Flow Regime Requirements for Habitat Restoration along the Sacramento River between Colusa and Red Bluff

CALFED Bay-Delta Program
1416 Ninth Street, Suite 1155
Sacramento, California 95814

916-657-2666

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**Integrated
Storage
Investigation**

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1. Introduction

1.1 Scope and Objectives

The Sacramento River is the largest and most important river in California (Figure 1.1-1). It drains over 15 percent of the state, and its waters support agriculture and urban growth in the most powerful economy in the world. The Sacramento River was once flanked by extensive forests of riparian vegetation, but only about 2 percent of the original forests remain as a result of clearing, land conversion, and flood control (Bay Institute 1998). Along with the San Joaquin River, the Sacramento River and its tributaries formerly supported runs of chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*) trout that probably totaled 2-3 million annually (Yoshiyama et al. 1996). Native runs of these salmon and steelhead are extinct in many drainages, and several runs are listed under the state and federal endangered species acts. With the recognition of the value of riparian forests in providing habitat for a range of species, including salmon, there is an increasing consensus on the need to preserve and restore these forests. The health and ecological value of these forests depends, in turn, upon the flow regime of the river and the ability of the channel to migrate across its floodplain.

The flow regime of the Sacramento River has been profoundly modified by reservoirs, diversions, levees, flood control channels, and land-use change in the watershed. Most notably, Shasta Reservoir has reduced flood magnitudes and cut off the upstream sediment supply, as is especially evident in the reach near Redding (Parfit and Buer 1980). Less than 2 percent of the original riparian forest remains along the Sacramento River, primarily because of conversion to agriculture (and to a lesser extent urbanization), facilitated by reduced flood magnitudes and extensive levee construction.

Despite these human-induced changes, the Sacramento River from Red Bluff to Colusa still exhibits limited processes and characteristics of a dynamically migrating, meandering alluvial river, including the establishment and successional change of riparian cottonwood forests.

Off-stream storage facilities proposed under the CALFED Bay-Delta Program, such as Sites Reservoir, would probably involve diversion of up to 5,000 or 10,000 cubic feet per second (cfs) during winter high flows, further modifying the river's hydrology. These existing and proposed changes occur in the context of initiatives to preserve and restore natural ecosystem processes along the Sacramento River. For example, the Senate Bill 1086 (SB 1086) program (described below) facilitates purchase or easement of floodplain lands in the potential meander path of the river, to permit dynamic migration of the channel. The CALFED Bay Delta Program Ecosystem Restoration Program and the U.S. Fish and Wildlife Service Anadromous Fish Restoration Program are supporting land acquisitions and easements under the SB 1086 program, and funding other efforts to reestablish dynamic river processes. For these various programs to succeed requires not only acquisitions and in some cases physical modifications, but also a flow regime adequate to drive dynamic channel processes and suitable for establishment of riparian vegetation.

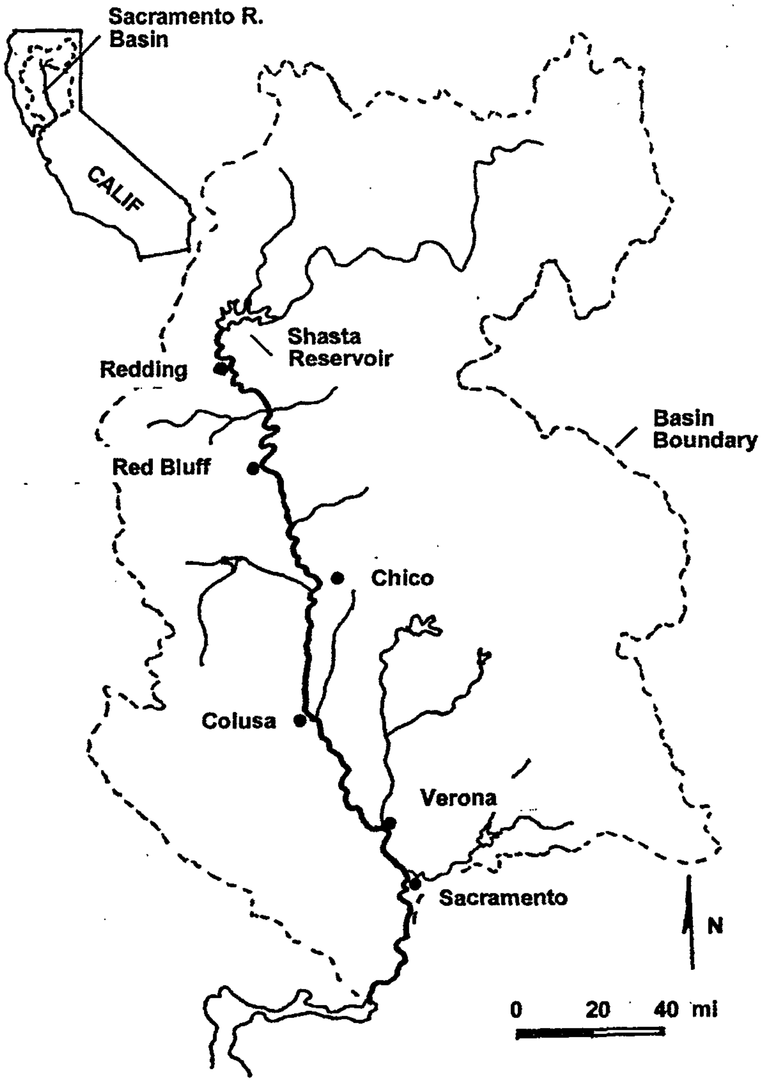

FIGURE 1.1-1A
Location map of the Sacramento River and watershed. The study area for the project is the reach between Red Bluff and Colusa

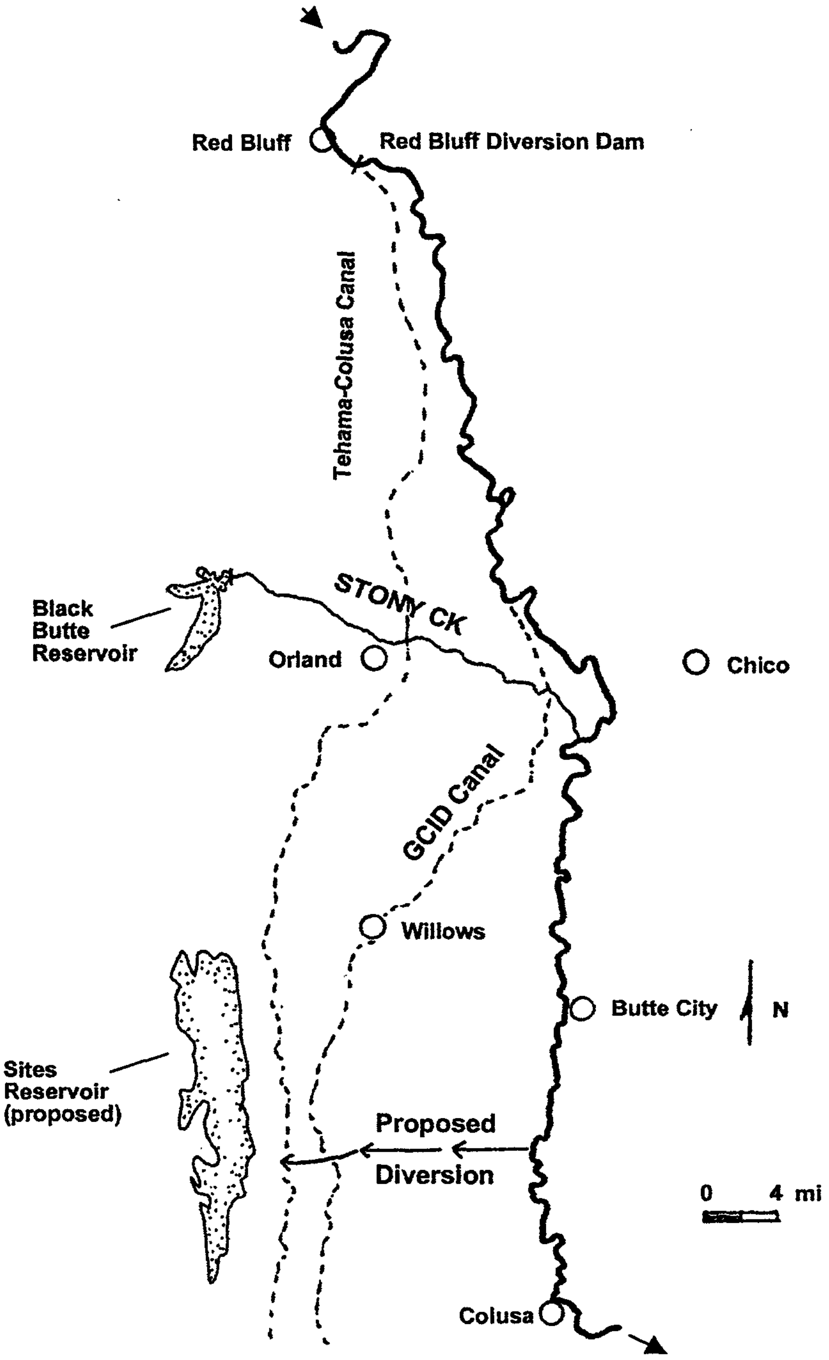

FIGURE 1.1-1B
Detailed map of the study reach showing location of proposed Sites Reservoir, possible new diversion points, and the Tehama-Colusa and the Glen-Colusa canals

The objectives of this paper are to outline and initiate long-term studies to address the flow regime requirements for riparian habitat restoration along the Sacramento River between Colusa and Red Bluff and to provide some initial environmental guidelines for the diversion of 5,000-10,000 cfs for the proposed Sites Reservoir. Specifying flow regime requirements for riverine ecology is a broad topic, and it cannot be adequately addressed in the time available for this report. However, we can articulate elements of a long-term, more comprehensive study that can actually address the important issues.

We can define a larger question, within which is a smaller question: The big question: "What kind of flow regime is necessary in the reach to maintain or rehabilitate riparian and riverine habitat?" This larger question should be answered in light of the pre-disturbance flow regime, riparian success under current modified flow conditions, and with a realistic understanding of the capabilities and constraints of current infrastructure, including potential re-operation of reservoirs, flood bypasses, and diversions as the first preferred approach to developing an ecologically beneficial flow regime. Within this analysis is the more specific question, "What are the potential effects of diverting 5,000-10,000 cfs during high flows?", or restated, "Under what conditions – what season, what frequency, what duration, and under what flows – could we divert 5,000-10,000 cfs without adverse impacts to environmental values?" The potential effects of diverting water for off-stream storage must be considered in light of the already severe reductions in high flows caused by Shasta Reservoir and the reductions in bank erodibility caused by extensive riprap along the banks.

Physical and ecological objectives of the flow regime on the Sacramento River should include:

- Periodically mobilizing the channel bed
- Maintaining/enhancing channel migration and meander cutoff processes
- Establishing riparian vegetation and maintaining a diverse assemblage of riparian habitats
- Producing over bank flooding to provide fine-grained substrate for late successional stage vegetation

The objective of mobilizing the bed is not directly related to riparian habitat maintenance or creation, and the bed mobilizes at lower flows than those required to drive channel migration. It is also more amenable to analysis, so we have analyzed this process, in part as a surrogate for the less well understood relations between flow and bank erosion and point bar deposition. In this paper, we have not attempted to analyze flow required to produce overbank sedimentation.

In order to specify flow requirements, these ecological objectives must be expressed first in terms of the physical processes, then in terms of actual flows needed, as illustrated in Figure 1.1-2. To properly address these processes would require more than the four months that were available for preparation of this report, but we have attempted to address these issues to the extent possible with available information and to indicate an adaptive management program through which our understanding of the system and its flow requirements can be improved.

Ecological Objectives	Physical Process/Requirements	Flow Requirements
Create fresh surfaces for colonization →	Channel migration, point bar deposition, meander cutoff →	Adequate τ to erode banks, transport bedload; overbank flows
Facilitate seedling establishment and survival →	Adequate soil moisture from sufficiently slow water table decline; seedlings/saplings not scoured →	Gentle recession limb after large flood in year 1 (establishment); no severe scouring flows in years 2 & 3
Establish late successional stage trees →	Over bank (fine-grained) sedimentaition on floodplain patches, patches stable long enough (~40 yrs) to allow late successional trees →	Overbank flows to deposit fine sediment, meander migration not so active to preclude patches stable enough to develop late successional vegetation

Notes: The overall riparian objective is to create a functional riparian corridor within the zone of frequent inundation (approximately 4 yrs). Physical processes listed also require adequate sediment supply and transport regime.

FIGURE 1.1-2
Conceptual linkages between ecological objectives and flow requirements

1.2 Context

Restoration of riparian and aquatic habitat in the Sacramento River has received increasing attention in recent years. Several major efforts have contributed to the heightened level of activity associated with ecological restoration of the river system. The objectives of this White Paper are addressed in light of those efforts, recognizing the restoration goals and objectives each program has for the Sacramento River.

The CALFED Bay-Delta Program is one of the major programs interested in restoration of the Sacramento River. The program is a joint effort among state and federal agencies with management and regulatory responsibilities in the Bay-Delta system. The mission of CALFED is "to develop a long-term comprehensive plan that will restore ecosystem health and improve water management for beneficial uses of the Bay-Delta system." CALFED addresses problems in ecosystem quality, water quality, levee system integrity, and water supply reliability.

The CALFED Ecosystem Restoration Program Plan (1997) has set strategic goals aimed at the restoration of the Bay-Delta ecosystem through the processes associated with streamflow, stream channels, watersheds, and floodplains. The Sacramento River plays an important role in the integrity of the Bay-Delta system, providing about 80 percent of the inflow to the Delta. CALFED has identified the entire Sacramento River as one of several Ecological Management Zones in the Bay-Delta system and developed "visions" for specific reaches of the river. The vision for the reach of concern in this White Paper emphasizes maintaining and expanding the quality and quantity of the stream meander corridor and its associated riparian forest.

The Central Valley Project Improvement Act (CVPIA) also has objectives related to the restoration of riparian and aquatic habitat in the Sacramento River. The CVPIA seeks to achieve a reasonable balance among competing demands for the use of CVP water, including the requirements of fish and wildlife, agriculture, municipal and industrial users, and power contractors (USFWS, 1997). The CVPIA directed the development of the Anadromous Fish Restoration Program (AFRP) to address certain CVPIA goals. The primary goal of the AFRP is to "ensure that, by the year 2002, natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967-1991." One of the general objectives of the AFRP aimed at meeting this goal is to "improve habitat for all life stages of anadromous fish through provision of flows of suitable quality, quantity, and timing, and improved physical habitat."

SB 1086 is another major program actively engaged in the restoration of the Sacramento River. SB 1086 was passed by the State Legislature in 1986 and called for a management plan for the Sacramento River that would protect, restore, and enhance fish and riparian habitat. The management plan, entitled Upper Sacramento River Fisheries and Riparian Management Plan, was prepared by an Advisory Council and action team. The plan includes both a specific action-oriented fisheries plan, and a more conceptual riparian habitat plan.

The stated purpose of the Upper Sacramento River Fisheries and Riparian Habitat Management Plan (SB 1086 Advisory Council and Action Team, 1989) is "to preserve remaining riparian habitat and reestablish a continuous riparian ecosystem along the Sacramento River between the mouth of the Feather River and Keswick Dam." The management plan introduces the idea of a meander belt along the Sacramento River where natural fluvial processes could be allowed to occur. Four reaches of the Sacramento River are identified in the management plan. The reach between Red Bluff and Chico Landing is described as "the most significant area of remaining habitat, as well as the most feasible location for reestablishing a functional Sacramento River riparian ecosystem." As stated in the goals and recommended solutions in the management plan, the primary focus of the SB 1086 program has been to work with landowners, the public, and local government to set aside and protect land within the proposed meander corridor. To date, this effort has met with significant success.

The recommendations in this White Paper complement the work currently under way through SB 1086, CVPIA, and CALFED. This White Paper makes initial recommendations on flow frequency, magnitude, and duration necessary to achieve geomorphic and riparian restoration goals of CALFED and SB 1086 inside the meander belt being acquired through SB 1086 efforts between Red Bluff and Colusa. A parallel effort is under way by a team of salmonid scientists to develop flow recommendations that would improve salmonid survival and production in the Sacramento River. Because conditions in the Sacramento River system have been so altered since 1850, completely re-establishing the pre-1850 hydrograph is neither possible, nor necessarily desirable. Thus, flow recommendations to achieve specific objectives in channel form, sediment quality, riparian vegetation establishment, or salmonid life history are not always complementary. For example, flow recommendations to re-establish specific components of the annual hydrograph to satisfy one objective may conflict with another objective.

Ultimately, the recommendations developed by the different disciplines need to be integrated into a single flow recommendation, or at least, the probable tradeoffs associated with each decision need to be clearly articulated.

1.3 Previous Work

Channel dynamics along the Sacramento River have attracted study by a number of authors in recent years. The geologic and Cenozoic tectonic framework was mapped and described by Helley and Harwood (1985) and Harwood and Helley (1987). Geologic constraints, reach-to-reach variations in grain size and channel slope, and features of the Sacramento River Flood control project were concisely summarized by Fisher (1994).

The U.S. Army Corps of Engineers (USACE)(1981) conducted a sediment budget study in support of a bank protection project from Chico Landing to Red Bluff. The stated justification for the project was to prevent river banks from eroding, thereby reduce delivery of sediment to navigation channels downstream. The premise of this project was somewhat naïve, in that it failed to recognize the usual behavior of migrating, meandering channels: they are translated across the bottomland but generally maintain their original dimensions. Thus, the expectation that reducing bank erosion would significantly reduce sediment yield to downstream channels was questionable at best, in that it would be correct only if the channel was progressively widening. DWR (1984) estimated sediment supply from various sources and concluded that 85% of spawning sized gravel was derived from bank erosion, therefore reducing bank erosion would have negative ecological consequences to salmon habitat. About half of the bank protection project was completed despite strong scientific criticism and growing opposition from many sources. Ironically, less than 20 years later, the need for a dynamically migrating, eroding and depositing river channel, is widely recognized (if not universally accepted), and restoration of dynamic river processes is a goal of both the CALFED and USFWS AFRP programs, as well as the SB 1086 process, discussed above.

Brice (1977) studied lateral migration in a 50-mile reach from Chico Landing to Colusa, based on historical maps (1867-1949) and aerial photographs (1924-1974). He observed that the sinuosity of the river (defined as the channel length divided by the valley length, a measure of "crookedness") decreased from 1.56 in 1896 to 1.35 in 1974, principally through meander cutoffs. Brice noted that the mechanism of meander cutoff was erosion of straight or diagonal chutes across the meander necks, rather than gradual narrowing of the necks. He also observed that flood flow velocities across meander necks (and elsewhere across the floodplain) would have increased as a result of removal of the riparian forest, and thus he concluded that removal of riparian forest had increased the frequency of cutoffs and decreased total channel length and sinuosity. He noted that the long-term average bank erosion rate (1896-1974) was 1.8 ac/mi.

WET (1988) studied geomorphic and hydraulic conditions in the reach from Woodson Bridge to Hamilton City, noting that sinuosity in this reach was slightly higher in 1923 (1.62) than in 1896 (1.57). WET argued that since channel slope would be lowest when channel length was greatest (i.e., when sinuosity was highest), the lower slope would lead to reduced sediment transport capacity, inducing shoaling in the upstream limb of the meander bend, thereby inducing meander cutoff. While it is clear from the geomorphic literature that channel changes can be endogenic (resulting from progressive internal changes), the shoaling argument does not clearly distinguish cause-and-effect, and it implicitly assumes that the channel has sufficient sediment load that if the slope flattens slightly, deposition will ensue. (This assumes that the channel is not sediment starved.) The *shoaling hypothesis also does not exclude the potential for meander neck devegetation to* increase overbank flow velocity and thereby increase chute erosion as a mechanism for meander bend cutoff.

The role of post-Shasta-Dam-reduced flood magnitudes (Section 2.1) in reducing channel migration is not clear, but extensive bank protection projects, both public and privately funded (Figure 2.2-2), have certainly reduced the meander migration potential of the river.

Riparian forest establishment and succession (in the context of geomorphic channel dynamics) along the Sacramento River were described in general terms by the California State Lands Commission (1993) and papers in Warner and Hendricks (1984). Changes over time in riparian forest extent were described by Katibah (1984), The Bay Institute (1998), and Greco (1999). Detailed geomorphic and ecological (current and historical) studies, linking channel processes and riparian succession, have been undertaken on rivers elsewhere in North America (e.g. Johnson 1992, Rood et al. 1998, and Dykaaar and Wigington *in press*). On the Sacramento River, however, the most notable example is the Ph.D. thesis of Greco (1999): a detailed study of riparian vegetation change since 1938 over River Mile 196-219, ultimately with application to habitat for the ESA-listed yellow-billed cuckoo.

2. Physical Setting

2.1 Hydrology

The Sacramento River drains about 8,900 square miles at Red Bluff, the northern end of the reach of greatest concern for this report, and about 12,100 square miles at Colusa, below which the river is tightly constrained by levees. The river receives a majority of watershed runoff during winter rain storms and spring snowmelt. Geomorphically, spring-summer snowmelt runoff is less important than it is in tributaries that drain the generally higher terrain of the Sierra Nevada mountains. The combination of relatively low elevation mountain ranges and volcanic terrain contributed to a moderate magnitude spring snowmelt component and sustained moderately high summer baseflows compared to central and southern Sierra tributaries. The ratio of bankfull discharge (estimated by $Q_{1.5}$=85,000 cfs) to mean annual flow (Q_{mean}=11,000 cfs), used to indicate the relative influence of winter storms and annual low flow periods, is 7.4 for the Sacramento River (by comparison, this ratio for northern California coastal watersheds ranges as high as 50). Additionally, the high proportion of the watershed that lies below the rain/snow transition elevation produced large magnitude winter storms from rainfall events, and potentially more frequent rain-on-snow events. Flows in the Sacramento River are highly variable, both between and within years, although the variability has been significantly reduced since 1943 by flow regulation by Shasta Dam. Appendix A presents hydrographs for the Sacramento River at Bend Bridge from 1892-1997.

The river's hydrology has been profoundly altered by dams and diversions, which now reduce peak flows (Figures 2.1-1, 2.1-2) and increase summer flows (Figure 2.1-3). Besides Shasta Dam, major water supply projects include:

- The Glenn-Colusa Irrigation District diversion, located just upstream of Hamilton City at RM 206, began diverting summer flows for irrigation around the turn of the century, and has a diversion capacity of about 3,000 cfs.
- The ACID diversion, located on the north side of the City of Redding downstream of Shasta Dam, began diverting for irrigation during the summer months, around 1917.
- The Red Bluff diversion and Tehama-Colusa Canal at Red Bluff was built in 1964, and diverts during the summer months for irrigation.
- The Trinity River Division of the Central Valley Project was completed in 1963, and typically diverts over 1,000,000 acre-ft of Trinity River flows into the Sacramento River basin just below Shasta Dam.

There were also large diversions for agricultural water supply downstream from Chico even before construction of the ACID diversion, but these other diversions had little effect on flood flows. The Sacramento River Flood Control Project (authorized by the U.S. Congress in 1917) uses natural floodbasins as bypasses for floodwaters: the Butte Basin with a design capacity of 130,000 cfs, the Sutter Bypass with a design capacity of 180,000 cfs, and the Yolo

Bypass with a design capacity of 362,000 cfs (Fisher 1994). The effect of Shasta Dam on flows in the river is illustrated (Figures 2.1-4 to 2.1-8) by annual hydrographs showing both computed inflow to Shasta Reservoir and outflows measured at Keswick for years of varying wetness: 1990 (dry); 1980 and 1984 (normal); and 1983 and 1998 (wet).

This hydrological evaluation has two purposes: to illustrate how water supply development has changed components of the annual hydrograph, and to provide the framework to illustrate how specific changes may have impacted the ecosystem. Primary ecosystem components of concern discussed in this paper are:

- Geomorphic processes, including bed mobility, bedload transport, and channel migration.
- Riparian processes, primarily initiation, establishment, and succession, and to a lesser degree, woody debris input.
- Salmonid life history, including life history related flow needs for spring-run chinook salmon, fall-run chinook salmon, winter-run chinook salmon, and winter-run steelhead (are being summarized for the entire Sacramento-San Joaquin-Delta system in a white paper on salmonids now in preparation.

A useful way to describe streamflow hydrology in a manner that these geomorphic, riparian, and biological ecosystem components can be related to is by describing hydrograph components. This also better enables us to predict how changes to natural or existing hydrograph components expected by the proposed off-storage diversion will impact (or improve) components of the ecosystem described above. We identified four primary components of the annual hydrograph that are present during most or all water year types (Figure 2.2-9: annual hydrograph of water year (WY) 1938 at Red Bluff): (1) low summer baseflows extending from July through September/October, (2) large magnitude, short duration winter floods during December through April, (3) sustained high winter baseflows intermittent between high flow events, and (4) a spring snowmelt flood of long duration, but typically moderate magnitude. To compare the effects of major hydrologic alteration on streamflows, we estimated the streamflow for each hydrograph component for "unimpaired" conditions (WY 1892 to WY 1943) and post Shasta Dam regulated (WY 1944 to WY 1998) periods:

- **Summer baseflows** were computed as August daily average flow. Summer baseflows began following the spring snowmelt recession in July and August and lasted through autumn when the first rainfall events occurred. During unimpaired conditions, summer baseflows ranged from 2,500 to 3,500 cfs during dryer water years, and as high as 9,000 cfs during wetter water years. Summer baseflows were significantly increased by construction of Shasta and Trinity River Projects, which store spring runoff and increase water delivery to the San Francisco Bay Delta diversion facilities during the summer. Regulated summer baseflows during dry years ranged from 4,000 to 10,000 cfs, and as high as 15,000 cfs during wetter years.
- **Winter floods** were computed as the maximum daily average flow during the water year, in contrast to the annual instantaneous maximum used in flood frequency analysis. The Sacramento River exhibited an extremely wide range of winter flood flows during unimpaired conditions, ranging from 28,000 to 80,000 cfs during dry years, 80,000 to

130,000 during normal water years, and up to 260,000 cfs during wetter water years. The instantaneous peak flood of record, approximately 291,000 cfs, occurred in February 1940. Winter flood magnitude and frequency were significantly reduced by regulation from Shasta Dam. During dry water year types, the annual maximum discharge was reduced to 11,000 to 31,000 cfs. The post-dam instantaneous peak flood of record was only 157,000 cfs. The 1.5-year flood, often used as an indicator of a channel forming flood, has been reduced from 86,000 cfs to 61,000 cfs, a 30 percent reduction.

At Red Bluff, the average annual flood was 121,000 cfs before construction of Shasta Dam (1879-1943), and 79,000 cfs thereafter (1944-1993). The 10-year flood has been reduced from 218,000 cfs to 134,000 cfs. This has reduced the overall energy available to transport sediment and drive channel migration. At the same time, sediment supply to the river has been reduced by sediment trapping in reservoirs, mining of sand and gravel from channel beds, and artificial protection of river banks whose erosion had formerly supplied sediment to the channel. It could be argued that flood control operations, by releasing prolonged bankfull flows, may actually have increased the potential for bank erosion; if this effect is real it has been more than offset by extensive riprap along the river. Peak flows below Butte City are also sharply reduced by diversions into the Butte Basin (Figure 2-1-2).

Winter baseflows were computed as the median flow for February and March of each year. Winter baseflows occurred between storm runoff events from November through April/May, and varied depending on winter storm magnitude, duration, and frequency. During unimpaired conditions, winter baseflows ranged from 5,000 to 11,000 cfs during dry water years, 11,000 to 22,000 cfs during normal water years, and as high as 50,000 cfs during wet years. Streamflow regulation from Shasta Dam had variable effects on winter baseflows. Winter baseflows during dry water years were reduced to a greater extent than during wet water years: dry water years range from 4,000 to 7,000 cfs, while wet water year types range from 15,000 to 50,000 cfs.

Spring snowmelt runoff occurs between mid-April and mid-June. Peak floods during the snowmelt hydrograph were much smaller than peak floods during winter storm events because most of the Sacramento River watershed is lower elevation than adjacent rivers that drain the higher elevations of the Sierra Nevada Mountains. The snowmelt runoff is biologically very important because many species of riparian vegetation disperse seeds, and several species (and runs) of fish migrate during this runoff period. The range of the snowmelt runoff period and magnitude of peak flows are longer and larger for wetter water years, and shorter and smaller for drier water years. Peak flows historically ranged from 4,000 to 13,000 cfs for drier water years and over 30,000 cfs during wetter years. Flow regulation from Shasta Dam, and flow augmentation from the Trinity River Diversion, virtually eliminated the shape of the natural snowmelt runoff hydrograph (Figures 2.1-4 to 2.1-8). While changes to peak flows were moderate (drier years ranged from 6,000 to 10,000 cfs, and over 25,000 cfs during wetter years), the gradual seasonal recession limb was replaced by an artificially managed hydrograph, which in some cases involved rapid up-ramping and down-ramping, but overall, changes in discharge, averaged over two week periods from mid-April to mid-June, have somewhat moderated in the post-Trinity period, compared to the pre-Shasta period (Figure 2.2-10), with fewer strong decreases in flow during the germination period of seeds of willows and cottonwoods.

TABLE 2.1-1
Principal Gauges on the Sacramento River

Location (no) Period of Record	DA (mi^2)	Q_{av} (cfs) (period)	Remarks
Keswick (3705) 1939-present	6,470	8,380 (1939-1963)	Drainage area excludes Goose Lake Basin. Average flow adjusted for change in contents and evaporation from Shasta Reservoir
Red Bluff (Bend Bridge) (3771) 1892-present	8,900	11,400 (1892-1962)	Diversions from the Trinity Basin began in 1963
Butte City (3890) 1921-present	12,080	13,130 (1939-1991)	Located upstream of flood overflow into Butte Basin
Colusa (3895) 1921-present	12,090	11,340 (1946-1992)	Located downstream of flood overflow into Butte Basin
Verona (4255) 1930-present	21,300	18,800 (1930-1991)	Located downstream of Feather River confluence; flood flows bypass gauge.
Sacramento (Freeport) (4476) 1949-present	23,500	23,330 (1949-1991)	Located below confluence of American River; flood flows bypass gauge.

2.2 River Channel

From Red Bluff downstream, the Sacramento River meanders within a belt of recent alluvium. The channel forms of the Sacramento River are the result of geomorphic processes, the influence of geologic structures, and human alterations. The river is characterized by an active channel, with point bars on the inside of meander bends, and flanked by active floodplain and older terraces. While most of these features consist of easily erodible, unconsolidated alluvium, there are also outcrops of resistant, cemented alluvial units such as the Modesto and Riverbank formations (Helley and Harwood, 1985). The region is tectonically active, with many landscape features formed as a consequence of a history of east-west compression progressing up the valley, corresponding to the northward migration of the offshore Mendocino triple junction over the last 25 million years (Harwood and Helley, 1987). The channel bed is composed of gravel and sand with the proportion of sand increasing downstream and on point bars. The bottomlands flanking the channel consist of silts and sands (deposited from suspended load in floodwaters) commonly overlying channel gravels and sands. Higher, older surfaces consisting of commonly cemented Pleistocene deposits are also encountered. The Sacramento River in our study reach lies between faults associated with the Chico Monocline to the east and the Willows and Corning faults to the west. The widest zone of active alluvium occurs between Hamilton City and Butte City (RM 200-170), where the river follows the axis of the Glenn syncline (Harwood and Helley 1987).

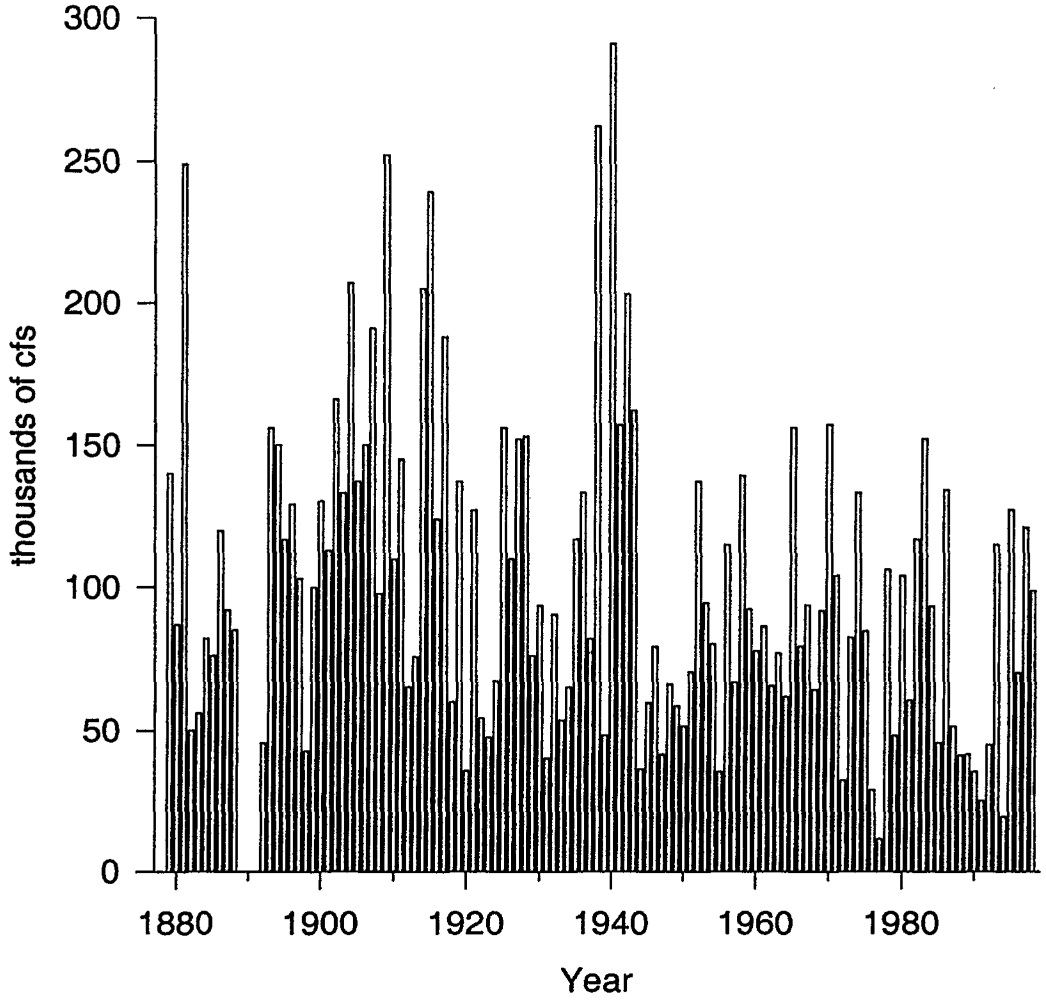

FIGURE 2.1-1
Annual peak flows in the Sacramento River near Red Bluff (Bend Bridge), 1879 – 1998. Peak flows have been affected by Shasta Dam since 1943. Data from U.S. Geological Survey internet site (www.usgs.gov).

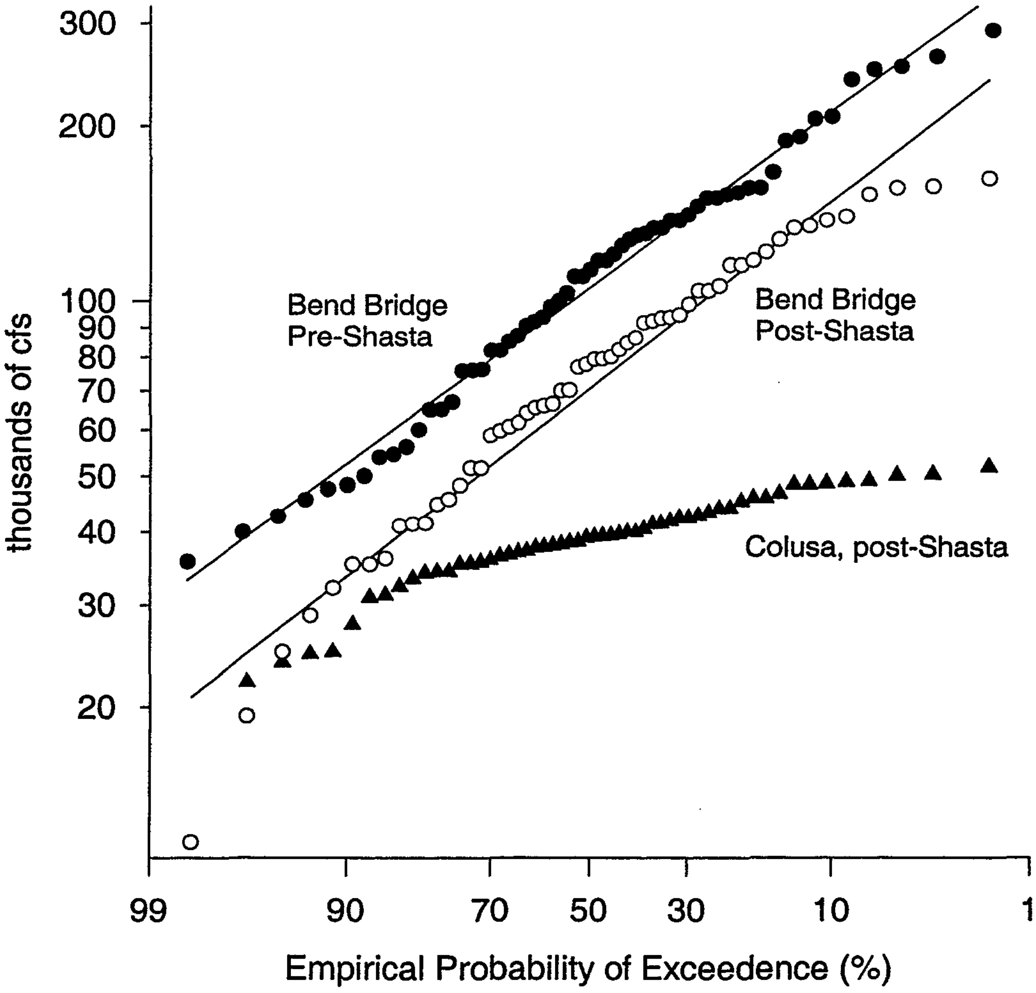

FIGURE 2.1-2
Empirical flood frequency plots for the Sacramento River at Red Bluff (Bend Bridge gauge) for pre- and post-Shasta periods, and downstream at Colusa for the post-Shasta period. The reduced peak flows at Colusa reflect diversions into the Butte Basin between the two gages. Data from U.S. Geological Survey internet site (www.usgs.gov), Red Bluff (Bend Bridge) and Colusa gages.

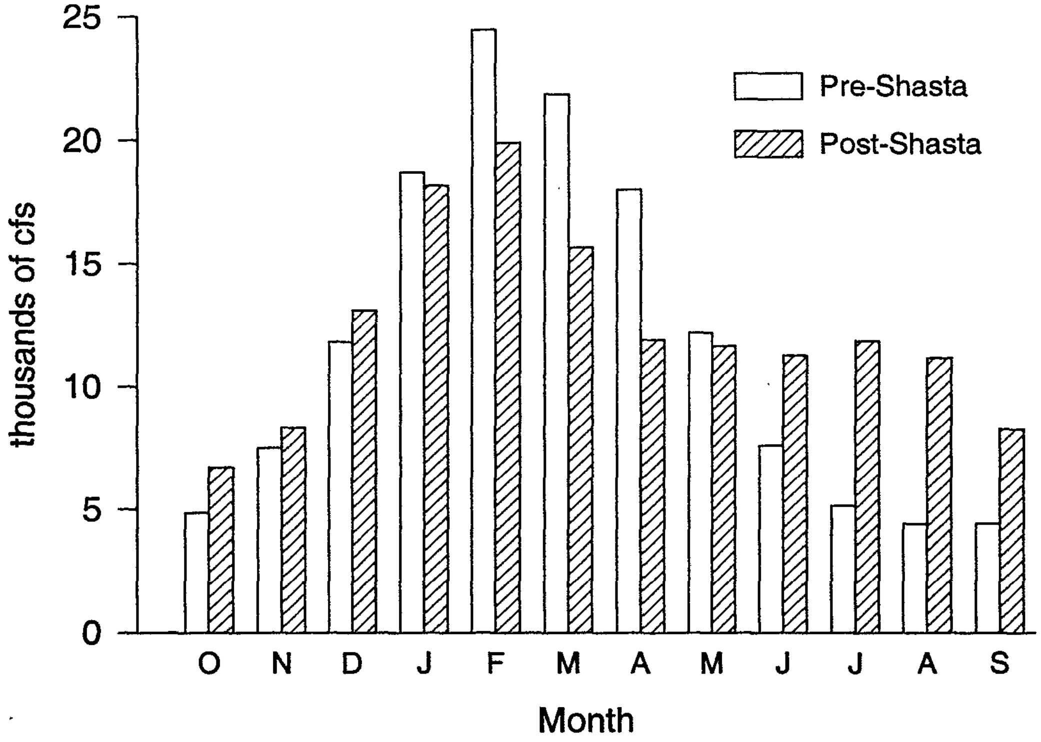

FIGURE 2.1-3
Mean monthly flows in the Sacramento River near Red Bluff, before and after regulation by Shasta Dam. Monthly mean flows for May have been almost unchanged, but mean flows for July and August have been more than doubled. Data from USGS, Bend Bridge gage.

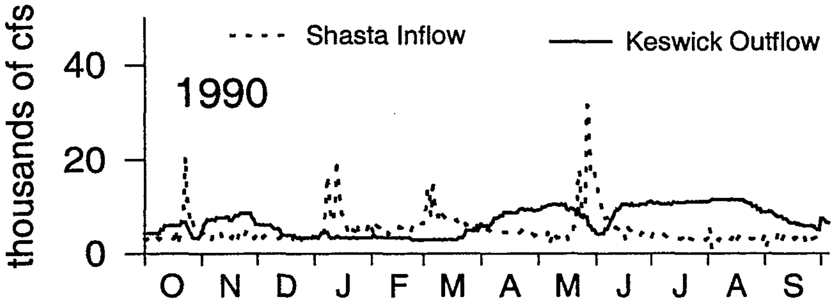

FIGURE 2.1-4
Computed natural inflow to Shasta Reservoir and Keswick outflow for Water Year 1990 (dry). Data from U.S. Geological Survey internet site (www.usgs.gov) for the Keswick gage, and U.S. Bureau of Reclamation for inflow.

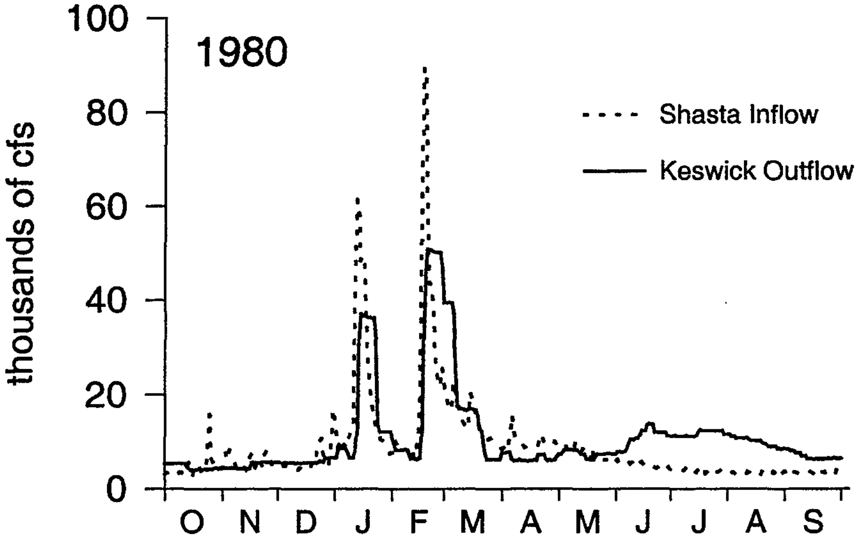

FIGURE 2.1-5
Computed natural inflow to Shasta Reservoir and Keswick outflow for water year 1980 (normal).

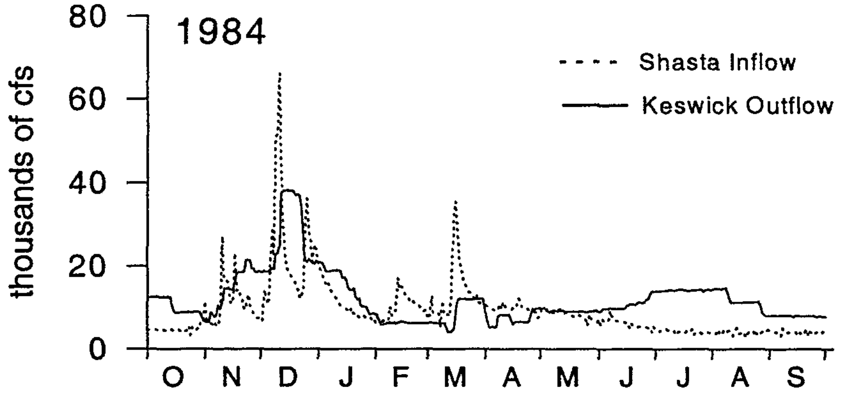

FIGURE 2.1-6
Computed natural inflow to Shasta Reservoir and Keswick outflow for Water Year 1984 (Normal).

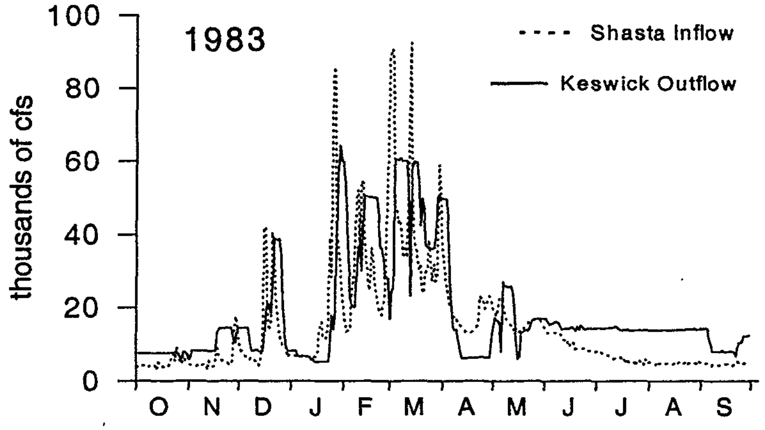

FIGURE 2.1-7
Computed natural inflow to Shasta Reservoir and Keswick daily flow for Water Year 1983 (Extremely Wet).

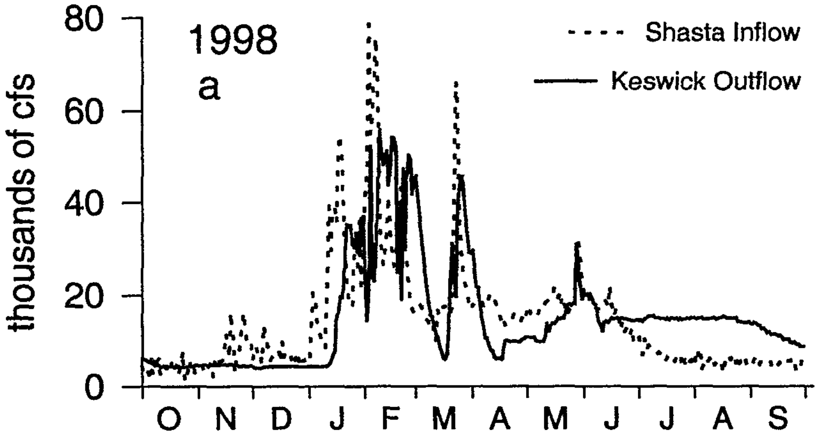

FIGURE 2.1-8
A) Computed natural inflow to Shasta Reservoir and Keswick Daily Flow

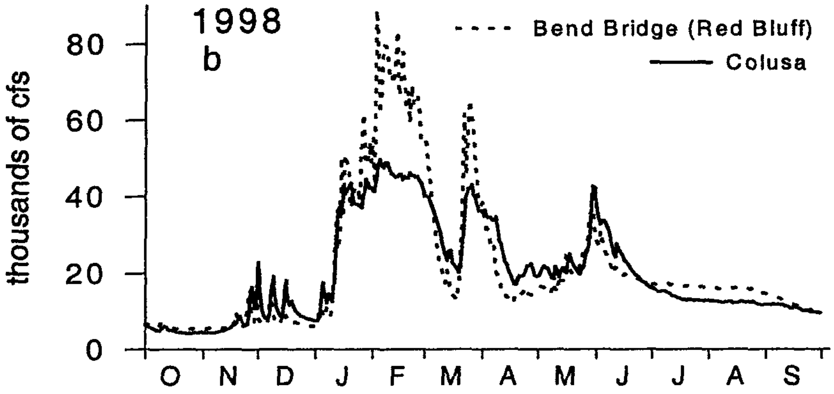

FIGURE 2.1-8
B) Mean daily flows at Red bluff (Bend Bridge) and Colusa for Water Year 1998 (Extremely Wet).

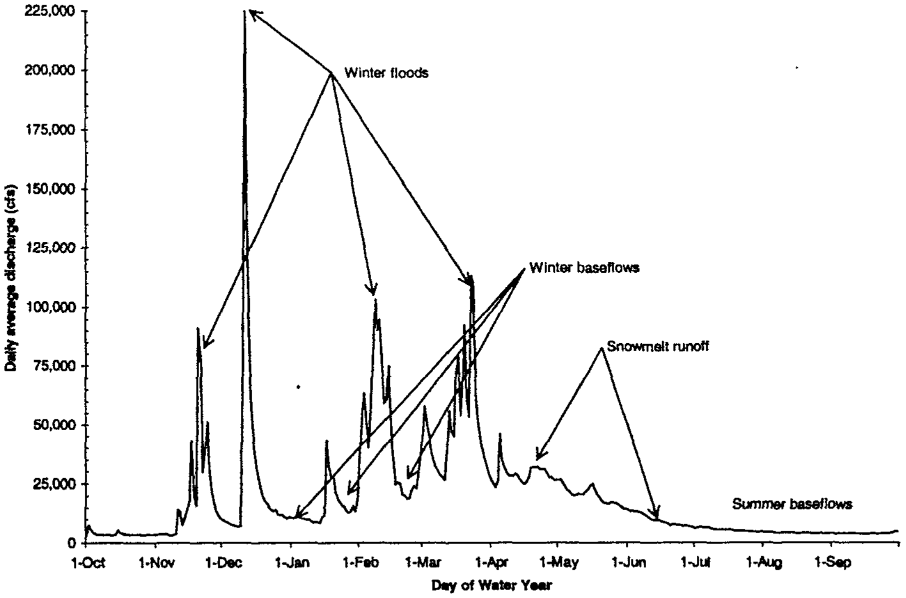

FIGURE 2.1-9
Sacramento River hydrograph components illustrated in the 1938 hydrograph for the Sacramento River above Bend Bridge, near Red Bluff gaging station.

