Exhibit AR-11

San Joaquin Basin Ecological Flow Analysis

Prepared for the

Bay -Delta Authority

by the

Natural Heritage Institute

August 2003

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Berkeley, California

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Chapter 1. Executive Summary

1.1 INTRODUCTION

The hydrology of the San Joaquin River Basin system has been significantly altered by dams and diversions, which supply water to support a multi-billion dollar agricultural industry in the San Joaquin Valley. The CALFED Strategic Plan prioritizes re-establishment of more dynamic, natural high-flow regimes in regulated rivers to meet restoration objectives, and the CALFED Ecosystem Restoration Plan (ERP) emphasizes the reestablishment of hydrologic and geomorphic processes associated with high flow events. Specifically, the ERP calls for reestablishing hydrologic regimes that shape and maintain channel, floodplain, and riparian habitats. Before dams sharply altered the hydrology of the San Joaquin Basin Rivers, large flow events annually mobilized the river beds - cleansing gravel for spawning salmon and rejuvenating riparian forests along the bank and floodplain. Native fish and other aquatic species adapted their life cycle to these annual hydrologic patterns and exploited the diversity of physical habitats created by the ever changing channel.

Today, however, most of the native aquatic species of the San Joaquin Valley are extinct, extirpated, endangered, or declining. The dynamic alluvial rivers that once supported them are now fossils – static channels, relicts of the past, that seldom change except during infrequent large floods when the upstream reservoirs spill. To be certain, altered hydrology is not the only culprit in the decline of these river ecosystems. A host of other human perturbations including vegetation clearing for agriculture, over fishing, exotic species introductions, instream aggregate mining, urbanization, and levees for flood control have all contributed to their demise. But the dramatic reduction in the frequency of large flow events that historically mobilized the bed and inundated the floodplain is by definition the reason the bed seldom mobilizes and the floodplain rarely floods. To the extent that these processes are important for creating habitats for native aquatic species, their elimination has certainly contributed to the decline of these species.

This study assumes that reestablishing a more natural flow regime is the most ecologically promising approach for restoring regulated rivers, but we acknowledge that it may not be the economically preferred approach. Other analyses and restoration efforts such as the Merced River Restoration Plan have focused on another approach – scaling down the channel dimensions and the size of bed material to reestablish geomorphic and riparian function under the existing regulated regime. Although this approach will require less water and changes in reservoir reoperations, it will entail a significant investment in channel reconstruction. The channel dimensions and geomorphology of these rivers were formed by the natural hydrology, and efforts to reshape the channel to function geomorphically under the existing regulated hydrology may not be physically possible. On the other hand, human alterations to the channel, most notably from aggregate mining have already changed the dimensions of the channel to the extent that simply reestablishing the natural hydrograph may not be sufficient either. Ultimately, some combination of both approaches will be necessary to restore the rivers of the San Joaquin Basin. While other efforts have focused on rebuilding the channel and floodplain habitats to function under a highly artificial flow regime, this study has focused on restoring a more natural hydrologic regime to improve highly degraded channel and floodplain habitats.

Reestablishing a more natural hydrologic regime on the San Joaquin Basin Rivers will entail dramatically altering flow release patterns from a mammoth system of reservoirs designed and built to provide water for the worlds most productive agricultural economy. The flows necessary to mobilize the channel bed and recruit riparian vegetation downstream of the reservoirs are often 1- 2 orders of magnitude greater than typical reservoir releases. In the past, resource managers have been reluctant to even attempt to quantify, let alone mandate, the flows necessary to reestablish geomorphic and ecological processes in the San Joaquin Basin because of a presumption that it is not economically feasible to re-operate the reservoir system without harming the basins agricultural economy. Instead managers, under the mandate of state and federal laws, have focused their efforts on establishing minimum instream flows to sustain remnant populations of salmonids. While these flows are undoubtedly an improvement on the once dismal flow conditions for native salmonids, they do not remedy the underlying ecological degradation precipitated by radical changes to the natural hydrology from upstream reservoir operations.

1.2 PURPOSE AND OBJECTIVES

The purpose of this study is to evaluate the feasibility of restoring ecological and geomorphic flows on the rivers of the San Joaquin Basin without reducing water supply deliveries to existing water users. Our thesis is that reservoirs operated today for a limited set of water supply and flood control objectives could be reoperated to achieve newly defined ecological objectives without compromising existing objectives. This opportunity was recognized by the authors of CALFED's Strategic Plan for Ecosystem Restoration:

> "There is underutilized potential to modify reservoir operations rules to create more dynamic, natural high-flow regimes in regulated rivers without seriously impinging on the water storage purposes for which the reservoir was constructed. Water release operating rules could be changed to ensure greater variability of flow, provide adequate spring flows for riparian vegetation establishment, simulate effects of natural floods in scouring riverbeds and creating point bars, and increase the frequency and duration of overflow onto adjacent floodplains"

Clearly defining this new set of ecological objectives and estimating the flows necessary to achieve them is the first step toward evaluating the feasibility of restoring these flows. The biological and physical processes that support natural riverine functions are complex and numerous rendering the task of defining environmental flow regimes enormously difficult. For the purpose of defining an environmental flow regime and assessing the feasibility of attaining it, we have identified a simplified but broad set of water intensive ecological objectives that best capture the full range and magnitude of environmental flow requirements in the San Joaquin Basin. These objectives include:

- Geomorphic Processes: sediment transport, channel geomorphology, floodplain inundation.
- Riparian vegetation: cottonwood recruitment and maintenance flows
- Fall Chinook and Steelhead: stream temperatures and adequate flow for various life stages.

This study focuses on the *magnitude of flows* necessary to replicate key ecological and geomorphic processes, but also considers the flows necessary to provide suitable conditions for various life stages of Chinook salmon and steelhead. This study does not identify specific population targets for salmonid restoration, nor does it address important non-flow objectives such as habitat area required for restoration of target species or augmentation of coarse sediment supplies necessary to restore full geomorphic structure and function. Rather this study focuses on magnitude, pattern, and quantity of water necessary to restore ecological functions assuming that adequate physical habitat exists or will be created to complement a suitable environmental flow regime. The rationale of this focus is to identify a hypothetical environmental flow regime for the purpose of evaluating whether it is possible to reestablish ecological and geomorphic flows on the rivers of the San Joaquin Basin without reducing water supply deliveries to existing water users.

