current Arizona state law does not allow interbasin transportation of groundwater to offset groundwater withdrawals in areas which may negatively impact riparian areas.

RIPARIAN VEGETATION AND HYDROLOGIC INTERACTIONS

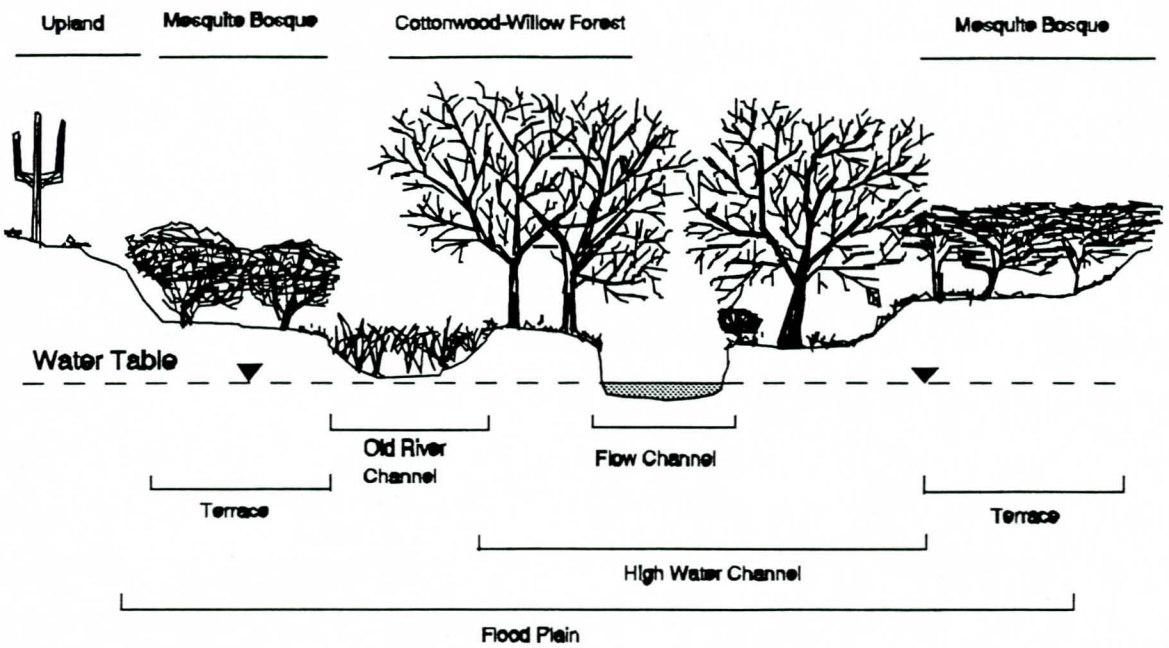
Riparian systems are dynamic by nature. Stream channels are continually aggrading (e.g. building up) and degrading (e.g. down-cutting), while riparian vegetation establishes episodically in response to flood flows and associated processes. Surface water and hydraulically connected groundwater all contribute to the type of riparian community present, influencing its density, vigor, composition, and ability to continue to regenerate and maintain itself at a given site. Surface water and groundwater are necessary together or individually, to initiate, maintain, and complete various plant lifecycle stages and functions. In return, riparian vegetation plays an important role in stream and alluvial aquifer system maintenance and development.

RIPARIAN VEGETATION/GROUNDWATER RELATIONSHIPS

In southwestern deserts, where evaporation exceeds precipitation, groundwater is a critical source of water for maintenance of many riparian zones. Groundwater available for riparian vegetation occurs in alluvial aquifers which directly support riparian ecosystems. These areas are generally located adjacent to streams where water level elevations are essentially flat in the area of the riparian zone. The depth to water increases as the land surface elevation increases with distance away from a stream channel. Depth to groundwater plays an important part in the distribution of most riparian vegetation, therefore the greater the depth to water below the land surface, the less abundant the riparian vegetation.

Many types of riparian vegetation depend directly on water in floodplain aquifers and indirectly on groundwater in regional basin fill aquifers as a source of floodplain aquifer recharge (Figure 1). On many desert rivers, wide floodplain aquifers allow for extensive development of riparian vegetation. Sonoran riparian forests of Fremont cottonwood and Goodding willow, for example, grow hundreds of feet from the active channel in riparian

Figure 1. Schematic of riparian floodplain



zones where groundwater is only several feet below the floodplain surface. On many mountain streams, warm and cold-temperate mixed broadleaf forests form narrower riparian zones supported by a narrow floodplain aquifer. Within these riparian ecosystems, riparian plant species are distributed along gradients of depth to groundwater, because each species (and each life stage) has a unique rooting depth, unique tolerance for drought and soil saturation, and unique ability to absorb water from different parts of the riparian zone. Goodding willow and Fremont cottonwood, for example, are shallow-rooted trees that absorb water mainly from the saturated groundwater zone, and give way to deeper rooted mesquite as depth to groundwater increases. Just as the depth to groundwater is important to riparian vegetation, so too is the rate and extent of capillary water rise (or soil moisture) in the soil zone lying above

the water table. Riparian sacaton grasslands, for example, grow in fine-textured floodplain soils which allow for extensive movement of capillary water into the root zone from the water table. Some vegetation types, found in cienegas (or marsh areas of very shallow groundwater), grow only where groundwater intersects the ground surface, and are very sensitive to water table fluctuation.

RIPARIAN VEGETATION/SURFACE WATER RELATIONSHIPS

Nearly every riparian vegetation type in Arizona is dependent on surface water. Surface flow laterally recharges riparian soils, moistens floodplain soil surfaces during overbank flood flows, and transports new sediments and seeds. Where surface water and groundwater are hydraulically connected in riparian ecosystems, surface water recharges alluvial aquifers and raises water levels.

The water supply in a surface water system is controlled by precipitation and regulated through interactions between geology, soils and vegetation. Precipitation on impermeable soil and bedrock will enter a channel system rapidly. Conversely, precipitation on permeable, well-vegetated soil will enter the groundwater system and may not reach a main channel for many seasons. One way floodplain vegetation and a stream channel interact is through temporary water storage in the streambanks affected by normal and high flows. Both deep rooted woody and fibrous rooted herbaceous plant species aid to stabilize soils, increase organic matter content, and trap silt and clay which improves the water holding capacity of streambank soils. The available water storage capacity in some streambanks can be significant enough to reduce flood peaks. The resulting sustained flow and reduction in peak flood events aid to support healthy riparian ecosystems.

Watersheds that lack sufficient vegetative cover and have been subject to sheet and gully erosion can develop rapid, concentrated surface runoff which increases peak flows, promotes down cutting and produces large amounts of sediment. While channels

transport increasingly more floodwater without significant overbank flooding, the elevated terrace adjacent to the eroded channel becomes increasingly more arid. In addition, as channels are downcut into alluvial aquifer systems, these systems release water into the channel until the water level in both the channel and the aquifer achieve stability. The result is an increased depth to groundwater and a channel that must widen prior to reassuming the aggradation process.

HYDROGEOLOGIC ANALYSIS OVERVIEW

To evaluate the response of riparian vegetation to groundwater withdrawals and surface water diversions, an understanding of the stream-aquifer system and related riparian ecosystem is necessary. For the purpose of this discussion the stream-aquifer system is generally composed of one or more aquifers in direct hydraulic connection with a perennial stream, and a riparian community dependent on the water resources.

Certain species of riparian vegetation survive only where perennial streamflow and shallow water levels provide a permanent source of water within reach of the plant's roots. A stream-aquifer system that supports this type of riparian vegetation is hydraulically connected, meaning water withdrawn from the aquifer directly impacts the stream, and the water level elevation in the aquifer is equal to the water surface elevation of the stream. The water table is essentially flat in the proximity of the stream, but water levels may be higher or lower than the stream with increasing distance laterally away from the stream.

Other, more drought tolerant types of riparian vegetation, occur along intermittent or ephemeral streams where streamflow is seasonal or flows only in direct response to storms. There is no groundwater-surface water connection for much of the time in this type of stream-aquifer system.

Surface Water

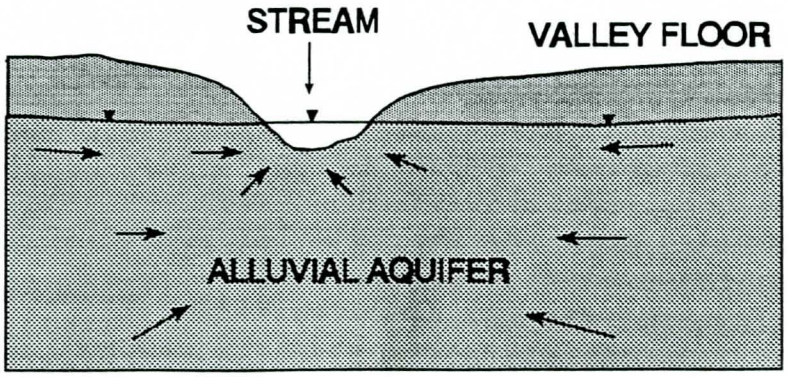
Surface water or streamflow is the occurrence of water in a natural channel. Water that comprises streamflow is ultimately derived from precipitation falling on the earth's surface, however this water may reach a stream channel through different routes. Streamflow is comprised of three main components including surface runoff, interflow, and base flow. Surface runoff is precipitation that flows over the land surface and accumulates in stream channels. Surface runoff from precipitation varies widely throughout Arizona depending primarily on elevation and geographic location. Interflow is precipitation that infiltrates and moves laterally through the unsaturated zone above the water table (vadose zone) until draining into a stream channel. Streamflow includes baseflow where the groundwater table intersects a stream channel and discharges groundwater to a stream. Stream reaches receiving baseflow are referred to as "gaining reaches" as shown in Figure 2.

Baseflow can maintain streamflow during periods when there is negligible runoff, therefore, this component is critical for maintaining certain types of riparian areas. The proportion of direct runoff to baseflow varies between basins, with time, and from one location to another on a stream.

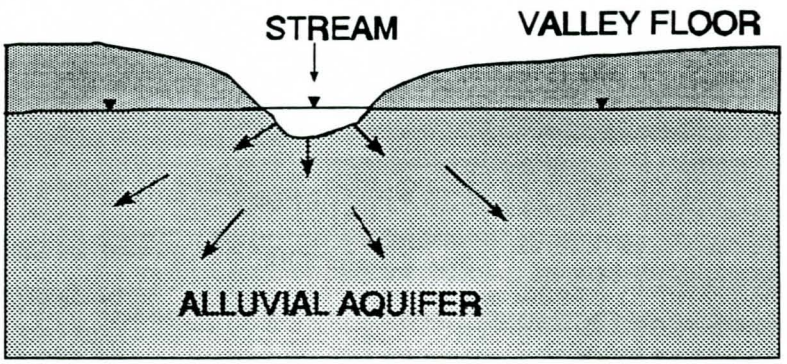
Rivers and streams are classified as perennial, intermittent, or ephemeral depending on the duration of surface flow throughout the year (Figure 2). Perennial streams flow continuously throughout the year. Intermittent streams flow for long periods and are typically seasonal in nature, flowing continuously during most of the year when water is contributed from baseflow or surface runoff. Ephemeral streams flow only in immediate response to precipitation events and do not derive any of their flow from groundwater discharge. Many of Arizona's low-flow perennial streams exhibit "interrupted-perennial" reaches where streamflow at the surface is lost, but flow continues through the stream alluvium as subflow. These reaches are referred to as "losing reaches" (Figure 2).

Figure 2. **Diagram showing perennial, intermittent and ephemeral stream types**

Perennial Streams

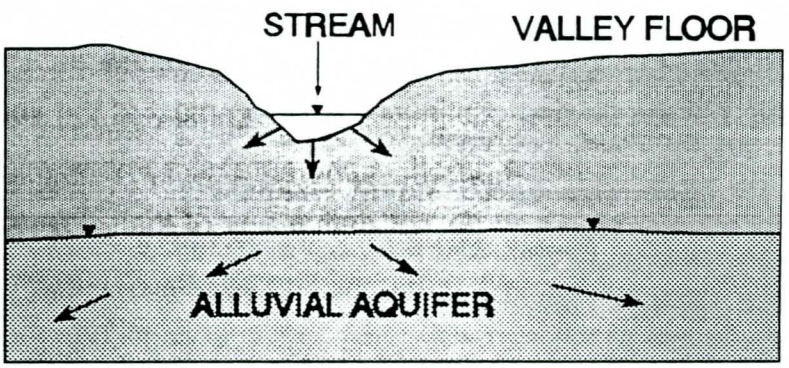


Gaining Reach



Losing Reach

Intermittent or Ephemeral Stream



Losing Reach

▼ WATER TABLE ← DIRECTION OF FLOW

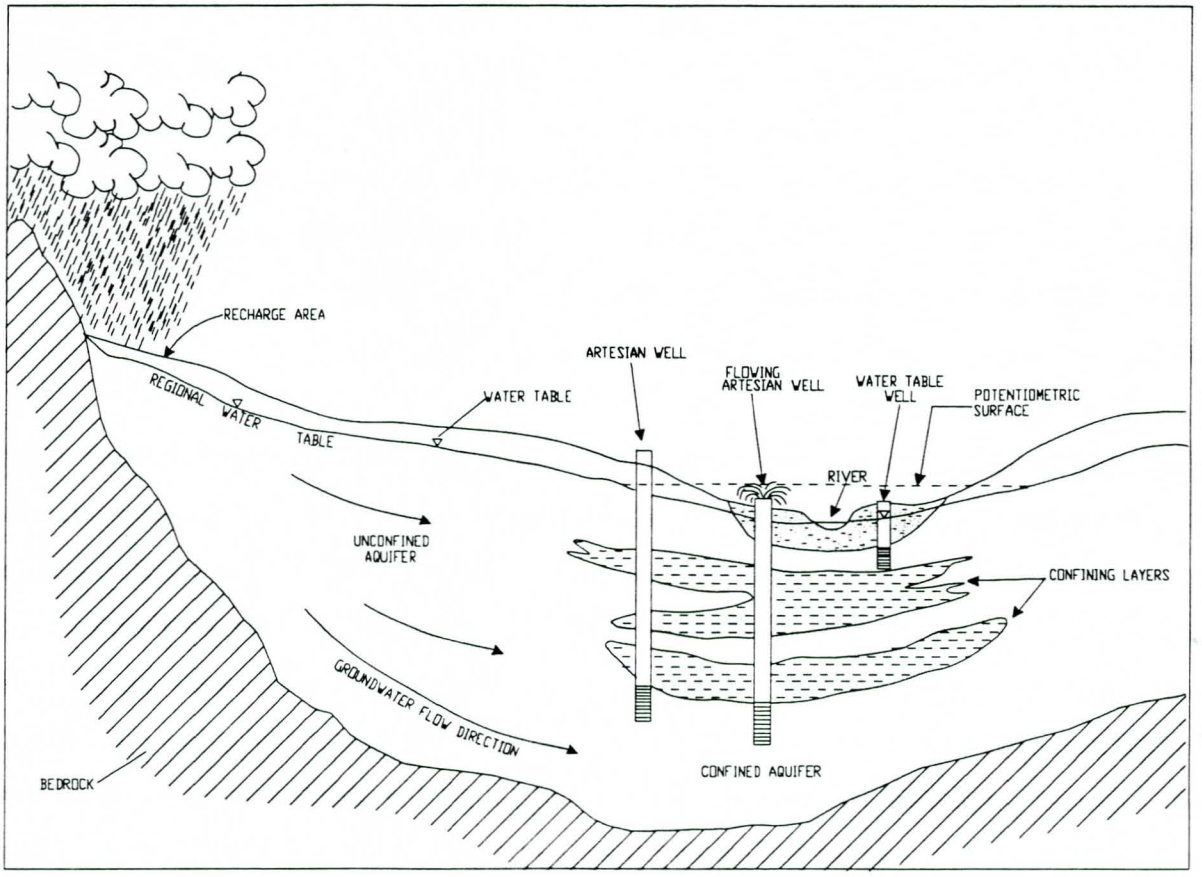
Groundwater

Underground water occurs in two zones, the unsaturated or vadose zone and the saturated zone. The vadose zone lies between the land surface and the saturated zone and contains a combination of water and air. Water in this zone is at less than atmospheric pressure (e.g., it would not flow freely into an open well). The unsaturated zone is an important conduit for water to reach the groundwater zone. Groundwater is the subsurface water that occurs beneath the water table in fully saturated soils and geologic formations.

Geologic formations or rock units that are saturated and yield usable quantities of water to wells or springs are called aquifers. Most commonly, aquifers in the alluvial basins of the southwest are composed of unconsolidated materials derived from weathered and eroded particles of clay, silt, sand, and gravel. This type of aquifer material makes up the majority of the alluvial valley-fill aquifers in the southwest. Groundwater occupies the pore spaces or voids that occur in the particles of silt, clay, sands and gravels that make up the alluvial material. Other aquifers that occur in the state consist of saturated consolidated formations or hardrock formations and may consist of various rock types. Water can occur in the fractures, joints, or solution cavities created both during and after the rocks were formed.

Groundwater may occur in an aquifer under unconfined or confined conditions (Figure 3), which will affect how the aquifer and the stream interact hydraulically. In unconfined aquifers, there are no hydrologic restricting units, therefore, groundwater levels are free to rise and fall in response to atmospheric pressure. The water table is the upper surface of the saturated zone and is usually measured as the static water level in wells. Confined or artesian aquifers consist of water-bearing material bounded by much less permeable material, such as an overlying clay layer (Figure 3). This less permeable layer is termed an aquitard or aquiclude, which simply means it either retards or prevents the vertical flow of water from one layer to another. Because confined aquifers are fully saturated and

Figure 3. Diagram of regional alluvial aquifer system



under greater than atmospheric pressure, they do not have a free water table. The pressure head or potentiometric surface, by definition, is always above the top of the confined aquifer. If a well is completed in a confined aquifer, the water in the well will rise to correspond to the pressure or potentiometric surface. If the potentiometric surface is above the land surface, water will flow naturally to the land surface (e.g., flowing artesian well) (Figure 3).

Aquifers serve as underground reservoirs by storing water from precipitation that has infiltrated into the ground. This natural recharge or addition of water to the aquifer occurs from direct infiltration of runoff flowing across alluvial fans bordering mountain ranges, or along stream channels. Recharge can also occur by groundwater movement from

another aquifer system (e.g., from an underlying or overlying aquifer). Recharge can vary with such factors as precipitation amount and timing, land use and evaporation.

Groundwater within undisturbed alluvial basins usually flows from mountain fronts located at basin margins to the center of the basin where it can be drained by a stream. Local barriers to flow, including pumping wells, may cause exceptions to the general flow directions in some basins. This can be quite severe as seen in the Salt River Valley, the Santa Cruz Valley, and in Pinal County. In these areas, groundwater discharge due to continuous well pumping for agricultural, municipal, and industrial purposes has severely lowered water tables in the surrounding aquifers to the point where groundwater can no longer discharge to a stream. Another primary cause of groundwater discharge is evapotranspiration by vegetation during the growing season.

Stream-Aquifer Systems

Two important types of stream-aquifer systems that are common in Arizona are: (1) narrow valleys developed in hardrock formations typically located in mountainous terrain, and (2) broad alluvial basins lying between mountain ranges typical of southern and central Arizona. The first type of stream-aquifer system consists of a narrow alluvial valley cut into impermeable hardrock. Stream alluvium composed of unconsolidated silt, sand, and gravel fill a channel and where saturated form a highly permeable aquifer. The impermeable hardrock forms a boundary that limits the extent of the aquifer. In this type of "single aquifer" system, a perennial stream developed on the alluvium is hydraulically connected to the underlying alluvial aquifer. Such an aquifer may be up to a few thousand feet wide and less than 100 feet thick and is characteristic of many of the aquifers found in the central and northern Arizona.

The second type of stream-aquifer system consists of a large alluvial basin which is comprised of multiple aquifers. These aquifers consist of basin fill alluvium that may be several thousands of feet thick and many miles wide. The basin fill alluvium can be

separated into various aquifer units, depending on the site and complexity of the hydrogeology specific to each basin. Alluvial basin aquifer systems typically contain both confined and unconfined aquifers. Figure 3 provides an illustration of a multi-layered, alluvial basin aquifer system.

In addition to the multi-aquifer alluvial system, a floodplain aquifer is typically found within the central valley of a basin. A floodplain aquifer is formed from unconsolidated alluvial materials deposited by a stream. Floodplain aquifers can be several hundred feet thick and several miles wide within the basin. These stream-aquifer systems are dynamic and interact through a constant exchange of water, from both surface water infiltration from the stream which recharges the aquifer and from groundwater discharge from the aquifer to the stream which provides baseflow (see Figure 2). Riparian areas are usually found on the floodplain alluvium where shallow aquifers are present.

The amount of streamflow may differ from place to place along a river. For example, during seasonal low flow periods in some streams, flow may completely disappear for a distance and then reappear downstream. This variation in flow is strongly dependent on the occurrence and direction of groundwater movement in an adjacent underlying aquifer. The hydraulic gradient indicates whether water flows toward the stream to supplement streamflow or away from the stream to recharge the aquifer. When the elevation of the water table in the aquifer adjacent to a stream is above the elevation of the streambed, groundwater flows toward the stream and is discharged to the streambed (Figure 2). This system acts as a drain for the aquifer, allowing water to move from the aquifer to the stream where it is expressed as baseflow.

An intermittent stream does not exhibit continuous flow. Natural use of water by riparian vegetation and/or cultural diversions may cause the water table to drop below the elevation of the streambed during certain times of the year, inducing streamflow to infiltrate through the bed of the stream to recharge the aquifer. When losses from stream

infiltration exceed surface flow, the stream will cease flowing. Even though the surface flow of the stream ceases, subflow can still be found at some depth in the permeable alluvial sediments beneath the stream.

HYDROLOGIC EFFECT OF GROUNDWATER WITHDRAWALS

In a natural, unimpacted hydrologic system, stream and aquifer systems achieve an equilibrium where long-term system inflows equal long-term outflows. In this type of balanced system, streamflow reductions would only occur during extended drought periods where below normal precipitation would result in a corresponding reduction in runoff and aquifer recharge. In developed watersheds, direct streamflow diversions and groundwater pumping can have an appreciable affect on the hydrologic system depending on the timing and magnitude of depletions and the location of these diversions. Often, depletions occur in or near riparian areas, where surface water is available and groundwater is close to the land surface.

Extensive pumping of groundwater results in depletion of streamflow by inducing infiltration of surface water through the streambed or interception of groundwater that would have recharged the stream. If the volume of water pumped exceeds the amount of natural recharge to the groundwater system, a deficit will occur causing a reduction in groundwater storage and declining water levels. A continuous trend of declining water levels indicates overdevelopment of groundwater resources. The degree of overdevelopment depends on the magnitude, duration, and distribution of withdrawals, as well as the hydraulic properties of the aquifer. Where multiple wells are clustered in close proximity to one another, the effect of pumping on the aquifer is compounded, as are impacts to any nearby stream.

Groundwater withdrawals by wells cause certain predictable aquifer responses. When groundwater is withdrawn through a pumping well, water is removed from storage creating a cone of depression in the affected aquifer. This causes water levels to drop in the

vicinity of the well as indicated in Figure 4. Where multiple wells are withdrawing water from an aquifer, the individual cones of depression will interconnect to form a regional cone of depression.

Ideally, groundwater flows radially toward a cone of depression and is removed from an aquifer by the well. The shape of a cone of depression depends primarily on the characteristics of the aquifer, the duration and rate of pumping, and the proximity of the well to groundwater recharge or discharge boundaries. If a well is pumped at a high rate for an extended period of time, the cone of depression will expand outward until further expansion is limited by the transmissive and storage properties of the aquifer or by intercepting an aquifer boundary such as a stream or impermeable hardrock boundary.

If the cone of depression of a pumping well intersects a stream, drawdown of the affected aquifer will cease along the stream bank and water will be drawn from the stream. Surface water will be induced to infiltrate through the permeable streambed to recharge the area of the aquifer dewatered by the pumping well. When the withdrawal rate of the well is balanced by induced stream recharge to the aquifer, the cone of depression will stop expanding in the direction of the stream. In some instances, pumping wells may change streamflow from perennial to intermittent or ephemeral by eliminating groundwater discharge to the stream and increasing streamflow infiltration.

Wells withdrawing groundwater from an aquifer that is hydraulically connected to a perennial stream will deplete or interfere with streamflow either directly or indirectly as illustrated in Figure 5. Direct interference occurs when a cone of depression expands into the stream alluvium of a river creating a groundwater gradient away from the stream. Streamflow losses increase as additional surface water infiltrates into the permeable alluvium to fill the area dewatered by the well. Indirect interference occurs when groundwater flowing toward the stream is intercepted by a cone of depression. Indirect interference has the affect of reducing the amount of groundwater that would have

Figure 4. Diagram of a cone of depression in an aquifer

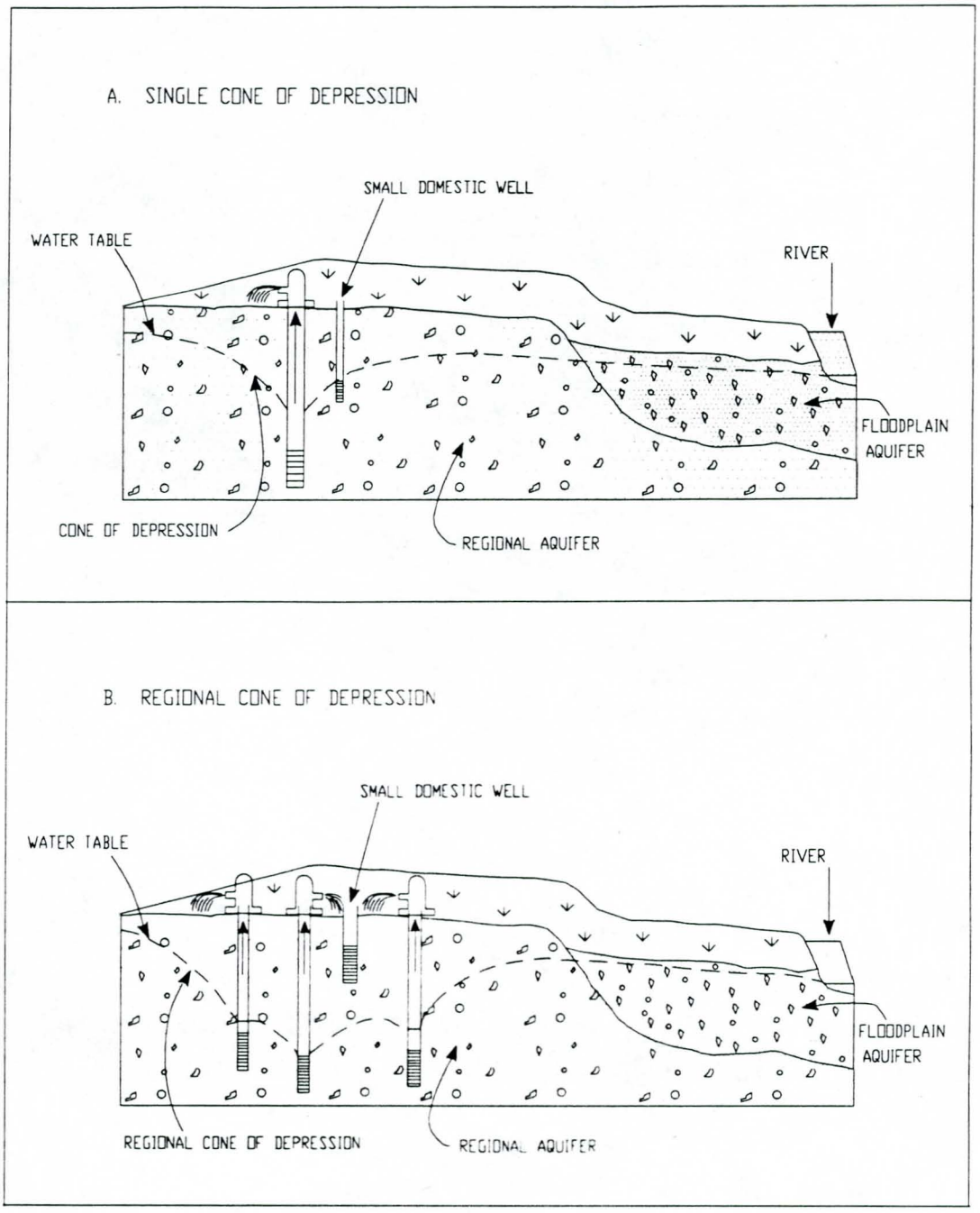
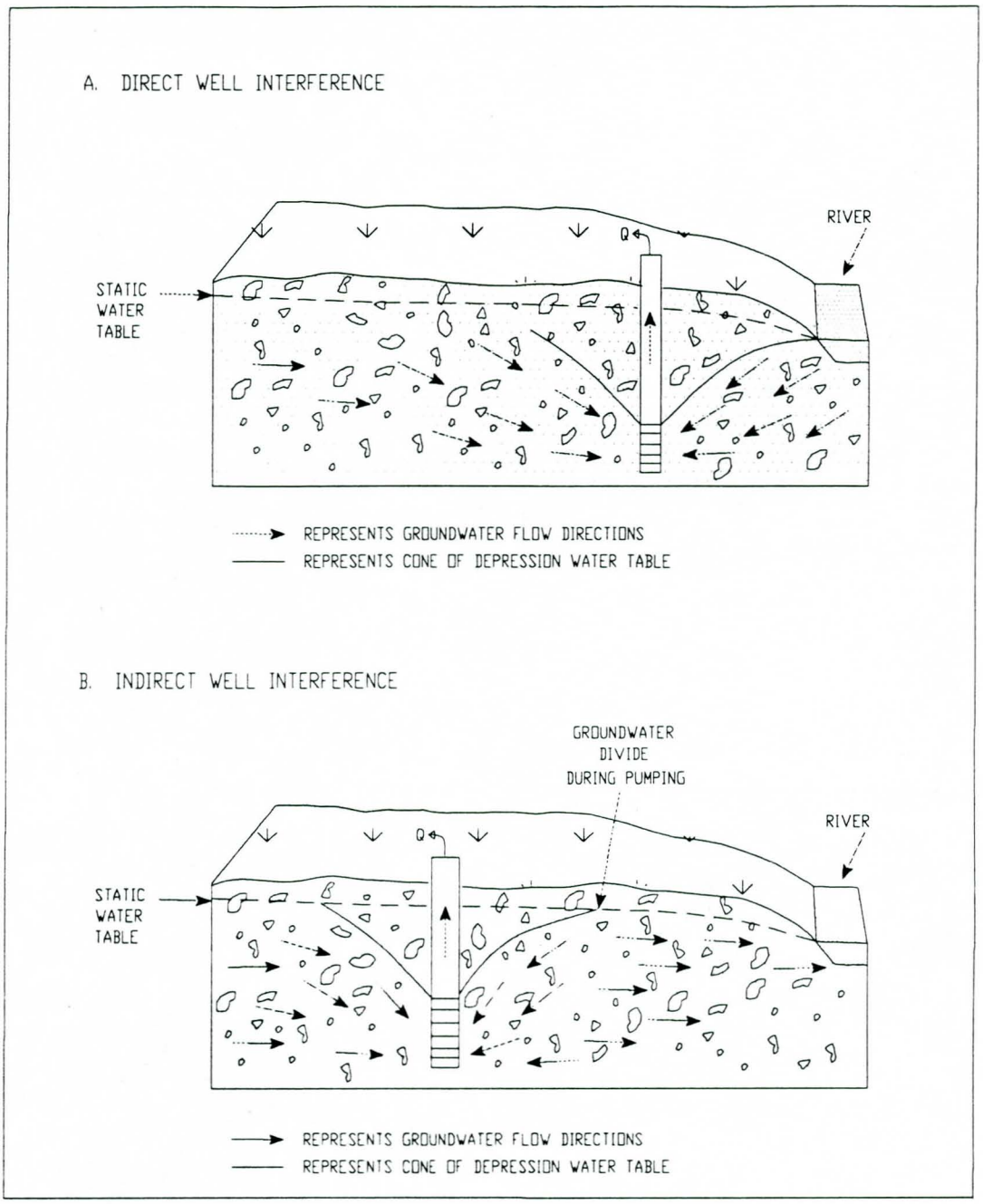


Figure 5. Diagram showing direct and indirect well interference



eventually discharged to the stream, thereby reducing baseflow. In both instances the well is depleting streamflow, either by inducing additional infiltration of streamflow, or by intercepting groundwater that would have discharged to the stream. In some areas, the impacts resulting from a pumping well adjacent to a stream are compounded by regional groundwater declines resulting from the combined affects of many pumping wells.

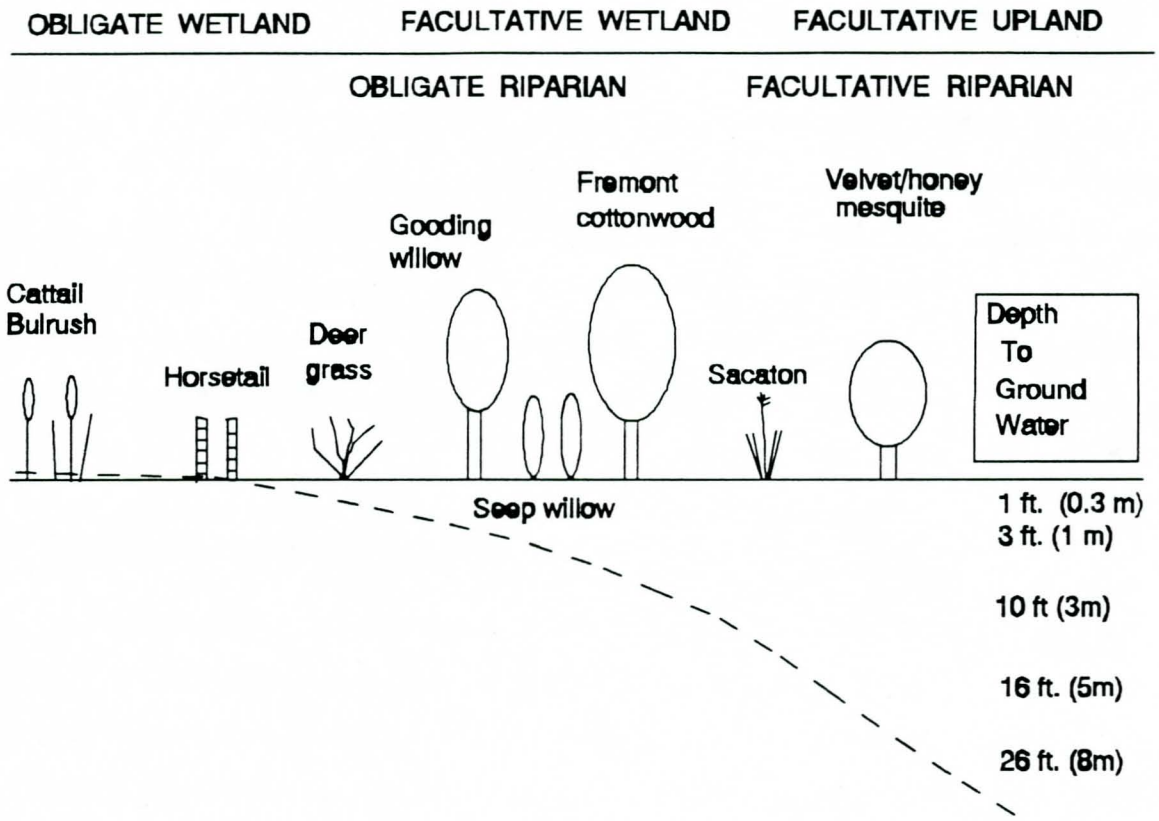
These declines can be quantified simply by measuring the surrounding groundwater levels in the floodplain and regional aquifers. These water level measurements can be used to determine impacts to the riparian areas associated with an adjacent stream. Figure 6 illustrates the species composition and relative depth to groundwater for typical southwestern riparian vegetation. As stated before, the farther away from the floodplain, the greater the distance between depth to groundwater and the land surface. Figure 6 also illustrates the general depth to groundwater requirements of various species of riparian vegetation.

Most of Arizona's riparian ecosystems have been lost or degraded by lowering of groundwater tables and increase in water table fluctuation resulting from (1) pumping of groundwater from wells in alluvial (floodplain) or regional (basin fill) aquifers; (2) development of infiltration galleries that intercept subsurface flow; (3) diversion of surface flow; (4) construction of upstream dams; and (5) detrimental land use practices in the watershed or riparian zone. Some of the ecological impacts of this groundwater decline include:

- Increase in physiological plant stress, reduction in growth rate and loss of vigor;
- Reduced seedling establishment and loss of age-class diversity;
- Plant mortality and reduction in plant density and cover;
- Sequential loss of increasingly more drought-sensitive vegetation types (e.g., loss of wetland plants and obligate riparian species followed by loss of facultative riparian vegetation types and ultimately of all vegetation);

- Replacement of riparian vegetation by more drought tolerant or upland vegetation or by "weedy" exotic species such as saltcedar;
- Reduction in biomass and structural complexity of the vegetation;
- Reduction in riparian zone width;
- Loss of wildlife habitat;
- Streambank erosion and channel widening;
- Increased downstream flood damage;
- Reduced purification of water quality;
- General loss of riparian function.

Figure 6. Species change with increasing depth to groundwater in a sonoran riparian ecosystem.



Several steps can be taken to prevent further riparian degradation and loss of function from groundwater decline. There is sufficient information to put in place a program that protects riparian areas by incorporating known ecologic needs into the decision making process regarding groundwater pumping. For example, each riparian species or plant association has a known optimum range of groundwater depths and conditions over which it grows; and a wider tolerance range within which it will persist. It is also known that structural and functional attributes of the plant community vary with depth to groundwater, and that these attributes change along a continuum. Groundwater models identify these general thresholds for plant association type changes, particularly for Sonoran riparian ecosystems. The groundwater models also indicate optimum groundwater depths over which riparian plant species grow (and establish), as well as the changes in stand density and structure that occur as depth to groundwater increases. These relationships between groundwater and riparian vegetation have been quantified for many riparian species, although there is a need for additional study particularly of species in high elevation riparian zones.

HYDROLOGIC EFFECT OF SURFACE WATER DIVERSIONS

The effects of existing surface water diversions are not addressed in this report. However, the effects of current diversions provide insight to the potential effects of future diversions and changes in use and point of diversion. Streamflow diversions are not quantified for most areas of the state. Therefore, only a qualitative evaluation of the effects of new surface water diversions and changes in existing uses and points of diversion can be made.

As a general rule, surface water diverted from a stream is not available to support the natural hydrologic system below the point of diversion. Surface water diverted by an instream diversion structure diminishes the flow volume of the stream directly, that is, for every acre-foot of water diverted, streamflow is also reduced by one acre-foot. Indirect diversion of surface water can occur when water withdrawn from a well includes both

surface water and groundwater components. In the case of indirect depletions by wells, streamflow depletion is not immediate, however, over the long-term, stream depletion may approach the amount pumped. In each case, not only is flow reduced downstream of the diversion, but downstream recharge is also diminished. Reduction of available flow for stream recharge may result in a decline in water levels in alluvial aquifers adjacent to impacted stream reaches. In instances where surface water is diverted from a stream and applied to irrigate crops on adjacent alluvial floodplains, a portion of the water that is not evaporated or transpired may return to the stream through deep percolation (irrigation return flows).

Streamflow diversions vary in volume from small irrigation ditches and instream pumps, which divert only a fraction of the total streamflow, to large diversion dams which divert the entire flow of a stream. In many natural perennial stream systems the stage (stream water surface elevation) and the adjacent aquifer in the stream alluvium are at equal elevations. In some instances however, water levels in an adjacent alluvial aquifer may be slightly above or below the river level within the riparian zone. For example, following the high flow season, saturated portions of the floodplain may temporarily exist above the river level and slowly drain back to the river sustaining flow during the low flow season (e.g., bank storage).

When surface water is removed from the stream by a diversion structure, the stage of the stream is lowered. As stream stage declines, the water level gradient between the stream and alluvial aquifer steepens and water drains from the aquifer to the stream. In a hydraulically connected stream-aquifer system, drainage from the adjacent alluvial aquifer to the stream results in a water table decline and leads to an increase in the distance between the water table and land surface (unsaturated zone).

While surface water flows are critical for riparian vegetation maintenance and regeneration, riparian vegetation serves to stabilize hydrologic systems. When surface

water is diverted and no longer available to support riparian ecosystems, riparian community densities are reduced or eliminated. Therefore, less vegetative cover and root structure support are available to slow flood flow velocities, stabilize soils and sustain lateral floodplain recharge. As a result, stream channels and associated floodplains become more susceptible to degradation and erosion processes, such as streambed scouring, and channel incision and widening. Channels impacted by these actions are highly erosive and carry greater sediment loads. Additionally, bank storage potential is reduced and therefore less discharge from stream alluvium is available to support baseflows in the stream during low flow periods. When flood events occur, the resulting system's inability to slow and retain some of the flow energy can result in greater flood related devastation.

Surface water also is of great importance to riparian vegetation. Many herbaceous riparian plants are rooted directly in the stream or depend on bank-stored stream water and are very sensitive to the loss of perennial flow. Many riparian trees use stream water at all life stages, while others use stream water as juveniles and as adults become indirectly dependent on surface water as a source of floodplain aquifer recharge. Surface flow variables that are important to riparian vegetation include the mean and median volume of flow during the year and particularly during the growing season; the base flow and the low flow volume during the dry season; the seasonal discharge pattern; the extent of annual fluctuation in flow; and the relative difference between low flows and peak flows. Whether or not the flow is perennial also is of major importance, as is the duration and timing of the no-flow period on non-perennial rivers. Frequency, duration, timing, and magnitude of peak flows also have ecological significance for riparian vegetation. Floods influence many ecosystem processes, and often serve as regeneration flows while other flows serve as maintenance flows.

Surface water has high variability in many of Arizona's rivers due to high climatic flux. Surface flow has been reduced or may become more variable as a result of: (1) surface

flow diversion; (2) river damming; (3) removal of effluent from stream beds; (4) development of infiltration galleries in the channel; (5) groundwater pumping from the floodplain aquifer; (6) groundwater pumping in the regional aquifer that changes the direction of groundwater flow towards the cone of depression and away from the river or river aquifer; and (7) various watershed and riparian land uses. Surface water decline has caused the same types of riparian loss or degradation as described above for groundwater decline. Surface water decline has had greatest impacts for Sonoran riparian ecosystems (e.g., cottonwood-willow forests, mesquite bosques, riparian marshlands) because low elevation desert rivers have been strongly affected by river damming and diversion. Mixed broadleaf riparian forests along higher elevation mountain streams also have been degraded by surface water diversions for agriculture, municipal use, and more locally, hydropower production.

Riparian ecosystems also have been altered and degraded by flood flow alteration. Dams are the primary cause of flood flow alteration and have caused extensive changes in below-dam as well as above-dam riparian ecosystems. Peak flows also have been altered by channelization of river beds; compaction of soil and pavement of surfaces in the watershed; and reduction in floodplain and watershed plant cover. These factors serve to intensify flow magnitudes in the downstream reach, and can degrade riparian ecosystems by increasing mortality from flood flows and reducing their ability to recover after the flood.

ALTERNATIVE REGULATORY PROGRAMS DISCUSSION

A review of Arizona water law was necessary before potential alternative regulatory programs could be developed. A discussion of this is found in detail in Chapter V, the Regulatory Strategies Report, and illustrates the problems facing the state in trying to deal with the legal differences between surface water and "percolating groundwater." Surface water rights permits can be issued for waters that are put to beneficial uses such as domestic, municipal, irrigation, stockwatering, electric power generation, recreation, wildlife including fish, artificial groundwater recharge and mining uses.

Groundwater is regulated separately from surface waters within the state, and only in designated areas where long-term groundwater withdrawals have exceeded the natural replenishment of groundwater supplies. Several programs have been established in these areas to alleviate severe overdraft conditions.

In addition to state laws governing the use of surface waters and groundwaters, there are federal laws have an affect on how the water resources on federal lands are managed. Many agencies including the U.S. Bureau of Land Management (BLM), U.S. Fish and Wildlife Service (USFWS), U.S. Forest Service (USFS), and the U.S. Environmental Protection Agency (EPA), can determine the fate of many riparian areas on lands owned by the federal government in Arizona. These agencies do this through their land management and how they affect land management practices. Several programs and laws which come into play include the Wild and Scenic Rivers Designation, the Clean Water Act (Section 404 permits), and the Endangered Species Act. Although these programs affect how an agency manages its lands, they may provide only limited levels of protection of riparian areas on federal lands. At issue are land management practices that may impact an entire hydrologic system and the riparian area rather than just a water resources or streamflow. Therefore, any riparian protection strategy developed for the state of Arizona not only has to recognize the gap between current surface and

groundwater law, but also provide additional support to current federal programs where gaps exist.

Arizona is not the first state to grapple with these issues and it should look to protection strategies used by other states for program ideas that may be applicable to our specific situation. Each state approaches wetland protection in different ways depending on the nature of the state's economy and natural resources problems. North Dakota, for example, pursues a wetlands preservation policy which allows the creations of wetlands to substitute for drainage projects. Oregon, on the other hand, has many programs related to riparian protection and developing voluntary committees to plan for the management of riparian and wetland areas. Most riparian protection practices in Oregon focused on forestry and logging management, however, water rights applications have to be reviewed for riparian impacts. Oklahoma has created state funded commissions to protect, plan, and manage scenic river segments. The Oklahoma commissions have broad and flexible authority to develop and implement management plans. Florida vests its local water management districts with authorities similar to state engineers in the western states. These districts are required to consider the impacts of potential new diversions and groundwater pumping on wildlife and riparian areas.

TYPES OF PROTECTION PROGRAMS

The following is a brief overview of the different types of regulatory or non-regulatory programs that may be used in a riparian protection program. Generally the range of administrative options to regulate water rights includes three approaches: 1) a statutory non-permit system, 2) statutory permit system, or 3) a local area management authority.

Statutory non-permit system

This type of regulation sets guidelines or provisions in statute to which all water users have to adhere. For example, all persons making new diversions or groundwater

withdrawals might be required to maintain groundwater tables at levels which do not cause diminishment of riparian vegetation.

The statute can set guidelines for enforcement. Any agency, such as ADWR or AGFD could be delegated the administrative authority to investigate complaints and enforce the statute. Sanctions could be set by statute. Enforcement could also be the responsibility of individual citizens. The statute might allow individuals to take civil action to enjoin groundwater users who may be causing damage to riparian areas through excessive withdrawals. The statute and court could establish who may sue, the criteria for showing damage and the limits to sanctions.

This type of regulatory system provides limited control to protect individuals' property and rights. In a complex ecosystem, it may be difficult to prove that groundwater withdrawals are affecting riparian habitats. The ability to manage excessive withdrawals may be difficult since damage to riparian areas must occur before action can be taken. Any civil action may also be costly and time-consuming which may limit the effectiveness of the process.

Statutory-Permit System

A statutory-permit system is the most common method of water rights governance. In this type of system, the statute requires the State to issue a permit before water can be used or diverted. Normally, the statute lists specific conditions which applicants must meet to obtain a permit. However, the statutory conditions might allow the departmental director to use broad discretionary powers to judge whether a permit should be issued. The statutory requirements are interpreted and implemented by administrative rule. Usually the court reviews contested administrative decisions of an agency director which may lead to court interpretations of the statutes. A permit system generally requires that the public be informed that an application to use or divert water has been made. The statutes define who may comment and what may be contested.

The conditions of a permit can be enforced by an agency through administrative action which might include cease and desist orders, fines or revocation of permits. The limits of an agency's authority can be set by statute. Colorado and New Mexico have a similar regulatory system however, enforcement is different. In both states the state engineer is given broad enforcement authority to control diversions, including directly opening and closing gate structures, however neither state has riparian protection authority.

A statutory permit system provides extensive control and dispute resolution depending on the statutory limitations. The development of a regulatory system is flexible. The legislature can establish very specific requirements to guide agency decisions or delegate very broad discretionary responsibilities. The level of sanctions can be limited or expanded by the legislature.

Local Area Management

Where intensive water rights management has been necessary to avoid conflicts, different types of management authorities have been formed to oversee the distribution of water. In some cases, an irrigation district has administered the water rights system by scheduling and accounting for water deliveries which are set by court decree. In Arizona, ADWR has been given the authority to measure and account for the use of groundwater in AMAs. Local area management authorities are often governed by elected or appointed boards whose authorities are described in statute. The boards establish operating policies in accordance with statutory provisions. Often the boards have the ability to generate revenues to support their activities. These activities may include preparing studies, building facilities and executing contracts or intergovernmental agreements. Local area management authorities have the ability to enforce regulations and ordinances. Often they are given the same authorities as municipalities.

CURRENT EXAMPLES OF REGULATORY SYSTEMS

The following provides current examples of regulatory systems that could be adapted and used as a template for a riparian protection program.

Statutory Non-permit System - Well Drilling Permit Example

Current Program Description

This type of regulatory system is used for new exempt wells (small domestic type) and replacement wells within AMAs and all wells outside of AMAs. An applicant who wishes to drill a well must notify the Department that a well is being drilled, its location and pertinent data. However, the Department can take no action other than to endorse the notice of intention to drill. The primary purpose of the notices of intention to drill is to maintain a current registry of the location of the wells for public informational purposes. The well must be drilled by a licensed well driller and be drilled according to well construction rules adopted by ADWR. The owner is responsible for compliance with all well drilling standards. Compliance investigations are only begun if there is a complaint.

Alternative Regulatory System to Protect Riparian Areas

This type of regulatory program could be expanded to require the development of rules for the protection of groundwater levels which support riparian habitats. Enforcement of the rules could be through an administrative process including arbitration, cease and desist orders, and fines.

The effectiveness of this program is dependent on being able to create rules which quantify the groundwater levels necessary to support riparian habitat areas. If scientific data were available, specific rules could be written for different stream reaches throughout the state.

Problems which might be expected with enforcement of these rules include inadequate monitoring of water levels and accounting for water level changes due to regional water

table declines or normal drought conditions. Monitoring water level conditions in riparian areas would probably only be feasible in selected areas or pursuant to complaints. If water level declines were observed, a potential complainant may claim that declines are due to regional effects of many wells, increased stream diversions, or reduced stream flows due to normal drought cycles. It would then be up to the injured party to prove otherwise. These types of extenuating circumstances may reduce the effectiveness of compliance activities. Compliance activities for this type of regulatory program take place after damage has been incurred.

Statutory Permit System - Surface Water Appropriations/Groundwater Withdrawal Permits

Current Permit Systems

All new diversions of surface water in the State require an application to appropriate water for a beneficial use. If the director finds the proposed use conflicts with vested rights, is a menace to public safety, or is against the interests and welfare of the public, the application shall be rejected. An application may be approved for less water than applied for, and may not be approved for more water than is needed for the beneficial use.

