Appendix I.
Implications of Water and River Management for the Southwestern Willow Flycatcher: The Fluvial, Hydrologic, and Geomorphologic Context for Recovery

A. Introduction

The rivers of the Southwestern United States create and maintain most of the riparian habitat that hosts the remaining population of the endangered southwestern willow flycatcher (Figure 1). For breeding habitat the bird relies on riparian forests composed primarily of willow and tamarisk, an ecological niche that in turn depends on the operation of the region's rivers to provide a substrate of water and near-channel landforms. Any policy seeking to enhance the recovery of the southwestern willow flycatcher population must therefore take into account the geographic distribution, hydrologic behavior, and geomorphologic processes associated with the host rivers. The purpose of the following review is to identify the impacts that water management has had on the fluvial system of the region, outline the recent history of changes in hydrology and geomorphology, and provide recommendations for the recovery of the southwestern flycatcher population.

This review concerns hydrography, hydrology, and geomorphology. *Hydrography* is the science of measuring, describing, mapping, and explaining the distribution of surface water. *Hydrology* addresses the physical and chemical processes related to water in the environment, including precipitation, surface runoff, channel flow, and groundwater. The primary focus of any review of hydrology related to the southwestern willow flycatcher is on channel flow because of the preference by the bird for riparian (or stream-side) habitats, but the connections with other parts of the hydrologic system such as groundwater cannot be ignored. *Fluvial geomorphology* addresses river processes and forms related to earth materials and surfaces, particularly the sediment that is eroded, transported, and deposited by channel flow in streams and rivers. The geomorphic work of sediment erosion and deposition creates the landforms, surfaces, and soils that support the riparian forests critical for southwestern willow flycatcher survival. The ultimate fate of the bird population rests in large part on successful creation and management of these physical systems. No matter what other measures are employed to encourage the recovery of the population, none will be successful without insuring that the physical basis exists to support the appropriate habitat.

The southwestern willow flycatcher population depends on breeding habitat in the southwestern United States with particular characteristics (Marshall, 1995). The birds prefer riparian forests with a dense understory of shrub-like vegetation where they typically construct their nests, with a more open canopy of larger trees, all situated near still or slow-moving open water. Commonly, the dense understory consists of willow (*Salix* sp.), seep-willow *(Baccharis sp.)*, arrowweed (*Pluchea* sp.), tamarisk (*Tamarix* sp.), or Russian olive (*Eleagnus* sp.). The scattered overstory often consists of cottonwood (*Populus* sp.). Flycatchers are most abundant in these habitats when they are located adjacent to slack water,

also known as lentic water. These riparian habitats were once much more common and spatially continuous, but human intervention in the southwestern river systems has now produced a geography of willow flycatcher habitat that is widely scattered, with small linear patches separated by dryland conditions. This habitat is the product of particular hydrologic and geomorphic conditions that are the subject of this appendix. The following sections of the appendix begin by establishing the general large-scale geographic framework of the issue of southwestern willow flycatcher recovery by describing the region's watersheds and river basins. Next, this appendix describes how humans have altered the hydrologic and geomorphic components of rivers through water and land management. A final section offers recommendations for management of water and water-related resources to enhance the probability of success for southwestern willow flycatcher recovery.

B. Fluvial Systems Components of Flycatcher Habitat

The hydrography of the Southwestern rivers is a geography of watersheds and water courses created by the interaction of the regional geologic and climatic systems. These systems form the physical foundation of the habitat for the southwestern willow flycatcher. Annual precipitation exceeds 50 cm (20 in) only in coastal California or at higher elevations in the interior mountains and high plateaus. California coastal streams have enough precipitation in their headwaters to maintain perennial flow in most of their lengths, potentially supporting southwestern willow flycatcher habitat. In the interior, the arrangement of high terrain with intervening lowlands creates a river system with dichotomous characteristics. The small streams of the region are either at higher elevations and are perennial, or they are ephemeral lowland channels without southwestern willow flycatcher habitat.

The large rivers of the region, the Green, Colorado, San Juan, Little Colorado, Gila, and Rio Grande, accumulate water in their headwaters areas and loose water in their low elevation watercourses (Figure 2). This reflects the elevational and geomorphic forces on in-channel water balance factors. The net water balance in the channel goes from positive (or gaining) in the headwaters to negative (losing) in the lowlands. Natural factors that affect the balance include precipitation, evaporation, transpiration, and groundwater dynamics. The consequences of removal vary over the elevational/temporal gradient. For example, the withdrawal of water from lowland streams for agricultural, industrial, and urban uses causes depletions that are not replaced by natural runoff and the remaining water is lost to evaporation and groundwater recharge. On the other hand, a river's discharge may still increase downstream of the point of water removed from high elevation, water-source areas due to runoff, subsurface seepage, and precipitation. Southwestern willow flycatcher habitat occurs mostly in water deficit areas of the region. Intermediate scale streams such as the Virgin, Escalante, upper portions of the Little Colorado, and San Pedro have mostly perennial flow and support some willow flycatcher habitat, the habitat is of lesser extent than that found in association with the large regional streams.

C. River Basins and Watersheds

Because the southwestern willow flycatcher is a riparian bird, its population depends directly on water and water-related resources. From the standpoint of resources related to water, the American Southwest divides itself into watersheds which serve as obvious regions for analysis, decision-making, and management. Watersheds are drainage basins, portions of the surface that collect runoff from the surface, concentrate it into channels, and conduct the resulting flow to a definable outlet. Large watersheds are aggregations of smaller watersheds, producing a natural hierarchy. By conventional usage, the term watershed refers to a smaller drainage basin, while the term river basin refers to a larger one, but there are no specific definitions to separate the two. Watershed concepts are those analytic and management principles whose application relates directly to a geographic region defined by a drainage basin. Recent reviews of water-related resource management by the National Academy of Sciences (National Research Council 1999) and by a Presidential commission on western water (Western Water Policy Review Advisory Commission 1998) recommend watersheds as the spatial framework for planning and management of water and water-related resources.

Watershed boundaries are porous, in the sense that artificial transfers of water between watersheds are common, so that planning and management considerations may extend beyond the physical watershed boundaries. Examples include the export of water from the Lower Colorado River Basin to California, and the transfer of water from the Upper Colorado River Basin to the Rio Grande. Because of the importance of water and riparian environments to the recovery of the southwestern willow flycatcher population, planning and management for the opportunities and threats to the species should use watersheds as a geographic framework.

Definition of the watersheds and river basins of the Southwest is standardized among federal and state agencies by the National Water Resources Council and the U.S. Geological Survey who have created a series of watershed outlines (U.S. Water Resources Council 1978). It is therefore logical that a southwestern willow flycatcher recovery plan use the same definitions to facilitate interagency communication. This standard approach uses a hierarchical series of numbered hydrologic units, with each unit being a watershed or collection of watersheds (Seaber et al. 1987). The identification numbers, called hydrologic unit codes, use two digits for the largest divisions or regions, four digits for subdivisions, and six or eight digits for still finer subdivisions. The largest divisions in the classification system are 21 *water resource regions*, with each one containing either an entire river basin or a series of closely related basins, each identified with a two digit hydrologic code. The regions containing southwestern willow flycatcher habitat are the Rio Grande (region number 13), Upper Colorado River (14), Lower Colorado River (15), Great Basin (16), and California (18), with a total area of 1,738, 950 km^2 (671,410 mi^2). Table 1 summarizes the watershed regions, their hydrologic characteristics, dams, and human populations; Figure 3 provides a map of their extent. Although the California region extends into northern California areas not inhabited by the southwestern will flycatcher, the entire region is involved because of engineered water transfer facilities that connect the northern to the southern parts of the region.

The creators of the hydrologic unit code subdivided the water resource regions into *planning subregions*, designated with 4-digit code numbers; 6-digit code numbers identify the members of a still finer subdivision consisting of *accounting units*. The accounting units are aggregates of the smallest subdivisions, or *cataloging units*, identified by 8-digit

code numbers. The 21 water resource regions of the nation contain 2,150 of these smallest units, which have an average drainage area of about 1,750 km^2 (700 mi^2). For the purposes of the southwestern willow flycatcher recovery plan, the most useful scale of analysis is the accounting unit, or 6-digit coded watersheds. In Arizona, for example, this implies that watersheds such as the Verde River Basin, Salt River Basin, and San Pedro River Basin represent the most convenient scale (Figure 3).

D. Stream Channels

Runoff within watersheds and drainage basins concentrates into channels and creates the distinctive streams and rivers of the Southwest with their associated willow flycatcher habitat. Streams begin flowing at higher elevations and flow to lower elevations. Generally, the gradients of watercourses are relatively high near the source areas and decline to nearly level at lower elevations. Variations in geology, artificial structures, and even beaver dams produce localized reaches of exceptionally steep or shallow gradient. The high elevation, steeper gradient regions are the primary source areas for water, but they are also the primary source area for alluvium (substrate particles that typify flowing waters). In addition to their roles in delivering water and alluvium to the channel, steeper areas tend to be transport zones where water and particles move quickly downstream. Because of their gradient and stream power, these rivers tend to flow through narrow, incised channels and valleys with little storage of alluvium. The lower elevation and lower gradient areas are usually storage zones for water and alluvium, as indicated by flood plains that typify the larger, low elevation systems.

The spatial distribution of southwestern willow flycatcher habitat is a reflection of these dynamics. Relative to upland areas, riparian areas are usually richer and of greater areal extent where the substrate is comprised largely of inorganic alluvium, subject to flooding, and with high soil moisture and shallow groundwater. Thus, southwestern willow flycatcher habitat was naturally very limited along high gradient, high elevation watercourses that flow through canyons. At higher elevations, the bird was probably reasonably common in topographic situations that resulted in low gradients such as mountain meadows. The bird was probably very abundant and optimal in low elevation zones with broad flood plains. In the low elevation areas, habitat quality probably was suboptimal where water levels remained stabile and the substrate was highly organic (including cattail or tule marshes) because of the anaerobic conditions within the shallow root zone.

In the low elevation, low gradient rivers of this region, the temporal and spatial variability of runoff results in three common types of river channels: single-thread, braided, and compound. Each channel type has particular dynamics and spatial arrangements, and each supports a different arrangement for willow flycatcher habitat. *Single-thread channels* contain their flows between well defined banks, and may have planimetric configurations ranging from relatively straight to meandering. They usually result from hydrologic regimes that have only modest fluctuations of flow. The channels conduct flows of low magnitude, but those flows that are so large that they occur only once every few years exceed the channel capacity, and spill onto the adjacent flood plain. Flood plains are relatively flat surfaces, located next to the channel and outside the channel banks, and consist of sediments that are active in the present regime of the river (that is, they are mobilized at least once every few years). Dense riparian forests occupy the flood plain when they are undisturbed by direct human activities. Relative to those of thee other channel types, the riparian forests although patchy are relatively

continuous.. When composed of an appropriate assemblage of plant species and when located adjacent to open water, these forests can provide suitable willow flycatcher habitat. The flowing (lotic) water of the channel is sometimes augmented by slack (lentic) water in abandoned channels on the flood plain surface, usually the abandoned meanders (or oxbows) of the single-thread channel. Typical, large-scale examples of single-thread channels are the Lower Colorado River near Yuma and the Rio Grande downstream from Albuquerque, cases where controlled flows and levees have produced a single-thread channel. Natural examples of single thread channels include Aravaipa Creek in southern Arizona and many small coastal California streams.

Braided channels consist of a broad flow zone delimited at the edges by low but well defined banks. Between these banks are several channel threads intertwined among each other, with numerous mid-channel islands and bars. Occasionally, braided channels in the Southwest have flood plains which behave similarly to the flood plains of single-thread channels. In cases where braided streams occur without flood plains, their banks divide the channel from adjacent terraces, surfaces that do not experience flows during the present hydrologic regime of the river. Braided channels commonly result from highly variable flow regimes, channels with weakly consolidated bank materials, and/or watercourses with very heavy sediment loads. The islands and bars experience less overflow than other areas associated with many braided channels, and they tend to be the locations for willow flycatcher habitat, along with narrow ribbons of riparian vegetation on the banks. Unlike the flood plain forests, braided channels are unstable, and as floods rearrange the subchannels, islands, and bars, riparian forests change and are characterized by patchy vegetation with many inherent gaps.

Many lowland rivers of the Southwest were braided streams before human controls altered their flows, and under these conditions they hosted southwestern willow flycatcher populations. Historical accounts of streams ranging from the Los Angeles River to the San Juan River in southwestern Colorado describe such conditions for the pre-development era (*e.g.*, Kino 1919, Griffin 1943). In the Los Angeles River and the general Los Angeles Basin, for example, the wide-spread existence of wetlands associated with the low-gradient coastal rivers produced substantial southwestern willow flycatcher habitat. Willett (1912) reported willow flycatchers in the Los Angeles and Pasadena areas, and indicated that they were common in riparian areas. Egg collections at the Western Foundation of Vertebrate Zoology include 44 clutches collected in the period 1901-1910 in Los Angeles County alone. The specific sites included water courses in Los Angeles, Pasadena, and along the San Gabriel River in Cerritos and Artesia. Unitt (1987) reported 67 egg sets were collected in the Los Angeles basin before 1940. Subsequent urbanization with its attending channelization and changes in riparian land use decimated the southwestern willow flycatcher habitat in the basin.