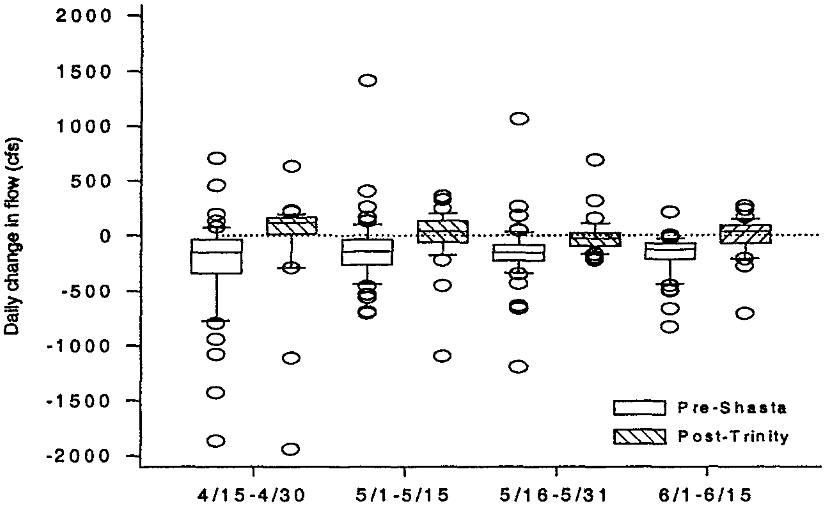

FIGURE 2.1-10
Box plot showing the distribution of changes in discharge in the Sacramento River near Red Bluff, averaged over 15 day periods, for the periods before construction of Shasta Dam and after construction of the Trinity River project. In each box plot, the box spans the 25th to 75th percentiles in the distributions, the line across the box shows the median, the "whiskers" show the 10th and 90th percentiles, and the circles show individual extreme values. Data from USGS, Bend Bridge gauge.

The river channel migrates across the floodplain to the limits of the meander belt, constrained only by outcrops of resistant units or artificial bank protection. As meander bends grow, they may become unstable and form cutoffs. Over time, meandering channels naturally tend to maintain roughly constant dimensions, as erosion of outside bends is balanced by deposition on point bars. However, most alluvial reaches of the Sacramento River have narrowed during this century in response to reduced flood flows and bank stabilization measures (Fisher 1994).

Floodplains are constructed primarily by lateral accretion of point bars and vertical accretion from suspended sediments in overbank flows (Wolman and Leopold, 1957). Other types of accretion, such as braided channel deposits, and accretion in abandoned channels can be important in some rivers (Nanson and Coke, 1992). Lateral point bar accretion and overbank deposition are readily observed along most meandering and wandering channels carrying a mixed load of gravel, sand, and silt/clay, and result in a characteristic floodplain stratigraphy of channel deposits (gravel and/or sand), overlain by point bar deposits of sand and perhaps gravel, in turn overlain by overbank deposits (sand and silt/clay), as illustrated in Figure 2.2-1. Irregularities in the surface of the coarse-grained bar deposits are smoothed out by deposition of suspended sediment from overbank flows, as overbank deposits tend to fill low points (e.g., channels) more than high points (e.g., bar tops). As a result of fine sediment deposition, many flood plains have a relatively flat surface. However, the surfaces of many floodplain are rough due to the hydraulic effects of trees and large woody debris, and differential deposition and scour associated with them. Along braided rivers, the floodplain surface may still bear the form of the braided bars in the river channel. Flow regulation or channel incision may reduce the rate of channel migration and frequency of overbank flooding, which, in combination with reduced suspended sediment loads below the reservoir, may result in reduced overbank deposition of the sand and silt needed to create and maintain floodplain habitats.

Downstream of Colusa, the Sacramento River has a sand bed and its banks are composed of fine grained flood deposits. the channel here was flanked by natural levees which formed when sediment-laden floodwaters left the channel and spilled on to the floodplain, slowing down and dropping the coarsest fraction of their suspended load next to the channel margin. The channel in this reach is now flanked by artificial levees.

Bank erosion involves a variety of processes, including fluvial entrainment, bank unraveling, and bank mass failure (e.g., Osman et al. 1988; Thorne and Osman 1988, Pizzuto and Meckelnburg 1989). The most obvious results of bank mass failure are the large "slump blocks" visible in many streams. The ground becomes saturated at times of high flow, and when the flow recedes large blocks of the bank fall into the stream, because "positive pore water pressure (in poorly drained banks) can weaken a bank by reducing its effective strength." (Thorne 1982). Mass failure can also occur if fluvial entrainment of bank material near the toe creates a cantilever that eventually collapses (Thorne 1982). Bank unraveling is similar to the mass failure described above. The bank, under the influence of flow forces and the effects of ground water return flow at lower stages, comes apart in smaller pieces that are removed by fluvial entrainment. Freezing and thawing can also create this type of bank erosion (e.g., Wolman 1959).

Although the static analyses of the soil mechanics of bank erosion are fairly straight forward (e.g., Thorne, 1982), dynamic analyses that link bank erosion to the mechanics of flow and establish an erosion rate related to the flow are much more difficult, and simplifications must be made. A simple hydraulic view of bank erosion is that flowing water exerts shear forces against the bank and directly entrains the bank material, so that erosion occurs locally in proportion to the magnitude of the local shear stress and in inverse proportion to the magnitude of the bank resistive forces. This must occur even when bank erosion involves mass failure, but in such cases material will accumulate at the toe of the bank before entrainment, rather than be directly removed from a steep or vertical bank (e.g., Hooke 1979; Thorne 1982).

Bank erosion may also occur as a result of water draining from floodplain and terrace surfaces as surface overland flow or subsurface pipe flow. Overland flow drainage of stormwater runoff can be locally important, creating impressive gullies and threatening structures, especially in urban areas. In larger floodplain-channel systems, drainage of overbank flow back into the channel on the flood recession limb can be an important mechanism of bank erosion, and is a common mechanism for breaching meander necks.

The diversity of riparian habitat depends upon the diversity of physical environments for vegetation, ranging from freshly deposited, coarse-grained point bars (colonized by early successional species) to higher floodplain surfaces underlain by fine-grained overbank sediments (supporting mature, later successional species) (Figure 2.2-1). The diversity of this physical habitat is maintained by active channel migration (Ward and Stanford, 1995), with the greatest diversity present in the actively migrating, meandering rivers. With reduced rates of channel migration below dams, the areal extent of pioneer forests may decline, offset by an increase in extent of later successional species, and resulting in an overall loss of species (and therefore habitat) diversity (Johnson, 1992). There is general agreement that meander cutoffs have become more common in the Sacramento River since the 19th century. Brice (1977) attributed the increased frequency of meander cutoffs – and resultant shortening of the river – at least partially to removal of vegetation from the floodplain in general and particularly from meander necks, which has reduced hydraulic resistance and increased velocities across meander necks, thereby facilitating meander cutoffs. WET (1993) attributed the increased cutoff rate to internal meander dynamics.

Meander migration and channel form have been profoundly affected by bank riprapping projects, which include both publicly funded projects and private protection funded by landowners. Although our study concerns flow regime, bank erodibility can be viewed as the "other factor" controlling meander migration rate. The extent of riprap is a constraint on re-establishing natural channel processes. The ongoing acquisition/easement efforts under SB 1086 are thus the logical complement to improvements to the flow regime considered in this study. Riprap is especially important when we consider that the zone of potential vegetation recruitment has been reduced by the reduced flows, and that this effect is compounded by stabilizing eroding bends, which narrows the channel and thereby compresses the zone of potential recruitment.

Downstream of Colusa, nearly the entire length of channel is riprapped and most is confined by close levees. In our study reach (from Colusa upstream to Red Bluff) the length of riprapped bank is equivalent to about half of the total channel length. This includes both federally financed riprap constructed by the U.S. Army Crops of Engineers and local, usually private landowner-installed rock. Some of this riprap no longer functions to control bank erosion because the channel has migrated away from it. However, the overall effect of this riprap on channel migrations is greater than the figure of 50 percent would suggest, because riprap is typically placed on the outside of meander bends and other locations where erosion would be expected to occur. This is illustrated in Figure 2.2-2, which shows the extent of riprap in a short reach near the mouth of Deer Creek near Vina, as mapped by Julie Cunningham and her colleagues at the Department of Water Resources in Red Bluff.

As meander bends migrate naturally, banks are undercut and mature trees (cottonwoods, valley oaks, etc.) fall into the channel and thereby become large woody debris (LWD). While the term "debris" recalls the negative connotations of wood in the river associated with navigation hazards and potential impacts to bridges and other infrastructure during floods, the ecological role of LWD is becoming increasingly recognized, especially for creating habitat for salmonids (Harmon et al. 1986, Maser and Sedell 1994). With time, LWD management will evolve to seek ways to permit some wood to remain in channels for ecological purposes, while modifying infrastructure to safely pass LWD during floods. Recruitment of LWD by channel migration depends not only on the rate of channel migration, but also the extent, distribution, and characteristics of the riparian forest.

2.3 Vegetation

Before European influence, a woody riparian vegetation mosaic covered the entire floodplain in the reach from Red Bluff to Hamilton City. South of this reach, the band of vegetation widened to 5 to 7 miles on either side of the river growing on the sands and silts of the natural levee deposits. Beyond the levees, the Butte basin to the east and the Colusa basin to the west, fine clay sediments accumulated in the wetlands and formed vast seasonal and permanent wetlands dominated by herbaceous plants, primarily Tules and Bullrushes. William Brewer observed in 1862 that the river channel was lined with a nearly continuous band of willows, cottonwood, Sycamore, and Valley oak from Sacramento to Red Bluff (Farquhar 1966). On the sandy and gravelly banks and point bars in the channel, several species of willow and Fremont's cottonwood established as seedlings, initiating the process of forest succession (see Section 3.2 for a detailed description). Away from the active channel, the floodplain sediments, composed of fine sands and silts, supported stands of Valley oak, Sycamore, Box-elder, Elderberry, and Oregon ash. A dense understory of grasses and sedges trapped fine sediments from the river with every flood. Where the river channel had been cut-off by channel avulsion, oxbow lakes and ponds, and dead-end sloughs supported open water communities, and were lined by swamps of Buttonbush, Valley willow, White alder, and Oregon ash (Thompson 1961; Katibah 1984).

Soon after 1850, the American and European gold miners realized the agricultural possibilities of the rich alluvial floodplain soils. Clearing of the forest commenced at this time for the production of winter wheat. Periodic flooding, however, limited this development to the higher portions of the floodplain and along the broad, natural levees of the river (Thompson 1961) . Within the Red Bluff to Chico Landing reach, this land use continued, along with livestock grazing, until the completion of Shasta Dam, when the threat of severe flood damage was removed from most of the floodplain (Kelley 1989). By the early 1960s, orchards of walnuts, almonds, pears, and prunes were being planted to the banks of the channel. Oxbow lakes and sloughs were filled using modern equipment and likewise converted to orchards. By 1996 estimates, less than 2 percent of the pre-1850

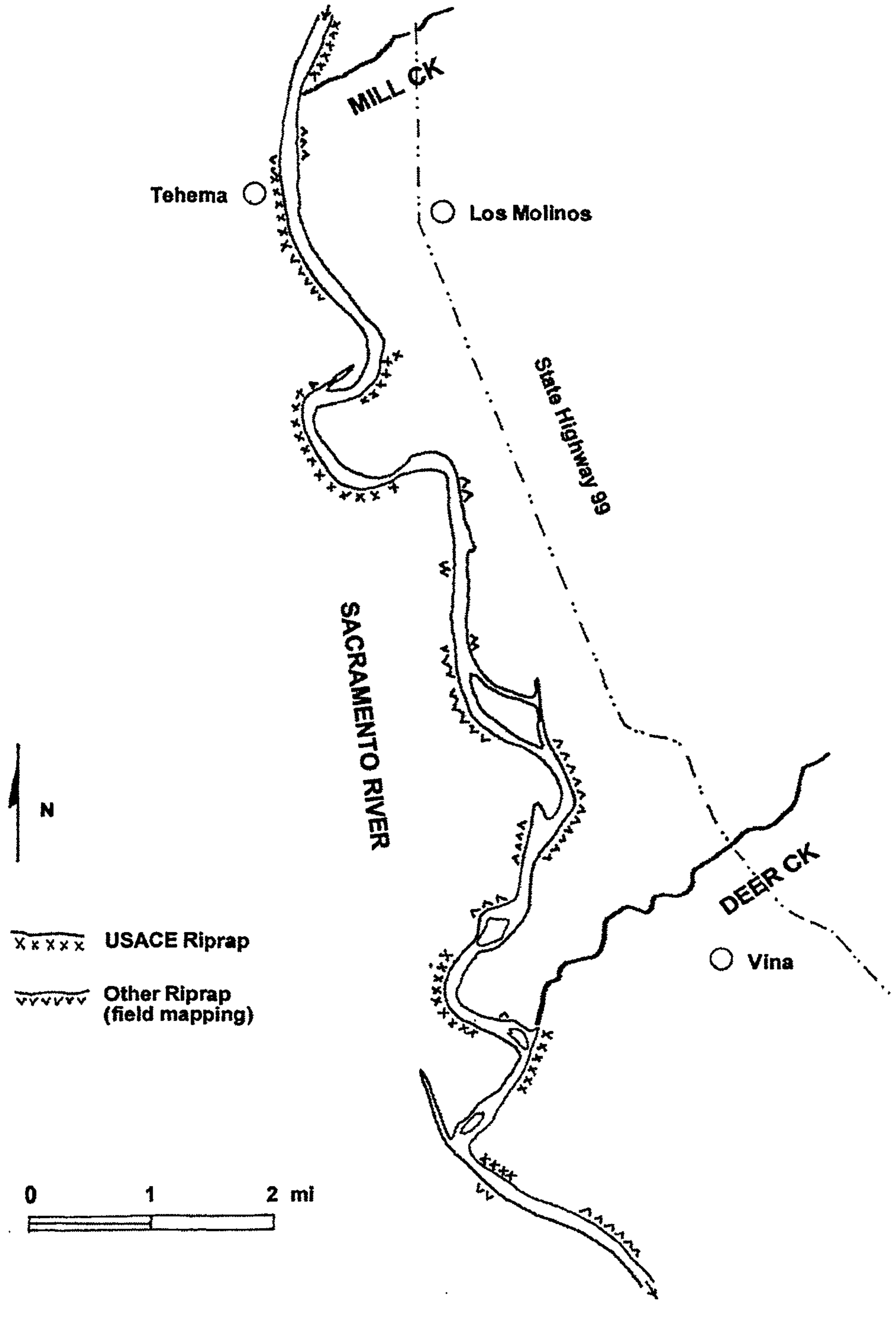

FIGURE 2.2-2
Map of riprap extent along the Sacramento River from the confluence of Mill Creek downstream to Woodson Bridge (adapted from unpublished map from Julie Cunningham, California Department of Water Resources, Red Bluff)

acreage of riparian forest remained, with virtually all of the Valley oak forest type gone (Bay Institute 1998).

To protect these orchards, riprap was installed, which altered channel form and the processes (see Sections 2.1 and 2.2). These changes affect willow and cottonwood seedling establishment. Where channels are stabilized by riprap, point bars tend to be subject to greater scour during winter flow, washing out seedlings . In addition, the increased flows from Shasta Dam during the spring and summer (see discussion of hydrograph model in Section 3.2) mean that the seasonal recession limb of the hydrograph no longer recedes slowly after the snowmelt run-off in May-June. Because of regulation, flows may increase from May to July, drowning seedlings of willow or cottonwood that may have established on point bars.

Several species of non-native (exotic) plants have invaded the riparian forests of the Central Valley since the arrival of Europeans. Giant reed (*Arundo donax*) and Salt cedar (*Tamarix parviflora*) grow most abundantly in the channel and can cause problems for flood damage control. These plants are a major component of the riparian vegetation on tributaries such as Stony Creek and Thomes Creek in the vicinity of gravel mines where they are apparently adapted to the frequent disturbance. Seeds and plant parts are washed into the Sacramento River each year where they establish new individuals. On the banks and floodplain Himalaya berry (*Rubus procerus*), Fig (*Ficus carica*), *Eucalyptus spp.*, and Black walnut (*Juglans hindsii)* often occupy many contiguous acres. Biologically, non-native plants do not provide the habitat values (foraging and nesting) for the native wildlife, and they take up space that could potentially be occupied by native trees and shrubs.

Agricultural weeds form another group of non-native plants that are in direct competition with seedlings and saplings of native trees and shrubs. The rich alluvial soil on the floodplain supports robust stands of Johnson grass (*Sorghum halapense*), Starthistle (*Centaurea solticialis*), Lambquarters (*Chenopodium spp*), and Pepperweed (*Lepidium latofolium*) which effectively prevent establishment by natives. These weeds will dominate a site until scour removes them, or they are buried under deposited sediment.

3. Issues

According to the intermediate disturbance hypothesis, an intermediate level of disturbance tends to produce the greatest species richness (Connell, 1978, Picket and White, 1985), and the role of disturbance in riverine ecosystems is increasingly recognized (e.g., Resh et al. 1988; Sparks et al. 1990). The term "disturbance" as used here refers to natural disturbances that tend to be transient, whereas human-induced disturbances tend to be more long-term. Moderate rates of bank erosion and bed mobility probably are such intermediate-level disturbances. Native fishes are adapted to natural flow regimes, and substitution of steady, regulated flows for naturally variable flows has probably facilitated establishment of exotic fish species that prey upon salmon below dams in California (Baltz and Moyle 1993). High flows and bank erosion are essential to maintain distribution, abundance, and diversity of species and successional stages of riparian vegetation (Scott et al. 1996; Hupp and Osterkamp 1996). Along semiarid channels, flooding may recharge the alluvial groundwater table, distribute seeds, and provide a pulse of moisture for their germination (Taylor 1982). Flood-driven channel migration, bank erosion, and deposition of fresh bar surfaces creates opportunities for pioneer species establishment and thus maintenance of diverse assemblages of riparian species (Scott et al. 1996). If high flows are reduced, riparian species and habitat diversity declines (Johnson 1992). On regulated rivers, bank erosion can be a major source of gravel for spawning habitat. On the alluvial Sacramento River, bank erosion now accounts for about 85 percent of the gravel supply (CDWR 1984).

3.1 Fluvial Processes

Fluvial processes cause the disturbance regime that is so important for a healthy ecosystem. Fundamental processes, and the channel morphology that results from these processes (form), include channel migration, bed mobility, balanced sediment budget (fine and coarse sediment transport), floodplain formation, riparian regeneration, and hydrologic variability (ERPP 1999; McBain and Trush 1997). These processes can and should be used as quantitative restoration objectives, or in the case of the Sacramento River, also used as maintenance objectives. Quantifying these processes usually requires a combination of empirical measurements and modeling, which entails more time and effort than allotted in this paper. Therefore, we present preliminary data and modeling output currently available that helps describe these processes and evaluate how potential diversion may effect these processes.

3.1.1 Bed Mobility

In many gravel-bed rivers the channel bed is scoured and mobilized about every year or two on average. If a dam reduces the frequency of scour, riverine food webs can be altered because reductions in floods allow increases in predator-resistant but scour-vulnerable invertebrates, effectively diverting energy away from the food chain supporting predatory fish (Wootton et al. 1996; Power at al. 1996). Below large storage dams, where flood flow magnitude and frequency has been significantly reduced, riparian vegetation has been allowed to establish and mature along the low flow channel, fossilizing alluvial deposits (bars),and thereby greatly reducing overall habitat availability (Pelzman 1973; McBain and Trush 1997). Under unimpaired conditions, frequent bed mobility and less frequent bed scour would discourage riparian vegetation from encroaching into the low flow channel.

The most commonly referenced need for bed mobility is the concept of "flushing flows." Below many dams, tributary-derived fine sediment has accumulated in gravel beds and pools because reduced high flows in the mainstem are inadequate to transport it downstream. A well-known example of this occurred on the Trinity River, where construction of Trinity and Lewiston Dams decreased the mean annual flood from 18,500 cfs to 2,600 cfs. Concurrent with this reduction of sediment transport capacity in the mainstem was an increased delivery of sand from tributaries affected by timber harvest. As a result, sand accumulated in the channel bed, filling pools and interstices of gravel and cobble riffles (Wilcock et al. 1996). Periodic scour of gravel beds is widely seen as necessary to flush fine sediment from gravels to maintain suitable conditions for spawning by salmon and trout (Milhous 1982) and from pools used as rearing or adult holding habitat.

However, the concept of "flushing" flows should be viewed in the context of the fine sediment budget, or the balance between fine sediment delivered to the channel from various sources and the rate at which fine sediment is transported downstream from the channel. The objective of a flushing flow is to decrease storage of fine sediment in the gravels. However, reduction in fine sediment storage in the channel can be accomplished either by increasing the transport from the reach (more water) or by decreasing the input to the reach (less fine sediment supplied to stream from upstream sources and bank erosion). Simply flushing the gravel without analyzing the complete sediment budget may lead to expensive, yet ultimately ineffective releases.

3.1.2 Channel Migration and Floodplain Formation

For riparian vegetation to flourish requires creation of suitable substrates on which seedlings of pioneer species can establish, the progressive build-up of sediment on those surfaces and they evolve from bare coarse-grained mineral soil to higher, finer grained soils on which later successional stage species can establish, and the periodic rejuvenation of floodplain by erosion of old surfaces with mature, late-successional stage trees and depostion of fresh bar surfaces for pioneer colonization. Thus, the physical processes of bank erosion, channel migration, deposition of point bars (and other fresh surfaces), overbank flooding and fine sediment deposition, are linked to the ecological processes involved in creating and maintaining a diverse assemblage of riparian vegetation of various ages and species (Figure 1.1-2). As well documented on the Missouri River below Garrison Dam, where reduced flood flows led to a reduction in stream power available to drive fluvial processes and channel migration was reduced, a drop in channel migration rate can lead to a dramaticdrop in the diversity of riparian habitats (Johnson 1992).

On the Sacramento River, it is not yet clear how meander migration rates have changed over the last 150 years, and how much such changes may have been due to reduced flood magnitudes and how much due to bank protection (the latter being probably the most important factor). However, to maintain and restoreriparian habitats along the Sacramento

River, we can envision the need for some flow regime to drive channel migration, coupled with a program to allow the river "room to move" across its bottomland. The latter has begun with the SB1086 program.

3.1.3 Sediment Transport, Sediment Budget, and Channel Maintenance

In natural alluvial channels (channels formed in erodible river deposits rather than bedrock), channel form is determined by flow and sediment load, with constraints set by geology and, especially in smaller streams, by vegetation. On many alluvial rivers, the peak flows occurring every 1-5 years on average are the flows that move the most sediment over time, and are considered the channel-forming flows. The dimensions of most alluvial channels are related to these flows, but only for channels roughly in equilibrium with prevailing flow and sediment load. In more arid environments, where the channel can be viewed as in a continuous state of adjustment to an episodic flow regime, channel dimensions may be scaled to less frequent, higher magnitude flows.

Because dams change the flow and sediment load downstream, they produce channel changes that are broadly predictable (Figure 3.1-1). For example, reservoirs trap gravel and sand, cutting off the supply to downstream reaches. If the downstream reaches still experience flows capable of transporting sediment, gravel and sand will be moved downstream without replacement, resulting in incision or downcutting of the bed and coarsening or "armoring" of the bed material. High flows released from dams, often called "sediment-starved" or "hungry" water, can eliminate formerly important spawning gravels for salmon. This has been an important impact on the upper Sacramento River and other tributaries that deliver coarse sediment to the Sacramento River (e.g., Clear Creek), and recent attempts have been made to partially mitigate for dam-related sediment starvation by adding gravel downstream of the dam (USFWS 1996). While this sediment introduction does increase alluvial storage in the river and increase sediment transport rates, introduction volume is nearly always a very small fraction of the pre-dam supply from the upstream watershed (Kondolf and Matthews 1993).

Another potential impact, as indicated in Figure 3.1-1, is when tributaries below the dam deliver high sediment loads of sand and gravel, and if the frequency of sediment transporting flows in the river is reduced, the bed may aggrade with sediment and become finer-grained. This occurred on the Trinity River after flow regulation by Trinity Dam (USGS, 1968). Along the Sacramento River, stream power is still high enough to transport most sediment delivered to it by tributaries, although some large bars have temporarily deposited at tributary confluences right after floods due to backwater effects of high river stage.

To address these sediment supply and transport issues, regulated rivers can be managed by releasing flows of magnitude and duration to transport tributary-derived sediments downstream, with coarse sediment introduction immediately downstream of the dam occurring at rates equal to maintain storage in the upper portion of the regulated reaches. For example, on the River Rhine, a gravel-sand mixture is added below the downstream-most dam (Iffezheim) in quantities equivalent to the river's sediment bedload transport capacity

(Kondolf 1997; Kuhl 1992). Sediment transport measurements and modeling efforts can help develop the tools necessary to improve flow releases and sediment introduction efforts.

Bank erosion can be an important source of sediment to the channel when viewed on time scales of decades-to-centuries, and especially downstream of dams, where upstream sediment supply has been eliminated. On the Sacramento River, DWR (1984) estimated that 85 percent of the supply of spawning sized gravel was derived from bank erosion. This is largely because other sources have been cut off; gravel from the watershed above Shasta Dam is trapped in the reservoir, and the river and many tributaries have been intensely mined for gravel, removing gravel from the streambeds that could have been transported to the mainstem Sacramento. Thus, in addition to rejuvenating riparian forests and maintaining dynamic processes in the bed, bank erosion serves an important role in salmon ecology in supporting spawning habitat. Viewed over a longer time period (centuries and greater) bank erosion is not a true "source," but simply amounts to taking gravel out of temporary storage in the floodplain.

3.2 Riparian Establishment

3.2.1 Riparian Vegetation Establishment

Riparian vegetation establishes in response to favorable conditions such as suitable substrate, soil moisture (generally a high water table), timing of seed dispersal with respect to the hydrograph, freedom from scour in the first years of growth, and freedom from excessive competition from other plants. In a naturally functioning river, these conditions are likely to be met on river margins, point bars, and some floodplains and other bars. On many gravel bed rivers, woody riparian vegetation typically establishes in a narrow band along the channel margin, between the zone of frequent scour and the zone of desiccation during the dry season. Seedlings that begin to grow on high surfaces will probably not succeed because of desiccation during the dry season, while seedlings that begin to grow on the active channel bed will likely be scoured by floods. With the focus of the SB1086 program on the riparian cottonwood forest, we focus here on requirements for cottonwood seedling establishment.

3.2.2 Riparian Species Succession

Species succession within the riparian forest follows a predictable sequence as river processes, interacting with the vegetation, creates and alters floodplain geomorphology. Fremont cottonwood and five species of willows colonize actively growing point-bars and other exposed sediment surfaces that are at, or near, the baseflow water table (Strahan 1984). As the seedlings grow larger over the years they trap sediments with each flood-event, causing the local vicinity to increase in elevation relative to the channel, forming a low depositional surface. As the area grows higher, flood frequency and flow velocities decrease, allowing the deposition of finer textured sediments, silts and clays, forming a higher surface above the river channel. These finer textured sediments provide the ideal seed-bed for species such as Box-elder, Oregon ash, and Basket sedge. With increasing density of vegetation, more and finer sediments are trapped, causing a land surface relatively high above the channel and immune from all but the biggest floods. These higher surfaces supported the Valley oak-Elderberry forests that today grow walnut orchards.

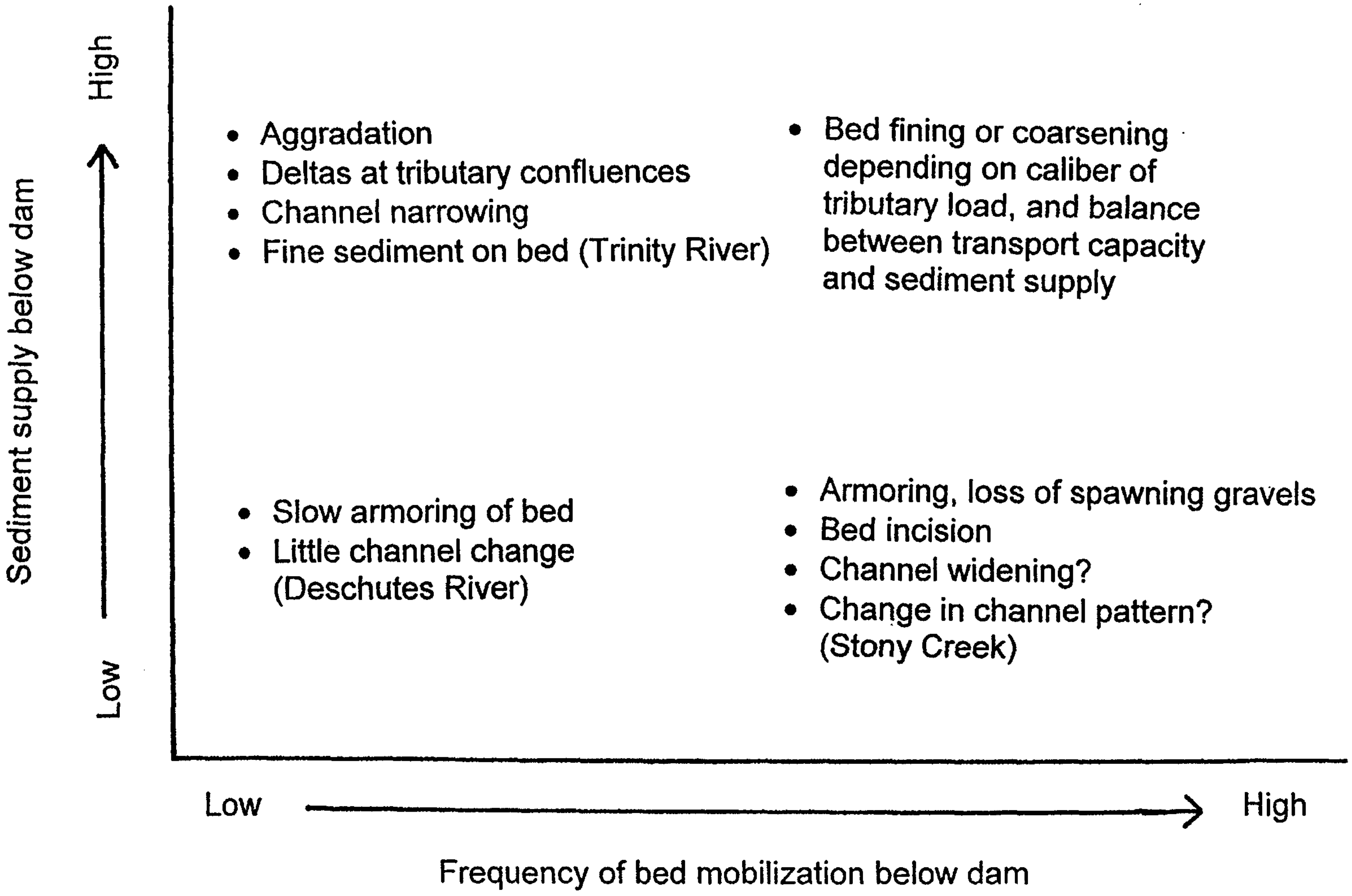

Figure 3.1-1

Chart showing channel changes below dams as a function of sediment supply from downstream tributaries and frequency of post-dam bed mobilization. Citations for examples listed are: Trinity River: Wilcock et al. 1996, Deschutes River: McClure 1998, Fassnacht 1997, Stony Creek: Kondolf and Swanson 1993.

TABLE 3.2-1
Riparian Woody Species Ecological Needs and Behavior on the Sacramento River

Species	Location on Floodplain	Light Needs	Water Table Needs	Drought Tolerance
Fremont cottonwood	Point-bars and avulsed channels	Full sun; very slow growth in partial shade	Must have roots in moist soils. In coarse sediments, roots must reach water table.	None
Valley, Arroyo, Yellow, Sandbar willows	Point-bars, avulsed channels, low terraces	Full sun; very slow growth in partial shade	Must have roots in moist soils. In coarse sediments, roots must reach water table.	None
Oregon ash and Box-elder	Usually away from active channel	Tolerates shade	Facultative	Drought tolerant in shade
California sycamore	Along secondary channels and oxbow lakes	Full sun; tolerates some shade	Must have roots in top of water table.	Resprouts from crown
White alder	Oxbow lakes	Full sun	Must have roots in top of water table.	None
Buttonbush	Oxbow lakes	Tolerates shade	Must have roots in top of water table.	Resprouts from crown
Valley oak, Elderberry, Rose	Highest terraces	Tolerates shade	Facultative	Well-developed

3.2.3 Conditions for Establishment of Riparian Vegetation

Typical temporal patterns of seed dispersal are shown in Figure 3.2-1. The hydrograph model shows the lines for the mean monthly discharges of the Sacramento River at Red Bluff, measured in cubic feet per second. A comparison of the pre-Shasta Dam progression through the year with that of post-Shasta Dam shows a marked difference, especially during the agricultural irrigation period of May through August. The horizontal lines with tree and shrub name labels are the dates of seed dispersal for each species (vegetative reproduction only for Arundo). The hydrograph model shows how the dates of each species' seed dispersal is adapted to the hydrograph. For example, cottonwood and willows are adapted to the receding limb of the hydrograph, while Sycamore, Alder, Ash, Box-elder, and Buttonbush are adapted to release their seeds prior to average peak flows for the year. Alteration of the hydrograph due to dams and water releases affects the seed and seedling biology of many of the riparian trees and shrubs. This, in turn, affects long-term succession of the riparian forest community.

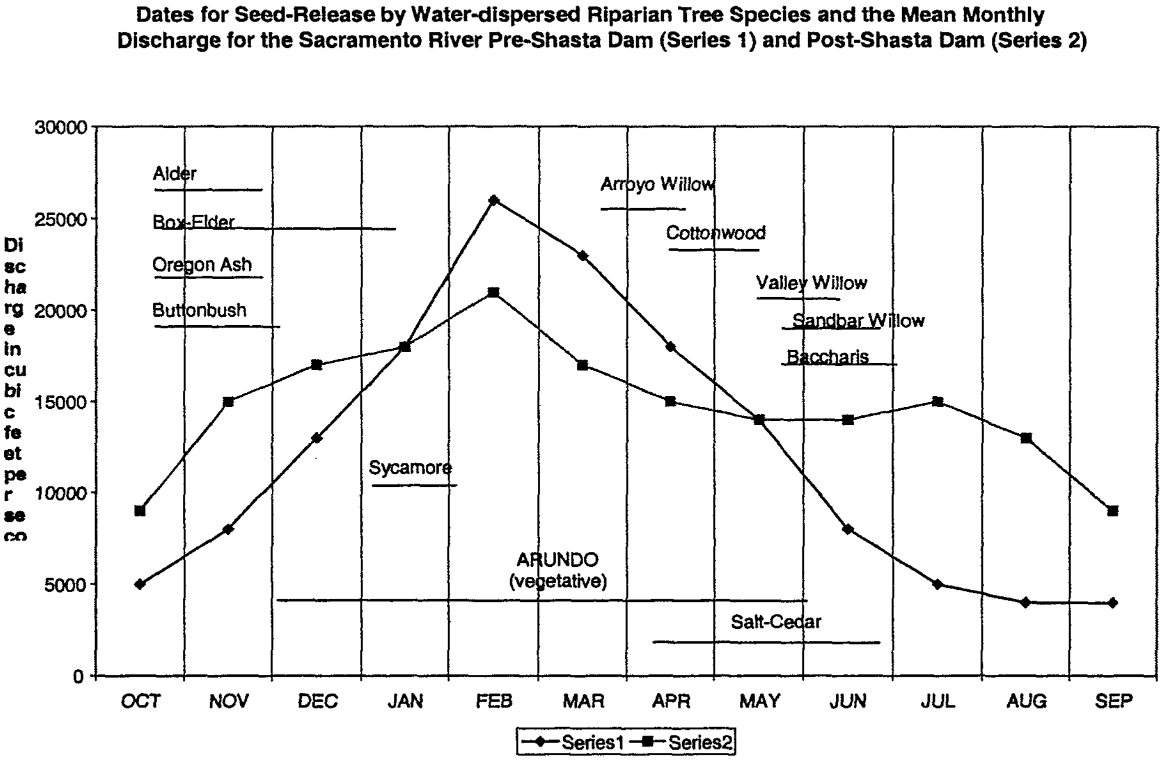

FIGURE 3.2-1
Riparian plant seed release (and vegetative propagation) periods and Sacramento River hydrology

3.2.4 Requirements for Cottonwood Seedling Establishment

Cottonwood trees do not establish every year, at least in large cohorts. A combination of circumstances - typically associated with large floods - appears necessary for successful recruitment (Johnson 1992; Friedman et al. 1996). On the Sacramento River, seedling establishment is further complicated by the altered hydrology. Our conceptual model of requirements for cottonwood seedling establishment (Figure 3.2-2) follows.

Bare mineral soil. Can be produced by scour or burial of a pre-existing surface, by creation of new point bar surfaces through channel migration, by deposition of other bars, and by sedimentation of cutoff meander bends. One feature of these fresh surfaces is a lack of competition from other plants (Rood et al. 1998, Braatne et al. 1996). For some riparian species such as valley oak, the reduction in herbivore populations following large floods is probably an important factor in successful seedling establishment. Exposure to sun is another important requirement for growth and development of cottonwood seedlings (Rood and Mahoney 1990, Johnson 1994), which tends to make larger channels with open bars better sites than small channels with closed canopies, and which excludes already vegetated sites. For seedlings to establish also requires that river level have dropped enough to expose the substrates for colonization.

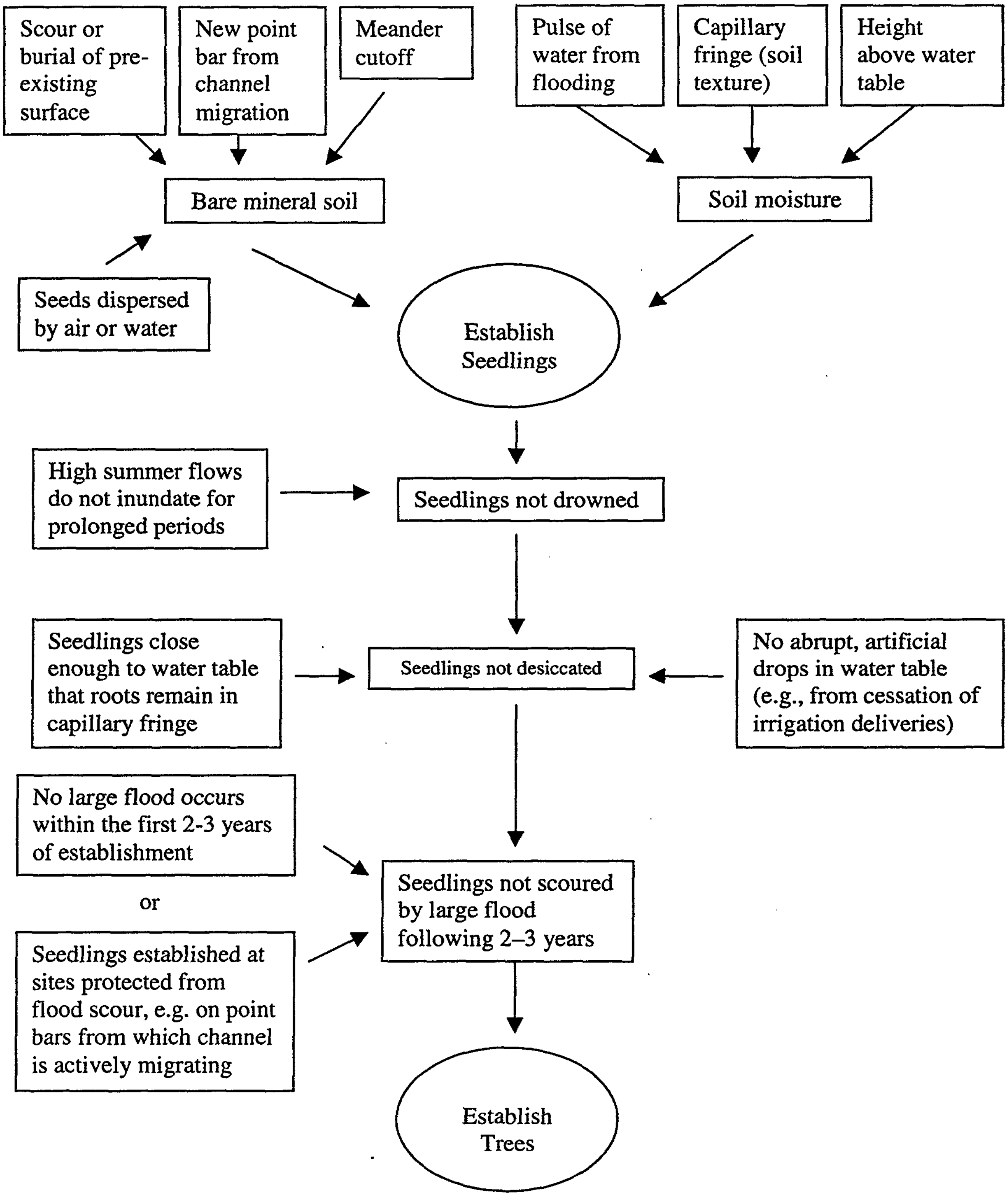

FIGURE 3.2-2
Conceptual model of requirements for cottonwood establishment on the Sacramento River

Elevation increases and finer sediments (silts) tend to occur with transverse distance from the channel centerline. These finer sediments retain moisture better and support a higher capillary fringe than coarse sands and gravel encountered along the channel itself. Moreover, these sites are less prone to flood scour than is the channel itself. Thus, seedlings established on these higher sites may have a better chance of survival, provided that height above the water table does not limit them. Larger floods are required to create fresh surfaces of bare mineral soils at these higher elevation sites.

Perhaps most important however, are abandoned channels such as meander cutoffs, which are depositional sites for fine sediments suspended in overbank flows. Colonization and succession (following the pathway described above) in these abandoned channels creates the largest areas of new riparian vegetation along the Sacramento under present processes (Greco 1999).

Adequate soil moisture. The seedbed must be moist during the period of seed dispersal. The cottonwood seed dispersal period on the Sacramento, in May, usually coincides with the recession limb of the seasonal hydrograph, so late storms that wet exposed soil by rainfall or by a brief increase in stage may be important for seedling establishment. Soil moisture is also affected by soil texture, which affects the moisture retention of recently wetted sediment, and which affects the height of the capillary fringe above the water table, a factor whose importance increases later in the season as the river stage (and alluvial water tables) decline. Adequate soil moisture, along with deposition of floating seeds at the margin of a receding river, explain the banding often observed in cottonwood stands. Wind blown seeds will be deposited over a large area, but suitable moisture conditions will occur only at specific elevations above the receding stream (Mahoney and Rood 1998).

Height above the late summer water table (usually inferred to be equivalent to river stage in gravel bars in the absence of observation wells), and the rate of seasonal decline of the water table, are important controls on seedling establishment. Mahoney and Rood (1998) propose the concept of a "recruitment box", a window in the seasonal hydrograph in which successful establishment can occur; the horizontal length of this box is the period of seedling dispersal, and the height is set by the rate of stage decline at which seedlings can extend their roots downward. For the Oldman River, Alberta, they estimated the rate of root growth at 2.5 cm/day; it may be higher along the Sacramento, but no data are available on this question.

The allowable rate of water level decline, or "ramping rate", is frequently specified below dams. While the ability of root growth to keep pace with water table decline is clearly an important factor, inspection of Sacramento River hydrographs in pre-dam years and during post-dam years known to have had good recruitment show recession rates in excess of 2.5 or even 5 cm per day. The rate of water table decline is buffered by the height of the capillary fringe above the water table, of course, and finer-grained substrates will have the capacity to hold moisture longer. Also, in late spring rains can provide much needed moisture, as occurred in 1995, one of the better recent recruitment years. The actual series of events leading to successful seedling establishment can be complex, so the ecological value of specifying a ramping rate is open to question.

Survival over summer-fall. Provided moist, bare surfaces are present, and assuming adequate seed dispersal occurs, we expect initial establishment of cottonwood seedlings to occur in May-June-July. Their continued development requires that they survive the dry period of late summer-fall. This requires that the seedlings not be desiccated during the seasonal recession, which implies that seedlings not be established too high above the baseflow water table and that flows should not drop more rapidly than roots can grow downward. This effectively sets an upper limit to the elevation above baseflow of seedling establishment, which ranges in published studies from about 1-2 m (Mahoney and Rood 1998).

The Sacramento River is used to convey irrigation water to downstream diversions, so its summer flows have substantially increased, from typically 5000 cfs pre-Shasta and Trinity Dams, to typically over 10,000 cfs. In many years, flows recede in the spring, only to rise in the summer due to irrigation deliveries, potentially drowning seedlings established at the lower level. Thus, to be successful, seedlings must germinate above the level of these irrigation-related flow reversals. Artificially abrupt drops in flow could affect seedling survival. For example, in 1982 flows abruptly dropped from about 60,000 cfs to under 20,000 cfs in mid April, probably associated with a change in reservoir operation rules effective on that date.

Thus, to survive the summer and fall requires that the seasonal recession not exceed the rate at which seedlings can extend their roots downward, that seedlings not be drowned by high summer flows, and that the seedlings not be desiccated by artificially rapid drops in stage.

Survival through year two. Survival requires that the plants not be scoured by floods. This requirement will select for seedlings established 1) in years that are not followed by high floods, 2) in sites protected from flood scour, such as meander cutoffs, or 3) in sites with low shear stress, such as point bars opposite an actively eroding (retreating) bank, where the principal erosive force is directed against the other bank and the entire channel is shifting away. In year two and beyond, developing saplings can trap suspended sediment from the water column, such that the elevation of the bar or floodplain is raised, thereby creating conditions for the colonization of later successional species, as described elsewhere.

Application of establishment requirements model to recent years with good recruitment. The conceptual model above implies that the best recruitment years would be those that follow a large flood, which would create new surfaces for colonization, and which, starting from a relatively high flow, experienced a gradual seasonal recession limb during and after seed dispersal. In addition, the subsequent two years would not have high scouring floods so that the seedlings become firmly rooted before being exposed to high shear stresses. Two recent years with evidently excellent recruitment (based on probable ages of cohorts observed in the field) were 1983 and 1995. 1983 was an extremely wet year, with multiple storms, a peak of about 100,000 cfs, and about two continuous months with flows over 50,000 cfs, followed by a fairly sharp drop in early April, a rise from late rains, and then increased flows for summer irrigation deliveries (Figure 3.2-3). 1995 had two rain-generated storm peaks of about 100,000 cfs followed by two peaks of over 40,000 cfs in mid-April and mid-May, caused by late rains, the last peak followed by a relatively gradual decline and then summer irrigation flows of about 15,000 cfs (Figure 3.2-4). In 1983, the sharp drop after the high flows and abrupt rise in May seems inconsistent with our requirement that plants not be drowned, but it may be that the successful plants established at higher elevations than affected by the May rise.

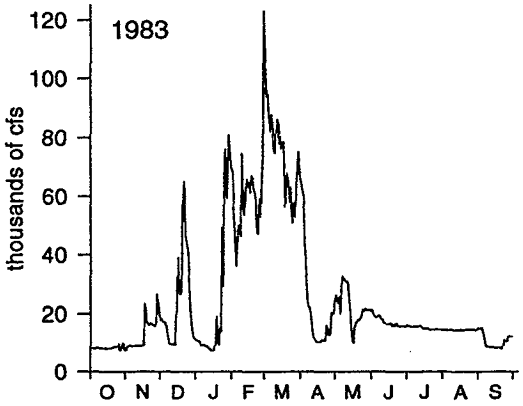

FIGURE 3.2-3
Hydrograph of mean daily flows for 1983, Sacramento River at Red Bluff (Bend Bridge). 1983 was an extremely wet year with excellent recruitment of riparian vegetation (source of data: United States Geological Survey internet site www.usgs.gov)

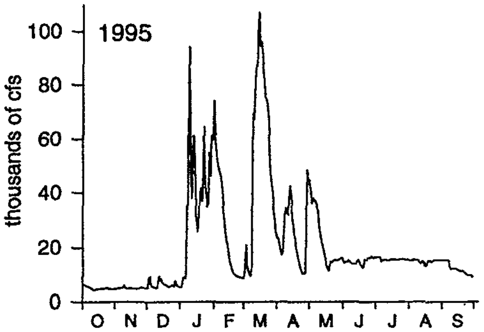

FIGURE 3.2-4
Hydrograph of mean daily flows for water year 1995, Sacramento River at Red Bluff (Bend Bridge). 1995 was a wet year with good recruitment of riparian vegetation (source of data: United States Geological Survey internet site www.usgs.gov)

3.2.5 Species with Spring Seed Dispersal

Following on the requirements for establishment of cottonwood described above, we can consider some of physiological characteristics of cottonwood and willows that may explain why they are rarely found as seedlings on the floodplain, but their seedlings are typically found on point-bars. Fremont cottonwood and the three willow species release their seeds at slightly different times on the recession limb of the hydrograph (in the spring), and seedlings germinate in the spring at the edge of flowing or standing water, growing roots downward to keep up with the receding water table. If they are unable to do this, they die. Cottonwood and willow seedlings and saplings cannot tolerate shading. Thus, these species will not establish under the canopy of existing trees or under herbaceous vegetation. This may explain the lack of seedlings on the floodplain, where woody and herbaceous species are in much greater density than on the point bar.