A water right, except instream flow rights, may be severed from the land to which it is appurtenant and transferred to another location, but only if the proposed transfer does not affect other vested rights, and it has the approval of the governing body of an irrigation district, agricultural improvement district, or water users association within which the water right is located. Such governing bodies must also approve severs-and-transfers within the watersheds or drainage areas which supply or contribute water for the irrigation of lands within their boundaries.

Within AMAs the ADWR can issue permits to withdraw groundwater if the proposed withdrawal does not unreasonably harm surrounding well owners. The criteria for determination of harm is established by rule. The type of analysis for establishing harm

is specific to a newly proposed withdrawal and does not necessarily account for the regional effects of many wells.

The current regulatory permit system for surface water appropriations and diversions allows landowners to obtain instream flow rights which presumably will protect riparian habitat. Landowners can apply for new permits to appropriate, but they may not obtain existing water rights which would have more senior dates of appropriation and change the use to an instream flow (although a state agency can do so). Once a permit to appropriate is approved and a certificate is issued, subsequent permits may not be approved which would cause damage to the water right.

Currently, compliance with permit requirements is investigated pursuant to complaint. Enforcement action is a civil court proceeding. ADWR has no administrative process to address complaints, or statutory authority to investigate compliance and take enforcement action.

Problems

The current regulatory system may not guarantee minimum stream flows during times of drought if senior upstream water right holders divert water flows. Irrigation districts may veto any proposed sever-and-transfer. Water quality is not protected by the water right. Withdrawals from wells are not necessarily controlled to protect groundwater levels near streams. Unless groundwater withdrawals are proven to show direct and appreciable reductions in surface flows, no action can be taken to enjoin groundwater pumpers from impacting water levels near streams.

Alternative Regulatory Programs to Protect Riparian Areas

Standards designed to protect riparian areas by requiring specific groundwater levels and stream flow volumes could be added to the statute. These standards could be used to determine whether a new permit to appropriate would be issued. Also, riparian

consumptive uses of water could be recognized as a beneficial use to the State and permits to appropriate could be issued for this specific purpose.

Present permits to withdraw groundwater and drill wells could be modified to address riparian areas. Any applicant who applies for a permit could have to demonstrate that they would not substantially impact the groundwater levels in riparian zones. Standards for determining substantial impact should be set by statutes. Sever and transfer of water rights to increase stream flow for instream or riparian uses could be allowed unless there is a finding of substantial negative impact on senior water right holders. The denial of severs-and-transfers by irrigation districts for applicants intending to change use for instream flow or riparian uses could require a finding of substantial negative impact as well.

The state, through one of its agencies, could be allowed to obtain and hold water rights for instream or riparian purposes. If the state held such rights in public trust, presumably actions to coordinate the protection of riparian and instream rights with other water rights may be enhanced.

A permit system could include standards which specify certain flow conditions for rivers and streams throughout Arizona. Minimum flows could be established for streams based on mean or median monthly flows. Streams in certain critical areas could be subject to special designation and applications for new wells or diversions would not be accepted. In addition, compliance and enforcement of permit conditions could be changed to require an agency to monitor and take administrative action to ensure compliance.

Local Area Management - Flood Control Districts/Active Management Areas

Current Regulatory Program

Management of riparian habitat and stream flow for fish, flora, fauna and recreation protection could be under the jurisdiction of special districts or agencies.

Special districts could be given many different authorities from taxing and land acquisition to monitoring and measurement of riparian conditions. Currently no examples of special districts for riparian protection exist in Arizona, but two models of broadly based local management include county flood control districts, and Active Management Areas.

County Flood Control Districts

County flood control districts have broad duties and powers to delineate floodplains, regulate development within the flood plain, acquire property and build flood control structures. They actively coordinate and confer with federal and state agencies which have specific regulatory responsibilities in floodplain areas. They create and enforce rules and regulations regarding land use and water use.

A similar type of district might be established for riparian protection. Such a district might be given the responsibilities to establish riparian protection zones where land use, groundwater withdrawals, surface water diversions and reservoir operations would be subject to minimum flow regulations, groundwater depth regulations, monitoring and compliance activities.

This type of district can provide comprehensive planning and management of riparian areas. It could also coordinate federal, state and local activities affecting critical areas. The limits of its power can be prescribed by statute. This type of district can be required to implement its programs consistent with the current water rights regulations of the state. If necessary, it could acquire property and water rights to preserve critical areas, or implement rules and permit programs to manage land and water uses. Such a district could enter into intergovernmental agreements with federal agencies to implement and coordinate projects.

Active Management Areas

Measurement, control and management of groundwater withdrawal and diversions could be carried out by the state through local management area authorities similar to Active Management Areas. The Director of ADWR could be required to inventory and assess the need for intensive water rights management in critical riparian areas, then create a management plan to control groundwater withdrawals and diversions. Advice about how critical riparian areas should be protected could be provided by an advisory board which is appointed by the governor. The advisory board might consist of local water users, other agency representatives and other experts.

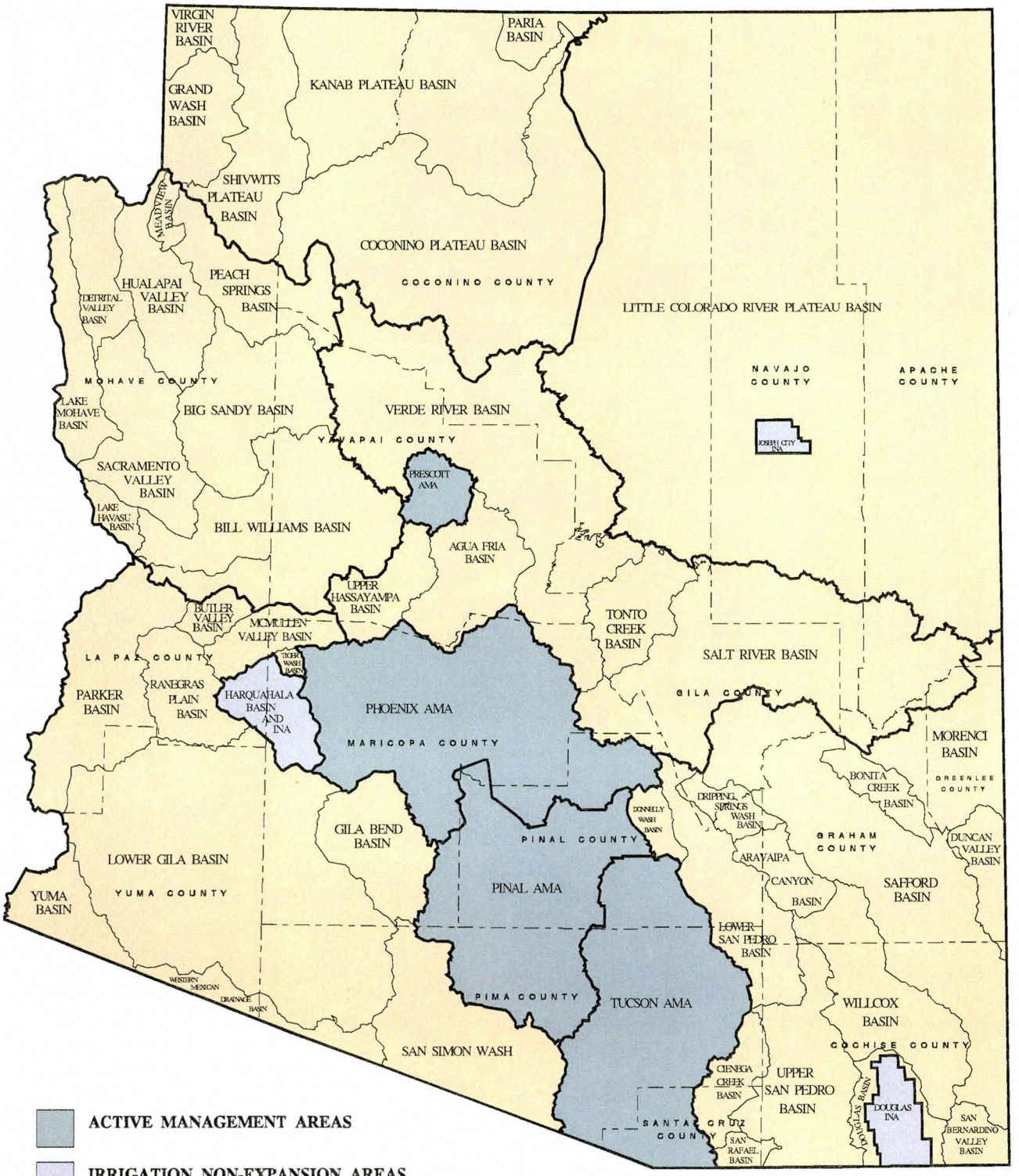
Duties and responsibilities of the Department would be delineated by statute, but all rules and regulations would be developed through a water management planning process. Rules and regulations would have to be consistent with the statutory provisions governing water rights. Such an entity could only affect water rights issues.

ECONOMIC IMPACTS OF A RIPARIAN AREA PROTECTION PROGRAM

In order to assess the potential economic impacts of a riparian area protection program, several economic activities were evaluated. These activities were grouped into four major categories separated by planning regions for the entire state (Figure 7). The major economic activities included municipal and industrial, irrigated agriculture, mining, and power industry activities. These broad sectors of the economy were chosen because they also represent the major water using sectors of the state. Water use for these economic sectors are projected to require 835,000 acre-feet of water to meet the projected demand in 50 years. This demand is projected to occur in the AMA and the Upper and Lower Colorado River Planning areas. This projected demand and water use was then evaluated relative to the employment sectors throughout the state by planning regions.

Figure 7

GROUNDWATER BASINS OF ARIZONA BY COUNTY AND PLANNING REGION



Current population and employment data for counties indicate the general size and structure of the economy. Grouping the population and employment data by county into the water planning areas demonstrates the relationship between water use and the economy on a very general level. Figure 8 contrasts the relative size of employment with water demand for each of the water planning regions.

Water demand and employment by the general categories described above can be contrasted. In Arizona, municipal and industrial water demand accounts for 17 percent, mining and power, for 3 percent, and agriculture, for 80 percent of total water demand. On the other hand, "all other" employment is 97 percent of state employment, including "hotels, lodging and other" of 2.5 percent. Agriculture employment is about 2.5 percent and mining about 0.8 percent of total state employment.

The relationship between water demand and total employment by planning region is illustrated by Figure 8. Maricopa County employment (approximation for Phoenix AMA) for 1990 was 63.3 percent of the state whereas water demand in the Phoenix AMA in 1990 was only 35 percent of water demand statewide. Pima County (18.2 percent) combined with Santa Cruz County (0.6 percent) were 18.8 percent of total state employment and water demand in the Tucson AMA was 4 percent of the State. The Pinal AMA consumed 15 percent of the State's water in 1990 while employing only 2.2 percent of the state's workers.

As can be seen from Figure 8 the majority of water use and the highest levels of employment within the state occur in the two major metropolitan areas of Phoenix and Tucson. However, water demand is also high in the Pinal AMA due to the amount of irrigated agriculture. Employment and water demand for the rest of the state is low and most likely reflects the rural character of these areas. The other exception to this is the Colorado River planning area, where water demand is high but employment remains relatively low.

The economic analysis was further refined on a planning region basis by analyzing water use, land ownership, and employment specific to these areas. Water resource data and information was collected and analyzed for groundwater basins for each water resource planning area. Population estimates and projections correspond to the planning areas, whereas economic data such as employment was reported by county. For this study, population by basin and planning area, and employment by county was used generally to describe the baseline economic conditions in the water resource planning areas. Changes in the economy are approximated by population projections to the year 2040.

PLANNING AREA ECONOMIC AND WATER RIGHT TRADEOFFS

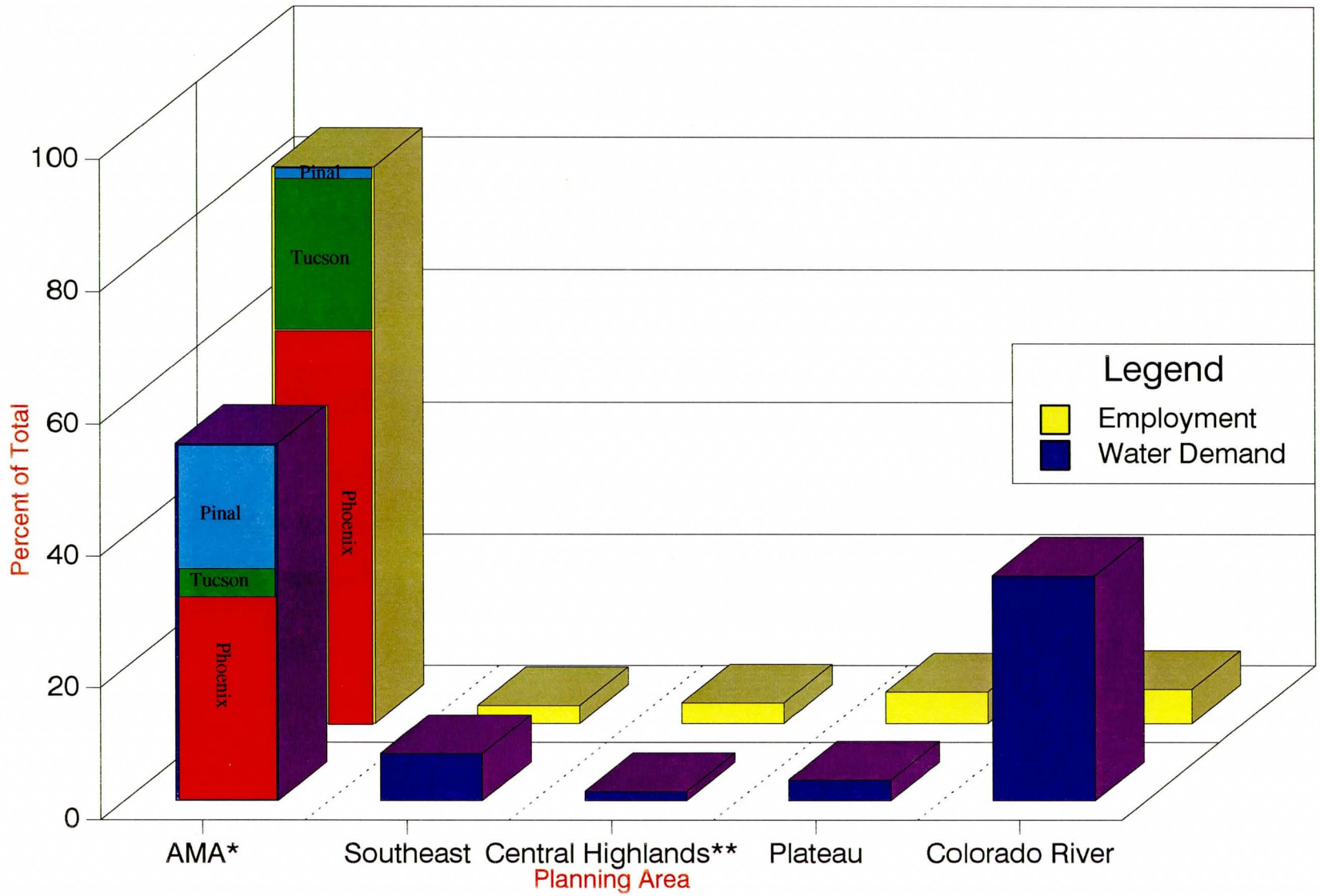
Riparian protection regulations will affect water users only if the proposed withdrawal, diversions or uses of water will change the pattern of streamflow in such a way as to negatively impact riparian vegetation. The flow of water in the major perennial stream reaches in Arizona must be maintained in order to fill senior downstream water right demands. Therefore, most streamflow patterns cannot be impacted by new diversions and changes in use, or place of diversion under the current water rights regulations. However, if new groundwater withdrawals are permitted, the potential effects on streamflow vary depending on where and when the withdrawals take place.

Economic tradeoffs may occur if potential new withdrawals or diversions are prohibited to protect riparian areas. The types of changes that might occur to streamflow patterns and the resulting tradeoffs of which might occur if riparian protection regulations are enforced and described as follows.

Even if an existing withdrawal of water is prohibited in order to protect a perennial reach of stream, alternative water supplies may be available to meet all of the water demands. However, associated costs may be higher. A significant impact would be predicted if all of the following would occur: alternative water supplies were not available, the volume of water withdrawn supported many users, and the prohibition occurred immediately.

Figure 8

1990 Arizona Employment & Water Use



* - Does not include Prescott AMA

** - Includes Prescott AMA

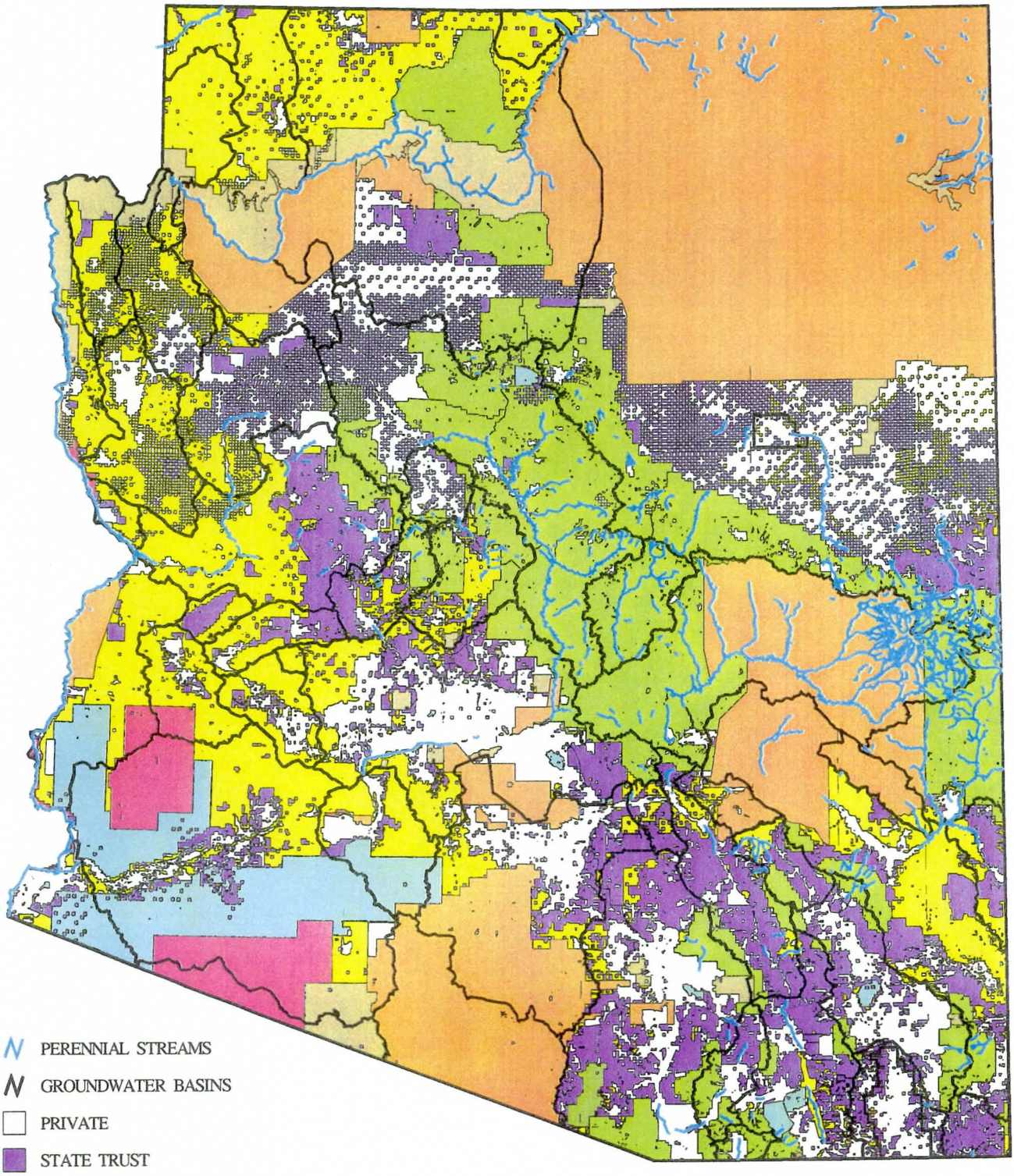
In the case of groundwater withdrawals, existing and future withdrawals may have to be managed to protect riparian areas, or substitute water supplies may have to be found to continue or expand water uses. The potential for conflict or tradeoffs between riparian protection and projected water use is different for each planning area.

Potential impacts arising from the above mentioned withdrawals are also conditioned by the ownership of lands located along perennial water courses. The results of measuring perennial streams by land ownership are given in Figure 9. Statewide in Arizona, out of a possible 5,013 miles of perennial streams, only 857 miles or 17.1 percent is owned by private interests and 146 miles or 2.9 percent is owned by the State of Arizona. The remaining 80 percent of perennial streams are located on public lands managed by the BLM, USFS, USFWS and National Park Service or on Indian lands held in trust by the Government of the United States. The management of the streams on public lands is governed by strict processes such as USFS forest plans, which must undergo a rigorous public review process. It is unlikely that future major groundwater withdrawals or diversions of perennial waters would occur on federal land. Therefore, any new restrictive state water law would probably only be relevant to private and state owned reaches of perennial streams, or approximately 1,000 perennial stream miles (20% of total).

Given the broad span of possible regulations and the diverse water use patterns within the state, impacts can vary widely. Generally, any riparian water right protection strategy will be expected to require maintenance of minimum flows in certain stream reaches. Maintenance of minimum flows enhances or ensures the availability of water for downstream water right holders without regard to their date of priority. New diversions may be precluded upstream of protected riparian areas. Existing and future groundwater withdrawals which may interfere with instream flows might be subject to increased management or reductions of withdrawals over time. But the exact nature and amount of potential reductions cannot be known without intensive data collection and scientific analysis. Little or no impact may occur for decades in some areas, but groundwater

withdrawals in other areas may immediately affect local reaches of a stream if the withdrawals are large enough and if the stream is hydraulically connected to the aquifer. These types of studies must be conducted on a very site-specific basis to provide the necessary information to base riparian protection while mitigating other concerns.

Figure 9



PERENNIAL STREAMS
GROUNDWATER BASINS
PRIVATE
STATE TRUST
BUREAU OF LAND MANAGEMENT
US FOREST SERVICE
INDIAN RESERVATION
MILITARY
FISH AND WILDLIFE SERVICE
NATIONAL/STATE/COUNTY PARK SERVICE
WILDERNESS AREAS
OTHER FEDERAL AGENCIES

PERENNIAL STREAMS/OWNERSHIP

NORTH

MILES

50 0 50 100 150

CHAPTER 2
HYDROLOGIC REPORT

DRAFT

CHAPTER II

HYDROLOGIC REPORT

DRAFT

TABLE OF CONTENTS

INTRODUCTION 2-1
PURPOSE AND SCOPE 2-1
Objectives 2-2
Chapter Organization 2-2
RIPARIAN VEGETATION AND HYDROLOGIC INTERACTIONS 2-5
Overview 2-5
Riparian Vegetation/Groundwater Relationships 2-5
Riparian Vegetation/Surface Water Relationships 2-7
PHYSIOGRAPHIC SETTING 2-8
CLIMATE 2-11
Precipitation 2-12
Evapotranspiration 2-17
Climate Summary 2-17

HYDROGEOLOGIC ANALYSIS 2-19
OVERVIEW 2-19
HYDROLOGIC CONCEPTS 2-21
Surface Water 2-22
Groundwater 2-28
Stream-Aquifer Systems 2-31
HYDROLOGIC EFFECT OF GROUNDWATER WITHDRAWALS 2-34
Groundwater Level Declines 2-36
Effect of Groundwater Withdrawals on the Hydrologic System 2-40
Quantifying Impacts of Groundwater Withdrawals 2-47
HYDROLOGIC EFFECT OF SURFACE WATER DIVERSIONS 2-55
Effect of Diversions on Hydrologic Systems 2-56
Quantifying Impacts of Surface Water Diversions 2-58
Statistical Analysis of Streamflow 2-60

SUMMARY 2-67

REFERENCES 2-73

GLOSSARY 2-77

LIST OF TABLES

Table 1 Climate characteristics within the San Pedro, Santa Cruz, and Verde River.study.areas 2-15

Table 2 Distribution of wells in selected areas of the state. 2-35

LIST OF FIGURES

Figure 1. Map of Arizona showing the case study areas 2-3
Figure 2. Schematic of Riparian Floodplain 2-7
Figure 3. Map of Physiographic Provinces of Arizona 2-9
Figure 4. Map showing the location of perennial streams in Arizona . . 2-13
Figure 5. Hydrologic cycle flowchart and diagram 2-23
Figure 6. Diagram showing perennial, intermittent and ephemeral stream types 2-24
Figure 7. Map showing the location of USGS streamflow gaging stations in Arizona during Water Year 1992 2-27
Figure 8. Diagram of groundwater zones 2-29
Figure 9. Diagram of regional alluvial aquifer system 2-30
Figure 10. Diagram showing an alluvial basin aquifer 2-33
Figure 11. Map showing location of wells in Arizona 2-37
Figure 12. Diagram of a cone of depression in an aquifer 2-41
Figure 13. Diagram showing changes in the shape of a cone of depression with variation in aquifer transmissivity 2-43
Figure 14. Diagram showing affect of an impermeable boundary on a cone of depression 2-43
Figure 15. Diagram showing direct and indirect well interference 2-44
Figure 16. Graph of delayed pumping effect 2-46
Figure 17. Graph showing monthly streamflow variability for USGS streamgage: Verde River near Camp Verde 2-62
Figure 18. Flow duration curves for specified streamgages on the San Pedro, Santa Cruz and Verde Rivers 2-65

APPENDICES

APPENDIX A. SENATE BILL 1030 ..... A-1
APPENDIX B. WELL NUMBERING SYSTEM B-1
APPENDIX C. LIST OF ANALYTICAL METHODOLOGIES C-1

INTRODUCTION

PURPOSE AND SCOPE

This study provides an assessment of the hydrologic affects of groundwater withdrawals and surface water diversions on riparian vegetation within Arizona. Arizona Revised Statute (A.R.S.) §45-101 (Appendix A), requires the Arizona Department of Water Resources (ADWR) to conduct a study to "evaluate the effect of groundwater pumping and surface water appropriations on riparian areas" and present the results of the study to the Legislature. The results of the study provides the framework necessary to allow state lawmakers and water resource managers to make informed decisions regarding the protection and management of Arizona's remaining riparian areas.

In addition to this report, the Arizona Game and Fish Department (AGF) and the Arizona Department of Environmental Quality (ADEQ) were required by A.R.S. §45-101 to conduct studies and provide the results to the Riparian Area Advisory Committee (RAAC). ADEQ was tasked with assessing activities and practices which impact riparian areas while the AGF was tasked with classification and mapping the state's remaining riparian areas. The RAAC will evaluate the individual components of the study and submit a final report of the committee's findings to the Governor, President of the Senate, and Speaker of the House of Representatives by December 1, 1994.

The ADWR determined that it would be impossible to accurately assess the impacts of groundwater pumping and surface water diversions presently occurring throughout the entire state within the time allotted due to the lack of hydrologic and ecologic data in many areas. Additionally, a comprehensive statewide map of riparian areas will not be available until completion of the AGF mapping project in December 1993. Therefore, the approach selected was to choose case study areas that would be representative of conditions that exist in key or critical areas of the state. The three sites selected were river segments that support well known riparian deciduous forests within the San Pedro,

Santa Cruz, and Verde River watersheds. Figure 1 shows the location of groundwater basins and stream segments selected for detailed case studies. Chapter 4 of this report provides a detailed hydrologic assessment of each of the riparian case study areas.

Objectives

Specific objectives of the study were to: (1) review and research methods for assessing the impacts of groundwater pumping on the floodplain aquifer, adjacent river, and riparian ecosystem, (2) review existing literature and construct ecological models to quantify the relationships between groundwater levels, streamflow volumes and health and vigor of riparian vegetation, and (3) evaluate hydrologic impacts at case study sites in southern and central Arizona.

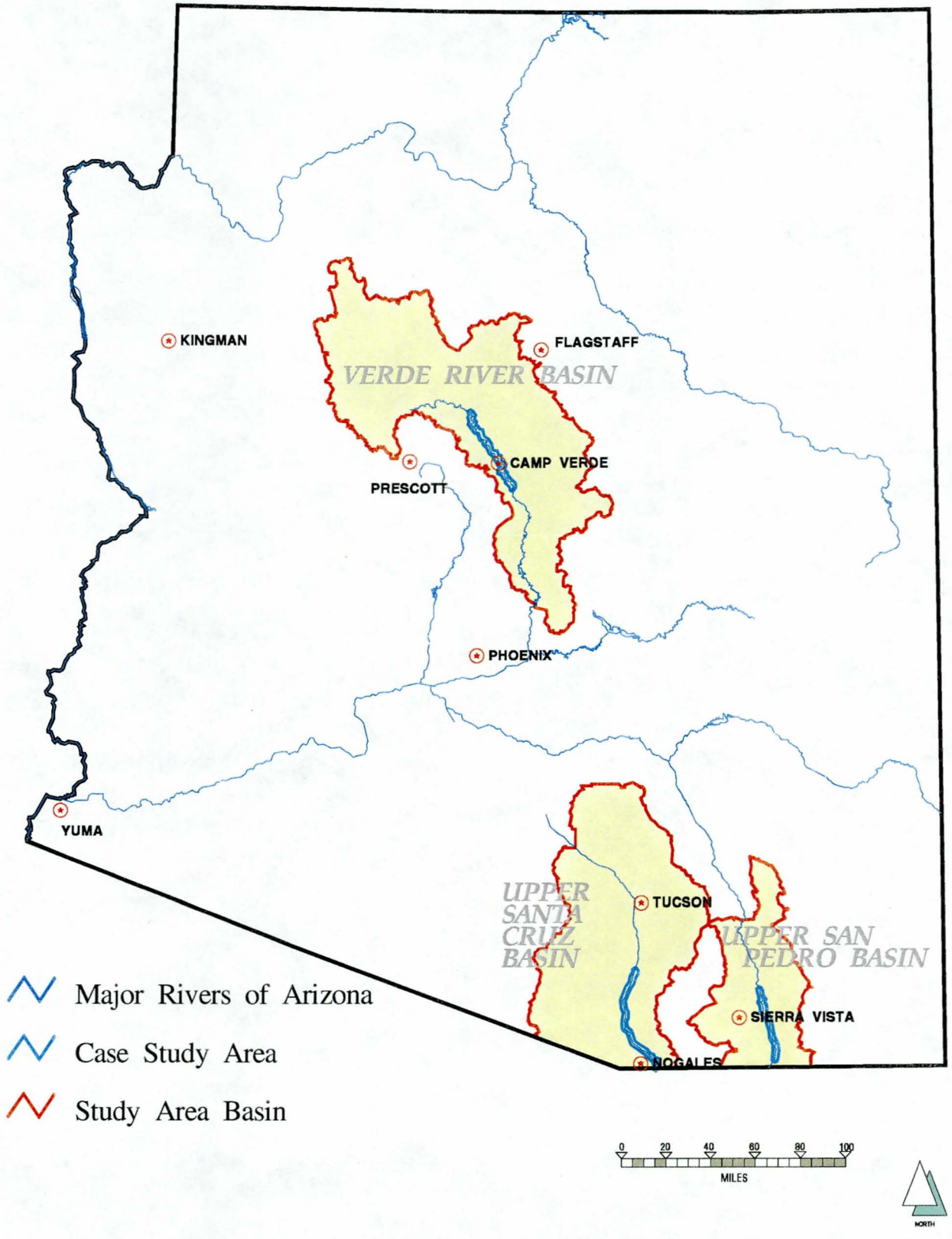
Chapter Organization

This chapter, the Hydrologic Report, includes the following sections:

- Section II, **Introduction**; the remainder of this section describes the approach and methods undertaken, briefly describes riparian ecosystem functions and values, and provides an overview of how Arizona's overall physiographic and climatic setting relates to water resource availability.
- Section III, **Hydrogeologic Analysis**; discusses hydrologic concepts necessary for an understanding of the issues. It provides: (1) a general discussion of the hydrologic effects of groundwater withdrawals, (2) descriptions of methods used to quantify impacts, and (3) a discussion of the hydrologic effect of surface water diversions.
- Section IV, **Summary**; discusses the major findings of the hydrogeologic analysis.
- Section V, **References**; provides a listing of references cited in this chapter.
- Section VI, **Glossary of Terms**; provides definitions of technical terminology used within this report.

Figure 1

GENERAL LOCATIONS OF THE CASE STUDY AREAS



RIPARIAN VEGETATION AND HYDROLOGIC INTERACTIONS

Overview

This section provides an overview of riparian vegetation functions and hydrologic systems interactions. For a more detailed discussion of factors that affect riparian ecosystems abundance and distribution within Arizona, refer to Chapter III , the Ecologic Report.

Riparian systems are dynamic by nature. Stream channels are continually aggrading (e.g. building up) and degrading (e.g. down cutting), while riparian vegetation establishes episodically in response to flood flows and associated processes. Surface water and hydraulically connected groundwater all contribute to the type of riparian community present, influencing its density, vigor, composition, and ability to continue to regenerate and maintain itself at a given site. Surface water and groundwater are necessary together or individually, to initiate, maintain and complete various plant lifecycle stages and functions. In return, riparian vegetation plays an important role in stream and alluvial aquifer system maintenance and development.

Riparian Vegetation/Groundwater Relationships

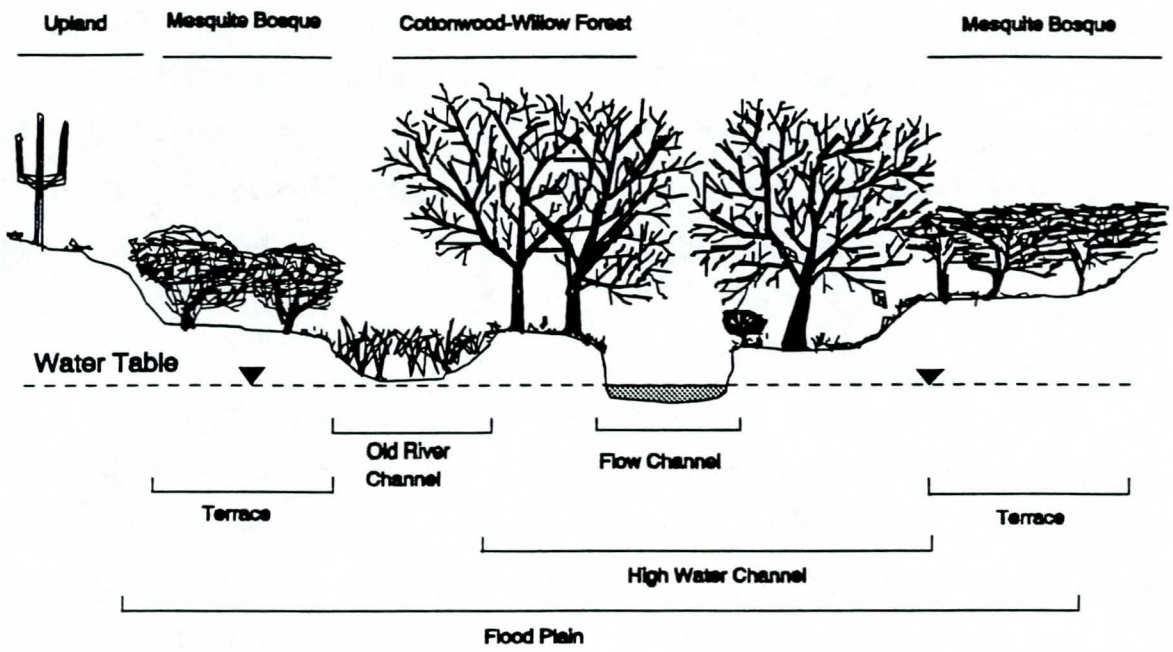
In southwestern deserts, where evaporation exceeds precipitation, groundwater is a critical source of water for maintenance of many riparian zones. Groundwater available for riparian vegetation occurs in alluvial aquifers which directly support riparian systems. These areas are generally located adjacent to stream edges where water level elevations have small gradients and are essentially flat in the area of the riparian zone. Stream channels occupy low elevations within the river valleys. The depth to water increases as the land surface elevation increases with distance outward from the stream channel. Depth to groundwater plays an important part in the distribution of most riparian vegetation, therefore the greater the depth to water below the land surface, the less abundant the vegetation. Localized, perched aquifers located at or adjacent to the land

surface can and do support some riparian habitat, however, these aquifer systems are not extensive.

All riparian species are distributed across their respective floodplains according to moisture gradients primarily associated with depth to groundwater (Figure 2). As depth to groundwater increases, riparian stands generally display reductions in vegetative parameters such as height, foliage or leaf area and basal area (i.e. stem or trunk area). Intercepted precipitation and overbank flooding of surface flows serve as additional water sources and assist in lifecycle functions.

One common riparian species, Fremont cottonwood (*Populus fremontii*), is found along alluvial Sonoran desert streams. Seedlings of this species are located closest to main channels, typically on point bars, secondary channels, or cut-off channels, while older trees are found on floodplains several hundred meters from the primary channel (Everitt, 1968; Bradley and Smith, 1986). This age segregation occurs because germination and establishment of this species occurs along active channels. As stands mature and develop, they act as barriers, slowing flood flows and trapping sediment from succeeding flood events. Therefore, the vegetation aids in floodplain aggradation processes by internally binding or holding the soil together, trapping floodborn sediment and increasing resistance to water flows. These actions, coupled with point bar progression, help reduce water flow, stabilize newly deposited material, and increase bank water storage capacity. As time progresses, the maturing stand is found on land located at progressively higher elevations above the aquifer and away from the active channel.

Figure 2. Schematic of Riparian Floodplain



Riparian Vegetation/Surface Water Relationships

Nearly every riparian vegetation type in Arizona is dependent on surface water. Surface flow laterally recharges riparian soils, moistens floodplain soil surfaces during overbank flood flows, and transports new sediments and seeds. Where surface water and groundwater are hydraulically connected in riparian ecosystems, surface water recharges alluvial aquifers and raises water levels.

The water supply in a surface water system is controlled by precipitation and regulated through interactions between geology, soils and vegetation. Precipitation on impermeable soil and bedrock will enter the channel system rapidly. Conversely, precipitation on permeable, well-vegetated soil will enter the groundwater system and may not reach a

main channel for many seasons. One way floodplain vegetation and the stream channel interact is through temporary water storage in the streambanks that affect normal and high flows. Both deep rooted woody and fibrous rooted herbaceous species aid to stabilize soils, increase organic matter content, and trap silt and clay which improves the water holding capacity of streambank soils. The available water storage capacity in some streambanks can be significant enough to reduce flood peaks (Freeze and Cherry, 1979). The resulting sustained flow and reduction in peak flood events aid to support healthy riparian ecosystems.

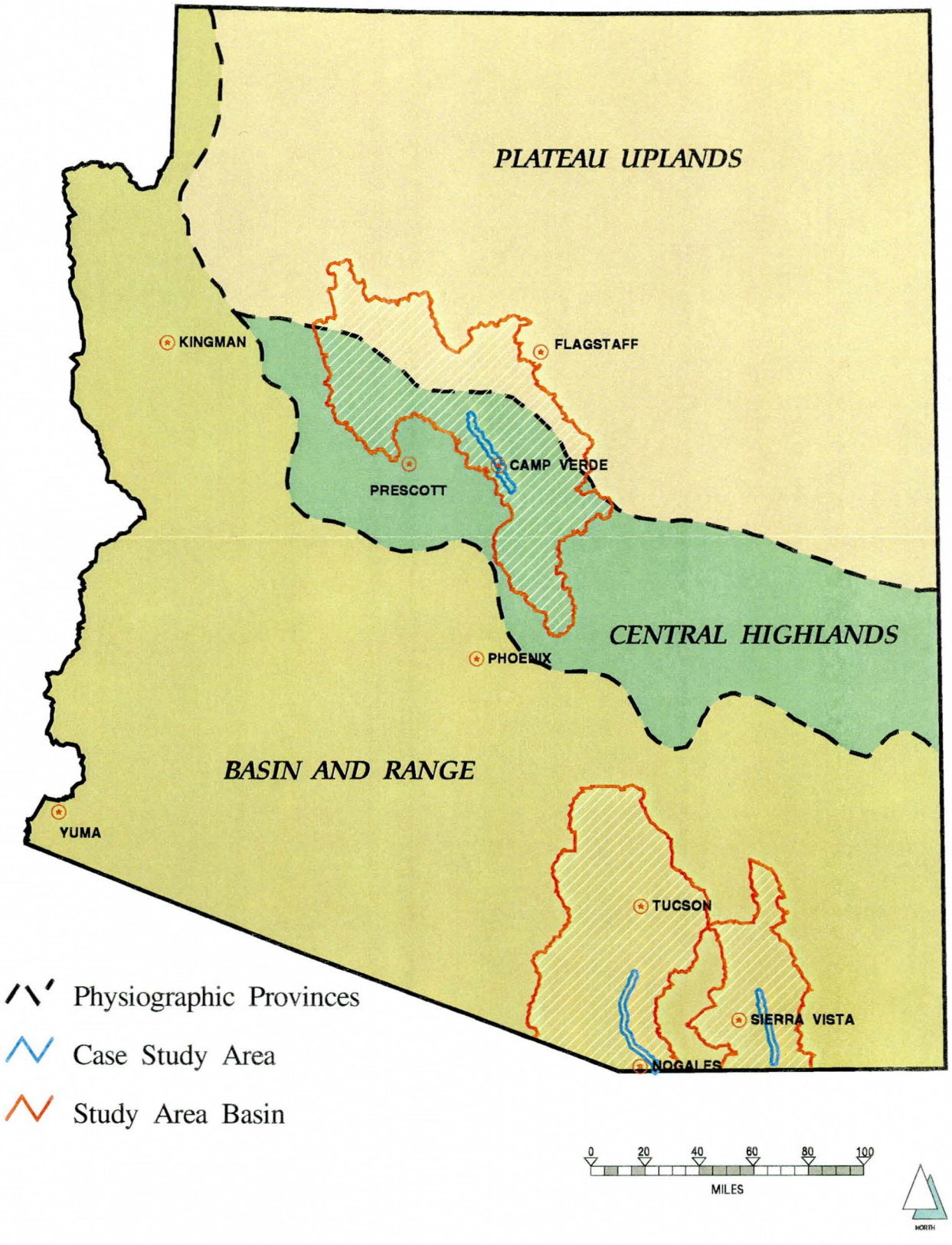
Watersheds that lack sufficient vegetative cover and have been subject to sheet and gully erosion can develop rapid, concentrated surface runoff which increases peak flows, promotes down cutting and produces large amounts of sediment. While channels transport increasingly more floodwater without significant overbank flooding, the elevated terrace adjacent to the eroded channel becomes increasingly more xeric. In addition, as channels are downcut into alluvial aquifer systems, these systems release water into the channel until the water level in both the channel and the aquifer achieve stability. The result is an increased depth to groundwater and a channel that must widen prior to reassuming the aggradation process.

PHYSIOGRAPHIC SETTING

The State of Arizona encompasses about 114,000 square miles of land that exhibits an enormous geographical diversity. Arizona can be subdivided into three major geographic regions or physiographic provinces that exhibit similar topography, elevation, climate, geology, and hydrologic characteristics; they are the Basin and Range Lowlands, the Plateau Uplands, and the Central Highlands Provinces (Figure 3).

Figure 3

PHYSIOGRAPHIC PROVINCES OF ARIZONA



The Basin and Range Lowlands province of southern Arizona is characterized by elongated, alluvium-filled valleys separated by north-south trending mountain ranges. Most of the groundwater withdrawals in the state occur here because of the extensive agricultural and urban areas located in the Salt River Valley and Lower Santa Cruz Valley (USGS, 1986). The San Pedro and Santa Cruz River study sites are located within the southern Basin and Range Lowlands Province.

The Plateau Uplands province covers the northern portion of the state. Groundwater development is greater in this area than in the Central Highlands, but is small in comparison to the Basin and Range Lowlands province. Most groundwater is pumped from regional aquifers which consist of layered sedimentary rocks, and locally from thin deposits of alluvium that form unconfined aquifers along some streams. Groundwater is used mainly for agriculture, domestic, and industrial purposes in population centers located within this region.

The Central Highlands province is the smallest of the three provinces and forms the transition zone between the Basin and Range Lowlands province to the south and the Plateau Uplands province in the north. Groundwater is obtained from thick alluvial deposits, layered sedimentary rocks, thin alluvial deposits along major streams, and locally from fractured crystalline, sedimentary and volcanic rocks. The Central Highlands province contains most of the states remaining perennial streams including the Verde, Salt, and Upper Gila Rivers. The location of Arizona's perennial streams is shown in Figure 4 with respect to the physiographic provinces.

CLIMATE

The climate of Arizona ranges from arid to humid. However, throughout most of the state climate is predominantly arid to semiarid, with the exception of a few isolated areas at higher elevations. In general, annual precipitation is low and temperatures are high. As

a result, insufficient precipitation is available for crop production and agriculture depends primarily on irrigation.

When viewed in an ecological context, precipitation totals and evaporation have the greatest effect on the availability of water necessary to sustain native vegetation. Precipitation varies from 3-30 inches per year and evaporation averages from 70-80 inches per year, depending on location and elevation. Thus, due to this moisture deficit, riparian vegetation is limited to areas where hydrologic conditions support adequate water supplies.

Climatic conditions in Arizona are extremely variable both spatially and temporally. Much of the spatial variability is directly related to the diversity in elevation between the low-lying southern deserts and the mountainous central highlands (Smith, 1956; Anderson and others, 1990). Temporal variability is inherent to semiarid desert regions. To illustrate the diversity of climatic conditions, Table 1 provides a summary of precipitation and temperature ranges for weather stations located within the watersheds of the three case study areas.

In general, an increase in elevation corresponds to an increase in precipitation and a decrease in temperature. However, the Colorado Plateau region represents an exception. Even though it is approximately 5,500 feet above the southwestern deserts, it is one of the driest areas in the state (Sellars and Hill, 1974).

Precipitation

Precipitation in the study areas is generally low and exhibits high variability of annual rainfall totals. Total annual precipitation is approximately 11-12 inches per year in the lower elevations of the valleys of the San Pedro, Santa Cruz and Verde Rivers (Table 1). Long term variability of precipitation is important since periods of drought set the lower

Table 1
Climate characteristics within the San Pedro, Santa Cruz, and Verde River study areas

STATION NAME	PERIOD OF RECORD	ELEVATION (Ft.)	MEAN ANNUAL PRECIPITATION (In.)	MEAN ANNUAL TEMPERATURE (Deg. F.)
SAN PEDRO RIVER				
APACHE POWDER COMPANY	1944-1990	3690	13.18	62.25
BENSON 6 SE	1990-1991	3690	11.99	62.75
FAIRBANK 1 S	1909-1973	3850	11.49	57.95
Y LIGHTENING RANCH	1939-1992	4550	13.63	No Data
SIERRA VISTA	1982-1992	4600	17.62	62.45
TOMBSTONE	1893-1992	4610	15.92	63.60
FORT HUACHUCA	1900-1981	4670	16.11	62.00
SANTA CRUZ RIVER				
SAHUARITA 2 NW	1956-1972	2690	12.85	67.10
NOGALES 6 N	1952-1992	3560	17.54	60.90
SANTA RITA	1950-1992	4300	22.59	64.15
VERDE RIVER				
BARTLETT DAM	1940-1992	1650	13.30	70.65
HORSESHOE DAM	1948-1992	2020	15.17	No Data
CHILDS	1915-1992	2650	17.92	64.35
COTTONWOOD	1949-1977	3380	11.86	61.75
TUZIGOOT	1977-1992	3470	14.00	62.85
IRVING	1951-1992	3800	20.53	No Data
BEAVER CREEK RANGER STATION	1957-1992	3820	15.19	61.60
JEROME	1857-1992	4950	18.83	59.50
BLUE RIDGE RANGER STATION	1967-1992	6880	20.86	47.60
HAPPY JACK RANGER STATION	1969-1992	7480	27.07	45.25
SOURCE: NATIONAL CLIMATE DATA CENTER, 1992				

persistence limit for some plant and animal species. To compensate for the deficiency and variability in rainfall, agricultural, municipal and industrial users rely heavily on surface water storage and groundwater pumping to supplement water supplies. Diversion of these water resources can detrimentally impact riparian vegetation and wildlife species dependent on the availability of these resources.

Precipitation is the climatic variable that has the greatest influence on hydrology and is the ultimate source of all surface water and groundwater resources. Average annual precipitation ranges greatly throughout Arizona, from less than 3 inches in the Yuma area to nearly 30 inches in the higher elevations along the Mogollon Rim and in the White Mountains (Anderson and others, 1990).

Two distinct periods of precipitation occur in the state: (1) a summer season, generally during July and August, and (2) a winter season, from December through March. The wettest months are commonly July and August, and in the southeastern part of the state nearly half of the total annual precipitation falls during this period. In the central and western sections of Arizona, total seasonal precipitation is greatest in the winter, however individual monthly precipitation totals are higher in the summer (Sellars and Hill, 1974). The driest months in Arizona are May and June with a less severe dry period typically occurring in October in the southern half of the state and November in the northern half (Sellars and Hill, 1974).

Summer season precipitation is characterized by high intensity localized storms of short duration (Anderson and others, 1990; Sellars and Hill, 1974). Moisture for summer storms comes primarily from the Gulf of Mexico, and moves roughly southeast to northwest across the state. Summer thunderstorms are most intense over the mountainous sections of the state, where combined effects of thermal heating, orographic uplift, and convergence of air on the windward side of mountain ranges causes the moist air to rise (Sellars and Hill, 1974).

Winter precipitation generally covers large areas and is generated from low intensity storms that are of longer duration than summer storms. Most of the precipitation occurring during the winter months in Arizona is associated with large scale cyclonic storms originating in the Pacific Ocean that move roughly west to east across the state. More than 75 percent of winter precipitation falls as snow in the higher parts of the state, including the Colorado Plateau and the mountain ranges that rise above 7,000 feet in the northwest, central, and southeast portions of the state (Sellars and Hill, 1974).

Evapotranspiration

Evapotranspiration is defined as water removed from an area by evaporation from water surfaces, evaporation from moist soils, evaporation from leaf surfaces, and transpiration by vegetation. Evapotranspiration (ET) impacts the availability of water resources by direct depletion of surface water and groundwater and by reducing the amount of recharge to an aquifer. The amount of rainfall available to recharge an aquifer is the residual of precipitation less ET. Evapotranspiration accounts for a major loss of water to the hydrologic system and in some areas of the state it represents the principal component of groundwater discharge (Anderson and others, 1990).