Although single-thread and braided channels are archetype morphologies for rivers, southwestern streams most commonly are of a third, hybrid type. The *compound channel* has the characteristics of both single- and multiple-thread arrangements (Gregory and Park 1974, Richards 1982, Graf 1988). At the lowest point of the cross section of a compound channel is the low flow channel, which conducts the usual low flow of the system either from natural sources or from low flows released by dams. Outside the banks of this low flow channel lie the braided channels, islands, and bars of the high flow system. This high flow portion is occupied by water only during the once in ten- or twenty- year flood under natural conditions, or by the rare spill or uncontrolled flow from dams. Beyond the banks of this high flow channel lies the terrace

that is not active in the present regime of the river. There usually is no flood plain in the normal sense of the term in this compound system. Southwestern willow flycatcher habitat occurs in the form of threads of riparian vegetation along the banks of the low flow channel, and if the watertable is high enough, dense forests may also occur within the high flow, braided portion of the channel. With the physical processes that form the compound channel being intermediate between those that drive single-thread and braided channels, the riparian vegetation is similarly intermediate. It is arranged as somewhat patchy with moderate levels of connection. Compound channels are common in the Southwest under present conditions, exemplified by the Salt and Gila Rivers in Arizona and many southern California streams. The Hassayampa, Santa Cruz, and San Pedro rivers are smaller inland examples.

E. Flow Regimes: Water Quantity and Patterns of Water Flow

Six components of flow regimes, amplitude, magnitude, frequency, duration, timing, and rate of change of hydrologic conditions, strongly influence the structure and function of riparian ecosystems (Poff et al. 1997). With respect to magnitude, for example, the width of riparian vegetation communities and their biomass increases with mean and median annual flow volume and drainage size in alluvial river channels (Stromberg 1993). Low flows and peak flows are of particular importance to regeneration and maintenance of southwestern willow flycatcher habitat in the arid Southwest. With insufficient low flows or extended loss of surface flow in the summer dry season, alluvial ground water levels decline. These changes can result in mortality of the shallow-rooted native trees and shrubs in which the willow flycatchers nest and cause a narrowing or contraction of the riparian corridor. Extensive research on cottonwood species, and to a lesser extent on willows and tamarisk, has defined the threshold values for depth to water table and water level recession rates that seedling and adult plants can tolerate. Smaller reductions in stream flow or ground water levels can cause plants to undergo physiological stress and lose productivity, with possible adverse implications for the southwestern willow flycatcher habitat. Even short-term loss of surface flows may reduce bioproductivity and habitat quality by stressing those insects with aquatic larval forms, a portion of the southwestern willow flycatchers food base.

Flooding is characterized by amplitude (difference between minimum and maximum flows in a given period), timing, magnitude, frequency and duration. Floods are the primary natural disturbance in riparian ecosystems (Poff et al. 1997). Floods exert important physical and biological controls on riparian zones. They inundate and moisten flood plain soils, raise water tables and recharge aquifers, mobilize and deposit sediment of various textures on flood plains that creates a seed beds for riparian plants, flush salts and redistribute nutrients, cause river channels to relocate and/or meander, create abandoned channels and backwater depressions, disperse and scarify plant propagules, scour and relocate vegetation, and deposit organic materials that have higher water-holding capacity than the inorganic materials in the substrate. These flood-driven fluvial processes maintain high species diversity, bioproductivity, and habitat complexity in riparian ecosystems.

The forces controlling the timing of floods large enough to destroy southwestern willow flycatcher habitat operate at regional and local scales. At the regional scale, these destructive floods result from global and sub-global atmospheric circulation patterns that deliver moisture from warm ocean surfaces to the continental areas by way of decaying tropical storms and major frontal systems in mid- or late winter. Extensive regional flooding results in these cases, as happened in

1941, 1978, or 1993, with widespread lose of riparian habitat. In the intervening years, the habitat recovers and regrows. On the time scale of decades to a century, therefore, it is reasonable to expect regional changes in the amount of available riparian habitat for southwestern willow flycatchers regardless of human-induced changes. Local flooding results from conditions connected to local thunderstorms in summer months which affect a single or a few watersheds. In these instances, loss of riparian habitat is small compared to the large regional events, but at the end of the twentieth century there are so few active southwestern willow flycatcher sites that even these events affecting limited areas may be important for the bird population.

Many of the riparian plant species in the Southwest such as Goodding willow are pioneer species that depend on periodic winter and spring flood disturbance for regeneration. Other species in the plant community regenerate in response to periodic summer floods. With respect to magnitude, the infrequent but very large floods reset the successional clock and rejuvenate large stands of the riparian forests upon which southwestern willow flycatchers depend. Smaller floods that inundate but do not destroy the forests help to maintain a diversity of understory and herbaceous plant species that may play important roles in maintaining the food base of the flycatcher.

Most of the human population of the Southwest views the water flowing through the river systems as a commodity with specific legal and economic attributes. From a fluvial hydrology and geomorphology perspective, as well as from the standpoint of southwestern willow flycatcher habitat, the water is a vital landscape component, not a separate commodity. Any attempt to utilize water to improve conditions for the flycatcher population, however, must take into account the legal and economic aspects of water. River flows in the Southwest are appropriated, meaning that individuals, corporations, and government entities own the rights to withdraw and use the water within a specific set of allocations and priorities. These rights may be bought and sold, offering the opportunity in some cases for purchase of water for use by wildlife. However, purchase of water rights for the flycatcher population has been limited and will likely continue to be insufficient to maintain or recover southwestern willow flycatchers. Instead, they have and will likely continue to rely on the existing (or highly similar) arrangement of water flows and rights.

The restoration of habitat for the willow flycatcher along channels throughout much of the Southwest can introduce reclaimed riparian landscapes that will benefit the flycatcher population. However, this restored landscape will not be the original natural landscape that existed prior to the advent of modern technological river controls. Two types of changes altered that original landscape: 1) reduction of downstream flows caused the active part of the channel and its associated landforms to shrink in their overall areas, and 2) a variety of influences resulted in substantial simplification of the remaining landscapes and habitats. These influences include the storage of sediment behind upstream dams, channelization, dredging, construction on banks, levee building, and urbanization. Because it is unlikely that all of these forces will be removed, restoration of flycatcher habitat will produce a viable habitat area, but one that is smaller than the original habitat. Because it will be smaller than the original habitat, this restored habitat does not require a return to the original hydrologic regime, but rather needs only modest flood events. Complexity of the habitat also will be on a smaller scale, but landscape variety can be introduced within the limited restored area.

The cost of water varies throughout the region, depending on the value of the end use, the availability of water, and

the expense of transporting it from source to use. Individual cases in limited areas have wide ranges in the value of water. Agricultural users in areas supplied by the Salt River Project in central Arizona, for example, may pay as little as $15 per acre foot, while some water used for fishing and whitewater boating in the Rio Grande has a value of $1,615 per acre foot (Frederick et al. 1995). In the Southwest, the highest single example for marginal values is $2,642 for fishing in the Lower Colorado Basin. Another indicator of economic value is marginal price, the cost to develop additional water supplies and deliver them to the user. Marginal costs are low where facilities are well developed and water is relatively plentiful, and high where water is scarce or where the available supply is fully developed. Marginal costs for the river basins of the Southwest include $191 per acre foot in the Rio Grande basin, the highest regional value in the nation. Marginal costs for other basins in the region are $122 in the Lower Colorado basin, $51 in California, $38 in the Great Basin, and $32 in the Upper Colorado basin.

Water rights, delivery contracts, legal commitments to power generation, and requirements for flood control are among the common constraints on making changes to the distribution of water in southwestern rivers and the management of dams and reservoirs. In the Colorado system, the "Law of the River" is the collection of international treaties, interstate compacts, court decrees, laws, rules, regulations and policies that govern the management, allocation and distribution of Colorado River water. Similar arrangements exist on all large rivers of the region that potentially provide southwestern willow flycatcher habitat, including coastal streams in California, the Rio Grande, and the Gila. However, there is some flexibility in these management systems, including the timing of some releases, storage locations, "bucket-for-bucket" transfers, and the handling and distribution of excess water, the amount that occasionally flows through the system in amounts greater than the allocations. Innovative use of this management flexibility and flood control releases can aid the recovery of the southwestern willow flycatcher without disrupting established legal commitments for water. In some cases, water purchases or modifications of legal arrangements might be negotiated.

F. Water-Related Activities that Impact Flycatcher Habitat

Human activities have introduced numerous modifications to the hydrography of southwestern rivers, so that the resulting hydrology and geomorphology are partly natural and partly artificial. These modifications included dams, diversion structures, canals, groundwater management, waste and tail water discharges, channelization, and levees.

1. Dams

Dams are the most pervasive and significant changes because they are ubiquitous and have radically altered the flows of water, energy, and sediment throughout the region. The five water resource regions of interest for the recovery of the southwestern willow flycatcher include 4,659 dams (U.S. Army Corps of Engineers 1996; structures are generally those 2 m or 6 ft high or higher, or those with reservoirs of 18,000 m^3 or 15 ac ft or more). Most of these structures are small but in the aggregate in local basins they are significant. A few very large ones exert substantial control with far-reaching consequences for hydrology and geomorphology of the region's rivers (Graf, 1999). Dams in the Rio Grande Basin, for example, can store an amount of water equal to almost 4 times the mean annual runoff (Table 1). These structures provide

societal benefits including urban water supply, irrigation, hydroelectric power, flood control, and recreation, but also cause environmentally costly changes in fluvial environments that include adjustments in potential habitat for the southwestern willow flycatcher. Important changes brought about by dams include upstream impacts related to reservoirs and downstream impacts related to controlled flows, sediment dynamics, water quality, and water temperature (Collier et al. 1997).

The impoundment of water and sediment upstream from dams causes changes in the fluvial hydrology and geomorphology because of inundation and the change in stream gradient as the streamflow enters the reservoir area. Those channels and near-channel surfaces that are in the reservoir area are drowned, either permanently or periodically, so that the habitat associated with them is lost. The shoreline of the newly formed reservoir may create new habitats where none existed previously. The headward-most portion of the reservoir, where the stream enters the lake formed by the dam, is a dynamic zone where deposition of sediment creates a delta because the lake area reduces the energy gradient of the flow. Flow velocity and stream power decline, with associated deposition of sediments that previously were carried by the stream. If the reservoir level fluctuates, the location of this delta building process also changes. If the reservoir level rises, the location of the deposition shifts upstream, and if the reservoir level declines, the location of deposition shifts downstream.

The delta surface is often the most important potential area for southwestern willow flycatcher habitat, because it offers moist sand deposits suitable for willow or tamarisk growth, and the associated lake surface offers slack water nearby. During the 1990s, southwestern willow flycatcher habitat of this type existed at the headwaters of Lake Mead behind Hoover Dam on the Colorado River; Lake Isabella on the Kern River in California; and Lake Roosevelt behind Roosevelt Dam on the Salt River, Arizona. This habitat situation is unstable, however, because it depends on a relatively unchanging lake level. Hydro-climatic variability that change inflow to the reservoir, and dam operations that change its outflow produce fluctuations in lake level, location of the delta deposition, and changes in the vegetation communities on the delta surfaces. If lake levels are stable for 3 to 5 years, substantial riparian vegetation may develop, only to be destroyed by changes in lake elevation. If the new levels remain relatively unchanging (that is, water levels do not fluctuate more than about 20 feet) for another 3 to 5 years, new deposition and vegetation growth will develop in the new location. Because of these adjustments, any specific southwestern willow flycatcher habitats at the headwaters areas of large reservoirs are temporary, but over a period of decades it is likely that some such habitat will be present temporarily at some location for many large reservoirs.

The downstream impacts of dams and their operations include depletion of sediment which is trapped in reservoirs, and several adjustments to fluvial hydrology including reduced total annual flow, reduced annual flood peaks, changes in low flows, changes in the timing of high and low flows, and altered short-term fluctuations (Figure 4). All these adjustments in river mechanics result in changes in the downstream geomorphology of channels and near-channel landforms, with accompanying changes in the potential to support vegetation communities favored by southwestern willow flycatchers. The changes in sediment flux downstream from dams is especially important because the relatively sediment-free water released by the dams erodes mid-channel bars, channel-side bars (or attachment bars), beaches, and flood plains, all important substrates for southwestern willow flycatcher habitat. Because sediment from upstream is trapped behind the dams, eroded

features downstream are not replenished. At further distances downstream, where tributaries deliver sediment to the dammed watercourse. However, without a flood hydrology, the sediments may continue to accumulate to a point where the riparian vegetation potential is altered. The increase in sediment may convert a reach from a single-thread to a braided channel, and may lower the depth from the grounds surface to the water table.

The specific hydrologic changes downstream from a particular dam depend on the inflows to the reservoir, the engineering characteristics of the dam, and its operating rules (Figure 4). For example, if the dam is primarily a diversion structure, it will drastically reduce the normal flows downstream, and at some distance downstream often to the point of near desiccation and loss of most riparian vegetation. On the other hand, a dam that is primarily for hydroelectric power will pass through to downstream areas an amount of water that is similar to the pre-dam amount. However, the delivery will be in a highly altered schedule determined by power grid demands, often with substantial daily river flow fluctuations that previously did not exist and may approach the amplitude of flows only seen over annual cycles. Table 2 summarizes common hydrologic changes downstream from dams of various types. Very large dams on major rivers are multi-purpose, and their operating rules represent an optimization strategy (including storage of water, generation of electrical energy, enhancing recreation opportunities, and flood control) that produces mixed results for river flows downstream.

Uncontrolled flows from dams cause instability and changes in willow flycatcher habitat in the impacted streams of the Southwest when the channels shrunken by levees and/or a response to the damming cannot contain the large floods. Riparian forests developed in compound channels are often partially or completely destroyed by uncontrolled or exceptionally high flows, but the forests redevelop on the surfaces abandoned by flood waters when flows return to normal.