Cottonwood and willow saplings and trees tolerate, and may even benefit from, sediment deposition around their stems. For example, a flood may deposit 5 feet of silt around a cottonwood or willow. The trees respond by growing new roots along the trunk and continue growing. Should the same thing happen to a Valley oak, it would likely die because its root system would no longer receive enough oxygen and it does not have the ability to grow new roots from its trunk.

Species with spring seed dispersal tend to be near the channel, and early successional species. Forests developed on a frequently flooded (e.g., return period of 1.5 to 2.0-year) floodplain would be dominated by these species.

3.2.6 Species with Fall / Winter Seed Dispersal

Box-elder, Oregon ash, Buttonbush, White alder, and Sycamore disperse their seeds in fall/winter and are characteristically mid-successional species (that is, they are common in the mixed riparian forest), growing on the floodplain away from the active channel. We hypothesize that the seeds of these species are dispersed in the fall so that the high winter flows will carry them away from the channel. Alder and buttonbush are characteristic around oxbow lakes. Today, alder is commonly found along the main channel only in riprap, a similar substrate to its characteristic location among cobbles along foothill streams. In fact, this entire group of species are, by far, the most common colonizers of riprap. It is possible that riprap protects the seedlings from scour, however this has not been shown empirically. Some other characteristics of fall/winter seed dispersers include:

- They require fresh sediments - finer in texture than point bar deposits - for successful seedling establishment.
- They are shade tolerant (Alder and Sycamore, less so; Ash and Box-elder, more so) and the seedlings can be found under the canopy of existing forest.
- They are moderately drought tolerant if growing in the shade. When soil moisture is depleted they stop growth and may even defoliate before the end of summer, but not die.

These species would tend to be present on surfaces flooded every four years or more on average.

3.2.7 Species with Animal Dispersed Seeds

Valley oak, Elderberry, Grape, Rose, and Poison oak seeds are typically dispersed by birds, and are characteristic of rarely flooded upper floodplain surfaces. Some characteristics of these species include:

- They will establish best where herbaceous vegetation has been scoured away.
- They are all shade-tolerant when young.
- They all have well-developed drought tolerance.
- Prolonged spring flooding (>2-3 weeks in April) will kill Elderberry.

These species are typical of less-frequently flooded surfaces, dominated by biological interactions rather than frequent abiotic disturbance.

3.2.8 Dispersal of Non-native (exotic) species

The most abundant non-native plants in the riparian zone today are Giant reed (*Arundo donax*), Fig *(Ficus carica)*, Black walnut (*Juglans hindsii*), and Salt-cedar (*Tamarix parviflora*). Giant reed reproduces exclusively by vegetative means, typically by fragmentation of its rhizomes and also by portions of stems. Any flood event at anytime of the year will disperse Giant reed. It is a drought tolerant plant that has adapted to the current unnatural hydrologic regimes associated with flood-control releases from dams and gravel mining operations. Salt Cedar is abundant on some of the tributaries on the west side and produces abundant water-dispersed seed each spring. Fig produces fruits that are consumed by both birds and mammals, which spread its seeds far and wide. Black walnuts float on flood waters and are deposited over large areas. Very dense stands of sapling walnuts can be found on some higher floodplain surfaces with no other tree species associated with them.

3.2.9 Vegetation Encroachment

With reduced flood flows below dams, however, vegetation may successfully establish in the active channel bed because the plants are no longer scoured regularly, a process commonly known as "vegetation encroachment" (Pelzman 1973; McBain and Trush 1997; and Kondolf and Wilcock 1996). Reduced frequency of scour may permit seedlings of riparian trees to establish and mature in the active channel, in a zone formerly scoured annually or biannually (Figure 3.2-5). With elimination of frequent scour, vegetation can encroach upon the channel and induce further narrowing by trapping sediment. This phenomenon occurred along the Trinity River following construction of Trinity Dam, as discussed in Wilcock et al. (1996) and McBain and Trush (1997).

3.3 Uncertainty and Adaptive Management

The processes of channel formation and riparian vegetation establishment are well understood in comparison to many of the hydrological and ecological processes in the Delta and estuary downstream, but considerable scientific uncertainty remains. Riparian vegetation was curiously neglected as an object of study until very recently. For example, the 1998 edition of Terrestrial Vegetation in California (Barbour and Major 1988) contains chapters on twenty vegetation types ranging from mixed evergreen forest to vernal pools, but none on riparian vegetation. A landmark conference on California riparian vegetation occurred fewer than 20 years ago, in 1981 (Warner and Hendrix 1984), and a First North

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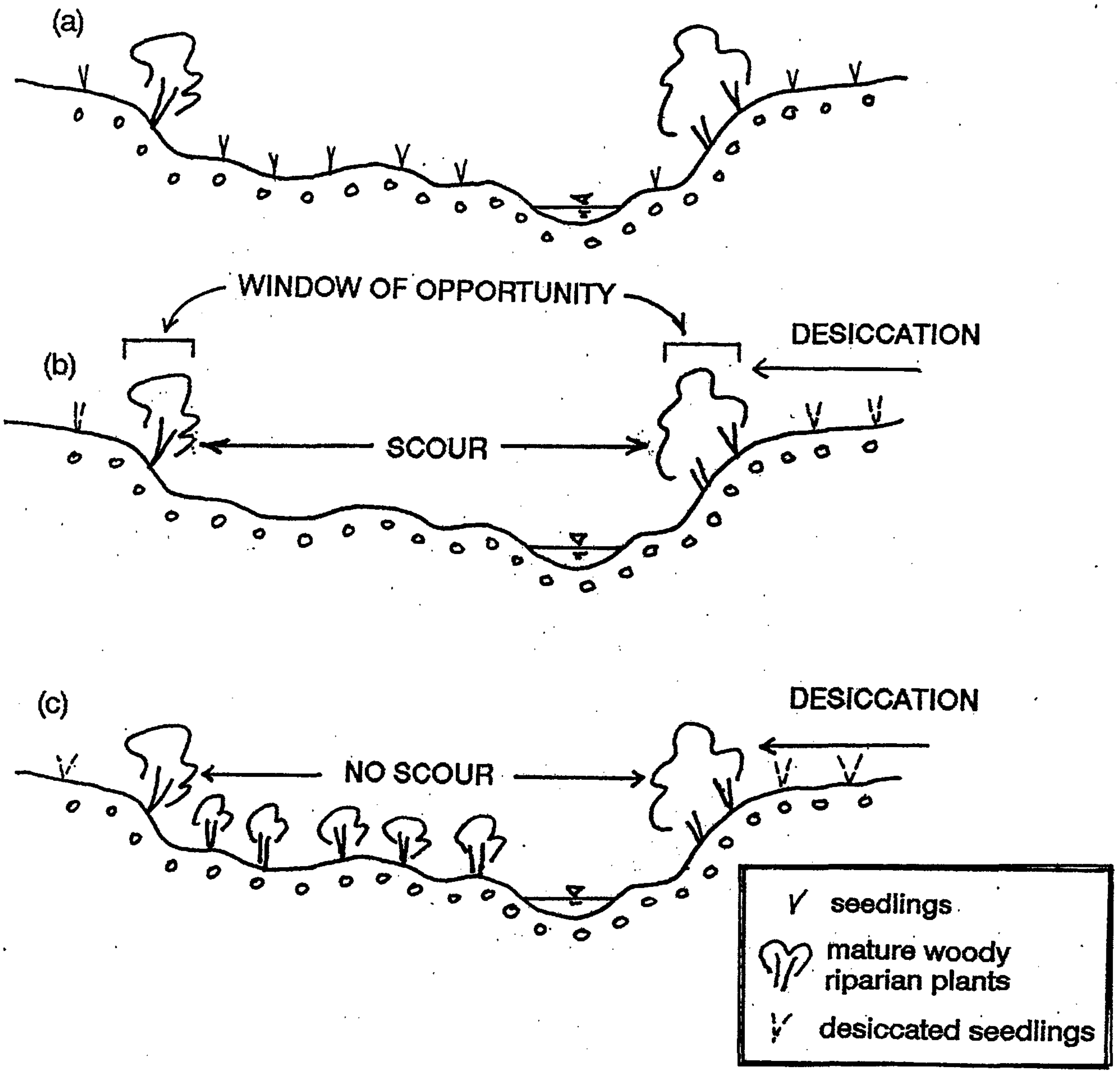

Figure 3.2-5

Schematic diagram illustration (a) seedling distribution following annual flood recession, (b) the "window of opportunity" for establishment of riparian vegetation between the zone of scour and zone of desiccation in an unregulated channel and (c) encroachment of vegetation into the channel after reduction of flood peaks by an upstream reservoir and elimination of scour. (Source: Kondolf and Wilcock 1996).

American Riparian Conference was held in 1985 (USDA Forest Service 1985). There are still so few observational studies of riparian vegetation establishment that it is difficult to draw secure generalizations or construct reliable models on the relevant processes.

Moreover, fluvial geomorphology is inherently complex. Many critical physical processes occur during high flows or floods and are impossible to observe directly. Channels are highly variable spatially, and sediment mobilization and deposition are affected by fine-scale phenomena such as velocity fluctuations in turbulent flow and eddies behind larger bed particles or vegetation. This imposes fundamental limits on the accuracy of generalizations about channel behavior at scales coarse enough to be of practical use.

Since the riparian vegetation is defined and sustained by local geomorphology and river processes, predictions of cause and effect suffer from the same challenges of uncertainty. For example, no two vegetations have the same structure, species composition, or diversity because each has a unique history and grows on a unique substrate (Warner 1984). Riparian vegetations are subject to being torn up and rearranged by floods. Each stand has a unique set of hydrologic conditions determining the amount and timing of water it receives, imposing site-specific conditions of presence/absence and growth rate of the various species comprising the vegetation.

A recent discussion of the difficulties with predicting one important factor, the discharge at which sediment movement begins (Wilcock et al. 1996a), provides an unfortunately typical example of the uncertainties involved.

> "The problem of predicting the critical river discharge (Q_c) that initiates sediment movement is of wide importance. Estimates of Q_c are needed to determine sediment transport rates, the frequency and duration of channel-forming flows, the dimensions of stable channels, and the occurrence of bed scour, armoring, downstream fining, and fine sediment infiltration or removal. Because Q_c depends on local channel properties, the entrainment problem is commonly posed in terms of a critical bed shear stress τ_c for incipient motion, which may be defined in terms of sediment properties alone. For application, an estimate of τ_c must be coupled with an estimate of the bed shear stress τ_o as a function of discharge, channel geometry, and hydraulic roughness.
>
> A number of factors limit the accuracy of Q_c in large gravel-bed rivers, preventing routine application from readily observable properties of the channel geometry and sediment. One problem is uncertainty in determining values of τ_c from the bed size distribution. Ideally, τ_c should be estimated as a function of easily measurable properties of the bed sediment, particularly its size distribution, but problems of method, measurement, and accuracy give rise to uncertainty in the prediction of τ_c for mixed-size sediments (Wilcock 1988; 1992). Another obstacle is the typically large spatial variability of both flow and grain size in large gravel-bed rivers. In simple equilibrium transport fields, such as flumes or small rivers with uniform geometry, spatial averages of τ_o and grain size may be used to estimate τ_c and Q_c. The spatial variation of flow and grain size in larger rivers ensures that this approach will be inaccurate locally; the net effect of local error may be quite large, particularly when transport occurs in part of the channel even though the section-average τ_o is less than τ_c. Error in either τ_c or τ_o is compounded by the steep, nonlinear relation between τ_o

> and the sediment transport rate, which can produce large errors in calculated transport rate from small errors in either τ_c or τ_o.
>
> A third obstacle to predicting Q_c concerns measurement logistics and accuracy: in large rivers it is generally not possible to measure flow and sediment entrainment with sufficient accuracy at a temporal and spatial resolution appropriate to the elementary physics of the problem. Clearly, both spatial variability and measurement problems contribute directly to uncertainty in developing predictive relations for τ_c.
>
> Finally, the stochastic nature of gravel transport ensures that no single value of Q_c exists. Grain motion near τ_c occurs in sporadic, brief events, separated by relatively long periods of immobility. The range of grain sizes typically present on a gravel bed, combined with the spatial variability in grain size and bed topography, ensures that uniform entrainment will not occur at a single Q but will consist of individual grain displacements whose frequency varies spatially and increases with Q. . ."

The adjustment of the Sacramento River channel to flow regulation by Shasta introduces an additional problem for studying fluvial geomorphology and riprap vegetation. There is good evidence from bridge records, aerial photography, and other sources that the channel has incised and decreased in width, as would be expected based on the behavior of rivers elsewhere (Collier et al. 1996; Williams and Wolman 1984), but the evidence has not been systematically compiled and analyzed. The rate of adjustment presumably has decreased over time, but the transitional nature of the channel for the period for which good evidence is available complicates interpretation of the data.

Sensible statements about the relation between the flow regime and sediment transport can still be made, as can sensible statements about the relation between the flow regime and riparian vegetation, but the uncertainty associated with these topics must be recognized and taken into account, as must the stochastic nature of many of the processes involved.

The need to acknowledge and deal directly with scientific uncertainty has been a major theme in the professional literature on resource management in the last decade (e.g., Ludwig et al. 1991; Mangel et al. 1996; Christensen et al. 1996, Francis and Shotton 1997; and Healey 1997). Briefly, it is now recognized by leading professionals that (1) management actions are experiments and should be treated as such; and (2) although decisions must be made and actions taken in the face of uncertainty, irreversible actions should be avoided if possible. This point of view is embodied in the widely advocated approach of adaptive management" (e.g., Holling 1978; Walters 1986; Volkman and McConnaha 1993; Healey and Hennessey 1994; Castleberry et al. 1996; Healey, 1997; Williams 1998; and CALFED 1999), and in the "Precautionary Principle" (Cameron and Abouchar 1991; Garcia 1994, 1995; Hilborn and Peterman, 1996).

Peterman and Peters (1998) describe three possible approaches to making decisions in the face of uncertainty: a "best-estimate" approach, a qualitative approach, and a quantitative approach. The best estimate approach effectively ignores uncertainties and bases decisions on only the best available estimates. Historically, this has been the most common approach, probably because it is the simplest, although it frequently leads to incorrect or suboptimal decisions.

The second approach accounts for uncertainties only qualitatively, often in a subjective way intended to support one policy position or another, as in arguments about the burden of proof that can be used to justify either the status quo or extremely conservative positions. The approach can also be used to justify more moderate and "reasonable" positions, either optimistic or conservative, but again the decisions are based primarily on policy rather than science.

The third and preferred approach accounts for uncertainties in some quantitative way such as Monte Carlo simulations (Walters 1986; Walters and Green 1997), decision analysis (Peterman and Peters, 1998; Peterman and Anderson, 1999), or formal optimization (Walters and Hilborn 1976; Smith and Walters 1981; Clark 1990). Such methods necessarily involve the development and use of models of the resources or processes involved that embody the available knowledge about them. In this approach, for example, the conceptual models described in this report regarding the establishment of new stands of riparian vegetation would be formulated as simple numerical models. Alternative forms of the models or alternative parameter values within models would represent different hypotheses of some "state of nature" such as the relation between the survival rate of riparian seedlings and the rate of change of stage in the river during the spring, which would be tested against new evidence or re-evaluation of existing evidence such as historical flow records and aerial photography. The plummeting cost of computing power has rapidly increased the feasibility and utility of these methods, which are now limited mainly by the availability of scientists trained in these methods and by current scientific understanding of the resources of interest.[1]

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[1] Hilborn and Mangel (1997) provide an introduction to modeling approaches that are useful in this context.

4. Opportunities and Constraints

Because CALFED's goals can be reached only by restoring geomorphically effective flows and flows that will allow for more recruitment of riparian vegetation, opportunities to enhance riparian and aquatic habitat through increased water for geomorphic and riparian flows should be considered. Water for deliberate "geomorphic and riparian flows" in the Sacramento River can come from only two sources: 1) releases of water that would otherwise be stored, and 2) modified flood management operations that would allow temporary increases of storage at Shasta above the limits currently set by flood management policies. This water could be released in a pulse, creating a high flow without a net loss of water for diversion to use. Because of competing uses for water, however, modified flood operations probably is the only realistic source.

In terms of flood management, however, Shasta is a difficult reservoir to operate. The watershed responds quickly to precipitation, and flows from unregulated tributaries below Shasta Dam such as Cottonwood Creek can use most or even all of the conveyance capacity of the existing channel of the Sacramento River. During a series of storms, operators may find it impossible to maintain flood storage in Shasta without releasing flows high enough to cause flooding in the town of Tehama or other damage. Encroachment into the flood storage pool to store water for pulse flows could easily create serious problems for flood management if there were an unexpected turn in the weather.

Because of problems with operating Shasta , the feasibility of deliberate releases of high flows appears to depend upon actions to increase the flows that can be released without unacceptable damage. Such actions, for example building a ring levee around the town of Tehama or putting existing houses on raised foundations, probably would benefit flood management in any event by giving dam operators greater flexibility to release incoming floodwaters, regardless of the environmental benefits from more frequent high flows. Evaluating opportunities for improving the capacity for high flow releases in the Sacramento River will require careful study of the damage that actually occurred during recent high flows and consideration of measures that could minimize or avoid the damage.

At the same time, consideration should be given to measures that would reduce damage in the event of severe flooding. For example, advance planning and flood-proofing of existing settlements and homes might allow for deliberate flooding of historical flood basins, as occurred accidentally in the flood of 1997. Similarly, the effects of the Deep Water Ship Channel on the conveyance capacity of the Yolo Bypass should be investigated, and mitigated if it proves a problem. Such actions could decrease the damage resulting from major flooding, and would also reduce the "worst case" consequences of modified flood operations that allow storing water for deliberate high flows.

Modification of the Butte Basin weirs may also allow for greater channel migration in the reach below Chico. High flows from the Sacramento River enter the Butte Basin over three weirs in this reach. Concern over this "flow split" is often raised as an objection to allowing or encouraging channel migration in the river near Chico. Developing new weirs or enlarging the existing weirs to provide additional overflow capacity would address this objection. Similarly, acquisition of land or "erosion easements" in key areas where the levees are close together may allow for maintaining a meander belt between Chico and Colusa.

Based on current conditions, understanding of relevant geomorphic and ecological processes, and support of landowners and the public in general, these opportunities appear feasible:

- Support continued implementation of the SB1086 program of voluntary land acquisitions and easements to develop an inner-river management zone encompassing the valley bottom occupied by the channel over the past 100 years and projected natural migration over the next 50 years.
- Set back levees wherever possible.
- Begin dismantling bank stabilization where SB1086, USFWS AFRP, CALFED, USACE Comprehensive Study, or other public and private actions make it safe to do so.
- Begin detailed monitoring to develop stage discharge relations for sites of cottonwood establishment and refine biophysical models of riparian vegetation establishment and succession (from which further actions to address riparian diversity can be developed).
- Identify areas at risk of flooding at or below 100,000 cfs and initiate actions to floodproof, such as constructing ring levees or raising structures, or provide financial incentives to encourage moving flood-prone activities elsewhere.
- Modify Butte Basin weirs to provide additional overflow capacity to permit greater channel migration in the reach downstream of Chico.
- Modify Shasta Dam releases to develop a naturalized hydrograph to facilitate seedling establishment.
- Establish a functional riparian corridor within the area inundated by approximately the 4-year flood.
- Continue traditional restoration plantings of later successional stage riparian vegetation on higher surfaces that are unlikely to see frequent flooding and thus unlikely to be restored by natural river processes.

5. Analyses

5.1 Methods

5.1.1 Meander Migration Modeling

To evaluate the effects of diversions to off-stream storage on channel migration, we applied a meander migration model based on a model developed by Johannesson and Parker (1989). The JP model has been applied by a number of investigators to various rivers (Ikeda et al. 1981; Johanesson and Parker 1985 and 1989; Parker and Andrews 1985; Howard 1992; and Larsen, 1995) including the Sacramento River near Woodson Bridge (Larsen et al. 1998). Despite various simplifying assumptions gives good estimates of bank erosion rates in natural channels when used appropriately (Howard 1992). As examples, the model has been applied successfully to the Mississippi River, a large river with a large width to depth ratio and a small gravel and cobble bed stream with smaller width-to-depth ratios (Larsen 1995). The model should also perform well for the Sacramento River, whose characteristics fall somewhere between these two examples, and has been applied to a reach of the river at Woodson Bridge (Larsen et al. 1998).

Although details of the model and its implementation are complex, the approach is based on the assumption that the rate of bank erosion at a point along the channel is proportional to the difference between the shear stress near the bank and the average shear stress. From this, it can shown that the rate of bank erosion is a linear function of a velocity factor:

$$R = E_o u'_b \qquad [1]$$

where R is the rate of bank erosion rate, E_o is a bank erodibility coefficient, and u'_b is a velocity factor. These terms are explained in the following subsections.

Velocity factor

The nut of the model as applied here involves calculation of the velocity field. This is done in a coordinate system that follows the path of the channel centerline. The vertically averaged downstream velocity at each model node is expressed as the sum of the reach averaged velocity U and a velocity "perturbation" u′ that varies across the stream. The velocity perturbation near the channel bank u'_b is the velocity factor in equation [1]. Nodes are spaced about one channel width apart. The analytic solution for the velocity results from simultaneous solutions of six partial differential equations representing key physical processes for channel behavior. The downstream and cross-stream conservation of momentum are expressed using a version of the so-called "shallow-water equations." Downstream bedload transport calculations are based on Engelund and Hansen (1967), and cross-stream bedload transport is related to downstream transport using a relation derived by Ikeda that is well described in Parker and Andrews (1985). The conservation of fluid and sediment mass is represented with traditional continuity equations.

The near-bank velocity perturbation u'_b calculated by these equations peaks somewhat downstream from the meander-bend axis, as occurs in natural streams; as a result, as also occurs in real streams, the simulated meanders tend to migrate downstream. This aspect of channel behavior is hard to capture with empirical data from widely spaced fixed cross-sections

Velocity varies with discharge, so the model as used here requires estimation of a characteristic or signature discharge that mimics the integrated effect of the variable real flow regime. In effect, this assumes that bank erosion is slow enough that erosion from individual flow events can be modeled as a continuous process (Howard 1992). The rationale is the same as in traditional geomorphic analyses that scale channel form and processes by the "bankfull" or "dominant" discharge (Wolman and Leopold 1957; Wolman and Miller 1960). The model as applied here uses the 2-year recurrence interval flow as the characteristic discharge. Accordingly, the model does not try to simulate the effects of particular flow events, and produces estimates of *long-term* rates of erosion or channel migration.

Bank Erosion Coefficient

Although the velocity field is calculated in some detail, the erodibility of the bank is represented by a single coefficient that is empirically estimated. Mathematical expressions for these factors that potentially could be used in modeling have been developed (Thorne 1982; Hasegawa 1989a and 1989b), but accurately estimating the parameters for these expressions would require impracticable amounts of field data. When there is error in estimates of parameters, the predictive capacity of models actually decreases when more than a few parameters are included (Ludwig 1994). When empirically estimated, the coefficient does include a factor of river scale, but Larsen (1995) has shown that it does not function to compensate for errors in the calculation of the velocity field. The longer the time period for calibration, the better the bank erosion coefficient can represent the integrated effects of local variation in bank characteristics.

By equation [1], the rate of erosion is directly proportional to the erodibility coefficient. Because the coefficient is constant in the model, sensitivity analyses are unnecessary to see, for example, that a 1-percent change in the coefficient will result in a one percent change in the estimated rate of erosion. The simulations reported here used a bank erodibility coefficient of 3×10^{-7}, which results in realistic erosion rates for the Sacramento River. Results here are presented in non-dimensional form, i.e., as percentages, so using a different value for the coefficient would not affect the results.

In sum, the model should be regarded as a reasonable representation of the main factors involved with bank erosion, rather than as a detailed representation of all the factors that may affect erosion rates at any particular site. The behavior of stream channels is so complex and involves so many random events that trying to model the exact behavior of a channel is impossible. If it were possible, it would be pointless because the model would be too complex to be useful; one would do better to study the river instead. Modeling of necessity involves many questions about what to ignore. In general there is no "correct" answer to these questions, because the answer depends on the particular purpose of the modeling. However, many experienced and mathematically sophisticated modelers believe that, for most purposes, simpler is better (e.g., Hilborn and Mangel 1997).

The model was used to address three questions:

Question 1: What would be the effect on long-term rates of channel migration of diversions of 5,000 or 10,000 cfs during periods of high flow?

Modeling was performed to address this question using data from a real and an idealized reach of the Sacramento River. For the real reach, the modeling used data developed by Larsen et al. (1998) for the river at Woodson Bridge, but extending further up and downstream for a total reach length of 13 km. This reach includes non-erodible banks at several locations that affect the generality of the modeling results. Therefore, simulations were also done with data from an idealized channel of appropriate size, slope and sinuosity that was developed from a sine-generated curve. Simulations for the no-project case at Woodson Bridge used the two year flow of 88,000 cfs from the Vina gage as the characteristic discharge, and channel dimensions as reported in Larsen et al. (1998). The characteristic discharge was reduced by either 5,000 or 10,000 cfs in subsequent runs, and channel dimensions were reduced using hydrologic geometry relations to match the reduction in characteristic discharge. Simulations for the synthetic reach used a somewhat larger characteristic discharge of 96,000 cfs, representing a site further downstream, and somewhat different hydraulic geometry (wider, shallower, and steeper).

Question 2: What is the effect of Shasta Dam on long-term rates of channel migration?

Data from the idealized reach were used to address this question. The 2-year flows for the pre- and post-Shasta periods were determined from the Bend Bridge USGS gage (119,150 and 79,250 cfs) and used as the characteristic discharges. Channel dimensions were increased for the pre-Shasta case using hydraulic geometry relations.

Question 3. What is the effect of bank stabilization measures on long-term rates of channel migration?

This question was addressed using the idealized channel, and comparing the simulated channel migration with simulated riprap on zero, one, or two of the outer bends of the channel.

Analysis of DWR Erosion Transect Data

From 1986 to 1988, Koll Buer and his colleagues at the Northern District Office of the California Department of Water Resources have measured bank erosion rates at 16 sites between river miles 156.5 and 232.5. At the field sites, bench marks were set on the inside of bends and the distance to the opposite bank was measured in fixed directions. The distances were resurveyed approximately semi-annually to document detailed bank erosion rates. Results from the field surveys through 1993 were published by CDWR (CDWR, 1994) and showed that bank erosion at the sites was highly variable but averaged about 8 feet per year for this period; subsequent survey results have not yet been compiled and published. For this report, we analyzed DWR bank erosion data from seven selected sites, from 1986 to 1992, in relation to flows occurring between the surveys.

To relate the erosion at each site to flow, we needed some reasonable description or parameterization of the flow regime during the intervals between surveys. For this purpose we calculated a "cumulative effective stream power" for each measurement interval. Stream power (Ω) is a rate of potential energy expenditure per unit length of channel, calculated as the product of discharge, slope (S) , and the specific weight of water (γ),

$$\Omega = \gamma QS \qquad [2]$$

so for a given slope it is directly proportional to discharge. Presumably there is a threshold discharge ($Q_{threshold}$) below which erosion is negligible, so for each site for each day we calculated the effective stream power (Ω_e) as:

$$\Omega e = \gamma QS \qquad \text{if } Q > Qthreshold \qquad [3a]$$

$$\Omega e = 0 \qquad \text{if } Q <= Qthreshold, \qquad [3b]$$

where Q is the mean daily flow at the site, estimated from available gauging records. We then calculated the cumulative effective stream power (Ω_{ce})by summing over the days in each measurement interval:

$$\Omega ce = \sum \Omega e. \qquad [4]$$

Because $Q_{threshold}$ is unknown, we calculated Ω_{ce} for a range of values of $Q_{threhold}$, and selected the value that best fits the surveyed amounts of erosion. The rate at which this fit deteriorates as the estimate of $Q_{threshold}$ changes provides some measure of confidence in the best estimate of $Q_{threshold}$.

We recalculated Ω_{ce} with simulated diversions of 5,000 and 10,000 cfs, when flows were between 20,000 and 55,000 cfs, and used the empirical relations between Ω_{ce} and bank erosion to estimate the change in bank erosion that would result from the diversions. Note that if the results are given non-dimensionally, i.e., as percent change, then the same results would be obtained using cumulative effective discharge, rather than stream power.

5.1.2 Bed Mobility and Bedload Transport Methods

As described by the Wilcock (1996) excerpt above, a precise bed mobility threshold in natural river channels typically does not exist due to the spatial variability in particle size throughout a reach of interest. Even in the most simplified case of a reach with the same gravel-cobble mixture across the entire bed, smaller particles tend to mobilize before the larger ones (Parker 1982; Andrews 1994; and many others). In rivers with complex channel morphology and a wide range of particle sizes supplied to it by the watershed, hydraulic variability during high flows will cause complex particle sorting mechanisms, resulting in a mosaic of "patches" throughout the reach. Patches of finer particles will tend to mobilize even sooner than in the idealized example above, causing the bed mobilization "threshold" to be even more variable depending on what the particle size of interest is. In other words, there are usually multiple bed mobility thresholds. For example, as discharge increases, sand deposits in pools will mobilize first, followed by gravel deposits in pool tails, point bars on the inside of meander bends, and ultimately, the transverse bars that form the riffles. The generally accepted conceptual model is that the coarser components of riffles are mobilized by flows slightly less than bankfull discharge, which typically corresponds to a 1.2 to 1.5 year flood event. Thus, a "bed mobilization threshold" is problematic to define, measure, and model. Nonetheless, we estimated bed mobility using available channel geometry and bed material size data and the Andrews (1994) equation to provide a first cut estimate of bed mobility (Appendix B).

The applicability of the Andrews (1994) equation is debatable, as it was developed on Sage Hen Creek, a small gravel-bed stream, and Andrews (1994) cautioned that accurate values of reference shear stress need to be determined for a given site before applying this method. Scaling up to a river the size of the Sacramento, without better information on the distribution of particle sizes is enough to give pause in applying this method. Moreover, results of the exercise seemed unrealistic, so we have not included a lengthy description of the methods nor their results in the report proper (see Appendix B).

5.1.3 Riparian Vegetation Analyses

We inspected hydrographs of mean daily flows for each year of record from the Red Bluff (Bend Bridge) gauge and visually assessed the suitability of each year for riparian establishment. We could not convert these to stage changes because no stage-discharge relations now exist for sites of potential riparian vegetation recruitment; stage discharge relations exist only for gauges, which tend to be located in straight reaches confined by hard banks, precisely the channel cross sections where we would not expect to see riparian vegetation establish. The only currently available data relating stage to discharge in reaches between gauges are the stage heights predicted by the HEC-RAS modeling conducted by the U.S. Army Corps as part of the ongoing Comprehensive Study.

Elevation transects through bands of vegetation on point bars can reveal ages of the bands when compared with records of channel location and movement and the flows which created the sediment surface where the bands are growing today. We selected two sites to survey vegetation transects:

RM 192.5R, suggested by Michael Roberts, hydrologist for The Nature Conservancy Sacramento River Project, as a geomorphic surface capable of supporting riparian vegetation recruitment (if the appropriate hydrologic conditions occur).

RM 197L, suggested by Koll Buer, Chief Geology Section DWR Red Bluff, as a good example of a point bar.

Ideally, actual age of individual trees would be determined across the cross section to precisely relate vegetative growth with geomorphic and hydrologic history. To get individual tree ages involves excavation by backhoe of trees down to the root-flare at the surface where seed germination occurred and careful stem cores to show annual-ring growth. This is a multi-day task for two people, as described by Merigliano (1996) for aging cottonwoods on the Snake River in Idaho and Dykaar and Wigington (in press) along the Willamette River in Oregon. In Chapter 6, we recommend such investigation in the future, but for this report there was insufficient time, and thus we do not know for certain when the vegetation established on the site after it was formed. At each site a measuring tape was laid out from the edge of the water surface upslope through the vegetation to the largest (assumed to be the oldest) cottonwood trees at each site. A tripod and level with scope were set up and elevations were measured using a staging rod at 10-foot intervals along the tape using standard surveying techniques. In addition to surveying elevations above baseflow water surface (and with respect to a permanent benchmark installed at the site), we noted grain size and species/size of trees encountered along the cross section.

5.2 Results

5.2.1 Bank Erosion

Meander Model

Question 1: What would be the effect on long-term rates of channel migration of diversions of 5,000 or 10,000 cfs during periods of high flow?

Question 2: What is the effect of the operation of Shasta Reservoir on long-term rates of channel migration?

Application of the Johannesson and Parker (1989) model by Larsen (1995) on a 13-km reach at Woodson Bridge and an idealized 7-km reach showed that over the range of variables considered: the change in the simulated long-term rate of bank erosion is directly proportional to the change in the characteristic discharge, with a constant of proportionality of about 1.25. That is, if the characteristic discharge is decreased by 1 percent, the simulated long-term rate of channel migration is decreased by about 1.25 percent. The results of the various model studies for 100-year simulations are summarized in Table 5.2-1 and Figure 5.2.1

TABLE 5.2-1
Percent change in long-term (100 year) bank migration rates and discharge, compared to base cases, for model studies of the Woodson Bridge reach and idealized reach using post-Shasta hydrology, and an idealized reach with pre- and post-Shasta hydrology

	Change (Percent)		
Reach	**Discharge (Q)**	**Erosion**	**Del E/Del Q**
Woodson Bridge: diversion = 5,000 cfs	5.7	6.9	1.21
Woodson Bridge: diversion = 10,000 cfs	11.4	15.2	1.33
Idealized Reach: diversion = 5,000 cfs	5.2	6.4	1.23
Idealized Reach: diversion = 10,000 cfs	10.4	14.0	1.35
Idealized Reach: Pre and Post-Shasta	33.6	42.3	1.26

The results were obtained simply by measuring graphical representations of model output for subreaches of each modeled reach, as illustrated in Figure 5.2-2, for one bend in the Woodson Bridge reach.

Question 3: What is the effect of bank stabilization measures on long-term rates of channel migration?

Based on 100-year simulations, the effect of bank stabilization on channel migration dies out within two river bends or one channel wavelength. In the simulations channel migration goes to zero at the bank stabilization sites, where change in simulated channel migration is greatest. The change in simulated channel migration decreases downstream to a zero at somewhat more than half the channel wavelength from the stabilized site, and then increases somewhat for approximately one quarter of the channel wavelength, with a maximum increase of about 4 percent. Generally, these results are consistent with an analytical relation described in Larsen (1995) according to which the effect of bank stabilization varies approximately as e^{-x}, where x is approximately 100 times distance downstream divided by channel depth. The effects of bank stabilization at different sites are independent in the simulations; that is, the effect of stabilization at one point does not propagate beyond the next.

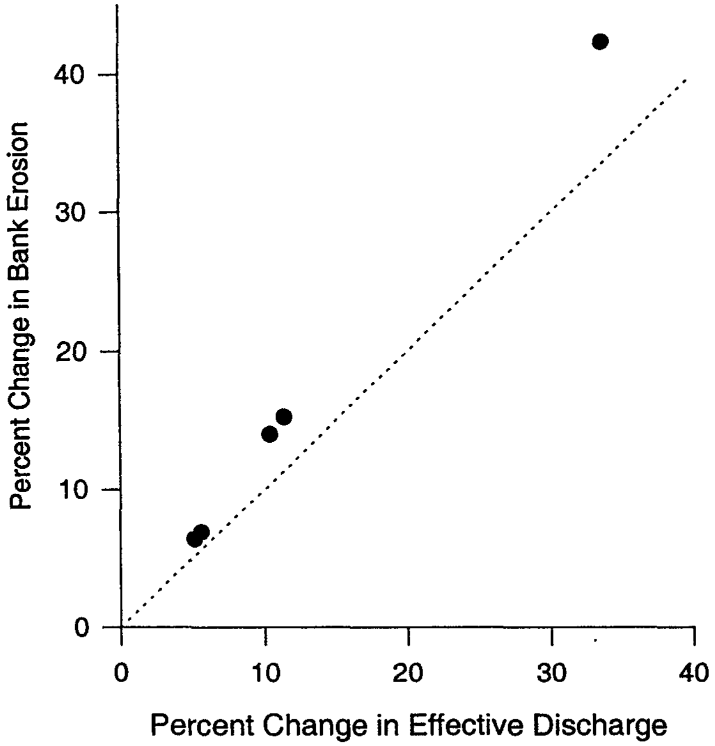
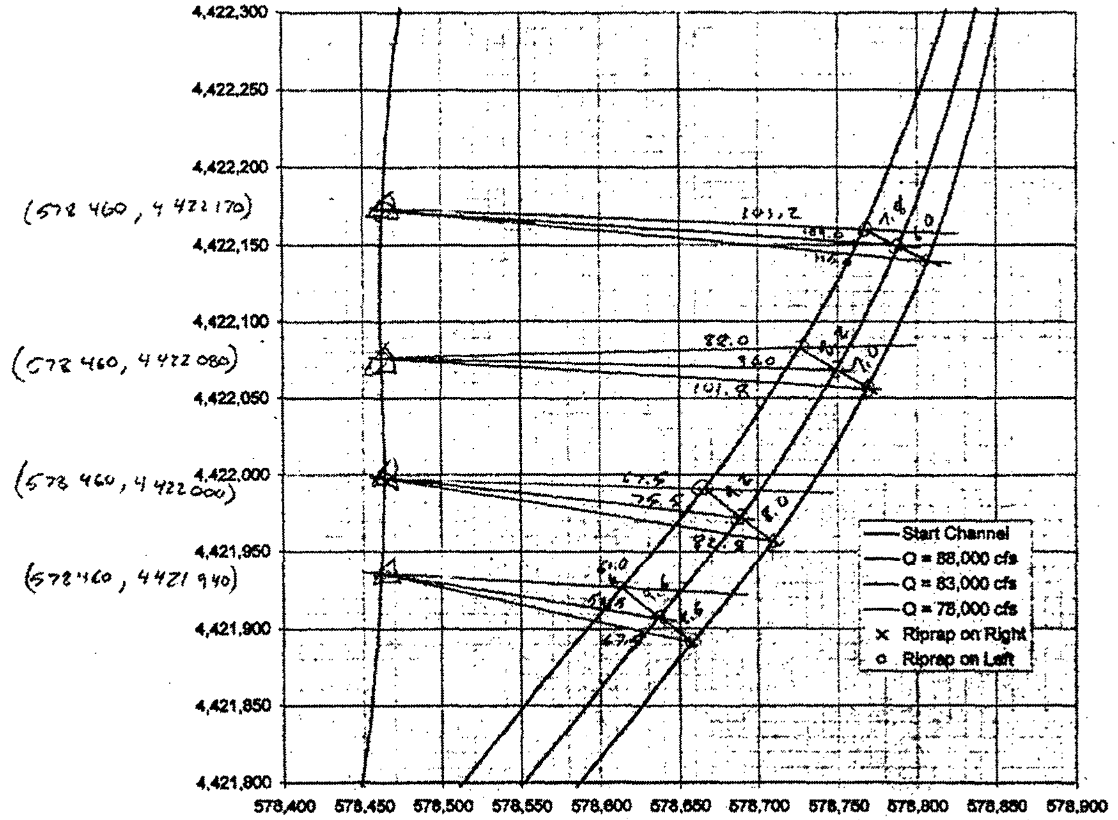


FIGURE 5.2.1
Percent change in bank erosion plotted over percent change in discharge, based on simulation modeling; dashed line shows 1:1 relation.



Percent change in bank erosion plotted over percent change in effective discharge; dashed line shows 1:1 relationship.

FIGURE 5.2-2
Illustration of the method for obtaining estimates of the change in bank erosion between model runs.

Empirical Studies

Limitations in the available data compromise the utility of analyses of the empirical bank erosion data. The data span four to six dry years, followed by one "normal" year in which there was much more erosion than in the previous years. Accordingly, analyses including the normal year (1993) are dominated by one data point. On the other hand, analyses excluding 1993 reflect only dry year conditions, and although they are much more robust statistically they cannot reasonably be used to estimate bank erosion under the normal range of conditions.

At least as applied to dry year conditions, cumulative effective stream power appears to be a good parameter for relating records of daily flow records to recorded rates of bank erosion in the CDWR data (Table 5.2-2). Applying linear regression to the cumulative effective stream power at each site within each measurement interval and the average amount of bank erosion at the site resulted in values of the coefficient of determinate (R^2) of 0.64 to 0.96 using an optimal threshold discharge Q_t. Based on inspection of curves of R^2 over Q_t we selected a value of 15,000 cfs as the best fit for the entire data set. Using this value resulted in R^2 ranging from 0.54 6 to 0.90; scatterplots with regression lines for Rancho de Farwell are shown in Figure 5.2-3 as examples.

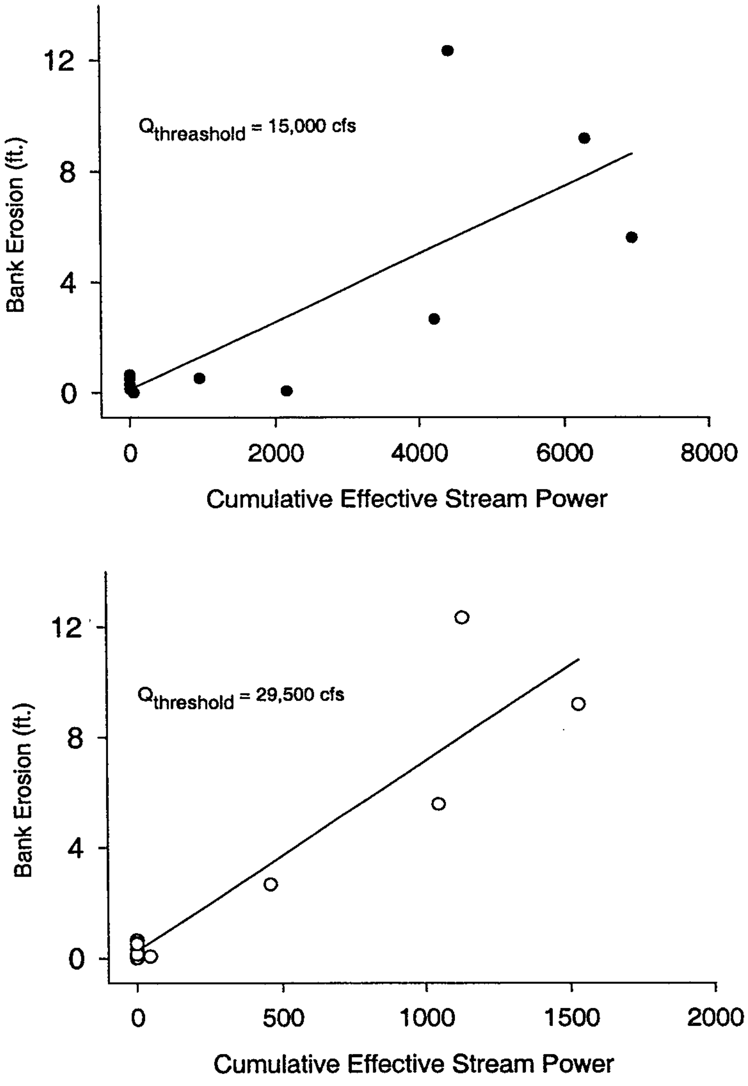


FIGURE 5.2-3
Empirical relation between cumulative effective stream power and bank erosion at the Rancho de Farwell site, calculated with $Q_{threshold}$ set at 15,000 cfs (above) and 29,500 cfs (below).

The low values of Q_t may reflect the low flows prevailing during the period of record used in the analysis: 1986 – 1992, and we are anxious to repeat the analysis with data from recent high-flow years included. We suspect that including the more recent data will give higher values for the threshold discharge, and that a non-linear relation may give better results. Despite the shortcomings of these data, however, they do establish that some channel migration occurs even at relatively low flows, so that diversions to off-stream storage can be expected to have some effect on rates of channel migration below the diversion. The question is not whether such an effect will occur, but whether it will be small enough to tolerate.

TABLE 5.2-2
Characteristics of Empirical Analysis of Bank Erosion Rates

Site	River Mile	Slope	# Data Points	Optimal Qt (cfs)	Optimal R^2	Slope of Fit Line, Q_t = 15,000	R2 with Qt =7,500
Toomes	222	0.0005	10	9,000	0.73	0.00025	0.64
Rancho de Farwell	186	0.0004	10	29,500	0.86	0.0012	0.60
Hartley 2	172.5	0.00035	6	25,000	0.96	0.00017	0.90
Larkins	171	0.003	11	14,000	0.64	0.0000017	0.64
Packer Island	167	0.0003	7	10,000	0.89	0.00088	0.82
Princeton	164.7	0.0002	11	7,500	0.81	0.00062	0.54
Jimeno Rancho	156.5	0.003	7	10,000	0.92	0.00077	0.86

5.2.2 Bed Mobility and Bedload Transport

See Appendix B for results of the bed mobility analysis. As noted above, the equation used was probably not suited to the Sacramento River, so we have discounted the results. As mentioned in Appendix B, there are few bedload data for the river, and thus far, no bedload transport routing model completed for the Sacramento River, although Mike Singer of UC Santa Barbara has begun work developing one.

5.2.3 Vegetation

Visual Inspection of Annual Hydrographs

Based upon the model presented in Section 3.2.3, we define a "favorable" hydrograph for establishment of seedlings of cottonwood and willow as one with higher flows in late April and May (at the beginning of the spring recession limb and during seed-dispersal) than the summer base/irrigation flows. This would ensure that seedlings would establish at an elevation above summer irrigation flows.

Our visual comparison of hydrographs at Bend Bridge pre-Shasta Dam with hydrographs post-Shasta Dam, indicated that in the Pre-Dam period (1892-1943), in only 11 years out of 51 was the receding limb probably NOT suitable for establishment and growth. These were years of less than average rainfall or years with minimal snowpack (1908, 1918, 1920, 1923, 1924, 1929, 1932, 1933, 1934, 1936, and 1939). In the Post-Dam period (1944-1997), in only 15 years out 53 was the receding limb POSSIBLY SUITABLE for establishment and growth. These were generally wet years with a larger than average snowpack (1948, 1952, 1954(?), 1956(?), 1958, 1963, 1965(?), 1967, 1971(?), 1974, 1975, 1978, 1982, 1983, and 1995). We emphasize that this assessment is qualitative only, based on the apparent patterns of seasonal flow decline. To undertake this analysis properly would require stage-discharge relations for potential vegetation establishment sites, used with historical flow data to simulate changes in stage, and then compared with vegetation distribution patterns observed at detailed study sites to develop criteria for hydrologic conditions for vegetation establishment.

Riparian Vegetation Transects

Figures 5.2-4, 5.2-5 and 5.2-6 show the results in graphic form for both transects. The figures also show surface sediment composition, cottonwood growth form, and diameter at breast height (dbh) for cottonwood trees. Predicted discharge at two-foot stages above the water surface are also noted on the figures. These predicted discharges are generated from a HEC-RAS analysis with gains and losses between the Hamilton City gage and the Ord Ferry gage NOT accounted for.

Aerial photos from 1952, 1958, 1976, 1988, and 1997 were compared to determine when the transect location formed. In addition, channel location was documented from maps appearing in the River Atlas compiled for the Middle Sacramento River Spawning Gravel Study (Dept. of Water Resources 1984).

RM 192.5R – Figure 5.2-4

The photographs and river atlas reveal that this site was in the channel in 1969. By 1976 the upper end of the transect was beginning to form, and by 1988 the upper one-third of the transect was in place, with a faint band of vegetation, probably being the largest cottonwoods at the upper end of the transect. Reviewing the list of favorable hydrographs, it appears that the largest trees may have established in the spring of 1974, while the 8 to 12 inch dbh individuals may have established in 1978.

The lower two-thirds of the transect was present by 1997. The cottonwoods labeled as "sprouts" from a four inch diameter stump likely established in the 1983 hydrograph. The few 1 inch diameter cottonwoods probably established in the 1995 hydrograph. This is circumstantial evidence because it was not possible to directly determine the age of these plants under the time constraints of this project.

RM 197L – Figure 5.2-5

Review of the aerial photos and channel locations map in the river atlas show this site in the channel in 1969 and in 1976. The channel had moved by 1981 and the transect site is formed by 1988. All the cottonwoods likely established under the 1982 or 1983 hydrograph.