ET rates are potentially high in Arizona due to high average temperatures and low average rainfall. Average daily temperatures range from the middle 90's (F°) below 500 feet elevation to the high 50's (F°) at elevations above 8,000 feet (Sellars and Hill, 1974). Therefore, ET rates are greatest at lower elevations with high average temperatures. ET rates also vary seasonally in direct response to seasonal variations in temperature. In most sections of the state, temperatures increase thirty to forty degrees between January and July. Direct recharge of rain falling on the land surface is minimal because most precipitation is returned to the atmosphere due to high ET rates.

Climate Summary

Climatic variables that influence the water supply available to riparian vegetation to the

greatest degree in the study areas are precipitation and evapotranspiration. Major climatic changes would result in corresponding changes in streamflow availability and aquifer storage, however, quantification of the effects of climate on runoff, groundwater recharge, and riparian health is not within the scope of this report.

The relationships between climate and hydrology as it relates to riparian ecosystems is summarized below:

1. In the primarily arid southern portion of the state most rainfall occurs during the summer months when high temperatures result in high evapotranspiration rates. High intensity summer storms produce heavy rains that often exceed the infiltration capacity of the soils. The high volume of precipitation associated with these storms results in a concentration of runoff in major streams draining the watersheds.

2. Most precipitation occurs during the winter in central and western Arizona and the cooler temperatures result in less evaporation losses and greater infiltration to the aquifer. Much of the winter precipitation falls as snow in the higher elevations, therefore runoff tends to be extended over a longer period increasing the infiltration potential.

3. Direct recharge from rainfall is generally small in Arizona because little precipitation is available for recharge and losses due to evapotranspiration are large.

4. The summer months of May and June receive the lowest precipitation amounts and experience high evapotranspiration rates. Summer is also the peak growing season when demands for water for both natural and agricultural vegetation is greatest, therefore, impacts to riparian vegetation are most likely to occur during the summer season.

HYDROGEOLOGIC ANALYSIS

OVERVIEW

To evaluate the response of riparian vegetation to groundwater withdrawals and surface water diversions, an understanding of the stream-aquifer system and related riparian ecosystem is necessary. For the purpose of this discussion the stream-aquifer system is generally composed of one or more aquifers in direct hydraulic connection with a perennial stream, and a riparian community dependent on the water resources.

Certain species of riparian vegetation (hydro-riparian) survive only where perennial streamflow and shallow water levels provide a permanent source of water within reach of the plant's roots. A stream-aquifer system that supports this type of riparian vegetation is hydraulically connected, and the water level elevation in the aquifer is equal to the water surface elevation of the stream. The water table is essentially flat in the proximity of the stream, but water levels may be higher or lower than the stream with increasing distance laterally outward from the stream. Other, more drought tolerant types of riparian vegetation, occur along intermittent or ephemeral streams where streamflow is seasonal or only in direct response to storms. There is no groundwater-surface water connection for much of the time in this type of stream aquifer system. Only riparian areas associated with perennial streams were addressed in this report.

Quantification of impacts to the hydrologic component of the stream-aquifer system may be accomplished using a variety of established methodologies which allow the assessment of surface water and groundwater resources. The availability of streamflow and groundwater must first be quantified prior to addressing hydrologic impacts to a stream-aquifer system. Streamflow is typically measured at USGS stream gaging stations and may be quantified using statistical methods. However, runoff is highly variable in Arizona and the prediction of available surface water supply has a corresponding high

degree of variability. Groundwater resources are less variable than surface water supplies due to the relatively slow movement of groundwater through the aquifer and ability of an aquifer to store large volumes of water.

Groundwater level declines can be directly determined by measuring water levels in observation wells in the riparian area. Monitoring changes in groundwater levels through time provides the basic data needed to predict impacts to riparian areas. Observation wells are often not present in adequate numbers in the area of interest to accurately define the groundwater surface. To resolve this situation, installation of additional wells to fill in data gaps can be accomplished quickly and inexpensively in riparian areas where groundwater levels are shallow.

Another method that can be used to determine impacts to both the groundwater and surface water system separately or together is development of equations or models that describe the physical systems in mathematical terms. Mathematical techniques include both analytical and numerical methods. These mathematical procedures allow quantitative assessment of the response of the aquifer to groundwater withdrawals in terms of the hydraulic head or water levels in the aquifer, which then can be used to determine water available for riparian vegetation. Application of mathematical methods requires knowledge of the hydraulic properties of an aquifer and an associated stream, groundwater level elevation data, location of a well in relation to a riparian area, and the rate and duration of groundwater pumping and streamflow diversion. These data variables are used to construct models which in turn can be used to predict the response of an aquifer and an adjacent, hydraulically connected surface stream to surface water diversions or pumping stresses. Accurate model predictions rely heavily on an adequate conceptualization of the hydrologic system as well as accurate hydrologic data that are well distributed spatially and temporally.

Methods used to assess impacts to the hydrologic system resulting from groundwater withdrawals and surface water diversions are initially described in this section of the report in a general sense. Specific examples are provided to determine impacts within each of the three case study sites located on the San Pedro, Santa Cruz, and Verde Rivers (refer to Chapter IV., Case Studies). Methods utilized include (1) direct measurements, (2) analytical methods, and (3) numerical models.

A sub-regional numeric groundwater flow model was developed and used as part of this study. This model was based on the MODFLOW code developed by the USGS (McDonald and Harbaugh, 1984). It was patterned after a small area of the USGS Upper San Pedro by model by Freethey (1982). As a result, the time and cost requirements associated with development and use of the model are minimal when compared to regional models. The accuracy of each of the methods described above were examined by comparing predicted results to actual water levels found at each site.

It is not feasible to assess impacts to all riparian areas in the state based on a single methodology. This is primarily due to great diversity in hydrology, geology, and ecology. Selection of the appropriate method, in general, should be based on the availability of hydrologic data and the degree of accuracy required in the prediction. Accurate solutions to mathematical methods require that the limiting assumptions are valid for the area being assessed. In general, these methods are useful for alluvial aquifers that are hydraulically connected to perennial streams and not for consolidated aquifers where subsurface flow is primarily through fractures, joints, and solution channels. The applicability of each method is discussed in greater detail in the Case Studies report.

HYDROLOGIC CONCEPTS

A thorough evaluation of the hydrologic impacts to riparian areas requires that some key hydrologic concepts be defined. This section of the report provides a brief discussion of

hydrologic principles and concepts that relate to surface water, groundwater and stream-aquifer systems.

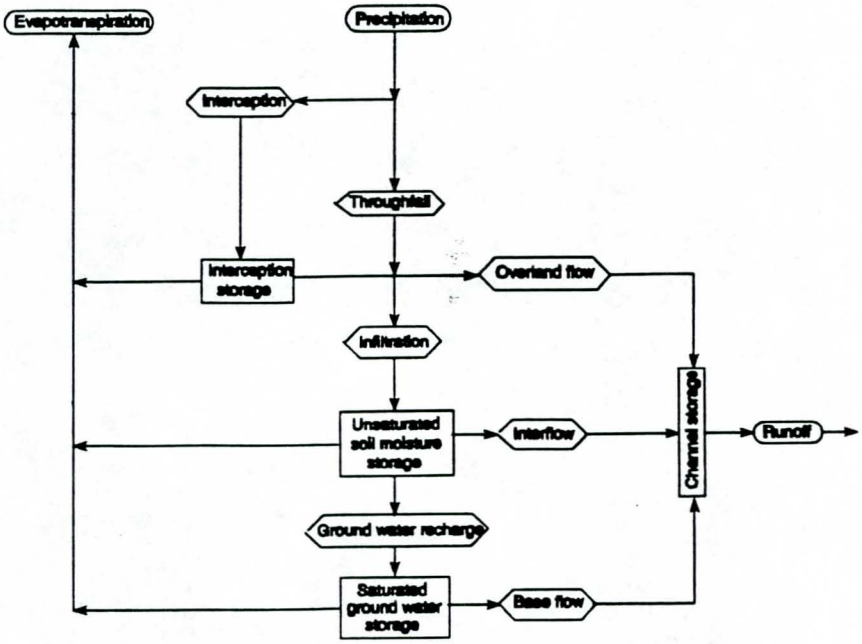
Water continuously circulates in nature through a complicated process of evaporation, precipitation, interception, transpiration, infiltration, percolation, storage, and runoff. The "hydrologic cycle" shown in Figure 5 illustrates the distribution of water stored underground, flowing over the land surface, and in the atmosphere. Because the natural components of the hydrologic cycle are unevenly distributed in time, the magnitude of streamflow expressed in a particular stream reach and the volume of groundwater storage within an aquifer naturally fluctuate through time.

Surface Water

Streamflow is the occurrence or discharge of water in a natural channel (Langbein and Iser; 1961; Schulz, 1973). Water that comprises streamflow is ultimately derived from precipitation falling on the earth's surface, however this water may reach the stream channel through different routes. Streamflow is comprised of three main components including surface runoff, interflow, and base flow (Linsley and others, 1975). Surface runoff is precipitation that flows over the land surface and accumulates in stream channels. Surface runoff from precipitation varies widely throughout Arizona depending primarily on elevation and geographic location. Interflow is precipitation that infiltrates and moves laterally through the unsaturated zone above the water table (vadose zone) until draining into a stream channel. Streamflow includes baseflow where the water table intersects a stream channel discharges groundwater to a stream (Figure 6). Stream reaches receiving baseflow are referred to as "gaining reaches."

Baseflow can maintain streamflow during periods when there is negligible runoff, therefore, this component is critical for maintaining certain types of riparian areas. The proportion of direct runoff to baseflow varies between basins, with time, and from one

Figure 5. Hydrologic cycle flowchart and diagram (Freeze and Cherry, 1979)



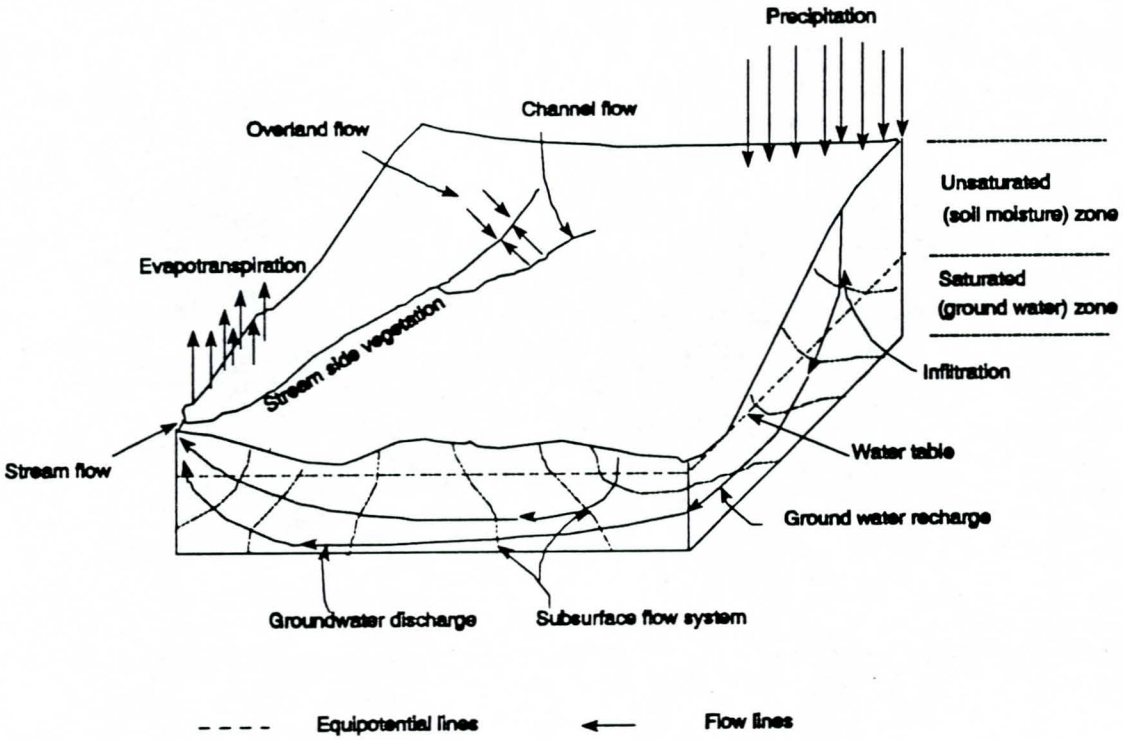
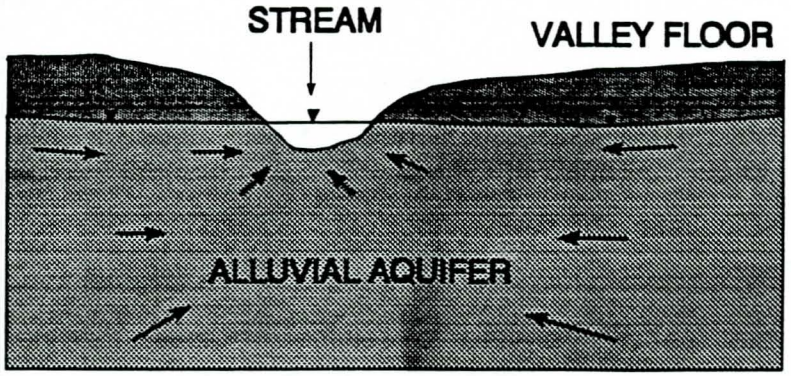
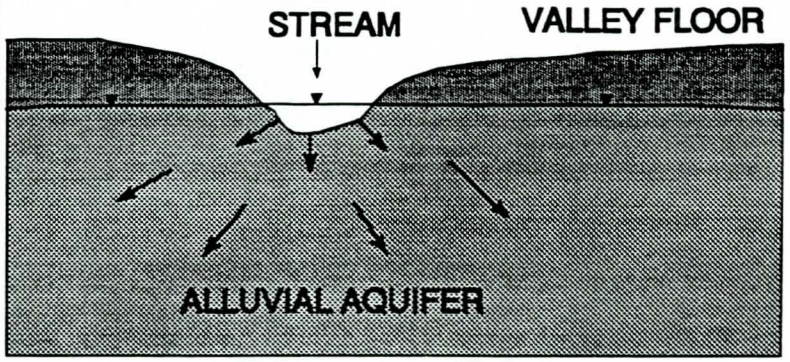


Figure 6. Diagram showing perennial, intermittent and ephemeral stream types

Perennial Streams

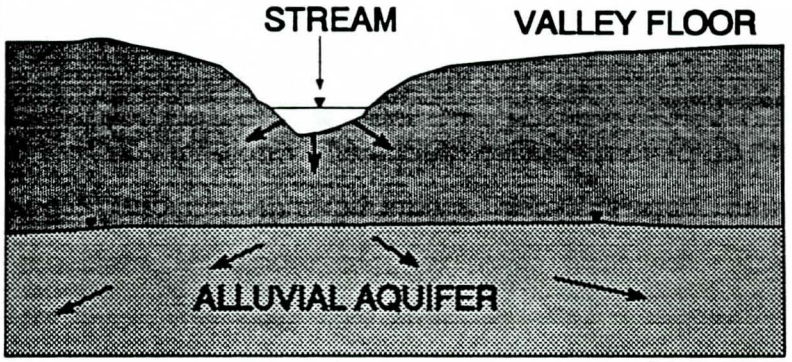


Gaining Reach



Losing Reach

Intermittent or Ephemeral Stream



Losing Reach

▼ WATER TABLE ← DIRECTION OF FLOW

location to another on a stream. It also varies seasonally depending on the amount of water used by riparian vegetation and diverted for cultural uses. It is at a maximum during the winter when stream depletions are at a minimum. Baseflow is at a minimum during the summer when ET and cultural depletions are most pronounced. Baseflow can be estimated at a streamgage by visually separating the runoff component from total streamflow.

The portion of streamflow contained within the stream alluvium is called "subflow." Subflow supports riparian areas throughout the state by providing shallow groundwater immediately adjacent to a stream. Arizona contains many small perennial streams that exhibit low flows during certain times of the year. Perennial flow may be "interrupted" by reaches with no surface flow, however, there is often a significant volume of subflow moving downgradient through the alluvium. Streamflow is readily observable and can be accurately measured using standard USGS streamgaging procedures. Subflow, however, is not as readily observable and its measurement is less direct than streamflow. The technical criteria necessary to define subflow include:

1. Water must flow through the sand and gravel constituting the bed, banks or land adjacent to the stream. The stream alluvium can extend vertically and horizontally to another geologic unit.

2. Subflow must be in direct hydraulic connection with the stream.

3. The water surface elevation of the subflow must have the same gradient, elevation, and direction of flow as that of the surface stream.

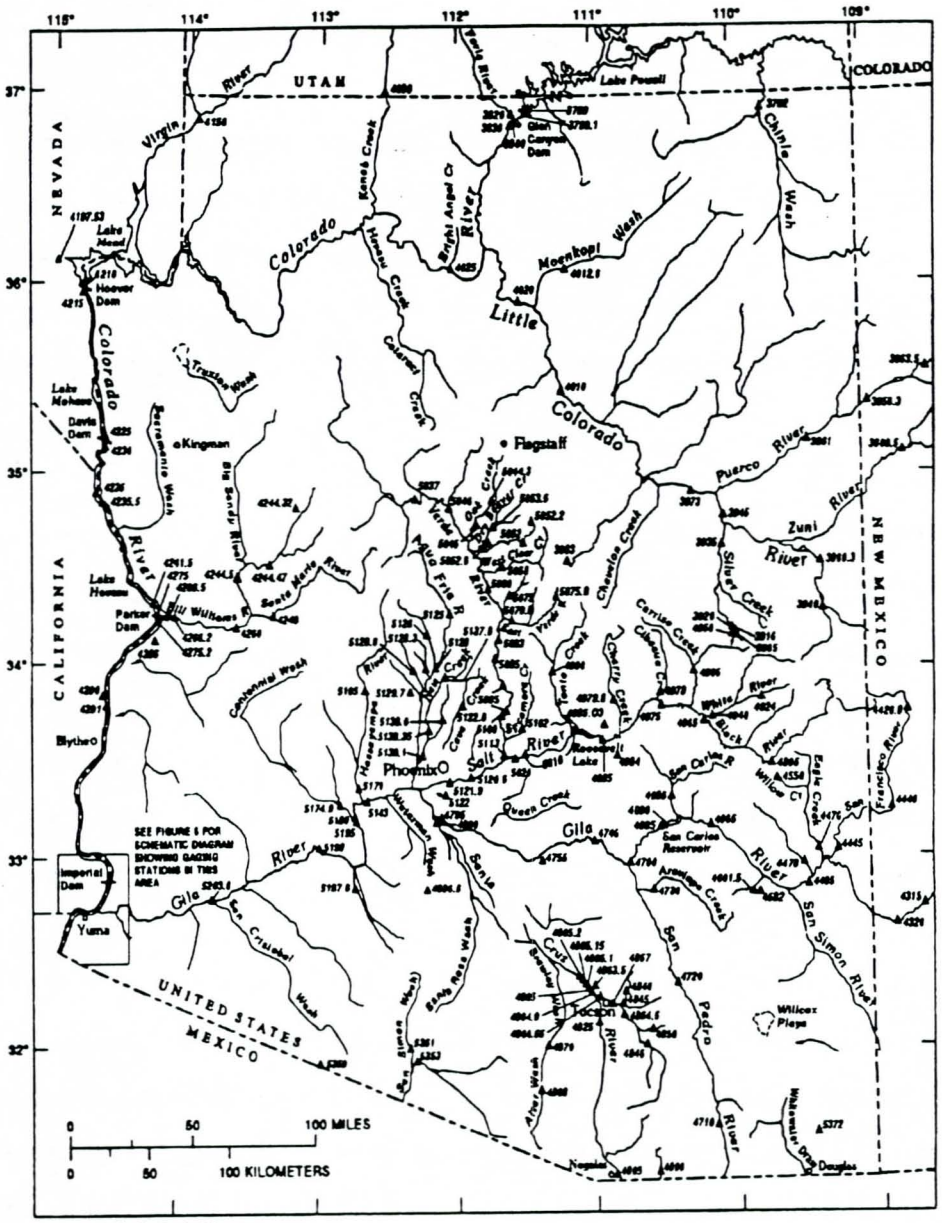
4. Withdrawal of subflow must diminish surface streamflow directly and appreciably. Excessive withdrawal can deplete streamflow, sever the hydraulic connection and eliminate the subflow which may have existed.

Rivers and streams are classified as perennial, intermittent, or ephemeral depending on the duration of surface flow throughout the year (Figure 6). Perennial streams flow continuously throughout the year. Intermittent streams flow for long periods and are typically seasonal in nature, flowing continuously during most of the year when water is contributed from baseflow or surface runoff. Ephemeral streams flow only in immediate response to precipitation events and do not derive any of their flow from groundwater discharge. Many of Arizona's low-flow perennial streams exhibit "interrupted-perennial" reaches where streamflow at the surface is lost, but flow continues through the stream alluvium as subflow. These reaches are referred to as "losing reaches."

Streamflow is measured by the Water Resources Division of the USGS at gaging stations on a limited number of streams throughout the state. These records are critical for assessing the availability of streamflow, and in most instances provide the only available direct source of historical hydrologic data for an area. Streamflow records may be estimated for ungaged streams and extended for streams with short periods of record. Methods available to estimate flows include runoff-area relationships, regression analysis of gaged to ungaged streams, and relating tree-ring data to runoff. These methods are limited in that only annual flows are estimated. Data collected by the USGS is published annually in their reports entitled "Water Resources Data Arizona" (USGS,1992). During water year 1992, discharge records were published for 182 streamflow gaging stations throughout the state. A map showing the location of active gaging stations is presented in Figure 7.

Determination of the flow characteristics of a stream requires a record of flows over an extended period, however the records for streamgages in Arizona can vary from a single year to over 50 years. Flows measured at a gage may not represent flows elsewhere on the stream due to the effects of intervening diversions and inflows to the system, differences in geology and watershed area, and gaining or losing reaches. Because

Figure 7. **Map showing the location of USGS streamflow gaging stations in Arizona during Water Year 1992** (USGS, 1992)



Base from U.S. Geological Survey State base maps, 1:500,000, Arizona, 1974; Nevada, 1965; New Mexico, 1965; and Utah, 1959

EXPLANATION

▲4465 STREAMFLOW-GAGING STATION AND ABBREVIATED NUMBER—Complete station number is 09466500

streamflow may vary considerably between gages, it is difficult to determine the exact impact to streamflow at a point on the stream that is not near a streamgage. Variations of streamflow volume can be determined at a gage site with accurate long-term records. However, some gage records are fragmentary or discontinuous and the data do not reflect streamflow conditions as they presently exist.

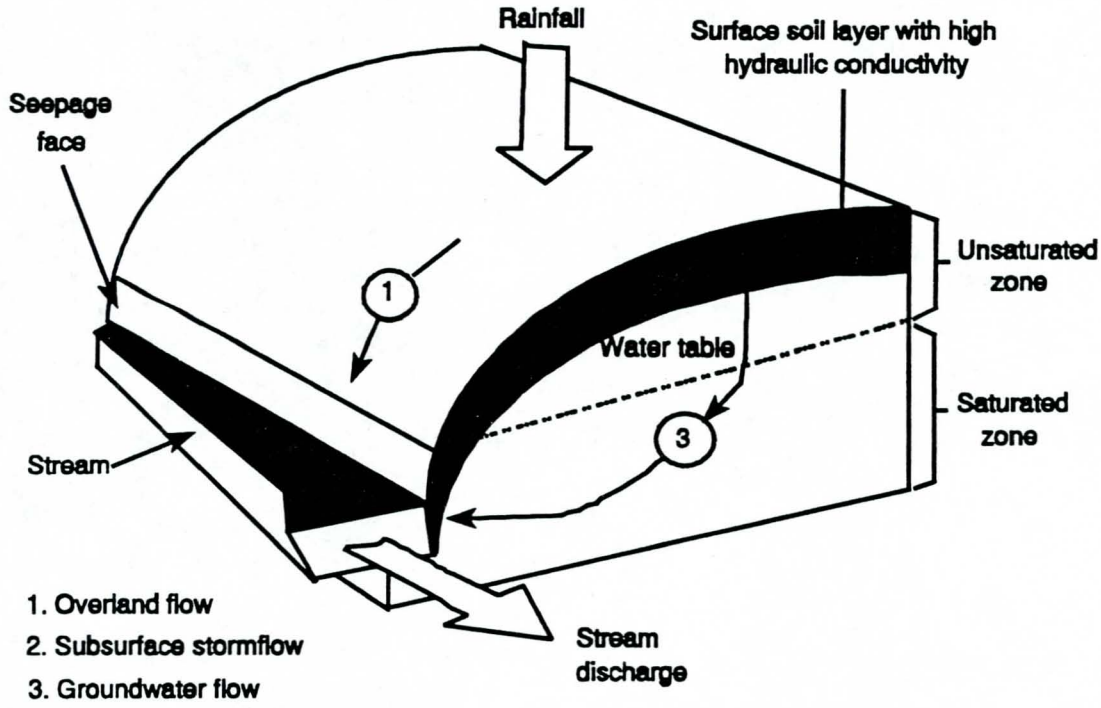
To have a good understanding of the surface water system in a particular reach, in addition to USGS gage records, diversions and return flows should be determined. Presently however, no state regulation requires surface water diversions to be measured because water rights have not been adjudicated. In areas where surface water diversions are not measured, estimates can be made by measuring the capacity of diversion canals and ditches.

Groundwater

Underground water occurs in two zones, the unsaturated or vadose zone and the saturated zone (Figure 8). The vadose zone lies between the land surface and the saturated zone and contains a combination of water and air. Water in this zone is at less than atmospheric pressure (i.e., it would not flow freely into an open well). The unsaturated zone is an important conduit for water to reach the groundwater zone. Groundwater is the subsurface water that occurs beneath the water table in fully saturated soils and geologic formations.

Geologic formations or rock units that are saturated and yield usable quantities of water to wells or springs are called aquifers. Most commonly, aquifers in the alluvial basins of the southwest are composed of unconsolidated materials derived from weathered and eroded particles of clay, silt, sand, and gravel. This type of aquifer material makes up the majority of the alluvial valley-fill aquifers in the Basin and Range physiographic province. Groundwater occupies the pore spaces or voids that occur in the alluvial material. Other

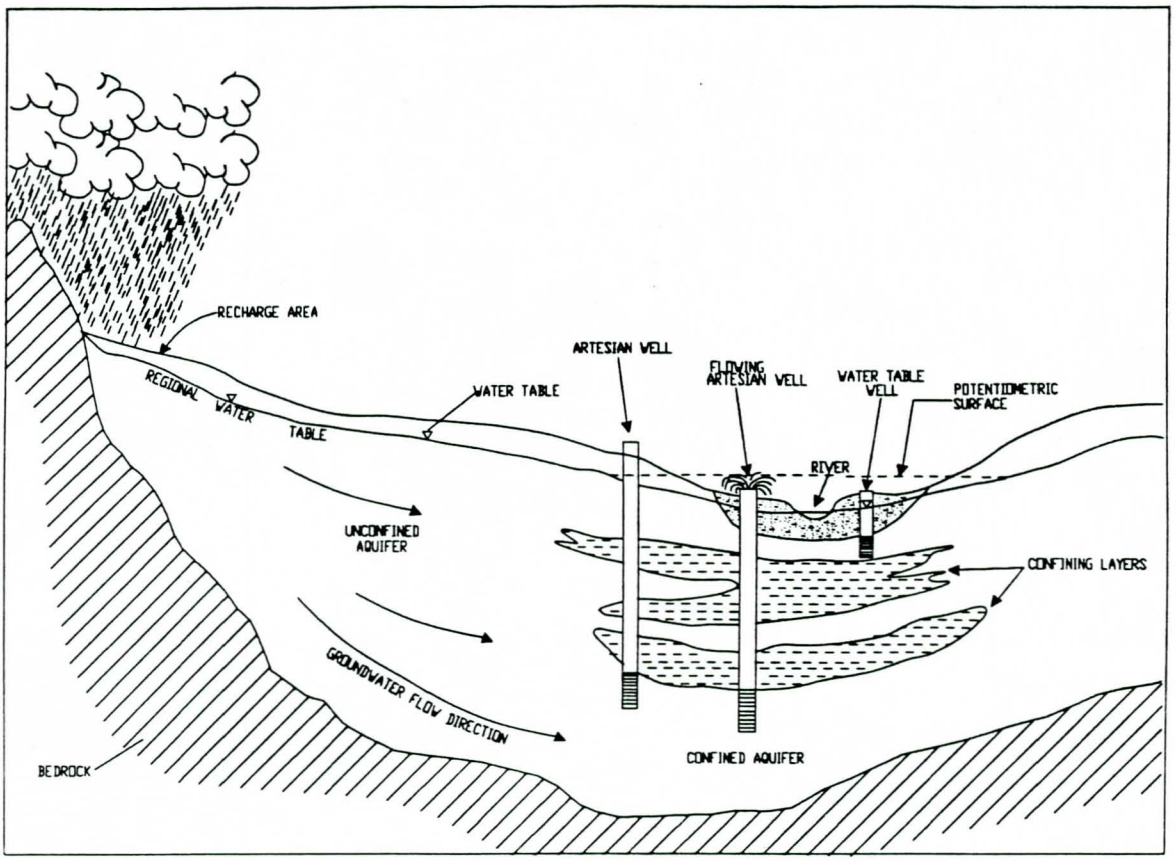
Figure 8. Diagram of groundwater zones (Freeze and Cherry, 1979)



aquifers that occur in the state consist of saturated consolidated formations. These types of aquifers consist of sedimentary, metamorphic, and igneous rocks that include limestone, sandstone, granites, and basalts. Water can occur in the fractures, joints, or solution cavities created both during and after the rocks were formed.

Groundwater may occur in an aquifer under unconfined or confined conditions (Figure 9). In unconfined aquifers, there are no hydrologic restricting units (e.g., clay layers), therefore, groundwater levels are free to rise and fall in response to atmospheric pressure. The water table is the point at which hydraulic pressure is equal to atmospheric pressure and is usually measured as the static water level in wells. Confined or artesian

Figure 9. Diagram of regional alluvial aquifer system



aquifers consist of water-bearing material bounded by much less permeable material, such as an overlying clay layer. This less permeable layer is termed an aquitard or aquiclude, which simply means it either retards or prevents the vertical flow of water from one layer to another. Because confined aquifers are fully saturated and under greater than atmospheric pressure, they do not have a free water table. The pressure head or potentiometric surface, by definition, is always above the top of the confined aquifer. If a well is completed in a confined aquifer, the water in the well will rise to correspond to the pressure or potentiometric surface. If the potentiometric surface is above the land surface, water will flow naturally to the land surface (e.g., flowing artesian well).

Aquifers serve as underground reservoirs by storing water from precipitation that has infiltrated into the ground. This natural recharge or addition of water to the aquifer occurs from direct infiltration of runoff flowing across alluvial fans bordering mountain ranges, or along stream channels adjacent to the alluvium. Recharge can also occur by groundwater movement from another aquifer system (e.g., from an underlying or overlying aquifer). Recharge can vary with such factors as precipitation amount and timing, land use and evaporation.

Groundwater within undisturbed alluvial basins usually flows from mountain fronts located at basin margins to the axis of the basin where it can be drained by a stream. Local barriers to flow, including pumping wells, may cause exceptions to the general flow directions in some basins. This can be quite severe as seen in the Salt River Valley, the Santa Cruz Valley, and in Pinal County. In these areas, groundwater discharge due to continuous pumping for agricultural, municipal, and industrial purposes has severely lowered water tables in the surrounding aquifers to the point where they are no longer drained by a stream. Other causes of groundwater discharge include evapotranspiration by vegetation during the growing season.

Stream-Aquifer Systems

Groundwater and surface water were historically considered as separate and distinct resources in Arizona. Accordingly, water laws were created to manage water resources based on this concept. In reality, groundwater and surface water form an interconnected hydrologic system in which quantities of water are exchanged between the stream and the aquifer based on changing hydrologic conditions. Therefore, quantification of groundwater-surface water interactions requires that a conceptual model of the stream-aquifer system be developed.

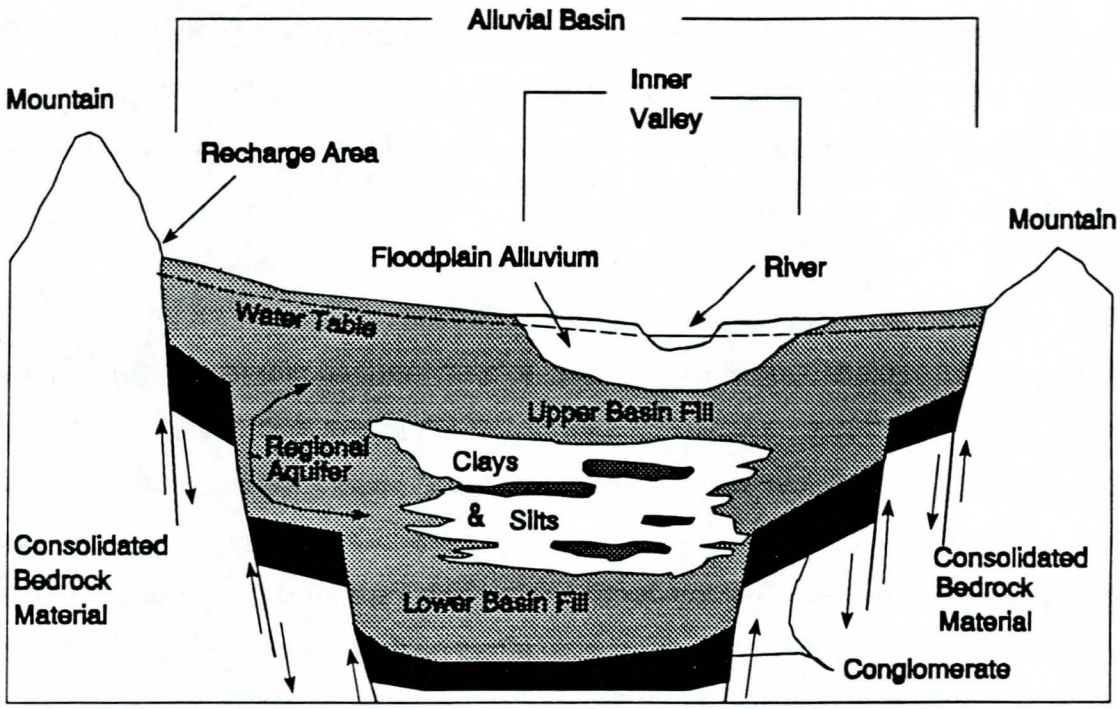
Two important types of stream-aquifer systems that are common in Arizona are: (1)

narrow valleys developed in hardrock formations typically located in mountainous terrain, and (2) broad alluvial basins lying between mountain ranges in southern and central Arizona. The first type of stream aquifer system consists of a narrow alluvial valley cut into impermeable hardrock. Stream alluvium composed of unconsolidated silt, sand, and gravel fills the channel and where saturated it forms a highly permeable aquifer. The impermeable hardrock forms a boundary that limits the extent of the aquifer. In this type of "single aquifer" system, a perennial stream developed on the alluvium is hydraulically connected to the underlying alluvial aquifer. Such an aquifer may be up to a few thousand feet wide and less than 100 feet thick and is characteristic of many of the aquifers found in the Central Highlands province.

The second type of stream-aquifer system consists of a large alluvial basin which is comprised of multiple aquifers. These aquifers consist of basin fill alluvium that can be several thousands of feet thick and many miles wide. The basin fill alluvium can be separated into various aquifer units depending on the site and complexity of the hydrogeology specific to each basin. Alluvial basin aquifer systems typically contain both confined and unconfined aquifers. Description of the aquifer system present at each case study area is discussed in detail in the case study section. Figure 10 provides an illustration of a multi-layered, alluvial basin aquifer system.

In addition to the multi-aquifer alluvial system, a floodplain aquifer is typically found within the central valley of the basin. The floodplain aquifer is formed from unconsolidated alluvial materials deposited by a stream. It can form an aquifer several hundred feet thick and several miles wide within the basin. These stream-aquifer systems are dynamic and interact through a constant exchange of water, from both surface water infiltration from the stream which recharges the aquifer and from groundwater discharge from the aquifer to the stream which provides baseflow.

Figure 10. Diagram showing an alluvial basin aquifer



The amount of streamflow may differ from place to place along a river. For example, during seasonal low flow periods in some streams, flow may completely disappear for a distance and then reappear downstream. This variation in flow is strongly dependent on the occurrence and direction of groundwater movement in an adjacent underlying aquifer. The hydraulic gradient indicates whether water flows toward the stream to supplement streamflow or away from the stream to recharge the aquifer. When the elevation of the water table in the aquifer adjacent to a stream is above the elevation of the streambed, groundwater flows toward the stream and is discharged to the streambed (Figure 6). This system acts as a drain for the aquifer, allowing water to move from the aquifer to the stream where it is expressed as baseflow.

An intermittent stream does not exhibit continuous flow. Natural use of water by riparian vegetation and/or cultural diversions may cause the water table to drop below the elevation of the streambed during certain times of the year, inducing streamflow to infiltrate through the bed of the stream to recharge the aquifer. When losses from stream infiltration exceed surface flow, the stream will cease flowing. Even though the surface flow of the stream ceases, subflow can still be found in the permeable alluvial sediments beneath the stream.

HYDROLOGIC EFFECT OF GROUNDWATER WITHDRAWALS

In a natural, unimpacted hydrologic system, stream and aquifer systems achieve an equilibrium where long-term system inflows equal long-term outflows. In this type of balanced system, streamflow reductions would only occur during extended drought periods where below normal precipitation would result in a corresponding reduction in runoff and aquifer recharge. In a developed watershed, direct streamflow diversions and groundwater pumping can have an appreciable affect on the hydrologic system depending on the timing and magnitude of depletions and the location of these diversions. Often, depletions occur in or near riparian areas, where surface water is available and groundwater is close to the land surface.

Extensive pumping of groundwater results in depletion of streamflow by inducing infiltration of surface water through the streambed or interception of groundwater that would have recharged the stream. If the volume of water pumped exceeds the amount of natural recharge to the groundwater system, a deficit will occur causing a reduction in groundwater storage and declining water levels. A continuous trend of declining water levels indicates overdevelopment of groundwater resources. The degree of overdevelopment depends on the magnitude, duration, and distribution of withdrawals, as well as the hydraulic properties of the aquifer (Anderson and others, 1990). Where multiple wells are clustered in close proximity to one another, the effect of pumping on the aquifer is compounded, as are impacts to any nearby stream.

Currently, the ADWR maintains records of wells within the state in two separate databases. These are the Wells-55 and the Groundwater Site Inventory (GWSI). The Wells-55 contains a listing of all registered wells. It includes all classes of water production wells such as irrigation, domestic, and municipal wells, in addition to non-production wells such as monitor wells, piezometers, and exploration wells. At present, the database contains listings for over 89,500 registered wells. For a description of the well identification numbering system used in Arizona, refer to Appendix B.

The GWSI database includes only wells inventoried, field inspected and mapped by the USGS or ADWR. The GWSI provides the most accurate account of wells in Arizona and currently includes over 37,700 wells. Wells are distributed irregularly throughout the state, mainly concentrated within a few major urban and agricultural areas as shown by the well density map (Figure 11). The Phoenix, Tucson, Pinal, and Prescott Active Management Areas (AMAs) together contain over one-third of the state's wells. Table 2 lists the number of field inspected wells located within the study areas and within the AMAs. It is also apparent from the well density map (Figure 11) that a large number of the state's wells are concentrated along rivers and streams. In some instances the streams have lost perennial flow and riparian areas declined or were eliminated as a result.

Table 2
Distribution of wells in selected areas of the state

LOCATION	NO. of WELLS	PERCENT OF TOTAL
Upper Santa Cruz River basin	3952	10.5
Upper San Pedro River basin	1411	3.7
Verde Valley basin	1214	3.2
Phoenix AMA	6577	17.4
Tucson AMA	4939	13.1
Pinal AMA	4282	11.4
Prescott AMA	738	2.0

Groundwater Level Declines

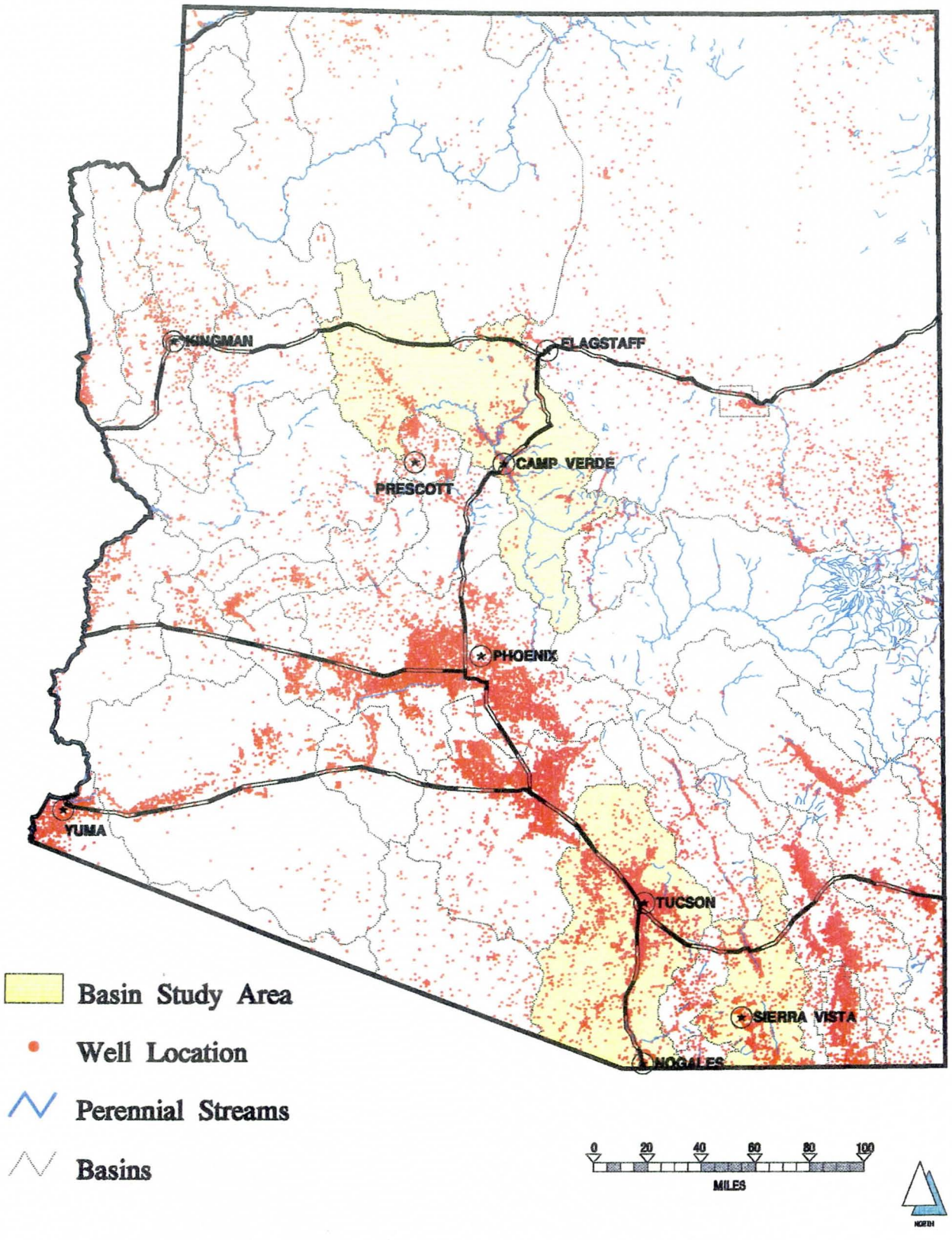
Declines in groundwater levels occur when the rate of pumpage exceeds the rate of natural and artificial recharge. Water level declines may be localized resulting from a single well, or regional in extent due to the many interfering cones of depression in an overdeveloped groundwater basin. No comprehensive statewide assessment of groundwater declines is currently available with the level of accuracy needed to predict impacts to riparian vegetation. Declines of only a few feet may have negative repercussions to the health of certain types of riparian ecosystems (refer to Chapters III and IV, Ecologic and Case Studies Reports, respectively).

Hydrologic data are collected throughout the state each year by the USGS and ADWR in an ongoing program to evaluate the groundwater conditions of the state. Sixty-eight groundwater basins and sub-basins lie within Arizona and each year several of these areas are selected for studies to evaluate groundwater conditions. The results of these studies are published as Hydrologic Map Series (HMS) reports showing depth to water in wells, water level altitude, and changes in water levels. HMS reports have been completed for 24 groundwater basins or sub-basins to date. Additional sources of hydrologic data may be available for areas of the state not presently assessed in an HMS report. These include water resources assessments prepared by the USGS or ADWR for special studies.

A statewide network of observation wells (index wells) is monitored annually to assess changes in hydrologic conditions through time. There are approximately 1,160 index wells throughout the state. However, most of these wells are not ideally located to monitor groundwater levels in or near riparian areas. The database is constantly being updated as additional information is collected. Out of the total number of wells in the state, a very small percentage of them are monitored on a regular basis. Of the few that are, it is unlikely that an adequate number of monitor wells would occur in a riparian area

Figure 11

WELL LOCATION/DENSITY



being assessed. In addition, the wells that do occur in a riparian area may not be effective as a monitoring tool for these areas. Most of the wells throughout the state are used for irrigation and other water supply purposes and penetrate multiple aquifers. Water levels from these wells reflect a regional rather than specific aquifer system. Usually, aquifer-specific data is not available, and when available is spatially non-contiguous. Accurate assessments of impacts to riparian areas cannot be made until basic hydrologic data are available.

Anderson and others (1990) reported general water level declines in most of the alluvial basins of southern and central Arizona. The Verde Valley, Upper Santa Cruz, and Upper San Pedro River basins have experienced declines of less than 50 feet (for more specific information on water level declines within these areas, refer to the case studies report, Chapter IV). Some basins however, are presently exhibiting declines exceeding 300 feet including the Salt River Valley, Stanfield, Eloy, Wilcox, San Simon, and Harquahala basins. Groundwater declines are also occurring in the Plateau Uplands province. Industrial wells at power generation facilities near Springerville, Concho, St. Johns, and Joseph City have exhibited significant groundwater declines. Other areas of groundwater level declines are found in northern Arizona including Black Mesa, Snowflake, and Kingman.

Groundwater pumpage in Arizona was estimated at 3.2 million acre-feet in 1986 (Konieczki and Wilson, 1992), the most recent year data were available. Agriculture accounted for 2.3 million acre-feet or 72.7% of total withdrawals. Public and domestic supply composed 15.1% and industrial use represented 4.4% of the total. Basins experiencing the largest pumpage volumes correspond to those in which agriculture is prominent (primarily in the Basin and Range lowlands province). These include the Lower and Upper Santa Cruz, Douglas, Avra Valley, Gila Bend, Gila River, Willcox, Safford, Salt River Valley, and Yuma basins.

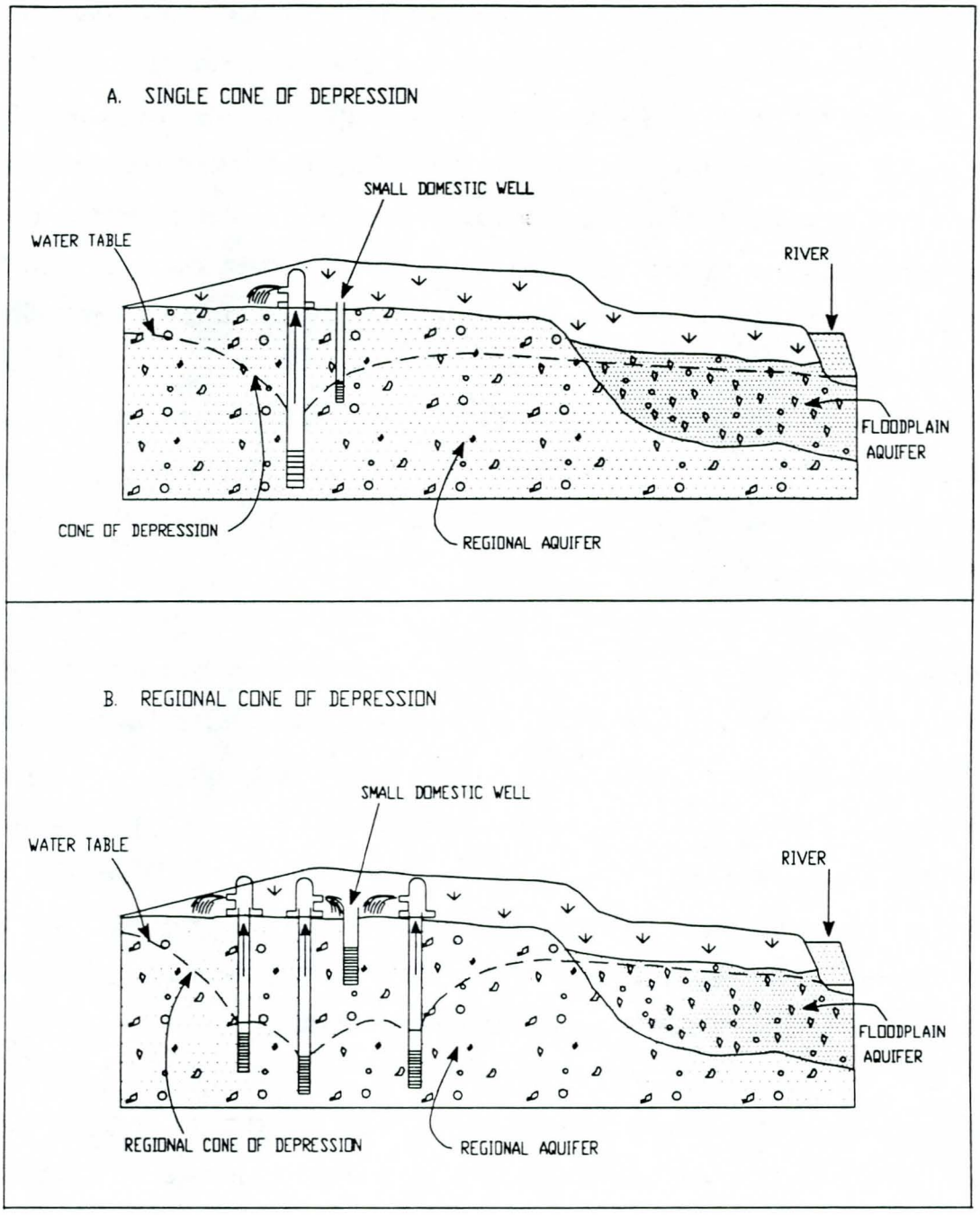
Groundwater use is regulated in the AMAs by the ADWR pursuant to the 1980 Groundwater Management Act. ARS §45-598 requires ADWR to assess all applications for new wells in the AMAs to ensure that proposed pumping rates will not cause "unreasonably increasing damage" to surrounding land or other water users. The ADWR can deny permits for new municipal, industrial, and agricultural wells (excluding domestic wells) in AMAs that would result in additional groundwater level declines exceeding 25 feet. Municipal water supply wells are subject to assured water supply rules (A.R.S. § 45-576) and may not cause a projected decline rate exceeding 10 feet per year, or that would result in water levels exceeding 1,200 feet below land surface after 100 years. Outside the AMAs, groundwater withdrawals are not regulated.