Dams also alter water quality. Salinity increases can be very high in the downstream reaches of dams or intensive agricultural areas, as in the lower Colorado River. Generally, according to the U. S. Environmental Protection Agency, the primary sources of salinity are irrigation water and reservoir evaporation (Briggs and Cornelius 1998). In the lower Colorado River, these sources contribute 50% of the salinity. Salinity increases can be biologically significant. Most native willows and cottonwoods are relatively intolerant of salt (Jackson et al. 1990, Shafroth et al. 1995). Germination rate of Goodding willow declines continuously with salt content, falling to less than 50% germination at values above 100 meq/l of sodium chloride (Siegel and Brock 1990). Tamarisk germination, in contrast, increases with salinity. Dams also eliminate the floods that otherwise would flush salts from flood plains.

Levels of nutrients can be reduced downstream from dams. Phosphorous typically adheres to clays and silts and thus tends to decline in below-dam systems as the fine sediments are deposited in the reservoir. Nitrogen levels can remain high if nitrogen-fixing plants such as mesquite remain abundant. Effects of nutrient reductions or changes in nitrogen-to-phosphorous ratios on quality of southwestern willow flycatcher habitat are unknown.

Water temperature regimes downstream from dams are often substantially modified from pre-dam conditions. Solar energy is stored in the surface waters of reservoirs and deeper waters remain cold. Most dams withdraw water from the hypolimnion, the cold, deep water below the thermocline, a sharp temperature boundary in the vertical stratification of many reservoirs. As long as storage is adequate to keep the withdrawal levels below the thermocline, the dam releases cold water. The distance downstream that the dam influences the water temperature varies based largely on water velocity, its

turbulence, channel velocity, and air temperature. The cooler water temperature modifies microclimates in riparian zones and alters the aquatic invertebrate base which forms the flycatcher's food base. When a reservoir's withdrawal level coincides with the thermocline and the epilimnion (the warmer waters above the thermocline), downstream water temperature rapidly and dramatically increases. The result is severe stress on the aquatic communities.

Stratification of reservoirs poses other consequences to downstream river reaches. At depths, there is often intense biological oxygen demand that results from the decomposition of incoming organic material and the "rain" of surface-water algae. It is amplified by the lack of turnover with oxygenated waters. As a result, deep waters often are very anaerobic and of low pH and many ions are reduced to forms inhospitable to aquatic life. When water is discharged from that reservoir level, downstream impacts on the aquatic community can be severe until the flowing water oxygenates.

The hydrologic and geomorphologic effects of dams in the Southwest have only recently become apparent, partly because of increased interest in environmental quality and changes, but also partly because of the relative recency of dam closures in the region. The impacts of dams on southwestern willow flycatcher habitat is also relatively recent, becoming apparent only within the past two or three decades. The three major river basins in the region, however, have somewhat different histories in the development of their cumulative reservoir storage, a general measure of the impacts of dams on the regional hydrology (Figure 5). The greater the reservoir storage in a basin, the greater the impact on hydrologic systems, including those upon which the southwestern willow flycatcher depends. In the case of the Rio Grande, reservoir storage has increased gradually over the past century. Closure of flood control structures during the 1960s represented the most significant additions to the storage system. In the combined Upper and Lower Colorado River basins, the completion of two large structures, Hoover Dam in 1936 and Glen Canyon Dam in 1963, dominate the history of reservoir storage. After the early 1960s, dams had their most significant influence on the basin hydrology, geomorphology, and riparian ecology in the Lower Colorado River. Significantly, riparian bird populations appear to have begun their decline in the Lower Colorado in the 1960s and thereafter (Rosenberg et al. 1991). In California, rapid increases in storage associated with federal, state, and local water projects dramatically increased the total storage between about 1955 and the late 1960s. Therefore, taken together, the major basins of the Southwest experienced their most important increases in reservoir storage and artificial hydrologic adjustments in the decade of the 1960s.

The effects of dams on riparian ecosystems vary widely depending on many factors, including the nature of the dam management and the fluvial geomorphic setting. If accompanied by extensive water diversion that eliminate water from the channel, such as the Salt River below Granite Reef Diversion Dam near Phoenix or the Gila River below Ashurst-Hayden Dam near Florence, the downstream riparian vegetation inevitably is lost, reduced in area, or replaced by more xeric vegetation. In cases where base flows are unchanged or increased, and the magnitude and/or frequency of large scouring floods is decreased, the channel often narrows while riparian vegetation increases (Williams and Wolman 1984). This increase in vegetation is a result of high water tables and lack of destructive floods, and is particularly evident on braided rivers (Friedman et al. 1998) or in canyons downstream from dams. Moderation of peak flows may be responsible for increased vegetation cover on river sections such as the middle Gila below Coolidge Dam between Hayden and Kelvin (Graf 1982). Along the undiverted Bill Williams River, where summer base flows have increased and the natural cycle of

flood scour and pioneer plant recolonization has been disrupted by Alamo Dam, the flood plain presently supports more extensive vegetation than it would were the dam not present (Shafroth, 1999).

Due to the many changes that accompany dam construction and management, the quality and structure of the post-dam vegetation often differs substantially from the pre-dam state. Compositional changes include a simplification of the flora, an increase in exotic species, a loss of native species, shifts from pioneer to later successional vegetation and older individuals, closing in towards the narrowing channel, and shifts from hydric to xeric species. Along the Bill Williams River, as well as along the Gila River and Upper Colorado, most of the 'added' vegetation is composed of exotic tamarisk. Tamarisk is reproductively opportunistic, has high water-use efficiency and deep roots, and is tolerant of drought and salinity (Busch and Smith 1995, Smith et al. 1998). Thus, tamarisk has a competitive advantage over cottonwoods and willows on regulated rivers subject to altered seasonal timing of regeneration floods, reduced stream flows and overbank floods, lowered water tables, and increased salinities. Increase in tamarisk abundance, together with a general increase in live and dead plant biomass, sets the river up for a shift from a flood-disturbance system to a fire-disturbance system, with implications for southwestern willow flycatcher habitat quality.

Dams have played a role in the decline of riparian cottonwood and willow forests throughout the western United States (Rood and Mahoney 1990). This decline is attributed to many factors: reduced rates of sediment deposition and increased rates of scour, reduced river meandering and channel realignment reduce availability of the "nursery bars" needed for seed germination, reduced frequency and size of winter and spring flooding reduces establishment rate of these spring-germinating species, more rapid declines in stream flows on the receding limbs of flood hydrographs cause seedlings to die, and reduced flows of water stresses and sometimes kills very young and very old trees in particular, as do increases in salinity (Braatne et al. 1997).

2. Diversion Structures

Diversion structures are low dams designed to divert river flows into the headings of canals and their distribution systems. Unlike other dams, diversion structures do not primarily store water. They are run-of-the-river dams; that is, they can not control the downstream discharge during medium or high flows and do not significantly reduce flood peaks. Neither do they redistribute downstream flows according to a release schedule. During low flow conditions, however, diversion works usually divert some or all of the flow from the river, so that downstream reaches of the river are desiccated. The result is the loss of riparian vegetation and potential southwestern willow flycatcher habitat downstream from such structures. The reaches upstream from diversion works may offer opportunities for southwestern willow flycatcher habitat because these are typically reaches with sedimentation and associated islands, bars, beaches, and banks suitable for willow or tamarisk and other riparian trees. There is usually also some slack water nearby created by ponding of water before it flows through canal headings at the diversion structure.

Perhaps the most dramatic case of diversion of surface flow, and ultimate restoration of flow to an arid region stream, involves Mono Lake and its tributary streams in the Sierra Nevada of California. While outside the range of the southwestern willow flycatcher, the case is nonetheless instructive in considering water management options for the

recovery of the bird elsewhere. After a ramp-up in the rate of stream diversion by the City of Los Angeles, the riparian forests along some of the diverted tributary streams underwent a massive die-off and the level of Mono Lake declined. Invoking the Public Trust Doctrine, the California Supreme Court ultimately ruled that the ecosystems on federal lands had high value to the public and required the city of Los Angeles to restore flows to the diverted stream channels (Wiens et al. 1993). Flows are now being released from the diversion dam at sufficient quantity to maintain the base flows and shallow water tables required by the cottonwood-willow forests (Los Angeles Department of Water and Power 1995). Los Angeles since has been pursuing alternative and creative measures to attain municipal water. For example, in return for expending the money to increase the efficiency of agricultural irrigation techniques such as laser-leveled fields, the city obtains the water 'salvaged' as a result of the increased efficiency.

Stream diversions sometimes have more subtle ecological effects. In central Arizona, for example, mid-summer diversions for agricultural use sharply reduce the base flows in the free-flowing Verde River. Although the Verde River still supports cottonwood-willow forests, the seasonal dewatering may be exerting subtle effects on southwestern willow flycatcher habitat quality by causing physiological stress in the trees and variously reducing bioproductivity rates, plant cover and density, and age class diversity (Smith et al. 1991).

3. Canals

Once diversion works direct water out of river channels, canals and lateral distribution ditches conduct it to fields or urban treatment plants. These canals often offer the potential for southwestern willow flycatcher habitat because they have slow moving flows by design, and if their beds and banks are not completely sealed, seepage from them supports canal-side vegetation. These strips of vegetation and associated artificial water courses provide southwestern willow flycatcher habitat in the Upper Gila River Valley near Cliff, New Mexico. In many areas, managers remove the canal-side vegetation to improve flow efficiency or eliminate evapotranspirational water loss. Alternately, canals that are lined with impervious materials to prevent seepage and eliminate substrate for riparian vegetation growth. Removal or prevention of riparian shrubs and trees reduces the amount of potential flycatcher habitat. Where seepage from canals supports recharge to other water bodies, its control can diminish the amount or quality of potential habitat.

4. Wastewater and Tail Water Discharges

Stream reaches desiccated by diversions receive water inflows downstream from the diversion points through the return of some flow via wastewater or tail water discharges. Wastewater from urban treatment plants sustain continuous flows below the outfall points for the plants, often creating compound channels with enough water on and near the surface to provide for riparian forests potentially suitable for southwestern willow flycatcher habitat. An example of this arrangement is Las Vegas Wash, downstream from the city of Las Vegas, where wastewater discharges sustain an extensive area of tamarisk and other riparian species that host a southwestern willow flycatcher population. Along other rivers, cottonwood-willow forests have developed as an unintended consequence of return of treated municipal wastewater to dry river channels (Stromberg et al. 1993). If untreated or inadequately treated, urban return flows can be of reduced water quality,

threatening to flycatcher food quality and quantity.

Two reaches of the Santa Cruz River in southern Arizona exemplify contrasting consequences of releasing effluent into channels where the flood-plain aquifers are deep relative to the channel. The Santa Cruz flows freely from it's headwaters in Arizona's desert grasslands, through northern Mexico, and back into the United States near Nogales. Some of the upper Santa Cruz River remains ephemeral and devegetated as a result of groundwater pumping to supply water to the border cities known as Ambos Nogales. In the reach below the Nogales International Wastewater Treatment Plant, release of effluent directly into the channel has caused stream flows and water tables to once again increase to levels that support cottonwood-willow forests. This hydrologic restoration, coupled with natural flood flows, has allowed for flood-plain wide recovery of cottonwood-willow forests along several miles of the river. Much farther downstream, release of similar amount of effluent from Tucson into a similarly sized channel but underlain by a heavily overdrawn groundwater basin has produced only a narrow, short stringer of riparian vegetation. The effluent rapidly percolates into the aquifer and falls below the zone available to riparian plant species, producing habitat of limited quality for species such as the flycatcher.

The example of the Santa Ynez River illustrates the changeable nature of habitat strongly influenced by human activities, including the release of urban wastewater. Suitable riparian habitat for the bird probably existed on a sporadic basis during relatively moist periods, but the release of urban waste water insured continuous maintenance of the habitat even during drought periods. During the middle 1990s, at least 3 territorial pairs used the riparian area of the river partly sustained by wastewater. However, the habitat eventually was lost as part of channel controls instituted by Santa Barbara County for flood protection (Holmgren and Collins 1995).

There is reticence on the part of some land and water managers to release effluent into river channels or constructed wetlands because of concerns over odor, human health risks from mosquito-borne diseases, or poor water quality. Along the Salt River downstream of Phoenix, managers are finding that some of these concerns can be alleviated by managing for, or allowing for habitat complexity. For example, complex habitats that support insect predators, such as topminnows, allow natural predation-prey interactions to keep the disease organisms at low levels.

Non-urban activities also create discharges of water into otherwise dry channels and provide for useful flycatcher habitat by supporting the appropriate vegetation communities. Agricultural irrigation usually returns some flows to the river that supplied the original withdrawals, and these tail waters occupy low flow channels bordered by dense growth of riparian vegetation. Tail waters are rarely able to sustain continuous flows of distances of many km, but in some cases downstream from large irrigation areas a semblance of dense riparian forest is possible. Such forests are not as extensive as the ones that existed in pre-development periods, but they may serve as the only available substitutes. Irrigation return flows to the Middle Rio Grande support extensive riparian vegetation that hosts some of the currently active southwestern willow flycatcher habitat in that system. Irrigation return flows typically are higher in dissolved solids and salts than are the irrigation inflows due to the tendency of irrigation to concentrate solutions through evapotranspiration and dissolution form the soils. Saltier water can shift the potential species mix of riparian vegetation from natives to salt cedar, and potentially beyond the tolerance limits of salt cedar. Pesticides and herbicides and their breakdown products can potentially alter the flycatcher's food quantity and quality in discharge areas.