The RM 197 point bar has stopped growing because of the installation of riprap in 1975 on the opposite bank. This has caused a change in the slope of the transect (see Figure 5.2-6) to a very steep bank and not conducive to cottonwood establishment, even under an ideal hydrograph. The cottonwood sprouts may well be the same age as the trees at the upper end of the transect due to the effects of river scour and by the browsing of beavers. In order

FIGURE 5.2-4

Sacramento River: Transect for river mile 192.5R – October 26, 1999 – Stage at Hamilton City = 129.73 ft (5030 cfs)

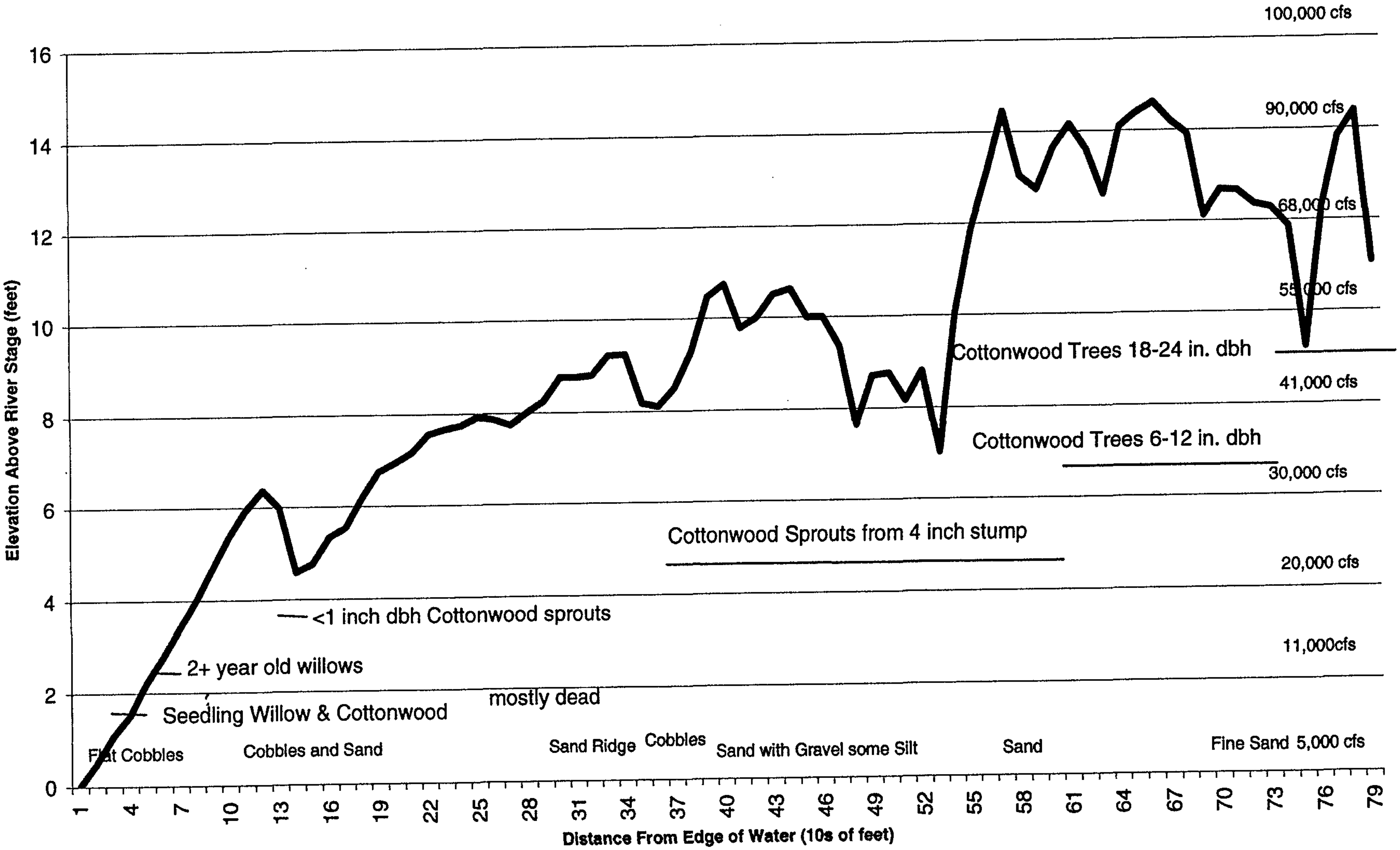


FIGURE 5.2-5
Sacramento River: Transect for river mile 197L – October 27, 1999 – Stage at Hamilton City = 129.74 ft (5059 cfs)

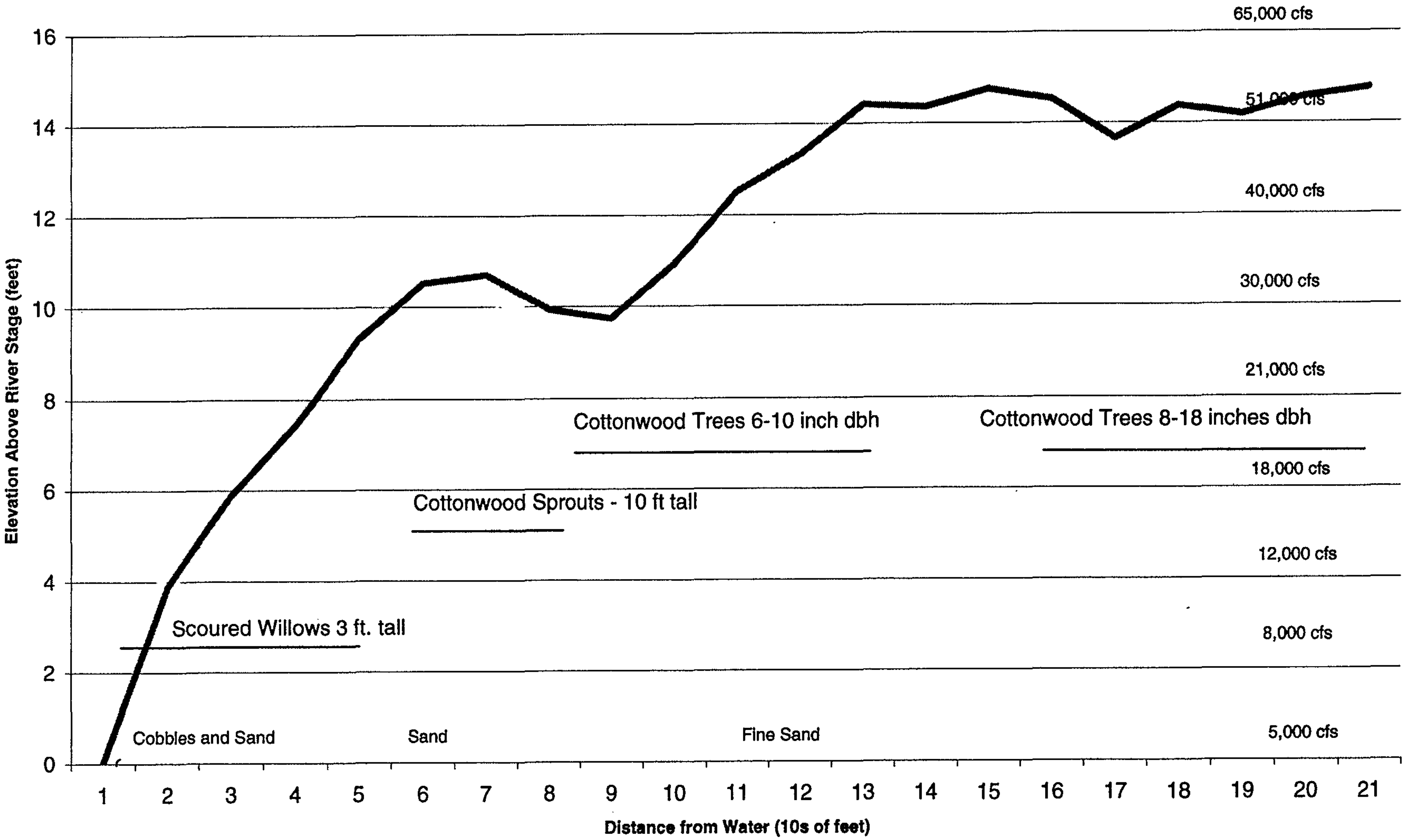
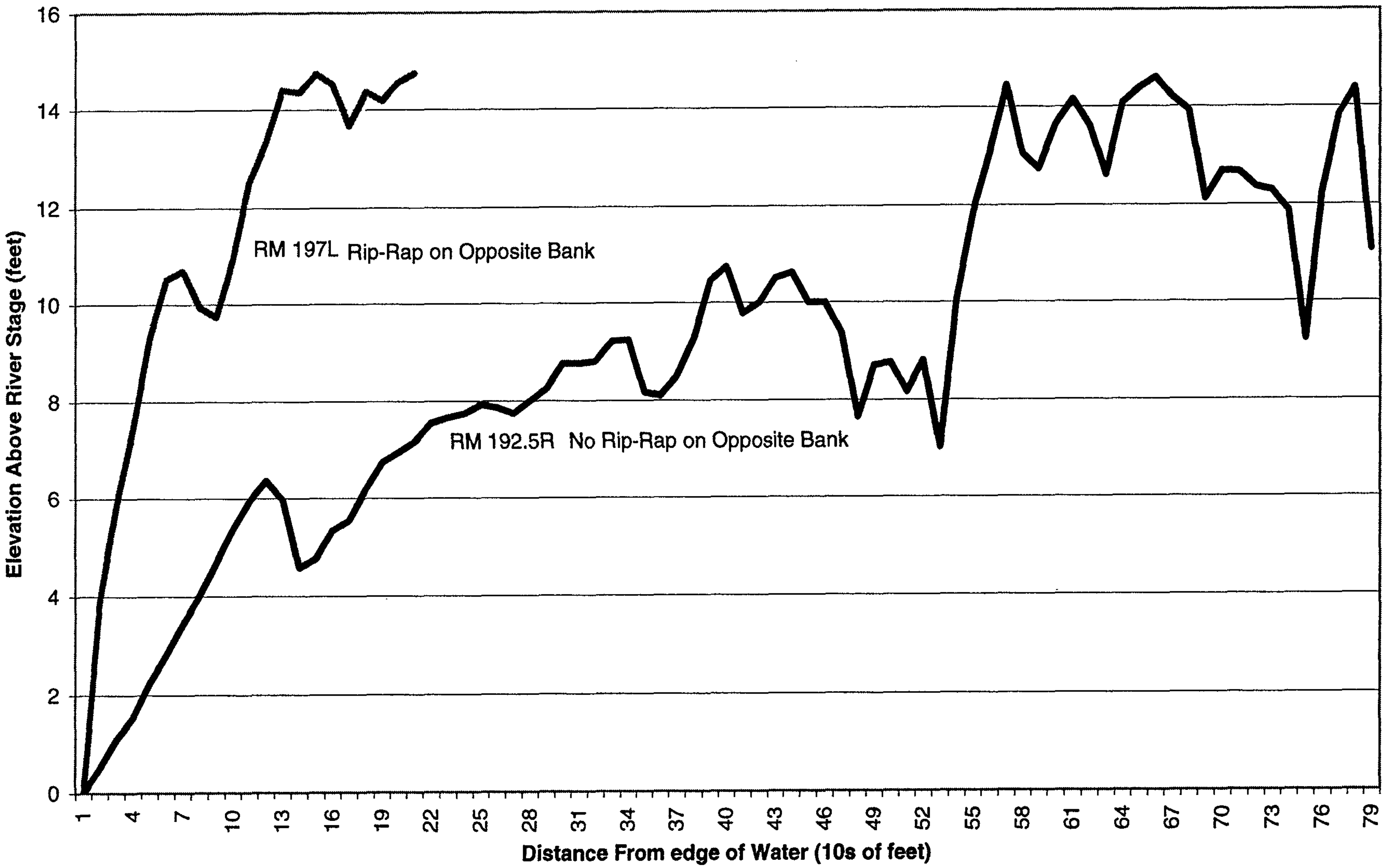


FIGURE 5.2-6
Comparison of transects



to accurately determine this interpretation, accurate ages of the trees and shrubs should be carried out by excavation and stem coring.

5.3 Discussion

Meander Modeling and Erosion Data

The modeling reported here estimates that diversion of 5,000 cfs during periods of high flow will reduce the rate of channel migration by 6 to 7 percent. This result seems consistent with the available empirical evidence on channel migration, although more analysis of the empirical data is needed to confirm this. Evaluation of the significance of this reduction in channel migration must take account of the reductions in channel migration that have already occurred from modification of the flow regime by Shasta Dam, and by extensive riprapping of those parts of the channel that are most likely to migrate rapidly.

Bed Mobility

We have presented bed mobility estimates based on crude models (which may not be applicable under conditions in the Sacramento River) and limited field observations to provide another way of estimating geomorphic thresholds in the Sacramento River. These estimates deserve to be treated with caution and should not be a principal basis for important management decisions. Our reservations regarding the bed mobility data include: Buer's bedload traps were located downstream of sites of artificial gravel introductions, and bedload samples collected at lower discharges may have consisted largely of small gravels transported over a stable gravel bed. The reaches thus sampled may not reflect conditions (slope, bed material size, curvature) in the sites of particular interest for our study.

The bed mobility model was developed from observations on a small gravel bed stream and may not be suitable for application on the channel geometry, scale, and grain size in our study area. Moreover, the model predicts marginal bedload mobility, when only a few particles are moving at a time, not the general bed mobility that might be implied. This model predicted very similar results for the four cross sections, which can be largely attributable to using the same particle size and slope for all sections. More importantly, the model predicted mobility at relatively low discharges. This may be an artifact of the bed mobility equation used, or it may reflect the location of the study sites (RM 169-187) near the gravel-sand transition on the Sacramento River. This transition zone is identifiable on many rivers, and reflects a change in style of channel processes. In the gravel-bed reaches upstream of the transition, we typically expect gravel beds to mobilize every year or two, while sand beds can be moving much or most of the year. With these study sites located close to the transition, relatively frequent mobilization may be implied.

Vegetation Transects

The trees on point bars are typically older with distance from the channel (or back from the tip), except for young individuals of later successional stage species that establish on surfaces previously colonized by pioneer species. These cohorts occur in successive bands that reflect episodes of establishment during (relatively infrequent) favorable hydrologic conditions. We might expect that similar sized tress (dbh classes) would have established on the two bars during the same event. The different elevations above baseflow for the same size classes at the two sites may reflect differences in stage-discharge relations, or differences in events responsible for establishment.

Bank stabilization appears to affect point bar configuration, and thus subsequent germination and growth of early successional vegetation, by causing the point bars opposite of the hardened bank to be steeper, as illustrated in Figure 5.2-6 and documented for numerous sites by CDWR. In fact, selection of point-bars for our field study was difficult, because we could find few point bars with the "classic" shape or topography of a bar surface gently-sloping up from the channel. Most point-bars on the Sacramento River are steeply sloped, evidently due to hardened banks across the channel from the bar (Figure 5.2-6). Likewise, it is difficult to find stands of young (< 20 feet tall) cottonwoods.

Without active channel migration, a bimodal vegetation structure appears to develop: 1) low vegetation struggling to establish in the artificially narrowed (and thus restricted and scour-prone) channel, and 2) older vegetation on higher surfaces that established prior to bank stabilization. Intermediate level, mid-successional forest stands typically do not exist.

A high priority study over the next two years should be forensic geomorphic/ecologic study and careful future monitoring of a set of point-bars to document seedling and sapling recruitment in relation to flows and channel form, especially to test for effects of bank-hardening and the interaction of altered flows.

Hypotheses Developed from Conceptual Models

Among hypotheses generated from the channel migration and riparian seedling establishment conceptual models that could be tested by forensic geomorphologic/ecologic studies and future observations at long-term study sites in an adaptive management program are:

- Area of suitable substrate for seedlings decreases with steepness of point bar face.
- The channel has narrowed since construction of Shasta Dam, and this has changed the stage-discharge relation to reduce the area of suitable colonization surfaces on point bars.
- Hardening of banks limits point bar development.
- Gopher populations are depressed after floods, and herbivory is thereby reduced, increasing seedling success.
- Soil textures are finer with distance from the channel, leading to better moisture retention and higher capillary fringes.
- Fremont cottonwood and the willow species show different establishment success on the point-bar at different elevations above the channel.
- The date of the beginning of the recession limb will determine the relative abundance of seedlings of each species on a point-bar.
- High summer flows followed by abrupt drops in October lead to desiccation of seedlings.

Data Gaps/Areas of Disagreement:

What has been the history of riparian vegetation establishment along the Sacramento River? The Bay Institute (1998) and others have developed overall estimates and detailed histories developed for short reaches (e.g., Greco 1999), but detailed historical mapping is needed for the entire study reach to better understand the processes and factors influencing riparian vegetation establishment.

- How frequently were significant cohorts established pre-dam? What hydrologic conditions were involved?
- How high above the September baseflow water table are summer irrigation delivery flows?
- Effect of riprapped banks on adjacent channel form.
- Maximum ramping rates based on Sacramento River cottonwood root growth
- Is most cottonwood regeneration from seed or suckering (root cloning).
- Under current conditions, where is forest regeneration taking place, on point-bars, on the floodplain, or in cut-off channels? How does this compare with pre-dam condition?
- Disagreement over cause of increased cutoff rate in 20th century.
- Data gaps also include bed mobility experiments, any bedload transport measurements, and bedload routing model.

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6. Flow Regime for Maintenance and Restoration of Riparian Vegetation

6.1 Flow Recommendations for Maintenance and Restoration of Riparian Habitat

6.1.1 Geomorphic Flow Requirements

Flow Requirements for Channel Migration

These flows are most simply specified as the flows above a threshold producing bank erosion. In reality, this threshold will differ for different reaches or sites, but some range of flows must be selected to provide operating criteria.

The available evidence indicates that both gravel movement and bank erosion occur at moderate rates of flow. Bedload traps indicate that gravel movement begins at approximately 24,000 cfs (Koll Buer, DWR Red Bluff, pers. comm. 1999) and the DWR survey data shows that channel migration begins at similar flows. However, the rates of both processes at such flows are very low. Bed mobility at such flows presumably occurs in the "partial transport" mode, in which there is only occasional movement by gravel particles in more exposed positions on the bed, and transport is strongly size-dependent (Andrews 1994). The biological significance of bedload transport at such low rates is unclear. We do not have data on bedload transport upon which to base an estimate of the flows at which more general mobilization of the bed occurs, and as noted by Wilcock et al. (1996, quoted above) predicting these flows in the absence of data is very difficult.

Based on the DWR survey data, which are the best available for analysis within the time constraints of this study, the relation between flow above a low threshold and channel migration is approximately linear. This is inconsistent with common impressions, however. Koll Buer of DWR reports that significant bank erosion begins at about 55,000 to 60,000 cfs, for example, and we think that the linear relation in the available data may reflect the relatively dry period over which the published data were taken. 55,000 cfs also seems a reasonable "guesstimate" of the flows at which mobilization of the channel bed occurs, so in the absence of better information we have selected 55,000 cfs as a critical threshold for geomorphic processes. A better estimate probably can be developed using the unpublished DWR transect data and from re-analysis of historical maps and aerial photography, as recommended below. The actual threshold of general bed mobility and bank erosion will differ at different points along the river, as a function of factors such as channel slope, channel width and depth, bed material size, and erodibility of banks. In any event, it bears repeating that bank erosion provides 85 percent of the supply of spawning gravel in the Sacramento River below Red Bluff (CDWR 1984). Thus, there are good reasons to preserve a range of flows above 55,000 cfs to maintain the river's capacity for channel migration at different sites along its length where banks are not protected by riprap.

Setting Objectives for Meander Migration

Even if the flow required to drive channel migration can be precisely specified, there remains the question of *how much* channel migration is needed to meet our goal of maintaining/restoring riparian habitat. Besides setting arbitrary targets, we can envision at least two approaches to setting this objective.

Reference to Historical Conditions is useful as it provides a context within which to place current conditions and our restoration efforts. However, historical conditions cannot be duplicated because of the profound and irreversible changes wrought by land conversion and flow regulation. Unlike many channels in the Sacramento-San Joaquin River system, the mainstem Sacramento still exhibits many characteristics of a dynamic river, albeit reduced in extent and activity. Some percentage of the historical meander migration rate could be used as an objective.

Ecologically-Based Objectives can be developed from a (future) improved understanding of the functioning of the physical and ecological system. The goal can be to maintain a certain mix of species and successional stages, and to specify a rate of channel migration sufficient to rejuvenate the floodplain while allowing successional stages to develop. Towards this end, a simple model of riparian establishment in relation to geomorphic processes, such as that developed by Johnson (1992) for the Missouri River, would be a very useful tool.

6.1.2 Riparian Vegetation

For establishment of vegetation, in addition to flows needed to create fresh surfaces for colonization (through meander migration as discussed above), flow needs include periodic overbank flows (which will occur with flows >100,000 cfs as already specified), high flows to disperse seeds and recharge floodplain aquifers, and preservation of a gradual seasonal recession limb. In the pre-dam Sacramento River hydrograph, snowmelt peaks occurred during the seasonal decline from winter high flows. Because these occurred during seed dispersal periods for many species, they probably played an important role in establishing riparian vegetation. These snowmelt flows have largely been eliminated by reservoir storage, because by the time the late-spring snowmelt runoff arrives at the reservoirs, their operating rules permit them to encroach into their flood pool and so the snowmelt flows are largely stored in the reservoirs.

The high flows preserved for geomorphic reasons (>55,000 cfs) will probably serve as well to disperse seeds (if the timing coincides with seed dispersal dates). Probably the most important feature of the hydrograph that can be readily influenced at this point is the rate of seasonal recession. As discussed above, studies of cottonwood establishment elsewhere in western North America have indicated that a recession rate of 2.5 cm per day is one with which root growth can keep pace (Mahoney and Rood 1998). We emphasize that no similar studies have been undertaken in the Sacramento River system, and organisms can display considerable adaptability to different environmental conditions, so the comparable values here might be quite different. Nonetheless, 2.5 cm per day is a useful initial value to set criteria for maximum ramping rate. Hill et al. (1991) recommended that ramping rates be limited to 10 percent of the previous day's flow, e.g. if the flow today is 50,000 cfs, the flow tomorrow should be at least 45,000 cfs, and the flow the following day should be at least 40,500 cfs, etc. This criterion has the advantage of being easily applied, but is clearly a rough rule of thumb.

The criterion of limiting stage decline to 2.5 cm per day is biologically based, but to express it in terms of stage change, this criterion must be converted to flow using rating curves characteristic of sites where we expect to see establishment of riparian vegetation. At present, no stage discharge relations exist except at gages, which are typically located in reaches that are narrower and more stable than average, and where the stage discharge relation is apt to be steeper than in wider reaches.

6.2 Diversion Criteria for Off-stream Storage

6.2.1 Geomorphic Criteria

As noted above, in the absence of better information, we suggest 55,000 cfs as a threshold flow above which significant channel migration occurs, and recommend that the frequency, magnitude, and duration of flows greater than 55,000 cfs not be reduced, except as necessary for flood management. We emphasize the weakness of the data supporting the 55,000 cfs criterion, however, and suggest it only for the purposes of initial, feasibility level investigations of diversions to off-stream storage. A permissive standard seems appropriate for such initial investigations. We emphasize that better information may well lead to a different criterion.

Based upon the modeling results described above, regulation of the Sacramento River by Shasta Dam has reduced the average, long-term rate of channel migration in the upper Sacramento Valley by about 40 percent, independently of any bank stabilization measures, and additional reductions in flows will cause additional reductions in the rate of channel migration. Although the actual decrease in the rate of channel migration is not well known, the model results are consistent with available information. In view of the very large reduction in channel migration that has already occurred, and future reductions that can be expected to occur because of bank stabilization measures, we recommend that additional reductions in the high flows that drive channel migration be avoided. We recognize that the vulnerability of some houses and infrastructure to flooding sets constraints on the magnitude of flows that can be provided for environmental benefits. However, we regard these constraints as significant barriers to the realization of CALFED objectives, and recommend that actions to increase the allowable rates of flow be explored and implemented if feasible. Such actions would allow for improved flood management as well as permitting environmental benefits from higher flows.

6.2.2 Vegetation Criteria

Because of the modest contribution of snowmelt to the seasonal hydrograph of the Sacramento River, especially upstream from the flood basins, it is unclear what role snowmelt runoff plays in creating favorable conditions for seedling establishment by cottonwoods and willows. It is clear that cottonwoods and willows need a damp soil surface for germination and early survival, but in the absence of good stage-discharge data it is not possible to determine by inspection of flow data whether these conditions are, or historically were, created by high stage in the river or by rainfall from late storms. Therefore, at this time we are not proposing a control on decreases in flow during the spring, but instead recommend studies over the next two years that will include development of stage-discharge data and other information that will allow a more informed analysis of this issue.

6.3 Study Effort Over the Next 2 Years

Here we attempt to specify data requirements and modeling needs for better decision-making over the next two years (Figure 6.3-1), a period of time that should permit some uncertainties to be reduced and thereby refine the flow criteria.

6.3.1 Daily Time Step Operations Model

Current operations models run on a monthly-time-step, although a version of DWR's CALSIM model with a weekly time-step is under development. However, a model with a time-step no longer than a day is needed to analyze adequately the environmental effects of water management alternatives, and the effects of environmental constraints on operations. As a simple example, it will be difficult to model the effects of the constraints of diversions to off-stream storage that we recommend here using a monthly or even a weekly model. Similarly, a daily model is necessary to evaluate the effects of other water management alternatives on channel migration. We recognize that developing such a model will be a significant effort, but it is long overdue.

6.3.2 Sediment Mobility and Transport

Restoring and/or maintaining the natural frequency of bed mobilization is a first priority, followed by maintaining sediment routing processes and sediment budget. Little empirical information is available to estimate a threshold discharge for bed mobility, and the data available for the simple modeling performed in this paper were not collected to be used in this manner, and may be inadequate. Future evaluations should focus on empirical methods to estimate bed mobility thresholds (tracer rocks, bedload samples), supplemented with more detailed modeling approaches to predict bed mobility thresholds in case empirical estimates are not obtained due to a low flow year.

Additionally, because channel form and migration rates vary not only with flow regime but also with sediment transport, a sediment-routing model is needed to predict behavior of the system in general and to identify potential effects of reductions in transport capacity that might be associated with flow reductions at diversions. A model based on downstream routing of sediment from cell to cell (reach-to-reach), based on available data (which are not extensive) and transport formulae, would be an appropriate approach. Sediment input data from major upstream tributaries (e.g., Cottonwood Creek, Deer Creek, etc.,) would provide estimates of volume and caliber of sediment entering the Sacramento River from non-terrace sources.

6.3.3 Empirical Relations Between Flows and Channel Migration

Updating CDWR Bank Erosion Site Data

The CDWR bank erosion sites (CDWR 1979, CDWR 1994) should be resurveyed, and as-yet-unprocessed survey data from recent years should be analyzed, to update the excellent history of bank erosion at these detailed study sites. This is especially important given the wet years that have occurred recently, which can potentially expand the utility and of the data set, extending its range of application across a broader range of flows.

Analysis of Mapped Channel Change and Meander Migration

In addition to the detailed study of specific sites, CDWR Northern District have also mapped historical channel locations of the Sacramento River from historical maps and aerial photographs. These were published as appendices to the Middle Sacramento River spawning Gravel Study (CDWR 1984), and were later digitized as AUTOCADD files, which are available on the web. However, the technology available today is considerably better than that available when the mapping was first done. Moreover, the definition of banks has not necessarily been constant over time or among researchers. Usually, the outside banks of meander bands would be unambiguously defined, but there can be large differences in interpretation at the inside of meander bends and in straight reaches. The channel centerlines were also mapped, but because in many places the channel width has changed over time, channel centerlines may have changed as an artifact of width changes, without true translation of the channel.

The mapped meander migrations potentially provide an excellent data set, which combined with flow records for the intervening periods, could yield additional data for empirical relations between flow and rates of meander migration. It should be possible to measure meander migration rates for different time periods directly from the mapped channel centerlines. However, before undertaking this analysis, Buer and colleagues recommend (and we concur) that the mapping be redone using modern digitizing tablets and rectifying software, and with the opportunity to revisit the definition of banks in older maps and aerial photographs. This is potentially the most important set of analyses that can be undertaken to better specify the range of flows needed for channel migration. The data exist for the most part, but require systematic vetting and analysis, which the staff of Koll Buer and colleagues at the DWR Northern District (who collected the data in the first place) are ideally suited to undertake.

6.3.4 History of Changes in Riparian Vegetation

Overall, valley-wide maps of riparian vegetation distribution (at small scale) have been developed by the Bay Institute (1998) and other authors, and more detailed maps have been developed for short reaches, such as the excellent work of Greco (1999). Detailed riparian vegetation mapping should be conducted going back at least to the earlier aerial photographs, around 1939. This work can be done concurrently with the more accurate remapping of channel change discussed above.

6.3.5 Relation Between Hydrograph Shape and Riparian Vegetation Establishment

To better specify flow patterns needed to establish riparian vegetation will require detailed information on hydrologic controls on vegetation establishment from field study sites, along with historical analysis of conditions leading to establishment of important cohorts of vegetation identified in the field. It is not difficult to envision hydrograph patterns that would lead to the loss of a cohort of riparian vegetation, such as probably occurred in 1982, when flows abruptly dropped in April from about 60,000 cfs to 10,000 cfs. However, the actual effect of different patterns of stage decline during the seasonal recession limb on riparian vegetation establishment cannot be quantified now for a lack of basic field observations.

To sensibly interpret the existing vegetation patterns requires first that we know the stage discharge relation for each site and that we know the history of channel change and vegetation establishment. Unfortunately, stage-discharge relationships now exist on the Sacramento River only at streamflow gauges, which are typically located in straight, narrow reaches often bounded by hard banks, precisely the sites where we would not expect to find riparian vegetation recruitment. Thus, stage recorders are needed at a number of sites to develop a data base from which to determine the inundation frequencies associated with various surfaces and their particular suites of vegetation. Topography and particle size distribution should also be documented for sites of vegetation establishment. The ages of cottonwood trees should be measured directly by excavating the trunk down to its establishment surface, and then coring the trunk to count its annual rings. The history of bar growth and vegetation establishment can be further documented from analysis of historical aerial photographs, and the history of flows estimated from U.S. Geological Survey streamflow gaging station records.

Thus, a set of study sites should be established with continuous stage recorders, observation wells, vegetation transects, faces (sediment deposit) mapping, all keyed into topographic surveys, to permit the hydrologic controls on riparian vegetation establishment to be measured. We recommend that about a dozen such sites be established and monitored indefinitely, or until the relations between flow and vegetation establishment are sufficiently well known that we can predict the effects of various water management scenarios. The Nature Conservancy (TNC) has take a first step this year by establishing four study sites, at which transects have been surveyed and stage recorders installed, but TNC staff emphasize that their sample size is small and must be enlarged to develop reliable results for decision making (Mike Roberts, pers. comm. 1999).

6.4 Long-Term Effort

Long-term study efforts (Figure 6.3-1) should be focused on developing better information to link flow releases to the physical and ecological processes that maintain riparian vegetation. With a better understanding of the relations among flow releases, geomorphic processes, and ecological processes, we can more precisely modify reservoir flood control operations and time diversions for off-stream storage to minimize negative impacts and, ultimately, to improve flow conditions for riparian vegetation along the Sacramento River. Management actions should be undertaken in an adaptive management framework, in which management actions are taken so to maximize learning value, and targeted research is undertaken to reduce uncertainty about the system's response to our management actions. Continued, ongoing targeted research should include continued surveys of CDWR bank erosion sites and analysis of those data, continued analysis of channel form and channel change from frequent sequential aerial photography, and continued studies of riparian vegetation establishment at detailed study sites.

6.5 Recommended Locations for Geomorphic and Riparian Monitoring

Potential sites for monitoring riparian vegetation are listed in Table 6.3-1. Monitoring at these sites will need to include geomorphic variables, and these sites may also be suitable for geomorphic monitoring that is more directly related to salmon spawning habitat, although this remains to be confirmed. Recommendations for geomorphic and riparian monitoring that were developed for the CALFED Comprehensive Monitoring, Assessment and Research Program (CMARP) are attached in Appendix A. These should be reviewed in light of the specific hypotheses that are proposed in this report, and modified if need be.

TABLE 6.3-1
List of Potential Study Sites for Riparian Vegetation

River Mile	Bank	
174	R, L	Hartly Island
178.5	R, L	Llano Seco
192	R	Shaw and Phelan Island Unit, Sac. R. NWR
194.5	L	Chico Landing (Bidwell Sac. R. State Park
197	L	Mouth of Pine Creek
203	L	Wilson Landing
207	L	Snaden Island
209.5	L	Mouth of Burch Creek
210.5	R	Foster Island
227	L	Mouth of McClure Creek
234.5	L	Sacramento Bar (Ohn Unit Sac. R. NWR)
237	R	Todd Island

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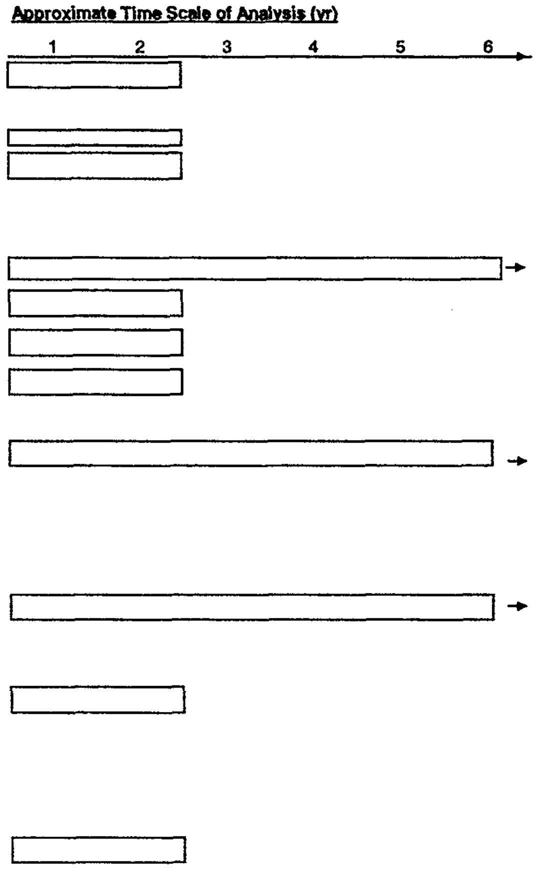


Objectives	Analysis Needed
Flow requirements for channel migration (flow duration vs. erosion relation)	•Historical channel migration analysis from maps/airphotos (DWR Northern District)
	•Analysis of bank erosion survey data, 1977-present (DWR Northern District) -analyze inundation/duration frequency at erosion sites
	•Continued bank erosion surveys & analysis -Analysis of LWD effects on channel processes & fish habitat -Analysis of 1997 Flood effects and options for alternative flood management
Document effects of riprap on channel migration	•Mapping riprap extent (done), relate to channel migration; assess potential riprap removal sites
Flow requirements to establish pioneer riparian vegetation	•Forensic geomorphic/ecologic studies at (12) sites of successful cohorts: -survey topo & vegetation distribution -develop stage - q relations -flow history: water table, scour regime -detailed historical aerial photo analysis
Flow requirements for vegetation succession	•Forensic geomorphic/ecologic studies at sites of mature late-successional stage vegetation -As above, but reconstruct history of overbank sediment, document tree ages
Effects of flow alteration on sediment transport & channel/floodplain morphology	•Empirical analysis of suspended sediment transport •Mathematical modeling (sediment routing) •Analysis of cross-sectional & planform change
Changes in channel geometry, channel migration, and sediment supply from bank stabilization	•Develop reach-by-reach history of bank stabilization from field evidence, aerial photographs, and agency records •Document over time and contrast between eroding and stabilized reaches: -bank erosion rates -channel geometry -riparian establishment and succession

FIGURE 6.3-1
Proposed analyses – short term and long term

8. References

Andrews, E. D. 1994. Marginal bedload transport in a gravel stream, Sagehen Creek, California. *Water Resources Research* 30: 2241-2250.

Andrews, E.D. and J.D. Smith. 1992. A theoretical model for calculating marginal bed load transport rates of gravel. Pages 41-52 in P. Billi, R.D. Hey, C.R. Thorne, and P. Tacconi (eds.), Dynamics of Gravel-Bed Rivers, John Wiley, New York.

Auble, G. T., J.M. Friedman, and M.L. Scott. 1994. Relating riparian vegetation to present and future streamflows. *Ecological Applications* 4(3): 544-554.

Baltz, D.M. and P.B. Moyle. 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. *Ecological Applications* 3(2):246-255.

Barbour, M.G. and J. Major (eds.). 1988. Terrestrial Vegetation of California. Special Publication/ California Native Plant Society; No. 9.

Bay Institute. 1998. From the Sierra to the Sea: the ecological history of the San Francisco Bay-Delta Watershed. The Bay Institute, San Francisco. 240 pp (appx).

Benda, L.E. 1994. Stochastic geomorphology in a humid mountain landscape. Doctoral dissertation. University of Washington, Seattle.

Bisson, P.A., G.H. Reeves, R.E. Bilby, and R.J. Naiman. 1997. Watershed management and Pacific salmon: desired future conditions. Pages 447-474 in Strouder, D.J., P.A. Bisson, and R.J. Naiman (eds.), Pacific Salmon and Their Ecosystems: Status and Future Options. Chapman and Hall, New York.

Botsford, L.W., J.C. Castilla, and C.H. Peterson. 1997. The management of fisheries and marine ecosystems. *Science* 227:509-515.

Braatne, J.H., S.B. Rood, and P.E. Heilman. 1996. Life history, ecology, and conservation of riparian cottonwoods in North America. Biology of Populus and its Implications for Management and Conservation. 57-85.

Bradley, C. and D. G. Smith. 1984. Meandering channel response to altered flow regime: Milk River, Alberta and Montana. *Water Resources Research* 20(12): 1913-1920.

Brice, J. 1977. Lateral migration of the middle Sacramento River. U.S. Geological Survey Water-Resources Investigations 77-48.

Brunke, M. and T. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* 37:1-33.

Burt, D.W. and J.H. Mundie. 1986. Case histories of regulated streams flows and its effects on salmonid populations. *Canadian Technical Report of Fisheries and Aquatic Sciences* 446.

CALFED Bay-Delta Program. 1999. Strategic Plan for Ecosystem Restoration, Ecosystem Restoration Program. Draft Programatic EIR/EIS Technical Appendix.

CALFED. 1997. Ecosystem Restoration Program Plan: Volume III – Vision for Adaptive Management.

California State Lands Commission. 1993. California's Rivers, A Public Trust Report.

California-American Water Company. 1998. Reconnaissance-level feasibility study of the operational reconfiguration of the lower Carmel Valley Wells, Phase I. Draft Scope of Work submitted to the State Water Resources Control Board, 18 Sept. 1998.

Cameron, J. and J. Abouchar. 1991. The precautionary principle: a fundamental principle of law and policy for the protection of the global environment. Boston College International & Comparative Law Review 14:1-27.

Castleberry, D.T., J.J. Cech, D.C. Erman, D. Hankin, M. Healey, G.M. Kondolf, M. Mangel, M. Mohr, P.B. Moyle, J. Nielsen, T.P. Speed, and J.G. Williams. 1996. Uncertainty and instream flow standards. *Fisheries* 21(8):20-21.

CDWR (California Department of Water Resources). 1979. Observations of Sacramento River bank erosion, 1977-1979. CDWR, Northern District, Red Bluff.

CDWR (California Department of Water Resources). 1984. Middle Sacramento River Spawning Gravel Study, and Appendix: Sacramento River Atlas..

CDWR (California Department of Water Resources). 1994. Sacramento River bank erosion investigation memorandum progress report.. CDWR, Northern District, Red Bluff.

CDWR (California Department of Water Resources). 1984. River Atlas – Appendix to: Middle Sacramento River Spawning Gravel Study.

CDWR (California Department of Water Resources). 1994. Sacramento River Bank Erosion Investigation Memorandum Progress Report. CDWR, Northern District, Red Bluff.

CDWR (California Department of Water Resources). 1994. Sacramento River Bank Erosion Investigation Memorandum Progress Report. CDWR, Northern District, Red Bluff.

CDWR (California Department of Water Resources). 1995. Memorandum Report – Sacramento River Meander Belt Future Erosion Investigation. CDWR, Northern District, Red Bluff.

Christensen, N.L. and 12 others.. 1996. The report of the Ecological Socitey of American Committee on the Scientific Basis for ecosystem management. *Ecological Applications* 665-691.

Collier, M., R.H. Webb, and J.C. Schmidt. 1996. Dams and Rivers: a primer on the downstream effects of dams. U.S. Geological Survey Circular 1126.

Connel, J.H. 1978. Diversity in tropical rain forests and coral reefs. *Science* 199:1302-1310.

Dayton, P.K. 1998. Reversal of the burden of proof in fisheries management. Science 279:821-822.

Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and development of coarse surface layer in gravel bedded rivers. *Nature* 340:215-217.

Dolcini, A. 1979. Observations of Sacramento River Bank Erosion. Department of Water Resources, Northern District.

Dover, S.R. and J.W. Handmer. 1995. Ignorance, the precautionary principle, and sustainability. Ambio 26:92-97.

Dykaar, B.B., and P.J. Wigington Jr. 1998. Floodplain formation and cottonwood colonization patterns on the Willamette River, Oregon, USA. Environmental Management (in press).

Ebersole, J.L., W.J. Liss, and C.A. Frissell. 1996. Restoration of stream habitats in managed landscapes in the western USA: restoration as re-expression of habitat capacity. *Environmental Management.*

Efron, B. and R. Tibshirani. 1991. Statistical data analysis in the computer age. *Science* 253:390-395.

Efron, B. and R. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York.

Einstein, H.A. 1950. The bedload function for sediment transportaton in open chanel flows. U.S. Department of Agriculture Technical Bulletin 1026.

EIP Associates. 1993. 1993 survey results for California red-legged frog (rana aurora draytoni), southwestern pond turtle (Clemmy marmorata pallida), California spotted owl (Strix occidentalis occidentalis) in the Carmel River drainage. Unpublished report to the MPWMD.

Engeund, F. and Hansen, E. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen, Denmark.

Fenner, P., W. Brady, and D. Patton. 1984. Observations on seeds and seedlings of fremont cottonwood. *Journal of Desert Plants* 6:55-58.

Fischer, K.J. 1994. Fluvial geomorphology and flood control strategies: Sacramento River, California. The Variability of Large Alluvial Rivers 115-119.

Fisher, B.N. and H.B. Shaffer. 1996. The decline of amphibians in California's great Central Valley. *Conservation Biology* 10:1387-1397.

Fogarty, M.J., R.K. Mayo, L. O'Brien, F.M. Serchuk, and A.A. Rosenberg. 1996. Assessing uncertainty in exploited marine populations. *Reliab. Eng. Syst. Saf.* 54:183-195.

Francis, R.I.C.C. and R. Shotton. 1997. "Risk" in fisheries management: a review. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1699-1715.

Fraquhar, Francis P. 1966. Up and down California in 1860-1864. The journal of William

Frissell, C.A., W.J. Liss, R.E. Gresswell, R.K. Nawa, and J.L. Ebersole. 1997. A resource in crisis: changing the measure of salmon management. Pages 411-444 in Strouder, D.J., P.A. Bisson, and R.J. Naiman (eds.), Pacific Salmon and Their Ecosytems: Status and Future Options. Chapman and Hall, New York.

Garcia, S.M. 1994. The precautionary principle: its implications in capture fisheries management. *Ocean & Coastal Management* 22:99-125.

Geist, D.R. and D.D. Dauble. 1998. Redd site selection and spawning habitat use by fall chinook salmon: the importance of geomorphic features in large rivers. *Environmental Management* 22:655-669.

Gilbert, G. K. 1917. Hydraulic mining debris in the Sierra Nevada. United States Geological Survey Professional Paper no. 105.

Gilbert, J., D.L. Danielopol, and J.A. Stanford. 1994. *Groundwater Ecology*. Academic Press.

Gordon, D.V. and G.R. Munro, editors. 1996. Fisheries and uncertainty: precautionary approach to resource management. University of Calgary Press, Calgary, Canada.

Greco, S. E. 1999. Monitoring riparian landscape change and modeling habitat dynamics of the yellow-billed cuckoo on the Sacramento River, California.

Harmon, M. E, .J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkamper, et al. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. Advances in Ecological Research. A. MacFadyen and E. D. Ford. New York, NY, Harcourt Brace Jovanovich. 15: 133-302.

Harwood, D.S., and E.J. Helley. 1987. Late Cenozoic tectonism of the Sacramento Valley, California. U.S. Geological Survey Professional Paper 1359.

Hasegawa, K. 1989a. Studies on qualitative and quantitative prediction of meander channel shift. Pages 215-236 in S. Ikeda and G. Parker (eds.) River meandering. *Water Resources Monograph* 12. American Geophysical Union.

Hasegawa, K. 1989b. Universal bank erosion coefficient for meandering rivers. *Journal of Hydraulic Engineering* 115:744-765.

Hayes, M.P. and M.R. Jennings. 1986. Decline of ranid frog species in western North America: are bullfrogs (Rana catesbeiana) responsible? *Journal of Herpetology* 20:490-509.

Healey, M. 1997. Paradigms, policies and prognostication about watershed ecosystems and their management. In Naiman, R.J. and R.E. Bilby (eds). River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Sppringer-Verlag, New York.

Healey, M., and T.M. Hennessey. 1994. The utilization of scientific information in the management of estuarine ecosystems. *Ocean and Coastal Management* 23:167-191.

Healey, M., W. Kimmerer, G.M. Kondolf, R. Meade, P.B. Moyle, and R. Twiss. 1998. Strategic plan for the ecosystem restoration program. report to the CALFED Bay-Delta Program, Sacramento, California.

Hecht, B. 1981. Sequential changes in bed habitat conditions in the upper Carmel River following the Marble-Cone fire of August, 1977. Paper presented at the California Riparian Systems Conference (University of California, Davis, Sept. 17-19, 1981), reprinted in J.G. Williams and G.M. Kondolf (eds.), 1983, Guidebook for the 16-18 June Conference on Channel Stability and Fish Habitat, Carmel River, California.

Helley and Smith. 1971. Development and calibration of a pressure difference bedload sampler. Geological Survey open file report.

Helley, E.J., and D.S. Harwood. 1985. Geological map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California. U.S. Geological Survey Professional Paper 1359.

Hilborn, R., and M. Mangel. 1997. The Ecological Detective; confronting models with data. *Monographs in Population Bio*logy # 28. Princeton University Press.

Hilborn, R., and R.M. Peterman. 1996. The development of scientific advice with incomplete information in the context of the precautionary approach. FAO Fish. Tech. Pap. No. 350/2. Precautionary approach to fisheries. pp. 77-102.

Hilborn, Ray. 1987. Living with uncertainty in resource management. *North American Journal of Fisheries Management* 7:1-5.

Hilborn, Ray. 1992. Institutional learning and spawning channels for sockeye salmon (Onchrhynchus nerka). *Canadian Journal of Fisheries and Aquatic Sciences* 49:1126-36.

Hodge, R. 1990. Statement of Decision, Environmental Defense Fund v. East Bay Municipal Utility District.

Holling, C.S. 1978. Adaptive Environmental Assessment and Management. John Wiley & Sons. London, England.

Horwood, J. Stochastically optimal management of fisheries. ICES CM D:26. ICES,

Howard, A. 1992. Modeling channel migration and floodplain sedimentation in meandering streams. Pages 1-41. P.A. Carling and G.E. Petts (eds.) Lowland Floodplain Rivers: Geomorphological Perspectives: John Wiley & Sons.

Hupp, C.R., and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14 277-295.

Johannesson, H. and G. Parker. 1985. Computer simulated migraton of a meadering river in Minnesota. Unpublished. M.S. Thesis, University of Minnesota.

Johannesson, J. and G. Parker. 1989. Linear theory of river meanders. Pages 181-214 in S. Ikeda and G. Parker (eds.) River meandering. *Water Resources Monograph* 12. American Geophysical Union.

Johnson, W.C. 1992. Dams and riparian forests: case study from the upper Missouri River. *Rivers* 3:229-242.

Katibah, E. F. 1984. A brief history of riparian forests in the Central Valley of California. Pages 23-29. California riparian systems: ecology, conservation, and productive management. R. E. Warner and K. M. Hendrix (eds.). Berkeley, CA. University of California Press.

Kelley, R. 1989. Battling the inland sea. Univ. of California Press, Berkeley.

Kondolf, G.M. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* 21(4):533-551.

Kondolf, G.M., and G. Matthews. 1990. Assessment of potential impacts of Monterey Peninsula water supply project on downstream channel geomorphology on the Carmel River. Unpublished report to the MPWMD.

Kondolf, G.M., and P.R. Wilcock. 1996. The flushing flow problem: defining and evaluating objectives. *Water Resources Research* 32(8):2589-2599.

Kondolf, G.M., and S.M. McBain. 1995. Carmel River: The Dampierre restoration project: factors leading to project failure and recommendations for future management. Unpublished report to the MPWMD.

Kondolf, G.M., and W.G.V. Matthews. 1993. Management of coarse sediment in regulated rivers of California. University of California Water Resources Center, Riverside. Report No. 80.

Kondolf, G.M., E. W. Larsen, and J.G. Williams. Submitted *to North American Journal of Fisheries Management*. Measuring and modeling the hydraulic environment for determining instream flows.

Kondolf, G.M., J.C. Vick, and T.M. Ramirez. 1996. Salmon spawning habitat rehabilitation in the Merced, Tuolumne, and Stanislaus Rivers, California: an evaluation of project planning and performance. University of California Water Resources Center Report No. 90, Davis, CA.

Krebs, C.J. 1989. Ecological Methodology. HarperCollins Publishers, New York.

Kuhl, D. 1992. 14 years of artificial gravel feeding in the Rhine downstream of the barrage Iffezheim. pp 1121-1129 in Proceedings 5th International Symposium on river sedimentation, Karlsruhe, Germany.

Kupferberg, S.J. 1996. Hydrologic and Geomorphic factors affecting conservation of a river breeding frog (Rana boylii). Ecological Applications 6:1332-1344.

Larsen, E.W. 1995. The mechanics and modeling of river meander migration. Ph.D. dissertation, Universtiy of California at Berkeley.

Larsen, E.W., S.E. Greco, and C.H. Baker. 1998. Channel migration of the Sacramento River near Woodson Bridge State Recreation Area: a case study of alternaive channel management strategies. Appendix II in Woodson Bridge State Recreation Area, long-term solutions study, working draft. California Department of Water Resources, Northern District, Red Bluff.

Lauck, T., C.W. Clark, M. Mangel, and G.R. Munro. 1998. Implementing the precautionary principle in fisheries management through marine reserves. *Ecological Applications* 8(1) Supplement:S72-S78.

Lee, Kai N, and Jody Lawrence. 1986. Adaptive management: learning from the Columbia River Basin fish and wildlife program. *Environmental Law* 16:431-460.

Leopold, L.B., M.G. Wollman and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman, San Francisco. —

Ligon, F.K., W.E. Dietrich, and W.J. Trush. 1995. Downstream ecological effects of dams, a geomorphic perspective. *Bioscience* 45(3):183-192.

Littleworth, A.L. and E. Garner. 1995. *California Water*. Solano Press Books.

Ludwig, D. 1994. Uncertainty and fisheries management. Pages 514-528 in S.A. Levin (ed.) Frontiers in Mathmatical Biology. Springer-Verlag.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science* 260:17,36; reprinted with responses in Ecological Applications 3:547-549.