Current regulations only require determination of impacts associated with an individual proposed well and do not consider cumulative impacts of the proposed well and existing wells. In addition, small domestic wells with pump capacities less than 35 gpm, are exempt from impact regulations. Thus, well spacing and well impact criteria currently used by ADWR falls short of protecting an aquifer from regional groundwater declines resulting from multiple withdrawals. While, individually, wells may cause localized impacts, cumulative impacts result in reduced groundwater storage and regional water level declines. This regional decline dewaters streams and reduces riparian abundance.

Effect of Groundwater Withdrawals on the Hydrologic System

Groundwater withdrawals by wells induce certain predictable aquifer responses. When groundwater is withdrawn through a pumping well, water is removed from storage creating a cone of depression in the affected aquifer. This causes water levels to drop in the vicinity of the well as indicated in Figure 12a. Where multiple wells are withdrawing water from an aquifer, the individual cones of depression will interfere to form a regional cone of depression (Figure 12b).

Figure 12. Diagram of a cone of depression in an aquifer



Ideally, groundwater flows radially toward a cone of depression and is removed from an aquifer through a well bore. The shape of a cone of depression depends primarily on the hydraulic characteristics of the aquifer, the duration and rate of pumping, and the proximity of the well to groundwater recharge or discharge boundaries. For example, Figure 13 shows how variations in aquifer transmissivity affect the shape (and area of influence) of a cone of depression. A well pumping in a highly transmissive aquifer will produce a cone of depression that is large in areal extent with a shallow drawdown, while a well withdrawing water from an aquifer with a low transmissivity will tend to produce a cone of depression that is less extensive areally but with a much greater drawdown.

If a well is pumped at a high rate for an extended period of time, the cone of depression will expand outward until further expansion is limited by the transmissive and storage properties of the aquifer or it intercepts an aquifer boundary such as a stream or impermeable hardrock (Figure 14).

If the cone of depression of a pumping well intersects a stream, drawdown of the affected aquifer will cease along the stream bank and water will be drawn predominantly from the stream. Surface water will be induced to infiltrate through the permeable streambed to recharge the area of the aquifer dewatered by the pumping well. When the withdrawal rate of the well is balanced by induced stream recharge, the cone of depression will stop expanding in the direction of the stream. In some instances, pumping wells may change streamflow from perennial to intermittent or ephemeral by eliminating groundwater discharge to the stream and increasing streamflow infiltration.

Wells withdrawing groundwater from an aquifer that is hydraulically connected to a perennial stream will deplete or interfere with streamflow either directly or indirectly as illustrated in Figure 15.

Figure 13. **Diagram showing changes in the shape of a cone of depression with variation in aquifer transmissivity** (Driscoll, 1986)

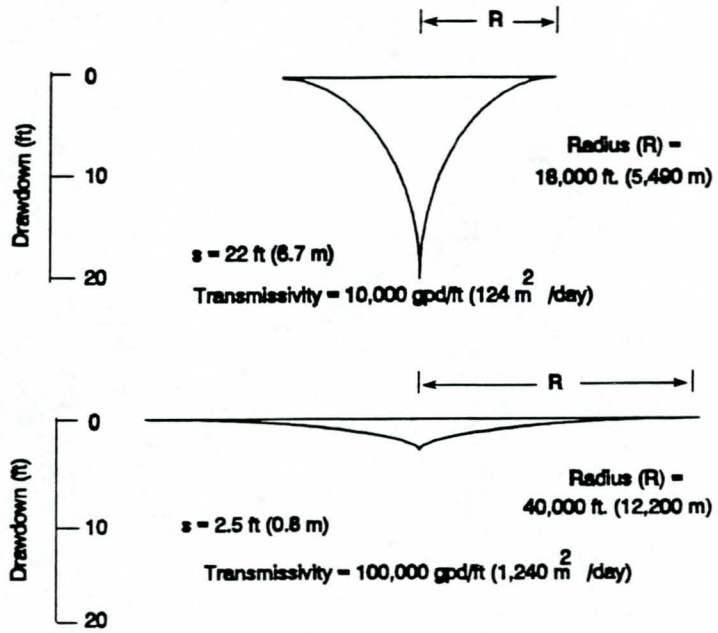


Figure 14. **Diagram showing affect of an impermeable boundary on a cone of depression** (after: Heath, 1993)

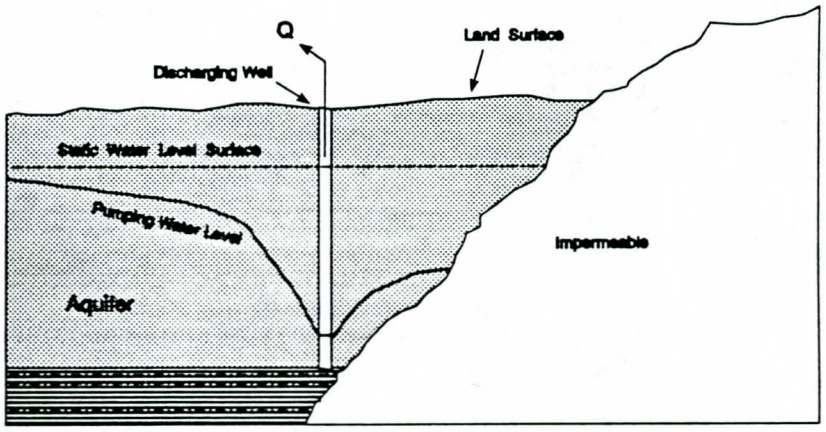
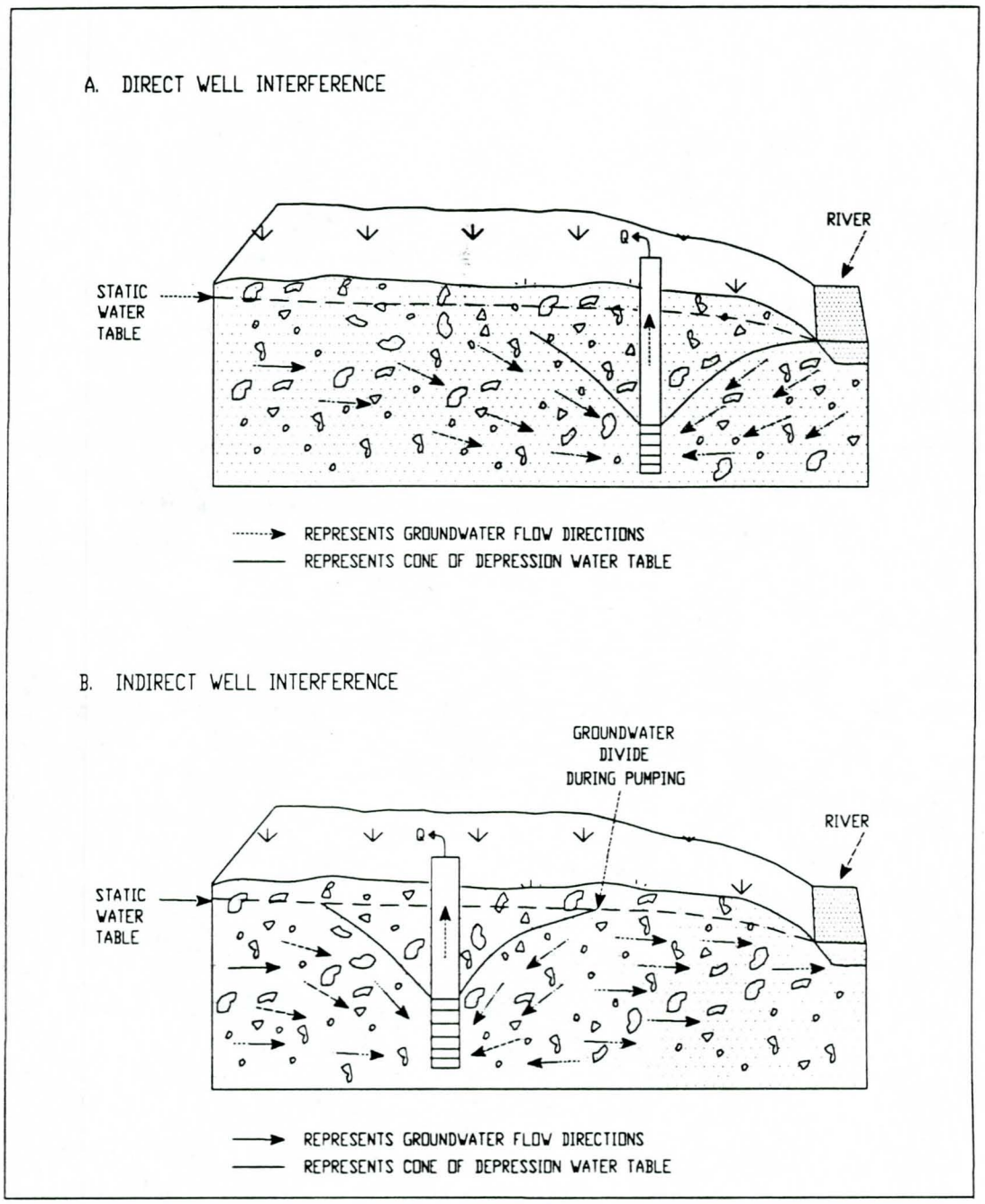


Figure 15. Diagram showing direct and indirect well interference

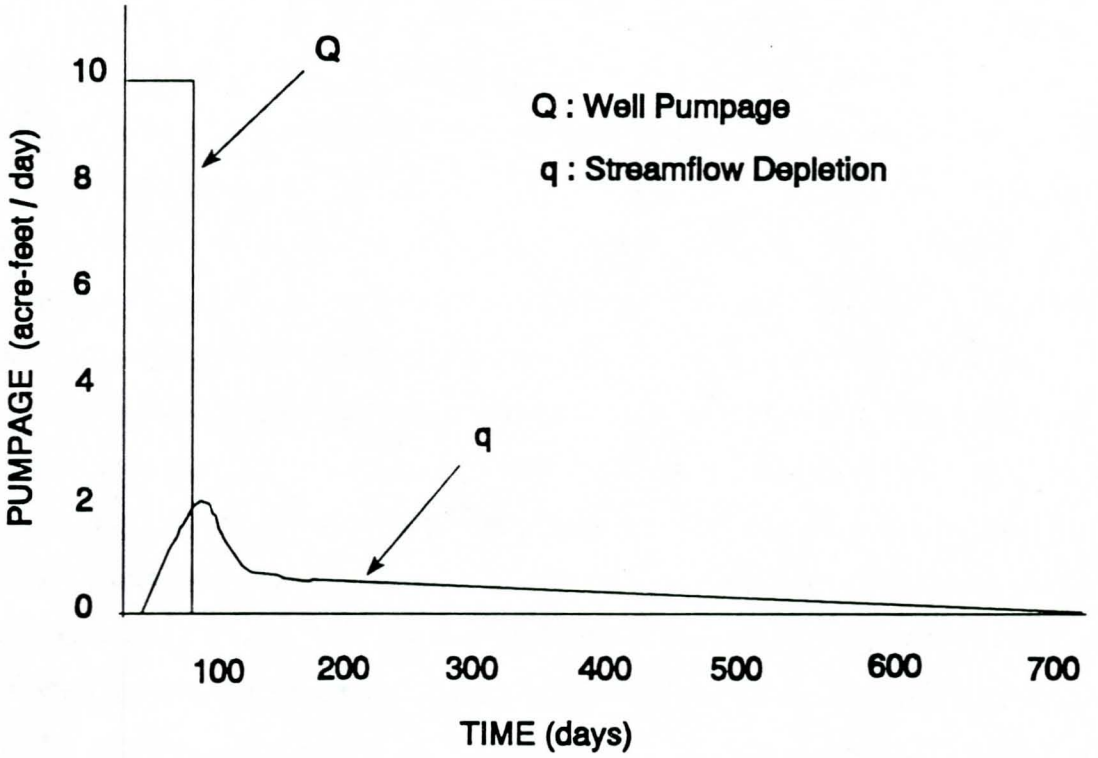


Direct interference occurs when a cone of depression expands into the stream alluvium of a river creating a groundwater gradient away from the stream. Streamflow losses increase as additional surface water infiltrates into the permeable alluvium to fill the area dewatered by the well. Indirect interference occurs when groundwater flowing toward the stream is intercepted by a cone of depression. Indirect interference has the affect of reducing the amount of groundwater that would have eventually discharged to the stream, thereby reducing baseflow. In both instances the well is depleting streamflow, either by inducing additional infiltration of streamflow, or by intercepting groundwater that would have discharged to the stream. In some areas, the impacts resulting from a pumping well adjacent to a stream are compounded by regional groundwater declines resulting from the combined affects of many pumping wells.

The effects of groundwater withdrawals on a stream do not occur the instant a well begins pumping and do not stop immediately after pumping ceases. A considerable lag time in a stream's response to pumping can occur (Jenkins, 1968a). Even if pumping is continuous, it can take decades for water levels to decline to the point where indirect interference becomes direct, and streamflow changes to intermittent or ephemeral. Once withdrawals have been discontinued, water will continue to fill the cone of depression, thereby continuing to deplete streamflow by either reducing the volume of water discharged to the stream or inducing streamflow infiltration. In addition, the volume of groundwater pumped from a well is not instantly removed from a stream. The aquifer tends to attenuate stream depletion. Stream depletion can increase to a maximum, after pumping has stopped, then gradually decrease over time. In the example shown in Figure 16, a well located 3,656 feet from a stream is pumped continuously for 35 days at a rate of 10 acre-feet per day (5 cfs). The maximum rate of stream depletion, 2.7 acre-feet per day (approximately 1.4 cfs), occurs 10 days after pumping ceases and is still about one half the maximum rate 45 days after cessation of pumping (Jenkins, 1968).

In an unconfined aquifer, pumping dewaters a previously saturated aquifer within the area of the cone of depression. Withdrawals from confined (artesian) aquifers do not cause aquifer dewatering unless the potentiometric surface falls below the top of the aquifer (Figure 9). Rather, stored water is released due to compaction of the aquifer and expansion of the water as pressure is lowered. In some areas, leakage from a confined aquifer can be an important source of recharge to an overlying, unconfined aquifer and an associated riparian area. However, generally a direct hydraulic connection does not exist. Therefore, water withdrawals from confined aquifers were not evaluated in this study.

Figure 16. Graph of delayed pumping effect (Jenkins, 1968a)



Quantifying Impacts of Groundwater Withdrawals

Various methods exist that can be used to assess the effects of groundwater withdrawals on an aquifer and an adjacent stream. Most methods depend on mathematical equations to describe the interaction between an aquifer and a pumping well. These methods require data regarding the storage and water yielding properties of an aquifer and the pumping parameters of a well. All of the methods have a common foundation in the fundamental theories of hydrology that describe groundwater flow through porous geologic material (i.e., silt, sand and gravels that comprise alluvial aquifers). Differences between the various methods are due to simplification of the idealized equations through limiting assumptions that may not always exist in nature. Selection of the appropriate method depends largely on the type of information being sought, the availability of accurate hydrologic data with sufficient coverage, and the level of detail required.

The following section discusses some accepted methods that are documented in literature and have been used by ADWR in past studies. This section includes discussions of direct and mathematical methods.

Direct Methods

Direct methods simply refers to measuring the height or elevation of water levels in a well. Measurements of depth to water below land surface are plotted over time in the form of a water level hydrograph for the particular well. Direct measurement of water levels in the area being studied is the most accurate way to measure impacts caused by a pumping well or to monitor for regional groundwater declines. Several examples of hydrographs within the study areas are provided in the case studies report (Chapter IV). The most accurate riparian zone water level measurements can be obtained from monitor wells constructed in the floodplain alluvium specifically for this purpose, however, measurements can also be obtained from other existing nearby wells. Water levels documented over time indicate long-term trends or seasonal fluctuations occurring in an

aquifer. This water level data can be related to riparian abundance and can be used to quantify changes in riparian vegetation. The relationships between riparian health and abundance are discussed further in Chapters III and IV.

Basic groundwater level data provides critical information and insight to an aquifer system by: (1) determining aquifer characteristics when collected during a pumping well test, (2) indicating the relationship between different aquifer units (when perforating a specific aquifer), and (3) determining the relationship between groundwater and streamflow. Although groundwater level data is collected on a statewide basis annually (refer to the Groundwater Level Declines section), much of that information is limited to providing a snap-shot in time of a regional, rather than floodplain aquifer system. Additional aquifer-specific data should be collected for high risk riparian areas. In some instances, existing information is adequate to make general assessments using mathematical methods. However, mathematical models will not provide accurate results without site-specific, accurate hydrologic data. Thus, mathematical methods should only be applied to ideal situations and should not substitute for direct field studies.

Mathematical Methods

A mathematical hydrological model is a set of equations, subject to certain assumptions, that describe the physical processes active in an aquifer and can be used to approximate the behavior of a stream-aquifer system (Mercer and Faust, 1981). Development of a mathematical model must be preceded by construction of a conceptual model of the system being assessed. A conceptual model allows an investigator to make appropriate simplifying assumptions and select the appropriate groundwater flow equations, boundary and initial conditions. Solutions to mathematical models are expressed in terms of hydraulic head (groundwater levels), which in turn defines the rate and direction of groundwater flow within a hydrologic system.

Solution of a mathematical model may be accomplished analytically or numerically. If, based on the conceptual model, the groundwater system meets certain simplifying assumptions, the equations can be converted to a form that can be solved analytically. In cases where data are lacking, or the aquifer does not conform to the simplifying assumptions, analytical solutions should be viewed as a first approximation.

Often, the hydrologic system is complex and does not meet the simplifying assumptions used for analytical solutions. In these instances the flow equations can be approximated numerically using finite-difference or finite-element techniques which define discrete variables for grid blocks or nodes (Mercer and Faust, 1981). Differential equations defining aquifer head are solved for each model node using a digital computer. Numerical groundwater flow models are more difficult to construct due to extensive data requirements, however, they are not limited by many of the simplifying assumptions necessary for analytical models. Whether an analytical or a numerical solution is used should be based on the ability of a hydrologic model to adequately assess site-specific aquifer conditions using available data. In either case, the solution should be verified for accuracy of prediction against known results (i.e., direct measurement).

Analytical Methods

Analytical methodologies introduced by Theis (1935), Jacob (1950), Glover and Balmer (1954), and Jenkins (1968) represent a few of the many available approaches used to interpret aquifer parameters and determine groundwater and surface water interactions. This section briefly discusses a few of the applicable methods. Appendix C provides a detailed list of analytical methods that can be used to assess impacts of well pumping on the stream-aquifer system. Information is also provided regarding techniques to develop the necessary aquifer parameters using well-log and specific capacity data. Analytical methods are utilized in conjunction with ecological models in the case studies reports (Chapter IV) to estimate the amount of riparian vegetation decline resulting from

groundwater withdrawals.

Analytical methods can be used to solve for several unknown parameters. For this study, water level declines (i.e., drawdown) in an aquifer, due to a pumping well, served as the unknown parameter of interest. In addition, these methods can be used to solve for the rate and volume of stream depletion caused by a pumping well. They also provide a way to determine the effect of well pumpage on the riparian areas by quantifying the impacts to the hydrologic system, or more specifically, to the adjacent alluvial aquifer and surface stream that supports a riparian ecosystem. While there are several assumptions that must be used and only apply to idealized situations, these solutions can provide reasonable results even though the assumptions are, in many cases, inconsistent with field conditions. The assumptions are as follows:

1. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent, with a straight, fully-penetrating stream boundary.
2. Groundwater flow is horizontal and uniformly distributed over the thickness of the aquifer.
3. The pumping rate is constant through time.
4. The well fully penetrates the aquifer.
5. Groundwater is instantaneously released from storage.
6. Drawdown is considered negligible compared to aquifer thickness.
7. Laminar flow exists throughout the aquifer and near the well.

One analytical method that can be used to evaluate the effects of pumping wells on an aquifer and subsequently on an associated riparian area is the Theis Non-Equilibrium Equation. The Theis method originated on the basis of the analogy between flow of water in an aquifer and the flow of heat in a thermal conductor (Theis, 1935). Since the original conceptual use of the Theis equation, it has been applied to a variety of situations with differing constraining conditions.

In its simplest form the Theis equation is:

$$s = \frac{114.6\,QW(u)}{T}$$

$$u = \frac{1.87\,r^2 S}{Tt}$$

Where:

s = drawdown, in feet (ft)

Q = pumping rate in gallons per minute (gpm)

T = transmissivity of the aquifer, gallons per day (gpd/ft)

W(u) = "well function of u"

r = distance from the center of the pumped well to a point where drawdown is measured (ft)

S = specific yield (or storage coefficient)

t = time since pumping started in days

The Theis equation can be rearranged and solved for a specified drawdown. Using aquifer parameter data reported in Putman and others, (1988), the following examples were developed. For example, if an agricultural well perforated in the floodplain alluvium was pumping at 1000 gpm, for a period of 180 days, the above equation can be used to solve for the radial distance outward from the pumped well where drawdown (s) is one foot. The aquifer parameters required include transmissivity, which was assumed to be approximately 80,000 gpd/ft (10,700 ft^2/d), and specific yield of 10 percent. This resulted in a one-foot drawdown contour at approximately 5,070 feet from the pumping well.

This same example can be used to demonstrate the extent and location of the one-foot contour of the cone of depression if the well was located in the basin fill alluvium instead. Assuming a transmissivity value of 60,000 gpd/ft (8,000 ft^2/d) and a specific yield of 8 percent, results in a one-foot drawdown contour at approximately 6,190 feet from the pumping well. The variation in the lateral extent of the cones of depression in these two examples functions similarly to those illustrated in Figure 13. Using this analysis under ideal conditions (i.e., a flat water table), and depending on the location of the pumping well relative to a stream, theoretically, impacts would occur more than a mile from the pumping well.

In addition to the Theis equation, several equations have been developed to ascertain the rate and volume of stream depletion by a pumping well (Glover and Balmer, 1954; and Jenkins, 1968b). These methods attempt to simplify complex integral equations through the use of graphical and mathematical techniques.

Using the Jenkins equation, the volume of water that is pumped from the stream can be determined. The only additional parameter that is needed to make this determination is the stream depletion factor (sdf) (for further information refer to Appendix C). The following relationship was developed by Jenkins (1968b), where:

$$sdf = a^2 S/T$$

Also used are the terms:

$$q/Q$$

and

$$v/Qt$$

Where:

sdf = stream depletion factor or the amount of time for a steady stress to affect the stream

a = distance from the well to the stream

q = rate of stream depletion

v = volume of stream depletion

T, S, Q, and t are as previously defined above.

When pumping wells are located in close association with a nearby stream, the potential for depletion of streamflow exists. Using the data presented in the previous examples, it is possible to determine the potential streamflow depletion. For example, assuming a pumping well is located 1,000 feet from a stream in the floodplain alluvium, the volume of water pumped from the stream would equate to approximately 517 acre-feet or 65 percent of the total volume of water pumped from the well. If it is assumed the well is located in the basin fill alluvium, one mile (5,280 feet) from the stream, then 143 acre-feet of water would be derived from the stream. This is approximately 18 percent of the total volume pumped. Documentation of these and other techniques are provided in Appendix C.

Analytical equations can also be used to evaluate different scenarios, such as long- term continuous pumping for municipal water supplies, or seasonal pumping for agricultural uses. Other examples of determinations that can be made include: (1) the rate of stream depletion at any time during the pumping period, (2) the volume induced from the stream during pumping or after cessation of pumping, and (3) the effects of intermittent pumping (Jenkins, 1968a).

Numerical Methods

Analytical techniques can be used in many instances to determine adjacent stream impacts adequately. However, these techniques are less useful in determining impacts farther away from a river or within multiple aquifers and are unable to incorporate multiple boundary conditions. In contrast, numerical groundwater models allow solutions for more complex stream-aquifer systems. Two basic types of numerical groundwater flow models can be used to represent stream-aquifer systems. These include a finite-difference or node-centered model and a finite-element or mesh-centered model. Both models use a set of differential equations to represent the aquifer system and solve for an unknown parameter, such as groundwater level or hydraulic head. Groundwater flow models can be used to evaluate aquifer systems with irregular boundaries and/or heterogeneous aquifer properties. In addition, variable stresses can be applied to aquifer systems, such as pumpage, evapotranspiration, or recharge. The advantage of using a groundwater flow model is that fewer simplifying assumptions are required, and the results provide a more realistic representation of hydrologic systems.

The groundwater flow model that has been developed for use in this study is based on the USGS Modular, Three-Dimensional, Finite-Difference Groundwater Flow Model (MODFLOW) computer code by McDonald and Harbaugh (1984). This model code was chosen because it was readily available, and could mitigate all of the simplifying assumptions that are required by analytical solutions. The model has been widely used in the hydrologic professional community and is generally accepted as a valid model to simulate groundwater flow. The model also incorporates a streamflow-routing package developed by Prudic (1989). This allows simulation of the interrelationship between a stream and an aquifer system.

The groundwater flow model was calibrated using the Freethey model (1982) of the Upper San Pedro basin. This led to the development of the "vertical slice" model which can be

used to assess impacts for a smaller area of the watershed and groundwater aquifer. Even though it is called a vertical slice model, it should more aptly be called a sub-regional 3-dimensional groundwater flow model. This is because it is multi-layered (i.e., 3-dimensional) and simulates radial flow. However, for brevity's sake, it will be called the "vertical slice" model throughout this report and the San Pedro case study. The vertical slice model takes less time to develop than a regional groundwater flow model, can incorporate many of the limiting factors that prohibit the application of analytical methods, and can be readily adapted to the other case study areas.

The vertical slice model developed for this study consists of 38 rows, 28 columns, and 3 layers, and covers an area 8 by 9 miles or 72 square miles. The layers replicate the younger floodplain alluvium, a confining layer, and two layers of basin fill material. The model also handles several differing boundary conditions from a specified flux (or flow boundary) to a specified head boundary. Parameters including mountain front recharge, areally distributed recharge such as precipitation (if significant) are also incorporated. The model incorporates a general water level distribution and includes discharge parameters such as groundwater pumpage and evapotranspiration. As the model has been developed, a river can be simulated with gaining or losing reaches. And finally, the model can accommodate changes in stress over time. This would include changes in recharge and discharge values, as well as changes in streamflow. The vertical slice model will be presented in more detail in the San Pedro case study.

HYDROLOGIC EFFECT OF SURFACE WATER DIVERSIONS

This section of the report provides a general description of the effects of surface water diversions on the hydrologic system and discusses methods used to quantify streamflow availability. Discussion of the response of riparian vegetation to streamflow depletions is addressed in the Ecologic Report (Chapter III), while in-depth riparian vegetation responses are discussed in the individual case studies reports in Chapter IV.

ARS §45-101 (Appendix A) requires an evaluation of the hydrologic effect of surface water appropriations on riparian areas resulting from new surface water appropriations and changes in the use or point of diversion of existing surface water appropriations. The effects of existing surface water diversions will not be addressed in this report. However, the effects of current diversions provide insight to the potential effects of future diversions and changes in use and point of diversion. Because adjudication of water rights in Arizona has not been completed, streamflow diversions are not quantified for most areas of the state. Therefore, only a qualitative evaluation of the effects of new surface water diversions and changes in existing uses and points of diversion can be made.

Effect of Diversions on Hydrologic Systems

As a general rule, surface water diverted from a stream is not available to support the natural hydrologic system below the point of diversion. Surface water diverted by an instream diversion structure diminishes the flow volume of the stream directly, that is, for every acre-foot of water diverted, streamflow is also reduced by one acre-foot. Indirect diversion of surface water can occur when water withdrawn by a well includes both surface water and groundwater components. In the case of indirect depletions by wells, streamflow depletion is not immediate however, over the long term, stream depletion approaches the amount pumped (Jenkins, 1968). In each case, not only is flow reduced downstream of the diversion, but downstream recharge is also diminished. Reduction of available flow for stream recharge may result in a decline in water levels in alluvial aquifers adjacent to impacted stream reaches. In instances where surface water is diverted from a stream and applied to irrigate crops on adjacent alluvial floodplains, a portion of the water that is not evaporated or transpired may return to the stream through deep percolation (irrigation return flows).

Streamflow diversions vary in volume from small irrigation ditches and instream pumps,

which divert only a fraction of the total streamflow, to large diversion dams which divert the entire flow of a stream. In many natural perennial stream systems the stage (stream water surface elevation) and the adjacent aquifer in the stream alluvium are at equal elevations. In some instances however, water levels in an adjacent alluvial aquifer may be slightly above or below the river level within the riparian zone. For example, following the high flow season, saturated portions of the floodplain may temporarily exist above the river level and slowly drain back to the river sustaining flow during the low flow season (bank storage). When surface water is removed from the stream by a diversion structure, the stage of the stream is lowered. As stream stage declines, the water level gradient between the stream and alluvial aquifer steepens and water drains from the aquifer to the stream. In a hydraulically connected stream-aquifer system, drainage from the adjacent alluvial aquifer to the stream results in a water table decline and leads to an increase in the distance between the water table and land surface (unsaturated zone).

While surface water flows are critical for riparian vegetation maintenance and regeneration, riparian vegetation serves to stabilize hydrologic systems. When surface water is diverted and no longer available to support riparian ecosystems, riparian community densities are reduced or eliminated. Therefore, less vegetative cover and root structure support are available to slow flood flow velocities, stabilize soils and sustain lateral floodplain recharge. As a result, stream channels and associated floodplain structures become more susceptible to degradation and erosion processes, such as streambed scouring, and channel incision and widening. Channels impacted by these actions are highly erosive and carry greater sediment loads. Additionally, bank storage potential is reduced and therefore less discharge from stream alluvium is available to support baseflows in the stream during low flow periods. When flood events occur, the resulting system's inability to slow and retain some of the flow energy can result in greater flood related devastation.

Quantifying Impacts of Surface Water Diversions

In order to determine the effect of new surface water diversions on a stream-aquifer system, it is necessary to quantify both the amount of streamflow available and the amount of the proposed diversion. Streamflow availability is best determined when adequate streamflow data exists. Streamflow records from USGS gaging stations vary in accuracy depending upon gage site, channel characteristics, and the period of record. If records are not available, flow may be estimated by correlation with other nearby gaged streams, or through establishment of a streamflow measurement program. In general, stations with long periods of record more accurately define the flow regime of the river under study and may allow the detection of trends or cycles in streamflow due to stream depletion or runoff variability.

The average flow of a stream varies daily, seasonally, and annually (Linsley and others, 1975). Variability occurs naturally as a function of precipitation, temperature, and evapotranspiration. Flow volume and flow rate are often artificially altered by water use practices such as operation of reservoirs, agricultural, municipal and industrial diversions, return flows, watershed management activities, and streamflow depletion by wells and infiltration galleries. It is difficult to determine the exact impact to streamflow at a point on the stream that is not near a streamgage. Large scale diversions often result in direct and appreciable streamflow reductions and corresponding lowering of stream stage below the point of diversion. Sullivan and Richardson (1993) reported that surface flow of the Verde River is entirely depleted by irrigation diversions in the Cottonwood area during the peak growing season. Also, the San Pedro River is typically dry below the irrigation diversions in the St. David-Benson area. In addition to impacts caused by large scale diversion, the cumulative effect of many small, individual diversions and groundwater withdrawals may cause regional stream depletion over an entire watershed. However, because of natural streamflow variability and the lack of accurate streamflow diversionary records, it is often impossible to discriminate between individual and cumulative impacts.

The volume of surface water diverted from a stream can be measured directly by the installation of a streamflow measuring device, such as a flume or weir, in a diversion ditch or canal. However, no regulations presently exist that require measurement of surface water diversions on Arizona rivers and streams. Thus, surface water diversions are rarely quantified. Exceptions do occur however, such as with some of the larger irrigation districts (SRP) and industrial users (e.g., mining related inter-basin water transfers on the Black and East Verde Rivers). Diversions may also be estimated by calculating canal capacities or crop irrigation requirements. The accuracy of these estimates however, depends on determination of such variables as conveyance losses and application rates and are site specific.

Aside from areas currently undergoing adjudication, ADWR has no accurate, comprehensive database regarding surface water diversions. This includes quantities diverted and diversionary impacts information. Impacts due to diversion activities are apparent along some streams, such as the Salt River below Granite Reef Dam and the Gila River below Ashurst-Hayden Dam. However, other stream systems which presently exhibit perennial streamflows and support relatively undisturbed riparian forests, bear the potential for impacts by future water resources development (see Chapter II, Ecologic Report).

A statewide assessment of the present condition of riparian ecosystems associated with perennial and intermittent streams does not currently exist and was not undertaken for this report. However, instream flow water right applications on file with the ADWR indicate some Arizona streams that are presently being impacted or have potential for future impacts. Land owners and managers have filed over 70 applications for instream flow rights on about 50 Arizona streams and rivers in order to preserve surface water for fish, wildlife, recreation, and riparian ecosystems. Several streams currently supply municipal and/or irrigation water, or are located in the vicinity of populated areas or areas

that may potentially undergo future development. Some examples of these streams include the Virgin River in the Littlefield area, the Verde River and its tributaries (e.g., Oak Creek, Beaver Creek and West Clear Creek), the Hassayampa River near Wickenburg, Cienega and Sabino Creeks near Tucson, the San Pedro River near Sierra Vista, Bonita Creek near Safford, and Billy Creek in the Pinetop-Lakeside area. Streams that may be further impacted by mining diversions include Francis and Burro Creeks near Bagdad. In addition, water transfers and exchanges may currently threaten flow regimes along streams, such as the Bill Williams River below Alamo Lake.

Statistical Analysis of Streamflow

Historical streamflow data are necessary for making quantitative hydrologic assessments. Water measured at a gaging station quantifies the outflow of the watershed from the area upstream of the gage. Streamgage data reflect the combined effects of climate, topography, and geology and provide information regarding the distribution of flows in time and magnitude (Searcy, 1959). Historic streamflow records can be used to predict the future flow regime assuming that the period of observed flow is adequate, the climatic regime has remained relatively stable, and no significant changes in water use have occurred. Practices that may alter streamflow characteristics include reservoir operations, diversions, and watershed alterations which impact runoff.

Statistical analysis of historic data is used to estimate the future probability of the occurrence of flows of specific magnitude and duration. Streamflow data can be assessed statistically on an annual, monthly, or daily basis. Daily or monthly analyses are preferred for assessing relationships between flow and riparian vegetation responses because they provide a more detailed characterization of streamflow availability. The following sections briefly describe basic statistical methods used to assess the flow of a stream.

Mean vs. Median Flow Values

Mean annual flow values represent the arithmetic mean of the individual daily mean discharges for each year, averaged for the period of record. However, while most daily flows in Arizona streams are low, occasional high flow events tend to skew the mean flow value upward. This results in a value that would indicate more water is available as streamflow than actually may occur. Daily flows that meet or exceed the mean annual flow may actually be uncommon. Jackson and others, (1987), found mean flow rates to be more useful as descriptors of runoff volumes for water supply studies and for defining seasonal trends in runoff volume.

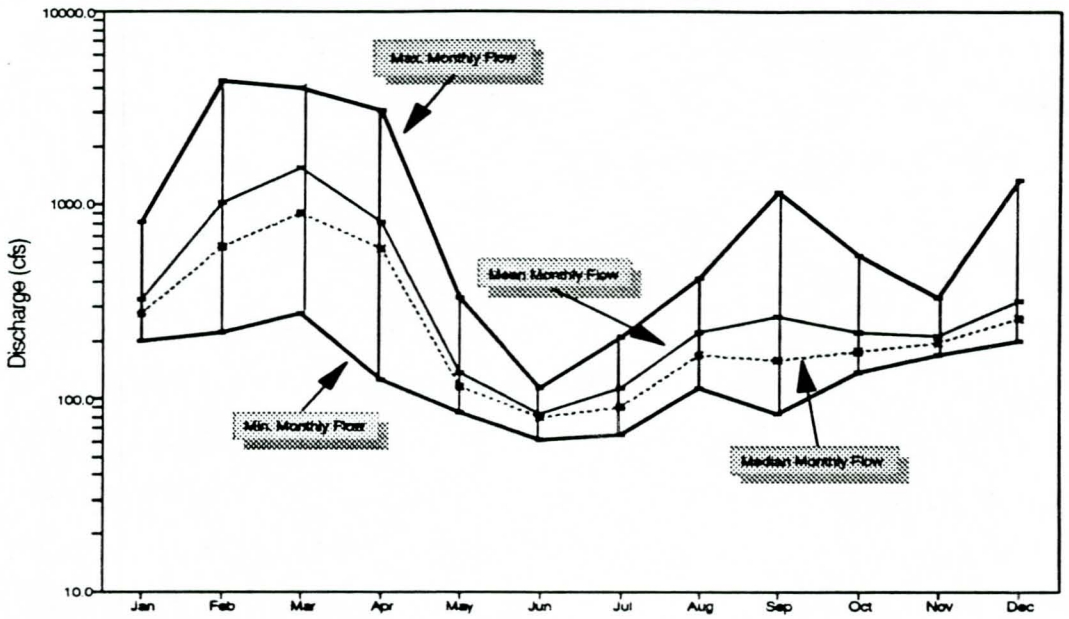
The median differs from the mean in that it represents the middle value of a set of flow data that are ranked in order of magnitude. It is the flow rate that is exceeded 50% of the time and is considered closer to the "typical" flow that can be expected in a stream. Therefore, median flow values more accurately indicate flow availability than mean flow values for a majority of Arizona streams.

Annual and Monthly Flow Analyses

Annual flow data provides insight into annual flow volumes and trends in available streamflow. Monthly flow data, on the other hand, provides a better description of seasonal streamflow variation than daily or annual values. Statistics of monthly flows provide an indication of flow distribution by month during an average year. Monthly analysis can be used to determine high and low flow periods, percent of annual runoff per month, and monthly average, maximum, and minimum flows. It is particularly valuable for evaluating seasonal impacts during low flow and high demand periods. For example, Figure 17 is graph generated from streamgage data for the Verde River near Camp Verde. It is representative of the general, annual flow trends commonly observed on many Arizona streams. Monthly flow data is presented as maximum, minimum, mean, and median flow values by month. As demonstrated, a large flow variability exists during winter (December-April) and summer (August-October) flow seasons. The effects of

diversions during these periods, particularly small individual diversions, may be masked by this variability, as well as by the cumulative impacts of other diversions. The diagram also displays the low flow period (May-July). During this period little streamflow variability exists and median and mean flow values are essentially the same. This period occurs during the growing season, when the streamflow is being actively diverted, both directly and indirectly, and coincides with a period of typically high temperatures and low precipitation. Therefore, it represents the most flow limiting period of the riparian ecosystem.

Figure 17. Graph showing monthly streamflow variability for USGS streamgage: Verde River near Camp Verde



Daily Flow Analysis

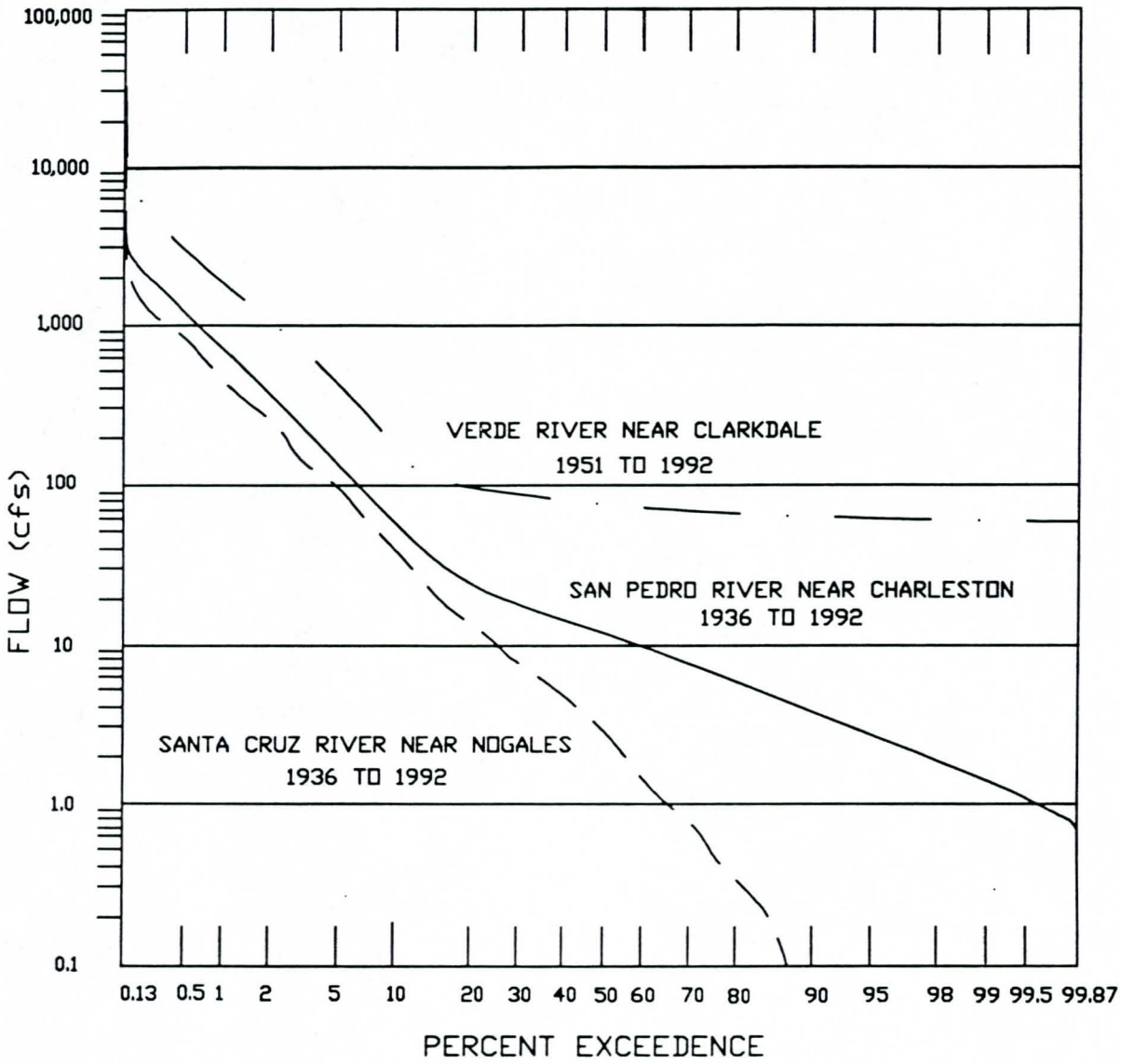
Mean daily flow data are necessary to characterize streamflow statistically, whether for yearly, monthly or daily flow descriptors. The relative magnitude of an individual daily

flow rate can be determined by relating it to all other previously recorded mean daily flows and calculating how frequently a flow of that size has occurred in the past.

Flow duration analysis is commonly used to assess the flow characteristics of a stream using mean daily flow data through cumulative frequency or "flow duration curves." A flow duration curve represents all mean daily flows of record with the flows arranged in order of magnitude. Flow duration analysis expresses the percent of time during the period of record that streamflow was above or below a discharge of a specified magnitude. Searcy (1959) observed that if the period of streamflow data used in construction of the curve is of long enough duration to represent the long-term flow of the stream, the curve can be used as a probability curve to predict the percent of time that a flow of a certain magnitude will be equalled or exceeded in the future. Flow duration curves are limited in that they do not indicate when a specified flow occurs, and therefore, do not address seasonal variability of flow.

Figure 18 presents three flow duration curves generated using streamgage data from each case study area. Curves representing streamflow from the Verde River at Clarkdale and the San Pedro River at Charleston exhibit perennial flows. Verde River data indicates that flows of 70 cfs are exceeded 95-100% of the time, and discharges greater than 500 cfs occur less than 5% of the time. Near Charleston, discharge of the San Pedro River equals or exceeds 60 cfs only 10% of the time. Flows are less than 10 cfs 35% of the time. The Santa Cruz River near Nogales experiences much lower flows with flows less than 10 cfs occurring 75% of the time, while 35% of the time flows less than 1 cfs are measured. Median daily flow values obtained from the 50% exceedence value indicate that for the Verde, San Pedro, and Santa Cruz Rivers the median annual flow values are 82, 14, and 3 cfs, respectively. These curves, when compared with daily flow data from which they were generated, serve to illustrate the highly skewed nature of those flows and the general predominance of relatively low daily flows on an annual basis.

Figure 18. Flow duration curves for specified streamgages on the San Pedro, Santa Cruz and Verde Rivers



SUMMARY

The ADWR conducted a study to evaluate the hydrologic effects of groundwater pumping and surface water appropriations on riparian areas. This chapter of the report provides a review of the important hydrologic processes that govern the interaction and dynamics between hydrologic systems and riparian areas. The data and analyses previously presented in this report support the following statements:

1. Groundwater and surface water were historically considered as separate and distinct resources in Arizona. Water laws were created to manage the water resources based on this concept. However, in reality, groundwater and surface water form an interconnected hydrologic system in which quantities of water are exchanged between a stream and an aquifer based on changing hydrologic conditions. It is critical to have an accurate representation or conceptualization of the interconnected surface water and groundwater system in order to quantify any impacts.

2. The effects of natural climatic variability on components of the hydrologic cycle are unevenly distributed through time, and therefore the magnitude of streamflow expressed in a particular stream reach and the volume of groundwater in storage within an aquifer naturally fluctuate through time. This natural climatic variability was not assessed in detail in this report, but it is important to keep in mind the impacts that could occur during drought cycles or periods of low runoff or streamflow.

3. The concept of an "interrupted-perennial" stream reach is important because: (1) this type of flow has been included as appropriable surface water by the Department in the adjudication process, and (2) even though a stream may not

have been "mapped" as perennial flow by AGFD, subflow may still sustain a riparian ecosystem (e.g., the San Pedro River).

4. It is often difficult to determine streamflow characteristics for streams throughout the state other than at USGS streamgage locations. In addition, not all streams are gaged by the USGS. This in turn makes it difficult to accurately determine impacts to streamflow between gage locations. Furthermore, many gage records are fragmentary and discontinuous and the data do not reflect the entire range of streamflow conditions as they presently exist (e.g., many gages throughout the state are used to measure flood flows and are not set up to monitor more prevalent low flow conditions).

5. Long-term groundwater withdrawals have created regional groundwater declines areas such as the Salt River Valley, Pinal County, and Santa Cruz Valley. In these areas, continuous groundwater pumping for agricultural, municipal, and industrial purposes has severely lowered water tables in the surrounding aquifers. Groundwater levels have been lowered to the point where they are no longer connected to surface water flows.

6. Undisturbed stream-aquifer systems achieve an equilibrium where long-term inflows equal long-term outflows. In this type of balanced system, streamflow reductions only occur during extended drought periods where below normal precipitation results in a corresponding reduction in runoff and aquifer recharge. In a developed watershed, direct streamflow diversions and groundwater pumping can have an appreciable affect on the hydrologic system depending on the timing and magnitude of depletions and the location of these diversions. Often, depletions occur in or near riparian areas, where surface water is available and groundwater is close to the land surface.

7. Extensive groundwater pumping results in depletion of streamflow by inducing infiltration of surface water through the streambed or interception of groundwater that would have discharged to the stream. If the volume of water pumped exceeds the amount of natural recharge to the groundwater system, a deficit will occur causing a reduction in groundwater storage and declining water levels. A continuous trend of declining water levels indicates overdevelopment of groundwater resources. The degree of this groundwater mining depends on the magnitude, duration, and distribution of withdrawals, as well as the hydraulic properties of the aquifer. Where multiple wells are clustered in close proximity to one another, the effect of pumping on the aquifer is compounded, as are impacts to any nearby stream.

8. A statewide network of observation wells (index wells) is monitored annually to assess changes in hydrologic conditions through time. There are approximately 1,160 index wells throughout the state. However, most of these wells are not ideally located to monitor groundwater levels in or near riparian areas. In addition, out of the total number of wells in the state, a very small percentage of them are monitored on a regular basis. Of the few that are, an inadequate number of monitor wells occur in the riparian areas being assessed, and many of the wells that are present in riparian zones may not be effective monitoring tools for the particular area, depending on well construction and purpose. Most of the wells throughout the state penetrate more than one aquifers. Water levels from these wells reflect a regional, rather than a specific aquifer system. Usually, aquifer-specific data is not available, and when available, is spatially non-contiguous.

9. Direct well interference occurs when a cone of depression expands from the pumped well into the stream alluvium of a river creating a groundwater gradient

away from the stream. Streamflow losses increase as additional surface water infiltrates into the permeable alluvium to fill the area dewatered by the well. Indirect interference occurs when groundwater flowing toward the stream is intercepted by a cone of depression. Indirect interference has the affect of reducing the amount of groundwater that would have eventually discharged to the stream, thereby reducing baseflow. In both instances the well is depleting streamflow, either by inducing additional infiltration of streamflow or by intercepting groundwater that would have discharged to the stream. In some areas, the impacts resulting from a pumping well adjacent to a stream are compounded by regional groundwater declines resulting from the combined affects of many pumping wells.

10. The effects of groundwater withdrawals on a stream do not occur the instant a well begins pumping and do not stop immediately after pumping ceases. A stream's response to pumping can lag considerably after pumping has ceased. Even if pumping is continuous, it can take decades for water levels to decline to the point where indirect interference becomes direct, perhaps changing perennial streamflow to intermittent or ephemeral. Once withdrawals have been discontinued, water will continue to fill the cone of depression created by the pumping, thereby continuing to deplete streamflow by either reducing the volume of water discharged to the stream or inducing streamflow infiltration.

11. There are several methods that can be used to assess the effects of groundwater withdrawals on an aquifer and an adjacent stream. Most methods depend on mathematical equations to describe the interaction between an aquifer and a pumping well. These methods require data regarding the storage and water yielding properties of an aquifer and the pumping parameters of a well. All of the methods have a common foundation in the fundamental theories of hydrology that

describe groundwater flow through porous geologic material (e.g., silt, sand and gravels that comprise alluvial aquifers). Differences between the various methods are due to simplification of the limiting assumptions that may not always exist in nature. Selection of the appropriate method depends largely on the type of information being sought, the availability of accurate hydrologic data with sufficient coverage, and the level of detail required. Currently, these methods can be used to effectively evaluate hydrologic impacts and changes to riparian areas.