5. Groundwater Management

In many areas of southwestern agriculture, the return of irrigation tail waters to streams results in elevated groundwater levels. Saturated landscapes in and near river channels sustain extensive growth of phreatophytes in an arrangement that is determined partly by surface flows feeding water to the system and partly by groundwater pools whose influence extends far beyond the points of release of the surface waters. The extensive thickets and forests that survive on these groundwater pools cover thousands of km^2 along the large southwestern rivers with variable implications for flycatcher habitat. Along the middle and lower Gila River, some reaches have flycatcher habitat, such as those in the Safford Valley. On the other hand, flycatchers have not been recorded at seemingly similar reaches near the confluence with the Salt River and near Gila Bend.

River managers do not always view groundwater-supported phreatophyte forests positively. Water users suspect that the water transpired by the vegetation could be "salvaged" and used if they remove the phreatophytes, a concept that has given rise to phreatophyte removal programs beginning in the mid-1940s. Although extensive published research has indicated that water savings from phreatophyte removal would be very limited, such programs continue. Additional pressures to remove phreatophyte cover come from flood control interests who see phreatophyte growth in and near channels as reducing flow capacity and increasing the likelihood of flooding. Channel clearing efforts, followed by channel maintenance for phreatophyte control and flood conveyance reduce the forest and thicket coverage and are common in many parts of the southwest, including coastal California streams.

Groundwater pumping for municipal, agricultural, and/or mining activity has resulted in groundwater declines along many rivers in the southwest. Riparian water tables can decline if water is pumped directly from the alluvial aquifer or from the regional basin-fill aquifer. Along the San Pedro River in Arizona, aggressive pumping from the regional basin-fill aquifer has decreased flow into the local alluvial aquifer of the San Pedro River. The rate of groundwater flow from the regional aquifer to the alluvial aquifer has steadily declined in recent decades, as the nearby municipalities have pumped groundwater at a rate in excess of the recharge from runoff from the Huachuca Mountains. The net result has been a steady decline in base flows in the river. If the pumping and associated declines in river flow and water tables continue, the eventual loss of southwestern willow flycatcher habitat is inevitable. Remedial measures include recharging the aquifer with urban effluent, as in an experimental effort by the City of Sierra Vista and the U.S. Bureau of Reclamation.

On the other hand, Tucson and other cities, recharge groundwater through flow into streambeds, though all such efforts do not greatly benefit southwestern willow flycatchers. In some cases water is being recharged into small naturally ephemeral rivers, producing small patches of riparian vegetation that may not have appropriate nesting structure or may be distant from larger river networks. Planning efforts may be able to identify recharge sites that accommodate needs of water users and southwestern willow flycatchers.

The combination of ground water pumping and surface water diversion can be severe. Along the lower Gila River near Casa Grande, Arizona, groundwater was once within a shovel's reach of the flood-plain surface. But between loss of surface recharge following river diversion and pumping from agricultural wells, this water table has dropped by as much as 200 meters during this century (Judd et al. 1971). Riparian vegetation has been entirely replaced by upland vegetation

along some stretches of the Gila River. Throughout the desert Southwest, practically all intermediate and large rivers are affected by surface flow diversion and/or groundwater mining. Lowered water tables have cause death of riparian vegetation and/or replacement of hydric vegetation types by more xeric types as along the Mojave River and Carmel River in California, and the Santa Cruz River in Arizona (Bryan 1928, Groeneveld and Griepentrog 1985).

There are ample opportunities to enhance or restore riparian vegetation by recharging ground water into appropriate sites. For example, the State of Arizona was allotted 3.4×10^9 m^3/yr (2.8 million acre-feet/year) of Colorado River water annually under the 1928 Boulder Canyon Project Act (45 Stat. 1057) and the 1964 decree in *Arizona vs. California*. Through water-banking, some of the Colorado River allocation of Arizona is recharged or "banked" in aquifers along the 530 km of the Central Arizona Project canal from Parker to Tucson, Arizona. In this arid region of the southwest, with open water evaporation rates greater than 2.7 m per year, aquifer recharge is considered to be a more viable and desirable method of water storage than storage in surface impoundments. Importantly for the southwestern willow flycatcher, it is feasible to accomplish the dual goals of ground water recharge and riparian restoration. A recent modeling study predicted that extensive riparian forests could be re-established in a dewatered reach of the Agua Fria River below the New Waddell Dam in central Arizona, if Central Arizona Project water was released from the dam. The river corridor could essentially be used as a conduit for water delivery to the recharge/recovery zone, with the key side benefit of providing water accessible to riparian vegetation (Springer et al. in review). The total amount of water transpired by the vegetation is predicted to be less than the amount that presently evaporates from the storage reservoir. If managed appropriately, such a project could produce southwestern willow flycatcher habitat along the Agua Fria analogous to that along the nearby Hassayampa River. However, it should be noted that during extreme drought periods, Central Arizona Project water may not flow to Arizona, so that a disruption of this recharge and restoration process is possible.

6. Channelization and Levees

The protection of near-channel properties often leads to the construction and maintenance of channelized rivers and levees along southwestern streams. Channelization consists of a variety of structures including jetties, bridge abutments, grade crossings, and pilot channels to impose a single--thread, relatively straight geometry on the previous meandering or braided system. Pilot channels are trapezoidal in cross section, are small compared to the natural braided channel they replace, and lead low flow channels through otherwise more complicated arrangements in simple straight lines. Levees provide further flood protection, and are usually situated at some distance away from the low flow channel. Because of the value of near-channel property, there has been a historical tendency to construct levees as close to the low flow channel as possible, restricting active channel width as much as possible, so that land outside the levee is available for use.

To gain a cross-sectional area adequate to pass flood flows while minimizing land allocated (channel width) for that purpose, high levees are required. During peak flows, high levees restrict water to a high level relative to the surrounding protected area. This arrangement creates a great pressure differential (or hydraulic head) that stresses levee systems and the ground upon which they are constructed. The high pressure differential results in a high risk of failure, mandating intense maintenance of the levees themselves. Little habitat for any species is allowed in these cases due to the

fact that it, or some of the species it attracts, jeopardizes the levees integrity. Inside the levees, optimal flood control designs of waterways include allowances for only the most limited impedance to flow (roughness elements) such as riparian vegetation. To maintain its design flood capacity, management agencies are mandated to remove vegetation before it becomes limiting to flow. Deposition of sediment that was once spread across a broad cross section then becomes concentrated in a more narrow zone, and the bed of the channel between the levees gradually becomes elevated with respect to surrounding land. In some cases, the surrounding land subsides after being cut off from the hydrology of the river. The ironical result is that this situation reduces the hazard from moderate floods, but increases flood hazards in large floods because if the levee is accidentally breached in an uncontrolled situation, flows spilling from the elevated bed into surrounding lowlands are exceptionally damaging and difficult to control.

Flycatcher habitat is likely in some southwestern streams in the area between or within the levees. Such areas have slack water in low flow channels and have riparian forests and tickets if the vegetation is not mowed or removed. Active competing land uses are uncommon or within the levees because by definition such zones are high flow channels and subject to occasional inundation. Examples of these arrangements include extensive reaches of the Lower Colorado River, the Rio Grande in New Mexico (Figure 6), and some coastal California streams.

Southwestern willow flycatcher habitat can be restored or improved along some rivers by removing the physical barriers that separate a channel from its flood plain. Along the Colorado River, for example, there are opportunities to remove the dikes and levees and restore some degree of channel-flood plain connectivity. By allowing the water to periodically flow onto the flood plain, it is possible to provide the input of water, nutrients, sediments, and plant propagules to sustain the productivity and diversity of the riparian forest (Crawford et al. 1993).

G. History and Geography of Water-Related Impacts on Southwestern Willow Flycatcher Habitat

During the period after about 1880, significant changes in the fluvial hydrology and geomorphology of the Southwest resulted in the reduction, modification, and redistribution of willow flycatcher habitat. In most rivers of the region, human intervention in the flow of surface and groundwater as outlined above resulted in substantial reductions in the total length and width of flowing streams, and their riparian vegetation. In Arizona, for example, only about 15% of the original perennial flow remains. Throughout the region on small- to medium- scale rivers, dams and diversions have desiccated stream channels and changed them from moist corridors which supported southwestern willow flycatcher habitat in the nineteenth century to dryland conditions without suitable habitat. The Santa Cruz River in southern Arizona is an example.

Along small streams throughout the Southwest, marsh-like conditions existed on many alluvial valley floors which are likely to have been suitable willow flycatcher habitat similar to that now found in wet meadows of northeast Arizona. These valley-floor marshes, or cienegas, were reported by early Spanish, Mexican, and Anglo-American observers and were common up to the late 1800s. During the last two or three decades of the nineteenth century, intensive development that included road construction, railroad building, installation of drainage lines, and overgrazing lead to the destruction of almost all the cienagas of the southwest. The removal of their surface vegetation and the concentration of surface water flows led

to their excavation by vertical erosion of stream channels, resulting in the arroyos commonly found in their former locations today (Cooke and Reeves 1976). The arroyo cutting in turn lowered groundwater levels, so that dense vegetation suitable for southwestern willow flycatcher habitat is now absent from these locations.

Large regional rivers have a more complex history. Photographs, drawings, and paintings made of the rivers during the 1800s show that potentially suitable southwestern willow flycatcher habitat was discontinuous along such rivers as the Lower Colorado, San Juan, and Gila rivers, probably because of the general instability of these systems resulting from occasional large floods (Figure 7). The streams had large expanses of bare sand in the late 1800s as shown by the photographs of major survey parties such as the Powell and Wheeler Surveys on the Colorado River, and by various other investigators on other streams of the region. Floods may have been especially common in the early twentieth century, temporarily reducing cover of riparian vegetation by destroying it, with vegetation recovering between floods. Research using ground and aerial photography of generally unregulated streams shows that the vegetation communities and channels on the Gila River gradually expanded after flood events, only to see channel widening and loss of riparian vegetation in the next flood event (Burkham 1976; Figure 8). Thus, under pre-development conditions, southwestern willow flycatcher habitat was likely to be highly changeable over a period of decades, with habitat being simultaneously gained and lost in various places throughout the southwest. A result of the flood cycle driving riparian vegetation distribution was likely a broken pattern of habitat that was somewhat naturally fire-proof.

When modern photographers have rephotographed these historic sites, they document inconsistent changes (Stevens and Shoemaker 1987). Some sites are now more heavily vegetated than they were more than a century ago because upstream dams have controlled destructive floods, but other sites appear similar to their nineteenth century barren conditions. In many cases, modern vegetation is more dense than in the views of the late nineteenth century because of the invasion of tamarisk (*Tamarix* sp.), an exotic species from the Middle East which was a rapid and effective colonizer of exposed moist sand accumulations. Tamarisk spread rapidly throughout southwestern rivers after about 1900 (Graf 1978), and it replaced much of the willow cover lost because of dams and diversions. Tamarisk, with its aggressive, deep tap roots effectively survived depleted surface flows in many areas, and it dominates the communities in many of the rephotographed locations.

Groundwater management has affected southwestern willow flycatcher habitat through an intricate series of connections with surface flows to produce a complicated history of changes. Under pre-development conditions, most of the medium and large rivers of the Southwest had flow almost continuously, with the channel water seeping into the groundwater system which had its upper surface connected to the channels from which it derived its water. This condition was common throughout the region until the early 1900s. When dams and diversions removed this surface flow and severed this nourishing connection, groundwater levels declined in those areas downstream from the diversions. Often, groundwater pumping further depressed the water table, so that phreatophyte vegetation (even the exotic tamarisk with its extensive tap root systems) could not survive in riparian environments. In many agricultural and urban areas, this groundwater depletion accelerated with the introduction of high capacity electric pumps beginning in the 1950s; from that time on, reductions in the coverage of riparian forests was common in many areas, including coastal California and the interior alluvial basins

(Figure 9). The replacement of riparian trees with barren surfaces is usual course of events in urban areas of the Southwest that produces no suitable habitat for the willow flycatcher without extensive restoration efforts (Figure 10).

The changes imposed upon the southwestern fluvial system through human activities take place against a backdrop of otherwise natural changes in the prevailing hydroclimatic system. The arrangement of the atmospheric circulation system, frequency of incursion of major storms and ordinary low pressure systems, sea surface temperatures, and teleconnections such as the El Niño and La Niña phenomena have caused some measurable adjustments in the frequency of storms and in regional flooding (Hirschboeck 1988). These changes are small compared to the local changes caused by human activities. It is unlikely that future local hydrologic responses from global climate change will be directly significant in the recovery of the southwestern willow flycatcher, because such changes will only be a maximum of about 15-20 percent of present flows (Intergovernmental Panel on Climate Change 1995). This change is small compared to the changes brought about by dams which have altered annual water yields by as much as 100% and have provided the opportunity to store several year's flow of the regional streams (Table 1; storage compared to annual runoff). If global climate change affects southwestern willow flycatcher recovery, it will be through minor changes in an already over-appropriated water economy, and by increasing the marginal cost of water that might purchased from other uses and applied for restoration.

Nevertheless, extremes of drought and flooding do influence southwestern willow flycatcher habitat, particularly if compounded by synergistic interactions with human activities. For example, the American Southwest experienced an "extreme" drought in the 1950s (Swetnam and Betancourt 1998). This contributed to the collapse of the cottonwood-willow communities and aquatic ecosystems along those portions of the Santa Cruz River that were subject to ground water pumping. The combined effects of drought and pumping from the small alluvial aquifer caused water tables in the 1950s and 1960s to decline below cottonwood and willow rooting depths (Arizona Department of Water Resources 1994). Since the mid-1970s, the Southwest has been in a wet cycle, allowing for expansion of riparian forests in some areas.