Although this study identifies hypothetical restoration flow regimes for the San Joaquin River and its tributaries, we recognize that the most reliable method for developing a restoration flow regime is through a long-term adaptive management program including a series of trials that test the effectiveness of various flow prescriptions. The hypothetical flow regime that we have developed and identified in chapter 9 is imperfect, but is serves as a reasonable starting point for evaluating the feasibility of reoperating reservoirs without impacts on existing reservoir functions. The purpose of the hypothetical flow regime is to:

- Test the feasibility of reoperating the terminal reservoirs in the San Joaquin Basin without diverting additional water away from agriculture, and
- Develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the rivers of the San Joaquin Basin.

The assumptions and uncertainties associated with the hypothetical flow regime are as important as the flow regime itself. To cost effectively achieve restoration, managers will ultimately need to test these assumptions and limit the uncertainties through an adaptive management program consisting of a combination of modeling, pilot flow studies, model calibration, and long-term restoration implementation.

1.3 ENVIRONMENTAL SETTING

The San Joaquin River Basin drains 13,513.5 mi^2 (35,000 km^2), along the western flank of the Sierra Nevada and eastern flank of the Coast Range in the Central Valley of California. The Merced, Tuolumne, and Stanislaus rivers are the three major tributaries that join the mainstream San Joaquin from the east before it flows northward into the Sacramento-San Joaquin Delta (Figure 1.1). The four principal rivers of the San Joaquin Basin and their watersheds share relatively geologic, climactic, hydrologic, and geomorphic characteristics. These similarities have resulted in relatively similar patterns of vegetation and aquatic species. In this document, we refer to the San Joaquin River from Friant Dam to the confluence with the Merced River as the middle San Joaquin River. The lower San Joaquin refers to the San Joaquin River from the confluence with the Merced to the Delta.

There are over 80 dams with a total storage capacity of over 7.7 million acre-feet on the San Joaquin, Merced, Tuolumne, and Stanislaus Rivers. Combined, these facilities have the capacity to capture and control the entire average annual yield of the rivers they dam for the primary purposes of water supply, flood control, and hydroelectric power generation. This chapter provides and overview of the history, location, capacity, and operation of the dams and diversions on these four rivers.

Since 1940, salmon populations have plummeted in the San Joaquin Basin. This period coincides with the construction of large dams on all the major dams in the basin. As discussed in previous chapters, these dams have drastically altered the downstream flow regimes – particularly the peak flow events that shaped channel habitats and the high spring flows that recruited riparian vegetation and maintained cold water temperatures during the juvenile outmigration period. During wet periods such as the mid ninety eighties, salmon populations rebound significantly suggesting that increased stream flow results in larger salmon populations. But changes in streamflow conditions from large dams and the direct impacts on salmon and salmon habitat is only part of a larger story of ecological change to the rivers of the San Joaquin basin over the last century.

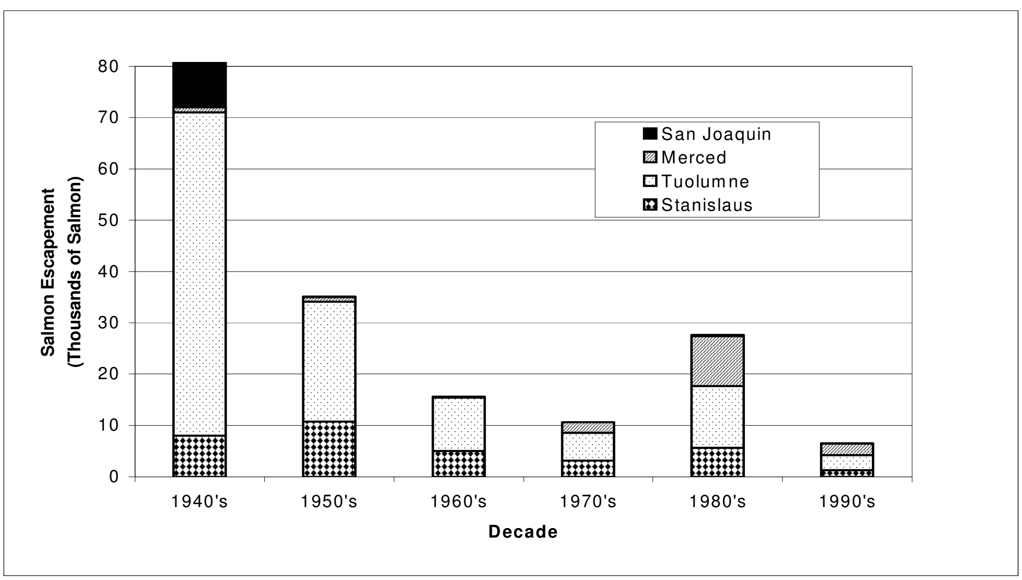


Figure 7.1. Average Annual Salmon Escapement in the San Joaquin Basin by Decade, 1940 to present. Data: CADFG 1961, 1994, AFB ADM. Rpt., Mills & Fisher. 1940 Stanislaus and Merced, and 1941 Stanislaus, Tuolumne, and Merced are partial counts.

In response to the decline of salmonid populations in the San Joaquin Valley, resources managers, have developed and mandated minimum instream flow requirements on tributaries in the San Joaquin Basin. Nearly all of these efforts have focused on establishing instream flows for anadromous fish, but none of them have specified flow regimes to achieve geomorphic or riparian vegetation objectives. Existing flow requirements bare little resemblance to the natural hydrologic pattern and in general were developed without a clear understanding of the historical hydrologic patterns and their role in shaping aquatic and riparian habitats.

1.4 MEASURING HYDROLOGIC CHANGE AND QUANTIFYING NATURAL FLOW REGIMES

This study emphasizes the analysis of historical hydrologic patterns. An evaluation of historical hydrology and habitat conditions can provide a useful reference point for identifying ecosystem restoration goals, but it is simply unrealistic to assume that it is possible to restore historic conditions in highly altered systems such as the San Joaquin. Nevertheless, analyses of historical hydrologic data is useful for describing natural patterns and identifying potential links between hydrology and the requirements necessary to maintain species and precipitate key processes.

We utilized two different analytical approaches, the Indicators of Hydrologic Alteration (IHA) and the Hydrograph Component Analysis, to quantify and characterize hydrologic patterns in the pre and post-dam era. The IHA method evaluates changes in 33 biologically significant hydrologic parameters. The HCA evaluates significant changes in components of the annual hydrograph. Together these analyses provide valuable insights on each tributary and the San Joaquin Basin as a whole. They provide a measure of hydrologic changes caused by dams and diversions and provide insight into how these regulated hydrographs could be altered to restore valuable geomorphic processes, riparian vegetation and salmon.