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GLOSSARY

Aggradation: The geologic process by which stream beds, flood plains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas.

Aquiclude: A material, impervious to water, that forms a boundary to an aquifer.

Aquifer: Rock or sediment in a formation or part of a formation which is saturated and sufficiently permeable to transmit economic or useable quantities of water to wells and springs.

Aquitard: A low-permeability unit that can store groundwater and also transmit it slowly from one aquifer to another.

Artesian Aquifer: Also referred to as a confined aquifer. An aquifer that is overlain by a confining bed (e.g., clay layers) with the groundwater under sufficient hydrostatic pressure to rise above the top of the aquifer.

Bank Storage: Water absorbed into the banks of a stream channel, when the stage in the stream rises above the adjacent water table in the bank formations. Water contained as bank storage then returns to the channel as effluent seepage when the stage in the stream falls below the water table in the adjacent bank formations.

Baseflow: That part of stream discharge from groundwater seeping into the stream.

Confined Aquifer: Also referred to as an artesian aquifer. Refer to Artesian Aquifer above.

Degradation: The geologic process by which streambeds and floodplains are lowered in elevation by removal of material.

Ecosystem: They are subdivisions of the biosphere. They consist of communities of plants, animals, and microorganisms along with the air, water, soil, or other substrate that supports them.

Ephemeral Stream: A stream that flows only in direct response to precipitation, and whose channel is at all times above the water table.

Evapotranspiration: The sum of water lost from a given land area during any specific time by transpiration from vegetation and building of plant tissue; by evaporation from water surfaces, moist soil, and snow, and by interception.

Floodplain: The lowland that borders a river which is usually dry but subject to flooding; the land outside of a stream channel described by the perimeter of the maximum probable flood.

Flume: A man-made or natural channel, of known size, that carries water, in which to measure streamflow.

Gaining Stream: A stream or reach of a stream that receives water from the saturated groundwater and whose channel is at times below the water table.

Groundwater: Water in the ground that is in the zone of saturation, from which wells, springs, and groundwater runoff are supplied.

Hydraulic Conductivity (K): Also referred to as permeability, is a property of the soil or rock material that describes the ease at which water flows through the soil, commonly expressed as a velocity (ft/day). Hydraulic conductivity varies from low values (e.g., clay and silt) to high values (e.g., sands and gravels). Hydraulic conductivity when multiplied by the saturated thickness of the aquifer yields the transmissivity of that aquifer.

Hydraulic Head: Referring to the energy contained in a water mass within an aquifer produced by elevation, pressure, and/or velocity. For example, the hydraulic head in an unconfined aquifer equals the water table surface (and in a confined aquifer the potentiometric surface).

Intermittent Stream: A stream which flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas. It is seasonal in occurrence.

Isotropic: Having the same properties in all directions.

Losing Stream: A stream or reach of a stream that contributes water to the saturated groundwater zone whose stream stage is above the adjacent water table.

Monitoring Well: A well drilled with the specific purpose of measuring groundwater elevation or quality.

Perched Aquifer: An aquifer separated from the underlying regional groundwater system by a layer of rock with a low hydraulic conductivity (e.g., aquiclude).

Perennial Stream: A stream which flows continuously.

Perforation: Puncturing of well casing opposite an aquifer to permit water to flow into the cased well.

Permeability: Also known as hydraulic conductivity, is a property of the soil or rock material that describes the ease at which water flows through the soil, commonly expressed as a velocity (ft/day). Hydraulic conductivity varies from low values (e.g., clay and silt) to high values (e.g., sands and gravels). Hydraulic conductivity when multiplied by the saturated thickness of the aquifer yields the transmissivity of that aquifer.

Point Bar: Sediment deposited along a stream on the inside of a growing meander loop.

Porosity: The ratio of the volume of the pores or interstices in a rock or sediment to the total volume of the rock or sediment.

Potentiometric Surface: Surface to which water in a confined aquifer would rise by hydrostatic pressure above the top of the aquifer.

Riparian Area: A geographically delineated area with a distinct resource value, that is characterized by deep-rooted plant species that depend on having roots in the water table or its capillary zone and that occurs within or adjacent to a natural perennial or intermittent stream channel or within or adjacent to a lake, pond, or marsh bed maintained primarily by natural water sources. It does not include areas in or adjacent to ephemeral stream channels, artificially created stockponds, man-made storage reservoirs constructed primarily for conservation or regulatory storage, municipal and industrial ponds or man-made water transportation, distribution, off-stream storage and collection systems.

Specific Yield: The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. The total volume of water an aquifer will yield by gravity drainage which may take many months to occur.

Stream Depletion Factor (sdf): sdf is a time factor expressed as a ratio of the distance from a well (a) squared and the aquifer's specific yield (s) to its transmissivity (t) ($sdf=a^2S/T$).

Stream Size: The elevation of a stream above or below an established datum or reference.

Subflow: Water which flows within the bed, banks or adjacent land that is in hydraulic connection with a stream and has the same gradient and direction of flow as the stream. Subflow can be considered a part of the surface flow.

Surface Water: Water that occurs on the land surface and includes water in streams, rivers, lakes, and marshes.

Transmissivity: The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media. Transmissivity when divided by the saturated thickness of the aquifer yields the hydraulic conductivity.

Transpiration: The quantity of water absorbed and transpired and used directly in the building of plant tissue, in a specified time.

Unconfined Aquifer: An aquifer in which there are no confining beds between the zone of saturation and the water table surface. There is a water table associated with an unconfined aquifer.

Vadose Zone: The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain air and water at less than atmospheric pressure. Perched groundwater may exist in the unsaturated zone. Also called the zone of aeration or unsaturated zone.

Vertical-Slice Model: Within this report this term refers to a subregional three-dimensional groundwater flow model.

Water Table: The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric.

Watershed: All lands enclosed by a continuous hydrologic-surface drainage divide and lying upslope from a specified point on a stream.

Weir: A notch or depression in a levee, dam, embankment, or other barrier across or bordering a stream, through which the flow of water is regulated or measured.

Xeric: Low or deficient in moisture for the support of life.

Zone of Saturation: The zone in which the permeable rocks are saturated with water. Water in the zone of saturation will flow into a well, and is called groundwater.

The above definitions are from or modified from the following references:

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CHAPTER III

ECOLOGIC REPORT

TABLE OF CONTENTS

INTRODUCTION 3-1
PURPOSE AND SCOPE 3-1
Objectives 3-1
Organization 3-2
RIPARIAN ECOLOGY 3-3
Environmental Influences 3-3
Riparian Classification and Terminology 3-9
Vegetation Dynamics 3-11
Functions and Values 3-12
RIPARIAN ECOSYSTEMS AND ENVIRONMENTAL STRESS 3-14
Hydrologic Change and Riparian Loss and Degradation 3-14
Ecosystem Stress Concepts 3-15
Detecting Riparian Stress 3-19
Recovery from Stress and Minimization of Impacts 3-21
RIPARIAN ECOSYSTEMS AND HYDROLOGY 3-21
Historical Perspective 3-21
Methodologies 3-22

RIPARIAN VEGETATION AND GROUNDWATER 3-25
IMPORTANCE OF GROUNDWATER TO RIPARIAN VEGETATION 3-25
Sonoran Riparian Forests 3-26
Sonoran Riparian Shrublands 3-35
Sonoran Riparian Marshlands and Herbaceous Vegetation 3-37
Warm- and Cold-Temperate Mixed Broadleaf Riparian Forests 3-40
Warm- and Cold-Temperate Marshlands and Riparian Grasslands 3-41
GROUNDWATER DECLINE AND RIPARIAN DEGRADATION 3-43
Riparian Areas Threatened by Groundwater Decline 3-43
Ecological Impacts of Groundwater Decline 3-45

RIPARIAN VEGETATION AND SURFACE WATER 3-50
IMPORTANCE OF SURFACE WATER TO RIPARIAN VEGETATION 3-50
Sonoran and Warm-Temperate Riparian Forests 3-52
Cold-Temperate Riparian Forests 3-54
SURFACE WATER DECLINE AND RIPARIAN ECOSYSTEMS 3-55
Overview of Ecological Impacts 3-55
Ecological Impacts: Sonoran Riparian Forests 3-56
Ecological Impacts: Warm- and Cold-Temperate Riparian Forests 3-62

FLOOD FLOWS AND RIPARIAN VEGETATION 3-64
ECOLOGICAL IMPORTANCE OF FLOOD FLOWS 3-64
Sonoran Riparian Ecosystems 3-66
Warm- and Cold-Temperate Riparian Ecosystems 3-69
FLOOD FLOW ALTERATION AND RIPARIAN ECOSYSTEMS 3-70
Cause of Flood Flow Alteration 3-70
Ecological Impacts of Flood Flow Alteration 3-72

RIPARIAN VEGETATION AND WATER QUALITY 3-78
IMPORTANCE OF WATER QUALITY TO RIPARIAN VEGETATION 3-78
Sonoran Riparian Ecosystems 3-79
Warm- and Cold-Temperate Riparian Ecosystems 3-81
WATER QUALITY ALTERATION AND RIPARIAN ECOSYSTEMS 3-82

CONCLUSIONS AND RECOMMENDATIONS 3-87
GROUNDWATER 3-87
SURFACE WATER 3-92
FLOOD FLOWS 3-94
WATER QUALITY 3-96

LITERATURE CITED 3-97

GLOSSARY 3-124

LIST OF TABLES

Table 1. Functions and values of riparian vegetation in the Southwest . 3-13
Table 2. Primary hydrologic causes of riparian loss and degradation . . 3-16
Table 3. Indicators of riparian vegetation stress or degradation 3-20
Table 4. Depth-to-groundwater ranges for several obligate and facultative Sonoran riparian tree species 3-29
Table 5. Depth-to-groundwater range for some obligate and facultative Sonoran riparian shrub species. 3-36
Table 6. Depth-to-groundwater range for several grasses of Sonoran, warm-temperate ecosystems. 3-38
Table 7. Salinity tolerance range (mg/l of TDS) for selected riparian plant species 3-80

LIST OF FIGURES

Figure 1. Distribution of riparian tree species across an elevation gradient 3-5
Figure 2. Distribution of riparian tree species along four central Arizona streams 3-6
Figure 3. Cross-section of warm-temperate and subtropical riparian forests 3-7
Figure 4. Species change with increasing depth to groundwater in a Sonoran riparian ecosystem 3-27
Figure 5. Diagram indicating movement of water in riparian ecosystems . . 3-51
Figure 6. The potential role of riparian monitoring and hydrologic and ecologic models in preventing riparian degradation 3-89

APPENDICES

APPENDIX D. Scientific and common names of Arizona riparian plant species D-1

INTRODUCTION

PURPOSE AND SCOPE

The Riparian Protection Act (A.R.S. §45-101) called for the Arizona Department of water Resources to "... evaluate the effects of groundwater pumping and surface water appropriations on riparian areas ... ." This chapter of the report summarizes information on the ecological component of this issue. Specifically, it provides an overview of the interrelationships between site hydrology and riparian vegetation, and the way in which riparian vegetation abundance and composition changes in response to human-related hydrologic alterations. Information is not presented on riparian animal life (e.g., birds, mammals, herpetofauna) or on aquatic components of the ecosystem (e.g., algae, submergent vascular plants, fish, or other aquatic biota). Many articles summarize the integral functional role of riparian vegetation in providing wildlife habitat (Ohmart and Anderson, 1986), including the parallel report prepared by the Arizona Game and Fish Department (AGFD, 1993). Several articles also summarize effects of hydrologic changes on native fish and other aquatic organisms (Miller, 1961; Minckley and Deacon, 1993; Grimm, 1993).

Objectives

This portion of the study had two general objectives. The first objective was to summarize existing literature on relationships between riparian vegetation and hydrological conditions in Arizona, with emphasis on those riparian vegetation types that are most susceptible to hydrologic changes or that have undergone the most historic change as a result of hydrologic alterations. This material is contained in this chapter.

The second objective was to conduct field research on relations between riparian vegetation and site hydrology in three case study areas, and use this information to describe techniques that can be used to assess ecological impacts of water diversions

or groundwater pumping. These results are presented in the Case Study chapter (Chapter IV).

Organization

This introductory section provides an overview of riparian ecology, riparian terminology, riparian functions and values, and ecosystem response to stress. The main body of this chapter (Riparian Ecosystems and Hydrology Section) begins with a discussion of methodologies that can be used to assess, detect, and minimize riparian alteration from hydrologic alteration, and then discusses the relationships of riparian vegetation with hydrology.

There are several ways to approach the topic of riparian vegetation/hydrology relationships. One method would be to identify riparian community types and systematically discuss hydrologic relationships for each riparian type. Another approach is to identify hydrologic variables of concern, and systematically address the relationships of each variable with riparian vegetation as a whole. This latter approach was taken in this paper, to conform with Arizona's legal framework in which laws exist that regulate specific hydrologic entities (e.g., surface water, groundwater), but none that address management of specific plant community types (e.g., cottonwood-willow forests, marshlands).

Riparian vegetation is discussed in relationship to four key hydrologic parameters: (1) groundwater, (2) surface water, (3) flood flows, and (4) water quality. For each of these parameters the general importance of the hydrologic variable to riparian vegetation is discussed, and quantitative information is provided on relationships of the variable with specific plant community types or species. Conclusions and recommendations for minimizing riparian degradation from hydrological alterations are presented at the end of

the report. Common and scientific names of plants referred to in this document are listed in appendix D.

RIPARIAN ECOLOGY

Environmental Influences

Riparian ecosystems are composed of biological components and physical components. The biological component includes terrestrial vegetation such as grasses, forbs, vines, shrubs, and trees; aquatic and semi-aquatic vegetation including vascular plants and algae and mosses; as well as animals, fungi, and microbes. The physical component includes the water, nutrients, soil and other factors that sustain the biotic organisms.

A number of factors including hydrology, elevation, climate, geology, and geomorphology interact to produce a great diversity of physical conditions and thus a great diversity of riparian vegetation types. As a result, riparian ecosystems in Arizona differ greatly in size (e.g., riparian zone width and length), species composition (e.g., diversity and identity of the species that are present), and community structure (e.g., canopy height and number of vegetation "layers"). Zimmerman (1969) stated that "Drainage area, geology, and flow regimen are probably the three most important controls in the distribution of valley-floor vegetation" in the arid Southwest. Robinson (1958) identified depth to the water table (or capillary fringe), groundwater quality, and climate as the three factors of greatest importance to the occurrence and growth of riparian plants. Baker (1989), Larkin (1987), Szaro (1989), and Valenciano (1992) identified elevation and several hydrogeomorphic components including drainage basin size, valley cross sectional area, and stream gradient as factors structuring the composition of riparian vegetation in semiarid areas of Arizona, Colorado, and New Mexico.

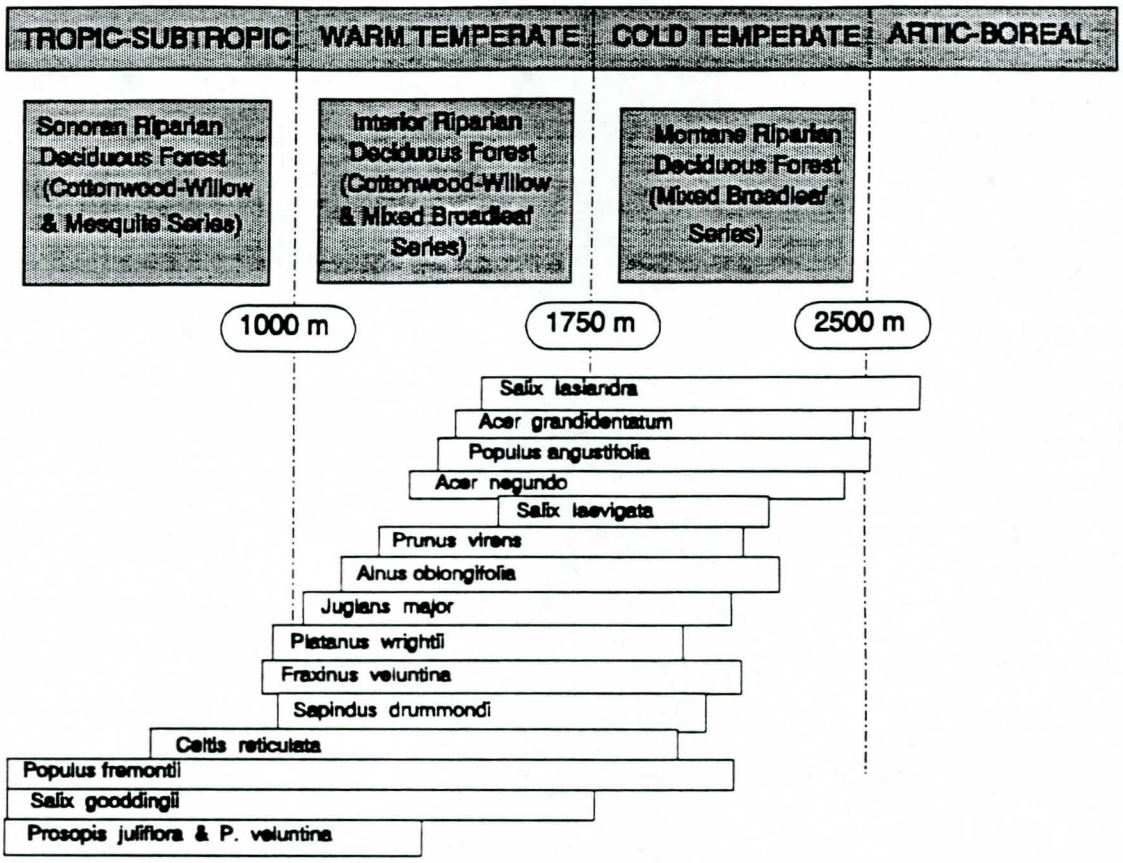
Surface water and groundwater hydrology play a primary role in influencing the composition, structure, and abundance of riparian vegetation, as discussed in detail in following sections. Water availability and hydrological conditions differ between streams, between reaches within a stream, and along lateral gradients from the stream to the floodplain perimeter. Hydrological factors that are of key importance to riparian vegetation include availability of groundwater and surface water, magnitude and frequency of flood flows, and water quality.

Many climatic factors, such as precipitation, temperature, and evaporation rate, influence riparian vegetation by controlling the availability and distribution of water. For example, the winter-dominated precipitation and streamflow pattern of northeastern Arizona supports a different assemblage of riparian species than does the summer-dominated pattern of precipitation and streamflow in southeastern Arizona. Besides varying with latitude and longitude, climate also varies strongly with elevation. Tree species such as thin-Pacific willow (*Salix lasiandra*), thin-leaf alder (*Alnus tenuifolia*), big-tooth maple (*Acer grandidentatum)*, narrow-leaf cottonwood (*Populus angustifolia*), and many conifer trees, for example, are adapted to the cold-temperate conditions of high-elevation montane zones (Figures 1 and 2). These give way to warm-temperate riparian forests of Arizona walnut (*Juglans major*), velvet ash (*Fraxinus pennsylvanica*), Arizona sycamore (*Platanus wrightii*), and other mixed broadleaf trees at mid-elevation zones (about 1,500 to 2,000 m, or 5,000 to 6,600 ft). Subtropical forests of Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii*), and honey or velvet mesquite (*Prosopis juliflora* or *P. velutina*) dominate at the lowest elevations in the state (less than about 1,000 m or 3,300 ft). Riparian shrubs and herbs similarly vary with elevation and climate.

Geomorphic and edaphic factors also influence riparian vegetation, in part because they influence water availability and flood intensity. For example, canyon width influences the scouring force of flood flows through the riparian zone; subsurface geology influences the

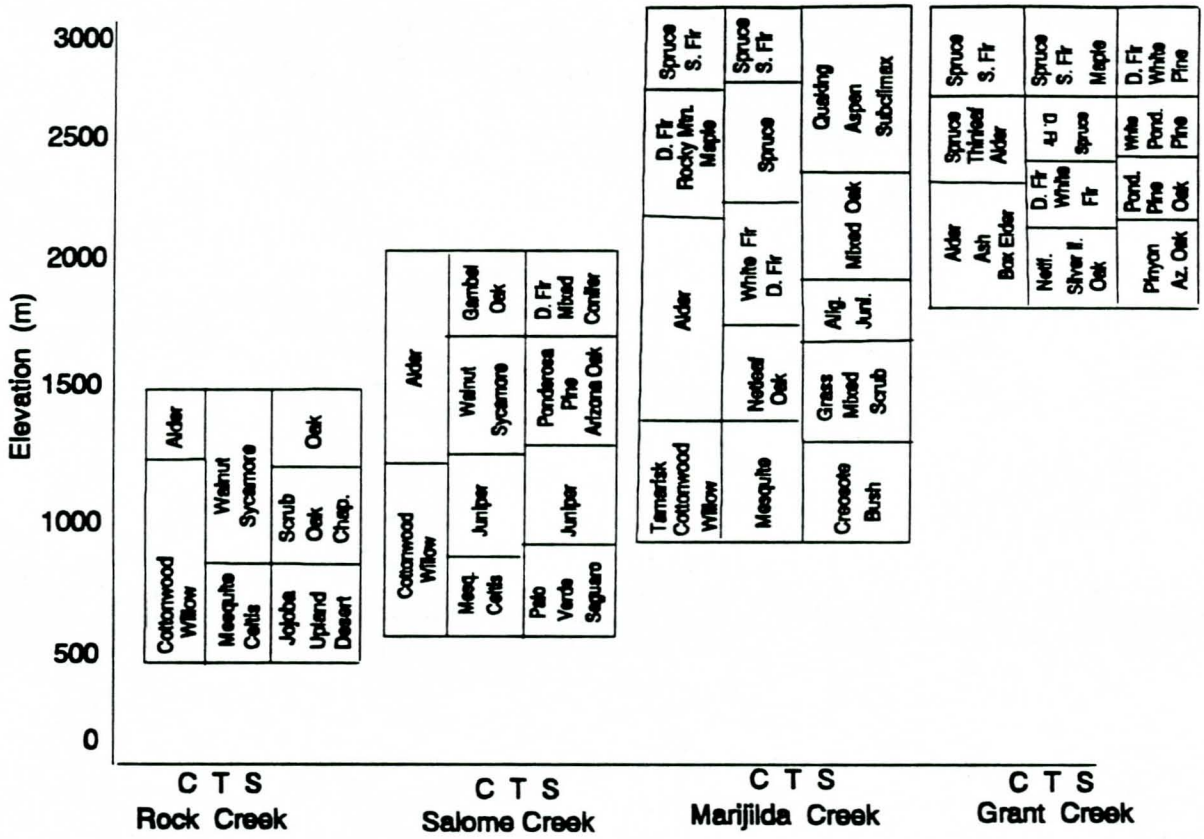
depth and extent of floodplain aquifers; floodplain soil texture influences soil moisture holding capacity and capillary water rise; and streambank soil substrate influences the extent of lateral water movement into stream banks. Along high-elevation mountain drainages, streams often flow with high gradient over a bedrock substrate with limited development of alluvium, and are constrained by canyon walls. Riparian zones in such areas typically are narrow, and form "stringers" of vegetation lining the streambed (Figure

Figure 1. Distribution of riparian tree species across an elevation gradient (after Brown, 1982)



3). Streams that have emerged from the mountains to the valley floor often meander areas typically are narrow, and form "stringers" of vegetation lining the streambed (Figure 3). Streams that have emerged from the mountains to the valley floor often meander laterally within a wide floodplain underlain by alluvium, and support wide riparian zones (Figure 3).

Figure 2. Distribution of riparian tree species along four central Arizona streams across an elevation and moisture gradient extending from the channel (C) to the terrace (T) and upland slope (after Valenciano, 1993)



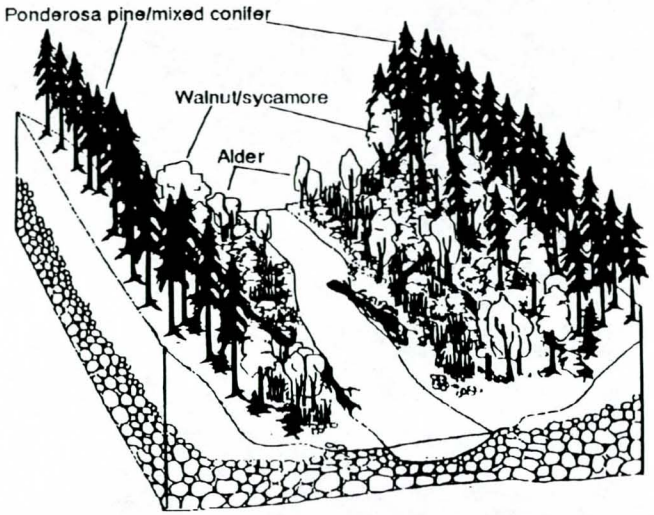
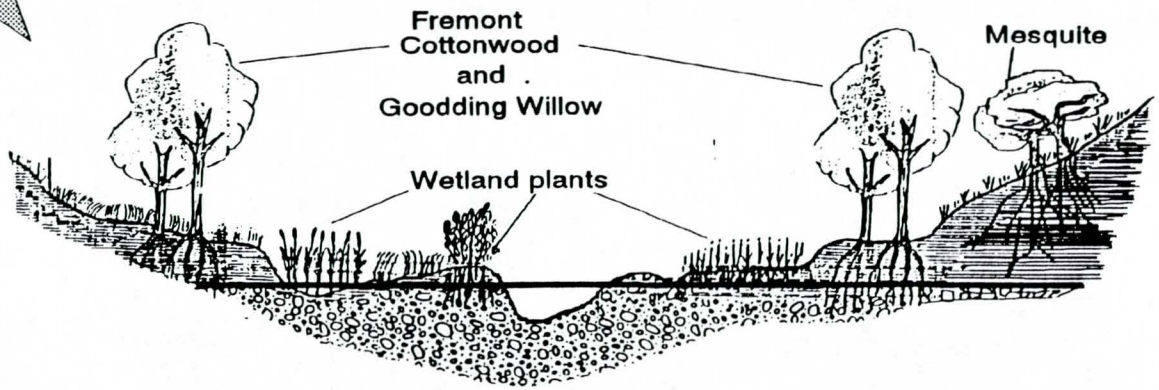


Figure 3. Diagrammatic cross-section of a typical warm-temperate riparian forest (above) and subtropical riparian forest (below), showing alluvial aquifer, water table, and zonation of characteristic riparian tree species.



Although physical components of the environment are the major determinants of riparian biotic communities, biological interactions also play a role. Biological interactions such as pollination of flowers by insects, dispersal of seeds by animals, competition between plant species, commensalism between plant species (e.g., creation of suitable habitat for one plant species by another plant species), parasitism of plants by species such as mistletoe, herbivory on plant leaves by insects or mammals, or spread of fungal or bacterial diseases, all influence the composition of riparian plant communities. The geographic location of the riparian zone also influences its species composition as it determines the floristic region. Although the dominant species of riparian zones often "cut across" floristic regions, it is also true that many upland species grow in the riparian zone on a facultative basis (see next section). As a result, each riparian zone supports a unique assemblage of plant species, and as evidenced by genetic studies, a unique gene pool (Spanglet, 1993).

Riparian Classification and Terminology

Because elevation and climate have such strong influence on riparian plant community composition, they form a basis for classification of major groupings of riparian vegetation (Figure 1). In addition to the broad groupings shown in Figure 1 (e.g., cold-temperate, warm-temperate, and tropical-subtropical wetlands), dozens of finer-level floristic riparian plant communities (series) and associations are recognized (Brown, Lowe and Pase, in Brown, 1982). Szaro (1989) identified 28 different wooded riparian community types, or associations, in Arizona and New Mexico. Riparian associations are named for either (1) the dominant riparian tree species in riparian forests, (2) the dominant shrub species where the vegetation is dominated by shrubs, or riparian "scrub" as it is sometimes referred to, or (3) the dominant herbaceous species where grasses or forbs predominate. Riparian zones are also classified on the basis of physical site characteristics such as geomorphology; according to management objectives; or according to functional type, as described further in the parallel Arizona Game and Fish Department report (AGFD, 1993;

Swank, 1990; Kovalcjik and Chitwood, 1990). The classification scheme followed in this report is the same as that used by AGFD (1993) (i.e., Brown, Lowe and Pase). As a consequence of the strong influence of water availability on riparian vegetation, many terms have arisen that classify or categorize riparian species or communities by their requirement for, or tolerance to, different degrees of water availability. One set of terms differentiates between hydro-, meso-, and xero-riparian habitats (Johnson and others, 1984). Species of **hydroriparian** habitats, such as Goodding willow, require perennially wet soil and do not tolerate drought. They are usually associated with perennial water.

Mesoriparian species have intermediate tolerance for drought, and include trees such as Arizona walnut. They are often associated with seasonally dry, intermittent streams, or with drier areas of floodplains of perennial streams. **Xeroriparian** species, such as blue paloverde (*Cercidium floridum*) or canyon ragweed (*Ambrosia ambrosiodes*), can withstand extended periods of low water availability such as occur along ephemeral washes. Only hydroriparian and mesoriparian habitats are considered as "riparian" under the context of the A.R.S § 45-101. Although the term has been defined in a broader context to include riparian ecosystems supported by ephemerally flowing water bodies (Johnson and others, 1984), A.R.S. §45-101 restricts the definition of "riparian area" to areas associated with perennial and intermittent stream channels or other natural water bodies.

Another set of terms differentiates between **obligate** and **facultative** riparian species. Obligate riparian plants grow only in the riparian zone, because the environmental conditions they need naturally occur nowhere else. Hydro- and meso-riparian plants usually are riparian obligates, as are some xeroriparian plants (e.g., canyon ragweed grows only in ephemeral washes). Facultative riparian plants can grow in riparian zones and in uplands with suitable moisture availability. Many facultative riparian species become riparian obligates at low elevations where the decreased precipitation no longer

allows them to persist in the upland habitat. Mesquite, for example, grows in the uplands in some of Arizona's grassland biomes, but is essentially restricted to the riparian zone within the drier Sonoran Desert. Many facultative riparian species display a different growth form and play a different ecological role when growing in riparian settings. Mesquite stands, for example, are considerably taller, denser, and lusher in riparian zones than in uplands, and create critical habitat for riparian animal species.

There is no document that indicates whether a plant species is obligate or facultative riparian, or whether it is hydro-, meso-, or xeroriparian. Plant species have, however, been assigned on a national and regional basis to one of five categories indicating their probability of occurring in wetlands: obligate wetland, facultative wetland, facultative, facultative upland, and upland (Reed, 1988). Many of our obligate riparian plant species fall into the categories of obligate wetland, facultative wetland, or facultative. Most of Arizona's facultative riparian species are not listed in Reed (1988). This is because wetlands, by definition, encompass only the wetter end of the riparian moisture continuum. Despite these deficiencies, Reed's (1988) designations are referred to in this report.

Vegetation Dynamics

Riparian zones are dynamic in space and time, and support a complex mosaic of plant species with different environmental requirements and different tolerance ranges for environmental variables. In broad alluvial valleys, streams which support riparian zones often have multiple historic or active channels which undergo continual lateral adjustment, as they meander and form new alignments. At any given point in time, the active channel can be found anywhere within the floodplain. The floodplain itself undergoes continual cycles of accumulation and loss of sediment, which can be composed of fine-grained or coarse-grained alluvial substrates. Many of these fluvial processes are driven by flood flows, which play a major role in the perpetuation and development of riparian systems

(Reichenbacher, 1984; Junk and others, 1989). The varied fluvial processes create spatial environmental gradients such as gradients of depth to the water table, frequency of inundation by flood waters, or soil particle size. These gradients allow for the occurrence of a diverse assemblage of riparian species, and for high biodiversity. Factors occurring in the surrounding watershed influence the ongoing changes in the riparian zone by affecting processes such as soil erosion and sediment delivery, and water runoff and flood magnitudes.

Functions and Values

Riparian corridors have been referred to as the "lifeblood" of Southwest ecosystems. They are ecotones (i.e., border, or edge ecosystems) that serve as linkages between streams and their surrounding terrestrial environments (Likens and Bormann, 1974). Healthy riparian zones provide many functions and values, as further described in AGFD (1993) (Table 1).

Water in stream channels and alluvial aquifers allows riparian vegetation to have high biomass (i.e., high amount of vegetative matter), high productivity and growth rate, and high structural diversity (i.e., tall canopies with a well developed mid-canopy vegetation layer and understory vegetation layer). Ongoing fluvial processes create a diversity of habitats and niches within the floodplain. As a consequence, riparian ecosystems play a major role in maintaining regional biodiversity (Naiman and others, 1993). For example, riparian forests support higher densities of breeding birds than any other habitat in the Southwest (Knopf and others, 1988). Between 40 and 85% of arid region animal groups (e.g., reptiles, amphibians, birds) depend in some fashion on riparian resources (Knopf and others, 1988). Riparian zones also create recreational habitat for picnickers, hikers, anglers, bird-watchers, campers, and others.

Table 1. Functions and values of riparian vegetation in the Southwest
Hydrologic Functions
• Reduce flood flow velocity
• Enhance groundwater recharge
Water Quality Functions
• Trap sediments
• Filter nutrients
Geomorphic Functions
• Stabilize stream banks
• Reduce soil erosion
Wildlife Habitat Functions
• Provide habitat for obligate and facultative riparian animals
• Provide habitat for fish and other aquatic organisms
Recreation and Aesthetics

As buffer zones between terrestrial and aquatic ecosystems, riparian forests perform many important water quality functions. Riparian forests have been equated to semipermeable membranes that allow the passage of some materials while retaining others, and that filter nutrients (primarily phosphorous and nitrogen) from adjoining terrestrial systems (e.g., agricultural lands) before they reach sensitive aquatic environments (Lowrence and others, 1984). Many of the nutrient transformations occur in the biologically-active hyporheic zone, which spans the width of the floodplain and can extend laterally from the stream for hundreds of feet.

The role of riparian systems in stabilizing sediment and streambanks is particularly important in arid settings, where inputs of sediment can be high and flood magnitude can be high relative to baseflows. Riparian forests play a major role in removing eroded sediments from floodwaters and stabilizing them in the floodplain. Without riparian

vegetation, rivers in arid regions undergo streambed scouring, channel widening, and carry increased sediment loads.

Although riparian vegetation consumes both groundwater and surface water, these aridland riparian systems perform water quantity, as well as water quality, functions. For example, riparian vegetation can enhance groundwater recharge by slowing flood waters and increasing water retention. Riparian vegetation can modify flood flows by increasing lateral spread of flood waters and decreasing downstream flow velocities.

RIPARIAN ECOSYSTEMS AND ENVIRONMENTAL STRESS

Hydrologic Change and Riparian Loss and Degradation

Direct hydrologic alteration of rivers and floodplains is a primary cause of riparian ecosystem loss and degradation. Riparian loss and degradation also result from indirect alteration of hydrologic function, through land use practices in the floodplain or watershed that alter water flow patterns or water retention capacity of the floodplain (Stromberg, 1993a) (Table 2). Plant stress and ecosystem degradation occur as a result of pumping groundwater from alluvial and regional aquifers; diversion of surface water; modification of peak flows, seasonal flow patterns, sediment flow, and water quality by dams; and alteration of water and sediment flow by riparian zone and watershed land use practices. The extent of human-caused hydrologic changes varies between regions of the state. Riparian areas in the more arid and more densely populated Basin and Range Province have been subject to greater reduction in water supply than have those in other regions. As a consequence, low elevation riparian vegetation types have undergone greater loss and degradation than other riparian types.

Continuous corridors of riparian vegetation once covered hundreds of miles along desert rivers of the Southwest. Many of the riparian zones along these desert rivers have been

destroyed or degraded (Dobyns, 1981; Swift, 1984). In Arizona, for example, decline and degradation have been documented on the Colorado, Gila, Salt, and Santa Cruz Rivers (Rea, 1983; Ohmart and others, 1988; Betancourt and Turner, 1993). Elsewhere in the Southwest, the Rio Grande in New Mexico, the Owens River in California, and the Virgin River in Nevada are examples of rivers that have been extensively degraded by human activities including river damming and diversion, groundwater pumping, and invasion by saltcedar (Brothers, 1984; Howe and Knopf, 1991; Hughes, 1993). As a consequence, two riparian forest types associated with alluvial desert rivers, Fremont cottonwood-Goodding willow forests and mesquite bosques, have undergone regional decline and are considered to be among the most threatened forest types in the United States. Loss of riparian marshlands associated with low elevation rivers also has been high (Hendrickson and Minckley, 1984). Today, hydrologic changes continue to stress desert rivers and their riparian zones and are increasingly affecting rivers along their upper reaches and tributaries.

Ecosystem Stress Concepts

Hydrologic changes brought about by human activities can stress and degrade riparian ecosystems. Stress can be defined, in a broad sense, as any factor that reduces the "biotic integrity" or functional ability of an ecosystem (Karr, 1991). Degradation is the consequence of this stress, and can be apparent in reduced plant density and cover, reduced age-class diversity, reduced species diversity, reduced structural diversity, or increased abundance of exotic species (e.g., saltcedar).

Stress can result from too little water (drought stress), too much water (inundation stress), or from any deviation from the conditions to which an organism is adapted. For example, some riparian species are adapted to germinate during spring, which is a natural period of high water in many Arizona streams. The plant population will be altered if the season of peak water availability is shifted from spring to summer.

Table 2. Primary hydrologic causes of riparian loss and degradation	
Activity	Hydrologic Change
Direct Hydrologic Alterations	
Groundwater pumping	Groundwater decline
	Increased groundwater fluctuation
	Surface flow reduction
Surface water diversion	Surface flow reduction
	Seasonal flow alteration
	Increased flow variability
	Groundwater decline
Dams and impoundments	Surface flow reduction
	Flood flow alteration
	Sediment and nutrient decrease
	Salinity increase
Indirect Hydrologic Alterations	
Floodplain clearing for agriculture; paving and urbanization; grazing	Flood velocity increase
	Stream bank erosion and sediment increase
	Salinity increase
Stream channelization	Floodplain inundation decrease
Watershed clearing/ grazing/ paving	Flood magnitude increase
	Baseflow decrease
	Soil erosion and sediment increase

Ecosystems can be degraded by **acute** (i.e., short but intense) exposure to stress, often referred to as a **perturbation**. This is exemplified by the extensive vegetation loss on Tonto Creek that occurred as a result of a flood in a poorly managed riparian zone (Myers, 1993). Ecosystems also can be altered by **chronic** (long-term, but low level) exposure to a stress. For example, sustained water table decline along the Gila River floodplain over several decades resulted in complete loss of a riparian mesquite bosque (Judd and others, 1971). Another example can be found in the extensive mortality of

Fremont cottonwood trees in the Bill Williams River riparian zone that occurred in the late 1980s when sustained releases of unnaturally high flows from Alamo Dam caused trees to die from inundation stress (i.e., lack of oxygen) (Hunter and others, 1987).

Ecosystems or species that remain unchanged when they undergo a stress or perturbation are considered to be **resistant** to that stress. An ecosystem is considered to be **resilient** to stress or perturbation if it undergoes temporary change but then recovers to a condition that resembles its initial state. Healthy riparian ecosystems show a fair degree of resistance and resilience to types of stresses or disturbances to which they are adapted, such as natural flood disturbance (i.e., infrequent occurrence of high magnitude but short duration flood peaks). The resistance and resilience of an ecosystem varies with each type of stress or disturbance to which it is exposed.

Riparian ecosystems respond to stress by undergoing changes that occur in **hierarchical fashion** (Taub, 1987). An ecosystem can be viewed hierarchically in the sense that it is composed of a community of interacting species, with each species being composed of a group of interacting individuals. At low levels of stress, changes may occur at the individual or population level. Riparian trees have been shown to undergo increases in physiological stress, declines in growth, outbreaks of disease, or increases in mortality and declines in population density as a result of water stress resulting from surface water diversion (Medina, 1990; Smith and others, 1991; Stromberg and Patten, 1992). Higher levels of stress cause ecosystem and community-level changes, such as loss of species of plant associations (e.g., marsh plants), changes in vegetation structure (e.g., reduction in canopy cover or replacement of tall forests by shrublands), and reductions in biomass. Extreme stress effects are exemplified by the conversion of portions of the lower Salt River floodplains from riparian forests to barren soils a result of surface water diversion, or by the conversion of riparian forests along the Gila River near Casa Grande to Sonoran Desert vegetation as a result of extensive groundwater pumping (Judd and

others, 1971). Reduction or loss of one species may have cascading effects throughout an ecosystem, given the interdependency of many riparian species (e.g., some understory plant species require the presence of a dense tree canopy).

Riparian ecosystems are composed of a suite of interacting species. Each species has its own particular set of **tolerance ranges** and **thresholds** for environmental variables. For example, each plant species will tolerate differing degrees of soil moisture stress; and each will have some upper and lower threshold value for moisture stress beyond which the species will not survive. Another response to stress, then, is a sequential loss from an ecosystem of species that are less and less resistant to that stress. For example, in response to drought stress and water table declines resulting from groundwater pumping, the first species lost will be those species that require perennially wet soils and shallow water tables, followed by species that are increasingly more tolerant of deeper water tables. Tolerance ranges and impacts of hydrologic changes are not fully understood for all riparian species, but are being summarized and studied as a part of this report.

Many hydrologic changes produce **long-term impacts** that last on the order of centuries. Arroyo cutting (channel entrenchment or incision) and associated water table decline that occurred during the turn of the century have produced long-term changes from which riparian ecosystems are still currently recovering. Dam construction also can produce long-term changes that may not be apparent for decades or centuries. Several decades or more may be required for the downstream riparian and aquatic ecosystems to reach an equilibrium with the altered environmental conditions (Petts, 1985; Pautou and others, 1991). For example, chronic nutrient depletion in below-dam reaches may take years to be expressed as changes in species composition or reductions in biomass. In addition, stress has been observed to decrease genetic diversity by reducing the number of individuals in a population. This can result in long-term impacts, such as future outbreaks of disease.

Finally, it is essential to consider the effect of **cumulative impacts** on riparian ecosystems. The combined effects of two or more stresses produces effects greater than that of either stress individually. Thus, riparian ecosystems can be severely stressed by cumulative impacts. Also as a general rule, there are few plants that tolerate the combination of chronic stress and frequent disturbance or perturbation. Chronic water stress, for example, can reduce the ability of riparian vegetation to recover from perturbation from flood or fire, or to cope with ever-present stress from parasites and pathogens (i.e., disease-bearing organisms).

Detecting Riparian Stress

Many techniques can be used to detect loss of riparian function or biological integrity. Early signs of stress or degradation can be detected by monitoring individual plants for reductions in growth rate; changes in physiological state such as increases in internal plant water stress; increases in canopy mortality; or increased outbreak of pathogens or disease organisms (Table 3). Stress also can be detected by sampling plant populations for reductions in age class diversity, or increases in plant mortality for susceptible age classes (e.g., very young or very old plants). Stress and degradation also can be detected by monitoring communities and ecosystems for changes in cover or biomass of the riparian stand, loss of biodiversity, or changes in species composition. A stressed community may show increased abundances of exotic species (which often are indicators of altered site conditions); decreased abundance of "keystone" species (pivotal species upon which many other species or ecosystem processes depend); or decreased abundance of indicator species that are very sensitive to ecosystem changes and that may serve as early warning detectors of stress. Detection of stress requires investment of time and resources, but can be accomplished through a variety of techniques (see Case Study Chapter IV).

Table 3. Indicators of riparian vegetation stress or degradation	
Biotic Indicators	
1. Physiological or growth changes:	• Increase in plant water stress
	• Decrease in growth rate or leaf size
	• Increase in pathogen outbreak
2. Population structure changes:	• Loss or reduction of sensitive life stages (e.g., seedlings of cottonwood or willow trees)
	• Reduction in age class diversity
3. Species composition changes:	• Loss or reduction of sensitive species (e.g., obligate wetland plants such as rushes)
	• Replacement of obligate riparian plants by facultative riparian plants
	• Increase in opportunistic exotic species (e.g., saltcedar)
4. Stand structure changes:	• Reduction of canopy foliage area
	• Reduction in canopy height
	• Crown dieback
	• Reduction in tree density
	• Reduction of ground cover
	• Replacement of tree growth form by shrub growth form
Physical Indicators[1]	
1. Changes in site hydrology:	• Declines in groundwater or increase in groundwater fluctuation
	• Reduction in streamflow volume, particularly during low flow periods (May and June)
	• Increase in non-perennial reaches
2. Changes in geomorphology or soils:	• Channel widening, or lack of channel re-narrowing after flood events (indicating disruption of stream recovery patterns)
	• Alteration of "normal" sedimentation and floodplain terracing patterns
	• Increase in soil salinity
	• Loss of fine-textured soil particles
[1] These often are the factors causing the ecological stress	

Recovery from Stress and Minimization of Impacts

Some types of hydrologic impacts produce irreversible ecosystem changes while others can be reversed with varying degrees of human assistance. Typically, the more extreme a stress has been, and the longer it has occurred, the more difficult it is to reverse.

Riparian vegetation along sites such as the Gila River and lower Santa Cruz Rivers where water tables have declined by hundreds of feet, for example, could theoretically recover if a commitment was made to undertake a massive groundwater recharge project in the area. Unique gene pools and rare species that may have been lost would not return, but the vegetation community as a whole could recover. Riparian zones that have been stressed by dams and surface flow diversion can be restored by releasing surface flows that mimic historic hydrograph data, but recovery will be less complete if a river has been hydraulically disconnected from underlying groundwater. Channelized rivers also can naturally recover over relatively long time spans, if the river system is allowed to operate under a more natural regime (Hupp, 1992). Generally, if remnant riparian plant populations still persist, the riparian ecosystem can recover naturally once the necessary physical conditions have been restored. Active restoration measures can hasten this natural recovery process. Ecosystem stress from hydrologic alterations can be minimized by ensuring that physical conditions and processes deviate as little as possible from historic "norms."

RIPARIAN ECOSYSTEMS AND HYDROLOGY

Historical Perspective

Early in this century there were several noteworthy articles that addressed relationships between riparian vegetation and hydrology, driven in part by hydrologic changes and riparian loss that occurred around the turn of the century (e.g., Bryan, 1928). During the 1940s to 1970s, however, riparian (phreatophyte) vegetation was viewed by many as

"worthless vegetation in the bottomlands" without substantial benefit to man (Gatewood and others, 1950; Robinson, 1967). Riparian research at this time focused on quantifying consumptive water use of riparian vegetation and on determining how much water would be saved by clearing the "infestations" of phreatophytic vegetation from the floodplains of desert rivers such as the Gila River in Arizona and the Rio Grande in New Mexico. Horton (1973) abstracted more than 700 publications dealing with the issue. The last few decades, however, have seen an increased recognition of the value of native riparian ecosystems to humans. Concomitant with this shift in values has been a shift in the nature of research. Several recent studies have expanded the knowledge base on riparian ecosystem function and relationships with hydrology (e.g., Busch and others, 1992). However, there is still much to learn.

Methodologies

Several approaches can be taken to assess relationships between hydrologic parameters and riparian vegetation. These include (1) laboratory, greenhouse, or field experiments; (2) studies of ecosystems presently undergoing hydrologic change or historical documentation of ecosystems that underwent past hydrologic change; and (3) studies of riparian vegetation change across natural spatial hydrologic gradients.

The main advantage of an experimental approach is the ability to hold other environmental variables constant while varying the single factor of interest (e.g., depth to groundwater or rate of groundwater decline). Disadvantages include the fact that lab experiments must realistically be restricted to short-lived plants or to juvenile life stages of trees (e.g., Mahoney and Rood, 1991). Field experiments can involve mature trees, but the opportunities to manipulate water resources on such a large scale arises infrequently. Also, such studies lose a certain element of reality because, in the natural world, many factors often change simultaneously.

Valuable information on ecosystem response to hydrologic changes also can be gained by studying ecosystems that are undergoing, or have undergone, hydrologic change. However, care must be taken that time-lag phenomena do not result in misinterpretation of results. For example, some ecosystem changes (e.g., reduction and ultimate loss of a species) may not be detected for decades after the hydrologic change has occurred. This problem can be minimized by studying past changes, provided there is sufficient information on site hydrology and vegetation abundance during the pre- and post-impact time periods. Or, riparian conditions can be compared between impacted and unimpacted stream reaches (e.g., upstream and downstream of a stream diversion) as long as the unaltered reaches serve as suitable "controls" for the hydrologically altered reaches. A caveat inherent in any field study is the fact that multiple environmental factors influence ecosystems, and it may be difficult to discriminate the effects of the hydrologic change from other factors undergoing simultaneous change.

A third methodology involves studying riparian ecosystem change across natural hydrological gradients. This type of study provides information on the natural environmental ranges of particular plant species or communities and is thus useful in predicting effects of artificially imposed hydrologic changes. This approach can be referred to as a space-for-time substitution, in the sense that changes observed across a spatial gradient are assumed to be representative of changes that would occur over time. It rests on the assumption that hydrologic variables are primary determinants of riparian composition and abundance. One advantage of this approach is that vegetation is in equilibrium with the environment (avoiding time-lag effects). Also, natural gradients are readily available to study, although it can be difficult to find riparian ecosystems that have not been modified by various types of land use activities.

For this study, a literature review was undertaken that summarizes results based on all three of the above methods, as well as on anecdotal reports. The new field studies that

were undertaken following the space-for-time substitution approach, and to a lesser extent, involved comparative studies of altered and unaltered reaches (see Case Study Chapter IV). Experimental studies were not conducted. Such studies would be of immense value but were beyond the scope of this report.

RIPARIAN VEGETATION AND GROUNDWATER

The objective of this section is to (1) review the importance of groundwater to riparian vegetation; (2) summarize information regarding the way in which vegetation communities vary in response to natural variations in groundwater conditions; (3) discuss the prevalence and ecological effects of groundwater-related riparian degradation in Arizona; and (4) suggest approaches that can be taken to prevent groundwater decline or extensive groundwater fluctuation from causing riparian loss or degradation.

IMPORTANCE OF GROUNDWATER TO RIPARIAN VEGETATION

Groundwater is a major determinant of riparian vegetation abundance, community structure, species composition, and population health. Groundwater in floodplain aquifers is of direct importance to many types of floodplain vegetation as well as to streambank vegetation, particularly in gaining streams where it contributes to surface water. Groundwater found in the regional (basin fill) aquifer serves as a source of water for the floodplain aquifers and as a water source for vegetation growing at seeps and springs. Some types of vegetation depend on groundwater found within localized "perched" aquifers (Renard and others, 1964). For more information on the stream-aquifer system, refer to the Hydrologic Chapter (Chapter II).