Seasonal changes in precipitation and flood patterns can influence southwestern willow flycatcher habitat, as well. After 1960, for example, climatic fluctuations tied to El Nino-southern oscillation weather patterns (Webb and Betancourt 1992) created a pattern of flood flows that was more favorable to cottonwood-willow establishment in parts of the southwest. Increased activity of Pacific frontal winter storms and of dissipating late summer and fall tropical cyclones resulted in increased magnitude of fall and winter floods (favoring the growth of willow and cottonwood seedlings by establishing enlarged potential seedbeds), while activity of convective summer thunderstorms decreased (favoring seedling survivorship). These flood patterns presumably facilitated the mid-century expansion of cottonwoods and willows over the length of the San Pedro River (Stromberg 1998) and possibly other rivers, as well. Of course, drought conditions and less favorable flood patterns may return at any time, underscoring the need for preservation of a variety of southwestern willow flycatcher river sites including the larger rivers and others with stable aquifers that are less subject to the vagaries of annual precipitation.

Several attempts have been made in western United States and Canada to restore riparian ecosystems by prescribing controlled flood flows (see Appendix K; habitat restoration). Some of these efforts have achieved notable success. To facilitate regeneration of cottonwoods, flood flows on the Oldman River tributaries (Canada) and Truckee

River (Nevada) were released at specific times in spring that coincided with the germination phenology of the target species, and with specific draw-down rates that were within the tolerance limits of the seedlings (Mahoney and Rood 1998). El Niño has assisted in the restoration of other rivers such as the lower Gila by filling reservoirs to levels that required spills from the reservoirs during spring and summer. With prior planning, water managers could be prepared to routinely release water in ways that facilitate riparian tree regeneration.

The case of the lower Gila River offers an object lesson in water management for habitat restoration for the flycatcher, and demonstrates the sorts of changes that would be needed in operating rules. Painted Rock Dam stores as much as 4 million acre feet of water, but is not designed to retain the entire amount. The dam is primarily a flood control structure, and present operating rules require that it be essentially empty by October 1 each year. If this requirement were relaxed to allow a minimal amount of storage, just enough to permit trickle flows downstream from the dam, habitat restoration would be greatly aided. The amount of flood storage thus reduced would be relatively small while at the same time improving sustainability of the flycatcher population.

Methods to manage flows on regulated rivers to favor native willows and cottonwoods over the tamarisk are being refined. Tamarisk overlaps with willows and cottonwoods in many of its ecological requirements. It is possible, however, to restore to regulated rivers some of the flow conditions under which the cottonwoods and willows are more competitive. For example, one can adjust the timing and duration of the spring floods to coincide with the desired needs of the desired species, or adjust the size and duration of the post-germination floods to levels that exceed seedling survivorship thresholds of the exotic species, but not the native species (Gladwin and Roelle, 1998).

H. Water-Related Recommendations for Flycatcher Recovery

Along with its population, the Southwest's demand for municipal and agricultural water, hydropower, and aquatic recreation continues to grow. The time for management compromise has arrived. We need to adopt strategies that will both protect our natural resources and allow sustainable human use. There are creative ways to allow for continued flow-regulation on dammed rivers, while also allowing for the return of more natural flow regimes, including the flood flows that are paramount in the regenerative process of native riparian woodlands. Because there are pre-existing demands on water supply or power supply , we must find creative ways to work within the political and institutional constraints to rehabilitate, if not fully restore, the ecosystems.

Ultimately, we can manage our water resources to restore the conditions that favor a diversity of native riparian species. With appropriate planning, we can intermingle these habitat restoration efforts with direct human uses of the flood plain, such as agriculture. There are indirect benefits to undertaking such dual approaches. For example, native riparian forests in agricultural landscapes supply farmers with a wide variety of insects to pollinate crops and a variety of insectivorous birds to consume crop pests (Anderson et al. 1984). Such ecological services are critically important and ultimately economically cost-effective.

I. General Guiding Principles for Recovery

1. *Reestablish and maintain physical integrity of rivers first, then proceed to biological integrity for flycatcher habitat.*

Physical integrity for rivers implies the restoration and maintenance of their primary functions of water and sediment dynamics, with some variability over time and space. The vegetation communities needed for flycatcher habitat require specific hydrologic and geomorphic conditions, the most basic of which are floods, sediments, and persistent water. Sediment supply is restricted below dams, and inflows from tributaries supply all that is readily available. Each case will need to be examined separately, but in some instances the reduced amount of sediment will coincide with reduced transport capacity, so that the imbalance is not as great as might be imagined.

2. *Monitor physical integrity for rivers using simple indicator parameters such as stream flow and channel morphology, particularly width and channel pattern.*

Monitor physical conditions photographically using repeat ground station or aerial photography.

3. *Set reasonable restoration and maintenance targets for physical integrity, recognizing the restored system will be a combination of natural and artificial processes.*

It is not possible to return the physical system to its pre-development condition, but it is possible to establish and maintain conditions that mimic those that existed before extensive development, although at a limited scale and at a limited number of sites.

4. Design flycatcher recovery strategies and objectives to accommodate rivers and lakes that change from time to time and place to place, rather than depending on a static, unchanging fluvial system.

Such an approach assumes that flood events and reservoir level changes will destroy some existing habitat, but that they will create opportunities for new habitat. Because of this changing nature of the fluvial system, target more of the fluvial system for recovery than will be needed at one time, because it is likely that at any one time, some of the system will not be useful.

J. Geographic Framework for Flycatcher Recovery

1. Focus recovery plans involving water-related resources locally on individual river reaches, but take into account the watershed areas upstream in planning and management.

Specific places for establishing or maintaining flycatcher habitat should be river reaches, stretches of channel and riparian zones that are a few km long and relatively similar geomorphologically throughout their extent. However, these localized efforts must take into account the entire drainage basin upstream, because activities (dam operations, tributaries, and other land-uses) in this larger framework influence water and sediment flows through individual reaches.

2. Manage and plan water-related resources in the southwestern willow flycatcher recovery effort on a watershed basis.

Use the six-digit coded hydrologic units as the basis of planning for water and water-related resources to facilitate communication among agencies and water users.

K. Opportunities in the Water-Related Resource System to Enhance Flycatcher Recovery

1. Modify dam operations to take advantage of system flexibility and water surpluses to create and maintain flycatcher habitat.

Although legal and economic considerations limit the flexibility of operations management, environmental restoration and maintenance are part of the operating strategies of many large, multi-purpose structures, and habitat considerations should be a part of decision-making for operating rules. Creative management offers many opportunities where water resource decisions can lead to important benefits to flycatcher habitat.

Use surplus / flood flows to increase or add water to marsh areas between levees and on flood plains where there are no conflicts with other land uses.

Experience on the Lower Colorado shows that occasionally flood flows are so large that water flows into the Sea of Cortez and it is not used. Rather than losing this water, it should be used through diversions onto flood plains behind levees (as discussed elsewhere) and stored as long as possible so that it may be used for restoration. Availability of the waters of flood flows and uncontrolled releases depends largely on climatic events. The use of the water in the Colorado River is presently regulated by laws and treaties; an Interim Surplus Criteria presently defines the use.

Maintain reservoir levels as constant as possible to allow the establishment of lake-fringe habitat.

Reservoir level fluctuations are inevitable, but when choices for change or stability are available, stability or slow change should be the objective. When changes are needed, seek a new level with the smallest changes possible to encourage the development of new vegetation at the new lake level on headwater deltas. Loss of habitat when one level is abandoned may provide the opportunity to establish replacement vegetation at a new reservoir level at a different delta location. Structurally create sub-impoundments at major and tributary inflows to settle sediments and remain moist environs to develop stable riparian deltas.

Keep daily ramping rates and absolute amplitude for dam releases as low as possible.

Ramping rates, the rates at which releases are increased or decreased, should be kept as gradual as possible to prevent bank erosion and loss of riparian vegetation through mechanical processes at the margins of downstream channels.

Maintain instream flow releases below dams at suitable levels to conserve or enhance instream values and public trust resources.

For those dams that are primarily flood control structures, release storage volumes to take advantage of both flood scouring processes and trickle flows over long periods to maximize groundwater recharge and small amounts of surface flow downstream from the structures.

Investigate multi-objective optimization methods for deciding best strategies for operating rules that explicitly take into account flycatcher habitat maintenance in addition to the other objectives for dam operations.

For those structures that have operating rules including environmental values, use the same analytic techniques for assessing options to maintain flycatcher habitat that are used for other water resource objectives. Operate dams systematically to attempt to mimic natural river processes at least occasionally. Distribute flood storage capacity differentially between dams in various years so the intervening watercourses will occasionally experience floods while the systems flood protection integrity is maintained. Release flows for purposes that will better simulate natural hydrology and/or specifically to enhance riparian systems – e.g., release water for recharge purposes along with peak flows to enhance the flood-like processes between the dam and point of diversion.

2. Focus some restoration efforts on river reaches that include outfall points for urban waste water and rural irrigation tail waters.

Such areas have the potential to support vegetation suitable for flycatcher habitat and often have open water surfaces. In the lower Colorado River flood plain, for example, irrigation of riparian trees and shrubs planted as part of revegetation / restoration efforts with agricultural return flows have increased the survivorship over plantings without irrigation (Briggs and Cornelius 1998). When utilizing return flows to support or create southwestern willow flycatcher habitat, it may be necessary to periodically flush the soils to reduce the concentrations of salts below the levels that are toxic to willows. Success also will be enhanced if water level fluctuations do not exceed tolerance ranges of the plant species (see Appendix K). Restoration efforts in waste-water systems need to monitor water quality and contaminant levels to minimize risks.

Investigate the feasibility of lining presently unlined canals and using the savings of previously lost water for habitat restoration purposes.

Substantial amounts of water are lost to the surface water system through the walls of unlined canals. Lining of these canals can result in savings of surface water that can then be redistributed to habitat restoration efforts. This same approach has been used by Southern California farmers whose canals were lined by cities who then have the use of the saved water. A similar arrangement should be explored for habitat, including identification of likely funding sources.

3. Manage ground water more effectively.

Integrated, watershed-based approaches to water management may suffice to reverse some of the changes resulting from ground water mining in some river reaches. All water users- be they municipal, agricultural, or industrial, need to work together and bear their share of water overdraft problems to achieve results. Approaches should focus on reducing

withdrawals (e.g., xeriscaping, replacement of high-water-use crops by those with high water-use-efficiency) and increasing recharge (e.g., recharge of aquifers with effluent). In cases of extreme dewatering, restoration of water tables may require importation of water from other basins.

4. Increase the width of the flow zone between levees to expand flood conveyance potential and to foster wider areas likely to support flycatcher habitat.

If the distance between levees is increased, more space results for dense riparian vegetation outside the low flow channel. Flood conveyance channels should be designed to provide adequate flood-flow capacity with a large portion of the width in riparian vegetation. For example, doubling the width of channel dedicated to flood conveyance could free half the width from the necessity of channel clearing. Schedule channel clearing activities in such a way that riparian habitat is continuously available in the area –i.e., do not mow or grade entire flood control systems simultaneously. In some cases, levees may need to be rebuilt, with attending restrictions of space on flood plains outside them, but this loss is compensated by increased flood conveyance capacity, reduced maintenance costs, and reduced flood hazard. Sizing the channel width using the "meanderbelt" concept has potential for yielding both flood control and aquatic/riparian values. Discourage other land uses (e.g., cultivated agriculture) within flood conveyance facilities when they are inimical to riparian vegetation growth.

5. Breach levees temporarily during occasional high flows to reactivate flood plain areas in marsh conditions suitable for flycatcher support and not dedicated to other purposes.

Along some channels where the flood plain marshes can be maintained, construct additional levees around them to set them off from nearby flood plain areas used for other purposes, and install gates or valves to connect them through the main river levees to the channel to facilitate occasional diversions.

6. Reactivate abandoned channel segments now isolated on flood plains away from the active channel.

Abandoned channels and oxbows can be excavated to remove sediment and can be reconnected to the main river channel through artificial channels with gates or valves to supply temporary flows.

7. Use areas characterized by at least occasional standing water and the potential to support a dense understory of tamarisk or willow for restored or newly created flycatcher habitat, including:

a. Canals, laterals, and irrigation drains

b. Flood channels

c. Recharge basins

d. Minor lakes and reservoirs.

These activities can become multi-purpose projects including southwestern willow flycatchers if the areas are sized and maintained so that riparian vegetation is permitted. The basins should be lined only when water is lost to unusable

sources. Managers should maintain water in unlined facilities beyond their original intended function so that they can act as recharge source areas where the aquifers are depleted. Along some streams, moving the point of diversion downstream as far as possible will ensure that a greater length of natural watercourse is watered.

8. Avoid creating a need to control riparian vegetation.

For example, size culverts and bridges so they are large enough to pass not only peak floods, but also the debris that the floods transport.

9. Land management agencies should assure through their activities and monitoring activities that all of their watercourses are rated as "properly functioning" (Bureau of Land Management 1995).

This basic management objective is the foundation upon which flycatcher habitat will result given adequate water, sediment, and rest from grazing.

10. Repatriate beaver in stream reaches devoid of flycatcher habitat to create still waters by impoundment and sediment storage.