1.5 DEVELOPING AN ENVIRONMENTAL FLOW REGIME FOR THE SAN JOAQUIN BASIN

Many previous flow restoration efforts in the San Joaquin Basin and elsewhere have focused on the flow requirements of specific species often at the direction of a court or legislative body. These efforts have been subjected to criticism of being species specific to the neglect of the larger ecological processes that are needed to maintain habitat for the target species. In response to the criticisms of species specific efforts, many programs including CALFED have embraced a more holistic approach advocating "ecosystem restoration" and reestablishment of ecological, geomorphic, and hydrologic processes. Although this new interest in ecosystem processes may be a step forward, there is a tendency for it to stall-out in vague goal statements about ecosystem health and processes that do not provide the specific guidance necessary to prescribe a restoration flow regime. Efforts to provide more specific measurements of ecosystem health run the risk of bogging down in long lists of ecological indicators, and indicators or processes for one river segment may be different than indicators for a downstream segment.

In other parts of the world, resource managers have been grappling with the question of how to identify the environmental flows necessary to sustain fisheries and ecological processes on regulated rivers. Over the past five decades, the development and application of environmental flow methodologies (EFMs) has rapidly progressed, as a means to help sustain or restore natural aquatic functions and ecosystems in the face of increasing demands for limited water resources. EFMs are science-based processes for assessing and/or recommending instream flows for regulated rivers. Their purpose may be as general as maintaining a healthy riverine ecosystem or as specific as enhancing the survival of targeted aquatic species. This document provides a literature summary on more than 200 EFMs, recorded worldwide. These include various modifications and hybrids of some commonly applied methods, site-specific approaches with limited applications, and procedures that are no longer in use. In actuality there are only a few dozen EFMs that are still widely applied. They can be divided into four major categories: 1) hydrological, 2) hydraulic rating, 3) habitat simulation, and 4) holistic methodologies.

We have employed a version of the holistic approach practiced in South Africa and Australia to identify an environmental flow regime for the San Joaquin Basin rivers. This approach relies heavily on hydrological evaluations, previous studies, and expert opinion to estimate environmental flow requirements and develop a long-term adaptive management plan for implementing and refining an environmental flow regime over time. The results of the holistic approach provide a framework for increasing knowledge regarding the relationship between flow and environmental objectives and refining water management practices over time. The output of the holistic method envisioned here provides not only an estimate of environmental flow requirements, but more importantly, an explicit identification of key assumptions and uncertainties that need to be tested overtime to more accurately describe the flow requirements necessary to achieve environmental objectives.

The holistic approach applied in this study consists of the following 6-step process to identify an environmental flow regime:

1. Identify specific environmental objectives (i.e,. target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).
2. Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes.
3. Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.
4. Identify obvious gaps between objective flow requirements and existing flows.
5. Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic

patterns, and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives.
6. Design an adaptive management program to further test and refine environmental flows.

We made two important assumptions in generally applying this method to all four of the major rivers of the San Joaquin Basin.

- Similarities in both the restoration objectives and the hydrologic, geomorphic, and ecological conditions on the Stanislaus, Tuolumne, Merced, and San Joaquin will result in relatively similar prescriptions for environmental management flows.
- The flow necessary to achieve restoration objectives may vary greatly depending on non-flow restoration actions such as improving spawning habitat, reconstructing degraded channel, removing levees to restore floodplain habitat, modifying and screening water diversions, reducing polluted run-off, managing ocean harvest, and other factors. In general, non-flow restoration actions will reduce the amount of water necessary to achieve restoration objectives.

1.6 EVALUATING THE FEASIBILITY OF RESERVOIR REOPERATION

We used the environmental flow hydrograph developed with the method described above to test the feasibility of reoperating the basin's terminal reservoirs. We utilized a spreadsheet accounting model and historical reservoir operations data to game various reoperation strategies with the aim of achieving the environmental flow hydrograph without reducing water deliveries to existing water users. We tested three general strategies under varying conditions, and for various objectives: 1) reshaping the flood hydrograph; 2) reshaping the flood hydrograph and increasing the maximum allowable flood release downstream from reservoirs; and 3) reshaping the flood hydrograph and implementing groundwater banking.

In total, we conducted over 1,150 "runs" encompassing 16 combinations of strategies and conditions on all four tributaries for a 16-20 year time span. The model and our gaming approach, while robust and appropriate for a screening level analysis, operated on the following assumptions: 1) We assumed historical reservoir operation and irrigation use patterns that have now been superceded by new operation standards; 2) Gaming benefited from year-round perfect foresight whereas historical operations decisions on were based on snow pack estimates available March 1; 3) Scenarios were gamed on a year to year basis (with one exception), which, while reducing the accumulation of error, ignored the multi-year benefits of groundwater banking; and 4) success was determined by restoring reservoir storage levels to historical levels within 12-14 months which assumes that historic levels were themselves optimal and may have resulted in overly conservative conclusions.

The screening-level analysis concluded that:
- Creating or augmenting existing high flows to increase the frequency of meeting geomorphic and riparian flow targets was possible without reducing deliveries to existing water users.

- The short, high magnitude flows, necessary for geomorphic processes and which generally occurred in the winter and spring are much easier to achieve than the lower magnitude yet longer, sustained flows necessary for temperature, outmigration, or attraction objectives that occur in the spring, summer, and early autumn when irrigation demands on the river are highest. As a result, we were unable to meet ambitious fish flow targets that required prolonged flows without significant water supply impacts.
- It is possible to increase the frequency of meeting floodplain inundation flow targets on all four tributaries without increasing the maximum allowable flood release or implementing groundwater banking.
- It is possible to increase the frequency of meeting bed mobility flow targets on the Merced, Tuolumne and Stanislaus Rivers without increasing the maximum allowable flood release or implementing groundwater banking. On the San Joaquin, the maximum allowable flood release is too restrictive to increase the frequency of meeting bed mobility flow targets.
- On all four tributaries, the maximum allowable flood releases, not water supply obligations, prevent increasing the frequency of meeting the channel migration flow targets.
- Flexibility in reoperation is, in part, a function of storage. New Melones Reservoir on the Stanislaus River has over 2.4MAF of storage space and is most flexible in reoperation. Millerton Reservoir on the San Joaquin has only 520TAF of storage space and operations are extremely constrained as a result.
- In the single game that involved multi-year gaming, groundwater banking was able to greatly contribute to lower flow, spring fish flow targets.
- Target flows for reoperation must be flexible enough to accommodate intra-year variability in flows. Reoperation should focus on restoring hydrograph components when it is possible and at appropriate frequencies rather than meeting all objectives for a given year-type (e.g. wet year flow targets) when those years occur.