Maddock, T. 1970. Indeterminate hydraulics of alluvial channels. *Journal of the Hydraulics Division* 96:2309-2323.

Mahoney, J.M., and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment-an integrative model. *Wetlands*. 18(4):634-645.

Mangel, M. 1994. Climate change and salmonid life history variation. Deep Sea Research II (topical studies in oceanography) 41:75-106.

Mangel, M. and 41 others. 1996. Principles for the conservation of wild living resources. *Ecological Applications* 6:338-362.

Mangel, M., R.J. Hofman, E.A. Norse, and J.R. Twiss, Jr. 1994. Sustainability and ecological research. *Ecological Applications* 3:573-575.

Maule, A.G., C.B. Schreck, C.S. Bradford, and B.A. Barton. 1988. *Transactions of the American Fisheries Society*:117:245

McBain and Trush. 1997. Trinity River maintenance flow study - Final Report. Arcata, CA. 316 pp.

Meffe, G.K. 1984. Effects of abiotic disturbance on coexistence of predator-prey fish species. *Ecology* 65:1525-1534.

Meffe, G.K., and W.L. Minckley. 1987. Differential selection by flooding in stream fish communities of the arid American southwest. Pages 93-104 in W.J. Matthews and D.C. Heins (eds.), Community and Evolutionary Ecology of North American Stream Fishes. University of Oklahoma Press, Norman, Oklahoma.

Merigliano, M.F. 1996. Ecology and Management of the South Fork Snake River Cottonwood Forest. Idaho BLM, Tech. Bull. 96-9.

Meyer-Peter, E., and R. Muller. 1948. Formulas for bed-load transport. Paper presented at the Third Conference of the International Association of Hydraulic Research, Stockholm, Sweden.

Milhous, R.T. 1973. Sediment transport in a grave-bottomed stream. PhD thesis, Oregon State University, Corvallis.

Mills, T.J., D. McEwan, and M.R. Jennings. 1997. California salmon and steelhead: beyond the crossroads. Pages 91-112 in D.J. Strouder, P.A. Bisson, and R.J. Naiman (eds), Pacific Salmon and their Ecosystem. Chapman & Hall.

Moyle, P.B. 1976. Inland Fishes of California. University of California Press.

Moyle, P.B. 1986. Fish introductions in North American: patterns and ecological impact. Pages 27-43 in Ecology of Biological Invasions on North America and Hawaii. Springer-Verlag, New York.

Moyle, P.B., M.P. Marcheitti, J. Baldridge, and T.L. Taylor. 1998. Fish health and diversity: justifying flows for a California stream. *Fisheries* 23(7):6-15.

Municipal Utility District, Alameda County (California) Superior Court Action Number.

Myers, R.A., and G. Mertz. 1998. The limits of exploitation: a precautionary approach. *Ecological Applications* 8:S165-169.

Naiman, R.J., and R.E. Bilby (eds.) 1997. River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York.

Nanson, G.C. and J.C. Croke. 1992. A genetic classification of floodplains. *Geomorphology* 4:459-486.

National Audubon Society v. Superior Court. 1983. 33 Cal. 3d 419.

National Research Council. 1996. Upstream: Salmon and Society in the Pacific Northwest. National Academy Press, Washington, D.C.

Nehlsen, W., J.G. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* 16(2):4-21

Nelson, R.W., J.R. Dwyer, and W.E. Greenberg. 1987. *Environmental Management* 11:479.

Nielsen, J.L. (ed.) 1995. Evolution and the aquatic ecosystem; defining unique units in population conservation. American Fisheries Society Symposium 17, Bethesda, Maryland.

Nilsson, C., R. Jansson, and U. Zinko. 1997. Long-term responses of river-margin vegetation to water-level regulation. *Science* 276:798-800.

O'Boyle, R. 1993. Fisheries management organizations: a study in uncertainty. Pages 423-436 in Risk evaluation and biological referenced points for fisheries management. *Canadian Special Publications in Fisheries and Aquatic Sciences* 120.

O'Neil, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A Hierarchical Concept of Ecosystems. *Monographs in Population Biology* No. 23. Princeton University Press.

Osterkamp, W. R., and C. R. Hupp. 1984. Geomorphic and vegetative characteristics along three northern Virginia streams. *Geological Society of America Bulletin* 95: 1093-1101.

Paintal, A.S. 1971. Concept of critical shear stress in loose boundary open channels. *Journal of Hydraulic Research* 9:91-93.

Parker, G. and E.D. Andrews. 1985. On the time development of meander bends. *Journal of Fluid Mechanics* 162:139-156.

Parker, G., P.C. Klingeman, and D.G. McLean. 1982. Bedload and size distribution in paved gravel-bed streams, *Journal of Hydraulic Engineering*, ASCE, 108(HY4):544-571.

Pelzman, R. J. 1973. Causes and possible prevention of riparian plant encroachment on anadromous fish habitat. Environmental Services Branch, California Department of Fish and Game. 26 pp.

Peterman, R.M. 1990. Statistical power analysis can improve fisheries research and management. *Canadian Journal of Fisheries and Aquatic Sciences* 47:2-15.

Peterman, R.M. and c.n. Peters. 1998. Decision analysis: taking uncertainties into account in forest resource management. Pages 105-128 in V. Sit and B. Taylor (eds.) Statistical methods for adaptive management studies. B.C. Ministry of Forests, Land Management Handbook No. 42.

Peterman, R.M. and J.L. Anderson. 1999. Decision analysis: a method of taking uncertainties into account in risk-based decision making. *Human Ecological Risk Assessment* 5(2).

Pickett, S.T.A., and P.S. White (eds.). 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press.

Pitnick, R. 1997. Wet dream. Coast Weekly, 11 September 1997.

Power, M.E. 1995. Floods, food chains, and ecosystem processes in rivers. Pages 52-60 in Linking Species and Ecosystems. Chapman and Hall, N.Y.

Power, M.E., M.S. Parker, and J.T. Wootton. 1995. Disturbance and food chain length in rivers. Pages 286-297 in Food Webs. Chapman & Hall, New York.

Power, M.E., W.E. Dietrich, and J.C. Finlay. 1996. Dams and downstream aquatic biodiversity: potential food web consequences of hydrologic and geomorphic change. *Environmental Management* 20:887-895.

Rader, R.B. 1995. A functional classification of the drift: traits that influence invertebrate availability to salmonids. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1211-1234.

Raymond, H.L. 1988. *North American Journal of Fisheries Management* 8:1.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349.

Resh et al. 1998. The role of disturbance in stream ecology. *Journal of the North American Benthological Society* 7:433-455.

Richards, L.J., and J.J. Maguire. 1998. Recent international agreements and the precautionary approach: new directions for fisheries management science. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1545-1552.

Richter, B.D., J.V. Baumgartner, D.P. Braun, and J. Powell. 1998. A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research and Management* 14:329-340.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10:1163-1174.

Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37:231-249.

Robichaux, R. 1977. Geologic history of the riparian forests of California. 21-34 pp. Riparian forests in California: their ecology and conservation. Anne Sands (ed.). Institute of Ecology publication #15.University of California, Davis, CA.

Rood, S.B., A.R. Kalischuk, and J.M. Mahoney. 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. Wetlands 18:557-570.

Rood, S.B., and J.M. Mahoney. 1990. Collapse of riparian forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management* 14:451-464.

Rosenberg, A.A., and S. Brault. 1993. Choosing a management strategy for stock rebuilding when control is uncertain. Pages 243-249 in Risk evaluation and biological referenced points for fisheries management. *Canadian Special Publications in Fisheries and Aquatic Sciences* 120.

Sacramento River Advisory Council. 1998. Draft Sacramento River conservation handbook. available from CDWR (California Department of Water Resources)., Northern District, Red Bluff.

San Francisco Estuary Project. 1992. State of the Estuary - A Report on Conditions and Problems in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary.

San Francisco Estuary Project. 1992. The effects of land use change and intensification on the San Francisco Estuary. San Francisco Estuary Project, Oakland, California. Available on line through the University of California, Berkeley Digital Library Project #642.

Sawyer, J. O., and T. Keeler-Wolf. 1995. A manual of California vegetation. Sacramento, CA. California Native Plant Society.

SB 1086 Advisory Council and Action Team. 1989. Sacramento River Fisheries and Riparian Habitat Management Plan.

Schmidt, J.C., R.H. Webb, R.A. Valdex, G. Richard Marzolf, and L.E. Stevens. 1998. *Science* and values in river restoration in the Grand Canyon. BioScience 48:735-746.

Scott, D., and C.S. Shirvell. 1987. A critique of the instream flow methodology and observations on flow determination in New Zealand. Pages 27-43 *Regulated Streams: Advances in Ecology*. Plenum Press, New York.

Scott, M.L., J.M. Friedman, G.T. Auble. 1996. Fluvial process and the establishment of bottomland trees. *Geomorphology* 14:327-339.

Segelquist, C. A., M. L. Scott, and G. T. Auble. 1993. Establishment of Populus deltoides under simulated alluvial groundwater declines. *American Midland Naturalist* 130: 274-285.

Shafroth, P.B., J.C. Stromberg, and D.T. Patten. Woody riparian vegetation response to different alluvial water-table regimes. Submitted to Great Basin Naturalist.

Shirvell, C.S. 1986. Pitfalls of physical habitat simulation in the instream flow incremental methodology. Canadian Technical Report of Fisheries and Aquatic Sciences No. 1460. Dept. of Fisheries and Oceans, British Columbia.

Sparks, R.E. 1992. Risks of altering the hydrologic regime of large rivers. Pages 119-152 in Predicting Ecosystem Risk. Advances in modern environmental toxicology, vol. 20.

Sparks, R.E. 1995. The need for ecosystem management of large rivers and their floodplains. *Bioscience* 45:168-182.

Sparks, R.E., P.B. Bayley, S.L. Kohler, and L.L. Osborne. 1990. Disturbance and recovery of large floodplain rivers. *Environmental Management* 14:699-709.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant. 1996. A general protocol for the restoration of regulated rivers. *Regulated Rivers, Research and Management* 12:391-413.

Stanley, T.L., K.D. Hyattm, T.G. Northcote, and R.J. Fielden. 1996. Status of anadromous salmon and trout in British Columbia and Yukon. *Fisheries* 21(10):20-35

Stephenson, R.L., and D.E. Lane. 1995. Fisheries management science: a plea for a conceptual change. *Canadian Journal of Fisheries and Aquatic Sciences* 52:2051-2056.

Strahan, J. 1984. Regeneration of riparian forests of the Central Valley. 58-67 pp. in R. E. Warner and K. M. Hendrix (eds.). California Riparian Systems: Ecology, Conservation, and Productive Management. Berkeley, CA. University of California Press.

Strange, E.M., P.B. Moyle, and T.C. Foin. 1992. Interactions between stochastic and deterministic processes in stream fish community assembly. Environmental Biology of Fishes 36:1-15.

Strouder, D.J., P.A. Bisson, R.J. Naiman (eds.). 1996. Pacific Salmon and Their Ecosystems. Chapman & Hall.

Studley, T.K., J.E. Baldridge, L.M. Wise, A.P. Spina, S.F. Railsback, E. McElravy, L. Travanti, T.D.F. Yuen, R.B. Lindahl, S.D. Chase, R.W. Smith. 1995. Response of fish populations to altered flows project, Volume I: predicting trout populations from streamflow and habitat variables. Prepared by Pacific Gas and Electric Company Technical and Ecological Services and Entrix, Inc.

Taylor, D.W. 1982. Eastern Sierra riparian vegetation: ecological effects of stream diversions. Contribution No. 6, Mono Basin Research Group, Report to Inyo National Forest, Bishop, California.

The Bay Institute of San Francisco. 1998. From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed.

Thompson, G.G. 1993. A proposal for a threshold stock size and maximum fishing mortality rate. Pages 303-320 in Risk evalatuion and biological referenced points for fisheries management. *Canadian Special Publications in Fisheries and Aquatic Sciences* 120.

Thompson, Kenneth. 1961. Riparian forests of the Sacramento Valley, California. Ann. Assoc. Amer. Geog. 51(3):294-315.

Thorne, C.R. 1982. Processes and mechanisms of river bank erosion. Pages 227-272 in R.D. Hey, J.C. Bathurst and C.E. Thorne (eds.) Gravel-Bed Rivers. John Wiley & sons.

Trenberth, K., and T.J. Hoar. 1995. The 1990-1995 El Nino-Southern Oscillation event: longest on record. Geophysical Research Letters 23:57-60.

U.S. Bureau of Reclamation South-Central California Area Office. 1998. Analysis of physical processes and riparian habitat potential of the San Joaquin River - Friant Dam to the Merced River.

U.S. Fish and Wildlife Service, Hoopa Valley Tribe. 1999. Trinity river flow evaluation final report.

U.S. Fish and Wildlife Service. 1997. Revised Draft Restoration Plan for the Anadromous Fish Restoration Program – A plan to increase natural production of anadromous fish in the Central Valley of California. Prepared for the Secretary of the Interior by the United States Fish and Wildlife Service with assistance from the Anadromous Fish Restoration Program Core Group under authority of the Central Valley Project Improvement Act.

U.S. Fish and Wildlife Service. Evaluation of the Sacramento River spawning gravel restoration project and winter-run chinook salmon redd survey, 1987-1993. U.S. Fish and Wildlife Service, Red Bluff, California.

USACE (U.S. Army Corps of Engineers). 1983. Sacramento River and tributaries bank protection and erosion control investigation. U.S. Army Corps of Engineers, Sacramento District.

Volkman, J.M., and W.E. McConnaha. 1993. Through a glass darkly: Columbia River salmon, the Endangered Species Act, and adaptive management. *Environmental Law* 23:1249-1272.

Vyverberg, K, B. Snider, and R.G. Titus. 1997. Lower American River chinook spawning habitat evaluation, October 1994. California Dept. of Fish and Game, Environmental Services Division, Sacramento, California.

Waldichuk, M. 1993. *Canandian Bulletin of Fisheries and Aquatic Sciences* 226:295.

Walters, C. 1986. Adaptive Management of Renewable Resources. MacMillian, New York.

Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. Conservation Ecology [online]1:(2):1. Available from the Internet, URL:http://www.consecol.org/vol1/iss2/art1.

Walters. C.J. and R. Hilborn. 1976. Adaptive control of fishing systems. *Journal of the Fisheries Research Board of Canada* 33:145-159.

Ward, J.V. and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers Research and Management* 11:105-119.

Ward, J.V., and J.A. Stanford. 1983. The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. Pages 347-356 in Dynamics of Lotic Ecosystems. Ann Arbor Sci. Pub., Ann Arbor, MI.

Warner, R. E. 1984. Structural, Floristic, and Condition Inventory of Central Valley Riparian Systems. In Warner, R. E., and K. M. Hendrix (eds.) 1984. California riparian systems: ecology, conservation, and productive management. Berkeley, CA. University of California Press.

Warner, R. E., and K. M. Hendrix (eds.) 1984. California riparian systems: ecology, conservation, and productive management. Berkeley, CA. University of California Press.

WET (Water Engineering and Technology, Inc.). 1988. Geomorphic and hydraulic engineering study of Sacramento River from Hamilton City (RM 199.3) to Woodson Bridge (RM 218.3). report to Glenn-Colusa Irrigation District.

Wiberg, P.L., and J.D. Smith. 1987. Calculation of critical shear stress for motion of uniform and heterogeneous sediments. *Water Resources Research* 23:1471-1480.

Wilcock, P. 1996. A method for predicting sediment transport in gravel-bed rivers. Johns Hopkins University, Baltimore.

Wilcock, P.R. 1988. Methods for estimating the critical shear stress of individual fractionsin mixed-size sediment. *Water Resources Research* 24:1127-1135.

Wilcock, P.R. 1992. Flow competence: a criticism of a classic concept. *Earth Surface Processes and Landforms* 17:289-298.

Wilcock, P.R., A.F. Barta, C.C. Shea, G.M. Kondolf, W.V. Matthews, and J. Pitlick. 1996. Observations of flow and sediment entrainment on a large gravel-bed river. *Water Resources Research* 32:2897-2909.

Wilcock, P.R., G.M. Kondolf, W.V. Matthews, and A.F. Barta. 1996. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* 32:(9):2911-2921.

Williams, G.P. and Wolman, M.G. 1984. Downstream effects of dams on alluvial rivers: USGS Professional Paper 1286.

Williams, J.G. 1980. Stream flow and reservoir yield at the San Clemente site, Carmel River. Unpublished report to the MPWMD.

Williams, J.G. 1989. Habitat change in the Carmel River basin. Pages 8-29 in J.G. Williams, G.M. Kondolf, D. Lindquist, and B. Laclergue (eds.), Guidebook, The politics and practices of restoration, symposium and field tour, Oct. 67, 1989.

Williams, J.G. 1995. Report of the special master for water years 1990-1993, EDF v. EBMUD, Alameda County Superior Court Action 425955.

Williams, J.G. 1996. Lost in space: minimum confidence intervals for idealized PHABSIM studies. *Transactions of the American Fisheries Society* 125:458-465.

Williams, J.G. 1997. Transcript of workshop on flow standards, April 7, 1995, University of California, Davis. University of California Water Resources Report No. 89.

Williams, J.G. 1998. Thoughts on adaptive management. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter 11(3):5-11.

Williams, N. 1998. Dams drain the life out of riverbanks. Science 276:683.

Wolman, M.G. and J.P. Miller. 1960 Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* 68:54-74.

Wolman, M.G. and L.B. Leopold. 1957. River flood plains: some observations on their formation. U.S. Geological Survey Professional Paper 282C, 87-109.

Wootton, J.T., M.S. Parker, and M.E. Power. 1996. Effects of disturbance on river food webs, *Science* 273:1558-1561

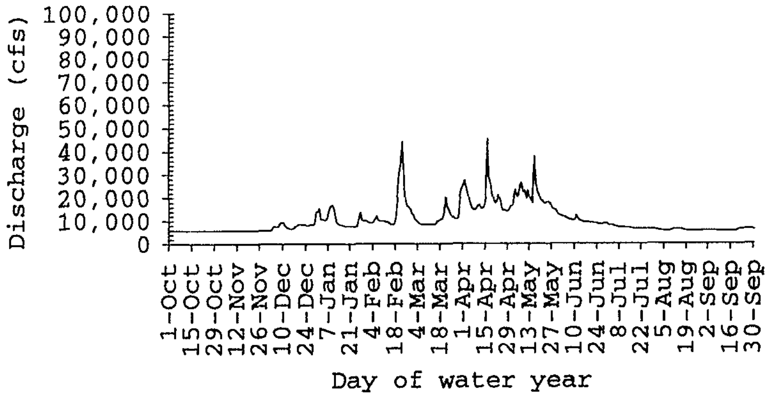
Yoshiyama, R. M., 1999. A history of salmon and people in the Central Valley region of California, *Reviews in Fisheries Science*, 7(3&4), 197-239.

Yoshiyama, R.M., E.R. Gerstung, F.W. Fisher, and P.B. Moyle. 1996. Historical and present distribution of chinock salmon in the Central Valley drainage of California. Pages 309-632 in Sierra Nevada ecosystem project: final report to Congress, Vol. III, assessments, commissioned reports, and background information. Davis: University of California, Centers for Water and Wildland Resources. Davis, CA.

APPENDIX A

Sacramento River Hydrographs, Bend Bridge Gage, 1892-1997

1892 Annual Hydrograph



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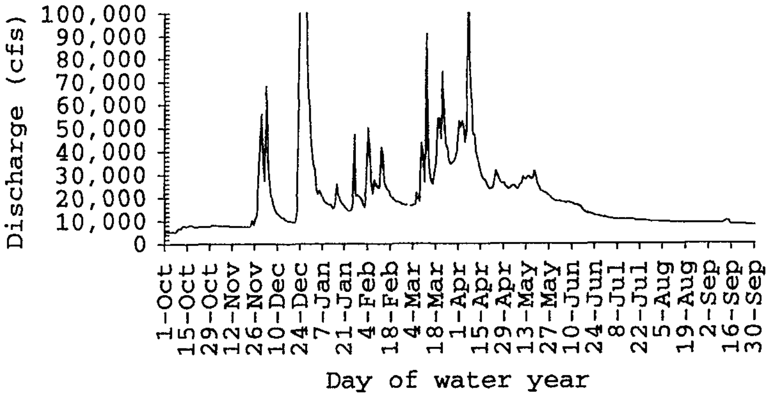

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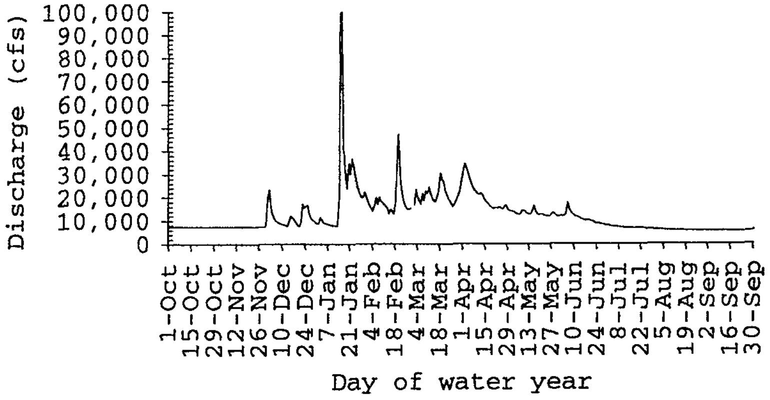

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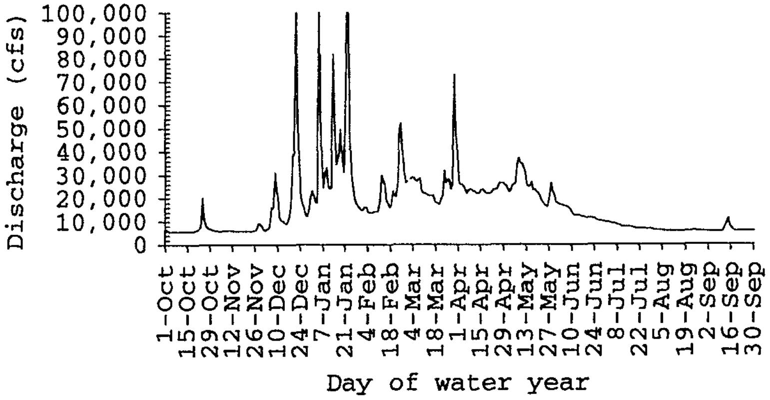

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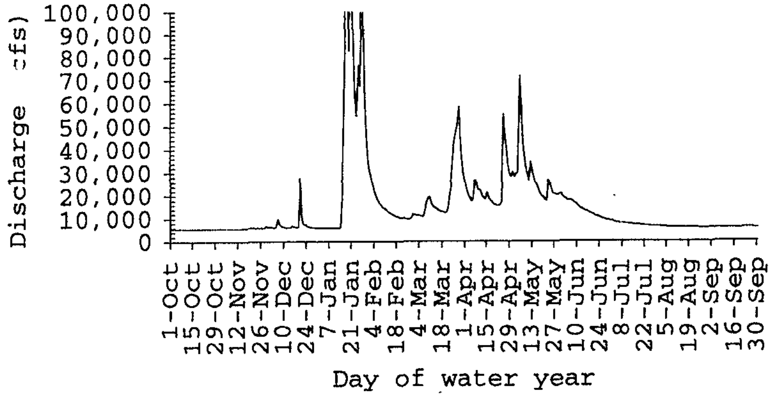

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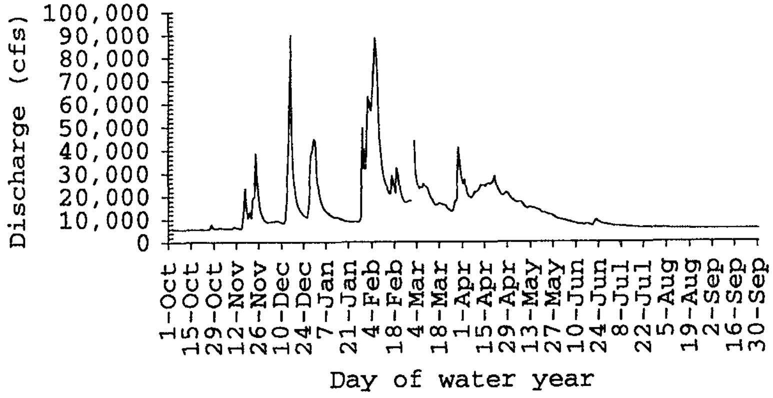

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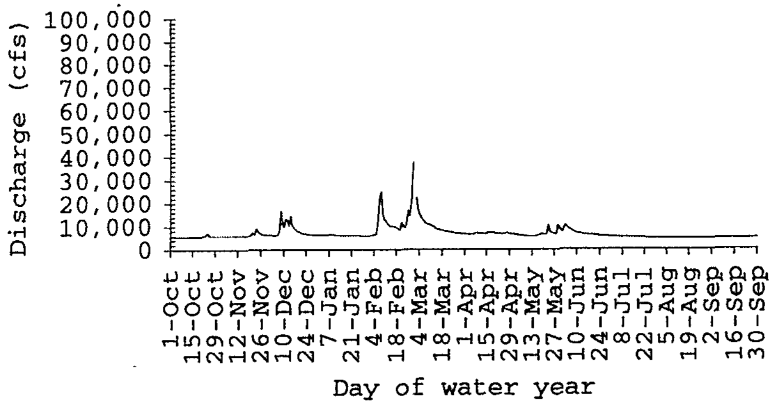

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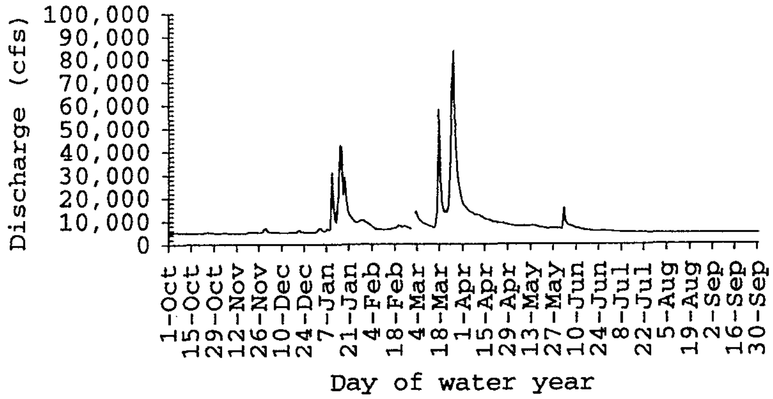
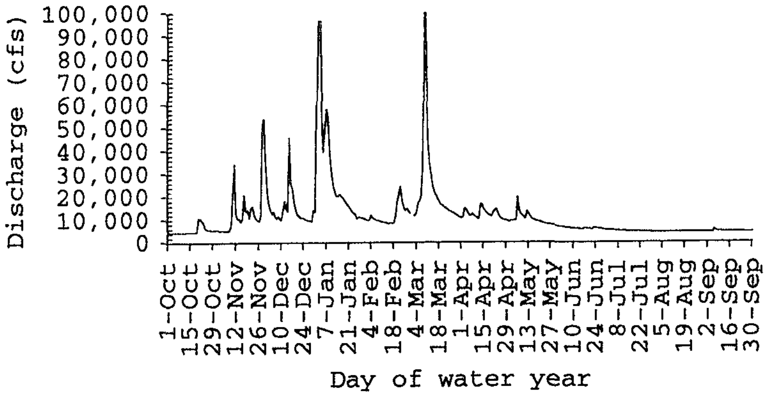
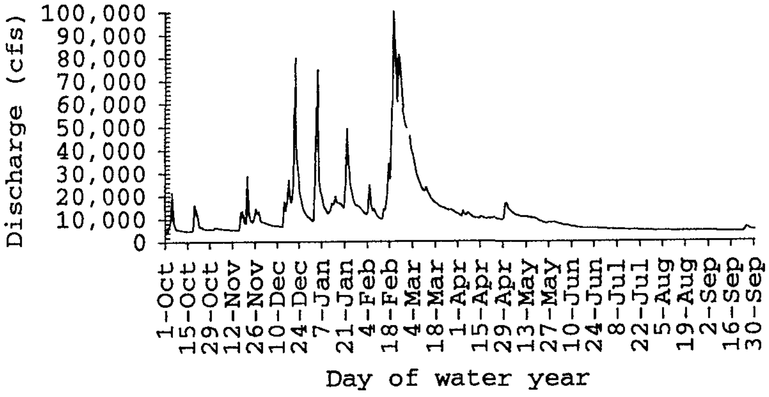



1900 Annual Hydrograph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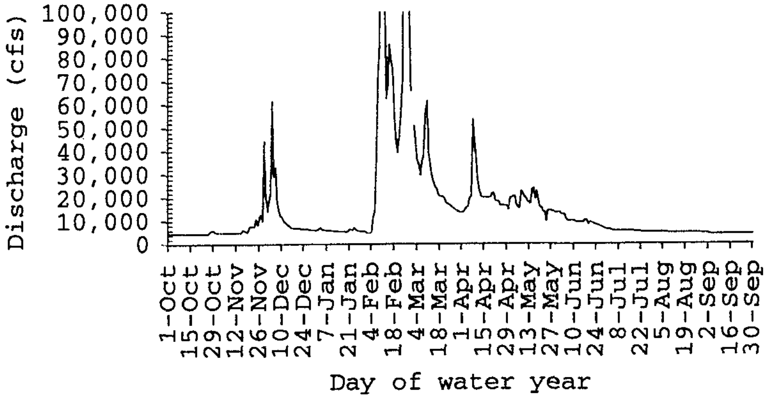
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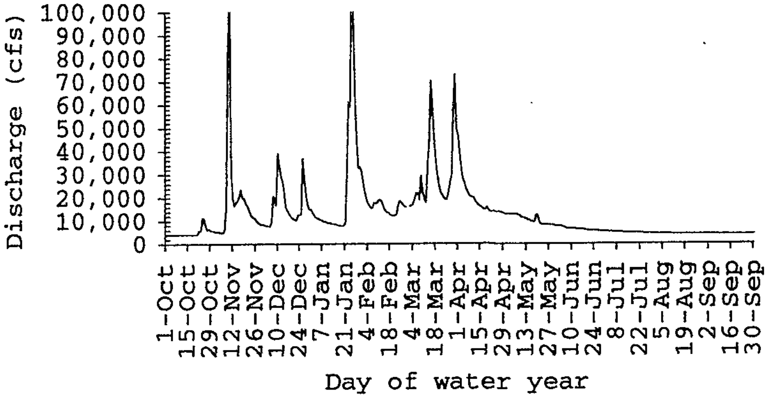
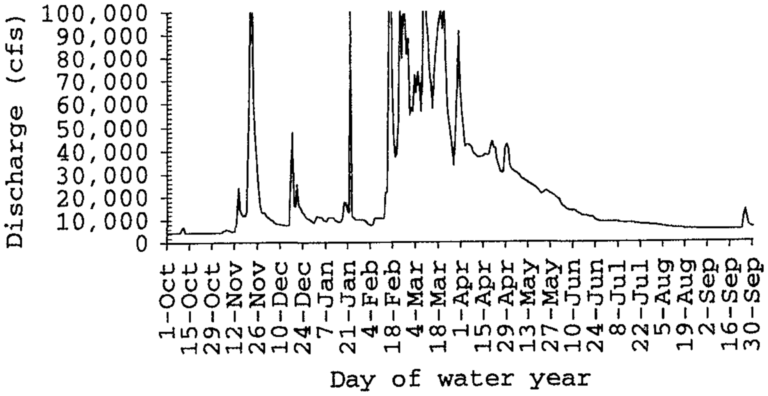

1903 Annual Hydrograph

1904 Annual Hydrograph



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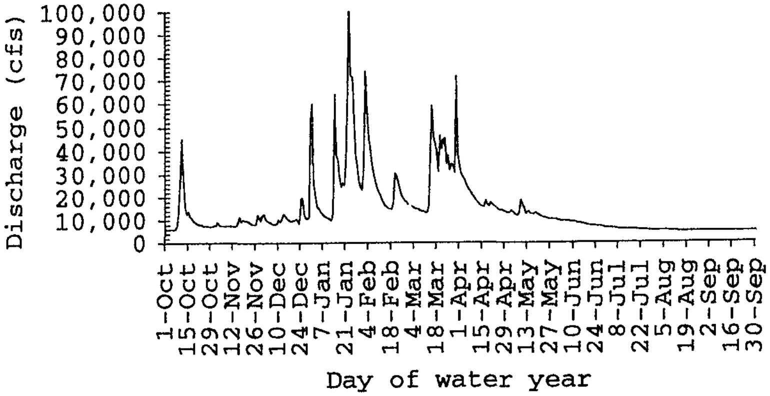
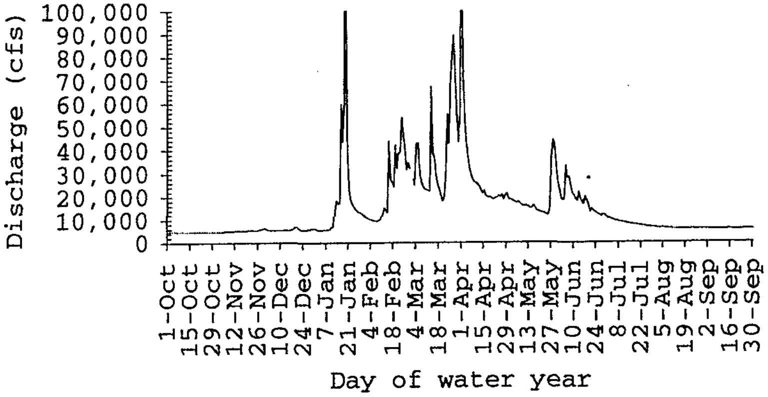


1906 Annual Hydrograph



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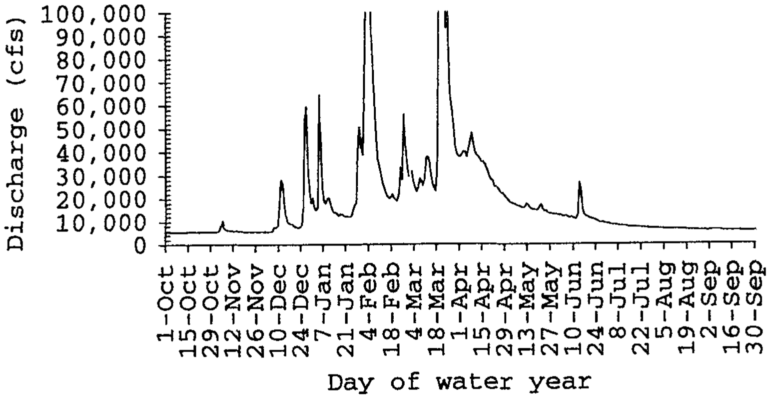

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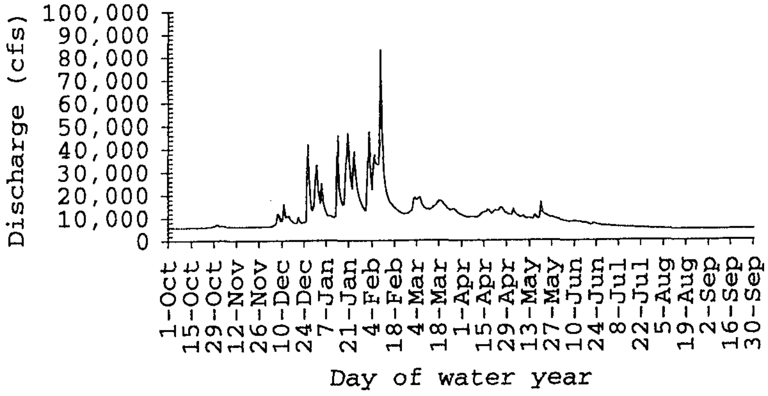

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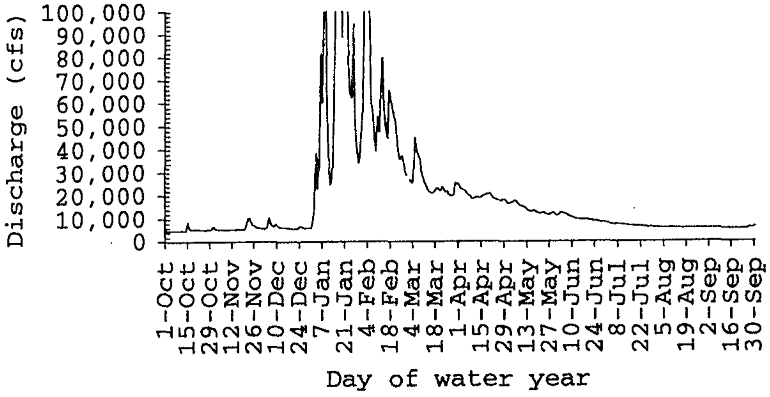

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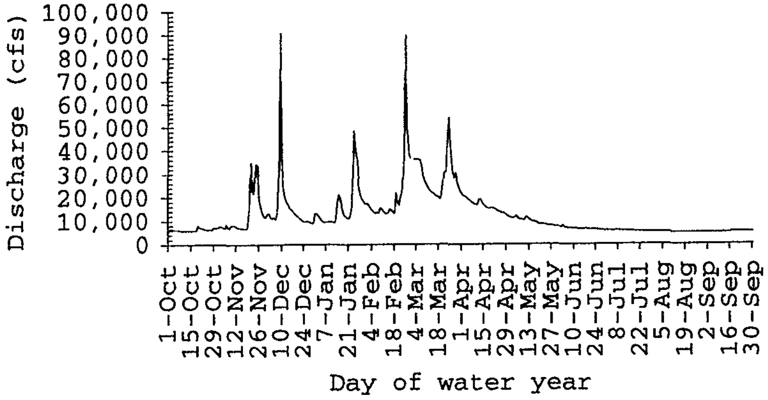
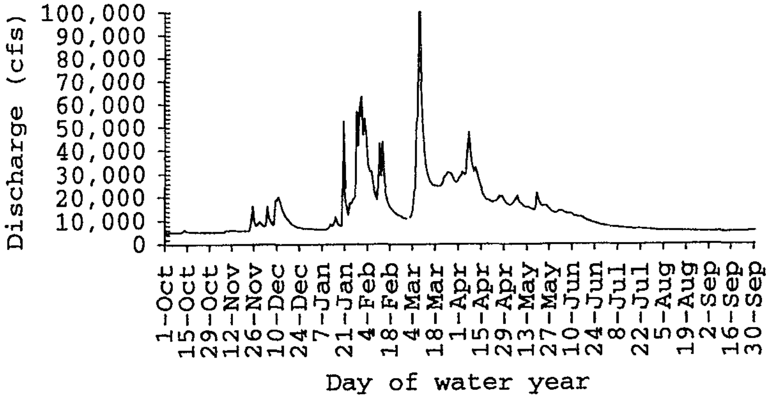


1911 Annual Hydrograph



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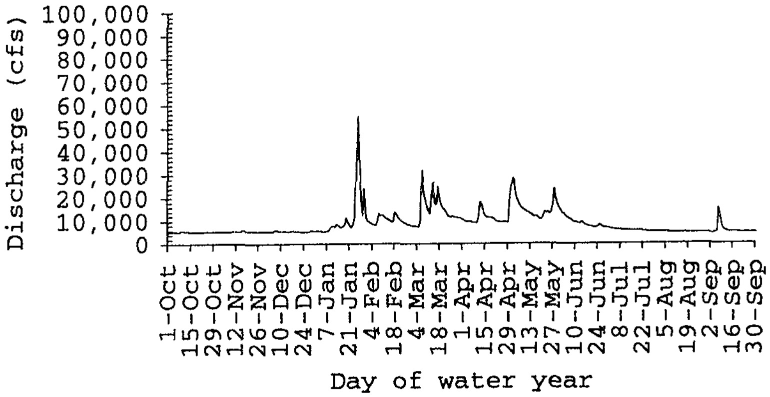

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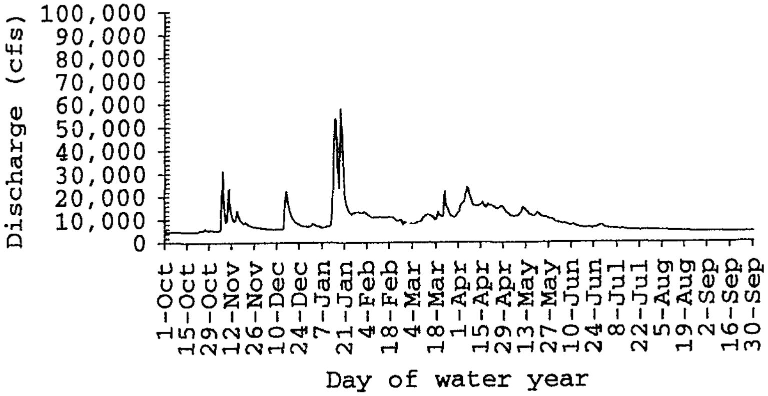

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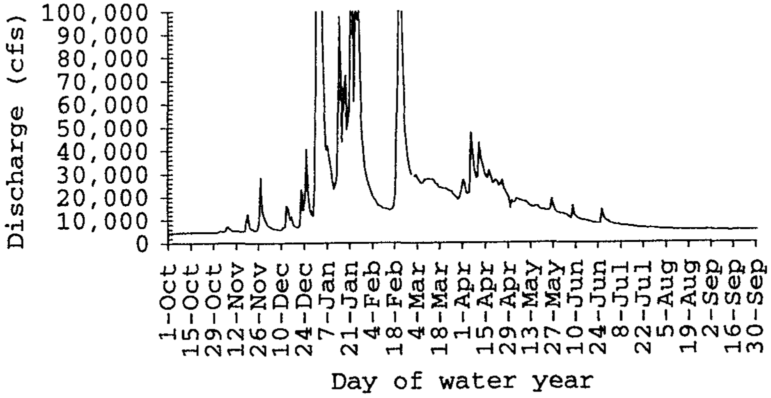
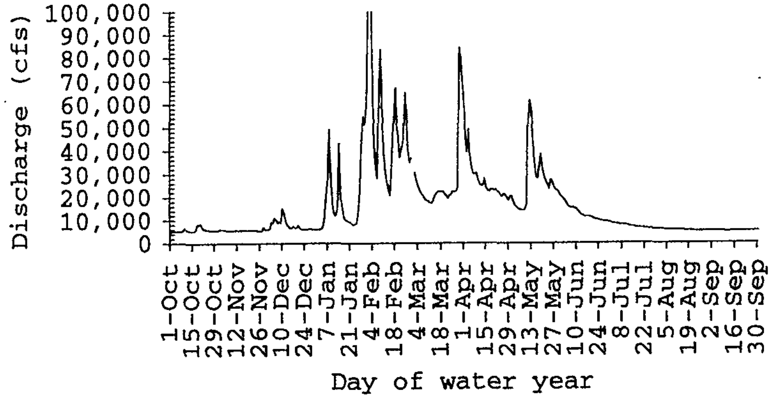
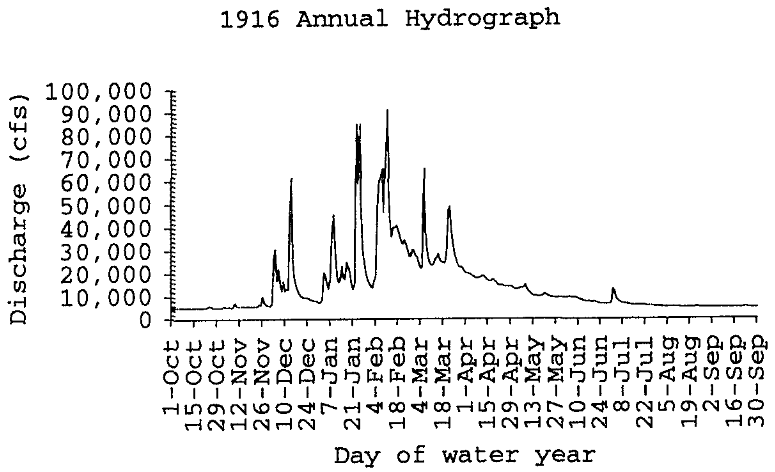
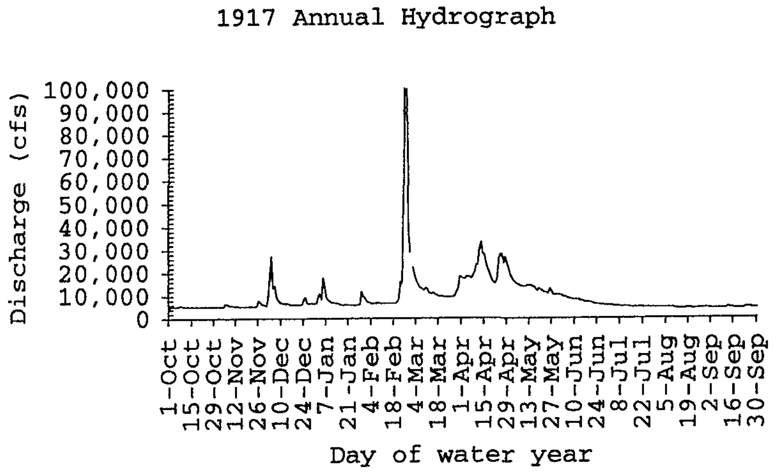
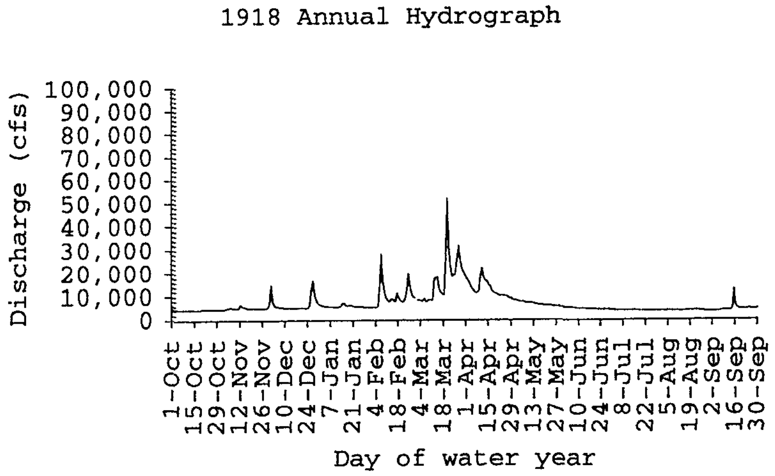