L. Conclusions

The recovery of the southwestern willow flycatcher population depends on the restoration and maintenance of suitable riparian forests which the bird uses for nesting. The forests, in turn, depend on a physical substrate that includes functioning river channels and near-channel sediments and landforms. There is intense competition among users for the water and landscapes that constitute the region's functioning fluvial systems, and in many cases making provision for a recovering southwestern willow flycatcher population resolves itself into a conflict over space. If the flycatcher population is to survive, some space must be allotted for that purpose, and water which is in transit or that is being used for other purposes may also be used to aid in the recovery of the bird population. Many water-related resources of the Southwest serve multiple purposes. The key to using those resources to aid the southwestern willow flycatcher population is to extend this multi-purpose approach to sustaining the physical and biotic environments needed by the birds. Multi-purpose approaches ultimately reduce costs to other users of the water related resources, and reduce conflict among competing objectives. Creative and innovative use of existing water-related resources can make possible economic and environmental productivity without sacrificing one for the other.

L. Literature Cited

Please see Recovery Plan Section VI.

Table 1. Southwestern Water Resource Regions and Dams

Water Resource Region	Rio Grande	U. Colorado	L. Colorado	Great Basin	California
Region Identifier	***13***	***14***	***15***	***16***	***18***
Total Area (sq mi)	132,510	112,110	139,130	140,110	147,550
Total Number of Dams	716	1,164	446	803	1,530
Total Storage (ac ft)	21,013,562	46,364,999	48,373,154	5,979,380	74,161,688
Total Annual Runoff (ac ft)	5,487,880	15,063,670	18,982,714	6,596,655	72,910,402
Population	2,566,000	714,000	5,318,000	2,405,000	32,060,000
Area/Dams (sq mi/dam)	185	96	313	174	96
Storage/Area (ac ft/sq mi)	159	414	348	55	503
Storage/Runoff	3.83	3.08	2.55	0.91	1.02
1st Year Storage > Runoff	1935	1950	1936	NA	NA
Persons per Dam	3,584	613	11,924	2,995	20,954
Storage / Person (ac ft/pr)	8.19	64.94	9.10	2.49	2.31
Numbers of Dams by Size Classes					
Size = 10^x ac ft, where x =					
Unknown	2	4	19	16	7
0-0.99	0	0	0	0	0
1-1.99	134	221	80	214	209
2-2.99	406	620	171	314	693
3-3.99	119	212	108	186	345
4-4.99	37	82	45	60	182
5-5.99	13	21	16	11	69
6-6.99	5	3	6	2	25
7+	0	1	1	0	0
Storage of Reservoirs by Size Classes					
Size = 10^x ac ft, where x =					
0-0.99	0	0	0	0	0
1-1.99	8,142	12,523	4,339	9,804	11,479
2-2.99	126,532	214,674	58,020	112,704	242,597
3-3.99	416,734	646,016	362,490	529,651	1,118,433
4-4.99	961,056	2,357,803	1,303,178	1,535,752	7,476,134
5-5.99	5,072,502	7,195,673	4,519,487	3,091,140	21,633,085
6-6.99	14,428,596	7,117,310	11,888,640	2,452,894	43,679,960
7+	0	28821000	30237000	0	0

Table 2. Summary of Downstream Impacts of Dams

Dam Operations →	Hydrologic Changes →	Geomorphic Responses →	Willow Flycatcher Habitat Responses
General system-wide	Reduced annual water yield; dessication in cases of diversion of all normal flow	Shrinkage of high and low flow channels, expanded flood-plain areas with increased stability; falling water tables in the case of dessication	Expanded flood-plain forest areas; elimination of riparian forests if water tables decline below 10 m (33 ft)
Flood control	Reduced flood peaks	Shrinkage of high flow channel, change from braided to single-thread or compound patterns	Expansion of riparian forests given sufficient water table support
Irrigation and urban water supply delivery	Increased low flows	Expanded low flow channel, change from braided to single-thread or compound patterns	Maintenance of ribbon or gallery riparian forests along the low flow channel
Local diversions of flows	Decreased low flows, dessication	Shrinkage of low flow channel	Loss of most riparian vegetation
Spills, uncontrolled flows	Rare, very large flows	Destruction of the established low flow channel, occupation of the high flow channel of the compound system	Temporary loss of riparian vegetation, establishment of a new arrangement
Most operations	Decreased annual fluctuations in flow	Simplification of the channel system, loss of medium-level forms such as beaches, attachment bars, flood plains	Simplification of habitats, reduced variety of ecological niches, reduced area of riparian forest, conditions more conducive to tamarisk and other exotic species, less favorable for native species
Hydropower (run-of-river)	Little change	Little change	Little change
Hydropower (peaking)	Increased daily fluctuations	Creation of a scoured low flow channel, erosion and instability near the channel	Unsuitable for riparian forest within the zone of fluctuation

Table 3. Water Withdrawals and Uses in Southwestern Willow Flycatcher Water Resource Regions. Data from Solley and others, 1998.

Surface Water Withdrawals						
Region	**Public Supply**	**Irrigation**	**Livestock**	**Industrial**	**Mining**	**Thermal Power**
	acre feet per year					
Rio Grande	147	5150	39	11	62	2
Upper Colorado	119	7840	60	7	26	164
Lower Colorado	782	4710	45	53	17	19
Great Basin	285	4500	96	102	83	24
California	3230	20400	507	605	87	226
Surface Water Uses						
Region	**Pop Served**	**Acres**	**Thermal Power**	**Hydropower**		
	thousand persons	thousand acre feet	millions kilowatt hours	millions kilowatt hours		
Rio Grande	735	968	7780	464		
Upper Colorado	407	1470	94000	7220		
Lower Colorado	2510	938	62400	9740		
Great Basin	1050	1060	16300	633		
California	17400	7060	76000	47000		

Appendix I. Figures

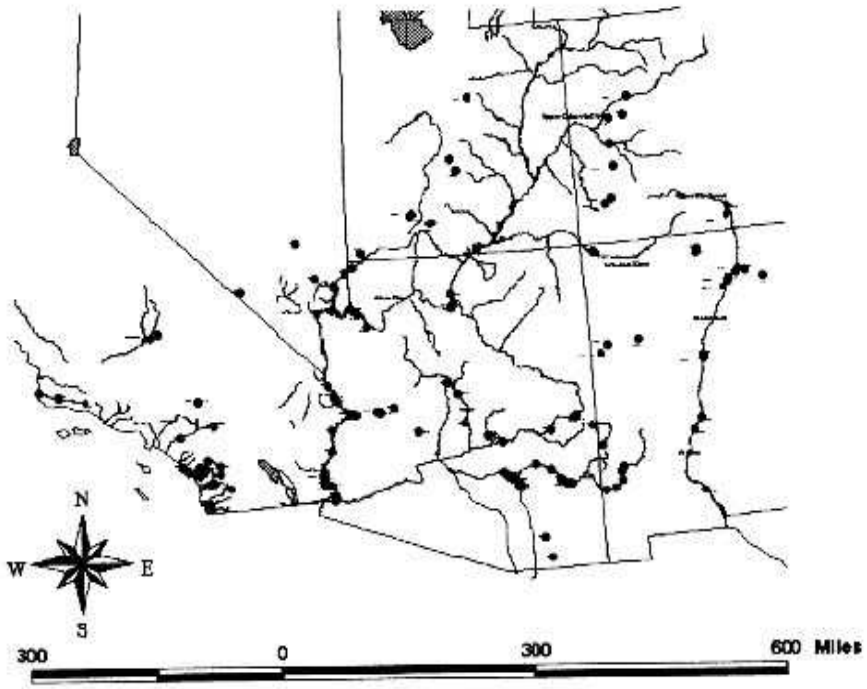


Figure 1. Map showing the present distribution of willow flycatcher nesting sites in the Southwestern United States.

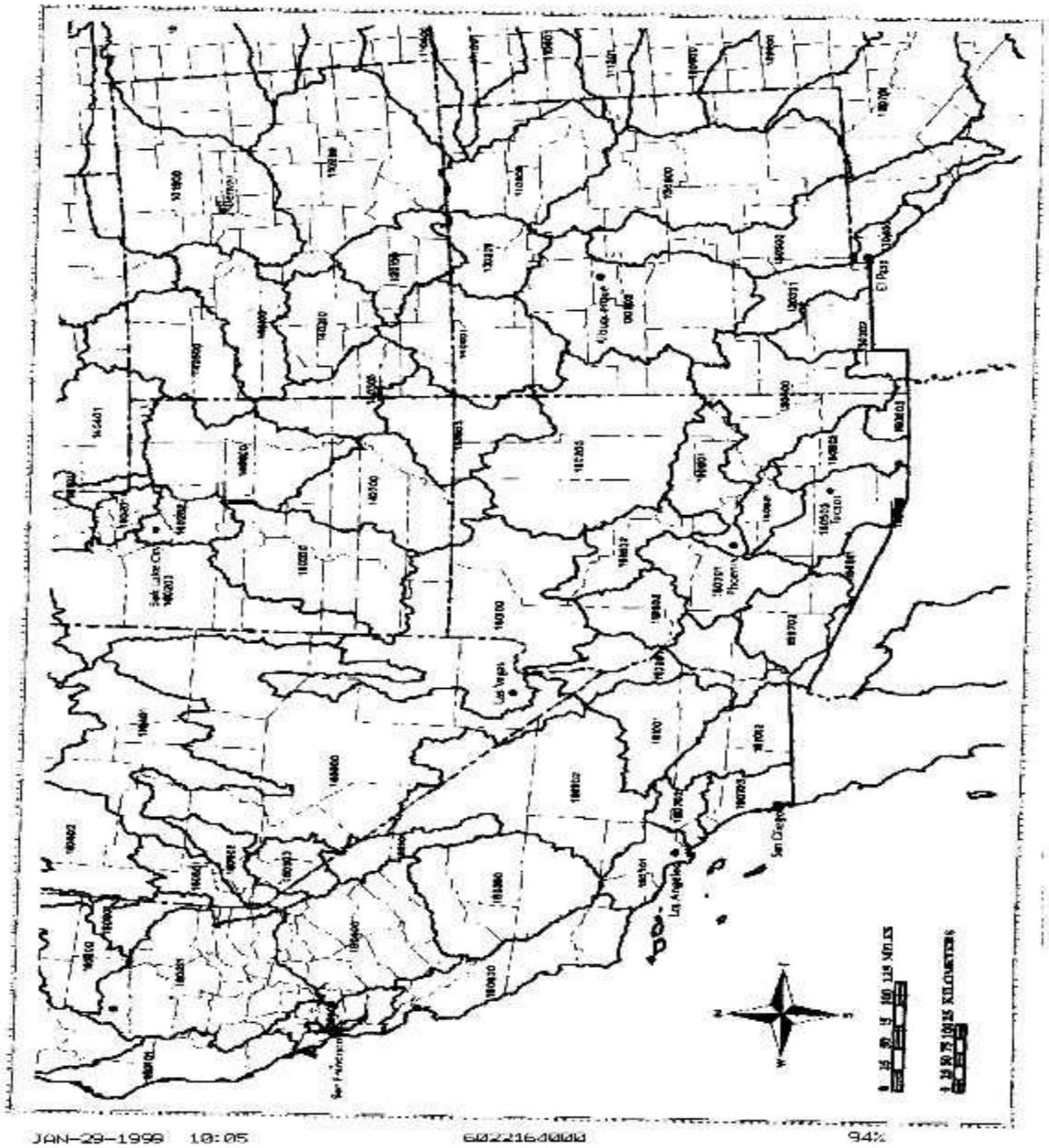


Figure 2. The watersheds and streams of the Southwest. Map created by William Cosgrove, U.S. Bureau of Reclamation, Phoenix.

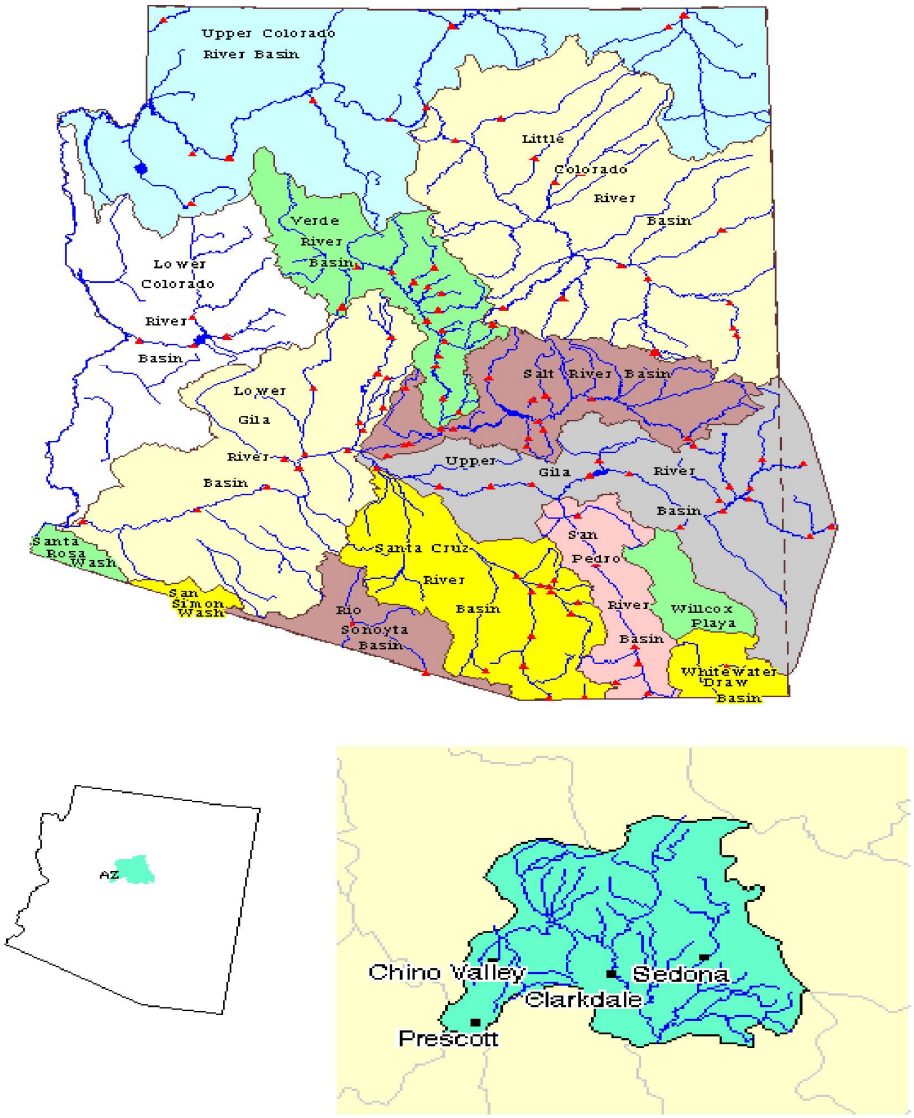


Figure 3. Varying scales of watersheds and river basins illustrated by watersheds in Arizona. Upper: the watersheds of the state outlined at using the 6-digit codes of the planning areas defined by the U.S. Geological Survey and the Water Resources Council. Small triangles are major stream gage sites (from the web site http://az.water.usgs.gov/rtaz/html /rtsw.html). Lower: the Upper Verde Watershed, an 8-digit code watershed, the smallest of the defined areas. It is 6,374 km^2 (2,461 mi^2) in extent. (From the web site http://www.epa.gov/surf2).