The size of the floodplain aquifer varies considerably with stream type, with consequences for riparian zone size and composition. Some stream types have limited development of alluvium, such as bedrock-controlled, high gradient canyon streams at higher elevations in the state. These small alluvial aquifers support relatively narrow riparian zones vegetated by warm-temperate and cold-temperate mixed broadleaf riparian forests (Figure 3). Other stream types, such as low gradient, meandering desert streams that have emerged from the mountains, often develop deep layers of flood-born sediment referred to as alluvium. Within such river systems, there usually is a very wide "stream" of water that flows beneath the floodplain within the alluvial aquifer. This water, in some

cases, flows at a greater rate through buried, paleo-channels rather than flowing uniformly through the alluvium. The thickness of the alluvial aquifer can vary from a few feet to hundreds of feet, depending in part on variations in depth to bedrock. Alluvial water can be forced closer to the ground surface in stream reaches underlain by shallow bedrock. At low elevations, these wide, shallow floodplain aquifers allow Sonoran riparian cottonwood-willow forests, Sonoran riparian mesquite bosques, and Sonoran scrub associations to grow within the floodplain at extensive distances from the stream channel (Figure 3). At higher elevations, such aquifers allow warm temperate riparian associations such as sacaton grasslands to do the same. In areas where the groundwater is extremely shallow or intersects the ground surface, cienega (marsh) vegetation can occur.

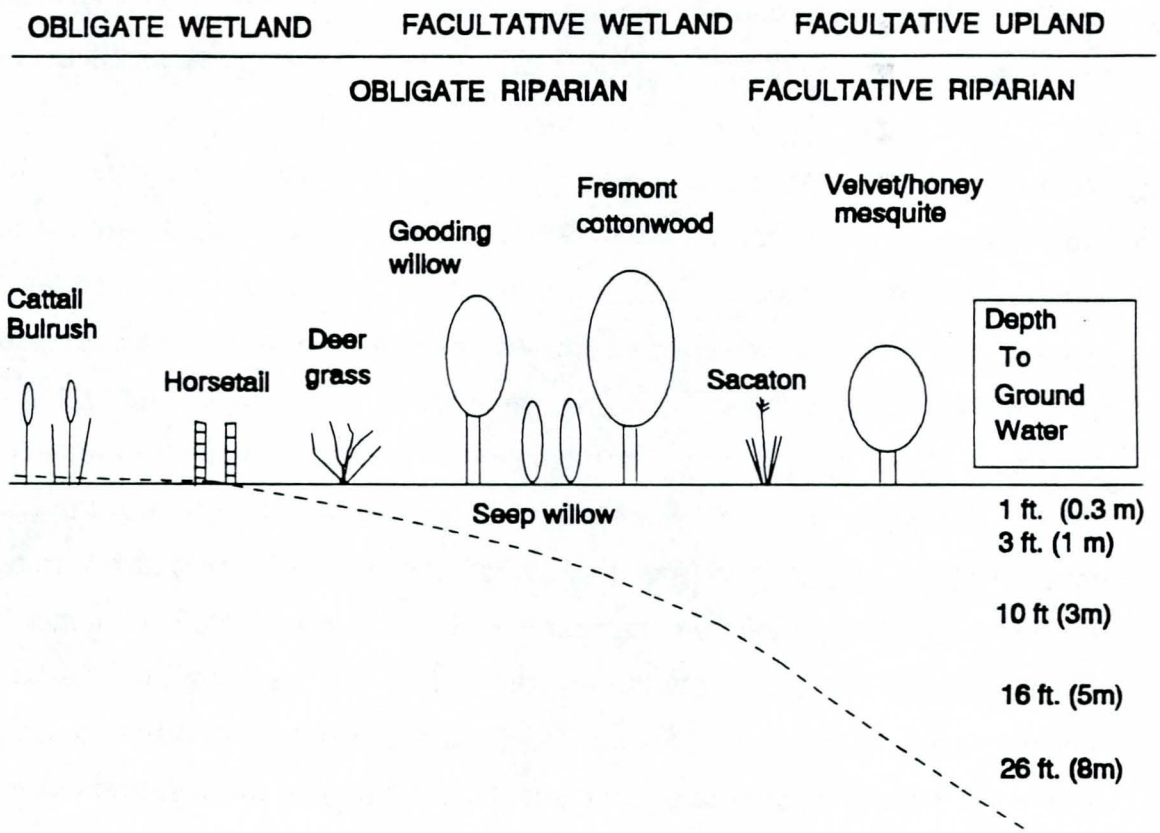
Groundwater variables that are of importance from the plant's perspective include the depth to groundwater from the floodplain surface or from the root zone; the rate and extent of capillary water rise in the soil zone lying above the water table (vadose zone); the depth of standing water in cases where water intersects the ground surface; the extent of fluctuation of the water table on a seasonal, annual, and longer-term basis; and the width of the zone in which the water table is shallow enough to support riparian vegetation.

Sonoran Riparian Forests

Within the Sonoran, Mojave and Chihuahuan Desert regions of the Southwest, Fremont cottonwood and Goodding willow associations are one of the principal types of riparian forest (Brown, 1982). Associated with the cottonwood-willow forests on higher floodplain terraces are riparian mesquite forests, or bosques. Both of these riparian types are best developed along alluvial floodplains of large, low gradient perennial streams in wide, unconstrained valleys, usually below 1,350 m (4,500 ft) in elevation (Szaro, 1989). These riparian forests co-occur with other vegetation associations including marshes and riparian shrublands (Marks, 1950). In many areas, these forests have been lost or degraded by the widespread establishment of invading saltcedar.

Each Sonoran riparian plant species has a slightly different habitat and niche within the riparian zone. As a result, the species within Sonoran riparian ecosystems are distributed within the floodplain across environmental gradients, similar to the case for other forested wetlands (Bell, 1974; Irvine and West, 1979; Reichenbacher, 1984) (Figure 4). Gradients of depth to the water table are prime determinants of riparian vegetation composition and abundance within alluvial streams in the arid Southwest (Richter, 1992). Gradients of inundation frequency or hydroperiod, which often predominate in mesic regions (Wharton and others, 1982; Hupp and Osterkamp, 1985), also play a role in many arid region streams (Auble and others, 1993).

Figure 4. Species change with increasing depth to groundwater in a Sonoran riparian ecosystem



Of all the Sonoran riparian tree species, Goodding willow occupies the wettest habitats. It is the least tolerant of drought and most tolerant of saturated soils, and is classified as an obligate wetland species (Reed, 1988). Groundwater and saturated soil water are the primary water source for mature Goodding willow, based on isotope studies conducted within the Bill Williams and Colorado River floodplains (Busch and others, 1992) and on older research methods (McQueen and Miller, 1972). Goodding willow trees typically grow at sites where the water table is less than about 3 m (10 ft) below the floodplain surface (Table 4), which correspond to its maximum reported rooting depth (7 ft+; Zimmerman, 1969).

Fremont cottonwood is often closely associated with Goodding willow, but is slightly more drought tolerant and can grow on sites that are slightly higher above the water table. There are conflicting reports regarding this issue, however. For example, Busch and others, (1992) reported that Fremont cottonwood used saturated groundwater, while McQueen and Miller (1972) indicated that it used water from above the saturated zone.

Most reports show an association of Fremont cottonwood with shallow groundwater (Table 4), although some authors have suggested that it is not restricted to shallow groundwater sites (Meinzer, 1927). Zimmerman (1969) noted that Fremont cottonwood grew at sites in Arizona where groundwater seasonally declined in summer to about 9 to 13 m (30-40 ft; Ash Creek); this may be a case where small "stringers" of Fremont cottonwood are supported by a combination of surface flow and seasonally high water tables. More recently, Fremont cottonwood has been reported from sites where groundwater was 5 to 6 m (about 16-20 ft) or 8 m (27 ft) below the floodplain surface (Table 4), but in these cases the stand was either in poor condition with low vigor or consisted of only a few isolated trees (see Santa Cruz Case Study, Chapter IV). There are no reports of large, dense stands of Fremont cottonwood forests occurring on sites with water tables deeper than about 3 m (10 ft) below the surface, and this may be taken

Table 4.
Depth-to-groundwater ranges for several obligate and facultative Sonoran riparian tree species

Depth to Groundwater (m)	Depth to Groundwater (ft)	Elevation (ft)	River	Citation	Notes
Fremont Cottonwood *(Populus fremontii)*					
3.5 ± 0.5	12 ± 2	500	Colorado	Busch and others, 1992	
1.0 ± 0.5[1]	3.3 ± 1.0	2000	Hassayampa	Stromberg and others, 1991	10-yr trees
2.6 ± 0.6	8.9 ± 2.0	2000	Hassayampa	Stromberg and others, 1991	40-yr trees
1.4 to 1.7	5 to 7	Unknown	Gila	McQueen & Miller 1972	
1.5 ± 0.5	5 ±2	4000	Sonoita Creek	Stromberg 1993c	<25-yr trees
2.7 ± 0.3	8 ± 1	4000	Sonoita Creek	Stromberg 1993c	130-yr trees
1 to 8[2]	3 to 27	4000	San Pedro	Jackson and others, 1987	
1.2 ± 1.0	4.0 ± 3.3	4000	San Pedro	Stromberg, unpub. data	Young trees
3.0 ± 1.8	9.9 ± 5.9	4000	San Pedro	Stromberg, unpub. data	Mature trees
Goodding Willow (*Salix gooddingii*)					
1.5 ± 0.5	1.5 ± 0.5	2000	Hassayampa	Stromberg and others, 1991	10-yr trees
1.3 to 1.8	4 to 6	2500	Gila	McQueen & Miller 1972	
1 to 5	3 to 17	4000	San Pedro	Jackson and others, 1987	
1.0 ± 0.8	3.3 ± 2.6	4000	San Pedro	Stromberg, unpub. data	Young trees
1.7 ± 0.7	5.6 ± 2.3	4000	San Pedro	Stromberg, unpub. data	Mature trees

[1] Mean ± standard deviation
[2] One tree reported at 27 feet

Table 4. continued
Depth-to-groundwater ranges for several obligate and facultative Sonoran riparian tree species

Depth to Groundwater (m)	Depth to Groundwater (ft)	Elevation (ft)	River	Citation	Notes
Fremont Cottonwood-Goodding Willow Association					
1.2 ± 0.3	4.0 ± 1.1	500	Bill Williams	Busch and others, 1992	
Velvet or Honey Mesquite Bosques (*Prosopis juliflora* or *P. velutina*)					
2 to 4	7 to 13	1500	Salt	Turner 1983	
1.3 to 4.2	4 to 14	2500	Gila	McQueen & Miller 1972	
5	16	<0	Salton Sea CA	Jarrell & Virginia 1990	
2.3	7.5 to 7.7	1350	Salt	Gary 1965	
2.7 ± 0.6	8.9 ± 2.0	2000	Hassayampa	Stromberg, Richter and others, 1993	
<14	<45	2000	Sycamore	Campbell & Green 1968	
<9	<30	Unknown	Various locations	Meinzer 1927	
1 to 8	3 to 26	<2600	Various locations	Stromberg, Wilkins and others, 1993	
3 to 8	10 to 26	4000	Sonita Creek	Stromberg 1993c	
<12 to 14	<40 to 45	Unknown	San Pedro	Zimmerman 1969	
4.6 ± 2.0	15 ± 7	4000	San Pedro	Stromberg, unpub. data	
Saltcedar (*Tamarix chinensis*) (Exotic)					
1.6 to 2.9	5 to 10	Unknown	Gila	McQueen & Miller 1972	
1 to 3	2.5 to 10	Unknown	Salt	Horton 1959	
0.8 to 1.7	2.7 to 5.7	1380	Salt	Gary 1965	
3 to 10	10 to 33	1000	Salt	Graf 1982	

as a maximum depth for optimum Fremont cottonwood forest development. This optimum depth may vary with elevation. For example, trees may grow over a wider groundwater range at their upper elevation limits because of increased precipitation and lower evaporative and heat stresses.

Across the groundwater continuum in Sonoran riparian ecosystems, Goodding willow and Fremont cottonwood give way to trees such as velvet mesquite, honey mesquite, cat-claw acacia (*Acacia greggii*), and netleaf hackberry (*Celtis reticulata*) that can either tap into deep groundwater or persist on capillary soil water (Figure 4). Mesquite forms "bosques" in areas where depth to groundwater ranges from about 2 to 15 m (7 to 50 ft), and is intolerant of very shallow water tables and saturated soils. The deep root system of mesquite is a primary reason for its prominence in riparian systems where groundwater is some distance below the surface. Honey mesquite roots have been reported as deep as 20 m (66 ft) and even >50 m (>160 ft) below the ground surface. In these situations, however, mesquite has limited above ground structural development (Kearney and Peebles, 1951; Phillips, 1963). In well-developed bosques, roots of mesquite typically are within the upper 5 m (16 ft) of the soil surface, extending only into the unsaturated zone of soil moisture (capillary fringe) above the generally shallow phreatic zone (Zimmerman, 1969; McQueen and Miller, 1972; Jarrell and Virginia, 1990). The capillary fringe can extend for up to 2.5 m (8 ft) or more above the water table, particularly in fine textured soils with high moisture holding capacity, with which mesquite is commonly associated. Along portions of the San Pedro River, for example, Zimmerman (1969) reported that mesquite grew on sites where depth to groundwater was about 12 to 14 m (40 to 45 ft), but had the bulk of its roots mainly in the first 6 to 7 m (20-25 ft). Mesquite also typically has an extensive network of shallow, lateral roots that absorb rainfall as well as surface moisture deposited during overbank floods (Zimmerman, 1969; Heitschmidt and others, 1988). Surface soil moisture from overbank flooding, bank-stored streamflow,

precipitation, and upland run-off all may serve as secondary sources of water for other riparian trees as well.

Saltcedar, an introduced tree species that has become prevalent on many hot desert streams, also can tolerate deep water tables. Saltcedar roots have been reported from depths of 10 to 30 m (33 to 100 ft), but saltcedar stands themselves have been reported to decline when groundwater drops much below 10 m (33 ft) (Gatewood and others, 1950; Van Hylckama, 1974; Horton and Campbell, 1974; Graf, 1982). Saltcedar has been reported to use groundwater as well as water from the unsaturated zone (McQueen and Miller, 1972; Busch and others, 1992).

Relationships with groundwater vary with age and life-stage of the riparian forest stand. Fremont cottonwood and Goodding willow, for example, are pioneer species that produce many tiny seeds, which germinate on saturated, unvegetated surface soil. Cottonwood seedlings have optimum growth and survival when the rate of water table decline below this surface level is less than 3 cm (about 1 inch) per day (Mahoney and Rood, 1991; Segelquist and others, 1993), which are characteristic rates of water table recession after winter or spring peak flows that stimulate cottonwood germination. One-year juveniles of both species have greatest survivorship on sites where the water table is between 0.5 and 1 m (about 2 to 3 ft) below the soil surface by summer's end, a zone in which seedling mortality is minimized both from drought and from late summer floods (Stromberg and others, 1991). Thus, although adult trees can tolerate deeper water tables, continued reproduction of the species requires short periods in spring in which water tables are very near the floodplain surface followed by a period in which water tables decline to a depth no greater than 1 m (3 ft) by summer's end.

Among older cottonwood and willow stands, relationships with groundwater also vary with age of the stand. Cottonwood and willow often form same-age stands that are spatially

separate, and that grow in linear bands parallel to the primary or secondary channels (Stromberg and others, 1991). The youngest plants (i.e, saplings) are closest to the channel, while the older trees can be found on floodplains several hundreds of feet from the primary channel. These patterns have been described as "isochrones" of trees (Everitt, 1968; Bradley and Smith, 1986). Younger trees typically occur on shallow groundwater sites and the oldest trees (100 to 130 yrs) occur on higher floodplains (Table 4). This is a consequence of two phenomena. First, mature trees have greater rooting depth than juveniles; and second, floodplains tend to aggrade (build sediment layers) with age as a result of forest-mediated sediment deposition during floods (Brady and others, 1985). Thus, floodplain elevation increases in tandem with tree age. As the floodplain ages, the soils not only increase in depth but also increase in content of organic matter and nutrients (e.g., phosphorus). The root crown of the mature trees becomes buried and the tree may produce adventitious roots (i.e., roots from buried stems) in the new substrate layers.

Relationships with site hydrology also differ between juvenile and adult life stages for mesquite. Whereas mature bosques tend to occur on floodplains that are 10 ft or more above the water table, seedlings tend to establish on sites with shallower water tables. Along the Hassayampa River, for example, mature bosques were about 3 m (10 ft) above the water table but mesquite seedlings had greatest survivorship on floodplain surfaces elevated 1 to 2 m (3 to 7 ft) above the water table (Stromberg and others, 1991). Mesquite seedlings arise from large seeds, and can readily grow tap roots to the capillary zone from floodplains of this elevation. This range undoubtedly varies with soil texture and soil moisture holding capacity, as well as with climatic zone. Seedlings, for example, establish more abundantly on higher floodplain terraces in the higher precipitation zone associated with the southern Arizona case study rivers.

Depth to groundwater influences stand structure as well as species composition. Fremont cottonwood stands, for example, decline in density and canopy foliage area as groundwater declines from about 2-3 m (7-10 ft) to about 5-6 m (16-20 ft) (see Santa Cruz Case Study, Chapter IV). Structural traits of mesquite stands, including canopy height and foliage area, also vary with depth to groundwater. Mesquite bosques with greatest structural development and greatest wildlife value, i.e., those with tall canopies (up to 12 m, or 40 ft, or more) and high foliage class diversity, are associated with groundwater depths in the range of about 2 to 8 m (7 to 25 ft) (Stromberg, Tress, and others, 1992; Stromberg, Wilkins and others, 1993) (Table 4). As groundwater declines below this range, plants decline in stature and foliage area. Velvet mesquite and honey mesquite are facultative riparian tree species that also can grow in uplands in climatic zones with sufficient precipitation (e.g., grassland savannah zones). In the uplands, however, they have very low density and stature. For example, in Sonoran Desert uplands, where mesquite occurs in only limited pockets, trees have a maximum canopy height of about 4 m (13 ft). This increases to about 6 m (20 ft) in xeroriparian washes, and to about 8 to 12 m (25 to 40 ft) in riparian sites underlain by relatively shallow water tables (Stromberg, Wilkins and others, 1993).

Vegetative and reproductive productivity of mesquite stands also change across groundwater gradients (Nilsen and others, 1984). These changes have effects on plant and animal species that depend on mesquite trees for nutrients, food or cover. For example, activity of the nitrogen-fixing bacteria associated with mesquite roots declines in water-stressed bosques, causing reduction in abundance of soil nutrients (Klemmedson and Tiedemann, 1986). Insect populations decline as mesquite flower production declines, resulting in lowered abundance of insectivorous birds (Ohmart and others, 1988).

Attributes of the riparian plant community as a whole, such as stand height and foliage area, also vary within floodplains across groundwater gradients. This occurs both because species composition changes across the gradients, and because characteristics of individual species change across the gradients. Indicators of stand structure and abundance, such as maximum canopy height, canopy foliage area, and stand basal area, change significantly with groundwater conditions within the floodplain (see San Pedro Case Study, Chapter IV). Most structural traits show a "bell-curve" shaped relationship with depth to groundwater. Stand structure and abundance can be relatively low on shallow groundwater sites near the stream edge, because such sites support young, early successional riparian forests in a process of normal recovery from flood scour. Sites with shallow groundwater that are not in flood-scour zones (i.e., such as those at Cook's Lake wetland) have very high values for stand structure and abundance. With increasing depth to groundwater, riparian stands show continual reduction in height, foliage area, and basal area. Tall trees, for example, give way to shorter trees as stature of individual species declines.

Sonoran Riparian Shrublands

Along some degraded rivers, Sonoran riparian shrublands are the dominant riparian vegetation type. More often, the shrublands grow intermixed in the floodplain with riparian forests and herbaceous plant associations. Similar to tree species, shrub species in alluvial desert rivers are distributed across groundwater gradients. Seepwillow (*Baccharis salicifolia*) and coyote willow (*Salix exigua*) are shallow-rooted obligate wetland species (Reed, 1988) that are restricted to stream edges and floodplains underlain by shallow water tables. Seepwillow dies when water tables exceed about 3 m (10 ft) below the floodplain surface (Stromberg and others, 1991, and Table 5). Gary (1963) indicated that seepwillow is seldom found away from perennial water courses, and that its roots (many of which were adventitious) were in the unsaturated zone of the Salt River floodplain.

Table 5.
Depth-to-groundwater range for some obligate and facultative Sonoran riparian shrub species.

Depth to Groundwater (m)	Depth to Groundwater (ft)	Elevation (ft)	River	Citation
Seep Willow (*Baccharis salicifolia*)				
1.0 ± 0.5 (2.6)[1]	3.3 ± 1.6 (8.6)[1]	2000	Hassayampa	Stromberg and others, 1991
<2	<6	2000	Sycamore Ck	Campbell and Green 1968
1.1 ± 0.9	3.6 ± 3.0	4000	San Pedro	Stromberg, unpub. data
1.2	4	Unknown	Salt	Horton 1959
1	2.5	Unknown	Salt	Gary 1963
Arroweed (*Tessaria sericea*)				
0 to 3	0 to 10	Unknown	Various locs.	Meinzer 1927
1.2	4	Unknown	Salt	Horton 1959
1.4 to 2.8	4.6 to 9.2	1350	Salt	Gary 1965
1.3 ± 0.2 (1.6)[1]	4.3 ± 0.7 (5.3)[1]	2000	Hassayampa	Stromberg and others, 1991
Desert Seepweed (*Suaeda torreyana*)				
<5	<15	Unknown	Various locs.	Meinzer 1927
Pickleweed (*Allenrolfea occidentalis*)				
0.4 to 6	1.3 to 20	Unknown	Various locs.	Meinzer 1927
Burro Brush (*Hymenoclea monogyra*)				
2.0± 0.5	6.6± 1.6	2000	Hassayampa	Stromberg and others, 1993
1.8± 0.8	5.9± 2.6	4000	San Pedro	Stromberg, unpub. data
Gray Thorn (*Zizyphus obtusifolia*)				
4.1± 2.0	13.5 ± 6.6	4000	San Pedro	Stromberg, unpub. data
3.2 ± 0.6 (3.6)[1]	10.6 ± 2.0 (12)[1]	2000	Hassayampa	Stromberg and others, 1991

[1] Mean and standard deviation, followed by maximum depth

Arrowweed (*Pluchea sericea*) is a facultative wetland plant that grows along Southwest floodplains in areas where there is abundant, shallow subsurface water (Shantz and Piemeisal, 1924). Marks (1950) indicated that water table depth is the primary

determinant of arrowweed occurrence, overriding factors such as soil texture. Arrowweed, like seep-willow, has a bimodal root structure with vertical roots that extend to a shallow water table and lateral roots that proliferate in the zone of streambank recharge (Gary, 1963). Gary (1963) stated that most of the root system of arrowweed was immediately above the saturated zone with some extending into the saturated zone.

Shrubs characteristic of sites with deeper water tables typically are either deep rooted or relatively drought tolerant. These include a variety of salt-tolerant shrubs including desert seepweed (*Suaeda torreyana*), pickleweed (*Allenrolfea occidentalis)*, quailbush (*Atriplex lentiformis*), and saltbush (*Atriplex polycarpa, A. canescens*, and others); and a variety of facultative riparian species that grow in open sunny locations including burro brush (*Hymenoclea monogyra*), rabbit brush (*Chrysothamnus nauseosus*), threadleaf groundsel (*Senecio longilobus*), and burro weed (*Isocoma tenuisecta*) (Table 5). Several facultative riparian shrubs including greythorn (*Zizyphus obtusifolia*) and wolfberry (*Lycium* spp.) often grow in the understory of mesquite on high floodplain terraces.

Sonoran Riparian Marshlands and Herbaceous Vegetation

Riparian zones support a rich diversity of herbaceous plants. Typically, the diversity and richness of herbaceous plants in the riparian zone is greater than that of woody plants. Water table depth and fluctuation, together with factors such as canopy cover, edaphic factors (e.g., soil texture and nutrient content), and site disturbance, all influence abundance and distribution of these herbs. Along the Hassayampa River moisture availability was found to be a primary determinant of herbaceous species distribution (Wolden, 1993).

Of all herbaceous riparian plants, those associated with marshes require the shallowest groundwater. Low elevation marshes grow in a variety of habitat types where the water table is near or above the ground surface. These include wet areas adjacent to edges

of perennial rivers, low-lying spots within the floodplain such as abandoned river meanders, or floodplains over shallow perched water tables. Marshes support obligate and facultative wetland species such as tropical cattail, bulrush, and other emergent macrophytes. These plants are typically very sensitive to small water level changes. Tropical cat-tail, for example, does not tolerate soil desiccation and typically grows where water levels are anywhere from about 0.3 m (1 ft) above the ground surface to about 0.7 m (2 ft) below the surface (Yatskievych and Jenkins, 1981; Jackson and Patten, 1988; Grace, 1989). Knot grass *(Paspalum distichum)* is an example of a native sod grass that is restricted to sites with very shallow water tables or banks of perennial streams, because it has high water requirements, low drought tolerance, and shallow rooting depths (Table 6).

Table 6.
Depth-to-groundwater range for several grasses of Sonoran, warm-temperate ecosystems.

Depth to Groundwater (m)	Depth to Groundwater (ft)	Elevation (ft)	River	Citation
Knot Grass (*Paspalum distichum*)				
0.3 ± 0.3 (0.4)[1]	1 ± 1 (1.3)[1]	2000	Hassayampa	Stromberg and others, 1991
Deer Grass *(Muhlenbergia rigens)*				
0.1 to 1.7	0.3 to 5.6	4000	Sonoita Creek	Stromberg, unpub. data
Salt Grass (*Distichlis spicata)*				
<3	<10	Various	Various locs.	Meinzer 1927
Giant Sacaton *(Sporobolus wrightii)*				
1 to 3.5	3 to 12	4000	Sonoita Creek	Stromberg, unpub. data
3.4 ± 1.5	11 ± 5	4000	San Pedro	Stromberg, unpub. data
Alkali Sacaton (*Sporobolus airoides)*				
1.2 to 8.2	4 to 27	Unknown	Sulpher Springs Valley	Meinzer 1927

[1] Mean and standard deviation, with maximum depth in parentheses

As floodplains increase in height above the water table, obligate wetland species give way to mixtures of facultative wetland, facultative, and facultative upland species. Along the Hassayampa River knot grass gives way to Bermuda grass (an exotic sod grass) as depth to groundwater increases. Other native riparian grasses associated with shallow groundwater zones or moist streambank edges include deer grass (*Muhlenbergia rigens*), a native bunch grass; salt grass (*Distichlis spicata*), a native sod grass; and various species of cup-grass (*Eriochloa* spp.) and sprangle-top (*Leptochloa spp.)* (see San Pedro Case Study, Chapter IV). Among the many forbs that are associated with shallow water tables are species of monkey flower (*Mimulus spp.*) and cardinal flower (*Lobelia cardinalis*). Yerba-mansa (*Anemopsis californica*) is reported to grow where water tables are less than 1.5 m (5 ft) below the surface (Meinzer, 1927). The exact make-up of the herbaceous flora (i.e., the species composition) varies considerably from river to river.

Highest floodplain terraces in the riparian zone support a mixture of plants that obtain water from a variety of sources. Some deep-rooted plants use water directly from the water table. The water source for shallow-rooted plants includes precipitation, stem flow (precipitation run-off from tree trunks), or groundwater that has been leaked into surface soils from the surface roots of deep-rooted trees (McQueen and Miller, 1972). In many cases, these shallow-rooted herbs grow in the floodplain because fluvial processes create habitat conditions that are favorable. For example, floods deposit sediments of varying water-holding capacity and create open sites that favor disturbance species. Also, the overstory vegetation moderates temperatures, increases soil nutrients, and increases relative humidity. Thus, these species are indirectly dependent on depth to groundwater as it influences overstory vegetation composition and structure. Among the many riparian plants that grow on high floodplains are sacred datura (*Datura meteloides*) and morning glory, passion flower, and milkweed vines (*Ipomoea*, *Passiflora*, and *Sarcostemma* spp.).

Warm- and Cold-Temperate Mixed Broadleaf Riparian Forests

Riparian forests at mid- and high elevations in Arizona typically grow along small mountain streams and form stands that are not as wide as those at lower elevations. However, these mixed broadleaf forests support a rich diversity of woody plants. Along channel edges and on sites where the water table is very shallow, the riparian zone is dominated by obligate riparian trees such as Arizona alder (*Alnus oblongifolia*), narrowleaf cottonwood, and Bonpland willow (*Salix bonplandiana*) (Laurenzi, 1982; Brown, 1982; Larkin, 1987; Valenciano, 1992). On floodplain terraces, where groundwater is deeper, there occur a mixture of obligate and facultative riparian trees. In a loose sequence from wetter to drier conditions, may be found velvet ash, Arizona sycamore, box elder (*Acer negundo*), Mexican elder, Arizona walnut, desert willow (*Chilopsis linearis*), and netleaf hackberry. Conifer trees such as juniper, ponderosa pine (*Pinus ponderosa*), and white fir (*Abies concolor*) also grow intermixed with the broadleaf trees. Several of these floodplain species appear to be restricted to sites with shallow groundwater. Flanagan and others (1992) and Jemison and Ffolliott (1993) suggested that Arizona sycamore relied on water obtained from the shallow water table at Paige Creek, near Tucson, and Bock and Bock (1989) concluded that high water tables were essential for seedling establishment of this species. Dawson and Ehleringer (1991) reported that mature big-tooth maple and box-elder absorbed water primarily from the aquifer even when growing at the stream edge, whereas juveniles of the same species used stream water and precipitation. Some of these higher floodplain terrace species, however, can grow in areas without permanently shallow water tables. For example, velvet ash, Arizona walnut, net-leaf hackberry, soapberry (*Sapindus saponaria*) and desert willow have been reported from sites where groundwater was anywhere from about 60 ft deep (18 m) (Paige Canyon) to 100 ft (33 m) deep (Zimmerman 1969). Rooting depths for these species (15 ft + for hackberry, 7 ft+ for walnut) suggest that they are not relying on groundwater at such sites. In such cases, ephemeral surface flow or seasonally high water tables may provide the necessary moisture. Dense stands with great structural development,

however, may be restricted to sites where water is permanently available at relatively shallow depths. Groundwater relationships for all of these high and mid-elevation riparian tree species needs further study.

Warm- and Cold-Temperate Marshlands and Riparian Grasslands

Cienegas (Spanish term for marshland) are herbaceous wetland communities that are strongly dependent on shallow water tables. Although much cienega vegetation has been lost, several cienegas persist within the Southern Arizona desert grassland biome along headwater stream sites where groundwater tables are still very shallow (Stromberg, 1993d). Water level and fluctuation have a strong influence on distribution and abundance of cienega plant species. Plants in these areas are often distributed in distinct bands along a gradient of standing water depth or depth-to-water (Stromberg, 1993d). Cross (1991) reported that variables related to moisture availability (including water depth) were primary determinants of species composition at Babocomari Cienega. Davis (1993) documented water level and soil moisture fluctuations for a mid-elevation cienega over an annual cycle and related this variation directly to the distribution and abundance of plant species. She reported that the abundances of dominant plant species were highly correlated with mean water levels, soil moisture, and seasonal variability in these variables, with species differing in their preferences or tolerances for wetter or drier sites, or stable vs. fluctuating water levels. Fishbein and Gori (1991) determined that water depth and fluctuation influenced distribution of several plant species at Canelo Hills Cienega. Cover of monkey flower (*Mimulus guttatus*) and large buttercup (*Ranunculus macranthus)* were found to be significantly related to mean depth-to-water, while cover of aster (*Aster coerulescens)* was related to minimum depth-to-water. Monkey flower, spike rush (*Eleocharis rostellata*) and several other species increased in abundance at the wet end of a water table hydrologic gradient, while bluegrass (*Poa pratensis*), rush (*Juncus mexicanus*) and others showed the reverse trend (Fishbein and Gori, 1991). Some species had broad tolerance ranges and did not vary in abundance with water table

conditions over the range of conditions measured, while others had narrow tolerance ranges.

Cienegas also occur at the headwaters of high elevation mountain streams (e.g., High Peak Cienega in the Pinaleno Mountains). These habitats have received little study (Patton and Judd, 1970). Elsewhere in the West, studies indicate that differences of even a few inches in microtopography can cause sufficient differences in water depth and in duration of saturated conditions to influence species composition of montane wetlands (Cooper, 1988).

In warm-temperate areas, giant sacaton (*Sporobolus wrightii*) and alkali sacaton (*S. airoides*) form a unique type of riparian community, a riparian grassland. These grasslands can form extensive stands on floodplains overlying shallow to deep water tables. Both are facultative riparian species that occur in uplands where water accumulates somewhat in excess of normal (e.g., depressions with fine-textured soil), but form dense, tall, continuous stands only in riparian settings. A primary water source for both species is subsurface water that feeds capillary water into the fine-textured alluvium of floodplain or playa soils (Stromberg, 1993e). Recharge of soil water by precipitation and periodic flood flows also serve as supplemental water sources (Groeneveld and others, 1985). Meinzer (1927) and Robinson (1958) reported that alkali sacaton occurred where depth to water below the land surface was about 2 to 8 m (5 to 25 ft), but that most luxuriant growth occurred at where depth to groundwater was less than about 5 m (15 ft). Soil moisture tests in areas of abundant sacaton growth revealed an abundance of moisture less than 1 m (3 ft) below the surface, indicative of the connection between the capillary fringe and the underlying water table (Meinzer, 1927). On the San Pedro floodplain, giant sacaton grows in abundance where depth to groundwater is about 3 to 5 m (10 to 15 ft) (See San Pedro Case Study, Chapter IV).

GROUNDWATER DECLINE AND RIPARIAN DEGRADATION

Riparian Areas Threatened by Groundwater Decline

Groundwater has undergone regional and local decline in parts of Arizona. These declines pose a threat to many riparian ecosystems. This section identifies some "at-risk" habitats in Arizona, but is not intended to provide a comprehensive list of riparian zones potentially or actually effected by groundwater decline.

Groundwater pumping for agricultural use has impacted Arizona's riparian areas for many decades and continues to do so today. For example, water tables have fallen sharply along Whitewater Draw in southern Arizona, as a result of high rates of water use for agriculture (see Hydrology Chapter, Chapter II). Quitobaquito Springs in Organ Pipe National Monument may be threatened by groundwater pumping for agricultural water use in Sonoyta Valley Mexico, despite a moratorium on new well development called for by the Mexican Government (Brown, 1991). Riparian areas associated with Leslie Springs, a cienega remnant near Douglas, also may be threatened by near-border groundwater pumping for agricultural use (Dr. W. Minckley, 1993). In central Arizona, groundwater pumping for agriculture reduces water available to the Verde River riparian zone and its tributaries (see Case Study Chapter, Chapter IV), and to the riparian cottonwoods and willows along Date Creek.

Municipal water use is forming an increasingly large part of Arizona's groundwater consumption. As a consequence, many riparian zones are threatened by municipal water withdrawals from aquifers that sustain riparian zones. For example, groundwater pumpage from the basin fill aquifer by Sierra Vista may intercept groundwater which would have eventually discharged to the floodplain aquifer that supports the San Pedro River's cottonwood-willow forests, mesquite bosques and other riparian and wetland formations (see San Pedro Case Study, Chapter IV). On the Babocomari River, one of

the main tributaries to the San Pedro River, an ecological assessment is needed to determine what effects a cone of depression associated with groundwater pumping by Huachuca City (Putman and others, 1988; Schwartzman, 1990) is having on riparian vegetation in this area. Pumping from the floodplain aquifer by growing populations near Nogales, Arizona and Nogales, Sonora poses a threat to the riparian forests along the Santa Cruz River (Stromberg and others, 1993; and see Santa Cruz Case Study, Chapter IV). Another municipality, Safford Municipal Utilities, obtains 3.1 million gallons per day of water from an infiltration gallery about 4 miles above the mouth of Bonita Creek, with unknown ecological consequences (U.S. Bureau of Land Management, 1993).

Among larger cities, regional groundwater declines and increased municipal water development pumpage near Tucson have threatened Tanque Verde Creek and may pose a threat to other riparian ecosystems in the area (Stromberg, Tress and others, 1992). Urban development east of Tucson may threaten Cienega Creek and its forests of mesquite, Fremont cottonwood, and mixed broadleaf trees (Fonseca and others, 1990).

The City of Phoenix has purchased land in McMullen Valley for groundwater withdrawal purposes. Consequences to riparian resources in the area, such as those located along Centennial Wash, are unknown (Folk-Williams, 1991). Groundwater pumping by the City of Scottsdale (Planet Ranch) from the alluvial aquifer of the Bill Williams River has reduced the amount of water available for the river's Fremont cottonwoods and other riparian vegetation. High rates of groundwater pumping in the Rio Verde area of the Phoenix metropolitan area may pose a threat to the lower Verde riparian zone (see Verde River Case Study, Chapter IV).

Farther north in the State, Flagstaff municipal well fields threaten water supplies to Oak Creek, while pumpage from the Big Chino Valley aquifer could pose a potential threat to the upper Verde River (Folk-Williams, 1991). High groundwater withdrawals from

Coconino aquifers could impact perennial flow in the Little Colorado River and degrade riparian resources that include coyote willow, arrowweed, cattail, giant reed, and the few remaining cottonwoods (Tremble, 1993).

Some river reaches have undergone water table increases in the recent past, as a result of effluent recharge of aquifers (e.g., see Santa Cruz Case Study, Chapter IV) or of reduction in agricultural pumpage (e.g., see San Pedro Case Study, Chapter IV).

Ecological Impacts of Groundwater Decline

The ecological impacts of groundwater decline, as documented below, include:

- loss of sensitive vegetation types (e.g., loss of wetlands and obligate riparian forests followed by loss of facultative riparian vegetation types under greater declines);
- replacement of hydro-riparian or meso-riparian types by xeroriparian or upland vegetation;
- replacement of native species by less desirable exotic species such as saltcedar;
- reduction in vegetative density and cover, age class diversity, and structural complexity;
- increase in physiological plant stress;
- streambank erosion and channel widening

Although it has long been realized that groundwater declines alter riparian plant associations (Bryan, 1928), ecological impacts of groundwater decline have not been thoroughly quantified in Arizona. Therefore, a few studies from other applicable, semi-arid areas of the Southwest are included in the following discussion.

During the period of arroyo cutting from about 1865-1915, human impacts including stream ditching and draining, timber harvest from riparian zones and uplands, and excessive cattle grazing, are believed to have interacted with drought and floods to cause

regional declines in water tables in the Southwest (Cooke and Reeves, 1976; Betancourt and Turner, 1993). This decline resulted in changes in plant associations along many rivers. Species requiring shallow water tables (e.g., cottonwood and willow trees, cattail and bulrush) were replaced by species able to obtain water from deep water tables (e.g., mesquite) or by upland species (Bryan, 1928; Leopold, 1951; Hastings, 1959; Lacey and others, 1975).

Turn-of-the-century arroyo cutting resulted in dramatic loss of wetland vegetation, a vegetation type that is very sensitive to water table changes. Hendrickson and Minckley (1984) describe the near complete loss of extensive cienega vegetation along several southern Arizona rivers, including San Pedro, Santa Cruz, and San Simon Rivers, and Cienega Creek. Although hydrological modifications impacted both riparian marshes and forests, marshes underwent greater loss because of their higher water tables requirements (Scurlock, 1988). For example, south of Arivaca are dry meadows, remnants of an extensive cienega that existed until marshland drainage and stream entrenchment activities were initiated in the 1890s (Hendrickson and Minckley, 1984). On the Santa Cruz River, marshes near San Xavier and at Tucson were eliminated when arroyos dropped 3 m (10 ft) during turn-of-the-century arroyo cutting (Betancourt and Turner, 1993). More recently, channel dredging on the lower Colorado River has lowered water tables and caused marsh plants in backwater areas to be lost. Cessation of flooding has also prevented new backwater marshes from forming (Ohmart and others, 1988).

Sacaton grasslands were historically abundant in southern Arizona, but now occupy only a small percentage of their historical range. Arroyo cutting, together with agricultural clearing, was a primary cause of this reduction. Bryan (1928) noted that the sacaton grass and "tule" (bulrush) covering the Santa Cruz Valley near Tucson disappeared when arroyo cutting began in the 1880s causing the channel to drop more than 5 m (15 ft)

below the floodplain surface. More recently, Lacey and others (1975) noted that deep-rooted mesquite were replacing sacaton in areas along the San Pedro River where channel cutting had lowered the water table.

Large mesquite bosques have been destroyed by water table decline associated with arroyo cutting, and by more recent groundwater pumping (Betancourt and Turner, 1993). Bosques along the Santa Cruz River near Tucson were described in 1905 as covering "...miles in extent, with a thick growth of giant mesquite trees, literally giants, ... many of them sixty feet high and over..." (Swarth, 1905). These were lost to groundwater decline, as was an extensive bosque known as the New York Thicket that existed near the confluence of the Santa Cruz and Gila River and three major washes (Vekol, Green, and Santa Rosa). This bosque was described in the late 1930s as being up to 10 km (6 miles) wide in areas with mesquite and screwbean mesquite (*Prosopis pubescens*) reaching heights of up to about 12 m (40 ft) (Neff, 1940). Rea (1983) reported that about 90% of the mesquite died in the late 1970s when groundwater pumping caused the groundwater table to decline to about 30 m (100 ft) below the land surface. Mesquite have deep roots and tolerate some water stress (Haas and Dodd, 1972; Nilsen and others, 1986), but lowering water tables below about 50 ft (15 m) results in death of riparian mesquite trees or in conversion of mesquite from a dense tree form community to a sparse shrub form community (Cannon, 1913).

Near Casa Grande, groundwater withdrawal for agriculture began at the turn of the century, but became much more intense in about the 1940s. Groundwater extraction from the aquifer associated with the Gila River caused water tables to decline dramatically. An extensive mesquite bosque in the area survived during a period (1900 to 1930) when the water table declined from about 2 to 13 m (6 to 40 ft), but all trees died during a period (1930 to 1950) when the water table dropped about 1 m (3 ft) per year to depths of between 13 and 30 m (40 to 100 ft) (Judd and others, 1971). The dead

trees within this large riparian mesquite forest are now preserved as a "skeleton forest" at Casa Grande National Monument. As of the 1970s, depth-to-water in this area was over 200 m (650 ft). A heavy infestation of mistletoe developed prior to death and may have hastened mortality. The site is now dominated by upland desert shrubs.

Along Tanque Verde Creek in Arizona, an ephemeral stream that has surface flow for about 180 days per year, riparian stress resulted from groundwater decline associated with withdrawals by the City of Tucson, superimposed on the existing regional groundwater decline (Stromberg, Tress and others, 1992). Groundwater within portions of the bosque declined from about 13 to 30 m (50 to 100 ft) during the late 1980s, at a rate of over 4 m (13 ft) per year. The water table under Tanque Verde Creek naturally fluctuates by up to several feet a year as a result of variation in watershed precipitation and aquifer recharge, but the extent of the decline rate in the late 1980s was unprecedented. As of 1990, in areas experiencing the greatest groundwater declines, mesquite were under sublethal stress as evidenced by low stem water potentials, reduced leaf size, and high levels of canopy mortality (>45%). Trees farther upstream, in areas where groundwater levels remained at about 3 to 5 m (10 to 16 ft), were in good ecological condition, with tall stature and no canopy dieback.

During the past several decades, groundwater pumping by mines and pecan growers has caused massive groundwater declines along the Santa Cruz River in Pima County. This resulted in total elimination of riparian habitat from portions of the river (see Santa Cruz Case Study, Chapter IV). More recently, groundwater withdrawals from the floodplain aquifer of the upper Santa Cruz River in Santa Cruz County has caused localized water table declines and reduced abundance of cottonwood-willow forests. Groundwater decline in the vicinity of a City of Nogales well field, for example, has caused low growth rate, low tree density and low canopy cover of Fremont cottonwood populations

(Stromberg, Sommerfeld and others, 1993; and see Santa Cruz Case Study, Chapter IV).

As of 1983, the city of Phoenix had an infiltration gallery and 14 groundwater wells in a section of the Verde River located in the Fort McDowell Indian Reservation, to supply about 20,000 af/yr of water for municipal use (Water Resources Associates, 1983). In 1977, very low flows were released to this section of the Verde River due to operation needs of Bartlett Dam by Salt River Project. McNatt and others (1980) reported that a combination of natural drought, groundwater pumping from the Verde River Infiltration Gallery and Well Facility, and low flow release from Bartlett Dam caused death of 46% to 84% of the Fremont cottonwoods along a stretch of the Verde River during the late 1970s. This issue was further investigated by Water Resources Associates (1983) who conducted short-term pump tests and simulations of the 1977 flow scenario. Based on these short-term tests, which showed only localized water table declines, they concluded that floods, rather than drought, were the main cause of the mortality. However, they did not explain why mortality of cottonwood was greater below the dam than above the dam.

During the 1940s and earlier, shallow water tables (7 m, or 23 ft) sustained saltcedar stands in the channel of the dewatered Salt River in Tempe (Graf, 1982). Without river recharge, intensified groundwater pumping by Tempe, Scottsdale and Mesa during the 1950s caused groundwater to decline to over 67 m (220 ft) in the 1960s, eliminating the saltcedar thickets.

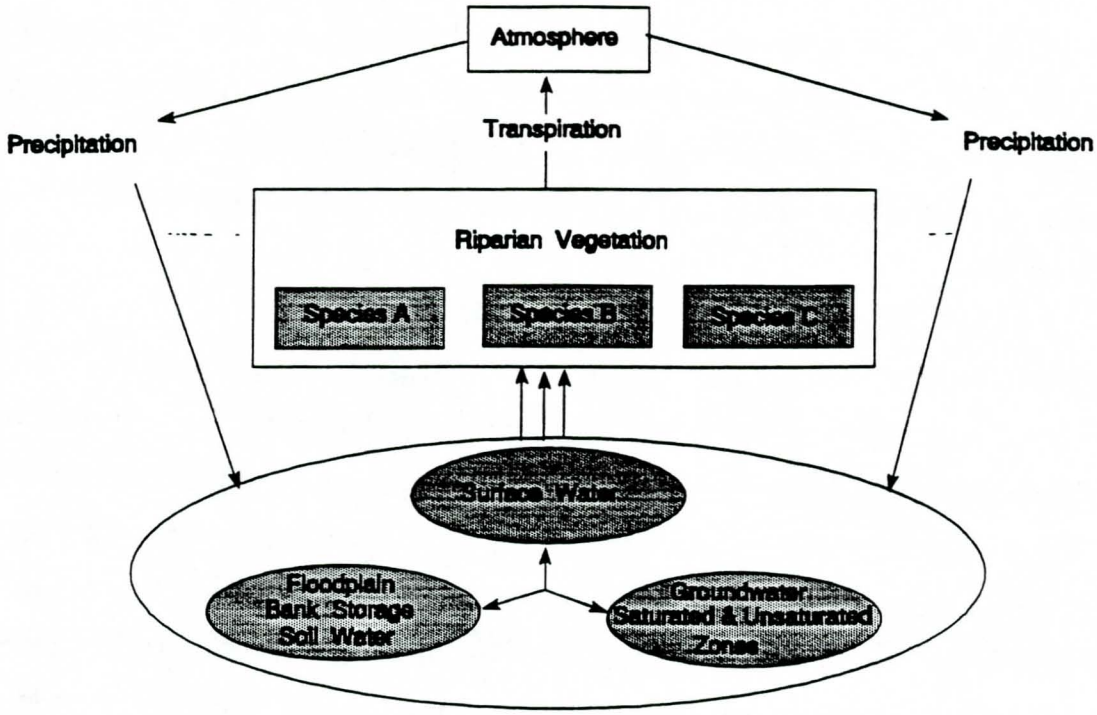
RIPARIAN VEGETATION AND SURFACE WATER

The objective of this section is to summarize the importance of surface water to riparian vegetation, summarize data describing how vegetation communities vary in response to natural variations in surface water, and discuss impacts to riparian ecosystems. Potential techniques to prevent riparian ecosystems from becoming degraded by surface water reduction are presented in the Conclusions and Recommendations section. Flood flows are discussed in a separate section, because of the significant role they play in riparian ecosystems.

IMPORTANCE OF SURFACE WATER TO RIPARIAN VEGETATION

Surface water, like groundwater, is a primary determinant of riparian vegetation abundance, composition, and vigor. Nearly every riparian vegetation type in the Arizona is dependent upon surface water in some fashion. Surface flows recharge streambank soil water, and thus is of importance to wetland and riparian plants that are rooted in the streambank and absorb water directly from the stream or from streambank soils. Surface flows also moisten floodplain soils during flood flows, and in riparian systems in which surface water is hydraulically connected to groundwater, recharge alluvial aquifers and raise water tables (Figure 5). Surface water is, therefore, of importance to plants located on floodplain terraces that absorb water from the water table, overlying capillary zone, or upper layers of the floodplain soil. The width of the riparian water table capable of supporting riparian vegetation often increases with surface flow volume (Jemison and Ffolliott, 1993). In cases where the surface flow has become hydraulically disconnected from the alluvial groundwater, riparian vegetation development is limited (see Hydrology Chapter for more information).

Figure 5. Diagram indicating movement of water in riparian ecosystems



For many riparian species, in-channel flows serve as maintenance flows, while flood flows (out-of-bank flows) serve as regeneration flows (see Riparian Vegetation and Flood Flows). For other species, surface water is of direct importance to juvenile life stages, while groundwater is used by adults. This is a consequence of the dynamic nature of the river-floodplain system that may distance the plant from the active channel, as well as differences in rooting depths and physiological characteristics between juveniles and adults (Flanagan and others, 1992).

Surface flow variables that are important to riparian vegetation include the mean and median volume of flow during the year and growing season, the baseflow and the low

flow volume during the dry season of the year, the seasonal discharge pattern, the extent of annual and seasonal fluctuation in flow, and the relative difference between low flows and peak flows. Whether or not the flow is perennial also is of major importance. In intermittent or ephemeral flow rivers, the duration and timing of the no-flow period also influences riparian vegetation. In addition, frequency, duration, timing, and magnitude of peak flows are ecologically significant, as discussed in the following section.

Despite the significance of surface water to riparian vegetation, few studies have attempted to quantify this relationship. Only recently have researchers focused on how much water must be maintained in a stream to support varying amounts and types of riparian vegetation. Studies in arid portions of California have shown that growth and canopy development of cottonwood trees increase significantly with annual streamflow volume, with flow volume in these studies serving as a surrogate indicator of water availability within the floodplain (Stromberg and Patten, 1991). Taylor (1982) developed empirical models that indicated that riparian strip width and plant diversity increased with surface flow volume of mid-elevation streams in the arid Eastern Sierra Nevada. Evapotranspiration (ET) models also have been used to estimate surface water needs of riparian vegetation stands of varying size (O'Keefe and Davies, 1991). Evapotranspiration models are useful for this purpose if a detailed hydrologic budget is available indicating how changes in surface flow rate relate to the changing availability of groundwater and water in floodplain soils.