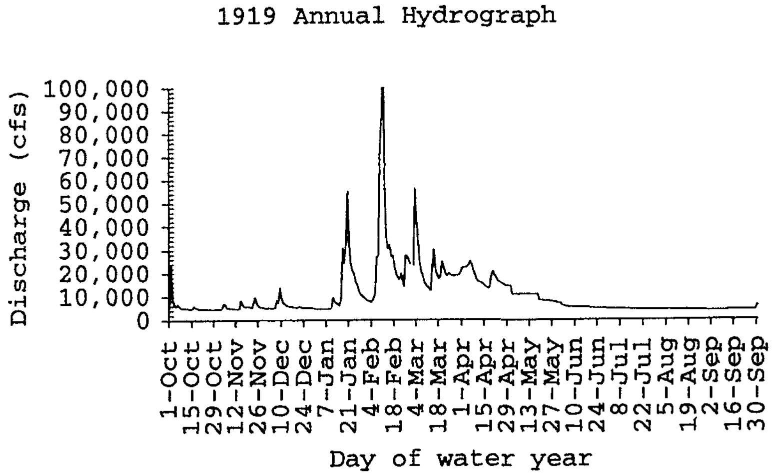
1915 Annual Hydrograph



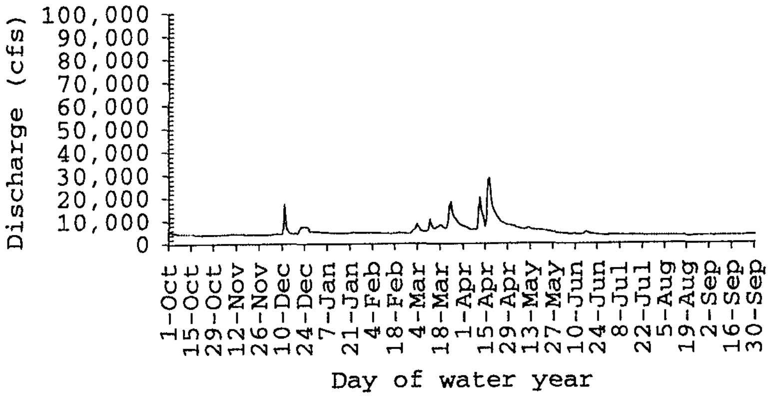

1916 Annual Hydrograph


1917 Annual Hydrograph

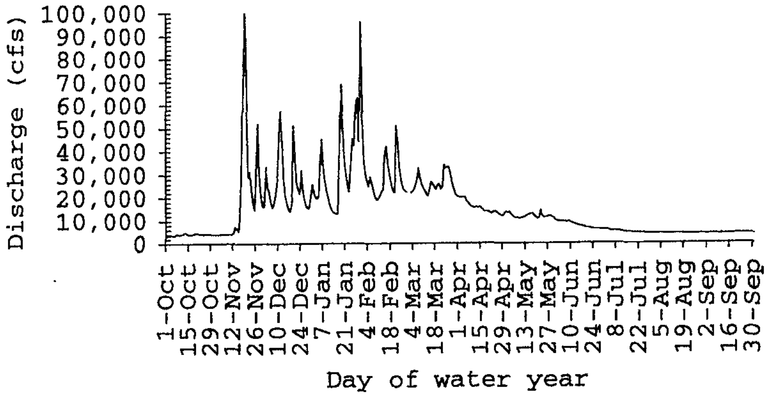

1918 Annual Hydrograph


1919 Annual Hydrograph

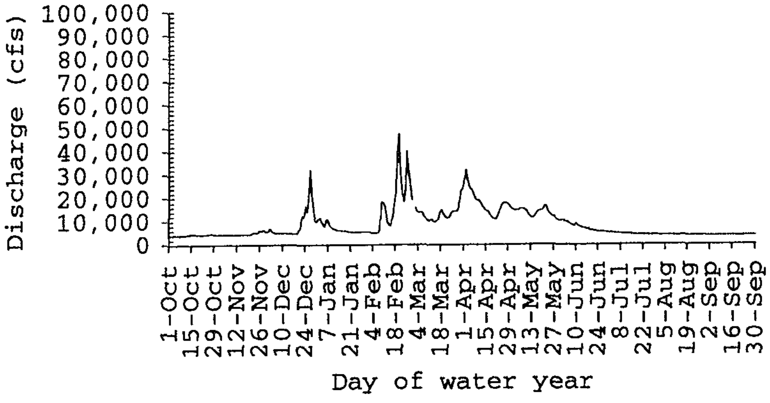
1920 Annual Hydrograph



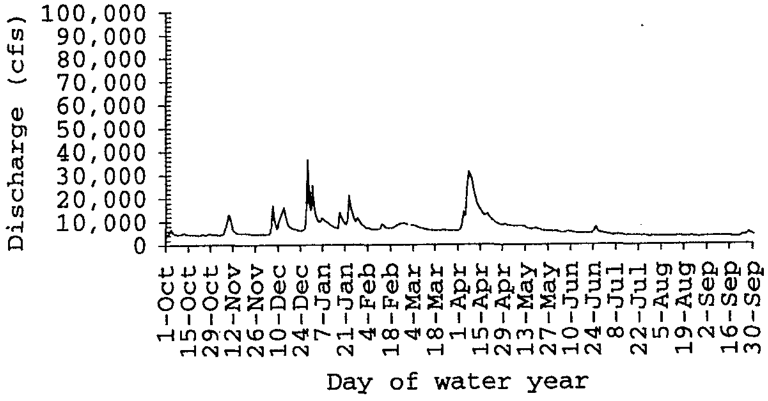
1921 Annual Hydrograph



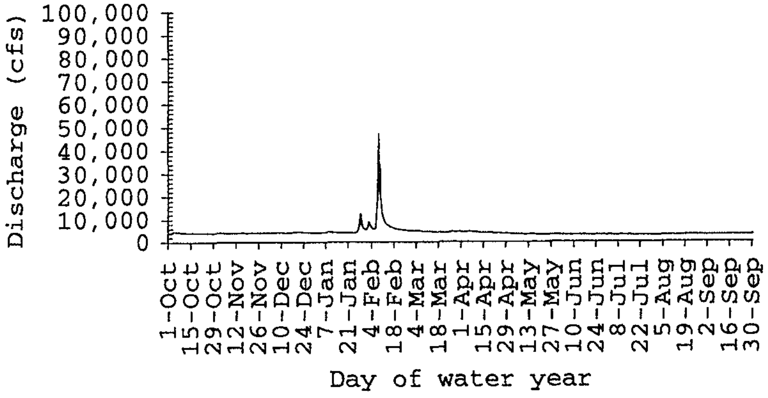
1922 Annual Hydrograph



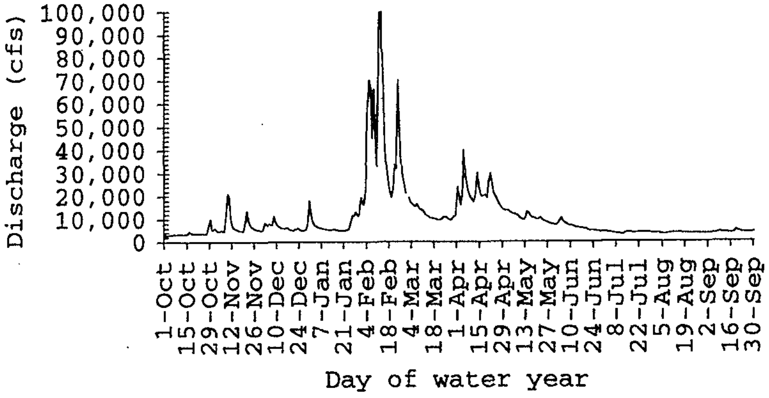
1923 Annual Hydrograph



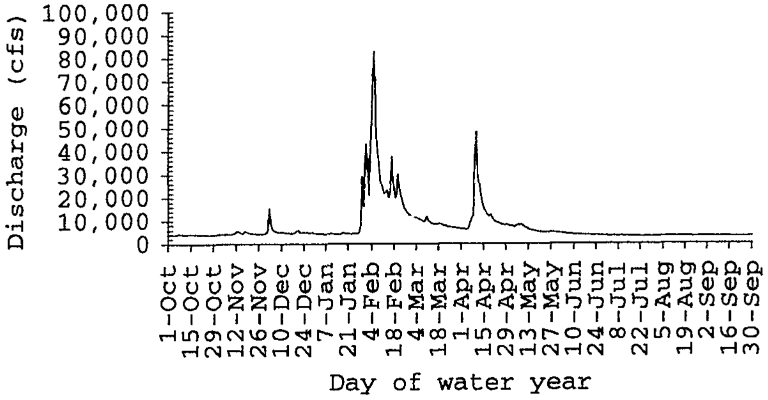
1924 Annual Hydrograph



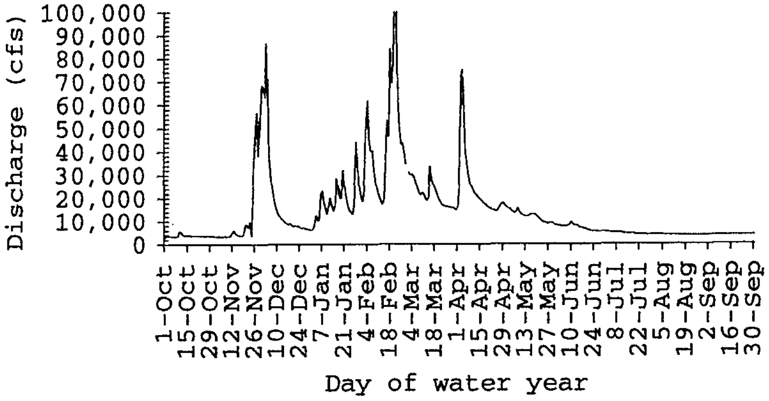
1925 Annual Hydrograph



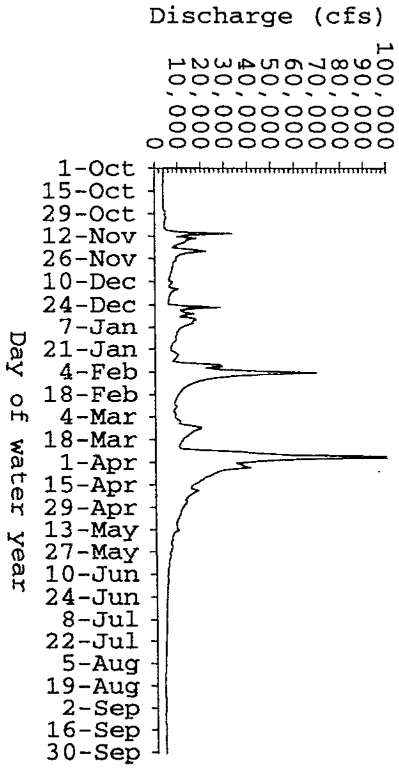
1926 Annual Hydrograph



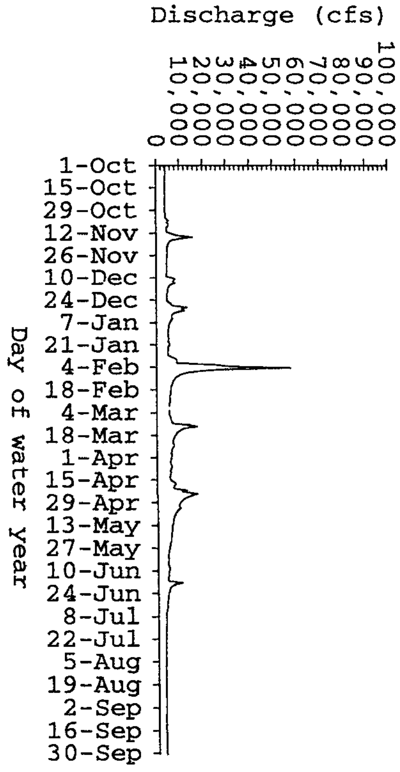
1927 Annual Hydrograph



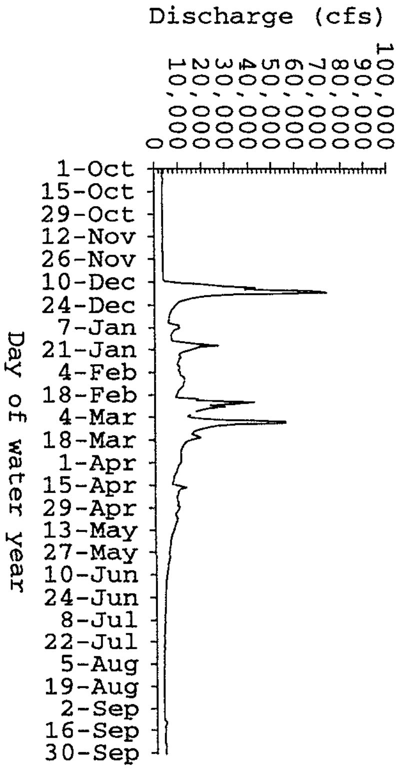
1928 Annual Hydrograph



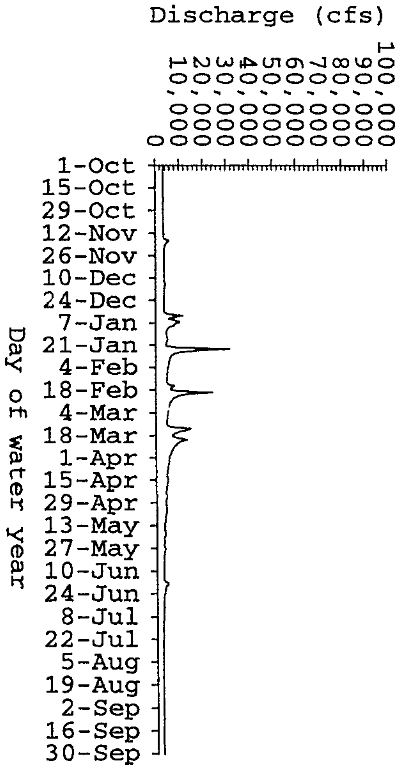
1929 Annual Hydrograph

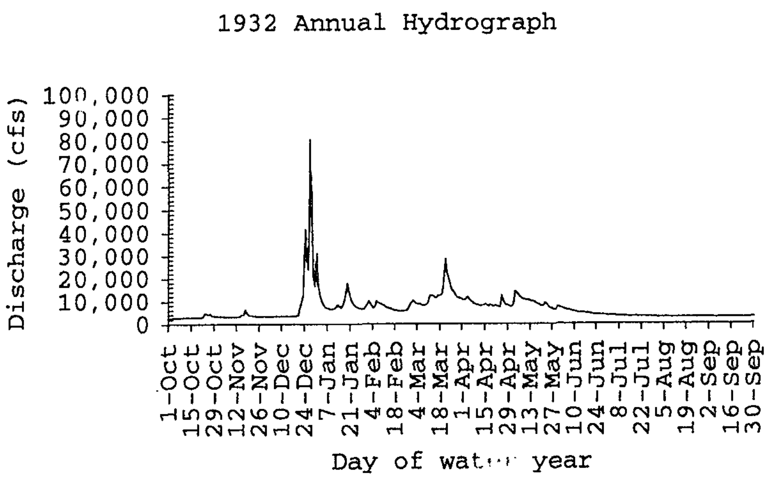


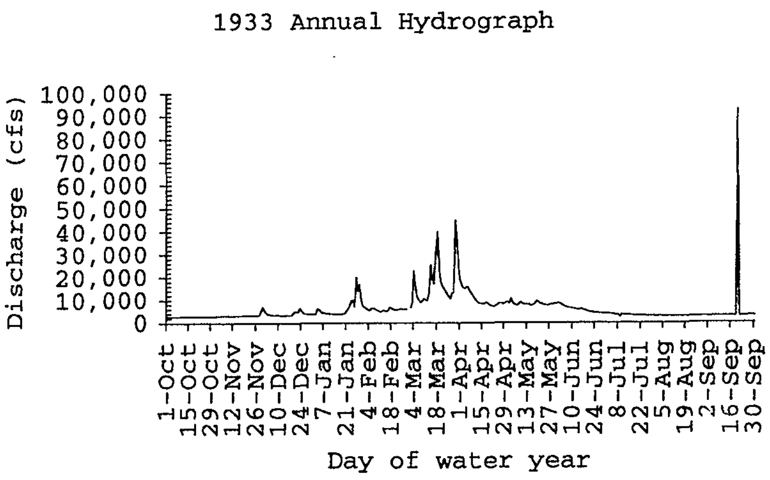
1930 Annual Hydrograph

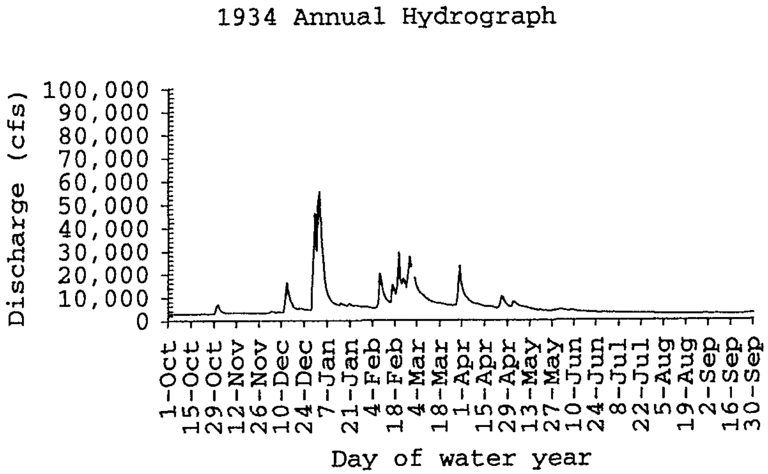


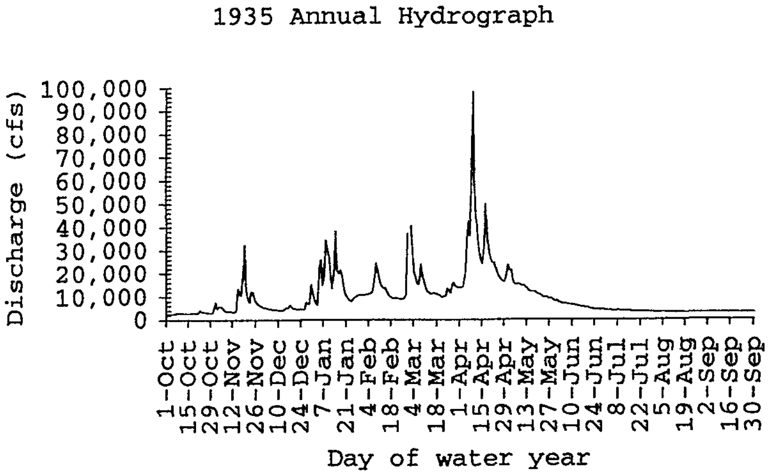
1931 Annual Hydrograph



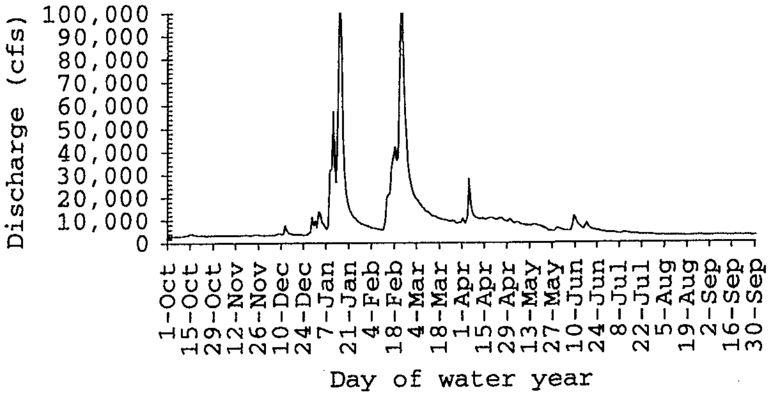

1932 Annual Hydrograph


1933 Annual Hydrograph

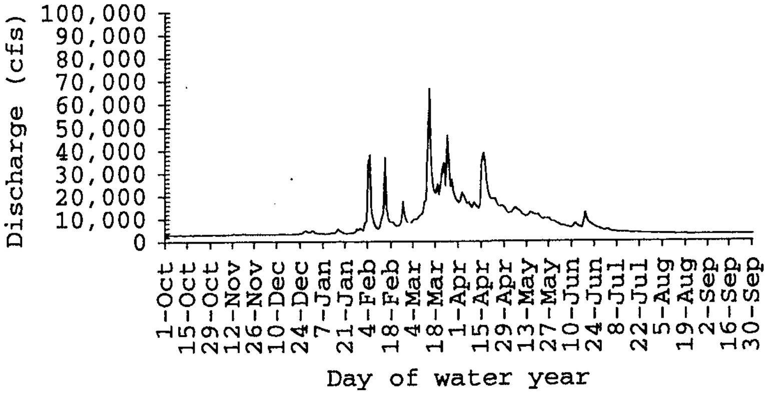

1934 Annual Hydrograph


1935 Annual Hydrograph

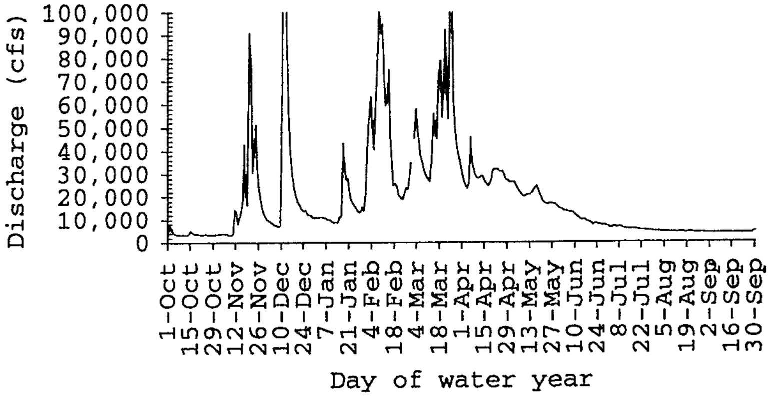
1936 Annual Hydrograph



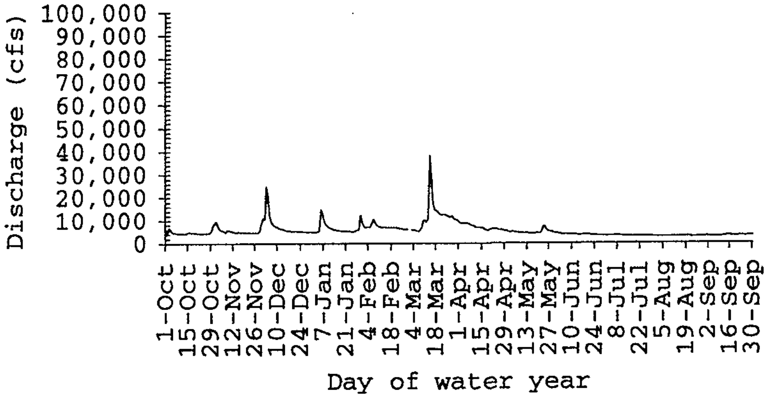
1937 Annual Hydrograph

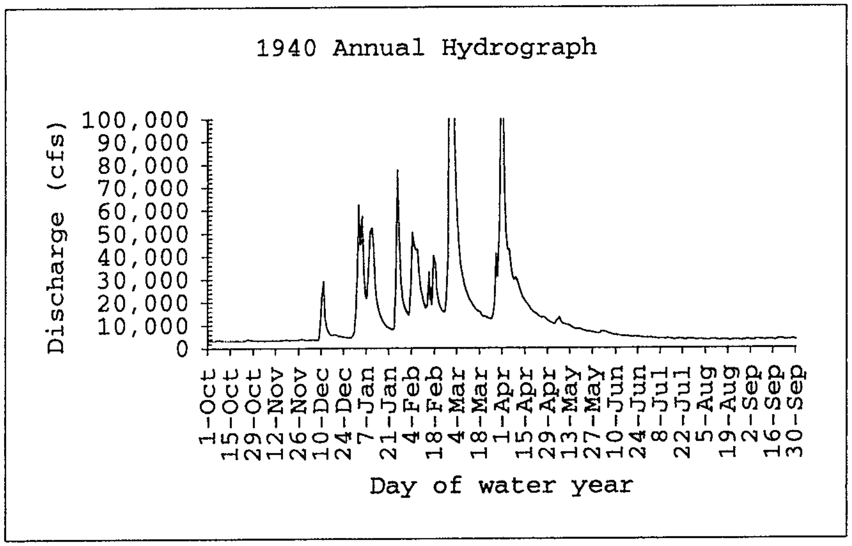


1938 Annual Hydrograph



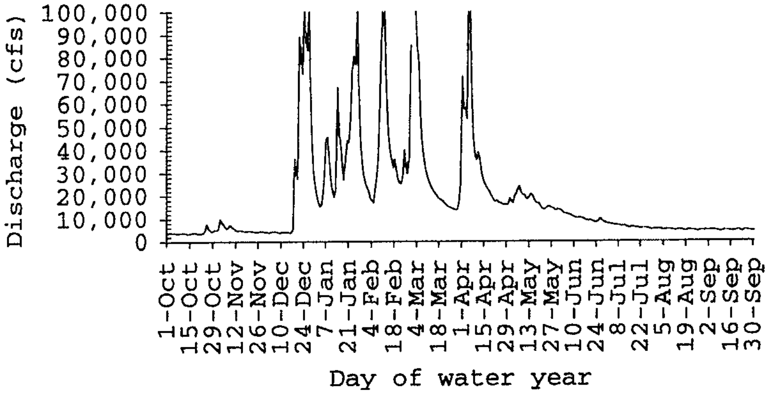
1939 Annual Hydrograph



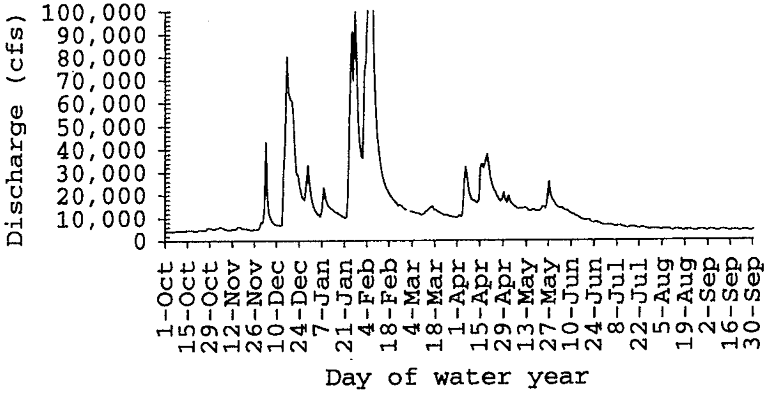


1940 Annual Hydrograph

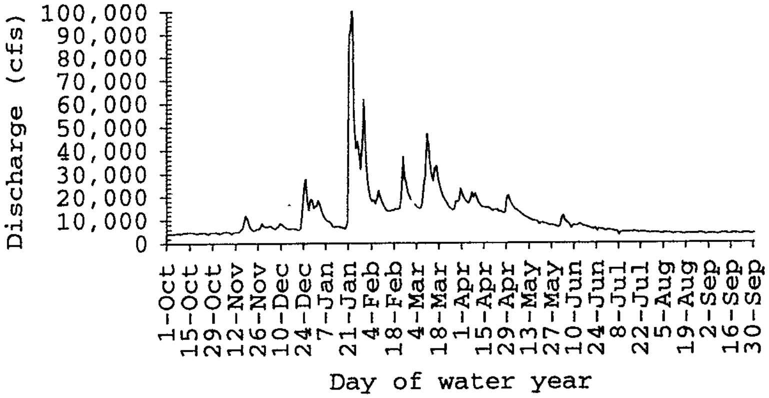
1941 Annual Hydrograph



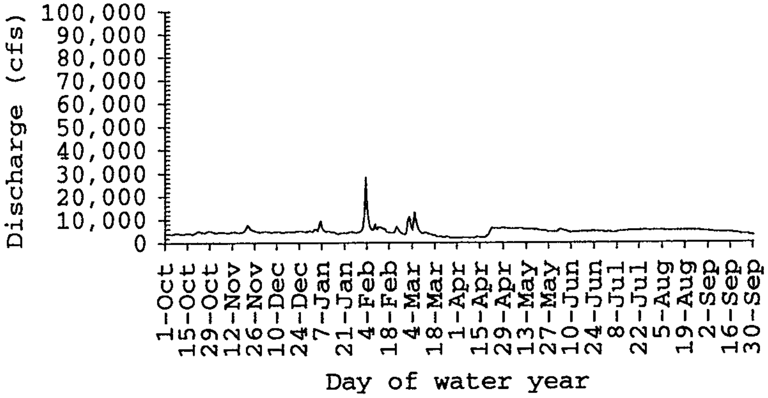
1942 Annual Hydrograph

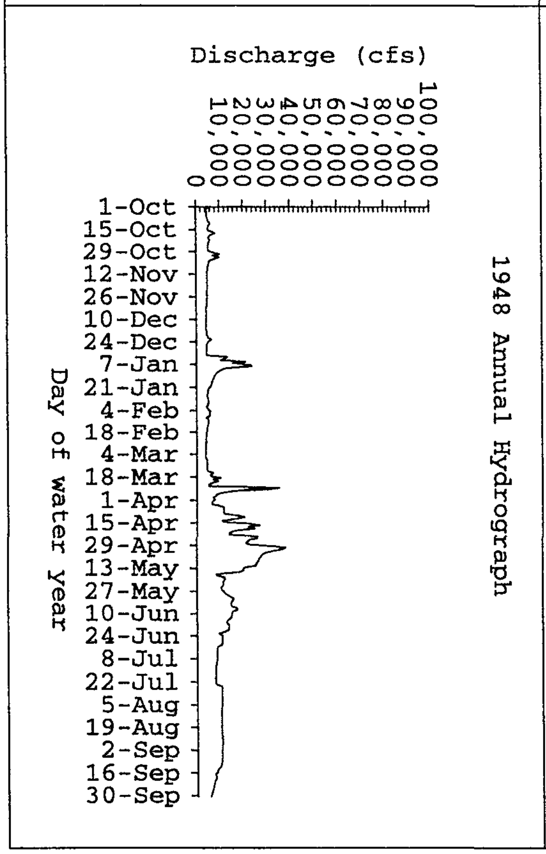


1943 Annual Hydrograph

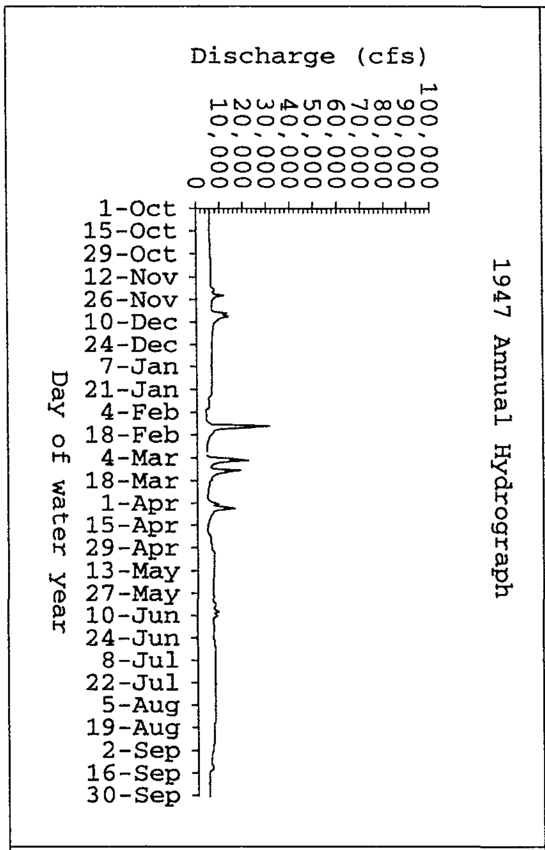


1944 Annual Hydrograph

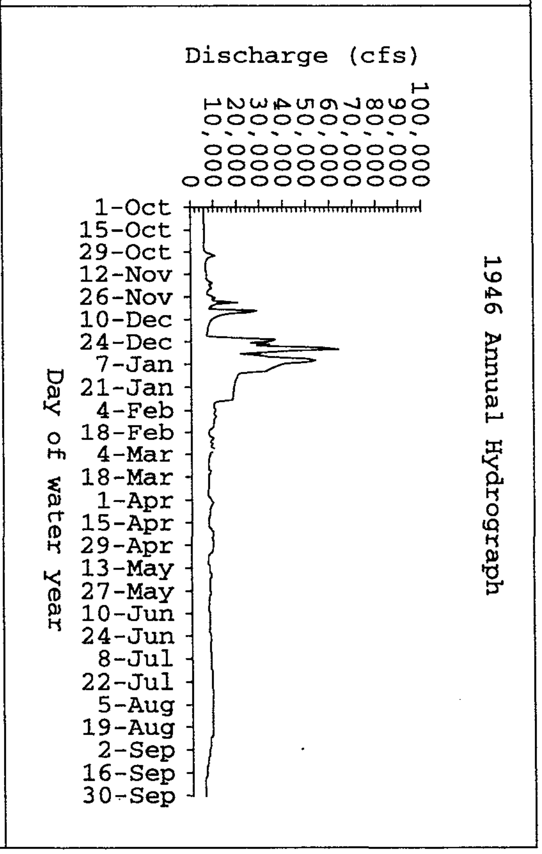




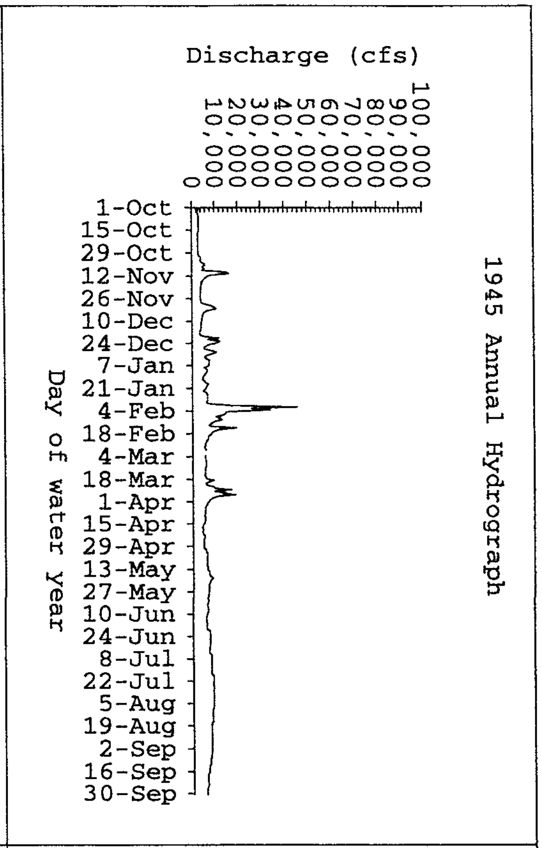
1948 Annual Hydrograph



1947 Annual Hydrograph

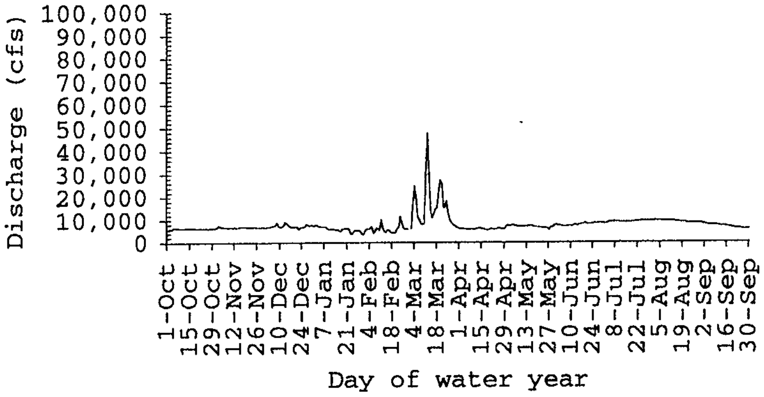


1946 Annual Hydrograph

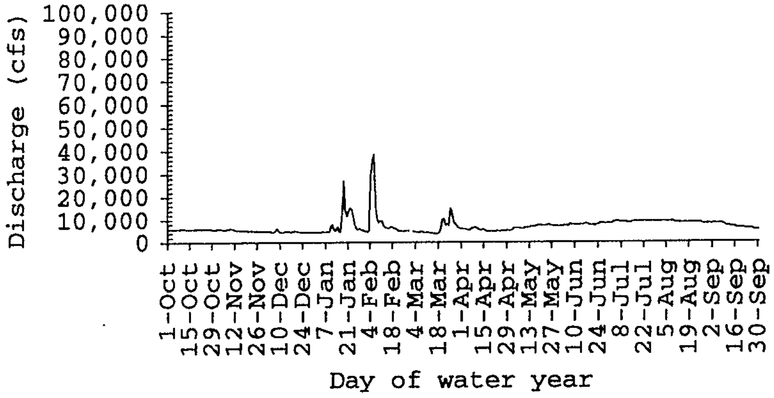


1945 Annual Hydrograph

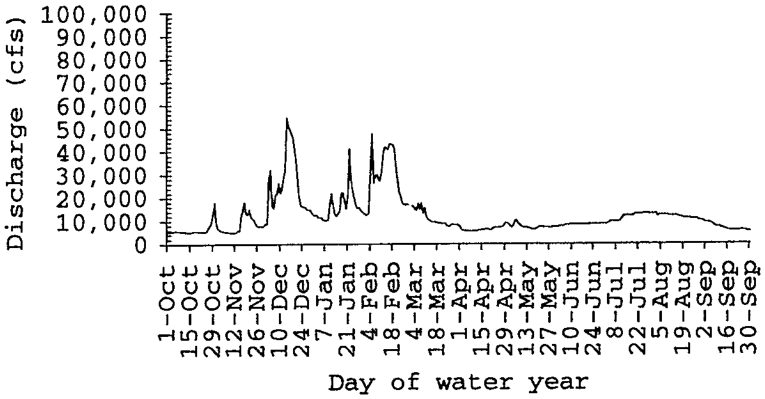
1949 Annual Hydrograph



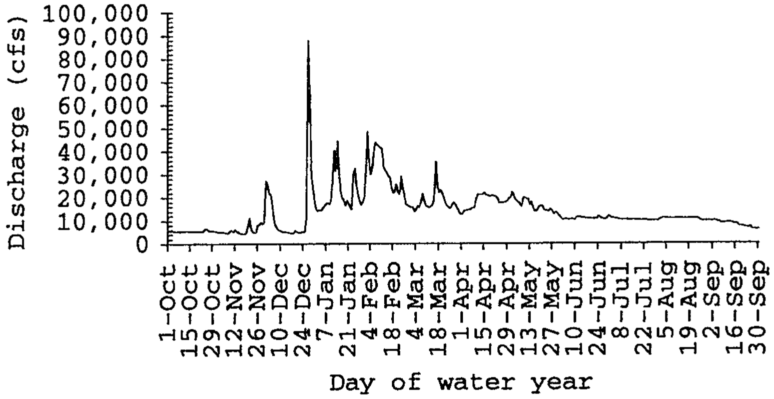
1950 Annual Hydrograph



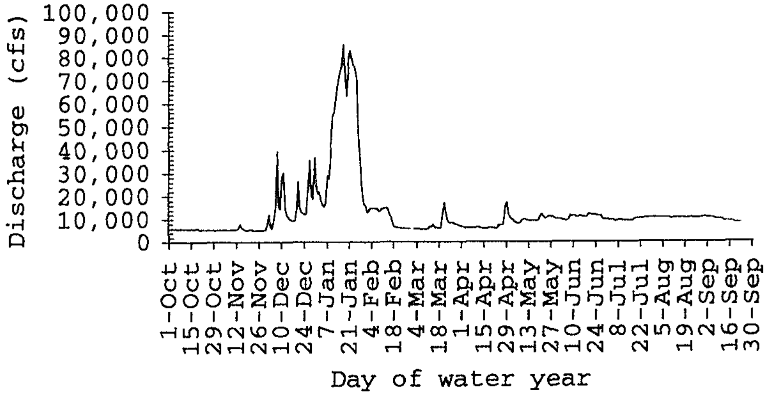
1951 Annual Hydrograph



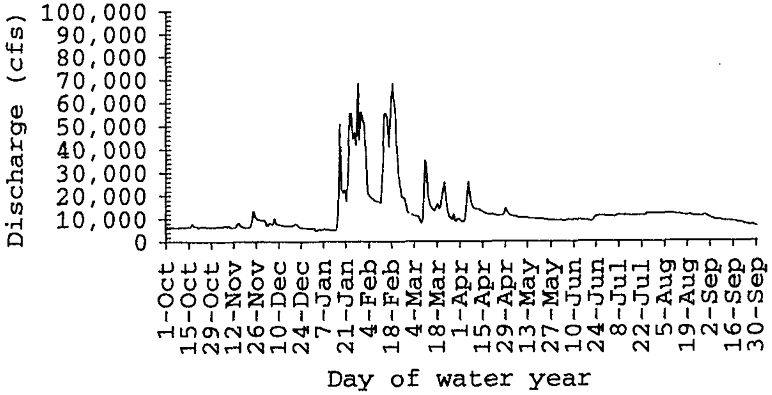
1952 Annual Hydrograph



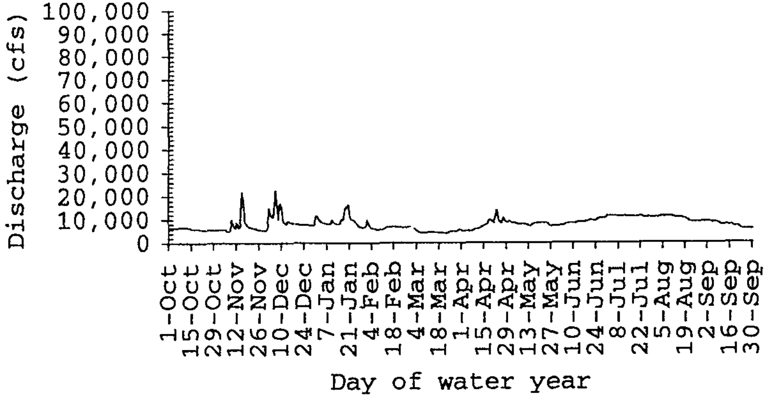
1953 Annual Hydrograph



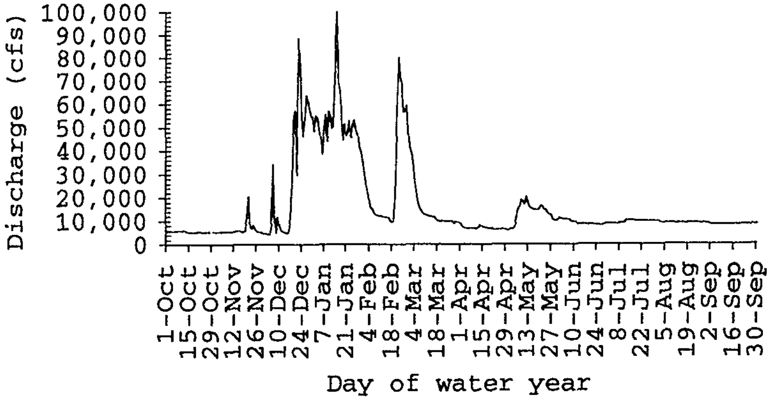
1954 Annual Hydrograph



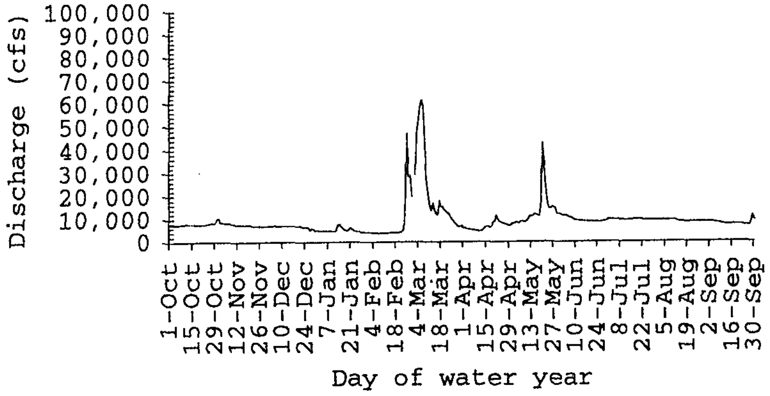
1955 Annual Hydrograph



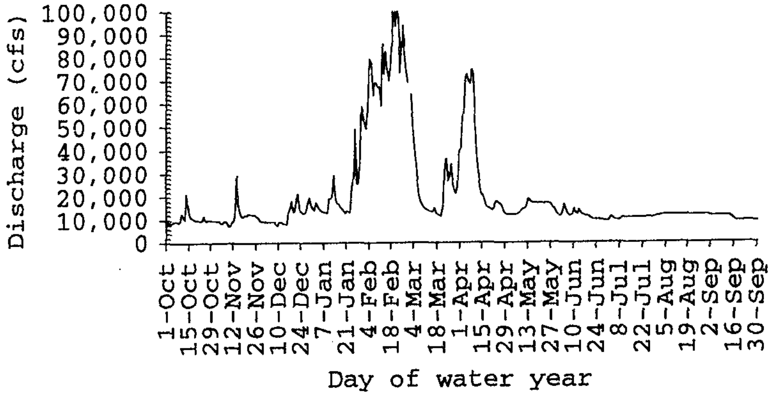
1956 Annual Hydrograph



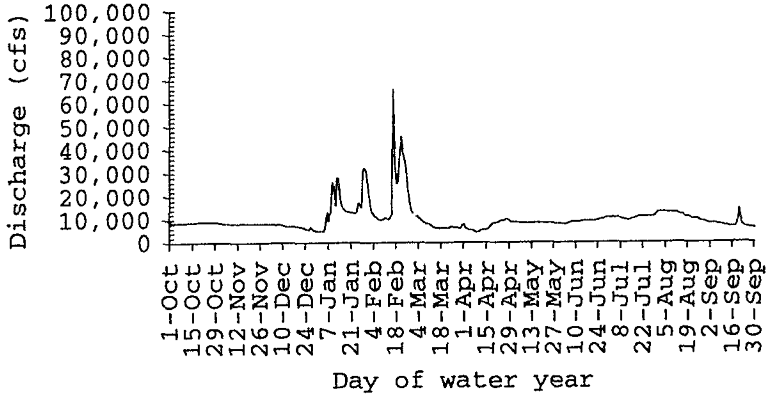
1957 Annual Hydrograph



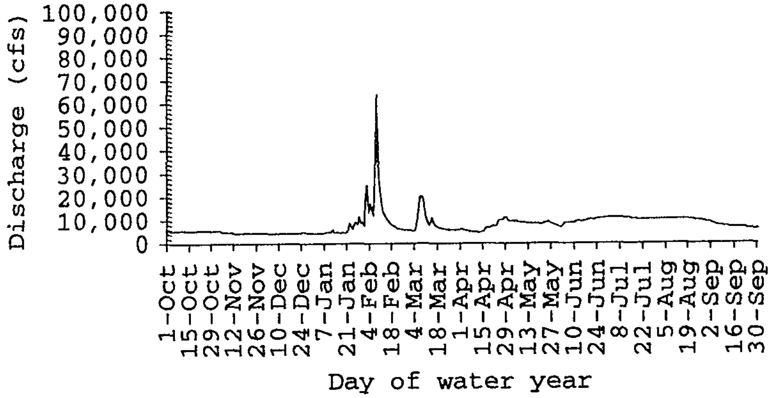
1958 Annual Hydrograph



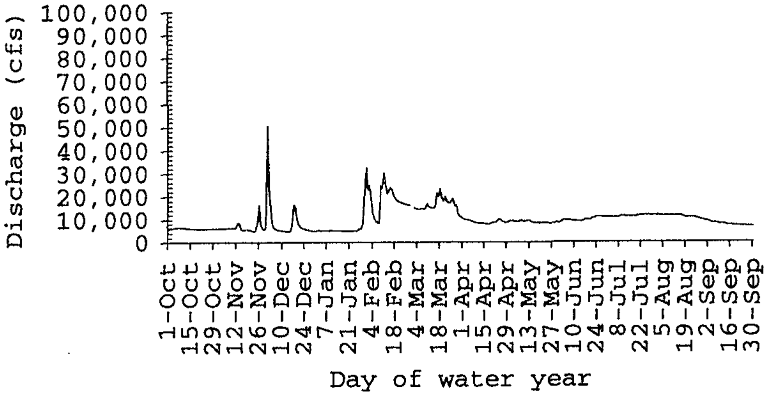
1959 Annual Hydrograph



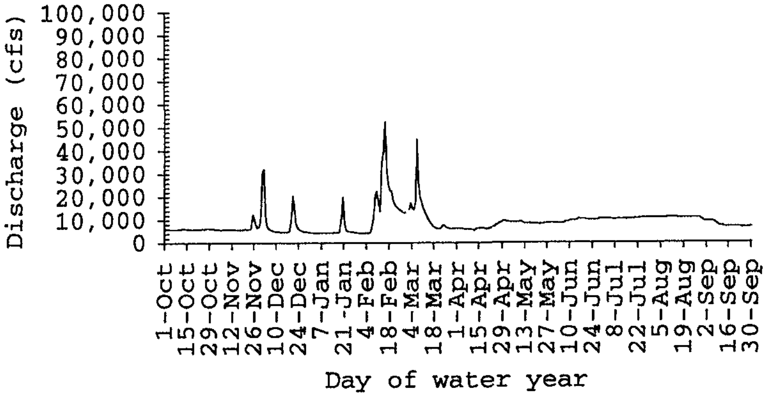
1960 Annual Hydrograph



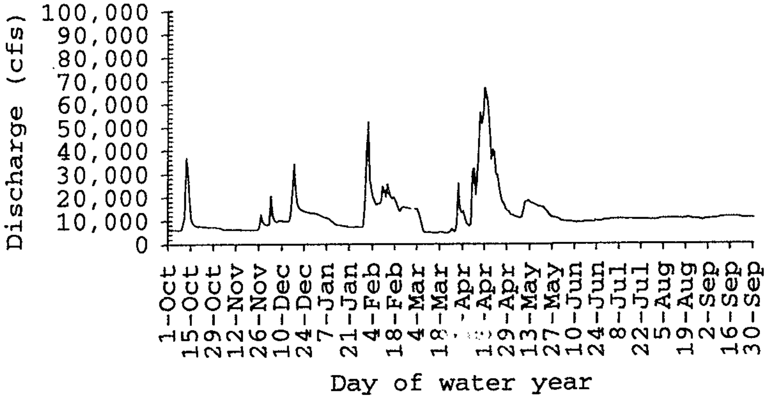
1961 Annual Hydrograph



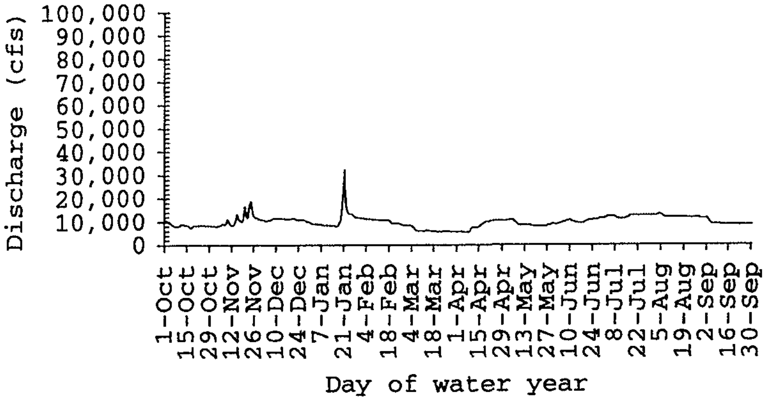
1962 Annual Hydrograph



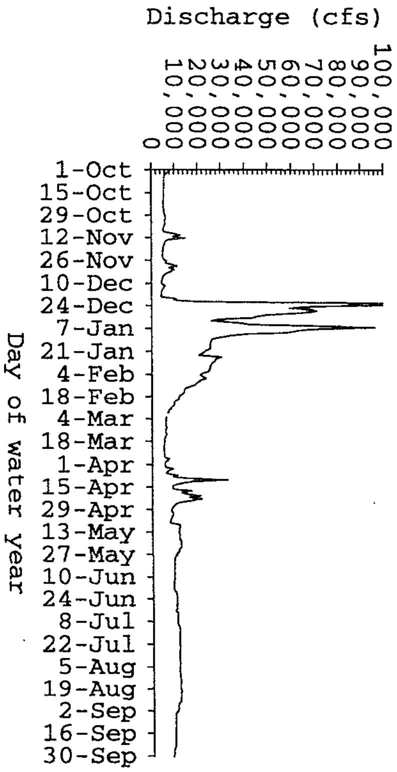
1963 Annual Hydrograph



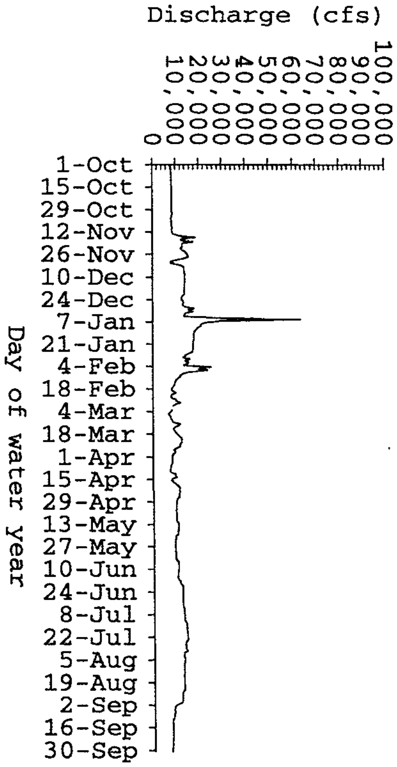
1964 Annual Hydrograph



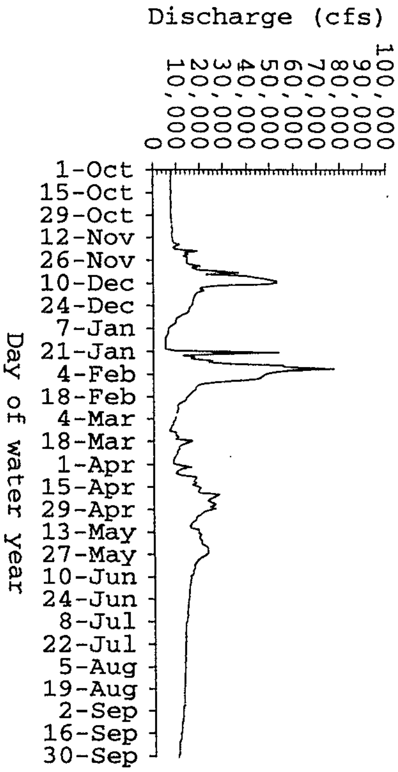
1965 Annual Hydrograph



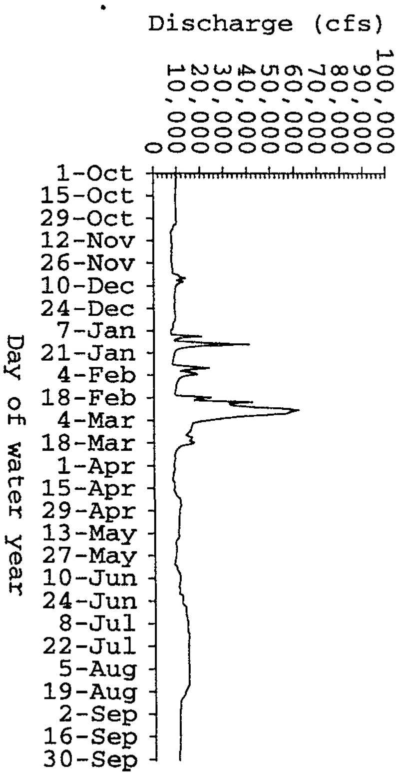
1966 Annual Hydrograph



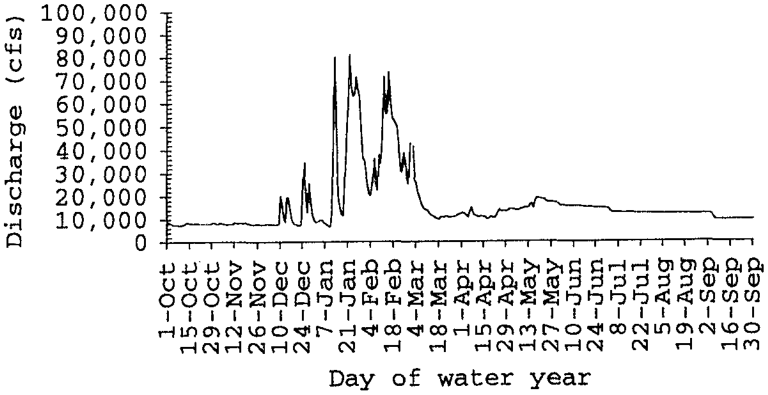
1967 Annual Hydrograph



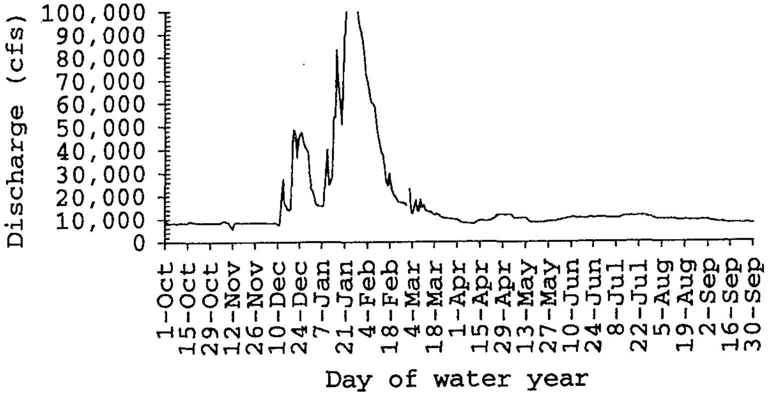
1968 Annual Hydrograph



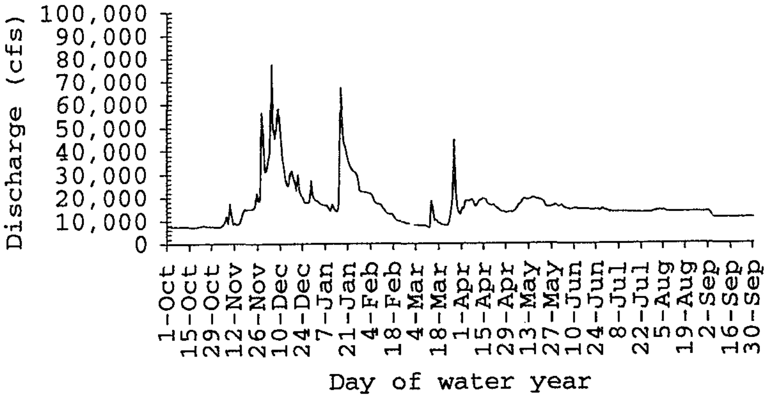
1969 Annual Hydrograph



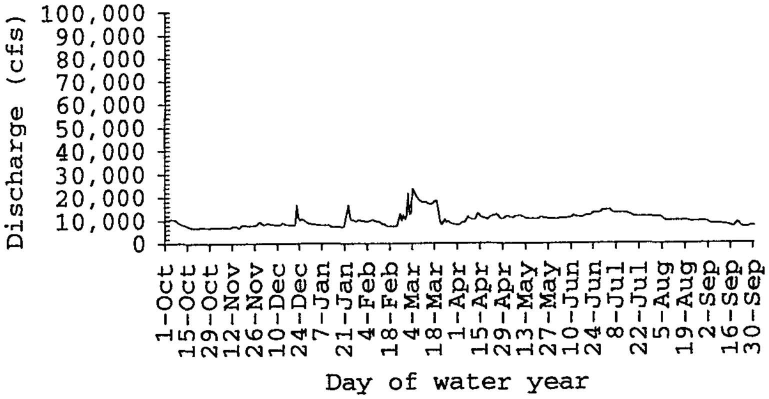
1970 Annual Hydrograph



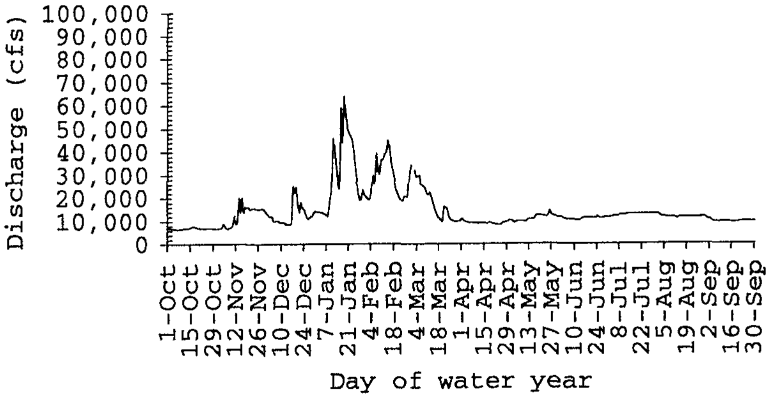
1971 Annual Hydrograph



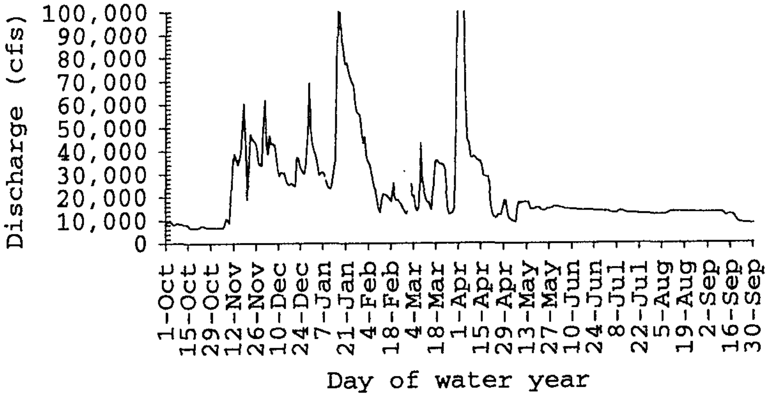
1972 Annual Hydrograph



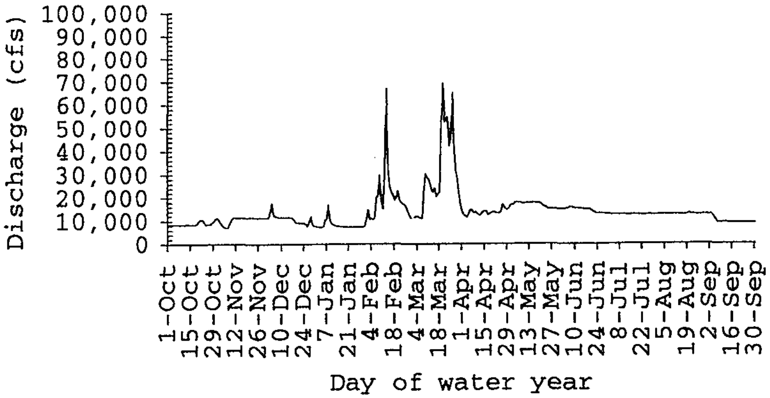
1973 Annual Hydrograph



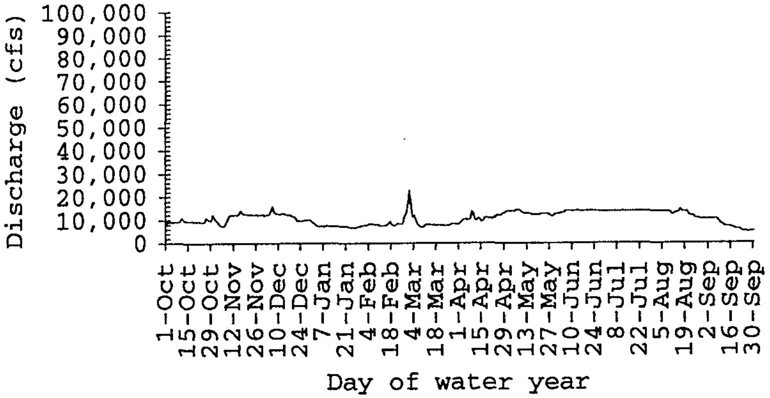
1974 Annual Hydrograph

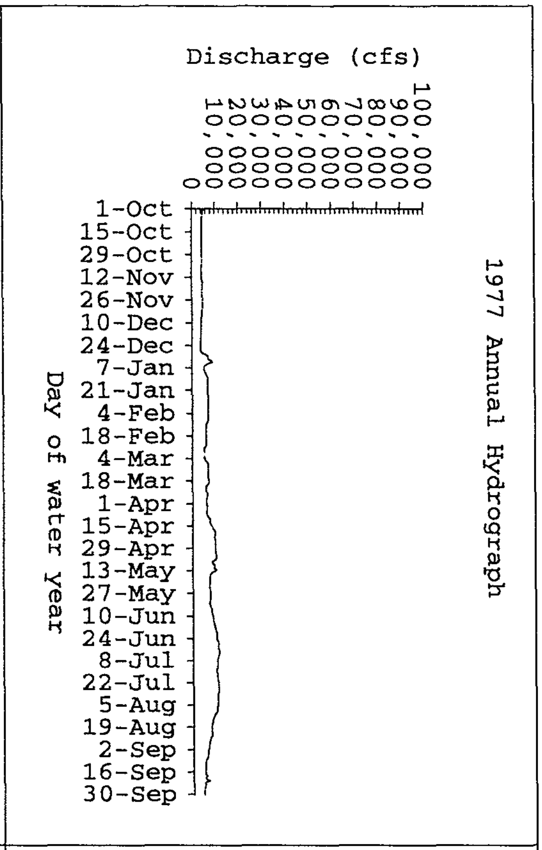


1975 Annual Hydrograph

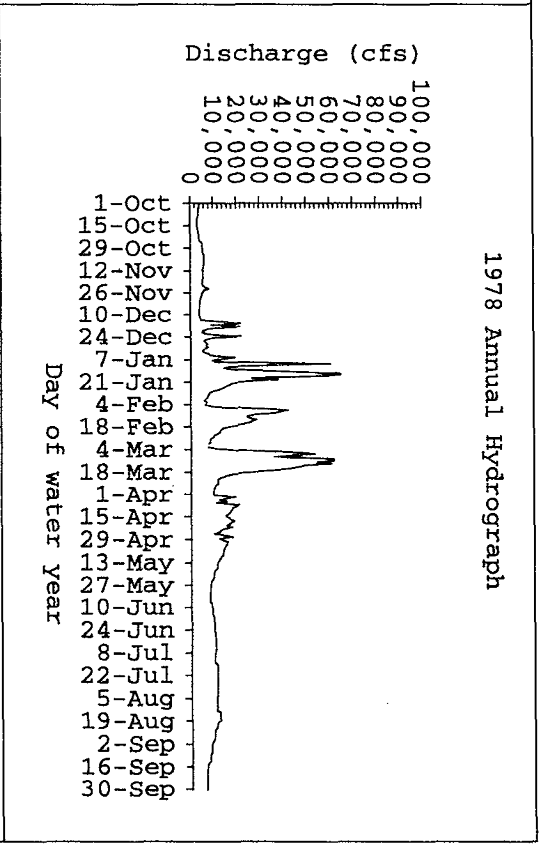


1976 Annual Hydrograph

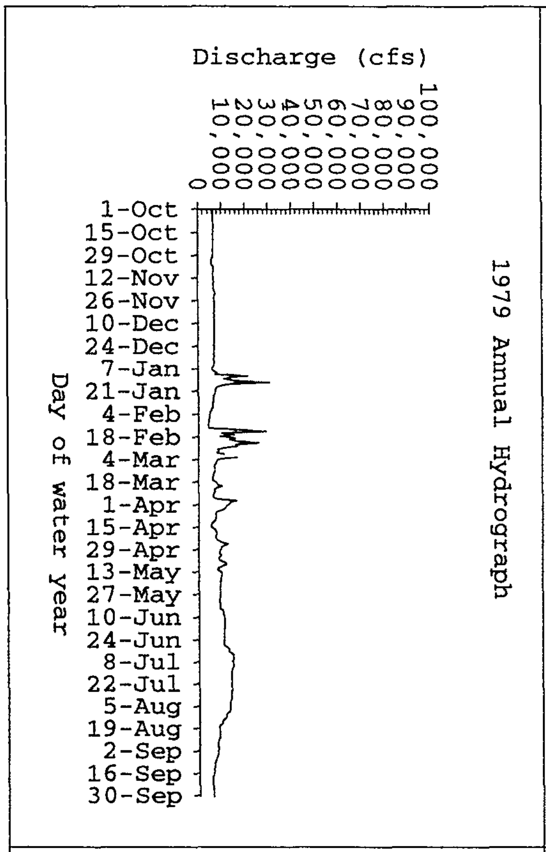




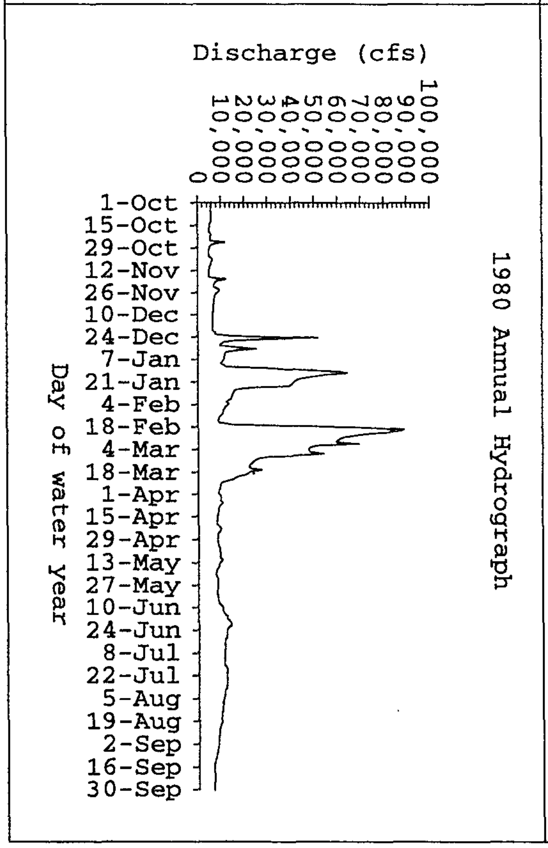
1977 Annual Hydrograph



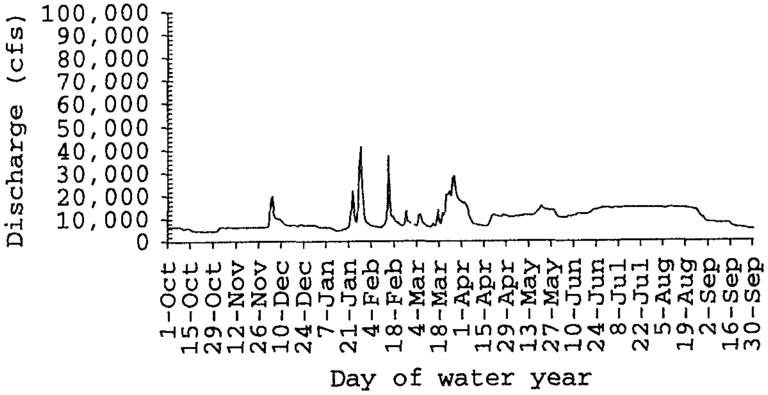
1978 Annual Hydrograph



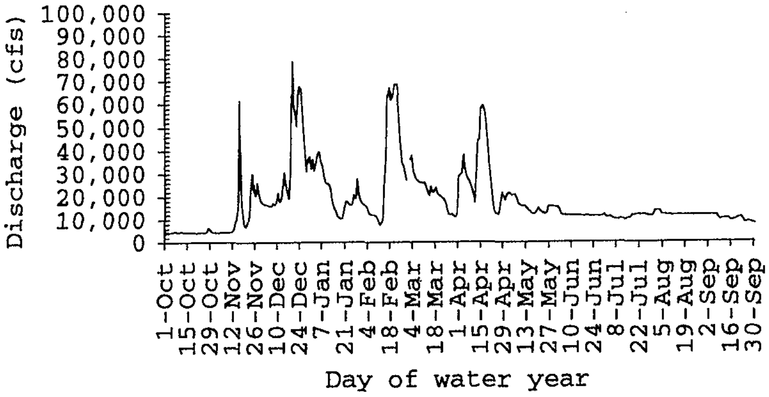
1979 Annual Hydrograph



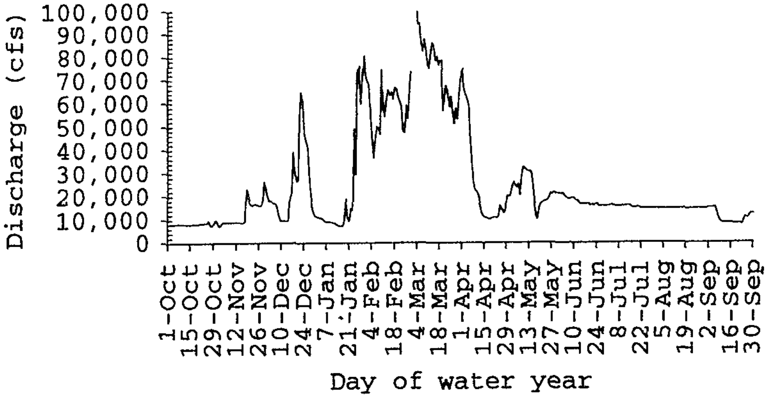
1980 Annual Hydrograph



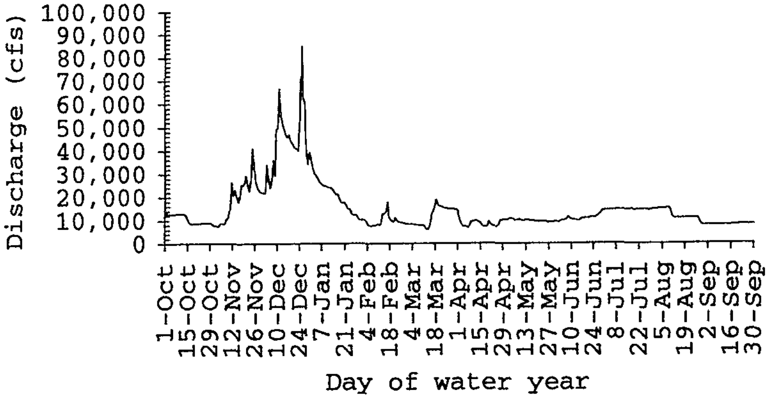
1981 Annual Hydrograph



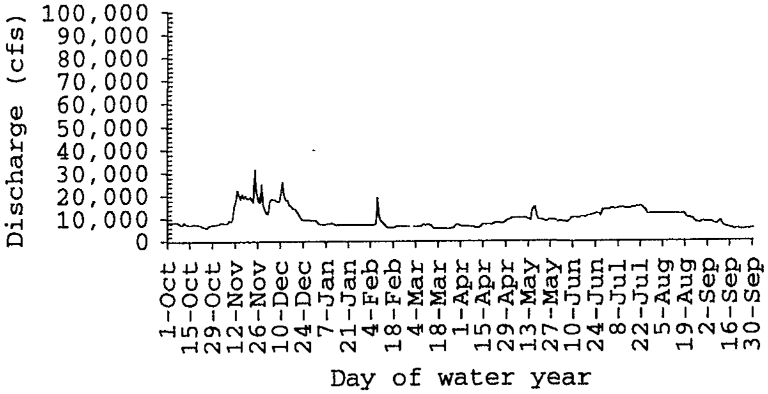
1982 Annual Hydrograph



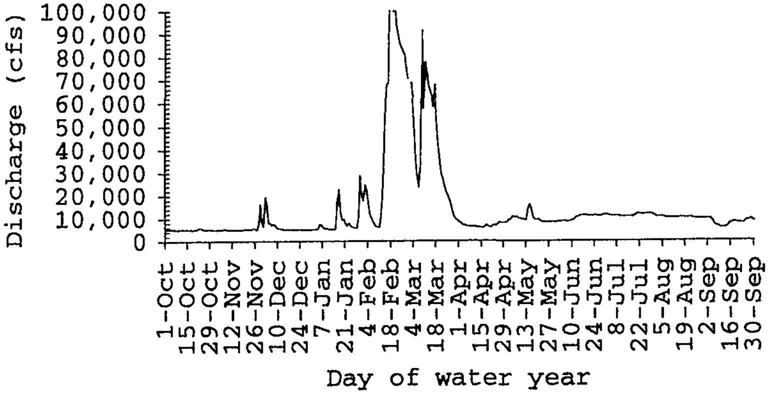
1983 Annual Hydrograph



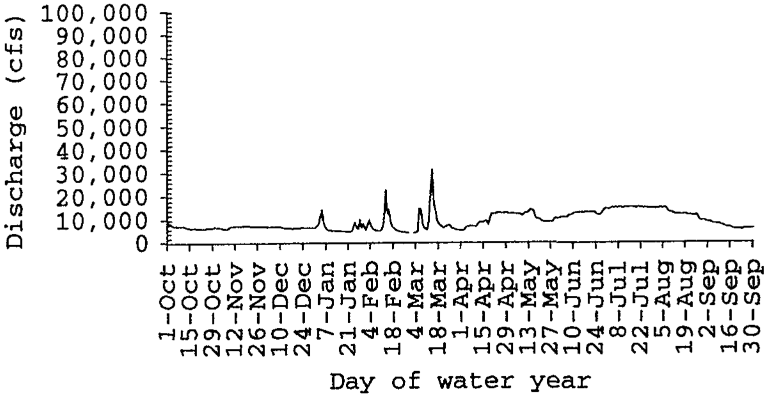
1984 Annual Hydrograph



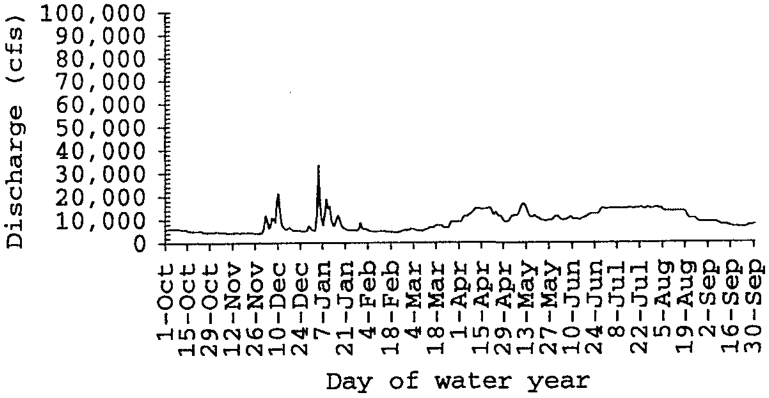
1985 Annual Hydrograph



1986 Annual Hydrograph

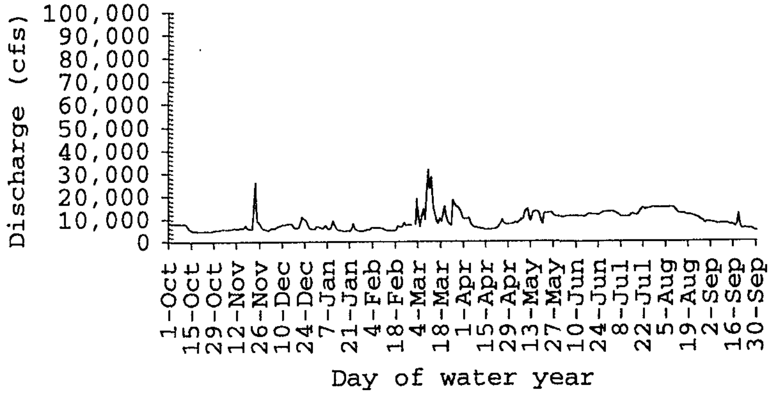


1987 Annual Hydrograph



1988 Annual Hydrograph

1989 Annual Hydrograph



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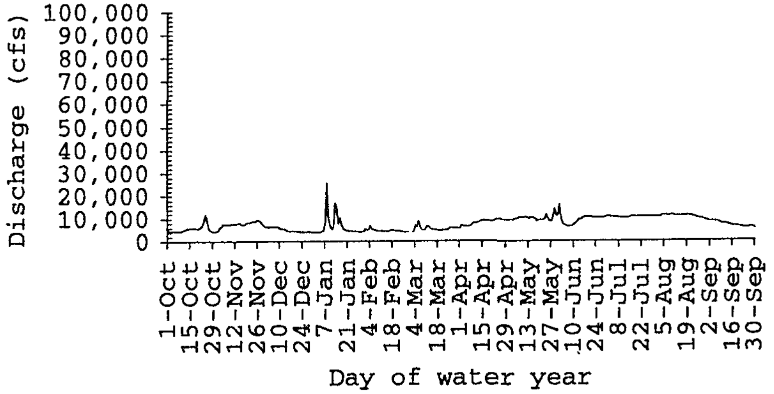

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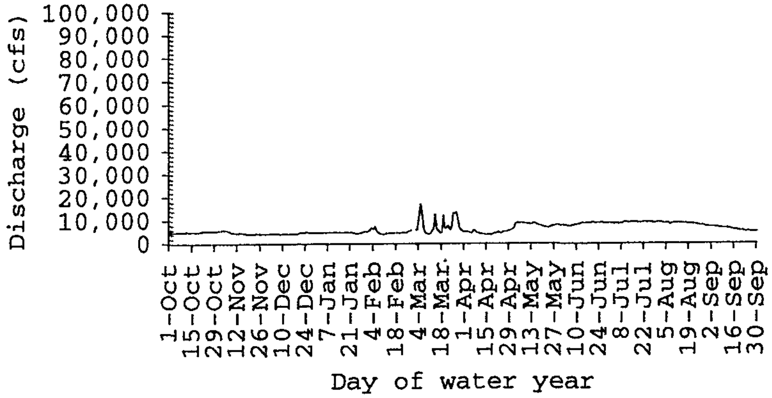

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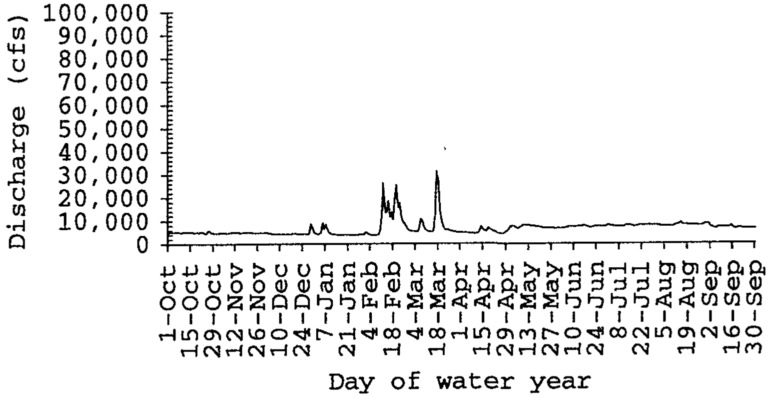
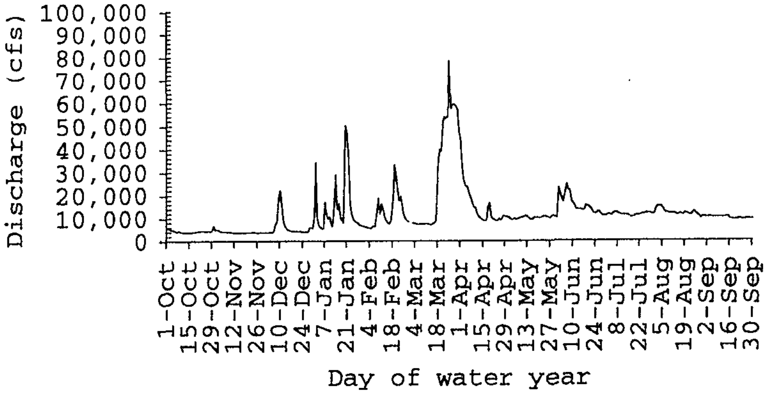


1993 Annual Hydrograph



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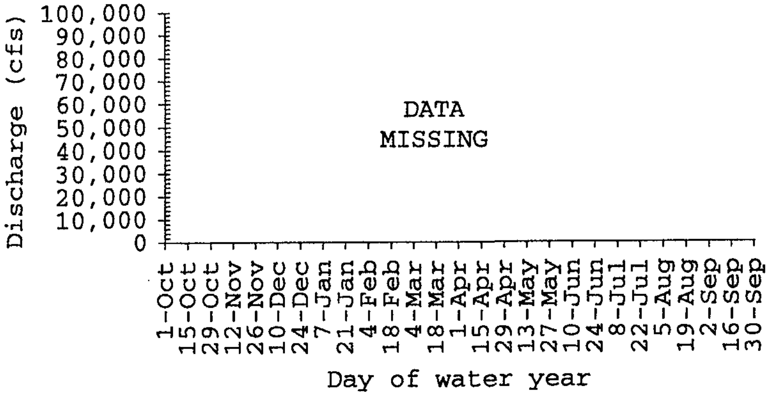
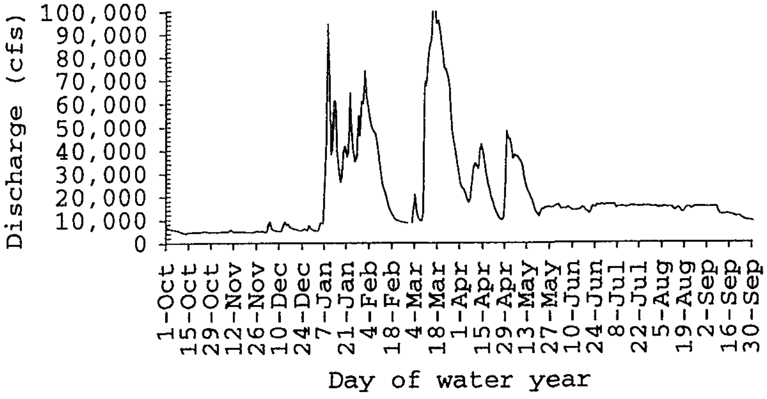
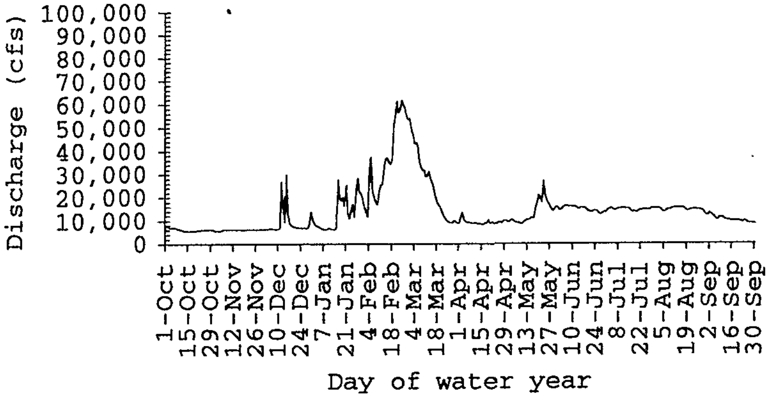
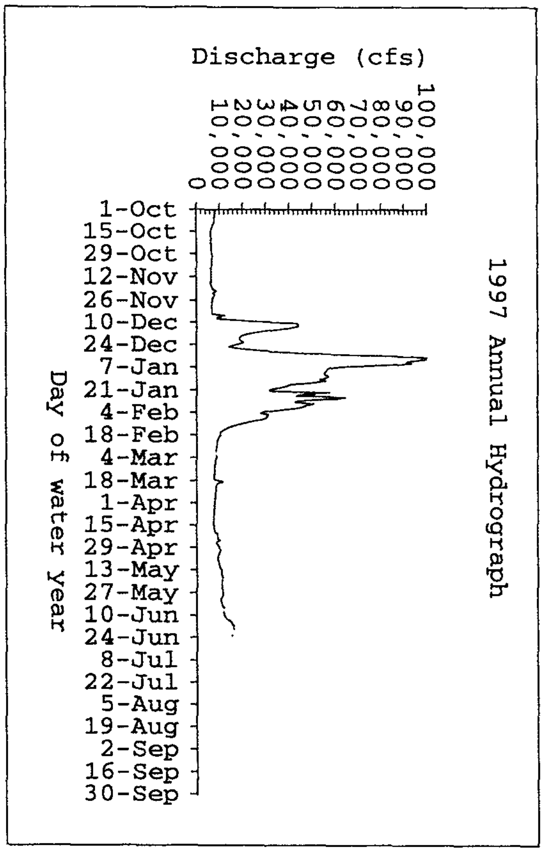


1995 Annual Hydrograph



1996 Annual Hydrograph




1997 Annual Hydrograph
Discharge (cfs)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Day of water year
1-Oct
15-Oct
29-Oct
12-Nov
26-Nov
10-Dec
24-Dec
7-Jan
21-Jan
4-Feb
18-Feb
4-Mar
18-Mar
1-Apr
15-Apr
29-Apr
13-May
27-May
10-Jun
24-Jun
8-Jul
22-Jul
5-Aug
19-Aug
2-Sep
16-Sep
30-Sep

APPENDIX B

Bed Mobility Analyses

Appendix B

Bed Mobility Methods

Bed mobility thresholds can be estimated using either empirical approaches or modeling approaches. The primary advantages of empirical approaches are that thresholds can be estimated in a variety of complex geomorphic surfaces (hydraulic predictions are not needed), and the results are accurate because predictive uncertainty is avoided (i.e., we measured that the bed was mobilized rather than we predicted it). The disadvantage is that it either requires a managed high flow release (preferred), or opportunistic action during a flood. Additionally, we need multiple data points (flows) to better pinpoint thresholds, which takes time and is expensive if controlled releases are used. Modeling provides the advantage of predicting bed mobility thresholds for any flow, and can be done without relying on a high flow event. The disadvantage of modeling approaches is that the prediction is only as good as the prediction of the hydraulics, which is typically good only in short reaches with simple hydraulics (long-straight riffles). Therefore, the other geomorphic surfaces that we may be interested in (point bars, medial bars, floodplains, pool tails) cannot be accurately modeled without a much more complex hydraulic model (2-d model rather than 1-d). With these limitations in mind, empirical and modeling methods are described below.

Empirical Methods

Three empirical approaches are commonly used: Marked rocks (or tracer rocks) to estimate whether a specific size rock is mobilized by an experimental flow(Wilcock, et al., 1995), bedload traps to estimate the largest particle size transported by a given experimental flow, and/or bedload transport measurements (e.g., Helley and Smith, 1971) to identify the largest particle size transported by a given experimental flow. On the Sacramento River, the only empiral methods that have been used to date are 55-gallon drum bedload traps in the upper reaches near Redding. The traps are used as follows: a backhoe excavates a large hole on an exposed point bar within the active channel, the 55-gallon drum is lowered into the hole until the lip of the drum is at the top of the gravel bar surface, and the hole around the drum is backfilled. During a discrete high flow, if a bed mobility threshold is surpassed and bedload transport occurs, rocks passing over the 55-gallon drum fall into it and are trapped. After the high flow recedes, the drums are revisited, sediment excavated from the drums, and analyzed for particl size distribution.

Modeling Techniques

Bed mobility threshold modeling is typically done by predicting the critical shear stress (force per unit area exerted on the bed) that begins to mobilize a certain particle size of interest within a particle size distribution. Shields developed a dimensionless critical shear stress for uniform sediments and later researchers developed models to predict dimensionless critical shear stress for mixtures of particle sizes (Parker, 1982; Andrews, 1994; and others). These methods were developed by plotting sediment transport rates as a function of dimensionless shear stress, and identifying the dimensionless shear stress value that occurs at a very small but measurable transport rate. This point is used as the dimensionless critical shear stress. The primary input variables to this type of model are shear stress, particle size, and channel geometry. :

$$\tau^*_{ci} = \frac{\tau_b}{(\rho_s - \rho_w) g D_i}$$

Where τ*ci is the dimensionless critical shear stress for a certain particle size, Di is the particle size of interest, τb is the boundary shear stress that causes movement, g is gravitational acceleration, and ρs and ρw are sediment and water density, respectively. under steady uniform flow conditions, this equation can further simplified to:

$$\tau^*_{ci} = \frac{\rho_w g R S}{(\rho_s - \rho_w) g D_i} \cong \frac{HS}{1.65 Di}$$

where R is hydraulic radius at the given flow (approximated by average depth, H, for wide streams like the Sacramento River) and S is the energy slope at the given flow (approximated by the water surface slope or thawleg slope over a reach exceeding 10 bankfull channel widths). There are numerous models to predict τ^*_{ci} for a given particle size of interest (e.g., for the D_{84}), and using these models and estimating slope from either field measurements or hydraulic model output, the hydraulic radius (or depth) for bed mobility can be computed. This depth can then be translated to a critical discharge through a stage-discharge rating curve for that particular cross section.

We applied Andrews (1994) surface based bed mobility model to predict the flow threshold to mobilize the surface D_{84} particle size:

$$\tau^*_{cD84} = 0.0384 \left(\frac{D_{84}}{D_{50}} \right)^{-.887} \qquad (2)$$

where D_{84} (32 mm) and D_{50} (16 mm) are surface particle sizes, as quantified by Water Engineering and Technology, Inc. (1988). Energy slope for Equation 1 was obtained from output from the ACOE Comprehensive Study HEC-RAS hydraulic model. Based on these estimates of slope and particle size, the critical hydraulic radius for mobilizing the D_{84} is computed by solving Equations 1 and 2. With this critical hydraulic radius and four cross sections (also from the ACOE Comprehensive Study) in hand, the discharge associated with this critical hydraulic radius can be predicted. We were not provided stage-discharge curves for the cross sections, so we applied Manning's equation to determine the discharge that caused the critical hydraulic radius. We assumed a Manning's *n* value of 0.03 based on the expected low relative roughness (large depth/small particle size).

A variant of this approach is to develop a bedload transport model for the reach. In hydraulically simple cross sections, predicted bedload transport rating curves can be extended to near zero to predict a bed mobility threshold. . Presently, there is no bedload model developed for this reach. However, Michael Singer, a PhD candidate at UC Santa Barbara has begun work on a sediment transport model for this reach, building from the hydraulic model developed by the Corp of Engineers Comprehensive Study. Until his study can be completed, a bed mobility threshold cannot be estimated from this method.