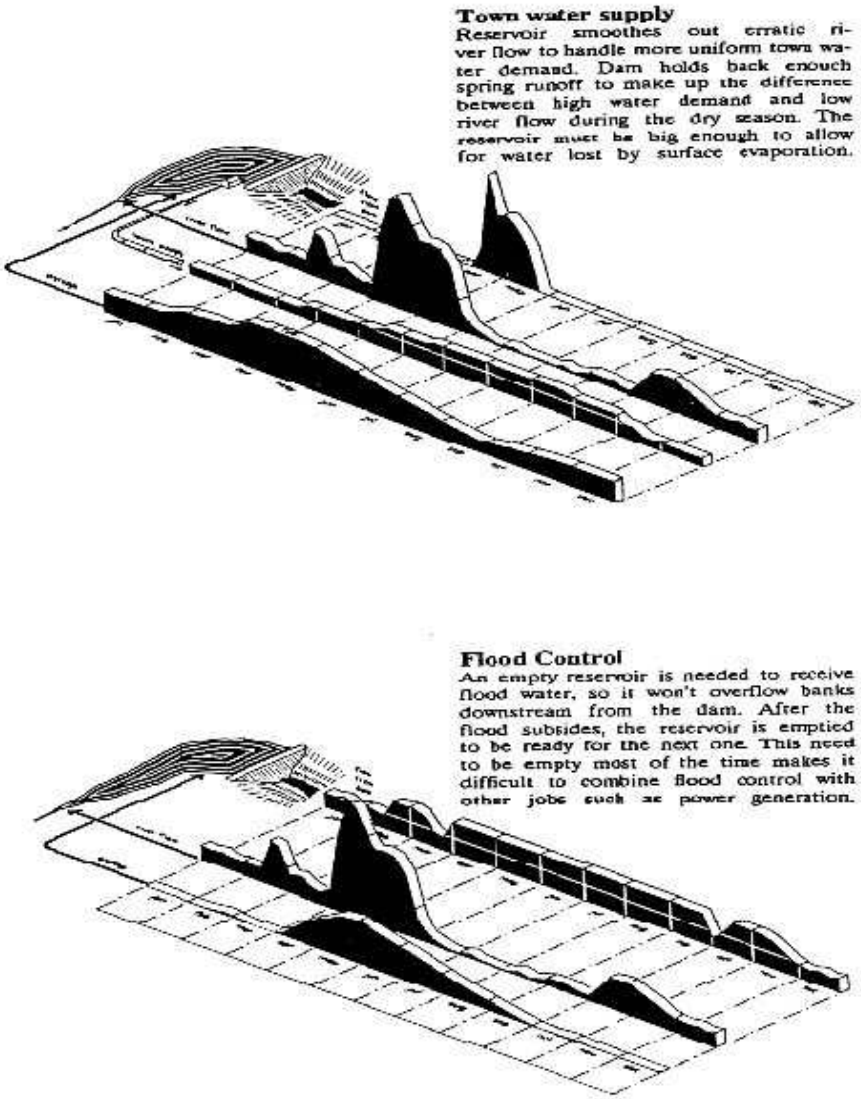
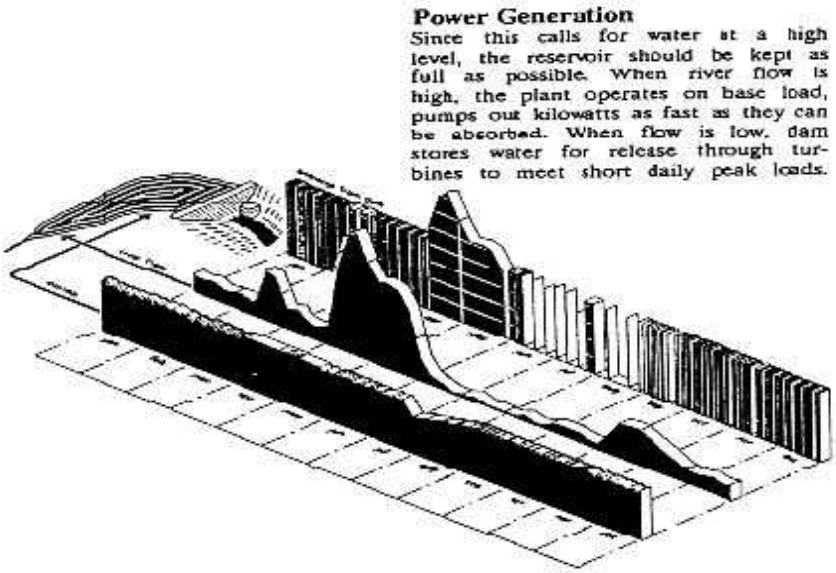


Figure 4. Effects of dams under varying operating rules in four hypothetical cases. (From Black, 1992).



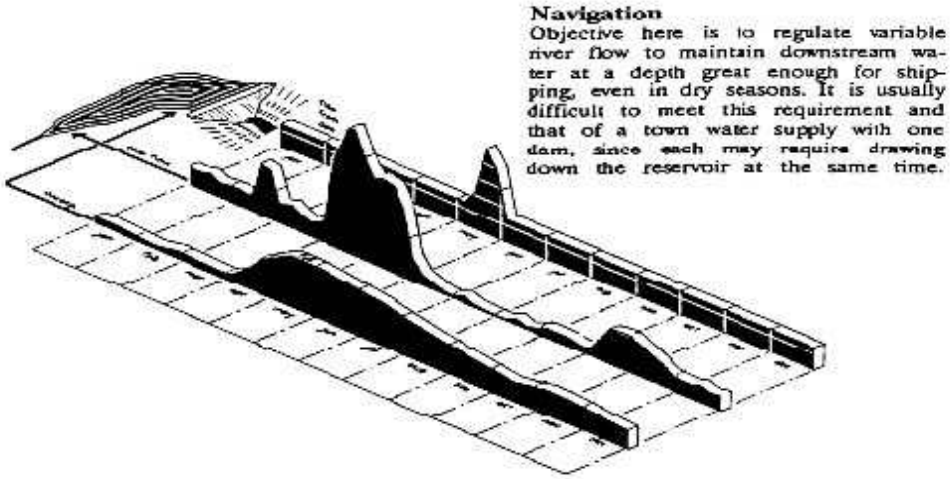


Figure 4 (continued). Effects of dams under varying operating rules in four hypothetical cases. (From Black, 1992).

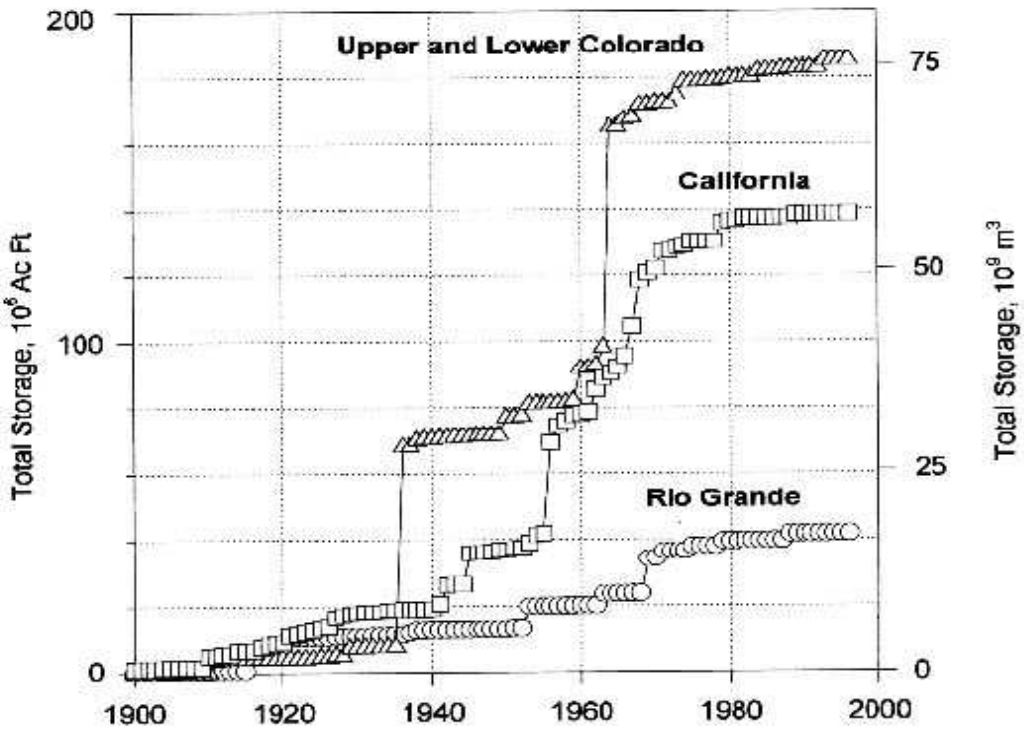


Figure 5. The history of increasing reservoir storage in Southwestern river basins. Data from U.S. Army Corps of Engineers, 1996; calculations from Graf, 1999.

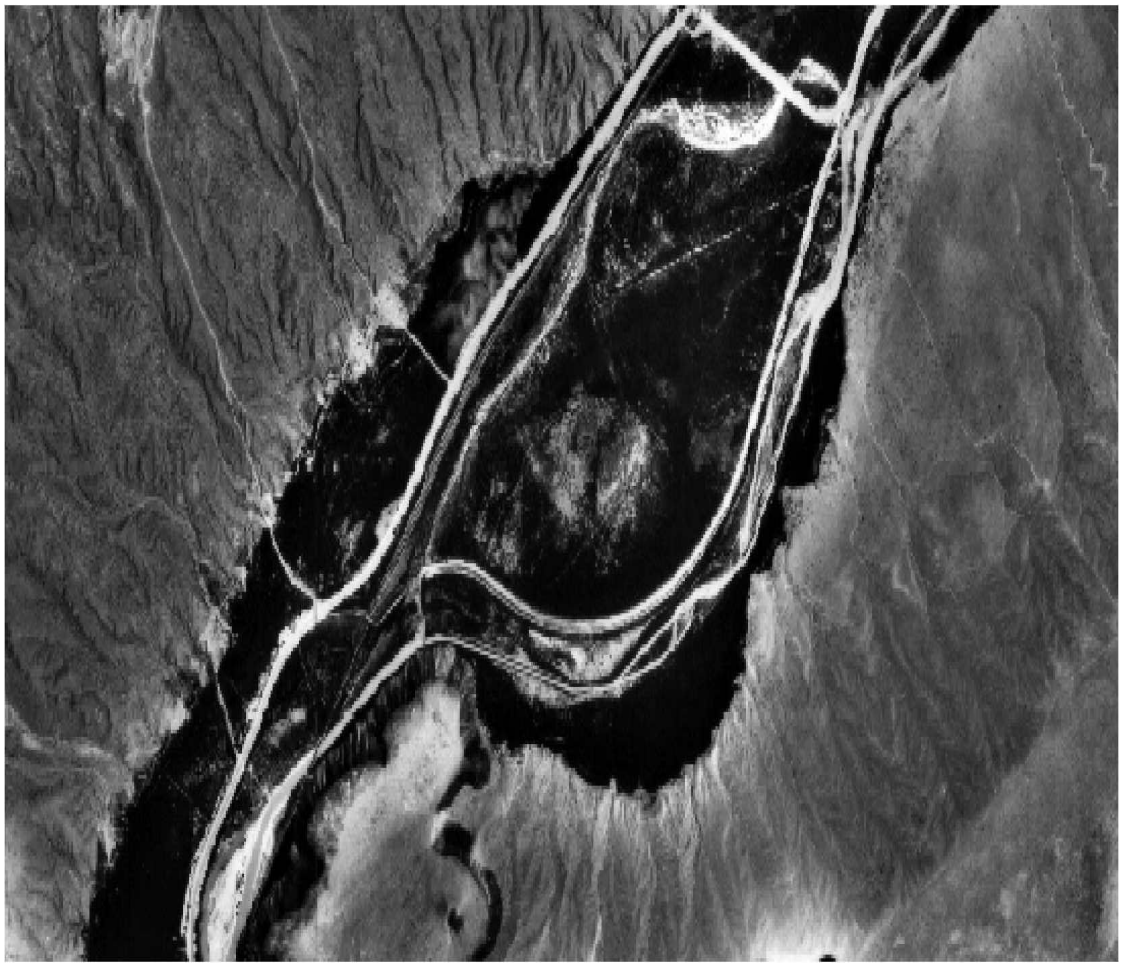


Figure 6. Aerial photograph of Rio Grande near San Marcial, New Mexico, in 1984 showing the density of riparian vegetation associated with a shrinking channel system and extensive diversions. The white lines are drains and canals with roads on their banks. U.S. Geological Survey mapping photograph from the EROS Data Center, Souix Falls, South Dakota.