Sonoran and Warm-Temperate Riparian Forests

Results from Stromberg (1993b) and the Verde River Case Study (instream models applied in case study developed from data obtained from the Verde, San Pedro, and Santa Cruz River watersheds) indicate that riparian vegetation abundance, as measured through several parameters, increases in conjunction with surface water volume increases. Streams evaluated ranged in size from small ephemeral tributary washes to

large perennial streams, and variously supported mesquite, net-leaf hackberry, Fremont cottonwood, Goodding willow and other broadleaf trees. Riparian zone width, canopy foliage area, woody stem basal area, and average canopy height all increased continuously with increasing surface flow rate. The flow variables most significantly related to the various vegetation traits were growing season flow rate (mean and median values) and "dry season" flows (May-June averages). The abundance of individual species also varied with flow rate. Basal area of Fremont cottonwood, for example, increased proportionately with growing season flow rate (see Verde River Case Study). Several species, such as Goodding willow, were absent from streams below a minimum flow rate. Instream flow relationships for the different watersheds were similar in some respects and different in others. For example, the width of the riparian zone dominated by obligate riparian trees was generally similar for a given flow rate on all watersheds. Within the southern Arizona watersheds, however, the total width of the riparian zone, inclusive of the facultative mesquite zone, was greater per unit of water (see Verde River Case Study, Chapter IV).

In these above studies, surface water served as a surrogate indicator of riparian zone water availability, resulting from both surface and subsurface water sources. In other similar studies, watershed size has been used as a correlate of riparian zone water availability. Warren and Anderson (1985) used this approach to study vegetation composition of ephemeral washes in the Organ Pipe area. Certain species such as desert broom (*Baccharis sarothroides*) and burro brush (*Hymenoclea salsola*) occurred only at sites where the watershed (and thus run-off) was greater than some minimum value.

Other types of studies that indicate the importance of surface water to riparian vegetation include observational studies of root systems. For example, arrowweed and seep-willow both have a bimodal root structure with vertical roots that extend to a shallow water table

and lateral roots that proliferate in the zone of streambank recharge (Gary, 1963). Mesquite often develops a bimodal root system that includes large shallow root systems (lateral spread to 18 m, or 60 ft) that absorbs surface soil water resulting from precipitation or streamflow, and a deeper tap root system to absorb capillary water rising from the water table (Heitschmidt and others, 1988; Jarrell and Virginia, 1990).

Demographic studies indicate the importance of surface flows to seedling establishment of many riparian plants. Seedlings of Fremont cottonwood and Goodding willow establish in years when high surface flows (and thus high groundwater tables) are sustained throughout the initial months following seedling establishment (e.g., spring and summer). High flood peaks in winter or spring initiate the process of germination and establishment (Stromberg and others, 1991).

Cold-Temperate Riparian Forests

General models are not available that relate surface flow to vegetation abundance in high elevation Arizona streams. A few studies have revealed the general importance of surface water to juvenile stages of many higher elevation riparian trees. For example, big-tooth maple and box elder rely on streamflow as juveniles (Dawson and Ehleringer, 1991; Flanagan and others, 1992). Larkin (1987) observed that seedlings of alder grew within about 3 m (10 ft) of the edge of three central Arizona mountain streams, and that box elder experienced the best regeneration rates when established near stream edges. Seedlings of several other tree species, including Arizona walnut, occurred over a broader range of sites within the floodplain and floodplain terraces. Mature stages of many tree species, including alder and some high-elevation willows, also are closely associated with edges of perennial streams (Larkin, 1987; Valenciano, 1992).

SURFACE WATER DECLINE AND RIPARIAN ECOSYSTEMS

Overview of Ecological Impacts

Although there have been obvious ecological changes on many of Arizona's dewatered or partially dewatered streams, there has been little documentation of these ecological effects. Riparian ecosystems can be altered by reductions in the volume or flow rate of surface water, particularly during drought years; changes in the seasonal pattern of discharge; and changes in the annual variability of water flow. Ecological effects of these changes can include:

- Mortality and thinning of riparian plant communities;
- Replacement of hydro-riparian plant species by meso- or xero-riparian species;
- Replacement of native species by exotics adapted to altered seasonal flow patterns or better adapted to drought;
- Reduced success of seedling establishment and loss of age class diversity;
- Reduction in riparian zone width.

However, although there have been obvious ecological changes along many of Arizona's fully dewatered or partially dewatered rivers, there has been little documentation of these ecological effects. Several studies have documented riparian decline associated with stream diversion in other semiarid parts of the west. These examples are illustrative for Arizona. Cottonwood-willow riparian forests along Rush Creek and other Mono Lake tributaries in California's eastern Sierra Nevada have undergone mortality, growth decline, and loss of vigor in recent decades as a consequence of diversion of about half the volume of surface flow into the Los Angeles aqueduct for municipal water use (Stine and others, 1984; Stromberg and Patten, 1990). Taylor (1982) also documented riparian vegetation decline on several diverted streams in the Mono Basin. Restoration of flow to some of these rivers, in contrast, resulted in recovery of cottonwood, willow and other riparian plants (Stromberg and Patten, 1989). Elsewhere, Reily and Johnson (1982)

reported reduced growth rates of several riparian tree species (many of which have closely-related Southwest riparian counterparts) below Garrison Dam on the Missouri River. Growth reduction was attributed to shifting the high river flow/water table season from spring and summer to winter, thus rendering water availability out-of-phase with the vernal growth pattern typical of important floodplain tree species. Auble and others (1993) also reported that riparian vegetation composition changed in response to altered seasonal flow release patterns, independent flow volume variability. In addition, reduction in surface soil wetting from overbank flooding was attributed with growth reduction.

Ecological Impacts: Sonoran Riparian Forests

In Arizona, ecological impacts of altered surface water flows have been high on large desert rivers such as the Gila and Salt, where a large percentage of the flow is diverted into canals or pipelines from dammed reservoirs. Many such river flows have been converted from perennial to ephemeral, flowing only during exceptional flood events. Salt River and Tonto Creek flows are impounded by Roosevelt Dam (constructed in 1911) to form Roosevelt Lake. Flow is regulated as it passes from Roosevelt Dam to several downstream dams (Horse Mesa, Mormon Flat, Stewart Mountain, and Granite Reef). Horse Mesa, Mormon Flat, and Stewart Mountain Dams were constructed between 1923 and 1930 to provide additional water storage capacity and hydroelectric power. At Granite Reef Dam (constructed in 1908), all the flow (except major flood flows) is diverted to the Salt River Project canal system for distribution in the Phoenix area. As a consequence, extensive riparian forests of cottonwood, willow, and mesquite that spanned more than a mile in width along this reach of the Salt River, including shrublands of seepwillow and arrowweed, and marshes of cattail and bulrush, disappeared during the last century (Graf, 1988). Riparian vegetation has been locally rejuvenated downstream of the Phoenix area by municipal effluent discharges.

Similar losses have occurred on the Gila River, another extensively dammed and diverted large desert river. Although the Gila flows unhindered in its headwaters, there are numerous irrigation diversions (exceeding 100,000 af/yr) from the river in the Safford Valley above Coolidge Dam (Graf and others, 1982). In this area, much native riparian vegetation has been replaced by saltcedar, because it can tolerate deeper water tables and water with higher salt content than native cottonwoods and willows. Saltcedar also has become abundant below Coolidge Dam, which has impounded the Gila River in San Carlos Reservoir for water storage since 1928. Farther downstream, the reach of the Gila immediately downstream of the San Pedro confluence (i.e., the "Buttes") is in fairly good ecological condition due in large part to San Pedro inflow (Rea, 1983). Below this reach, however, the flow of the Gila has been entirely diverted into San Carlos Project canals at Ashurst-Hayden Dam since its construction in 1923. Downstream of the dam the river flows ephemerally to its confluence with the Salt and Santa Cruz Rivers, both of which also are ephemeral at this point.

Historically, Sonoran riparian forests were particularly abundant at the confluences of large desert rivers. At the confluence of the Gila and Salt Rivers, the water flowing in the Gila is composed of flood flows, irrigation return flows, and municipal effluent from Phoenix. The vegetation consists of dense thickets of saltcedar with some native species including arrowweed, mesquite, cottonwood, and seepwillow. The waters of the Gila are again dammed and diverted downstream from Phoenix at Gillespie Dam for use by west valley irrigators, and at Painted Rock Dam, a flood control and river regulating dam. As a consequence of these dams and diversions, as well as floodplain clearing for agriculture, much of the native riparian vegetation along the lower Gila has been lost or replaced by saltcedar. Pockets of natural vegetation remain, particularly in areas sustained by effluent, but are severely reduced in size and quality (Graf, 1988).

The once extensive riparian cottonwood-willow-mesquite forests along the Colorado River also have declined substantially. Flow is regulated by a series of dams, including Glen Canyon and Hoover Dams on the upper Colorado and Davis, Parker, Headrock Gate, Palo Verde Diversion, Imperial, Laguna, and Moreles Dams on the lower Colorado. All of the water is allocated and used by seven states, and as a consequence, the regulated flows rarely reached the Mexican border below Yuma until recent high-flow years (Ohmart and others, 1988). Flow diversion, in combination with a multitude of factors including agricultural land clearing, river channelization, and increased salinity, has caused extensive loss and degradation of what was once Arizona's largest riparian zone (see Riparian Vegetation and Water Quality).

The lower Verde River was dammed in the 1930s (Bartlett Dam) for additional water storage for Salt River Project and the Fort McDowell Indian Reservation, and again in 1947 farther upstream at Horseshoe Dam, as part of a complex water trade involving Phelps Dodge. Riparian vegetation below these dams has been degraded. For example, 46% to 84% of the Fremont cottonwoods at a site along the Verde River died during a dry period in the 1970s, due to a combination of low flow releases from Bartlett Dam and groundwater pumping from the Verde River Infiltration Gallery and Well Facility (McNatt and others, 1980).

There are numerous river reaches in the State with small irrigation diversions that partially deplete downstream flow. Rivers that are not completely diverted retain greater amounts of riparian vegetation, but the cumulative impact of many small diversions can be high. Aravaipa Creek and the San Pedro River, for example, although free-flowing, support numerous diversion ditches. Flow in the middle Verde River is reduced by irrigation diversion ditches, including Hickey and Cottonwood Ditches, which divert 90% of the Verde River summer flows between Clarkdale and Camp Verde. This, coupled with

groundwater pumping is believed to be preventing new cottonwood recruitment (see Verde River Case Study, Chapter IV).

Riparian forests also have been lost or reduced on many smaller rivers in Arizona that have been partially or totally dewatered by diversion dams. The Agua Fria River, for example, was dammed by Waddell Dam in 1927 (Graf, 1988). Water is diverted from Lake Pleasant into the Beardsley Canal for irrigation. Flow below the dam has become ephemeral and the river now supports mainly xeroriparian vegetation. Flow upstream of the dam is perennial (for a short stretch) and supports cottonwood-willow riparian vegetation. Cienega Creek is dammed and diverted at the lower end of Pima County's Cienega Creek riparian flood-control preserve. Immediately above the dam, intermittent flow supports mesoriparian trees, while xeroriparian plants predominate below the dam (Julia Fonseca, personal communication). Sonoita Creek was dammed in 1968 to create Lake Patagonia, primarily for recreational use. Water flow is reduced below the dam because of evaporative water losses from the lake. Water is released downstream for below-dam users, but effects of altered and reduced flows on the downstream riparian community have not been studied. Cave Creek was dammed in 1923, however, resulting impacts were not documented (Graf, 1988).

Riparian vegetation along the Bill Williams River below Alamo Dam has been degraded due to a combination of many factors including periodic release of insufficient flows or sustained high flows, flood flow suppression, and physical consequences associated with dam construction, such as reduced sediment loads (see Riparian Vegetation and Flood Flows). Long and Peck (1988) determined that minimum flow release requirements from Alamo Dam (10 cfs) were insufficient to maintain water tables for downstream riparian forests, dominated by cottonwood, willow, mesquite and riparian shrubs. In addition to water stress resulting from inadequate flow releases from the dam and from current groundwater pumping at Planet Ranch, the Bill Williams riparian ecosystem is degraded

by post-dam geomorphic adjustments and livestock grazing practices (Jackson and Summers, 1988).

Municipal water is increasingly recycled and returned to rivers as effluent. Effluent release has resulted in increased riparian abundance along many rivers, particularly those that remain hydraulically connected to the water table. On the upper Santa Cruz River, for example, effluent is released into an "interrupted perennial" stream. These releases have raised previously declining water tables for several miles downstream and allowed Fremont cottonwood-Goodding willow forests to extend farther downstream than they have in the recent past (see Santa Cruz Case Study). Along historically dewatered reaches now receiving effluent, there is a need to determine how much riparian vegetation is sustained by the effluent, and whether the vegetation is depending solely on surface flows or on recharged water tables. For example, a dewatered reach of the Salt River downstream from the 35th and 91st Avenue wastewater treatment plants has been rejuvenated by effluent release and now supports a narrow riparian forest (Sullivan, 1991; Rea, 1983). Along this river reach, however, fluctuations in riparian abundance over time appear to be more strongly related to water table fluctuation than to annual changes in effluent release (Graf, 1982). Other historically dewatered river reaches that are now effluent-dominated include the Agua Fria River near Luke Air Force Base and the middle Santa Cruz River below Tucson wastewater treatment plants.

Although effluent can restore flow volumes and minimize adverse impacts of groundwater pumpage or surface flow diversion, it also can alter water quality. As a consequence, many riparian areas face the threat of cessation of effluent discharges or diversion of effluent from the stream channel as an alternative to meeting more stringent federal water quality standards. This would have negative consequences for the riparian vegetation (Jones and Snyder, 1984). Potential impacts are great because of the large number of riparian systems either totally dependent upon or supplemented by municipal-industrial

effluent (Tellman, 1992). There is some evidence that riparian vegetation sustained by effluent can improve water quality, but this area needs more research (see Riparian Vegetation and Water Quality).

Irrigation return flows also increase surface water, but alter water quality (see Riparian Vegetation and Water Quality). Along the upper Santa Cruz River water from irrigated fields may have locally sustained cottonwood trees during periods of drought and dewatering (see Case Study). Graf (1982), however, has stated that at least along the Salt River, irrigation return flows play only a small role in influencing riparian abundance.

Watershed practices that change soil infiltration and runoff patterns also can alter surface volume and timing of flow. Soil compaction and vegetation removal resulting from overgrazing and paving land surfaces both decrease the amount of precipitation that infiltrates watershed soils. Not only does compaction increase runoff volume, but it also may change flow regimes such that low flows are decreased while flood flow magnitudes are increased. Some methods to directly manipulate watershed flow patterns, such as phreatophyte removal to increase streamflow, are no longer widely practiced (Culler, 1970). However, removal or reduction of upland vegetation to increase watershed runoff (Brown and Fogel, 1987) continues to threaten riparian systems. Although vegetative reduction in the uplands can increase baseflows (Ingebo, 1971; DeBano and others, 1984; Debano and Schmidt, 1989 and 1990), this increase is often short-term, and has ecological implications for the upland ecosystems by affecting nutrient loss and wildlife habitat (Longstreth and Patten, 1975).

Riparian management practices that allow for greater vegetation cover can also alter streamflows. For example, the sponge-like organic soils that develop in cienegas and marshy stream edge areas serve to increase bank storage of surface water, which has been speculated to result in prolonged streamflows, particularly during dry periods.

Conversely, streamflow may become more variable if riparian zone management causes reduced plant cover and loss of fine textured or organic soil particles. Flow in streams, such as the San Pedro River and Cienega Creek, is believed to be more variable due to past stream entrenchment and loss of cienega vegetation and organic soils (Jackson and others, 1987; Block, 1991). It is difficult to determine the extent to which watershed or riparian zone land uses impact streamflow and thus riparian ecosystems, because there are no "control" watersheds that are managed entirely for their natural values.

Ecological Impacts: Warm- and Cold-Temperate Riparian Forests

Increasing residential development in mid and high-elevation zones of Arizona has reduced water supply to several streams (Bond and Dunikoski, 1977). Stream diversion for residential use (primarily second homes) and agricultural use has caused Pine Creek and other small mountain streams in central Arizona to be converted from perennial to ephemeral streams (Medina, 1990). This has stressed the riparian associations, which are vegetated by Arizona alder, box elder, Arizona walnut, and various conifers. Stress effects include lowered xylem water potentials (i.e., greater internal plant water stress), reduced rates of seedling establishment, and lowered tree densities.

Some of the effects of surface water diversions for agriculture are visibly apparent on riparian vegetation maps produced by AGFD (1993) and presented in the Case Study Chapter of this report. Riparian vegetation abundance, such as that found along West Clear Creek, can be observed on the maps to substantially decline downstream from points of diversion.

On mid-elevation streams (4,000 to 5,500 ft, or 1,200 to 1,700 m) draining the Pinaleno and Galiuro Mountains, diversion dams have converted perennial reaches to ephemeral or intermittent reaches and affected mixed broadleaf riparian vegetation. On Marijilda, Grant, and Ash Creeks, the riparian vegetation below diversion dams had low canopy

cover, low rates of riparian regeneration, low vegetation density, reduced abundance or loss of riparian obligates such as alder and willows, and increased relative abundance of facultative riparian trees (e.g., oaks) (Denis Humphrey, U.S. Forest Service RACES surveys, unpublished data).

A few mixed-broadleaf streams in Arizona are partially diverted for hydropower production. Among these is Fossil Creek which supplies power for Arizona Public Service Corporation. The hydropower diversion presently is under review for relicensing by the Federal Energy Regulatory Commission. Studies have been undertaken that recommend increased flows to sustain the mixed broadleaf forest and associated fish and wildlife species. Extensive studies on the impacts of hydroelectric power production on semi-arid mountain streams have been conducted in California, where many streams are diverted for hydropower production. On these Sierra streams, vegetation persists but biotic integrity has been reduced as a consequence of diversion patterns that cause low flow conditions to become more frequent and intense, while not diminishing the magnitude of large flood events. Reduced biotic integrity in these riparian areas is indicated by higher tree mortality, lower canopy foliage density, higher internal water potentials, and changes in vegetation cover, species composition, and community structure (Harris and others, 1987; Stromberg and Patten, 1992; Smith and others, 1991).

Riparian marshlands found at Peck's Lake and Tavasci Marsh, near Cottonwood on the Verde River, have been altered by surface water diversions, but still retain significantly valuable wetland habitat (VRCPSC, 1991).

FLOOD FLOWS AND RIPARIAN VEGETATION

The objective of this chapter is to provide an overview of the importance of flood flows to riparian vegetation, and summarize studies documenting the relationships between flood flows and riparian ecosystems. Potential techniques to prevent flood flow alteration from degrading riparian ecosystems are presented in the Conclusions and Recommendations section.

ECOLOGICAL IMPORTANCE OF FLOOD FLOWS

Floods are a natural disturbance in rivers of the Southwest. Flood flows are of significance to riparian vegetation because of the immediate, short-term physical effect of the disturbance, and because of longer-term effects on water availability, floodplain geomorphology, and soil characteristics. Floods influence water availability by recharging aquifers; raising water tables at key seasons of the year; periodically inundating floodplain surfaces; and depositing fine sediment layers that may create perched water tables. Floods modify floodplain and channel morphology and substrate by mobilizing, removing, and depositing sediment within the channel and floodplain; building (aggrading) and removing terraces (and thereby changing relative depth to the water table); causing river channels to relocate and meander; and creating abandoned channels and backwater depressions. Floods modify soil texture, chemistry, and water-holding capacity by flushing salts from floodplain soils and streambanks, and variously depositing silty, nutrient-rich soils or coarse-textured sediment with low fertility.

Flood flows are considered the "principal driving force responsible for the existence, productivity, and interactions of the major biota in river-floodplain systems" (Junk and others, 1989). With respect to floodplain vegetation, flood flows play an integral role in the dynamics of seed dispersal, plant establishment, and species replacement patterns. In addition, flood flows are important for maintenance of species diversity and "patch" diversity (i.e., diversity of habitat types), and nutrient cycling and productivity (Bell, 1974;

Reichenbacher, 1984; Stromberg and others, 1991). Floodplains are dynamic in space and time, in large part due to flood-related fluvial processes. Through such fluvial processes as channel relocation and terrace aggradation, floods create a diversity of microhabitats that vary in such conditions as depth to the water table (resulting from sediment accumulation or loss from floodplains); light availability (by causing localized tree mortality); and soil texture (resulting from deposition of different types of alluvium), and thus allow for high biodiversity in the riparian zone. Physical changes to the floodplain resulting from flood flows often set the stage for a new cycle of plant establishment. Riparian forest regeneration in arid regions is particularly dependent on flooding because regeneration often depends on periodic inundation of otherwise dry floodplain surface soils (Hughes, 1990).

Flood flow variables important to riparian vegetation include the magnitude and scouring force of the flood as it effects processes such as plant survivorship, channel movement, and sediment delivery; the timing of the flood relative to each plant's "schedule" for germination and growth; the duration of the flood, particularly in relation to a plant's ability to tolerate sustained inundation; and the rate of recession of the flood waters, as it relates to the ability of new root growth to keep pace with soil moisture decline following a flood event.

There are many aspects of vegetation-flood flow relationships that are relatively unknown, including the role of flows in providing nutrients to floodplain plants. The following discussion reviews available information on the functional role of floods in recruitment of new generations of pioneer riparian trees and mortality of existing vegetation.

Sonoran Riparian Ecosystems

Sonoran riparian systems are dependent upon natural processes, such as floods (Reichenbacher, 1984). Fremont cottonwood and Goodding willow trees are "pioneer" riparian species, meaning that they require some form of disturbance to perpetuate themselves. Both species establish episodically (i.e., they establish simultaneously in large numbers at infrequent intervals) after flood flows. Several studies have indicated the general importance of flood flows to recruitment of Fremont cottonwood (Turner, 1974; Fenner and others, 1985) and to cottonwood species in other semiarid regions (Baker, 1990; Rood and Mahoney, 1990). A study of riparian recruitment dynamics along the Hassayampa River in central Arizona indicated that Fremont cottonwood established after winter or spring floods of magnitudes equal to or greater than the seven-year return flow (Stromberg and others, 1991). Large winter floods set the stage for recruitment by scouring vegetation from channel banks and floodplains and depositing fresh alluvium (thereby reducing herbaceous and overstory competition, at least temporarily). Small flood surges in spring serve to moisten floodplains at an appropriate time (during the limited period of spring seed dispersal) and appropriate place (moderately high surfaces above the zone of frequent summer flood scour). High water tables produced by storm-runoff allow for high rates of seedling survivorship. Seedlings experience greatest survival when floodwaters recede slowly during the growing season (see Riparian Vegetation and Groundwater).

Small differences in timing of spring floods can influence recruitment success of Fremont cottonwood vs. Goodding willow, because they have different "emergence phenologies". Both species disperse seeds and germinate over a relatively short period of time in spring and early summer. Goodding willow, however, disperses seeds somewhat later in the season than Fremont cottonwood. As a consequence, later spring floods favor willow by inundating floodplains during its germination period, while earlier floods favor cottonwood for the same reason (Stromberg and others, 1991). Zonation of these two species in the

floodplain occurs for a similar reason, with Goodding willow occurring on floodplain terraces that are lower and closer to the stream than terraces supporting the earlier germinating Fremont cottonwoods.

Along the Santa Cruz River, Sonoita Creek, and some other southern Arizona rivers, climatic patterns have resulted in a more irregular occurrence of winter floods and consequently in less frequent cottonwood recruitment than in central Arizona (Stromberg, 1993c). For example, no large winter floods occurred on these rivers during the 1930s through 1960s (Betancourt and Turner, 1993). As a consequence, cottonwoods did not establish from about 1930 to 1960, although they established in abundance prior to that time, as well as during the last 30 years, where frequent winter flooding has occurred (see Santa Cruz Case Study).

Flood occurrence along many of Arizona's rivers is bimodal. Winter floods generally result from Pacific frontal storms, and cause widespread, regional flooding. Summer floods result from monsoonal storms, and are typically more localized, more frequent, and of shorter duration. Some riparian species, particularly those of subtropical origin, are adapted to germinate during the hot summer period with moisture provided by monsoonal floods. Mesquite is an example of such a species. Although many mammals also play a role in its establishment by scarifying and dispersing seeds in fecal matter, summer floods also facilitate its establishment by abrading seeds, dispersing them to appropriate establishment sites in the floodplain, and moistening these optimal germination sites. Sites which typically occur some distance away from the mature forest on lower elevation floodplains. Along the Hassayampa River mesquite seedlings were most abundant following late summer rains or floods of sufficient magnitude to inundate floodplain surfaces elevated 1 to 2 m (3 to 7 ft) above the water table (Stromberg and others, 1991). Late summer floods and rains also stimulate germination of many other riparian tree species, including desert willow (Zimmerman, 1969).

Riparian plant species differ in their ability to survive the physiological effects of flood inundation or the physical effects of flood scour, due to structural and physiological differences between species (Whitlow and Harris, 1979). Typically, arid region floods are characterized by a very high flow peak of short duration followed by a longer period of lower flood flows. Therefore, mortality of mature plants usually results from scour or abrasion, rather than from sustained inundation. Limited data is available on the length of time Fremont cottonwood and other native riparian trees can survive sustained inundation (Walters and others, 1980). With regards to survivorship of the scouring effects of high intensity peak flows, data from the Hassayampa River indicate that plant survivorship varies linearly with flow magnitude and also varies with position in the floodplain. Cottonwood and willow trees and saplings experienced high survivorship of recent 5-yr and 10-yr floods (Stromberg, Richter and others, 1993). A larger flood (25-yr return interval) in 1993 caused greater mortality. However, a large portion of the mature vegetation remains, while tree seedlings are establishing abundantly in the flood-scoured zone. The ultimate effect of the flood was to increase age-class diversity for pioneer riparian tree species.

Mesquite bosques at the Hassayampa River were not destroyed by the 10-yr or the recent 25-yr return floods (Julie Stromberg, personal observation). However, larger floods can destroy portions of mesquite bosques, particularly in degraded systems (see next section). Minckley and Clark (1984) described the loss of large portions of a Gila River mesquite as a result of prolonged flooding during 1978 which undercut and collapsed the floodplain. However, floods in turn create conditions that set the stage for new bosque development. Turner (1974) described the doubling in size of a Gila River bosque during a period of floodplain aggradation.

Many riparian shrubs recover after floods by reproducing vegetatively or through seeds. Arrowweed and burro brush can re-establish by forming large clones that arise from root

sprouts. Seepwillow, the dominant riparian shrub along the Hassayampa, sustained nearly 50% stem mortality during a 10-yr flood (which occurred in spring 1993) but recovered to pre-flood stem densities by late summer, primarily as a result of vegetative stem sprouting. After the recent 25-yr return event, however, which caused greater mortality, most reproductive recovery was through seedling establishment. Arrowweed, which was infrequent before the flood, is also establishing abundantly by seed (Julie Stromberg, unpublished data).

Herbaceous riparian plants differ in their susceptibility to scouring effects of floods and ability to regenerate after floods. Bermuda grass, an exotic riparian herb, regenerates rapidly after floods by vegetative propagation. Plants characteristic of Sonoran Interior Marshlands, such as tropical cattail, reed (*Phragmites communis*), bulrush (*Scirpus americanus* and *S. olneyi*) and other emergent plants, are periodically removed by floods, but recover and can even increase as a result of floods (Collins and others, 1981). Along the Hassayampa River, wetland plants are establishing in abundance because the flood in many areas scoured the floodplain terrace to a height very near the water table. Marsh soils also rebuild in between flood events, and stream channels narrow as vegetation recovers and stabilizes banks. Typically, diversity of riparian herbs is greatest in areas of the floodplain that are susceptible to an intermediate level of flood disturbance (e.g., under mature cottonwood forests) (Wolden, 1993). Floods also provide a means of dispersing propagules laterally within the riparian zone and from upstream to downstream reaches.

Warm- and Cold-Temperate Riparian Ecosystems

Effects of floods on riparian vegetation vary considerably as a function of stream type. Many mixed broadleaf riparian forests occur along high-gradient mountain streams that flow through relatively narrow canyons. Floods in these stream types are powerful with limited area to dissipate energy. Flood velocities and mortality resulting from these

events can be great. Floods exert less of an influence on mixed-broadleaf streams that grow along unconstrained streams with relatively low gradient or that are situated near the headwaters of a watershed. Few studies in Arizona examine the impact of these geomorphic differences on riparian composition and abundance. Baker (1989), in a study of Colorado streams, determined that drainage basin variables correlated with "low-frequency" aspects of the hydrologic regime (e.g., flood flows) were more strongly related to vegetation composition than were drainage basin variables associated with "high-frequency" aspects of the hydrologic regime (e.g., baseflows).

Within Arizona, Bock and Bock (1989) have suggested that flood scour is a cause of seedling mortality and infrequent sexual reproduction of Arizona sycamore, although there is evidence that floods set the stage for sycamore establishment. The recent floods in 1993, allowed establishment of sycamore and other mixed broadleaf species on streams such as Aravaipa Creek (Julie Stromberg, personal communication). There is circumstantial evidence that summer floods play a role in establishment of riparian sacaton grass (e.g., it germinates at high temperatures on moist surfaces when covered with a light layer of sediment, such as is produced by flood flows), but this issue has not been investigated.

FLOOD FLOW ALTERATION AND RIPARIAN ECOSYSTEMS

Cause of Flood Flow Alteration

Dams are the primary cause of flood flow alteration. Small dams and diversions along rivers have been common in the Southwest as far back as the Hohokam (AD 800) who farmed in the Salt River Valley near present-day Phoenix. The 20th century created a much greater demand for an assured supply of water for agricultural and urban water needs and for hydropower. As a consequence, most of the large rivers in Arizona and the Southwest are dammed and diverted. For example, the Colorado, Gila, Salt, and

Verde Rivers each are regulated by a series of water supply and/or hydropower dams. Smaller dammed rivers in the state include Fossil Creek (hydropower dam), the Bill Williams River (Alamo Dam; multipurpose), Agua Fria River (Waddell Dam; water storage and supply and recreation), Sonoita Creek (Patagonia Lake Dam; recreation), Queen Creek (Whitlow Dam; flood control), and many others (see maps in AGFD, 1993). Many headwater rivers in the State have small check dams to prevent streambank erosion (e.g., Arivaca Creek, Babocomari River). Construction of dams and large-scale diversions has slowed in recent years on a national scale, but pressure for new dams and structural "flood control" solutions persist.

Regulated flows often create a new flow regime for below-dam river reaches (Chien, 1985). Dams operated for water storage and supply, hydropower, flood control, or recreation can reduce the frequency and magnitude of floods, alter their seasonal timing, and increase or decrease their duration. While most normal flow regimes respond to precipitation or snowmelt events, a manipulated regime is a product of factors that control water release (e.g., agriculture and power demands) and may be flatter or have peaks and dips out of synchronization with natural processes, such as plant growth and regeneration. Seasonal peak flows may shift from spring to summer, as a result of higher summer water needs for irrigation or municipal use, or as a result of flow release only after reservoir filling. This pattern is strongly evident, for example, on the Salt and Gila Rivers and to a lesser extent on the Verde and Bill Williams Rivers. Often, dams reduce the frequency of small and medium-sized floods, while not reducing the occurrence of very large flood events (e.g., 100-yr+ floods). These types of flow are occur on the Salt, Verde, Bill Williams, and Agua Fria Rivers.

Peak flows also can be altered by upstream channelization of river beds or upstream reduction in floodplain and watershed plant cover. Both factors serve to intensify flow magnitudes in the downstream reach. Uplands with little vegetation or much paved

surface area have poor soil water percolation and increased overland runoff, which increases the velocities and volumes of flood flows, increases the erosive power of the water, and decreases the lag time between a watershed rainstorm and a flood event (Kondolf and Keller, 1991). Conversely, watershed and riparian management practices that increase vegetated surfaces and decrease soil compaction in the floodplain and uplands alike, allow for the development of "sponge like" soils that allow for slower, sustained release of water. It is difficult to assess the extent to which poor watershed management has affected Arizona's streams and riparian zones.

Ecological Impacts of Flood Flow Alteration

Ecological impacts of flood flow alteration include increased mortality of plants in degraded ecosystems due to increased flood impacts; mortality of inundation-intolerant plants and changes in species composition, if flooding is unnaturally high; and increased exotic species establishment and reduced native species composition above and below flow-regulating dams (Hagan and Roberts, 1973). Flow-regulating dams create upstream riparian habitat along the edge of a reservoir, but often this habitat supports exotic plant species and does not compensate for loss of native riparian habitat inundated by the reservoir. Downstream effects of flow-regulating dams can include loss of pioneer riparian species; increased relative abundance of later successional species, upland species, or opportunistic exotic species such as saltcedar; and reduced plant growth, cover, and density. On some dammed rivers (i.e., those confined in narrow canyons), reduced flood scour can result in increased abundance of riparian vegetation.

Factors that reduce riparian abundance (e.g., water diversion, groundwater pumping, cattle grazing, wood cutting) can decrease the natural resistance and resilience of riparian ecosystems to flood disturbance. Platts and others (1985) observed that large storm events of 1983 and 1984 had major impacts on heavily grazed riparian reaches, while effects were less pronounced in ungrazed watersheds in the Great Basin Desert region

of Nevada (a region similar to the Great Basin Desert area of Arizona). Off-road vehicle use in riparian zones also can destabilize soils and contribute to increased flood loss of mesquite and other riparian plants, as well as preclude natural recovery processes (Turner, 1983). Poor riparian management and low plant cover contributed to extensive scour of Tonto Creek by the 1993 winter floods (Myers, 1993). Similarly, cottonwood mortality from floods on the lower Verde River in the late 1980s may have been exacerbated by drought-related vegetation reduction (McNatt and others, 1980). Conversely, high flood survivorship on densely vegetated portions of Date Creek demonstrates the natural resilience of riparian zones (Knight, 1993).

Prolonged, unnatural flooding also can degrade riparian forests. Sustained flooding in some areas on the Bill Williams River from 1978 to 1980 (because of unnaturally high flow releases from Alamo Dam) caused death of nearly all cottonwoods (99%) and most willows (64%) (Hunter and others, 1987). River reaches below dams on the Colorado River also experienced prolonged high water releases, for up to 12 months, during the wet years of 1983, 1984, and 1986. These flows severely contrasted the normal pattern of high instantaneous peak flows followed by a relatively rapid return to lower flows (Ohmart and others, 1988). These sustained high flows killed trees intolerant of inundation, including mesquite and cottonwood. Inundation-tolerant trees, such as saltcedar and Goodding willow, were less affected. Flood losses were also increased by loss of bordering riparian vegetation that normally serves to dissipate flow velocity and retain sediments.

Riparian vegetation can increase below dams where baseflows are increased and flood frequency or magnitude is reduced (Williams and Wolman, 1984). This is particularly true in canyon habitats. Along the upper Colorado River, wetland and riparian vegetation have been observed to increase since closure of Glen Canyon Dam, although much of the riparian forest is composed of saltcedar. Inevitable uncontrollable floods periodically

scour the vegetation that has developed (Stevens and Waring, 1985). Moderation of peak flows also may be responsible for increased vegetation cover on river sections such as the middle Gila below San Carlos Dam between Hayden and Kelvin (Graf, 1982). However, because flood moderation often is accompanied by altered seasonal flow patterns (e.g., higher summer vs. spring flows) the result has been extensive replacement of native species by saltcedar on the Gila River.

Often, however, decreased flooding is a greater perturbation to riparian ecosystems than is flooding itself (Sparks and others, 1990). This is substantiated by the vegetational changes that occur on many rivers when they are dammed and flooding is suppressed (Reily and Johnson, 1982; Pautou and others, 1991). Because dams alter many components of the below-dam fluvial ecosystem, it can be difficult to discriminate between the various effects. Besides altering the magnitude, timing, and frequency of floods, reducing flow volume, and altering seasonal flow patterns, dams also often decrease river meandering, reduce the rate of channel realignment, increase water salinity, and reduce sediment and nutrient load. Sediment-depleted water with high erosive power also can cause localized channel bed degradation (downcutting) and water table decline in dammed river reaches. Williams and Wolman (1984) reported streambed degradation of up to 6 m (20 ft) on dammed alluvial rivers in the West.

Dams, in part because of the role they play in flood suppression, have contributed to the decline of riparian cottonwood and willow forests throughout the western United States (Rood and Mahoney, 1990). Part of this decline is due to reduced flow releases, which in particular stress very young and very old trees. Part also is due to reduction in rates of sediment deposition, river meandering and channel realignment, processes that create the "nursery bars" needed for seed germination. Another part of the decline is due to reduction in winter and spring flooding, which are needed for the germination and survivorship of new generations of spring-germinating tree species (Bradley and Smith,

1986; Rood and Mahoney, 1990; Johnson, 1993). For example, a short reach of the Salt River below the flow-regulating Stewart Mountain Dam (the Blue Point cottonwoods area) supports riparian forests of cottonwood and mesquite, shrublands of arrowweed, and cattail marshes (Rea, 1983; Graf, 1988). Fenner and others (1985) describe how loss of spring peak flows in this reach has reduced the frequency of Fremont cottonwood germination and produced a "decadent" (i.e., overmature) population with few young trees. Similar situations occur on the lower Colorado (Ohmart and others, 1988). On the Verde River, as well, reduction in March and April flows and flood reduction may be reducing cottonwood establishment between Bartlett and Horseshoe Dams (McNatt and others, 1980). Along the Bill Williams River immediately below Alamo Dam, the cottonwood population has been degraded because flows have cut the channel to bedrock. As a result, channel width-to-depth ratios have been reduced and fewer high flows reach the historic floodplain (Jackson and others, 1987; Jackson and Summers, 1988). Because the age of some dams (e.g., <50 years for Alamo Dam on the Bill Williams River) is young in comparison to the lifespan of each generation of the cottonwood forest (80 to 130 years), impending forest decline may be masked by the apparent vigor of the mature gallery forest (Petts, 1985; Howe and Knopf, 1991). Without new generations of trees to replace existing trees as they die, the forest will eventually be lost. Reduction in diversity of cottonwood and willow age classes has adverse effects on abundance and diversity of riparian wildlife (Ohmart and Anderson, 1986).

Dam building in the Southwest, by progressively modifying the natural drainage regime, also has created ideal conditions for the spread of saltcedar. Saltcedar (*Tamarix chinensis*) is an exotic riparian plant species introduced to the US from Eurasia that has greatly increased along Southwest rivers during the last century, a period in which riparian ecosystems have undergone many human-caused environmental changes (Harris, 1966; Everitt, 1980). While by no means restricted to dammed rivers, saltcedar is very abundant along reservoir edges and below-dam reaches (e.g., Gila River below Coolidge

Dam; Bill Williams near Alamo Dam; Colorado River, etc.). Saltcedar thrives along reservoir edges in part because alluvium in these areas is exposed during seasons of the year when seeds of vernally adapted native species (e.g., cottonwood and willow) are not present, and because soils along reservoir edges can be very saline (see Riparian Vegetation and Water Quality). When peak flows occur in summer or fall rather than spring, conditions in reaches downstream of dams favor the opportunistic saltcedar because it can germinate anytime during the growing season. Increased water salinities, altered sediment grain size, and lowered downstream water tables also favor saltcedar establishment. Once present, saltcedar excludes native species from its understory by pumping salt from groundwater to the surface soil and increasing fire frequency (Busch and Smith, 1993). Saltcedar stands have low habitat value for most wildlife because they possess little plant species diversity, low canopy height, and little structural complexity. Naturally timed floods, through a variety of mechanisms, including flushing of accumulated salts and recharge of water tables, can reduce the encroachment of exotic species and favor the abundance of native species adapted to the natural, flood patterns of the Southwest.

Reduced flooding can also impact vigor or composition of native floodplain herbs and forbs that are dependent on periodic inundation as a water or nutrient source. Cox (1984) speculated that the productivity of big sacaton has been lowered in many areas of southern Arizona because flood waters remain in now-channelized streambeds rather than spreading onto the floodplain. Studies conducted along the Gunnison River, in a semiarid region of Colorado, indicated that distribution of riparian herbs was related to inundation duration, i.e., to the amount of time a floodplain surface was inundated by floods (Auble and others, 1993). The authors concluded that reduction in frequency of inundation would cause more xeric plant species to increase at the expense of more hydric species.

Upstream from dams, riparian vegetation often increases because of raised water tables, increased sediment and nutrient retention, and abundant edge created around reservoirs. On headwater streams, check dams have been used to repair damage resulting from past watershed abuses and aid riparian recovery by increasing water retention time and bank storage (DeBano and Schmidt, 1989). On larger dammed rivers, however, Fremont cottonwoods and other native riparian species inundated by reservoir formation often are replaced by saltcedar (Turner, 1974). Szaro and DeBano (1985) and DeBano and Schmidt (1989) describe the development of an extensive riparian forest on Queen Creek above Whitlow Dam, which was built in 1960 as a flood control structure. Pre-dam vegetation consisted mainly of velvet mesquite, ironwood (*Olneya tesota*), and riparian shrubs. Increased water availability from bank storage resulting from flood water impoundment and increased soil fertility attributed to higher post-dam vegetation densities and the presence of some riparian obligates, such as Goodding willow. Saltcedar, however, constituted most of the post-dam vegetation.

Above some dams, marshes have become locally abundant. Along the Colorado River, for example, deltas formed behind Imperial Dam and Parker Dam (Lake Havasu) and enclosed by levees above Topock have been colonized by sedges, bulrush, cattail and reeds (Ohmart and others, 1988). A similar phenomenon occurred at the confluence of the Bill Williams and Colorado Rivers, where flood-inundated cottonwood forests near the delta were replaced by cattail marshes (Hunter and others, 1987). Ohmart and others (1988) indicate, however, that although some types of marshlands have increased along the Colorado from the 1970s to the 1980s, vegetation type are unstable, changing rapidly in response to river flow alterations.

RIPARIAN VEGETATION AND WATER QUALITY

The objective of this section is to overview the importance of water quality to riparian vegetation, and summarize studies of water quality tolerances for riparian plant species. Potential techniques to prevent poor water quality from degrading riparian ecosystems are presented in the Conclusions and Recommendations section.

IMPORTANCE OF WATER QUALITY TO RIPARIAN VEGETATION

Water quality potentially influences all types of riparian vegetation in Arizona, but generally water quantity issues override water quality issues. Often, water quantity influences both the abundance and composition of the riparian vegetation, while water quality influences only its composition. Gradients of water quality, for example, are known to influence plant composition within marshes, and gradients of salinity or soil fertility can influence species composition within floodplain forests. In some cases, however, poor water quality can reduce riparian abundance by exacerbating the effects of stream dewatering. High salt levels, for example, produce physiological drought, which in combination with "real" drought can be lethal to many riparian plants.

Water quality variables of greatest concern for Arizona riparian vegetation include salinity, alkalinity, nutrient and heavy metal content of surface water, groundwater, and floodplain soil water. Water sediment content also is of concern for wetland and riparian vegetation as it influences light penetration, terrace building, recruitment bar formation, and burial of seedlings or small plants.

Riparian plant species differ in their tolerance to various water quality factors including salinity and alkalinity, and in their nutrient requirements. Quality of surface water, groundwater, and floodplain soil water thus can influence riparian vegetation abundance and composition. Some species have broad tolerance ranges but others have specific

requirements and are good bio-indicators of such conditions as eutrophy (i.e., high nutrient levels), oligotrophy (low nutrient levels), or degree of alkalinity. Riparian plant species also may differ in their tolerances to heavy metals and other inorganic or organic pollutants, although little is known about this issue.

Sonoran Riparian Ecosystems

Goodding willow and Fremont cottonwood have low salt tolerance. Seed germination for both species is greatly reduced with salinities greater than 50 meq/l of NaCl (Siegel and Brock, 1990), while seedlings tolerate no more than about 3,000 mg/l of total dissolved solids (TDS) (Jackson and others, 1990) (Table 7). Optimum salt concentrations for both species is below 1,500 mg/l. Young alluvial soils in floodplains can have low nutrient content, but there is little data on nutrient requirements or relationships for Fremont cottonwood and Goodding willow. Both tree species have been reported to grow in areas with high concentrations of heavy metals (Sullivan, 1991).

Most species of mesquite have fairly high salt tolerance. Honey mesquite germinates at salinities up to 300 meq/l of NaCl (Siegel and Brock, 1990), and as adults can survive salt levels of up to 60,000 TDS (Jackson and others, 1990). Screwbean mesquite has somewhat lower salt tolerance, and has much reduced seedling survivorship at greater than 36,000 mg/l TDS. With regards to nutrients, mesquite and other legume trees essentially supply their own nitrogen through symbiotic soil bacteria associated with mesquite roots that "fix" atmospheric nitrogen into a form usable by the plant. Rates of nitrogen fixation by mesquite are higher in riparian stands than in upland sites, and vary with water availability in the riparian zone. Substantial amounts of nitrogen can accumulate in upper soil layers and be available for other riparian plant species as a result of mesquite leaf and seedpod litter fall.

The exotic tree saltcedar has high salt tolerance, as its name implies (Table 7). Saltcedar is a halophyte that pumps salt from the groundwater or soil water and deposits it on the floodplain surface.

Riparian shrubs with low or intermediate levels of salt tolerance include arrowweed, which usually grows in non-saline soils but is tolerant of intermediate salinities (Jackson and others, 1990) (Table 7). Among herbs, tropical cattail is an example of a species with an intermediate level of salt tolerance. Within Las Vegas Wash in Clark County, Nevada, for example, it grew in areas where soil water salinities were from 3,500 to 7,000 mg/L. It was replaced by common reed in areas where salinities were higher (6,000 to 67,000 mg/L) or by saltcedar in areas of highest salinities (from 4,500 to 95,000 mg/l) (Jackson and Patten, 1988). Riparian herbs also vary in their nutrient requirements. For example, herbaceous species that are restricted to mesquite understories may have high nutrient requirements.

Table 7.
Salinity tolerance range (mg/l of TDS) for selected riparian plant species[1]

Species	Optimum Range	Maximum Tolerance
Fremont cottonwood	0-1,500	3,000
Goodding willow	0-1,500	3,000
Arrowweed	0-6,000	18,000
Quailbush	0-18,000	60,000
Screwbean mesquite	1,500-36,000	36,000
Pickleweed	1,500-36,000	60,000
Honey mesquite	1,500-36,000	60,000
Saltcedar	1,500-36,000	95,000

[1] Based on Jackson and others (1990)

There are several salt-tolerant riparian shrubs and herbs which grow in areas that naturally accumulate high salt contents, such as floodplain edges where soil water evaporation rates are high and flushing flows are infrequent (Jackson and others, 1990).

Salt-tolerant shrubs include pickleweed, seepweed or iodine weed, quailbush, and various species of saltbush (Table 7). Salt-tolerant herbs include saltgrass (*Distichlis spicata)*, yerba-mansa (*Anemopsis californica*) and many chenopods and composites.

Among salt-tolerant and salt-intolerant species alike, increased salinities can reduce vigor and structural development. For example, tropical cattail has high vigor and abundance when salinities are low (ca. 1,200 mg/l). Vigor declines at intermediate levels of salinity (ca. 3,000 to 7,000) and plants become stunted at the upper range of its salinity tolerance. (e.g., 12,000 mg/l) (Jackson and Patten, 1988). Many salt-tolerant species, including saltcedar and quailbush, also show decreased growth as salinity increases (Jackson and others, 1990).

Warm- and Cold-Temperate Riparian Ecosystems

Salinity issues in general are not as significant to higher elevation riparian forest species as they are to lower elevation riparian species, because of factors such as lower evaporation rates. With regards to other water quality and soil chemistry parameters, there is some evidence that soil fertility influences broadleaf forest composition. For example, many riparian forests undergo a successional process in which cottonwood, willow and other pioneer species that establish on recently deposited alluvium, are replaced over time by species such as ash, walnut, maple, and hackberry. During this successional process, the floodplain surface generally increases in elevation above the water table as a result of vegetation-mediated sediment retention during overbank flows. In addition, ambient soils increase in silt, clay, organic matter, and nitrogen and phosphorous content (Johnson and others, 1976). These conditions favor late-successional species with high nutrient demands, such as hackberry (Van Auken and Lohstroh, 1990).

Nutrient relations of Arizona's wetland or riparian herbs have received limited study. Data from other regions, however, indicate that plant distribution in some wetlands is correlated with water nitrogen and phosphorous content. Some sedges are restricted to fine textured soils because of their demand for high levels of both nutrients and water. Cooper (1988) reported that nutrient and pH content were important gradients structuring Rocky Mountain wetland plant communities. Cooper (1988) also reported that Rocky Mountain marshes with the greatest diversity of plant species were those fed by groundwater that emerged through calcareous parent rock. Water parsnip (*Berula erecta)* is a species of southern Arizona cienegas that grows in areas rich in calcium carbonate. Water sediment content (i.e., turbidity) has been shown to influence marsh plant composition at Babocomari Cienega in southern Arizona (Cross, 1991).

WATER QUALITY ALTERATION AND RIPARIAN ECOSYSTEMS

Water quality can change as a result of direct streamflow alteration (e.g., river damming and diversion, effluent release, interbasin water transfers), floodplain land uses (e.g., floodplain agriculture or livestock grazing), watershed activities (e.g., livestock grazing, timber harvest, mining), or riparian vegetation changes (e.g., invasion of saltcedar). The extent of rivers with possible water quality changes can be determined to some extent by evaluating maps of rivers illustrating flow regulated by upstream dams or dominated by effluent, and floodplain land uses, such as agriculture, grazing or mining (e.g., maps in AGFD, 1993). Ecological impacts of these water quality changes include replacement of salt-intolerant riparian plants by salt-tolerant plants, such as saltcedar; replacement of species tolerant of low nutrients by those requiring high nutrients; and changes in species diversity.

Dams modify water quality in several ways. Salt content of surface water, groundwater, and floodplain soil water usually increase downstream from dams, because the large surface area in the reservoir increases evaporative loss and concentrates salts in the

water, and reduced occurrence of flushing flows allows salts to accumulate in floodplain soils. Dams also alter downstream sediment flow patterns and reduce downstream nutrient content. Nutrient-rich silts, that would normally be released to the below-dam river and deposited on floodplains during flood flows, instead accumulate in upstream reservoirs, with possible negative consequences for willows and other riparian vegetation (e.g., Stevens and Waring, 1988). The extent of this effect can be great. According to Williams and Wolman (1984), sediment concentrations and suspended loads decrease markedly for hundreds of miles downstream from dams in the western USA.