Bedload Transport Methods

Here, we are using bedload transport rates on the Sacramento River as an index of geomorphic work done, in effect, as a surrogate for the geomorphic work we are really interested in, namely bank erosion and meander migration, but for which no simple analysis is possible. In addition, bed mobility has important biological consequences of its own. The immediate application is to evaluate how changes in the magnitude and duration of high-flow releases from Shasta Dam (caused either by diversions or flow augmentation) will change how sediment is stored or routed through the system (i.e., the coarse sediment budget). For example, if the smaller Sacramento River flow regime is now causing coarse sediments to accumulate at tributary deltas (e.g., Cottonwood Creek), then we would be interested in predicting flow release magnitude and duration from Shasta Dam that would better route these sediments through the system (i.e., balance the input and output terms in the sediment budget). This requires an estimate of sediment input rates from the tributaries, which are not available except in crude form.

Empirical Methods

The empirical approach is to measure bedload transport at high flow, but we are aware of only a few such measurements having been conducted, all lower in the system. Sampling methods include 1) Helley Smith samplers (Helley and Smith, 1971), which consist of a metal orifice leading to a mesh bag placed on the bed for a period of time (the duration being a function of transport rates), 2) Vortex ejectors (Milhous 1973) which remove nearly all coarse sediment in transport to provide time-integrated volumetric or mass transport rate measurement, or 3) "flower box" samplers, which are boxes or pits in the river that also provide time-integrated transport rates, but only on a small portion of the cross section. Koll Buer used the latter method to measure the size of rocks in transport, but it is unclear whether or not he was able to calculate a transport rate (possibly due to his traps filling with sediment) (K. Buer personal communication 1999).

Modeling Techniques

Bedload modeling involves application of a transport function to predict bedload transport rates, usually as a function of excess shear stress or stream power and particle size distribution. (Excess shear stress is the shear stress above the critical shear stress for initiating bedload transport). The simplest approach is to apply an equation to a single cross section; however, more reasonable results are provided if many cross sections are included in the prediction (Einstein, 1950), or even better, if the sediment transport equations are integrated into a reachwide hydraulic model (e.g., HEC-6, Fluvial-12, etc.). There are many models in existence, many of which are not applicable to the Sacramento River because they were developed for sand bedded rivers, or are total load (bedload + suspended) models. Typical bedload transport models used for gravel bed rivers like the Sacramento River include Parker 1982, Parker 1990, and Meyer-Peter Mueller, 1948. As mentioned above, there is no bedload transport routing model completed for the Sacramento River, although Mike Singer of UC Santa Barbara has begun work developing one.

Results: Bed Mobility and Bedload Transport

The empirical data from Koll Buer's "flower box" experiments in the upper Sacramento River indicate that gravel transport begins at 24,000 cfs. The coarse riffles (small boulders and large cobbles), are probably armored from release of sediment-free flows from Shasta Dam. These armored riffles appear not to change and thus probably remain immobile even at flows exceeding 100,000 cfs (K. Buer, personal communication). A widely accepted conceptual model based on observations in other channels is that coarse bed particles are transported by flows slightly less than bankfull discharge. This conceptual model is probably applicable only to channels in 'equilibrium' and adjusted to frequent (e.g. 2-year) effective discharge, so this general notion should be applied to the Sacramento – or any river – only with caution. On the Sacramento River, the 2-year flood has been reduced from 119,000 cfs to 79,000 cfs since construction of Shasta Dam (as measured at Red Bluff). The reduction in flow has not been accompanied by a reduction in bed mobility threshold to decrease accordingly as the mobility threshold is a function of the particle size in the channel, which would not be expected to decrease with the change in flow regime.

Bed mobility modeling results

We applied Andrews (1994) bed mobility model to four of the ACOE Comprehensive Study cross sections as another bed mobility estimate to compare to Koll Buer's empirical bed mobility observations. Using surface particle size data (D_{84}=32 mm, D_{50}=16 mm for all four cross sections), Andrews (1994) model predicts a dimensionless critical shear stress value of 0.021 to mobilize the D_{84}. Solving Equations 1 and 2 predicts a critical hydraulic radius of 8.4 ft. Solving Mannings equation for discharge at each cross section suggests bed mobility thresholds between 15,000 cfs and 25,000 cfs (Table X).

Cross section	Discharge for D_{84} bed mobility threshold
RM 187	12,000 cfs
RM 184	15,000 cfs
RM 183	19,000 cfs
RM 169	13,000 cfs
AVERAGE:	14,750 cfs

Bedload transport results

There are no bedload transport measurements available, nor is there a bedload transport routing model completed for this reach, so no results are available at this time.

APPENDIX C

Report of the Fluvial Geomorphology and Riparian Systems Work Team (with selected appendices) for the CALFED Bay-Delta Program Comprehensive Monitoring, Assessment, and Research Program (CMARP)

COMPREHENSIVE MONITORING AND ASSESSMENT PROGRAM
SUBSTRATE PARTICLE SIZE SAMPLING

2 November 1998t

The objectives of the geomorphic monitoring are:

☐ To track the change over time in the shape and position of the channel, and in the size of the particles making up the channel bed, and

☐ to develop estimates of hydraulic parameters for use in developing estimates of the flows needed to initiate geomorphic processes, and for use in modeling flows and flow-related processes.

The sediment size distribution determined by quantitative sampling of the substrate is used to evaluate substrate suitability for spawning or other habitat needs (as defined by framework size or fine sediment content) , as a measure of substrate roughness and to provide the variables required for the equations used to calculate entrainment and bedload transport rates (Kondolf, 1997). Although the sampling and analytical approach ultimately depends on the question being asked, the following methods have broad application to the questions most likely in need of an answer, and will allow the greatest flexibility in application and interpretation of results.

1. Pebble Count Samples (for a more detailed discussion of the method and application of pebble count sampling, see Kondolf (1997):

Pebble counts (frequency by number samples) are theoretically equivalent to size distributions obtained from bulk samples (frequency-by-weight samples) (Church *et al.* 1987). If the populations sampled by the bulk and pebble count methods are the same, the size distribution resulting from the pebble count can be expected to be identical, on average, to the size distribution resulting from a sieve analysis (Wolman 1954, Kellerhals and Bray 1971). Thus, the differences between bulk and pebble count samples chosen from the same populations should be the result of real differences in surface and subsurface populations (*e.g.* from armoring) (Kondolf and Li 1992).

The pebble count is a simple, inexpensive, replicable technique applicable to coarse materials, and can be done on exposed bars or beneath several feet of flowing water. Because little equipment is required other than a measuring tape and appropriately sized templates for classifying particle sizes, the technique can be quickly applied at a large number of sites to provide a representative sample of a stream reach.

The primary disadvantage of surface pebble count technique is the inability to account for fine sediment. Surface gravels that a pebble count indicates are relatively free of fine sediment could contain enough fines in the spaces between particles of the underlying gravel to limit salmon spawning success (Kondolf and Wolman 1993). However, if fine sediment is not a concern, and if a good fit between the bulk and pebble count particle size has been determined then pebble counts should be an acceptable future alternative to the more demanding bulk sampling method.

The pebble count technique is also constrained by the lower limit of the sizes that can realistically be sampled. As recommended here, a lower limit of 8 mm was arbitrarily chosen because we assume the sampler is unlikely to touch and pick up particles much smaller than the tip of the index finger used to locate the particle (Lisle, among others, uses 4 mm).

Sample site selection: The general sampling areas should be defined by documented spawning use. This means, very likely, that the sampling area will include or be transitional between riffles, runs, pools, and glides and is probably best regarded simply as "spawning habitat." The intent is not (necessarily) to compare particle size distributions between sites but rather to compare each site against the range of gravel sizes known to characterize suitable spawning habitat.

☐ Number of sample sites: Three randomly selected sites per river reach with documented spawning use. The criteria used to designate a river reach should ultimately depend on the specific questions being pursued. However, channel form, gradient, substrate composition, presence or absence of tributary contributions (water and sediment), and spawning use will serve as a good starting point which may be further refined with time and experience.

☐ Maps: Use enlargements of aerial photographs of the study reach at a convenient scale such as 1 inch = 100 ft. If enlargements are made directly from contact prints, use only the central 6 by 6 inches of the 9 by 9 negative to avoid distortion near the edges (e.g., making 18 by 18 enlargements of the central 6 by 6 inches of 1:3000 negatives will make maps of a convenient size with 1 inch = 83 ft).

☐ Map particle size populations: Walk the study area, with careful attention to bed material size. The population area is defined as a "zone or area considered homogeneous" (Dunne and Leopold, 1978). The gravel may consist of a poorly sorted mixture of many sizes, but it should be consistently so over the entire patch. If only one population can be distinguished in a reach, the grain size distribution can be applied to the entire reach (Kondolf, 1997). Where more than one distinctive population exists, use wire pin flags to delineate the individual population boundaries, map populations, and conduct a separate pebble count for each population identified. Use a grid overlay to estimate the area covered by each population type (count the number of squares on the grid for each patch type, making visual estimates of fractions.) Randomly select patches within a population type, and conduct several pebble counts, as described in Kondolf (1997). Calculate the variance between the resulting size distributions for each unique population. If the variance for the D_{50} exceeds 10% between individual pebble counts of a unique population, calculate the number of additional pebble counts necessary to reduce the variance appropriately.