1.6 CLOSING THE GAP: COST EFFECTIVE STRATEGIES FOR ACHIEVING ENVIRONMENTAL FLOW

Enhancing instream flows for the environment need not require costly water purchases or contentious regulation. Changes in reservoir operations can significantly improve environmental flow conditions without reducing water deliveries for existing water users. Reservoir operation is more effective for achieving low frequency, relatively short duration events such as geomorphic flows or infrequent riparian recruitment flows (once every 5-10 years). These objectives can be achieved without significant water supply impacts by reshaping long duration wet year events. Frequent, longer duration flows such as improved summer base to maintain cool water temperatures are actually more difficult to achieve without water supply impacts then geomorphic objectives, because they 1) must occur annually to yield significant benefit, 2) they draw the reservoir down when demand is highest, and 3) they persist for several months resulting in a large volume of water.

When assessing the water supply costs of increasing instream flows, it is important to realize that simply increasing reservoir releases for environmental flows increases total yield to the extent that environmental flows are counted as yield. When water releases from the reservoir are increased for environmental purposes, the average reservoir level declines increasing the reservoirs' capacity to capture water in subsequent flood events that would have otherwise spilled. This phenomena is particularly true for reservoirs that spill frequently such as Millerton Lake. A recent analysis of water supply costs for restoration of the San Joaquin River concluded that somewhere between one quarter and one half of all water released for restoration was eventually recouped by increase spill capture in subsequent flood events. Thus, water users should not be compensated for water released, but only for water lost as a result of increased instream flows.

Although reoperating reservoirs for enhanced instream flows does not always require reducing deliveries to existing users, reoperation of reservoirs does increase the risk that existing users will face a shortage under certain conditions. If reservoir operators release a large peak flow for geomorphic purposes on the assumption that the reservoir is likely to spill and then that assumption does not prove out, there will be less water in the reservoir for other users. Thus, reoperating reservoirs for ecological objectives is as much a risk management problem as a water supply problem. In this case, government sponsored programs to increase flows through reservoir reoperation should focus on minimizing these risks through improved forecasting and statistical projection as well as by compensating water users for the risk assumed – not for the increased water released.

Groundwater banking is a promising strategy for reducing risk associated with reoperating reservoirs more aggressively to achieve instream flow objectives. Groundwater banking can help achieve ecological flows both by increasing the total yield of water captured and by providing a back-up water supply in drier years and seasons when reservoir releases for ecological flows reduce surface water availability. Water captured in wet and above normal years can be held over for use in drier years when water is scarce. In the event that increased reservoir releases results in surface water shortages during dry periods, banked groundwater can be used to reduce the risk that water users are forced to ration limited supplies.

Lastly, it will not be practical or feasible to achieve some important ecological objectives without expanding floodway capacity and changing existing flood rules. In particular certain geomorphic objectives such as precipitating channel migration and bed scour can only be achieved by changing existing flood rules currently dictated by the Army Corps of Engineers. On the San Joaquin Basin Rivers, the frequency of large geomorphic flows is limited not by the availability of water, but rather by Army Corps flood control regulations that specifically limit overbank flows to protect property or structures from inundation or damage. Expanding the floodways may require acquisition of flood easements or fee title along the entire course of a stream. Development of floodway corridors would be beneficial not only for the ecosystem, but also for reducing flood damage, increasing carryover storage in existing reservoirs, and recreation. Increasing the maximum allowable flood release is necessary to achieve these objectives. Increasing the maximum allowable flood release may actually reduce the frequency of catastrophic flooding and increase total water supply yield by increasing reservoir flexibility.

Chapter 2. Ecological Objectives

The purpose of this study is to evaluate the feasibility of restoring ecological and geomorphic flows on the rivers of the San Joaquin Basin without reducing water supply deliveries to existing water users. Defining these processes and estimating the flows necessary to restore them is the first step toward evaluating the feasibility of restoring these flows. The biological and physical processes that support natural riverine functions are complex and numerous rendering the task of defining environmental flow regimes enormously difficult. For the purpose of defining an environmental flow regime and assessing the feasibility of attaining it, we have identified a simplified but broad set of water intensive ecological objectives that best capture the full range and magnitude of environmental flow requirements in the San Joaquin Basin. These objectives include:

- Geomorphic Processes: sediment transport, channel geomorphology, floodplain inundation.

- Riparian vegetation: cottonwood recruitment and maintenance flows

- Fall Chinook and Steelhead: stream temperatures and adequate flow for various life stages.

These objectives are consistent with the objectives of the CALFED ecosystem restoration plan (ERP) and the federal Anadromous Fisheries Restoration Plan (AFRP) the Central Valley Project Improvement Act, and other restoration programs previously initiated in the San Joaquin Basin.

2.1 CALFED AND AFRP OBJECTIVES

The state and federal governments have already identified a suite of ecological objectives for the San Joaquin River and its tributaries. These objectives are identified in the Ecosystem Restoration Plan developed by CALFED and the Anadromous Fisheries Restoration Plan developed by the US Fish and Wildlife Services. Table 2.1 summarizes the objectives of these planning efforts and identifies the corresponding NHI objectives identified for this feasibility study. The ERP emphasizes reestablishment natural hydrologic and geomorphic processes, but does not identify the magnitude or quantity of flows necessary to restore these processes. In contrast the AFRP emphasizes flow conditions necessary to support target populations of anadromous fish species. This study focuses on the *magnitude of flows* necessary to replicate key ecological and geomorphic processes, but also considers the flows necessary to provide suitable conditions for various life stages of Chinook salmon and steelhead. Unlike the AFRP, this study does not identify specific population targets for salmonid restoration. It also does not address non-flow objectives identified in the ERP such as habitat area required for restoration of target species or augmentation of coarse sediment supplies necessary to restore full geomorphic structure and function. Rather this study focuses on magnitude, pattern, and quantity of water necessary to restore ecological functions assuming that adequate physical habitat exists or will be created to complement a suitable environmental flow regime. The rationale of this focus is to identify a hypothetical environmental flow regime for the purpose of evaluating whether it is possible to reestablish ecological and geomorphic flows on the rivers of the San Joaquin Basin without reducing water supply deliveries to existing water users.