Release of effluent into a stream channel can modify water quality by resulting in increased nutrient content as well as increases in some pollutants, such as heavy metals. Riparian vegetation in many of the state's effluent-dominated river reaches owe their existence to increased water availability, but there are unanswered questions about the impacts of effluent water quality on riparian ecosystems, and conversely about the impacts of riparian vegetation on effluent water quality (Tellman, 1992). Fast-growing trees, such as Fremont cottonwood, have a high capacity for nutrient uptake and can play a role in nutrient removal (Karpiscak and others, 1993). Along the effluent-influenced Santa Cruz River, nutrients and other water quality parameters rapidly return to ambient levels following passage though an extensive riparian floodplain (Stromberg, Sommerfeld and others, 1993). Heavy metals in effluent produced by industrial municipalities also can be taken up by riparian vegetation (Sullivan, 1991). Ecological effects of added nutrient or pollutant load, however, needs further study. The greatest concern may lie with higher-trophic level species (e.g., birds) that could suffer adverse effects from biomagnification of toxic materials.

Floodplain agriculture also can modify water quality, because water used for irrigation and returned to a river channel tends to have higher salt concentrations and can also contain high nutrient or herbicide/pesticide levels. The extent these concentrations modify

streamflow water quality depends on the percentage of total streamflow irrigation return flow constitutes in a channel, and the extent to which irrigation return flows pass through riparian ecosystems prior to reaching the channel. Riparian ecosystems can play a strong role in filtering nutrients from these irrigated fields. However, if this does not occur, the downstream ecosystem may undergo changes, such as increase in saltcedar abundance.

Interbasin transfers of water to recharge aquifers or to restore or augment riparian habitat also can have ecological impacts related to the water quality of the "new" water supply. For example, in the Owens River Valley of California, groundwater pumping in the 1970s resulted, among other things, in the dewatering of a spring-fed marsh. Prior to pumping, the spring flowed from a geologic fault and formed several ponds surrounded by marsh vegetation. After the spring ceased to flow, the marsh vegetation died. Attempts to restore the marsh by re-rerouting mountain surface runoff were only partially successful. The restored marsh was smaller and had different plant species composition than the original marsh, in part due to different water quality (Perkins and others, 1984).

Water quality is also a function of watershed conditions. Water flowing over landscape can accumulate sediment, salts, nutrients, and pollutants from rangelands, urban areas, or mines, which ultimately are deposited in the stream-aquifer system. Heavy metals, such as those produced as a result of mining operations near Superior, are accumulating in the floodplain sediments of Queen Creek above Whitlow Dam, with undocumented impacts for the riparian ecosystem. Processes that reduce upland vegetative cover, such as livestock grazing, vegetation clearing, and vegetation conversion (e.g., chaparral to grassland), can affect riparian systems by increasing sediment runoff. This in turn, can affect stream biota as well as riparian processes, such as seedling survivorship (Stromberg and others, 1991).

The Colorado River is representative of a large desert river that has undergone extensive ecological change as a result of multiple human impacts including river damming, flow regulation and diversion, stream channelization, agricultural floodplain use, and floodplain clearing (Ohmart and others, 1988). Many of the ecological impacts documented below are similar to those that have occurred on other large regulated rivers, such as the Gila River. The Colorado River in the last few decades has lost extensive acreage of native riparian vegetation (e.g., cottonwood-willow forests have been much reduced, and mesquite bosques alone have been reduced from about 100,000 ha [250,000 acres] to 6,000 ha [15,000 acre]) and has undergone shifts in composition to less desirable exotic species including saltcedar (Rosenberg and others, 1991). Causes of these changes include flow reduction and alteration of natural flow regimes, as well as changes in below-dam water quality. Flow in the middle and lower reaches of the Colorado River has been declining since the early part of this century in response to river damming and flow diversion. At the same time, salinity levels below most of the major dams have increased due to the creation of reservoirs with extensive evaporative surface area, depletion of surface flows that dilute saline agricultural irrigation return flows, and reduction in flood flows that periodically leach accumulated salts from floodplain soils. The net result has been that salinity levels, in some areas, exceed the tolerance level of salt-intolerant species such as Fremont cottonwood and Goodding willow. Along much of the Colorado River, Fremont cottonwood and Goodding willow have been replaced by saltcedar. The net result of the increase in saltcedar domination has been a loss of wildlife diversity and understory plant diversity, in part because of the intolerance of many native species to the highly saline soil conditions created by saltcedar.

The delta of the Colorado River historically supported extensive marshlands. These marshlands, including the Cienega de Santa Clara in northern Mexico (immediately south of Arizona), were essentially eliminated and dewatered as a result of damming and diversion of the Colorado River. The Cienega de Santa Clara was revitalized in the

1970s by over 100,000 af/yr of saline (2,000 ppm TDS) agricultural bypass water from the Wellton-Mohawk irrigation district. The brackish water was originally intended for delivery to the proposed Yuma Desalting plant, which finally was completed in the 1990s. Although revitalized, the "new" marsh had different species composition because of the elevated salinity of its water source. A salinity concentration gradient was produced in the marsh, resulting in a vegetation was composed of salt-intolerant species grading to less salt tolerant species. Cattail is the predominant species in the marsh. Operation of the Yuma desalinization plant, which may not occur because of factors such as high plant operation costs, would threaten the marsh by reducing flows to the marsh and to elevate salinity concentrations three times above present levels (ARW, 1993).

CONCLUSIONS AND RECOMMENDATIONS

GROUNDWATER

The knowledge base regarding groundwater and riparian vegetation relationships is expanding. It is clear that a continuum of response exists between depth to groundwater and some riparian vegetation attributes. For example, structural attributes of a riparian stand as a whole decline continuously as depth to groundwater increases. This same type of relationship holds for particular plant associations, although there are thresholds beyond which each species or association will not persist, as well as groundwater depths associated with optimum stand development. Mesquite bosques experience optimum development where groundwater is about 3 to 8 m (7 to 26 ft), but persist in areas where groundwater is up to about 15 m (50 ft). Structural traits of mesquite bosques that relate to wildlife requirements and other values, change continuously over this range. Structural attributes of Fremont cottonwood stands similarly vary along a continuum, with tree density and canopy cover declining as depth to groundwater drops from about 3 to 5 m (10 to 16 ft) below the floodplain surface.

Although there is need for additional study of vegetation-groundwater relationships for many species and plant associations (especially those of higher elevation riparian zones), general thresholds for plant association type changes can be identified for several dominant members of Sonoran riparian ecosystems and warm-temperate riparian zones. To sustain marshlands and cienegas composed of obligate wetland herbs, water tables should remain about 0.2 m (0.5 ft) above or below the floodplain surface; well-developed floodplain forest associations of Goodding willow and Fremont cottonwood require groundwater no deeper than about 3 m (10 ft); higher floodplain terrace associations such as sacaton grasslands have optimum development where groundwater is no further than about 5 m (16 ft) below the land surface; and mesquite bosques with understories of greythorn, wolfberry and other shrubs require water tables with a seasonal or annual

maximum depth of no more than about 8 m (26 ft) to maintain high structural development.

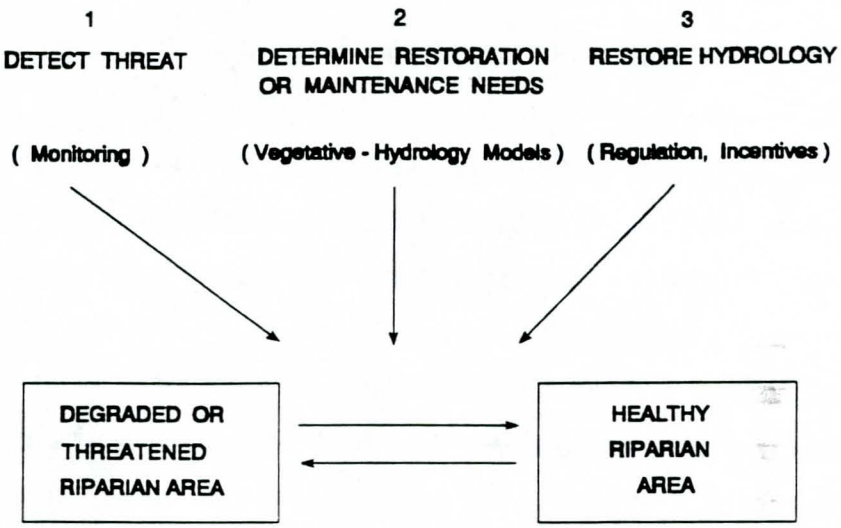
It also is clear that a different set of water table requirements must be met to allow new generations of riparian plants to establish. To allow for establishment or continued regeneration of Fremont cottonwood and Goodding willow, portions of the floodplain must be seasonally saturated and water tables maintained within 0.5 to 1 m (2 to 3 ft) below the water surface for several months, at least once every several years. Establishment requirements of additional riparian species need to be determined.

Some riparian plant/groundwater relationships have been extensively studied. Results of these studies indicate that these relationships are transferrable between like streams. For example, groundwater conditions associated with establishment of Fremont cottonwood do not strongly differ between rivers of similar elevation and climatic zone. Additional study is needed to determine whether this and other such relationships are "robust" in the sense that they are transferrable between streams located in different climatic zones (e.g., Sonoran Desert vs. semidesert grassland biome) or that differ in floodplain sediment texture (as it relates to water holding capacity and capillary rise).

Although information gaps exist, adequate information is available on vegetation-groundwater relationships to determine when groundwater level changes become ecologically significant (Richter and Richter, 1992). Groundwater-vegetation data can be used in conjunction with groundwater models and/or groundwater monitoring programs to identify vegetation-limiting groundwater conditions (Figure 6). Riparian monitoring programs that include a groundwater monitoring component are one tool that can, and should, be used to prevent groundwater decline from degrading riparian ecosystems. Monitoring wells should be established within floodplains that support valued riparian ecosystems and in regional aquifers that recharge the floodplain alluvium (Jenkins, 1989).

Additionally, numerical groundwater models should be developed for streams of concern to enable prediction of long-term groundwater trends that may affect alluvial aquifers. Monitoring wells can be used to calibrate and verify the models, and to provide direct information on alluvial groundwater change. Ideally, wells should be placed along a

Figure 6. The potential role of riparian monitoring and hydrologic and ecologic models in preventing riparian degradation



gradient away from the stream to the floodplain perimeter, and should be located within various vegetation types, particularly those most sensitive to groundwater change (Richter, 1992). Water tables should be monitored on a monthly basis, or at least biannually, including one reading in June, the driest month in the year (Briggs, 1993). Monitoring wells may need to be more abundant in stream reaches that are most

sensitive to water withdrawal, as identified through hydrological groundwater techniques, such as alluvial aquifer change models (Braun and others, 1992).

Declines in water tables below the norms or thresholds for each riparian type or indicator species can serve as a "red-flag" that signals a need to modify pumping, diversion, or other water uses. This type of approach to riparian protection resembles that currently being undertaken in the Owens River Valley (Groeneveld, 1989). The Inyo County Water Department was formed in 1980 to protect the Owens Valley environment from the effects of groundwater pumping by the Los Angeles Department of Water and Power (LADWP). An extensive riparian and groundwater monitoring program has been established that involves: (1) monitoring groundwater depths within the drawdown range of wells and at control sites using continuous recording groundwater level transducers and spot measurements on a larger sample of wells; (2) monitoring soil moisture using neutron probes; and (3) monitoring vegetation parameters, including new recruitment and vegetation change from baseline conditions using line and point-frame transects (ICWD 1993). Information on water requirements of the vegetation, including data on maximum rooting depths of riparian shrubs, is used as a basis for shutting down well fields when vegetation-limiting water conditions are reached (Groeneveld, 1989). Water-vegetation simulation models and remote sensing monitoring techniques are being investigated that would allow LADWP to determine in advance how much water could be pumped without harming the vegetation (ICWD, 1993). In Arizona, groundwater monitoring programs have been initiated on many streams, including the BLM's San Pedro Riparian National Conservation Area River, Cienega Creek, and several riparian zones managed by The Nature Conservancy (e.g., Sonoita Creek, Hassayampa River). Additional rivers are in need of such monitoring programs include the Verde, Santa Cruz, and Bill Williams Rivers.

Riparian monitoring programs should also include a biotic component. Although ecologically stressful groundwater levels can be identified a priori for some species, as described above, riparian stands can be monitored directly for stress and change in ecological condition without relying on physical measurements of groundwater. Direct monitoring of riparian vegetation is also valuable for those associations and species for which relatively little is known of their groundwater relationships. For example, remote sensing techniques including satellite imagery or repeat aerial photography can be used to detect riparian vegetation change over time in watersheds with high rates of groundwater pumping (Cuplin, 1985; AGFD, 1993; and see Santa Cruz Case Study). Ground-based monitoring methods that can serve this same purpose include repeat photography at fixed photo points; repeat measurements of vegetation traits, such as canopy foliage volume or leaf area index; or repeat measurements of physiological parameters, such as plant water potential (Table 3). Plant water potential, for example, responds rapidly to changing hydrologic conditions, and can serve as early warning stress detector (Kelly and Harwell, 1990). Low water potential readings in mesquite, for example, may indicate impending structural degradation from water stress resulting from groundwater pumping (Stromberg, Wilkins and others, 1993). For Fremont cottonwood, stomatal conductance (i.e., transpiration, or plant water loss) measurements may be a critical adjunct to water potential measurements because water potential readings alone can be equivocal (Kelliher and others, 1980; Williams, 1989; Kramer and Steinman, 1993).

In addition to continued study of vegetation-groundwater relationships and development of riparian monitoring programs, a tool that can be used is establishment of a series of "reference" watersheds that can be managed for their natural values. Such watersheds should include various types of riparian plant communities. Riparian zones in such watersheds provide an index of the species composition, plant abundance, and

community structure that are expected for each type under "natural" or unmodified hydrologic conditions.

Finally, there is need for a systematic study of riparian zone water table conditions, including existing and impending threats, similar to a study currently being conducted by the Pacific Institute (Oakland, California) to identify "at-risk" aquatic and riparian habitats in the US/Mexico border region.

SURFACE WATER

Surface water reductions, like groundwater declines, cause loss and degradation of riparian plant communities. Quantification of instream flow needs of riparian vegetation, however, has received comparatively little study in contrast to other types of instream flow studies (i.e., instream flow requirements for fish). Nonetheless, it is clear that riparian vegetation abundance changes along a continuum with surface flows. In other words, the amount of riparian vegetation increases as surface flows increase, except in sites where other factors constrain riparian development (e.g., canyon riparian zones). Conversely, riparian abundance declines continuously as the amount of diversion increases. Species composition also changes along a continuum, with several hydro-riparian species (such as willows and alders) requiring perennial surface flows and high flow rates, and meso-riparian species (such as Arizona walnut) and xero-riparian species tolerating lower flow rates or intermittent to ephemeral flows. To minimize riparian loss and degradation, it is evident that diversions should be minimized, particularly during natural drought years and during the growing season. Seasonal and annual flow patterns should closely track historical hydrograph information (i.e., seasonal high flows should remain in spring and late summer, or otherwise follow the natural seasonal flow pattern, and the magnitude of the flood flow rate relative to the low flow rate should not be altered). It also should be remembered that often the combination of surface flows and groundwater together sustain

large, healthy riparian vegetation zones, and thus surface waters should be allowed to remain hydraulically connected to groundwater.

Riparian vegetation instream flow models such as those described in this report (see Verde River Case Study) can be used in conjunction with hydrological models to predict some of the effects of flow diversion or groundwater pumping on Sonoran and warm-temperate riparian forests, including changes in overall riparian abundance (e.g., canopy foliage area) or abundance of particular species (e.g., Fremont cottonwood) (see Verde River Case Study). These models are a derivation of those developed by Taylor (1982) for riparian communities of eastern Sierra Nevada alluvial streams. His model was developed on undiverted streams, tested on diverted streams, and used to predict the effects of future stream diversion. The models developed in this study between vegetation and surface flow similarly can be used as a planning tool to predict riparian declines or identify flow requirements for riparian vegetation. The instream flow models are to some degree transferable between watersheds that do not differ greatly in elevation, climate, and stream and valley geomorphology, but accuracy will be greatest when using watershed-specific models. Instream flow models need to be developed for cold-temperate riparian forest types. When predicting such changes, it is important to be aware that surface water volume has large natural flux in Arizona's rivers because of the variability of rainfall in arid and semiarid regions.

Other types of models also could be developed to predict response of individual species to changes in flow in specific rivers. Instream flow models that relate tree growth to flow volume (using tree-ring studies) have been used to identify minimum annual flows to prevent cottonwood tree death and have documented flows needed to maintain vigorous canopies (Stromberg and Patten, 1990 and 1992). Also, demographic studies of seedling establishment should be undertaken to refine our knowledge of flow requirements for riparian regeneration. Instream flow studies also should be undertaken on effluent-

dominated streams to further our knowledge of relationships between volume and timing of effluent flow release and riparian stand size and composition.

It is also recommended that riparian monitoring programs be initiated on rivers of concern. Monitoring should include a physical and biological component. Discharge in many streams is monitored by USGS stream gages, although there is a need to expand and upgrade this streamgage network. Many other groups monitor instream flows through the use of streamgages, such as The Nature Conservancy along the Hassayampa River and other river preserves; and the Bureau of Land Management along the San Pedro River. Many high elevation streams, however, are not gaged, nor is there much quantification at any elevation of streamflow losses resulting from diversions. There is a need to obtain and analyze such flow data from the perspective of the vegetation, i.e., to focus on flow reduction trends that impact vegetation. Riparian vegetation health and status also should be monitored directly on streams potentially or actually affected by diversions or stream depletion from groundwater pumping. Many documents describe riparian monitoring techniques (e.g., Platts and others, 1987; Prichard, 1993).

FLOOD FLOWS

Floods are a natural process in riparian zones. Native riparian plant communities can be altered by changes in flood magnitude, frequency, and timing associated with river damming and diversion. Watershed and floodplain management activities also can reduce the natural resistance and resilience of riparian zones to floods, and result in higher than normal flood damage and reduced recovery ability.

For maximum ecological benefit, Arizona rivers should be managed such that their flow patterns closely resemble natural hydrographs. Flow regimes of above-dam control sites are frequently monitored, and could be used as templates or prototypes for potential below-dam flow regimes. Dam-influenced river reaches, as well as upstream controls,

should be monitored for other potential physical changes resulting from dam operations (e.g., sediment dynamics, soil salinity), and for biological factors such as age class diversity of tree species, herbaceous plant cover and diversity, and overstory cover and tree density.

The results of the monitoring program can be used as an indication of the need to modify the pattern or rate of water or sediment release from the dam. If ecological stress is apparent, flow releases may need to be modified to benefit the downstream system (often this means approximating natural flow patterns), or sediment may need to released to the below dam river. Determination of the release pattern will require site-specific study or review, such has been undertaken for the Rio Grande, a New Mexican river that supports a "dysfunctional" or "decadent" cottonwood population that has few young individuals to replace older members (Howe and Knopf, 1991). In Arizona, studies have been undertaken to determine how flow releases in the Grand Canyon can accommodate ecological health. Hydrologic studies can indicate which floodplains are inundated by flows of various magnitude and the rate water tables recede in response to flow reduction. Together with biological information on factors such as timing of tree seed dispersal and germination, seedling requirements for various rates of water table recession, and water table depths, appropriate riparian management can be accomplished.

There is also a need to adopt a "watershed-based" approach to riparian management (Doppelt and others, 1993). "Reference watersheds" should be established and managed for their riparian values. The response of the vegetation in such watersheds can be used as an indication of the biological potential of riparian vegetation to resist and recover after floods. Riparian abundance and survivorship should be monitored at sites where floodplains or watersheds are impacted by varying types of land uses that may modify flood flow intensities. If flood mortality is unnaturally high in comparison to the control or

reference watershed, land and water uses in the impacted watershed and riparian zone should be investigated to determine possible factors causing riparian degradation.

WATER QUALITY

Although water quantity is the primary determinant of riparian abundance and composition in semiarid region riparian zones, water quality also plays an important role in influencing species composition. For some water quality parameters, such as salinity, sufficient information is available to identify ecological threshold levels (e.g., salinity levels) that are related to riparian compositional changes and that warrant corrective measures (e.g., release of flushing flows from dams). Additional research is needed to determine the relationship of other water quality parameters (e.g., nutrients and heavy metals) to riparian vegetation and wildlife .

It is recommended that water quality, particularly salinity, alkalinity, nutrient levels, and heavy metals, be monitored in surface water, groundwater, and soil water in riparian zones of areas suspected of undergoing water quality changes, such as dammed rivers, effluent-dominated rivers, rivers receiving irrigation return flow or CAP water, or rivers undergoing other types of interbasin water transfers. Water quality is presently measured in several rivers (e.g., Colorado River, per the Colorado River Compact; rivers designated as Unique Waters; and rivers monitored as part of the USGS stream monitoring program), however, this program could be expanded.

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GLOSSARY

This glossary contains terms referring to ecological and riparian concepts. Hydrologic terms are in the Glossary of the Hydrology Chapter (Chapter II).

Age structure: The distribution of individuals in different age classes within a population.

Biomass: The total weight of the living components (producers, consumers, and decomposers) in an ecosystem at any moment of time. This is usually expressed in dry weight per unit area.

Community: The entire assemblage of species occurring together within an ecosystem; an association of interacting species.

Ecosystem stress: A physical or chemical factor to which an individual or population fails to make a satisfactory adaptation.

Ecosystem disturbance: A change in an ecosystem, natural or man-made, that alters abiotic and biotic factors of that system.

Ecosystem: The organisms in a community plus the associated abiotic factors with which they interact.

Edaphic: Pertaining to the influence of soil upon organisms growing in or on it.

Exotic, or non-native, species: Species that have been introduced to a region through human intervention.

Facultative, as in facultative riparian: Organisms that are able to live under more than one set of conditions or that have characteristics that permit alternate responses under different conditions.

Floodplain: Area adjacent to the active stream channel that is periodically inundated by flood waters.

Fluvial processes: Processes that pertain to streams.

Guild: Group of related species functioning in a similar fashion in the ecosystem.

Herbaceous vegetation: Plants without woody stems.

Hydro-riparian plants: Riparian plants that grow on the wetter end of the riparian moisture continuum. They require perennially wet soil and often grow along perennial streams.

Hyporheic zone: Area of abundant microbial activity occurring above the zone of saturated groundwater.

Keystone species: A single species that is critical to the community and may determine community structure. Removal of a keystone species from the ecosystem causes extensive change in community structure or function. Many times a top predator or dominant species will be a keystone species for a community.

Leaf area index: Ratio of the total area of leaf surface in a plant community to the ground surface.

Meso-riparian plants: Riparian plants that grow in the intermediate range along the riparian moisture continuum. They often are associated with intermittent streams, or higher floodplain terraces of perennial streams.

Niche: The functional role of a species in an ecosystem.

Obligate, as in obligate riparian: An organism restricted to a particular set of conditions, and that requires those conditions for its existence.

Phreatophyte: A term literally meaning "well-plant" that refers to plants that use groundwater. It is often used as a synonym for "riparian plant".

Plant establishment: The process of successful germination, growth, and survival of young plants.

Pioneer species: First species to colonize a site after a disturbance, in the first stages of ecological succession.

Population: Any group of individuals of one species that occupy a given area at the same time; in genetic terms, an interbreeding group of organisms.

Riparian ecosystem: An ecological community associated with a water body, considered together with the nonliving factors of its environment.

Species: Groups of actually or potentially interbreeding natural populations which are reproductively isolated from other such groups. A taxonomic group of morphologically similar individuals.

Species composition: The complement of species present at a site.

Succession: Process of sequential species replacement and ecosystem re-development that occurs after a natural disturbance or perturbation (i.e., after a flood).

Threshold: A level of change within the physical environment that causes the components of an ecosystem to be disrupted.

Vegetation association: A plant community defined by one or two of the dominant species.

Vegetation structure: Structural attributes of a plant community, including growth form, number and height of vegetation layers, etc.

Vigor: The strength or robustness of a plant or animal's health or rate of growth.

Wetlands: General term applied to shallow open-water habitats and seasonally or permanently saturated land areas, including lake edges, river margins, estuaries, and freshwater marshes.

Xeroriparian plants: Riparian plants that grow at the drier end of the riparian moisture continuum. They often grow along ephemeral washes and can tolerate more drought stress than can meso-riparian plants.

APPENDICES

APPENDIX A. SENATE BILL 1030

Appendix A

House Engrossed Senate Bill

FILED
ARIZONA
SECRETARY OF STATE

State of Arizona
Senate
Fortieth Legislature
Second Regular Session
1992

CHAPTER 298

SENATE BILL 1030

AN ACT

AMENDING SECTION 45-101, ARIZONA REVISED STATUTES; MAKING AN APPROPRIATION; RELATING TO THE RIPARIAN PROTECTION PROGRAM.

Be it enacted by the Legislature of the State of Arizona:

Section 1. Findings and policy

A. The purpose of this act is to provide for collecting scientific and economic data and developing analyses and reports on which the legislature may base decisions concerning protecting riparian areas.

B. This state's riparian protection program should be based on sound scientific and economic evidence. To develop an effective, well-balanced riparian protection program, it is necessary to identify and classify the riparian areas in this state based on functions and values, to assess the impact of various activities on riparian areas and to assess alternative strategies in light of their environmental costs and benefits and their economic impacts on various classes of landowners and land users and on this state. This act provides for reports, studies and recommendations to the governor and the legislature on which a riparian protection program can be developed. It is also necessary to have accurate information to fully evaluate any potential impacts that a riparian protection program may have on existing water rights, pending water right adjudications and negotiated water settlements.

Sec. 2. Section 45-101, Arizona Revised Statutes, is amended to read:

45-101. Definitions

In this title, unless the context otherwise requires:

1. "Commission" means the Arizona water commission.

2. "Department" means the department of water resources.

3. "Director" means the director of water resources, who is also the director of the department.

4. "Effluent" means water that has been collected in a sanitary sewer for subsequent treatment in a facility that is regulated pursuant to sections 49-361 and 49-362. Such water remains effluent until it acquires the characteristics of groundwater or surface water.

5. "Groundwater" means water under the surface of the earth regardless of the geologic structure in which it is standing or moving. Groundwater does not include water flowing in underground streams with ascertainable beds and banks.

6. "Interstate stream" means any stream constituting or flowing along the exterior boundaries of this state, and any tributary originating in another state or foreign country and flowing into or through this state.

7. "RIPARIAN AREA" MEANS A GEOGRAPHICALLY DELINEATED AREA WITH DISTINCT RESOURCE VALUES, THAT IS CHARACTERIZED BY DEEP-ROOTED PLANT SPECIES THAT DEPEND ON HAVING ROOTS IN THE WATER TABLE OR ITS CAPILLARY ZONE AND THAT OCCURS WITHIN OR ADJACENT TO A NATURAL PERENNIAL OR INTERMITTENT STREAM CHANNEL OR WITHIN OR ADJACENT TO A LAKE, POND OR MARSH BED MAINTAINED PRIMARILY BY NATURAL WATER SOURCES. RIPARIAN AREA DOES NOT INCLUDE AREAS IN OR ADJACENT TO EPHEMERAL STREAM CHANNELS, ARTIFICIALLY CREATED STOCKPONDS, MAN-MADE STORAGE RESERVOIRS CONSTRUCTED PRIMARILY FOR CONSERVATION OR REGULATORY STORAGE, MUNICIPAL AND INDUSTRIAL PONDS OR MAN-MADE WATER TRANSPORTATION, DISTRIBUTION, OFF-STREAM STORAGE AND COLLECTION SYSTEMS.

~~7.~~ 8. "Sanitary sewer" means a pipe or other enclosed conduit that carries, among other substances, any water-carried wastes from the human body from residences, commercial buildings, industrial plants or institutions.

~~8.~~ 9. "Surface water" means the waters of all sources, flowing in streams, canyons, ravines or other natural channels, or in definite underground channels, whether perennial or intermittent, ~~flood, waste~~ FLOODWATER, WASTEWATER or surplus water, and of lakes, ponds and springs on the surface. For the purposes of administering this title, surface water is deemed to include central Arizona project water.

Sec. 3. <u>Evaluation of hydrologic effect of groundwater pumping and surface water appropriations on riparian areas</u>

A. Consistent with the definitions prescribed by section 45-101, Arizona Revised Statutes, the director of water resources shall conduct studies pursuant to subsection B of this section to evaluate the effect of groundwater pumping and surface water appropriations on riparian areas, subject to the availability of appropriated monies for that purpose.

B. The studies shall include evaluations of:

1. The hydrologic effect of groundwater pumping on riparian areas.

2. The effect on riparian areas of new surface water appropriations and changes in the use or point of diversion of existing surface water appropriations.

3. Alternative regulatory programs designed to balance the protection of riparian areas with existing and future groundwater pumping

and new surface water appropriations and changes in the use or point of diversion of existing surface water appropriations. In evaluating the alternative regulatory programs, the director shall consider:

(a) The economic impacts on various classes of landowners, including federal, state, private and Indian landowners.

(b) The impacts on existing water rights, pending water right adjudications and negotiated water settlements.

(c) The availability of alternative water supplies for existing and future users.

(d) The environmental costs and benefits of the program.

(e) The costs to the department of water resources of implementing the program.

C. If such monies are appropriated for fiscal year 1992-1993, the director shall complete the studies and proposed regulatory program and report the results of the study on or before December 1, 1993 to the governor, the speaker of the house of representatives, the president of the senate and the riparian area advisory committee established under section 7 of this act. The director shall provide an opportunity for public comment on each proposed regulatory program and any recommendations to be submitted pursuant to this subsection.

Sec. 4. Appropriation

A. The sum of two hundred fifty thousand dollars is appropriated from the state general fund in fiscal year 1992-1993 to the department of water resources to pay the costs of the study described in section 3 of this act.

B. The appropriation made by this section is exempt from lapsing under section 35-190, Arizona Revised Statutes, except that monies remaining unexpended or unencumbered on June 30, 1994 revert to the state general fund.

Sec. 5. Duties of Arizona game and fish department

A. The Arizona game and fish department shall develop a system for classifying riparian areas in this state, including:

1. Physical and ecological criteria to be used to develop riparian designations consistent with the definition prescribed by section 45-101, Arizona Revised Statutes.

2. A hierarchical designation system according to relative functions and values.

B. After the riparian area classification system is developed under subsection A of this section, the department shall identify, classify and map riparian areas in this state with the cooperation of the department of environmental quality, the department of water resources and other appropriate agencies, instrumentalities and political subdivisions of this state. The department shall also consult with appropriate federal agencies. The department shall give priority to identifying, classifying and mapping riparian areas that are associated with perennial waters. In addition, the department shall identify:

1. The land ownership of identified riparian areas as Indian, federal, state or private and the current land uses of those areas.

2. Existing options for protecting riparian areas in each ownership category that may be available under existing state and federal laws.

C. Not later than December 1, 1993 the department shall submit a report of its findings under subsection B of this section to the governor, the president of the senate, the speaker of the house of representatives and the riparian area advisory committee.

D. Within six months after mapping and classifying riparian areas in any county or a logical portion of a county, the department shall publish a notice that the maps and classifications are available. The notice shall be published once each week for three consecutive weeks in two newspapers of general circulation in the county in which the riparian area is located. In addition, the department shall establish and maintain a mailing list of names and addresses of persons who request notice under this subsection by mail. The mapping and classification:

1. Is for informational purposes only.

2. Shall not require any land owner to contest or accede to the mapping or classification.

3. Does not preclude any land owner from subsequently contesting the mapping or classification.

Sec. 6. Duties of department of environmental quality

A. Consistent with the definitions prescribed by section 45-101, Arizona Revised Statutes, the department of environmental quality shall identify activities, operations and uses that occur on land in riparian areas of federal, state and private property in this state that involve removing or depositing material, removing vegetation or otherwise obstructing, altering or destroying riparian areas. The department shall evaluate at least the following activities:

1. Timber harvesting.
2. Agricultural land clearing.
3. Recreational use and development.
4. Commercial, industrial and residential development.
5. Road and bridge construction.
6. Dam and reservoir construction and operation.
7. Channelization and bank stabilization.
8. Sand and gravel extraction.
9. Wetland drainage.
10. Grazing.
11. Landfills and sewage treatment facilities.
12. Mining and metallurgical operations.

B. The department shall complete the tasks prescribed under subsection A and submit a report evaluating the identified activities to the governor, the president of the senate, the speaker of the house of representatives and the riparian area advisory committee not later than October 1, 1993.

Sec. 7. Riparian area advisory committee

A. The riparian area advisory committee is established consisting of the following members:

1. The director, or the director's designee, of:

(a) The Arizona department of agriculture.
(b) The department of environmental quality.
(c) The department of transportation.
(d) The department of water resources.
(e) The game and fish department.
(f) The state land department.
(g) The state parks board.

2. The following members appointed by the governor:

(a) Two members representing counties in this state having populations of less than five hundred thousand persons according to the most recent United States decennial census.

(b) One member representing counties in this state having populations of five hundred thousand or more persons according to the most recent United States decennial census.

(c) One member representing a municipality that owns and operates a wastewater treatment plant that is regulated pursuant to sections 49-361 and 49-362, Arizona Revised Statutes, and that is located in an active management area with a population exceeding one million five hundred thousand persons according to the most recent data compiled by the department of water resources.

(d) One member representing an Indian tribe in this state.

(e) The president of the Arizona association of conservation districts, or the president's designee.

(f) One member representing the timber industry.

(g) One member representing the real estate development industry.

(h) One member actively engaged in livestock ranching as the major source of income.

(i) One member actively engaged in farming as the major source of income.

(j) One member representing sand and gravel operations.

(k) One member representing the metal mining industry.

(l) One representative of an agricultural improvement district.

(m) One riparian researcher from a state university.

(n) One representative of the Arizona riparian council.

(o) One representative of an environmental organization who resides in Apache, Navajo, Coconino, Yavapai or Greenlee county.

(p) One representative of an environmental organization who resides in Gila, Maricopa, Mohave, LaPaz or Yuma county.

(q) One representative of an environmental organization who resides in Pinal, Graham, Cochise, Pima or Santa Cruz county.

(r) One representative of a recreational users organization.

3. In order to coordinate with existing federal programs that impact riparian areas, the chief federal administrative officer in this state of the following federal agencies, or that officer's designee, or, if there is no chief federal administrative officer for this state, an administrative officer in this state designated by the head of the appropriate federal administrative region in which this state is located shall serve as ex officio members:

(a) The army corps of engineers.
(b) The bureau of land management.
(c) The bureau of reclamation.
(d) The environmental protection agency.
(e) The fish and wildlife service.
(f) The forest service.
(g) The national park service.
(h) The soil conservation service.

B. The director of environmental quality shall chair the committee and the department of environmental quality shall provide staff support and meeting space for the committee. Members of the committee are not eligible for compensation or reimbursement of expenses.

C. Ex officio members of the committee representing federal agencies are not eligible to vote and are not members for purposes of determining the presence of a quorum, but the committee shall cooperate with and seek advice from the ex officio members in order to consider the relationship between existing and recommended future state and federal programs that impact riparian areas. The committee shall meet at least quarterly and may meet more often as called by the chairman or as requested by at least six of the members eligible to vote. Beginning November 1, 1993 the committee shall meet at least monthly to review and evaluate the information presented in the agencies' reports and may meet more often as called by the chairman or as requested by at least six of the members eligible to vote.

D. The committee shall:

1. Study the components of a riparian area protection program, including the provisions and activities conducted under this act, in comparison with other state and federal programs, including goal statements, regulatory methodologies, evaluation criteria, coordination with existing state and federal programs and guidelines, mitigation, incentives, funding mechanisms, public notification, education and involvement, enforcement and other elements that are essential to a successful riparian area protection program.

2. Assess alternative regulatory and nonregulatory strategies to protect riparian areas with an analysis of the fiscal, economic and environmental impacts associated with each alternative and consider whether the alternatives should vary based on different classes of landowners to address impacts on private property rights and the potential for multiple land use planning.

3. Evaluate the reports submitted pursuant to sections 3, 5 and 6 of this act.

4. Submit an interim report of the committee's findings under paragraphs 1 and 2 of this subsection to the governor, the president of the senate and the speaker of the house of representatives not later than July 1, 1994.

5. Based on the findings of the interim report and the identification, classification and mapping of riparian areas in this

state, prepare recommendations for proposed statutory provisions for a riparian area protection program in this state.

6. Submit a final report and recommendations with respect to the scope and parameters of any necessary regulatory program and additional statutory provisions that may be necessary to implement the recommendations to the governor, the president of the senate and the speaker of the house of representatives not later than December 1, 1994.

Sec. 8. Repeal

Section 7 of this act is repealed from and after December 31, 1994.

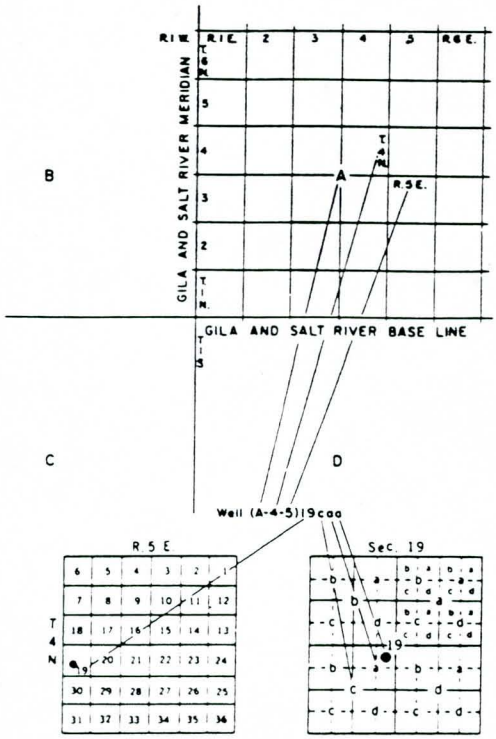
APPROVED BY THE GOVERNOR JULY 10, 1992.

FILED IN THE OFFICE OF THE SECRETARY OF STATE JULY 10, 1992.

APPENDIX B. WELL NUMBERING SYSTEM

Appendix B

Well Numbering System for Arizona (after USGS, 1992)



Well A(4-5)19caa

The numbers used to designate wells in this report are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the state into four quadrants. These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, and that south and east is in D quadrant. The first digit of a well number indicates the township, the second number indicates the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, 3 lower case letters are shown in the well number. In the example shown, well number (A-4-5)19caa designates the well as being in the NE1/4 NE1/4 SW1/4 of section 19, T. 4 N., R. 5 E. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

APPENDIX C. LIST OF ANALYTICAL METHODOLOGIES

List of Applicable Analytical Methods for determining Surface Water - Groundwater Interaction and Streamflow Depletion due to Withdrawals from Wells

This appendix provides a table of applicable methods that assess impacts of well pumping on the stream-aquifer system. This table has been reprinted from an internal ADWR report by Lizanic and others, 1988. The table presents generalized and special cases. The general cases are limited to the assumptions listed below. Special cases are where certain assumptions have been modified to meet a special condition such as an impervious boundary or a semi-impervious streambed. Special cases are applied and used when a specific field condition is known. Selected references have also been provided for additional information.

Main Assumptions:

1. The aquifer is homogenous and isotropic
2. The aquifer is of semi-infinite areal extent
3. Transmissibility of the aquifer is constant
4. Prior to pumping the water table and aquifer surface are nearly horizontal
5. The course of the river is idealized as a straight line
6. Groundwater is in free connection with the stream
7. Groundwater head at the stream does not change significantly because of pumping
8. The rate of well pumping is constant
9. Flow is predominantly horizontal
10. Water is released instantaneously from storage.

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Analytical Methods, A) Generalized Case

Method of Analysis References / Type	Type of Solution	Equations	Calculated Parameters
Theis (1941) Calculation	non-steady state	$P = \frac{2}{\pi}\int_0^{\pi/2} e^{-k\sec^2 u} du$	p - the ratio between the flux from the river and the pumped well.
Glover & Balmer (1954) Calculation	non-steady state	$\frac{q}{Q} = 1 - P(x_1\sqrt{4\alpha t})$	q/Q - the ratio between the flow taken from the river and the flow of the well.
Hantush (1959) Calculation & Tables	non-steady state	$S = \left(\frac{Q}{4\pi T}\right) M(u,\beta)$	S - the drawdown at any point in the vicinity of a well which is hydraulically connected to an infinitely long line of constant head.
Glover (1960) Calculations & Charts	non-steady state	$\frac{q_1}{Q} = 1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{x_1}{\sqrt{4\alpha t}}} e^{-u^2} du$	q_1/Q - Depletion of a stream by a pumped well (rate basis).
Glover (1960) continued	non-steady state	$\frac{\int_0^t q_1 dt}{Qt}$	- Depletion of a stream by a pumped well (volume basis).

Analytical Methods, A) Generalized Case

Method of Analysis References / Type	Type of Solution	Equations	Calculated Parameters
Theis & Conover (1963) Chart	non-steady state	$P = \frac{2}{\pi}\int_0^{\pi/2} e^{-k\sec^2 u}\,du$	Chart solving for P-the ratio between the flux from the river and the pumped well.
Jenkins (1968a, 1968b); Jenkins & Taylor (1972, 1974);	non-steady state	$sdf = a^2 S/T$	sdf, the stream depletion factor, is the time for a steady stress to affect the stream by a chosen percent of the accumulative stress.
		q/Q	q/Q - ratio of the rate of depletion of a stream (q) to the steady pumping rate (Q).
		v/Qt	v/Qt - ratio of the volume of stream depletion (v) to the volume pumped (Qt).
Glover (1977) Calculations	non-steady state	$f = 2KD\frac{\delta S}{\delta x} = \frac{Q}{\pi x_1}\frac{x_1^2 e^{-\left(\frac{x^2+z^2}{4at}\right)}}{(x_1^2+z^2)}$	f - the flow from the stream per unit length of the stream, as a result of pumping a well.

Analytical Methods, A) Generalized Case

Method of Analysis References / Type	Type of Solution	Equations	Calculated Parameters
	steady state	$\int_{-z}^{+z} f dz = \frac{Q}{\pi x_1} \int_{-z}^{+z} \frac{x_1^2 dz}{(x_1^2 + z^2)}$ $= \frac{2Q}{\pi} \arctan \frac{z}{x_1}$	$\int_{-z}^{+z} f dz$ - the flow coming from the river reach -z to +z.

Analytical Methods, B) Special Cases

Special Case Number - Main Assumptions	Methods of Analysis References-Type	Type of Solution	Equations	Calculated Parameters
Special Case 1: Semi-pervious Streambeds Main assumptions: Same as Generalized Case, except for assumption 6, which is now based on a semi-pervious streambed.	Hantush (1965) Calculations, Tables, Charts	non-steady state	$Q_r = Q[erfc(U) - exp[-U^2 + (U+\omega)^2] * erfc(U+\omega)]$ $V_r = Qt_o\{4/^2 erfc(U_o) + (1/\omega_o^2)[A]\}$ $[A] = [(Qa/Q) - 2\omega_o / erfc(U_o)]$	Qr - The rate of river depletion as a result of well pumpage, the streambed is semi-pervious. Vr - The volume of river depletion as a result of well pumpage, the streambed is semi-pervious.
Special Case 2: Discontinued Pumping Main assumptions: Same as Generalized Case, except for assumption 8, which is now based on discontinued pumping.	Jenkins 1968b Charts	non-steady state	$\frac{q}{Q}$ $\frac{vT}{Qa^2S}$	Curves to determine rate of stream depletion during and after pumping.

Analytical Methods, B) Special Cases

Special Case Number - Main Assumptions	Methods of Analysis References-Type	Type of Solution	Equations	Calculated Parameters
Special Case 3: Discontinuous Pumping Main assumptions: Same as Generalized Case, except for 8, which is now based on discontinuous pumping.	Jenkins 1968b Empirical	non-steady state	See charts and tables in reference	Jenkins concluded: The computed effects of intermittent pumping are compared to those of the steady rate. The comparisons indicate that within a large range of intermittency, the effects of intermittent pumping are approximately the same as those of steady, continuous pumping of the same volume.
Special Case 4: Right-angle stream bends Main assumptions: Same as Generalized Case, except for assumption 5, which is not based on right-angle stream bends.	Hantush 1967	non-steady state	See reference.	See Reference.
Special Case 5: Effects of a Regional Groundwater Gradient Main assumptions: Same as Generalized Case, except for assumption 4, now becomes a regional water table gradient.	Glover 1977 Tables and Calculations	non-steady state	$dq = \frac{4\alpha Q d\xi (x_1 - f(t-\xi) e^{-\left(\frac{(x_1 - f(t-\xi))^2}{4\alpha(t-\xi)}\right)}}{\sqrt{\pi}(4\alpha(t-\xi))^{3/2}}$	dq - Stream depletion at the time (t) due to removal or the volume of water $Qd\xi$ at the time ξ.

Analytical Methods, B) Special Cases

Special Case Number - Main Assumptions	Methods of Analysis References-Type	Type of Solution	Equations	Calculated Parameters
Special Case 6: Horizontal Leaky Water Table Aquifers Main assumptions: Same as Generalized Case except for assumption 1, which now becomes an isotropic and homogenous water table aquifer underlain by a confined aquifer with a semipermeable confining layer.	Hantush 1964 Calculations	non-steady state	$q_l = \left(\frac{Q}{2}\right)[M]$ *where:* $[M] = [M_1 + M_2]$ $M_1 = \exp\left(\frac{-x_o}{\beta}\right) erfc\left(U_o - \frac{(x_o/2\beta)}{U_o}\right)$ $M_2 = \exp\left(\frac{x_o}{\beta}\right) erfc\left(U_o + \frac{(x_o/2\beta)}{U_o}\right)$	q_l - The rate (q_l) of river depletion due to well pumping of a horizontal leaky water-table aquifer.
			$V_l = Qt\left(\frac{q_l}{Q}\right) + \left(\frac{U_o^2}{(x_o/\beta)}\right)(A - B)$	V_l - The volume of river depletion due to well pumping of a horizontal leaky water-table aquifer.

Analytical Methods, B) Special Cases

Special Case Number - Main Assumptions	Methods of Analysis References-Type	Type of Solution	Equations	Calculated Parameters
Special Case 6: (continued)			where: $A = \exp\left(\frac{x_o}{\beta}\right) erfc\left(U_o + \frac{(x_o/2\beta)}{U_o}\right)$ $B = \exp\left(\frac{-x_o}{\beta}\right) erfc\left(U_o - \frac{(x_o/2\beta)}{U_o}\right)$	

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APPENDIX D. Scientific and common names of Arizona riparian plant species referred to in report.

SCIENTIFIC NAME:	COMMON NAME:	FAMILY:
Abies concolor	White fir	Pinaceae
Acacia greggii	Catclaw Acacia	Leguminosae
Acer negundo	Box Elder	Aceraceae
Acer grandidentatum	Big Tooth Maple	Aceraceae
Allenrolfea occidentalis	Pickleweed	Chenopodiaceae
Alnus tenuifolia	Thin-leaf Alder	Betulaceae
Alnus oblongifolia	Arizona Alder	Betulaceae
Ambrosia ambrosoides	Canyon Ragweed	Compositae
Anemopsis californica	Yerba-Mansa	Sauruaceae
Aster coerulescens	Aster	Compositae
Atriplex canescens	Salt Bush	Chenopodiaceae
Atriplex torreyi	Torrey's saltbush	Chenopodiaceae
Atriplex polycarpa	All Scale Salt Bush	Chenopodiaceae
Atriplex lentiformis	Quail Bush	Chenopodiaceae
Baccharis salicifolia	Seep Willow	Compositae
Baccharis sarothroides	Desert Broom	Compositae
Berula erecta	Water Parsnip	Umbelliferae
Bromus rubens	Red Brome	Gramineae
Celtis reticulata	Net Leaf Hackberry	Ulmaceae
Cercidium floridum	Blue Palo Verde	Leguminosae
Chenopodium spp.	Pigweed	Chenopodiaceae
Chilopsis linearis	Desert Willow	Bignoniaceae
Chrysothamnus nauseosus	Rabbit Brush	Compositae
Cynodon dactylon	Bermuda Grass	Gramineae
Datura meteloides	Sacred Datura	Solanaceae
Distichlis spicata	Desert Saltgrass	Gramineae
Eleocharis rostellata	Spike Rush	Cyperaceae
Eleocharis spp.	Spike Rush	Cyperaceae
Equisetum laevigatum	Horsetail	Equisetaceae
Fraxinus pennsylvanica	Velvet Ash	Oleaceae
Hordeum leporinum	Wild Barley	Gramineae
Hymenoclea monogyra	Burro Brush	Compositae
Hymenoclea salsola	Cheesebush	Compositae
Ipomoea spp.	Morning Glory	Convolvulaceae
Isocoma tenuisecta	Burro Weed	Compositae
Juglans major	Arizona Walnut	Juglandaceae
Juncus mexicanus	Rush	Juncaceae

Leptochloa spp.	Sprangle-top	Gramineae
Lobelia cardinalis	Cardinal flower	Campanulaceae
Lycium spp.	Wolfberry	Solanaceae
Mimulus guttatus	Monkey Flower	Scrophulariaceae
Muhlenbergia rigens	Deer Grass	Gramineae
Olneya tesota	Desert Ironwood	Leguminosae
Paspalum distichum	Knot Grass	Gramineae
Passiflora spp.	Passion flower	Passifloaraceae
Phragmites australis	Reed	Gramineae
Phragmites communis	Bulrush	Gramineae
Pinus ponderosa	Ponderosa Pine	Pinaceae
Platanus wrightii	Arizona Sycamore	Plantanaceae
Poa pratensis	Kentucky Bluegrass	Gramineae
Populus angustifolia	Narrow-leaf Cottonwood	Salicaceae
Populus fremontii	Fremont Cottonwood	Salicaceae
Prosopis juliflora	Honey Mesquite	Leguminosae
Prosopis velutina	Velvet Mesquite	Leguminosae
Prosopis pubescens	Screwbean Mesquite	Leguminosae
Ranunculus macranthus	Large Buttercup	Ranunculaceae
Salix bonplandiana	Bonpland's Willow	Salicaceae
Salix exigua	Coyote Willow	Salicaceae
Salix gooddingii	Goodding Willow	Salicaceae
Sambucus mexicana	Mexican Elder	Caprifoliaceae
Sapindus saponaria	Western Soapberry	Sapindaceae
Sarcobatus vermiculatus	Grease Wood	Chenopodiaceae
Sarcostemma spp.	Milkweed	Asclepiadaceae
Scirpus americanus	Bulrush	Cyperaceae
Scirpus olneyi	Bulrush	Cyperaceae
Scirpus acutus	Great Bulrush	Cyperaceae
Senecio longilobus	Thread-leaf Groundsel	Compositae
Sorghum halapense	Johnson Grass	Gramineae
Sporobolus airoides	Alkali Sacaton	Gramineae
Sporobolus wrightii	Giant Sacaton	Gramineae
Suaeda torreyana	Desert Seepweed	Chenopodiaceae
Tamarix chinensis	Saltcedar	Tamaricaceae
Tessaria sericea	Arrowweed	Compositae
Typha domingensis	Tropical Cattail	Typhaceae
Zizyphus obtusifolia	Gray Thorn	Rhamnaceae