☐ If bulk substrate samples are to be collected, locate the bulk sample site in a patch of the population type for which the dominant surface particle size is closest to the D_{70} for the spawning reach, as calculated from the distribution of the combined pebble count results.

Sampling method: Measure 100 substrate particles using a template with square openings the same ratio as those of field sieves used to collect bulk samples. This will provide a measure of size equivalent to conventional sieving, and allow direct comparison of surface pebble count samples with bulk surface samples (Kondolf and Li 1992; Marchand *et al.*1984; Hey and Thorne,1983; Leopold 1970; Wolman 1954). Sampling points can be selected using a grid, at intervals along a tape laid on the bed or over the water or by selecting particles encountered by the toe of the observer's boot as a transect is walked across the sampling site. The gravel particles are to be randomly selected by touching the bed at grid points with eyes closed and collecting the first particle encountered by the tip of the index finger. Particles of similar size have a propensity to cluster together in an overlapping or imbricated fashion. In order to avoid sampling repeatedly from such a cluster, the sample interval should be at least 30 cm (Church *et al.* 1987).

☐ record each randomly collected and template-measured particle by size class (e.g., the pebble that passes through the 16 mm template opening but not through the 8 mm opening is recorded as a single particle in the 8-16 mm size class).
☐ Calculate the cumulative percentages of each size class (Kondolf, 1997).

2. Bulk Gravel Samples : Bulk sampling involves collecting a large volume of the river bed for mechanical analysis by sieving. In theory, the requisite size of a representative bulk substrate sample can be determined based on the size of the largest particle on the surface, provided the surface and subsurface gravels are part of the same deposit. It should not matter whether the substrate has been modified by armoring or spatial concentrations of coarse material, since the coarsest particles will remain on the surface (Church *et al.* 1987).

Sample site selection: The general substrate sampling areas should be defined by documented spawning use. If a single particle size population defines the reach, the bulk sample site may be arbitrarily located within the population. Where more than one population exists, the bulk substrate sample site should be located in a patch of the type for which the dominant surface particle size is closest to the D_{70} for the spawning reach, as determined by the pebble counts described above.

☐ Maps: As described above for the pebble count samples.
☐ Surveying: To document changes in channel form (aggradation, degradation) and habitat availability, survey the sample reaches with at least three cross-sections spaces at intervals of one-third to two-thirds channel-width. Each cross-section should encompass the channel banks to at least bankfull height, and cover all significant topographic features.

Sample size: The sample size criteria developed for accurate representation of the substrate are based on the premise that *"the largest class of grains present in the sample should define the sample size since they will be fewest in number, hence least well represented"* (Church *et al.* 1987). The criteria recommend that the largest particle sizes up to 32 mm comprise no more than 0.1% of the total sample weight, and that particles greater than 32 mm comprise no more than 1% of the total sample weight (Church *et al.* 1987). That is, the sample should be large enough so that the largest clast makes up no more than 1% of the sample by weight.

Sample excavation: If low flows allow sampling above the water line, shovels or a small excavator can be used to make an excavation of appropriate depth. If sampling must be done below the water line (subaqueous), the sample should be taken by inserting a cylinder of appropriate size (typically >60 cm) into the stream bed and extracting the bed material from inside the cylinder.

☐ If sampling above the water line, mark a meter-by-meter excavation area with wire pin flags. If sampling below the water line the area of excavation will be defined by the sampling cylinder.

Sample excavation depth: If the particle size distribution is to be used to evaluate spawning habitat, the depth of the excavation should be based on the maximum depth of the spawning nests. Unless site-specific observations dictate otherwise, an excavation depth of depth of 46 cm to 51 cm (18 to 20 inches) is recommended. The literature reports depths of between 30 cm to 60 cm (12-24 inches), consistent with redds measured on the American, Merced, Sacramento, and Cosumnes rivers. Substrate samples of appropriate depth and total weight may be collected from single excavations or compiled from subsample sites randomly selected from those patches with a surface particle size closest to the D_{70} (as determined by pebble counts) (Lisle and Madej, 1992).

Sample collection - Surface and subsurface bulk samples: The surface and subsurface components of each bulk substrate sample should be collected and analyzed separately as well as in combination.

☐ The surface sample is here defined as that portion of the substrate from the surface to the depth of the largest surface rock imbedded in the substrate. Having identified the largest rock in the surface, the rock should be removed by hand, and the depth the rock projects into the substrate measured. This depth defines the maximum excavation depth of the surface sample. Unless larger particles are subsequently found in the subsurface sample, this single rock should be measured and weighed as it will most likely also define the sample size. For example, if the largest rock in the surface sample weighs 2 kg (4.4 lbs), and it is to represent no more than 1 percent of the total bulk sample by weight (surface and subsurface samples combined), the total sample size will be 2 kg ÷ 0.01 = 200 kg (441 lbs).

☐ Bulk subsurface samples should be collected from the maximum depth of the surface sample to a depth of 46 or 51 cm. This will allow calculation of differences in surface and subsurface populations due to armoring, and the use of surface versus subsurface median particle size (D_{50}) as an indicator of whether the sediment transport rate exceeds the local sediment supply rate.

Sample measurement - sieves: A set of sieves whose sizes fall on all intervals of the Wentworth scale (ASTM STP 447B, 1985; Platts et al. 1983, Lane 1947) and span the entire range of the sample will allow the greatest flexibility in interpretation of results. Any grain size statistic such as geometric mean, sorting coefficient, or percent finer than a certain size can be easily extracted from a comprehensive grain size distribution (Lisle and Eads 1991). Recommended sieve intervals are included in the table below.

Field sieves with 128 mm (5 inch) mesh openings are readily available (Gilson Co. and cost about $25 dollars per screen and $200 per screen set (a rocker bottom to collect the gravel, and a screen frame). If one used a set for each sieve interval (I do) then the total investment in field sieves would be approximately $1800. Cobbles >128 mm (5 inches) should be measured by template with square openings that follow the same ratio as the sieves.

□ The particles collected on each sieve should be weighed and recorded by size class (e.g., the particles that collect on an 8 mm sieve are >8mm and smaller than the next largest sieve of 16 mm, and would be recorded as 8 mm or in the 8-16 mm size class).

Sample measurement - field weight: If the sample is collected above the water line, air dry the sample, and field sieve into appropriate size classes down to 8 mm. If the sample is collected below the waterline, all particles >8 mm may be wet sieved and weighed in the field assuming that the influence of any moisture remaining on the coarser particles is negligible relative to their weight, and that all moisture retained in the sample is associated with particles < 8 mm. (T. Lisle uses 11 mm, 1991). Material finer than 8 mm is decanted of any free water, then placed on a sloped surface to continue draining until weighed. The decanted and drained water may be discarded if the fine sediment content □1 mm (the approximate upper size limit of suspended sediment) has been otherwise determined to be of no concern. If the percentage or role of fine sediment relative to the question being asked is unknown, the suspended sediment will need to be measured. The suspended fine sands and silts may be accounted for by taking a sample of the agitated water, measuring the concentration and grain size of the fine sediment, and multiplying the volume of the water inside the sampling cylinder (subaqueous sampling) or other container used to hold the wash water (Lisle and Eads, 1991;Kondolf 1988; Platts et al. 1983; McNeil and Ahnell 1960; Lane, 1947). The particles of each size class should be weighed in the field (I use a 50 kg digital scale with ± 0.02 kg precision that cost about $600, but a 50 kg Pesola-type spring scale with ± 0.02 precision scale would be fine and cost about $120). When all other sampling and weighing are complete, all sediment <8 mm should be weighed. When the volume of fine sediment precludes retaining all excavated material, a sample splitter should be used to reduce the sediment into a smaller representative sample (ASTM, STP 447B, 1985). Once weighed, and, if necessary, split, each sample of fine sediment should be sealed in an air-tight container, and set aside for dry-sieving in the laboratory.

Field Sieves & Templates[3]	Size Classes[1]	Sieve Designation[2]	
	small boulder (≥256 mm)	256 mm	10"
	large cobble (≥128 mm)	180 mm	7"
		128 mm	5"
	small cobble (≥64 mm)	90 mm	31/2"
		64 mm	2½"
	very coarse gravel (≥32 mm)	45 mm	13/4"
		32 mm	11/4"
	coarse gravel (≥16 mm)	22 mm	7/8"
		16 mm	5/8"
	medium gravel (≥8 mm)	8 mm	5/16"
	fine gravel (≥4 mm)	4 mm	#5
	very fine gravel (≥2 mm)	2 mm	#10
	very coarse sand (≥1 mm)	1 mm	#18
	coarse sand (≥0.5 mm)	0.5 mm	#35
	medium sand (≥0.250 mm)	0.250 mm	#60
	fine sand (≥0.125 mm)	0.125 mm	#120
	very fine sand (≥0.065 mm)	0.075 mm	#200
		0.065	#230

1/ Wentworth (1922) grain size classification
2/ U.S. Standard/ASTM sieve designations
3/ Field sieves and templates: size of sieve openings.
4/ Lab sieves: sieve mesh number equals the approximate number of mesh openings per inch.

Sample measurement - Laboratory analysis: Sediment fractions <8 mm should be oven-dried and mechanically sieved with the appropriate whole-grade interval sieves. The material retained on each sieve should be weighed to the nearest gram on an electronic balance with an accuracy of 0.1 gram, and the total weight of the laboratory sample corrected for moisture content.

Data analysis: Sample size fractions by weight should be converted into size fractions percent by weight, with the percent by weight passing each sieve plotted as a curve on a semi-logarithmic scale. The plotted data will show the percentage of particles retained and passing through each sieve. The surface and subsurface bulk samples, and the pebble count samples should be analyzed separately and then collectively.

Descriptive Analysis: In addition to median diameter and the diameters at one (D_{84} and D_{16}) and two (D_{95} and D_5) standard deviations, the geometric mean (dg), the geometric sorting index (sg), and skewness (sk, Vanoni 1975), are computed as follows:

$$sg = (D_{84}/D_{16})^{0.5}$$
$$dg = (D_{16}D_{84})^{0.5}$$
$$sk = \log(dg/D_{50})/\log(sg)$$

The geometric sorting index (sg) reflects how well fluvial processes have concentrated particles of similar size. If a deposit has a small range of grain sizes, it is "well-sorted" and has a low sg value. If there is a wide range of grain sizes, the deposit is "poorly -sorted" and has a high sg value. A perfectly sorted sediment has a value of 1. An sg of less than 2.5 indicates a well-sorted sediment, about 3 is considered normal, and above 4.5 is poorly sorted.

The geometric mean particle size (dg) is commonly used as an indicator of stream bed material permeability. In general, permeability increases with an increase in geometric mean particle size. However, it should be noted that for a given mean particle size permeability will decrease with degree of sorting: in a poorly sorted sample (with a wide range of particle sizes), fine material can fill the voids between the larger particles, reducing permeability.

Skewness measures the asymmetry of the particle size distribution. If the distribution is not symmetric around the mean, then extreme values will pull the mean toward one tail of the distribution. Gravels of the size typically used by salmon for spawning are usually negatively skewed; that is, their size distributions are not perfectly log normal but are negatively skewed and are characterized by tails that extend into the fine sediment sizes (Kondolf 1988). This is also reflected in the tendency for D_{50} to exceed dg.

Pebble count samples and bulk samples are typically collected at different size ranges (i.e., 8 mm to 512 mm versus 0.063 mm to 512 mm). The proportion of particles in any one size class present in a distribution is influenced by the quantities of all sizes present. Therefore, if the pebble count data is to be compared with bulk sample data to determine the efficacy of using surface pebble counts in lieu of the more expensive and time consuming bulk sediment sampling, the bulk sample data set must be truncated at 8 mm (or the smallest pebble count size class used) and the percent weight of each bulk sample size class recalculated accordingly.

REPORT
FLUVIAL GEOMORPHOLOGY AND RIPARIAN ISSUES GROUP
2 November 1998

SUMMARY:

The monitoring program for fluvial geomorphology and riparian issues should consist of periodic aerial photography of all significant streams in the CALFED area of concern, supplemented by field studies at selected sites and a miscellany of other activities. The aerial photography can provide information on the planform of streams and other features in the landscape, the topography of the channel above the water surface and of adjacent riparian areas, the extent and nature of riparian vegetation, and human activities near streams and riparian areas.

The information from the aerial photography should be supplemented by detailed monitoring at selected study sites. Geomorphic monitoring at the sites should include surveys of the channel and riparian areas, especially subsurface features and topography under the riparian canopy, and measurements of the size distribution of channel bed materials. Vegetation monitoring should include dominant species composition and indices of stand structure, and related physical variables such as depth to water. Monitoring of birds should include species richness, species diversity,distribution (presence/absence on local and regional scales), and abundance and reproductive success of selected species. Recommendations for monitoring riparian insects, amphibians, reptiles, and mammals are not yet developed, nor are recommendations regarding vernal pools or seasonal wetlands.

Site selection for fluvial geomorphic and riparian purposes should be based on different criteria, so although some sites may serve both purposes others may not. For fluvial geomorphology, we recommend that about 40 to 50 long-term sites should be established over the area of concern, selected by professional judgement. We have not developed a recommendation for the number of riparian study sites, but criteria for site selection are discussed below. We emphasize here, however, that since long-term access must be a key criterion, the field sites will not provide statistically valid samples of the overall state of the area of concern.

The recommendations below describe the use of established methods. Technology is changing rapidly, however, and better methods to obtain the same information or provide alternative answers to the same questions probably will be developed over the period of monitoring. CMARP or its successor entity should be prepared to adopt new methods, although in general we recommend that the older methods not be discontinued until the new methods have been tested by actual use.

INTRODUCTION

Diverse points of view were represented on the work team, and because of the broad range of issues the recommendations generally were developed by small subgroups. Accordingly, the recommendations should not be taken as representing a consensus of the team, and the word "we" in the text is used loosely.

The recommendations in this report are intended to apply to Central Valley rivers up to the first major dam, or to the upstream extent of significant alluvial deposits. The downstream boundary is somewhat vague. The recommendations regarding aerial photography and riparian vegetation can apply to the Delta as well as to the rivers. The recommendations regarding fluvial geomorphology give greatest attention to gravel-bed reaches; additional consideration to soft-bottomed reaches may be appropriate, but the recommendations of the hydrodynamics work team would provide substantial information on channel morphology for these reaches.

The recommendations are intended to address monitoring needs at different spatial scales. For example, CALFED will need monitoring of riparian vegetation at a coarse or landscape scale to determine whether the amount of riparian vegetation is increasing or decreasing over the whole region of concern. It will also need monitoring at a medium or reach scale, in order to evaluate the effectiveness of measures such as deliberate changes in flow regimes that are intended to affect whole reaches of streams. It will also need monitoring at fine or site-specific scales, both to clarify the processes that are driving environmental changes and also to collect data on such things as bird populations, regarding which the answers to landscape scale questions can only be developed by aggregating site-specific data. In this context, the recommendations may involve inefficient approaches to answering coarse scale questions, because these approaches also produce data that is needed to answer questions at finer spatial scales. For example, landscape scale questions about riparian vegetation probably could be answered using satellite data, but since low altitude aerial photography will be needed for other purposes we are recommending that it also be used to answer the landscape scale questions.

In some cases recommendations are quite specific, although alternative approaches would be acceptable. We provide the detail in order to be clear about the recommendations, but the details should be understood as one way to get the desired information, and not necessarily the only way. Recommendations in this draft report deal primarily with monitoring, and except for birds and insects we have fallen short regarding recommendations for monitoring riparian animals. Similarly, we have not dealt with vernal pools, seasonal wetlands, or freshwater marshes.

The members of the Fluvial Geomorphology and Riparian Issues work group are Bill Alevizon, Randy Baxter, Stacy Cepello, Ann Dennis, Jeff Hart, Carolyn Marn, Scott McBain, Nadav Nur, Anitra Pawley, Kris Vyverberg, and John Williams. Others including Doug Morrison, Jerry Ripperdate, Tanis Toland and Scott Cantrell have attended one or both meetings of the group. John Williams, chair of the group, has written the body of the draft report. Appendices have been written by Kris Vyberberg, Nadav Nur, and Randy Baxter.

MONITORING

Aerial Photography:

Periodic stereoscopic aerial photography of all significant streams in the study area should provide the backbone of the monitoring plan. Aerial photography is a versatile monitoring method that can provide information at both site-specific and landscape scales. Mapping based on aerial photography is well suited for geographical information systems, and the photography preserves an historical record that can be consulted as new and unanticipated questions arise. Through photogrammetry, it can provide information on the topography as well as the planforms of features in the landscape. Periodic aerial photography would also provide cost-effective monitoring of individual restoration projects, and meet the needs of reclamation districts and other agencies that now contract for aerial photography independently.

The program should cover all major streams in the study area at regularintervals, or after major flow events. Tentatively, we recommend thatphotography be taken every five years, or after >10 year flow events,whichever comes first, and that it be taken in late summer, when flows are low but deciduous vegetation is still in leaf. We recommend the use color film rather than infrared film, since infrared film is less suitable for photogrammetry. Photography taken during high flows can document the relation between discharge and floodplain inundation. DWR typically has aerial photography flown during significant floods, but additional photography during somewhat lower lower flows may be appropriate.

The scale of the photography should depend on the scale of the stream in question and on the accuracy desired from photogrammetry, which is more demanding than mapping and analysis of riparian vegetation. A scale of 1:3000 (1" = 250') can provide spot elevations accurate to +/- 0.25', and allows construction of topographic maps with 1' contour intervals; 1:6000 (one inch = 500 ft) can provide spot elevations accurate to +/- 0.5' and maps with 2' contour intervals. In areas where gravel supplies for salmon spawning are a concern, for example, the ability to create maps with 1' contour intervals seem desirable. For leveed reaches of the lower Sacramento photography at 1:6000 or even 1:12000 should be adquate. More detailed recommendations regarding aerial photography are provided in Appendix A.

For landscape or reach-scale monitoring of riparian vegetation, maps should be created using suitable vegetation categories, and entered into a GIS database. For this purpose the photography should be scanned and rectified, which can now be done with equipment costing on the order of $10,000. The California Native Plant Society (CNPS) classification system (citation) is now the most commonly used and probably should be considered the default choice. The CNPA system is compatible with older mapping using the Holland system, and trials at the DWR Red Bluff office have shown the the CNPS system can be used with aerial photography at the scales recommended. Various indices such as areal extent, measures of connectivity, etc., can be calculated easily from the GIS data, and correlated with information on topography, soil types, geological formations, etc.

The planform and general characteristics of stream channels are easily determined from aerial photography, and can also be entered into GIS systems for analysis. It is often useful to classify stream channels or stream channel features for various purposes, but we caution against using complex general systems such as the Rosgen system (Rosgen 1996); stream channels respond to a large number of factors that vary continuously, so any classification system is inevitably arbitrary to some degree, and classifications that are useful for one purpose may be misleading for another. For example, salmon tend to spawn in areas that are bisected by boundaries drawn between pools and riffles, so these channel features are not optimal for describing or analyzing spawning locations. A classification of channel features that has been useful for work by the Department of Fish and Game is presented in Appendix B.

The topography of the channel above the water surface and of riparian areas can be determined by photogrammetry, and can be estimated by viewing the photographs through stereoscopes. This information can be extremely useful, particularly when changes in topography can be tracked through time. Durable, surveyed monuments should be established at the study sites and other locations (especially CALFED project sites) and marked for aerial photography so that absolute elevations and positions can be determined. However, photogrammetric analysis need be done only when there are specific uses for the information.

Geomorphic Field Sites:
Monitoring at the geomorphic field sites will provide information on the channel geometry and the channel substrate, and on hydraulic parameters at the sites. Dams interfere with the flow of water and sediment in almost all CALFED streams, and the continuing adjustments of the channels to these and other human modifications of the streams are a major concern to CALFED and also to other agencies. For example, CALTRANS has to replace bridges because of the continuing downcutting by the Sacramento River and other streams. CALFED is considering significant modifications in the flow regimes and intoduction of coarse sediment into rivers below dams, intended to reverse or moderate some of the effects of the dams.

In the context of adaptive management, the geomorphic (and riparian) field sites can serve different functions, depending upon the scale of the management interventions involved. At a medium or reach scale, for example, the size distribution of gravels at the sites will provide evidence of the overall effectiveness of programs to replenish supplies of gravel suitable for spawning. At a finer scale, the sites could also serve as controls for localized management experiments, such as efforts to enhance spawning gravel in particular areas.

We recommend that 40 to 50 long-term sites be established over the CALFED area. This number seems doable, and together with information developed from the aerial photography should be adequate to detect and to some degree to quantify the general response of channels to large scale human interventions or major natural events. The sites should be 20 to 50 channel widths* long, as recommended by Kondolf (1998) which should include a range of channel features such as pools and bars. The sites should be chosen to be reasonably representative of the channel in the area, based on professional judgement, but long-term access and predictable management of the sites are paramount considerations, so generalizations from the sites to the local areas should be made with caution. Sites that can also serve as riparian study sites should be preferred if they are available.

*[Channel width here means the average width of the unvegetated active channel. The width of the stream at "bankfull discharge" is often used but there are ambiguities with this concept for many regulated and semi-confined streams in the Central Valley.]

The channel geometry at the sites should be surveyed about every ten years, or more frequently if there is reason to think that significant change is occurring. For wadable streams and exposed areas, the surveys should use standard surveying equipment and protocols to survey a long profile along thalweg, and 10 to 20 monumented cross-sections spaced 2 to 5 channel widths apart. In streams too large to wade the data can be collected using standard surveying equipment with small boats and tag lines. In larger rivers the cross-sections and thalweg data should be collected with a hydrographic survey boat, with equipment such as a GPS integrated transducer, and supplemented with bathymetric data in enough detail to create maps with 2' contour intervals. More detailed recommendations for surveying with established methods will be provided with the final report.

Stage-discharge curves should be determined for the sites by measurements of water surface elevations at the transects. It is particularly important to establish the elevation of high water marks after high (> 10 year) flows, so that hydraulic parameters for the sites can be estimated from survey data, following re-surveys if these are indicated. Hydraulic parameters derived from such measurements will significantly improve the quality of hydraulic modeling of the river, and allow better calculation of the frequency with which gravel is mobilized or other geomorphic thresholds are exceeded.

The composition and size distribution of the substrate should be determined by standard laboratory methods for sites with fine-grained (silt and sand) substrates, and by pebble counts for surface sediments and bulk sampling of subsurface sediments for sites with coarse-grained substrates. Pebble counts (described in Kondolf 1997) are a simple method for estimating the size distribution of coarse-grained surface sediments. Bulk sampling is more difficult and expensive, because large samples are required for coarse gravel, but it provides more complete information on substrate size distribution, and the difference between the surface and subsurface size distributions provides an index of the sediment supply at the site* (Deitrich et al. 1989). Bulk sampling also provides data on the size distribution of material too small to sample by pebble counts. Bulk sampling and pebble counts are difficult in water more than a foot or two deep, so for deeper water sediment size distributions should be estimated by underwater video. Data from video or photographic methods are not consistent with data from pebble counts and bulk sampling, so size distribution data from video images should be kept separate; however, video data will allow assessment of change over time. More detailed recommendations for monitoring sediment size distributions are presented in Appendix C.

*[Direct measurement of bed-load sediment discharge is very difficult and we do not recommend it.]

Additional analyses may be appropriate where the sites are located in actual or potential salmon spawning areas, particularly for sites where salmon tend to avoid apparently suitable gravel. An approach to evaluating gravels as spawning habitat is provided in Appendix D.

Riparian Field Sites

Monitoring of vegetation at the riparian field sites will provide information that cannot be obtained from the aerial photography. Sites should be selected following an initial broad-scale analysis of existing conditions, using data on vegetation types developed from aerial photographs, topography, soils, geological formations, etc., and collection of field data at sites selected as randomly as possible given access constraints. With better information in hand regarding the extent and condition of existing riparain habitat, and the extent and distribution of sites with adequately secure access, a decision can be made whether to select size by professional judgement or by some objective method. Recommendations regarding the size of the sites and monitoring protocols should be developed as part of this process.

Some large fraction of the sites should be chosen to represent remaining intact stands of riparian vegetation. Monitoring in these sites will provide data that can be used to develop standards or targets against which to compare data from restoration sites. Sites should also be selected representing different degrees of habitat disturbance. These sites should be left untreated, to provide controls for evaluating individual restoration projects.

Base maps for the sites can be produced from digitized aerial photogrpahy, on which topography, soils, vegetation types, and other relevant features can be mapped. The CNPS system should be regarded as the default choice for classifying vegetation. Information on the history of the vegetation should be developed from past aerial photography or other sources. Observation wells should be installed at sites where groundwater levels are uncertain, and information on subsurface conditions should be collected and logged during the installation. The channel adjacent to the site should be surveyed using methods similar to those for geomorphic field sites, so that stage-discharge curves can be estimated from hydraulic models, and the frequency of inundation can be estimated from hydrologic records.

Sampling strata for vegetation should be developed based on the information gained during the initial mapping of the sites. Although monitoring protocols remain to be developed, they will probably provide that belt transects should be randomly located through the strata, running perpendicular to the stream from the outer edge of the site to the active channel (Warner 1981, Walker et al. 1986). Transects should be marked with permanent monuments that could also serve as control points for photogrammetry. At a minimum, observations in the transects should allow developing estimates of percent cover by dominant species by vertical layer (e.g., >1, 1-3, and >3 m). Additional observations to address specific questions should be made at selected sites. Monitoring should pay partiuclar attention to seedling establishment by riparian species, and to nuisance exotic species.

By-Passes and Floodplains:
Monitoring sites and protocols for the floodplains and by-passes should be selected by a process similar to that described for riparian sites. In addition, there is need for better information on inflows and stage-discharge relations for the bypasses and the channels within them. For the Yolo Bypass, for example, gages are needed within the bypass, on Knights Landing Ridge Cut, the Willow Slough bypass, and Putah and Cashe creeks near the bypass. A special program of aerial photography to document the relation between flow conditions and area inundated is needed. In general, the immediate need is for baseline data, and probably more data and experience need to be obtained before a monitoring protocol can be developed. More detailed information on monitoring needs are provided in Appendix E. Recommendations for an investigation of the use of floodplain habitats by fish are attached as Appendix F.

Avian Monitoring:
Monitoring of birds at the riparian sites should address questions regarding the status of avian populations, and the need for and effectiveness of management actions, at a regional or landscape scale. Monitoring at non-project sites would also provide controls for assessing the effectiveness of individual CALFED projects that have avian objectives.

The monitoring should measure species richness and species diversity, distributions (presence/absence at local and regional scales), abundance of selected riparian-associated species, and reproductive success of selected species. Except for reproductive success, these can be monitored by point counts at stations along transects. Surveys should be conducted at least twice and preferably three times during the breeding season. Separate surveys of migrating birds at fall stopover sites would be desirable. Sampling should be stratified by habitat, and since habitat types such as orchards will not be included among the riparian field sites the sampling should not be restricted to the sites. Monitoring reproductive success will require substantial effort but provide the most information about the environmental quality of the sites being monitored. Details on the monitoring and recommendations for species are provided in Appendix G. Estimates of the person-days required to perform the monitoring will be provided with the final report.

Miscellaneous Monitoring:

Discharge: The USGS maintains a network of gaging stations that measure discharge. Generally, the USGS has been cutting back on the number of gaging stations in response to budget considerations, and it is important that gages in the CALFED area be maintained. We have not yet checked the coverage of gaging stations systematically, but additional gages measuring inflow to the Yolo By-Pass from west side streams and cuts are needed.

RESEARCH AND ASSESSMENT

Discharge:
Brian Richter and his colleagues (Richter et al. 1996, 1997, 1998) have developed a set of 33 parameters to describe the flow regime in a river that can be developed from data on daily flows. If there are data for periods before and after construction of a dam or diversion, or if a record of daily unimpaired flows has been developed, the approach can be used to describe the effects of the water development on the flow regime. The method can also be used to develop first-cut flow objectives in an adaptive management context. This approach to describing flow regimes seems promising and we recommend that it be used, although it may be appropriate to modify the specific set of parameters for application to Central Valley rivers.

Water Temperature:
A number of agencies monitor water temperature in streams in the CALFED area. There is a need to compile a list of available data, evaluate the purposes and quality of existing data collection efforts, and develop a plan to fill gaps in coverage. There is also a need to develop some means to provide convenient access to the data.

Data collected by the City of Sacramento Water Treatment Plan show a biologically significant increase in water temperature during the spring (Williams 1995, p. 88). The reality of this increase should be verified, and if it is real the reasons for it should be determined.

River/Groundwater Exchanges:
The beds of streams are typically permeable to water, which can flow either in to or out of the stream depending upon local conditions. Gross accretions or depletions of streams can be determined by measurements of discharge taken along the stream and by estimates of groundwater levels developed from observations in wells, but greater detail is often needed to evaluate the environmental effects of river/groundwater exchanges. The increasing importance of water marketing and water transfers also creates a need for better understanding of river/groundwater exchanges.

Stable isotope ratios provide an underutilized approach to investigating the movement of water from rivers into groundwater basins. Precipitation at lower elevations has a higher proportion of heavy oxygen than precipitation at higher elevations, so Central Valley groundwater originating from recharge by streams draining the Sierras can be distinguished from groundwater originating from infiltrating precipitation (Davisson and Criss 1993, Davisson, Criss and Campbell 1993.) When combined with data on unstable isotopes such as Carbon 14 and traditional analyses of water chemistry, more detailed information regarding the source and movement of groundwater can be obtained. The potential for using isotope analyses as part of a groundwater monitoring program should be explored.

Groundwater Ecology:

There is a developing body of knowledge regarding organisms that pass part or all of their lives in alluvial aquifers (e.g., Gilbert et al. 1994; Brunke and Gonser 1997). Systems that have been studied in the USA include the alluvial aquifers of the Flathead River in Montana (Stanford et al. 1994) and the South Platte River in Colorado (Ward and Voelz 1994). There may be work on the fauna of Central Valley aquifers but we are unaware of any. Job and Simons (1994) consider groundwater ecology in the context of groundwater management, provide a list of research priorities, and conclude as follows:

> Advances in groundwater ecology have unraveled important physical, chemical, and biological relationships in the subsurface aquatic realm. The research infers a basic message for management: Protect groundwater quality by protecting ecosystem functions. It appears that groundwater biota effectively detoxify at least some contaminating stressors, thereby maintaining and improving groundwaters as potable resources, as well as reducing impacts on associated ecosystems, such as rivers, wetlands, and estuaries. This is a strong argument for implementing principles of groundwater ecology into water resources management activities. However, a better understanding of groundwater toxicology and the efficacy of using groundwater biota as biomonitors in needed. Biological, chemical, and physical indicators can be more effectively to quantify and prioritize protection strategies and management areas (e.g., strategic groundwater supplies for potable and agricultural use, and zones of high bioproductivity or refugia for endangered species). In many situations, the current regulatory framework in the United States could address the conservation and protection of groundwater ecological processes, especially with respect to influences on surface water quality. However, such a practice is not currently routine. The strategic plan of the U.S. Environmental Protection Agency for protection and enhancement of groundwater ecosystems provides a basis for more effectively applying regulatory processes to groundwater pollution problems. A significantly expanded ecological research effort, as prioritized in this plan, will be necessary as an information base to resolve the plethora of management considerations that are problematic in the United States and elsewhere.

A logical first step would be to commission a thorough review of this topic as it applies to the Central Valley. Such a review should consider the nature of the alluvial aquifers associated with Central Valley streams and the available information on the biota of comparable systems, and make appropriate recommendations for further work.

Recruitment of Riparian Vegetation:
Modification of natural hydrological regimes has affected the processes that create favorable conditions for the establishment of seedlings of riparian species in unregulated rivers. There is a need for more information and better understanding regarding the potential for seedling establishment along regulated rivers. Research at riparian field sites could provide this information.

CONCEPTUAL MODELS AND JUSTIFICATION FOR THE RECOMMENDATIONS

A number of relevant paradigms, hypotheses, points of view, or conceptual models are discussed in the literature. Starting at the top, the prevailing view of ecosystems has changed over the last few decades. As described in Mangel et al. (1996):

> Some call this "the new ecological paradigm." It should be emphasized that although the facts have been known by some ecologists, other scientists, and managers for many years, it is only recently that there is more widespread recognition of the knowledge. Formerly, the dominant paradigm was that of an ecosystem that was stable, closed, and internally regulated and behaved in a deterministic manner. The new paradigm is of a much more open system, one that is in a constant state of flux, usually without long-term stability, and affected by a series of human and other, often stochastic factors, many originating outside of the ecosystem itself. As a result the ecosystem is recognized as probabilistic and multi-causal rather than deterministic and homeostatic; it is characterized by uncertainty rather than the opposite.

In other words, there is no assurance that restoring important driving variables to past values will necessarily return the system to some past state. For example, the floodplains of rivers such as the Yuba or American that were heavily affected by hydraulic mining are now elevated with respect to the river channels, so that even if natural flows were restored to the rivers the past inundation regime for the floodplains would not, at least not within time scales of interest for planning. In consequence, continuing the same example, it is necessary to determine the inundation that will result from a flow with a given recurrence interval, rather than make assumptions based on geomorphic generalities. Similarly, downstream of dams that interrupt the flow of coarse sediment, high flows of water will have different environmental consequences than the combined discharge of water and sediment in an unregulated stream. In consequence, "flushing flows" intended to serve one environmental purpose may defeat another, and the specification of optimal flows requires quantitative estimates of sand and gravel transport (Kondolf and Wilcox 1996). This emphasizes the need for information from monitoring, as well as the need for clear statements of objectives.

A second and related concept of particular importance for fluvial and riparian systems is the intermediate disturbance hypothesis (Connell 1978, Pickett and White 1985), which states as a generality that biological diversity peaks in environments with an intermediate level of disturbance. An alternative formulation that has been applied to forest streams states that diversity peaks at an intermediate time following a major disturbance (Benda 1994, Reeves et al. 1995). Both formulations emphasize the importance of the "disturbance regime," for example the variability in flows in streams (see also Rood and Mahoney 1990 regarding riparian vegetation). A verbal "conceptual model" of Central Valley streams thattries to incorporate these ideas follows:

River channels are "self-formed" by flows of water and sediment, within constraints set by sea level, geology, vegetation, and human intervention. In the CALFED region, human intervention has taken various forms: hydraulic mining introduced great quantities of sediment into the rivers, logging increases inputs of sediment and decreases inputs of large woody debris, dams regulate the flow of water and interrupt the flow of sediment and large woody debris, diversions reduce the flow of water, levees restrict overbank flooding and simplify instream habitat by increasing stream power, loss of riparian forest reduces local supplies of large woody debris, riprap and other forms of bank protection inhibit channel migration, gravel mining removes coarse sediment from channels and creates pits in floodplains that can capture sediment, dredging removes sediment from channels, and snaging removes large woody debris.

The consequences of these interventions for river channels are understood in general (e.g., Williams and Wolman 1984, Andrews 1986, Ligon et al. 1995, Collier et al. 1996) but because of the number of factors that interact in usually non-linear ways responses can vary along channels and over time. For similar reasons, channel responses to management actions may be surprising. Monitoring basic attributes of channel form and substrate size is therefore important.

The biological consequences of these interventions are even more complex and varied, scientific understanding of them is still developing, and some have been discovered only recently. For example, Wootton et al. (1996) recently demonstrated that movement of gravel by winter flows can determine the relative abundance of various herbivorous aquatic insects the following summer, and so affect the food supply of juvenile salmonids. As a generality, the life cycles of many species are tuned to the seasonal cycles of the natural hydrologic regimes or to related physical effects such as sediment deposition and water temperature, and these have been disrupted. In most cases, however, the details are poorly known. As another generality, many species depend upon habitats that are created by episodic disturbances (Pickett and White 1985), and the fortunes of these species depends upon the effects of human intervention in hydrologic "disturbance regimes." Again, however, in most cases the details are poorly known.

Several members of the work team have put considerable effort into developing conceptual models that link directly with CALFED goals, but except for fluvial geomorphology (Appendix H) they have not yet been integrated with proposals for monitoring.

References:

Andrews, E.D. 1986. Downstream effects of Flaming Gorge reservoir on the Green River, Colorado and Utah. Geological Society of America Bulletin 97:1021-1023.

Benda, L.E. 1994. Stochastic geomorphology in a human mountain landscape. Doctoral dissertation. University of Washington, Seattle.

Brunke, M. and T. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37:1-33.

Collier, M., R.H. Webb, and J.C. Schmidt. 1996. A Primer on the Downstream Effects of Dams. U.S. Geological Survey Circular 1126.

Connel, J.H. 1978. Diversity in tropical rain forests and coral reefs. Science 199:1302-1310.

Davisson, M.L. and Criss, R.E. (1993) Stable isotope imaging of a dynamic groundwater system in southwestern Sacramento Valley, California, USA. Journal of Hydrology 144:213-246.

Davisson, M.L., R.E. Criss and K.R. Campbell. 1993. Preliminary report on the stable isotope imaging and characterization of surface and groundwater resources in the southern Sacramento Valley. Lawrence Livermore National Laboratory UCRL-ID-115393.

Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment Supply and development of coarse surface layer in gravel bedded rivers. Nature 340:215-217.

Gilbert, J., D.L. Danielopol, and J.A. Stanford, eds. 1994. Groundwater Ecology. Academic Press, San Diego, Ca.

Job, C.A. and J.J. Simmons. 1994. Ecolgocial basis for management of groundwater in the United States: statues, regulations, and a strategic plan. Pages 524-542 in Gilbert, J., D.L. Danielopol, and J.A. Stanford, eds. 1994. Groundwater Ecology. Academic Press, San Diego, Ca.

Kondolf, G.M. 1997. Application of the pebble count: notes on purpose, method, and variants. Journal of the American Water Resources Assocition 33:79-87.

Kondolf, G.M. 1998. Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. Unpublished report to US Fish and Wildlife Service, Stockton, California.

Kondolf, G.M. and P.R. Wilcock. 1996. The flushing flow problem: defining and evaluating objectives. Water Resources Research 32:2589-2599.

Ligon, F.K., W.E. Dietrich, and W.J. Trush. 1995. Downstream ecological effects of dams: a gemorphic perspective. BioScience 45:183-192.

Mangel, M. and 41 others. 1996. Principles for the conservation of wild living resources. Ecological Applications 6:338:362.

Maser, C. and J.R. Sedell. 1994. From the Forest to the Sea: the ecology of wood in streams, river, estuaries, and oceans. St. Lucile Press, Delray Beach, Florida.

Pickett, S.T.A. annd P.S. White. 1985. Patch dynamics: a systhesis. Pages 371-384 in The Ecology of Natural Disturbance and Patch Dynamics. Academic Press.

Power, M.E., W.E. Dietrich, and J.A. Finlay. 1996. Dams and downstream aquatic diversity: potential food web consequences of hydrologic and geomorphic change. Environmental Management 20:887-895.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A distrubance-based apprach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium 17:334-349.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun. 1997. How much water does a river need. Freshwater Biology 37:231-249.

Richter, B.D., J.V. Baumgartner, D.P. Braun, and J. Powell. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research and Management 14:329-340.

Rood, S.B. and J.H. Mahoney. 1990. Collapse of riparian forests downstream from dams in western praries: probable causes and prospects for mitigation. Environmental Management 14:451-464.

Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology, Colorado, pp. 347.

Stanford, J.A., J.V. Ward, and B.K. Ellis. 1994. Ecology of the alluvial aquifers of the Flathead River, Montana. Pages 367-390 in Gilbert, J., D.L. Danielopol, and J.A. Stanford, eds. Groundwater Ecology. Academic Press, San Diego, Ca.

Stromberg, J.C. and D.T. Patten. 1992. Mortality and age of black cottonwood stands along diverted and undiverted streams in the eastern Sierra Nevada, California. Madrono 39(3):205-223.

Walker, L.R., J.C. Zasada, et al. 1986. The roloe of life history processes in primary succession of an Alaskan floodplain. Ecology
67:1243-1253.

Ward, J.V. and N.J. Voelz. 1994. Groundwater fauna of the South Platte River System, Colorado. Pages 391-425 in Gilbert, J., D.L. Danielopol, and J.A. Stanford, eds. 1994. Groundwater Ecology. Academic Press, San Diego, Ca.

Warner, R.E. 1981. Structural, floristic, and condition inventory of Central Valley riparian systems. Califnira Riparian Systems Conference, University of California, Institute of Ecology.

Williams, G.P. and M.G. Wolman. 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286.

Williams, J.G. 1995. Report of the special master for water years 1990-1993, EDF v. EBMUD, Alameda County Superior Court Action 425955.

Wootton, J.T., M.S. Parker, and M.E. Power. 1996. Effects of disturbance on river food webs. Science 273:1558-1561. t

Central Valley Riparian Vegetation Inventory

Project History

Riparian mapping in the Sacramento Valley has been an ongoing process. The California Resources Agency's Sacramento River Atlas project began in 1975 and was published by the Department of Water Resources in 1978. "The Central Valley Riparian Mapping Project," presented at the California Riparian Systems Conference, University of California Davis, September 1981 (published in "California Riparian Systems: Ecology, Conservation, and Productive Management," edited by Richard E. Warner and Kathleen M. Hendrix, University of California Press, Berkeley, 1984), was the first attempt at large-scale mapping of riparian vegetation for the entire Central Valley. Since 1991, the focus has been on tracking riparian loss along the mainstem of the Sacramento River.

The Sacramento River Stream Corridor Protection Program (stream corridor mapping) began in 1991 as an effort to work cooperatively with local governments and state resources agencies to develop a mechanism to protect the biological and water quality values associated with riparian habitats. Specific objectives for the mapping project included:

a. identifying resources needing protection,
b. identifying the location of critical resources by mapping riparian vegetation,
c. creating a pro-active process within existing planning and building departments of local governments to inform local developers of requirements in order to protect resources along stream corridors, and
d. providing adequate information that would enable developers to incorporate protection measures into proposed developments.

The stream corridor mapping effort began in southern Shasta County using Sacramento River Fisheries and Riparian Habitat Management Program (SB 1086) funds. Ultimately, using a multitude of funding sources from agencies including the California Department of Water Resources, California Department of Fish and Game, U.S. Bureau of Reclamation, and CALFED, this effort included all major riparian streams in the Sacramento Valley.

The stream corridor mapping effort was the first Sacramento River effort to take advantage of geographical information system (GIS) technology. Maps were digitized at large scale so that local government and watershed planning groups could utilize the information. Using advanced technologies as they became available, the goal of the stream corridor project program was to develop a baseline GIS on the river that could be utilized and overlaid with future mapping efforts. The riparian vegetation coverage developed in this program is an integral part of the Sacramento River GIS developed by the California Department of Water Resources. It is also included as a foundation layer in virtually all locally based watershed-planning efforts in the northern Sacramento Valley.

The mapping process developed by the Geographical Information Center at California State University, Chico for the stream corridor mapping effort should be used as a model baseline for any Central Valley monitoring effort. While the mapping was a seven-year effort and only covered areas in the Sacramento Valley, it is the first time that large-scale riparian mapping has been attempted along such a large extent of the Sacramento River watershed.

Mapping efforts in the stream corridor mapping project include all tributary streams in the northern Sacramento Valley. While these efforts capture 100% of the riparian resource, they also require a large expenditure of funds and result in a large number of unusable aerial photographs. Future efforts should concentrate on flying individual streams. This will be extremely important in the San Joaquin Valley areas.

Interpretation of Riparian Vegetation

Riparian mapping is dependent on the availability of high quality, large-scale aerial photography. The identification of representative natural communities requires that the interpreter become familiar with known features on many photographs, so that the characteristic clues of shape, size, tone, pattern, shadow and texture become automatically associated with a particular natural community type. With practice, the interpretor can use key characteristics from known regions to determine chracteristics in unknown areas.

While the stream corridor maps were developed using false color infrared aerial photography, the current film of choice is true color. Interpreters tend to prefer the greens found in traditional color film to the magenta hues found in the infrared format.

Stream corridor mapping will be done with color aerial photography flown at the scale of 1"=1000' (RF 1:12,000). These scales enable interpretation using the California Native Plant Society's (CNPS) classification system, which is currently the most commonly used system in the state.

Photography will be flown with a 60% forward overlap and 30% sidelap. This enables the interpreter to make accurate interpretations of riparian vegetation by viewing aerials in 3D using a stereoscope.

While riparian boundaries are discernable on stereo pairs using a stereoscope, mapping will be done over digital orthophotographs. Digital orthophotographs are developed using scanned aerial photography and ground control points. Orthophotography software packages use a series of carefully spaced camera and ground control measurements to three dimensionally stretch the image into an orthophoto.

Digital images have map coordinates as do any map overlays produced from the data. As a result, interpreted riparian information can be overlaid with a base map to add road and place locations.

Survey control data is collected for the orthophoto conversion process using a global positioning system (GPS). A minimum of three reference points (typically six) per air photo are needed, evenly distributed throughout the mapped area. Repetition is allowed given the fact that photography has a substantial overlap.

Digital orthophotographs will be developed using software that can be exported as controlled TIFF's into ArcView 3.1 GIS software. Mapping overlays will be developed as overlays to the controlled orthophotos. Because they are photomaps, maps created on the orthos become maps that will stand alone as riparian overlays.

The resolution of the air photo scanning effort affects the final outcome and enlargement capability of the digital orthophotographs. Scans with high resolutions (25 microns) are preferred because picture element (pixel) sizes go down (a pixel is the size of the smallest visible unit on a digital photograph). A 25-micron (approximately 1,000 dpi) scan of a properly scaled aerial photograph will result in a nominal pixel size of 1 foot or smaller. A pixel size of 1 foot means that each dot on the scanned image represents a 1 square foot area on the ground. This means that the image can be enlarged significantly on screen before resolution is lost (i.e., more detail).

Working digitally on-screen gives the interpreter the ability to zoom in and out in order to obtain fine detail or obtain a more regional perspective where needed. As pixel sizes go down file sizes go up. Therefore, the advantages of high resolution have to be weighed against the processing delays that will be experienced when using digital orthophotography. Also, large file size means that only people with large processors and lots of computer RAM have access to scans and final products (orthophotos).

A compromise would be to do the original scanning at higher resolutions but provide degraded orthophoto images in the 400 dpi range for general distribution. The difference between files of 40 and 300 megabytes can represent significant timesaving in processing large images and will provide access to most anyone with an off-the-shelf personal computer.

Riparian Mapping

While interpreted natural community and riparian boundaries will be identified on digitized orthophotography, the actual photo interpretation will be done on-screen using overlays in ArcView, a state-of-the-art GIS software developed by Earth Systems Research Institute (ESRI) of Redlands, California. The advantages of digital output are:

a. digital maps can be plotted in quantity and at any time,
b. digital information can be easily updated and changed as conditions change, and
c. using GIS software, digital information can be overlaid and compared with future mapping efforts.

ArcView files are convertible to any standardized GIS or AutoCAD file format. Because digital orthophotos have registered ground control, overlaid riparian polygons also have map coordinates. Because these map coordinates have scale, it is possible to generate area statistics on polygoned riparian areas. Additionally, overlays can be brought into other registered GIS map coverages.

Mapping units should include developing a set of base data (roads, place locations, etc.). To date, the best overall data available includes a combination of enhanced 1'=2000' (RF 1:24,000) U.S. Census TIGER road files and U.S.G.S. digital line graph base information. Information is projected to Universal Transverse Mercator (UTM) –meters. Due to file sizes, roads are separated and edited by hierarchical need.

Polygons

For the purposes of this project, a polygon is a multi-sided figure representing an area on a map. Polygon mapping involves drawing lines completely around a feature; hence, a polygon has an area associated with it. Polygons are the preferred method of delineating natural community classes because areas can more easily be divided into aerial units and measured for quantitative purposes. Disadvantages of using polygons occur when features are very small (approaching or exceeding minimum mapping areas) or very narrow such as may occur on some reaches of smaller tributaries included in this program. While line and point mapping can be used effectively to delineate features which are very narrow (lines) or very small points, both of these techniques suffer from the inability to assign areas to them within the polygon. For this reason, in certain instances, vegetation classification may need to be generalized and grouped as opposed to showing all communities present along these narrow stretches.

The narrow nature of the plant communities being mapped here presents some special cartographic difficulties. While most vegetation mapping establishes a minimum polygon size that reflects the space needed to place an identifying symbol within the polygon, it is expected that symbols identifying long narrow natural communities will need to be placed outside of the polygon in a few areas.

Combining Attributes

Polygons will be labeled using the California Native Plant Society's classification system. However, the interpretation process will allow for the classification of riparian vegetation types based on an older system developed within the California Department of Fish and Game's Nongame Heritage Program (*Preliminary Description of the Terrestrial Natural Community of California* prepared by Robert Holland) and the CNPS system. Therefore, natural communities designations using the CNPS system can be "cross walked" into the previous classification system. This dual classification process is essential to maintain continuity with previous surveys.

Ground Truthing

Throughout the project, it is important to ascertain the classification accuracy. To make certain that proper vegetation classification will be made throughout the study area, training sites need to be selected in order to correlate color, patterns and tones of specific sites on the color infrared photos and the vegetation on the ground. This ground verification or "ground truthing" is used to test the accuracy of the classification done by the photo interpretation team for the various types of vegetation. Specific classification types that create difficulties from a photo interpretation viewpoint need to be identified and special efforts made to address these accurately. Remote sensing and photo interpretation techniques can only provide accurate map data when coupled with suitable ground data. Consequently, ground truthing checks will be conducted periodically using randomly chosen sites to confirm mapping accuracy.

Using Riparian Maps - A Process

This project is a planning effort whose goal is to protect the remaining riparian resources in the Central Valley from the loss that has been historically occurring as development continues to occur within the area. The final products will be incorporated into future planning documents and used as a gauge to monitor recent restoration projects and track riparian loss.

Aerial flights and riparian mapping will continue over time and are scheduled to occur at five-year intervals. This will enable agencies to monitor reclamation and restoration efforts. Exceptions include event driven mapping, which would be triggered by a one-in-ten or greater magnitude flood event.

Orthophotos and riparian maps aid in watershed mapping efforts. Maps give an inventory of the remaining resource over time. Digital orthophotos become a photographic record at a particular time and offer many uses to watershed planners.

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