2.2 ECOLOGICAL OBJECTIVES FOR THIS STUDY

For purposes of simplification, this study has intentionally focused on a limited set of ecological objectives that require flow conditions far different then the post-dam regulated flow regime currently provides (Table 2.2). These simplified objectives were selected to emphasize the high flow events necessary to initiate geomorphic processes, recruit riparian vegetation, reestablish connectivity between the channel and the floodplain, and provide adequate water temperatures for salmonids – particularly in the late spring when rising ambient temperatures require relatively high flows to maintain suitable water temperatures for outmigrating salmon. Flow regulation by dams on the San Joaquin Basin rivers have greatly reduced the high magnitude flows necessary to maintain these important ecological processes. By focusing on the ecological objectives associated with the high flow components of the hydrograph that have been most dramatically altered by regulated releases from the upstream reservoirs, we are best able to quantify the major adjustment to the existing flow regimes necessary to reestablish ecological and geomorphic processes in the San Joaquin Basin.

Although these objectives do not encompass all of the flow related considerations that must be addressed to provide for restoration of the San Joaquin Basin Rivers, they do capture and reflect the magnitude and general character of hydrologic changes necessary to restore a broad range of processes and species. In all likelihood, reestablishing flows to achieve this limited set of objectives will significantly contribute to attainment of other objectives. In recognition that restoration of high flow events for riparian and geomorphic processes do not capture the seasonal flow regimes necessary for restoration of anadromous salmon restoration, we have also attempted to identify the flow related objectives necessary for the freshwater life stages of Chinook salmon and steelhead in order to identify a hypothetical annual hydrograph that would satisfy the salmonid objectives identified in the ERP and the AFRP.

7.2.1 Geomorphic Process Objectives

The objectives for geomorphic processes focus on obtaining the flows necessary to mobilize coarse sediment on riffles, scour the bed, intitiate channel migration, inundate the floodplain, and deposit fine sediments on the flood plain. Mobilizing coarse sediment on riffles will periodically flush fine sediments from the gravels and generally looses embedded gravel riffles in order to provide better habitat for spawning salmonids and for more diverse and robust macro-invertebrate populations. Periodically scouring the bed of alluvial reaches will excavate pools for adult holding and juvenile rearing of salmon, transport gravel from riffles and pools to downstream riffles, and create a more complex and diverse channel morphology which in turn will provide a diversity of habitat types necessary for the various life stages of a variety of target species. Initiating channel migration will facilitate the succession of riparian vegetation types creating a mosaic of age classes and habitat types which in turn will provide for a diversity of riparian fauna. More regular inundation of the floodplain surfaces will provide for predator free rearing habitat for juvenile salmons, promote nutrient exchange between the river channel and the floodplain, and provide floodplain habitat for avian species and herptofauna.

7.2.2 Riparian Vegetation Objectives

The objectives for riparian vegetation focus on flows necessary for recruitment of cottonwood (Populus fremontii). We recognize that cottonwoods are only one of several important riparian species that should be restored to create a fully functional riparian ecosystem, and that the flow requirements of other species differ from the flow requirements necessary to recruit cottonwood. We opted to focus solely on the flows necessary to recruit cottonwoods, because the flow requirements of cottonwood recruitment better understood then those for other species and are generally more difficult to achieve than for the more common willow species. Cottonwoods generally colonize higher on the channel bank than other species and therefore require a higher magnitude flow to enable establishment at the proper elevation on the bank. Cottonwoods recruitment also occurs during a narrow window in the late spring when flows on the San Joaquin Basin Rivers have been greatly reduced due to stream flow regulation by upstream dams. Willow species, in contrast, generally establish lower surfaces on alluvial bars and during longer recruitment periods. As a result, recruitment of willow species is less challenging to achieve, and thus willow species are far more abundant than cottonwoods under the regulated flow regimes characteristic of the San Joaquin Basin Rivers. We did not consider flow regimes necessary to recruit several species of riparian vegetation that commonly occur on floodplains such as valley oak (Quercus lobata).

Conditions favorable for recruitment of cottonwoods are also likely to result in recruitment of several willow species. Willow seeds that disperse at the same time as cottonwoods will also germinate and establish coincidentally with cottonwoods. Furthermore, the gradually reclining spring and summer hydrograph necessary for establishment of cottonwood seedlings will also provide suitable conditions for recruitment of willows seeds that disperse after the primary cottonwood recruitment period. As cottonwood establishment flows gradually recede they will provide moist nursery sites on sand and gravel bars favorable for germination and growth of willow seedlings well into the summer months. During drier years when flows do not occur during the cottonwood seed release period or are not sufficient to establish cottonwoods on higher bank surfaces, they may still frequently produce wetted surfaces favorable for willow species that disperse seeds before or after the cotton germination period.

Flows favorable to establishment of cottonwood seedlings are also likely to provide excellent flow and temperature conditions for juvenile Chinook salmon during the late spring period when they are highly vulnerable to mortality from high water temperatures or entrainment by water diversions in the lower San Joaquin River and the Delta. As discussed in chapter 3 of this report, Chinook salmon are highly sensitive to mortality from elevated water temperatures during smoltification when they are migrating out of the rivers to the Pacific Ocean. The relatively high magnitude flows required for cottonwood establishment during April and May will create lower water temperatures during this critical period. Furthermore, the higher velocities associated with higher stream flows will facilitate juvenile salmon migration from the rivers to the Ocean. The higher velocities combined with higher volumes of streamflow will also reduce the potential for juvenile salmon to be entrained in water diversion structures in the Delta.

7.2.3 Fishery Objectives

Objectives for andadromous salmonids focus on achieving flow conditions favorable to the freshwater life stages of fall-run Chinook salmon, but should also benefit other native fish species. In addition to fall-run, we also considered the requirements of steelhead, particularly where they exceed the flow necessary to support fall-run salmon. On the middle San Joaquin River we considered the flow requirements of spring run salmon due to its historical importance in that reach of river. The most water intensive flow requirement for fall-run salmon, and thus the objective we focused most upon, was obtaining flow levels necessary to maintain adequate water temperature for outmigrating salmon juveniles and smolts in the late spring. For upstream migrating adult salmon, we considered the flows necessary to maintain adequate temperature and passage conditions. For spawning, we relied on previous studies to determine the base flow necessary to support suitable spawning. To facilitate juvenile rearing and growth, we considered a series of pulse flows to repeatedly inundate low-lying flood plains in the late winter and early spring.