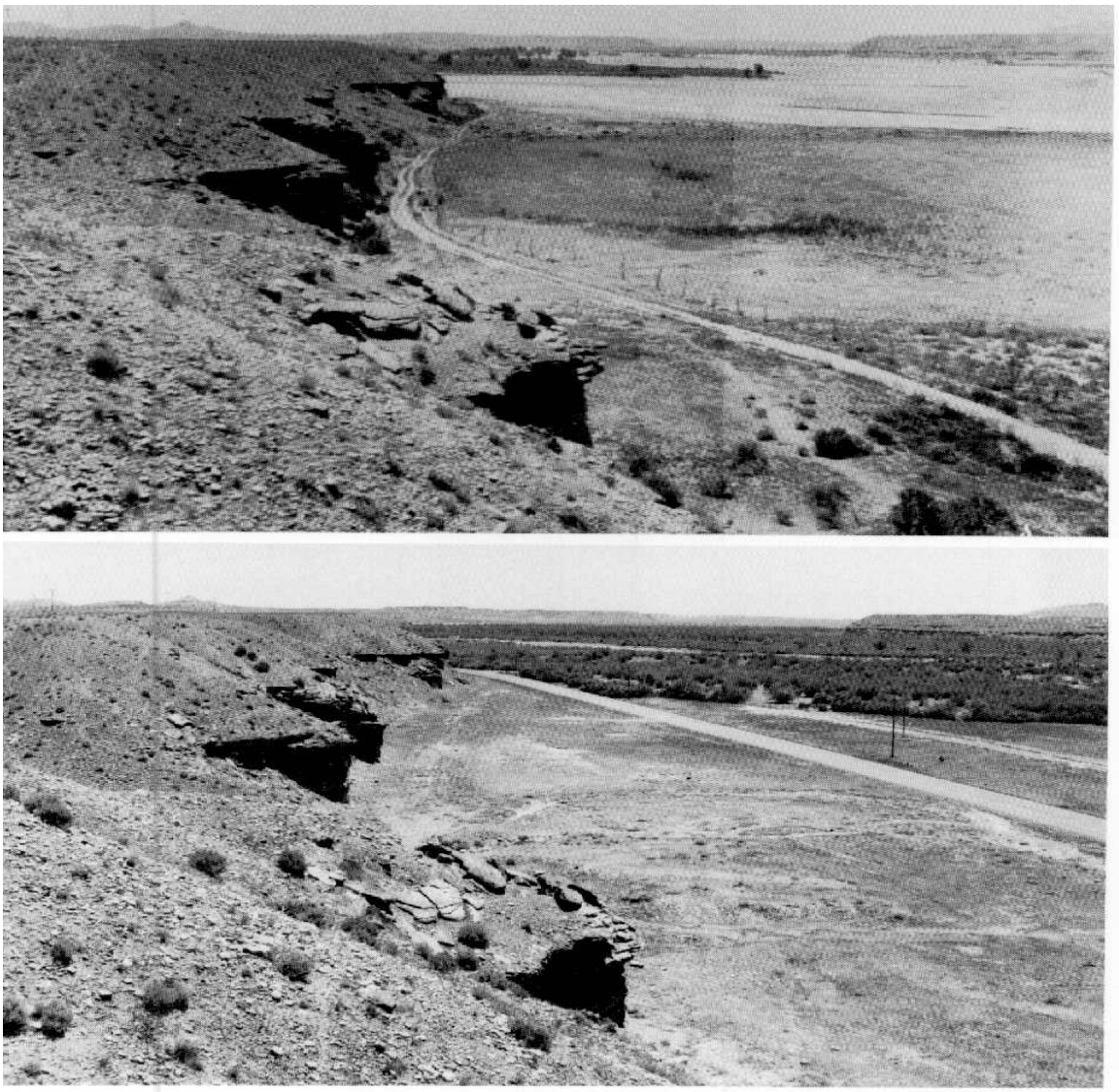


Figure 7. Repeat photographs of the San Juan River near Aneth, southeastern Utah, showing the change from a braided channel with little vegetation to a single thread channel with extensive phreatophyte cover. Navajo Dam substantially changed river flows in this reach after the completion of the structure in 1962. Above: 1928 photograph by H. E. Gregory. Below: 1982 photograph by W. L. Graf.

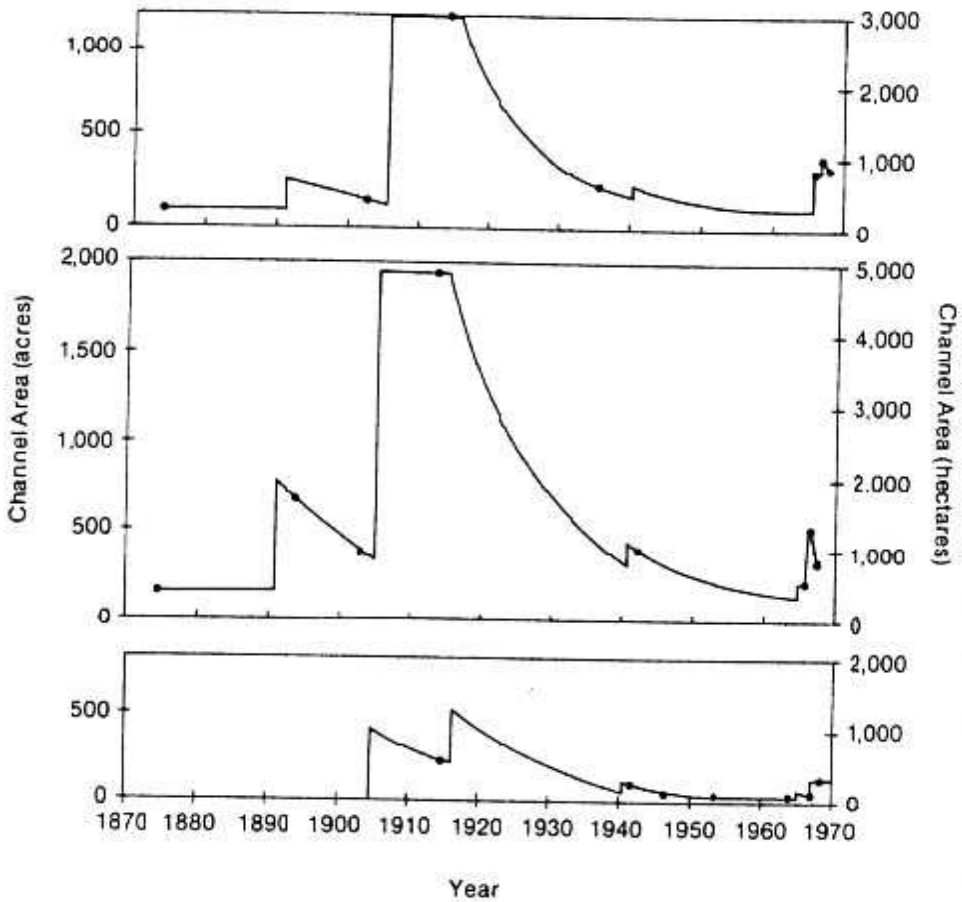


Figure 8. Channel and riparian vegetation area fluctuations on the Gila River in the Safford Valley, southeast Arizona. Each box represents a different river reach, with the total vertical extent of each box representing the total valley width. Within each box, the area below the plotted line is the channel, and the area above the plotted line is the riparian vegetation area. Rapid increases in channel width accompany the destruction of riparian vegetation in large flood events, followed by slow encroachment of vegetation on a gradually shrinking channel. There are no large dams upstream from these reaches. Data and design from Burkham, 1972.

Figure 9. Repeat photographs of the Gila River west of Phoenix at the Cotton Lane Crossing, showing the effects of groundwater pumping. The dense cover of tamarisk, fed by surface flows and groundwater, has given way to a nearly barren river bed with some temporary standing water but little else. Depth to groundwater is greater than 15 m in the later view. Above: 1949 photograph by the U.S. Army Corps of Engineers, with an arrow added by the photographer to show the direction of surface flow. Below: 1980 photograph by W. L. Graf.

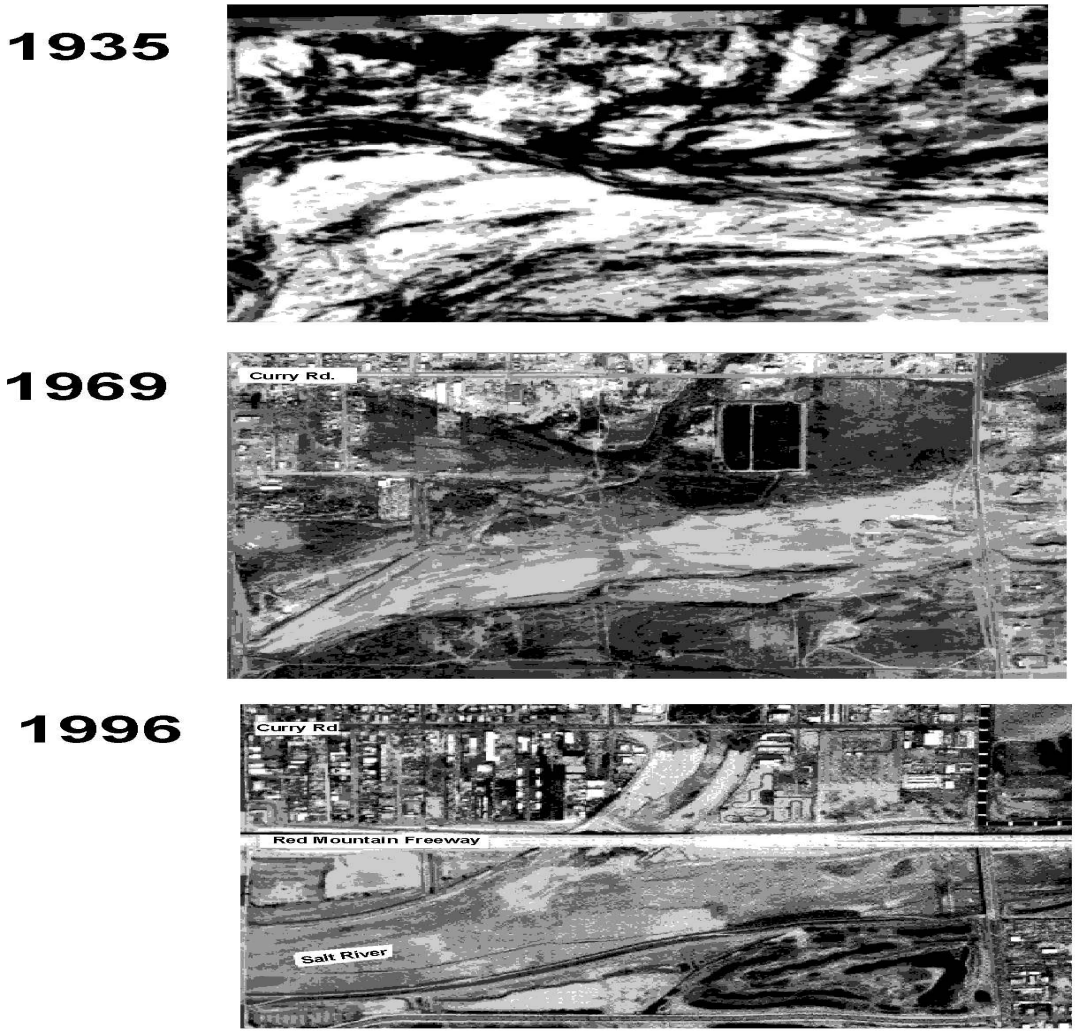


Figure 10. Series of aerial photographs showing the sequence of channel and riparian vegetation changes resulting from urbanization on the Salt River in Tempe, part of the Phoenix metropolitan area. All the photographs are registered to a common base using geographic information systems, and all show exactly the same one-mile reach of the river. 1935, prior to urbanization: Soil Conservation Service photograph showing a braided channel with a well-defined low flow channel, islands, bars, and ribbons of dark vegetation. 1969, urban fringe entering the area: Landis Aerial Survey, Inc., photograph showing the narrowed, simplified channel as a result of upstream dam closures, with building activities on the north bank and groundwater pumping that has lowered the water table. No riparian vegetation remains. 1996, urbanization complete: Landiscor, Inc., photograph showing a completely artificial channel, scheduled for some restoration, but none that is likely to reestablish the pre-development vegetation. Photographs from Nobel Science and Engineering Library, Map Collection, Arizona State University.