With the exception of cool summertime temperatures, we generally concluded that an environmental flow regime designed to meet the life cycle requirements of fall-run Chinook was also consistent with creating suitable flow conditions for spring-run and steelhead. Because both spring-run and steelhead over summer, we also considered the summer time base flows necessary to maintain suitable water temperatures in the stream reaches below the dams. Late winter flood pulses for fall-run salmon rearing would provide adequate flows for upstream migration of adult steelhead. Similarly, higher releases in late spring for fall-run outmigration would probably provide adequate flows for upstream migration of spring-run. Winter and spring release for fall-run outmigration would also be suitable for outmigration of spring-run and steelhead.

Flows suitable for fall-run, particularly an increase in late spring flows, should also benefit a variety of native fish. Higher flows, particularly in May and June will create cooler water temperatures and thus inhibit the reproduction of non-native centrarchids. Since predation and competition from centrarchids is probably a major factor limiting populations of native fish species and herptofauna, disturbing the reproductive cycle of centrarchids should benefit native species.

Table 2.1: CALFED, AFRP, and Other Program Objectives

Tributary	Program/Objective	Corresponding NHI Study Objective
All	**ERPP Strategic Plan**	
	Ecosystem Processes and Biotic Communities	
	Objective 1: Establish and maintain hydrologic and hydrodynamic regimes for the Bay and Delta that support the recovery and restoration of native species and biotic communities, support the restoration and maintenance of functional natural habitats, and maintain harvested species.	Applies to all NHI study objectives
	Objective 3: Rehabilitate natural processes to create and maintain complex channel morphology, in-channel islands, and shallow water habitat in the Delta and Suisun Marsh	Meet or exceed geomorphic flow targets
	Objective 4: Create and/or maintain flow and temperature regimes in rivers that support the recovery and restoration of native aquatic species.	Meet or exceed adult migration baseflow targets, spawning incubation temperature flow targets, and yearling rearing targets for fall-run Chinook
	Objective 5: Establish hydrologic regimes in streams, including sufficient flow timing, magnitude, duration, and high flow frequency, to maintain channel and sediment conditions supporting the recovery and restoration of native aquatic and riparian species and biotic communities.	Meet or exceed geomorphic flow targets geomorphic flow targets
	Objective 6: Re-establish floodplain inundation and channel-floodplain connectivity of sufficient frequency, timing, duration, and magnitude to support the restoration and maintenance of functional natural floodplain, riparian, and riverine habitats.	Meet or exceed geomorphic floodplain flow targets
	Objective 7: Restore coarse sediment supplies to sediment starved rivers downstream of reservoirs to support the restoration and maintenance of functional natural riverine habitats.	Meet or exceed geomorphic sediment transport targets
	Objective 8: Increase the extent of freely meandering reaches and other pre-1850 river channel forms to support the restoration and maintenance of functional natural riverine, riparian, and floodplain habitats.	Meet or exceed geomorphic channel morphology flow targets
	Final Restoration Plan for the Anadromous Fish Restoration Program	
	Improve habitat for all life stages of anadromous fish through provision of flows of suitable quality, quantity, and timing and improved physical habitat.	Meet or exceed all flow targets for fall-run Chinook
	Improve survival rates by reducing or elimination entrainment of juveniles at diversions.	Meet or exceed outmigration flow targets for fall-run Chinook
	Improve the opportunity for adult fish to reach their spawning habitats in a timely manner.	Meet or exceed adult migration and outmigration flow targets for fall-run Chinook
San Joaquin	**Friant NRDC Goal Statement**	

	Restore natural ecological functions and hydrologic and geomorphologic processes of the San Joaquin River below Friant Dam to a level that restores and maintains fish populations in good condition, including but not limited to naturally reproducing, self-sustaining populations of Chinook salmon.	Applies to all NHI study objectives
	ERPP Vol II	
	Ecological Processes, Central Valley Streamflows	
	Target 1: Manage flow releases from tributary streams to provide adequate upstream and downstream passage of fall-run and late fall-run chinook salmon, resident rainbow trout, and steelhead and spawning and rearing habitat for American shad, splittail and sturgeon from the Merced River confluence to Vernalis. (ERPP Vol. II, Page 365)	Meet or exceed adult migration and outmigration target flows for fall-run chinook
	Target 2: Manage flow releases from Friant Dam to Gavelly Ford to maintain sustainable populations of resident native fish. (ERPP Vol. II, Page 365)	Achieve AFRP targets for long term average escapement of fall-run Chinook
	Target 3: Optimize the ecological value of wet year flood releases below Friant Dam (ERPP Vol. II, Page 365)	Applies to all geomorphic flow targets
	Ecological Processes Central Valley Stream Temperatures	
	Target 1: Manage reservoir releases and other factors to provide suitable water temperatures for important resources from the Merced River confluence to Vernalis. (ERPP Volume II, Page 365)	Meet or exceed baseflow targets for migration, spawning incubation temperature flow targets, and yearling rearing flows for Fall-run chinook
	ERPP Strategic Plan, Appendix D	
	No relevant actions or objectives.	
	Final Restoration Plan for the Anadromous Fish Restoration Program	
	Action 1: Coordinate with CDFG and others to acquire water from willing sellers consistent with applicable guidelines as needed to implement a flow schedule that improves conditions for all life stages of San Joaquin chinook salmon migrating through, or rearing in, the lower San Joaquin River. (AFRP, Page 93)	Meet or exceed fall-run chinook and steelhead streamflow targets
	Evaluation 4: Identify and attempt to maintain adequate flows for migration, spawning, incubation, and rearing of white sturgeon and green sturgeon from February to May, consistent with actions to protect chinook salmon and steelhead and when hydrologic conditions are adequate to minimize adverse effects to water supply operators. (AFRP, Page 95)	Meet or exceed fall-run chinook and steelhead streamflow targets
	AFRP Guidelines	
	No relevant actions or objectives.	
Merced	**ERPP Vol. II**	
	No relevant actions or objectives.	
	ERPP Strategic Plan, Appendix D	
	No relevant actions or objectives.	
	Final Restoration Plan for the Anadromous Fish Restoration Program	

	Action 1: Supplement flows provided pursuant to the Davis-Grunsky Contract and FERC license with water acquired from willing sellers consistent with all applicable guidelines or negotiated agreements as needed to improve conditions for all life-history stages of chinook salmon (AFRP, Page 85)	No specific objective, applies to entire study
	AFRP Guidelines	
	Improve attraction flows and provide adequate water temperatures for fall-run chinook salmon migrating into and spawning and incubating in the Merced River	Meet or exceed adult migration baseflow targets, spawning incubation temperature flow targets, and yearling rearing flow targets for fall-run Chinook
	Improve spawning, incubating, and rearing flows and related habitat conditions for fall-run chinook salmon, and benefit sturgeon, striped bass, and other species through contribution to San Joaquin flows and Delta outflows	Meet or exceed adult migration baseflow targets, and spawning incubation temperature flow targets for fall-run Chinook
	Improve rearing and outmigration flows and related habitat conditions and provide adequate temperatures for fall-run chinook salmon in the Merced River; and contribute to improved conditions for survival of San Joaquin basin and Delta tributary fall-run chinook salmon migrating through the San Joaquin River and the Delta, and benefit other riverine and estuarine species, including other anadromous fish, through contribution to San Joaquin River flows and Delta outflows.	Meet or exceed outmigration flow targets, and yearling rearing flow targets for fall-run Chinook
	Improve rearing habitat for over-summering juvenile chinook salmon and steelhead.	Meet or exceed yearling rearing flow targets for fall-run Chinook
Tuolumne	**ERPP Vol. II**	
	No relevant actions or objectives.	
	ERPP Strategic Plan, Appendix D	
	Action 6. Explore actions to reduce ambient water temperatures, including increasing flows by purchasing water from willing sellers or developing new water supplies, as well as protecting and restoring riparian habitat (Strategic Plan, Page D-39)	Meet or exceed adult migration baseflow targets, spawning incubation temperature flow targets, and yearling rearing flows for fall-run ChinookAchieve riparian vegetation objectives
	Final Restoration Plan for the Anadromous Fish Restoration Program	
	Action 1: Implement a flow schedule as specified in the terms of the FERC order resulting from the New Don Pedro Project. Supplement FERC agreement flows with water acquired from willing sellers consistent with applicable guidelines or negotiated agreements as needed to improve conditions for all life-history stages of chinook salmon. (AFRP, Page 87)	Achieve fall-run chinook objectives
	Evaluation 4: Evaluate fall pulse flows for attraction and passage benefits to chinook salmon and steelhead. (AFRP, Page 89)	Meet or exceed adult migration baseflow targets for fall-run Chinook
	AFRP Guidelines	
	Improve attraction flows and provide adequate water temperatures for fall-run chinook salmon migrating into and spawning and incubating in the Tuolumne River	Meet or exceed adult migration baseflow targets, spawning incubation temperature flow targets, and yearling rearing flow targets for fall-run Chinook salmon

	Improve spawning, incubating, and rearing flows and related habitat conditions for fall-run chinook salmon, and benefit sturgeon, striped bass, and other species through contribution to San Joaquin flows and Delta outflows	Meet or exceed adult migration baseflow targets and spawning incubation temperature flow targets for fall-run Chinook
	Improve rearing and outmigration flows and related habitat conditions and provide adequate temperatures for fall-run chinook salmon in the Tuolumne River; and contribute to improved conditions for survival of San Joaquin basin and Delta tributary fall-run chinook salmon migrating through the San Joaquin River and the Delta, and benefit other riverine and estuarine species, including other anadromous fish, through contribution to San Joaquin River flows and Delta outflows.	Meet or exceed outmigration flow targets and yearling rearing flow targets for fall-run Chinook
	Improve rearing habitat for over-summering juvenile chinook salmon and steelhead.	Meet or exceed yearling rearing flow targets for fall-run Chinook
Stanislaus	**ERPP Vol II**	
	Ecological Processes, Central Valley Streamflows	
	Target 1: Maintain [stated] baseflows in the Stanislaus River below Goodwin Dam	Meet or exceed baseflow targets for migration and fry/juvenile rearing upstream flow targets for fall-run Chinook
	ERPP Strategic Plan, Appendix D	
	No relevant actions or objectives.	
	Final Restoration Plan for the Anadromous Fish Restoration Program	
	Action 1: Implement an interim river regulation plan that meeting the [stated] flow schedule by supplementing the 1987 agreement between USBR and CDFG through reoperation of New Melones Dam, use of (b)(2) water, and acquisition of water from willing sellers as needed. (AFRP, Page 90)	Applies to all flow targets
	Evaluation 3: Evaluate and refine a river regulation plan that provides adequate flows to protect all life stages of anadromous fish based on water storage at New Melones Reservoir, predicted hydrologic conditions and current aquatic habitat conditions. (AFRP, Page 91)	Meet or exceed fall-run chinook flow targets
	Evaluation 5: Evaluate the use of the Stanislaus River by American shad and consider increasing flows and maintaining mean daily water temperatures between 61 degrees and 65 degrees from April to June when hydrologic conditions are adequate to minimize adverse effects to water supply operations and in a manner consistent with actions to protect chinook salmon. (AFRP, Page 92)	Meet or exceed fall-run chinook flow targets
	AFRP Guidelines	
	Improve attraction flows and provide adequate water temperatures for fall-run chinook salmon migrating into and spawning and incubating in the Stanislaus River	Meet or exceed adult migration baseflow targets, spawning/incubation temperature flow targets, and yearling rearing flow targets for fall-run Chinook

	Improve spawning, incubating, and rearing flows and related habitat conditions for fall-run chinook salmon, and benefit sturgeon, striped bass, and other species through contribution to San Joaquin flows and Delta outflows	Meet or exceed adult migration baseflow targets for fall-run Chinook, and spawning/incubation temperature flow targets for fall-run Chinook
	Improve rearing and outmigration flows and related habitat conditions and provide adequate temperatures for fall-run chinook salmon in the Stanislaus River; and contribute to improved conditions for survival of San Joaquin basin and Delta tributary fall-run chinook salmon migrating through the San Joaquin River and the Delta, and benefit other riverine and estuarine species, including other anadromous fish, through contribution to San Joaquin River flows and Delta outflows.	Meet or exceed outmigration flow targets and yearling rearing flow targets for fall-run Chinook
	Improve rearing habitat for over-summering juvenile chinook salmon and steelhead.	Meet or exceed yearling rearing flows for fall-run Chinook

Table 2.2: Multi-Objective Template Used for this Study

Multi-Objective Ecological Flow Management				
ECOSYSTEM INDICATOR				***Objective/Notes***
Fall Chinook				
	Population Targets			
		long-term average escapement		escapement target; not specified.
		annual smolt production		production target; not specified.
	Streamflow Objectives			
		adult migration		
			baseflow	provide suitable temperature and eliminate migratory barriers
			attraction pulse flow	stumulate upstream movement into spawning grounds
		spawning/Incubation		assume same flow for each life history stage; may eventually differentiate;
			temperature flow	provide suitable temperature range during spawning
			habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);
		fry/juvenile rearing		
			upstream (gravel-bedded)	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat
			lower river (sand-bedded)	seasonal, short-duration pulse flow to allow rearing on inundated floodplains
			delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta
		outmigration (juvenile/smolt)		to convey fish through delta and pumps into Bay and Ocean
		yearling rearing		specify temperature range, and length of stream along which to provide suitable habitat
Steelhead				
	Population Targets			
		long-term average escapement		escapement target; not specified.
		annual smolt production		production target; not specified.
	Streamflow Objectives			
		adult migration		
			baseflow	provide suitable temperature and eliminate migratory barriers
			attraction pulse flow	stumulate upstream movement into spawning grounds
		spawning/Incubation		assume same flow for each life history stage; may eventually differentiate;
			temperature flow	provide suitable temperature range during spawning
			habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);
		fry/juvenile rearing		
			upstream (gravel-bedded)	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat
			lower river (sand-bedded)	seasonal, short-duration pulse flow to allow rearing on inundated floodplains
			delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta
		outmigration (juvenile/smolt)		to convey fish through delta and pumps into Bay and Ocean
		yearling rearing		specify temperature range, and length of stream along which to provide suitable habitat
			1+ juvenile rearing	
			2+ juvenile rearing	need to establish minimum age-class survival rates, determine habitat needed to meet these survival rates, then determine flow that provides this amount of habitat
Riparian Vegetation				
	Cottonwood			
		seed germination (cottonwood)		use cottonwood as target indicator species
		seedling growth/establishment		establish target floodplain elevations relative to channel thalweg for cottonwood establishment
		periodic large-scale disturbance		infrequent "resetting flow" to scour vegetation, create barren areas, and maintain age-class diversity
	Stand Structure and Diversity			
		age/species assemblage diversity		incorporate additional species and establish management objectives to achieve vegetation stand diversity
Geomorphic Processes	***Sediment Transport***			
		bed mobilization		target 75-90% mobilization of the D84 in riffle habitats
		bed scour		scour point bar units to approx twice depth of D84
	Channel Morpohology			
		channel migration		define and quantify in terms of lateral bank erosion
	Floodplain Processes			
		floodplain inundation/fine sediment dep		define frequency and duration of inundation

Chapter 3. Conceptual Model

3.1 INTRODUCTION

Conceptual models are explicit descriptions or illustrations of how scientists or resource managers believe the ecosystem functions, how they have been altered, and how various management actions might improve conditions. Conceptual models are ultimately a web of interdependent hypotheses regarding how the ecosystem functions and how it might respond to various management interventions. Like the ecosystems they describe, detailed conceptual models can become so complex that they fail to convey useful information to the decision makers about resource management priorities. In this chapter, we have attempted to provide simplified conceptual models that focus in on what appear to be the key factors limiting restoration of salmon, recruitment of cottonwood forest, and maintenance of geomorphic processes in the San Joaquin Basin. We have identified numerous flow related issues that could be limiting attainment of these objectives, but we have purposely focused on the few key issues that we hypothesize are most limiting. We have focused on flow related limiting factors because they are more relevant to the reservoir re-operation feasibility analysis we are conducting under the second part of this study. Other factors less related to flow such as ocean harvest, gravel mining, exotic species, land use or entrainment at the Delta pumps may ultimately be just as important to the restoration of the salmon fishery and riparian zone, but we have not emphasized those factors here because they are not sensitive to the reservoir re-operation opportunities that we are evaluating as part of this study.

3.2 GEOMORPHIC CONCEPTUAL MODEL

What follows is a coarse description of the conceptual model that links flows to specific geomorphic processes in San Joaquin tributaries. These processes, in turn, drive specific ecological functions, described in the preceding sections.

The conceptual model in its most succinct form is that high flows exert sheer stress on and transport sediment over the many structural components of a river channel and floodplain (bed, banks, other exposed surfaces) causing them to change, erode, migrate, and otherwise respond in a qualitatively predictable manner.

The conceptual model described below is based in inputs and outputs. Inputs into the model are in three categories: flow, topography, and sediment. The outputs of the model are physical functions that in turn support habitat and biotic responses in the river system.

The San Joaquin tributaries require a variety of high flows ($Q_{1.5}$ – Q_{10}) to clean sediment, rejuvenate alternate bar sequences, prepare the floodplain for vegetation recruitment, and drive channel migration. Each one of these functions supports a biotic or habitat response described previously in this chapter.

Figure 3.1 illustrates the relationships between flow, sediment, and topographic inputs, and ensuing geomorphic processes. The model has been simplified to focus primarily on restoration objectives of this project and the inputs we propose to modify to achieve these restoration objectives (outlined in bold). Figures 3.2 and 3.3 represent the flow thresholds of the various geomorphic functions as displayed against a conceptual river cross section and a conceptual wet year hydrograph.

3.2.1 Inputs

The driving inputs in the conceptual model fall into three categories: flow, topography, and sediment. In reality, the conceptual model is at least partly cyclic, where the outputs are also inputs into successive cycles.

Flow Inputs

Flow inputs can be divided into three broad categories: regulated runoff, unregulated runoff, and groundwater inputs. Regulated runoff refers to flow releases from reservoirs over which humans exert some control. This is of particular importance to this conceptual model because it is the input we propose to modify. Unregulated runoff refers to flow inputs on streams and rivers over which humans do not exert much control. As the distance between any point on a river and an upstream dam or diversion increases, so too does the influence of unregulated runoff. More tributaries enter the river and the unregulated drainage area increases downstream from the dam or diversion.

Groundwater refers to any inputs from subsurface flows. These are not, in fact, entirely independent of regulated or unregulated runoff. Interaction of high flows with floodplain surfaces, flow durations, and flow frequencies impact the quantity and timing of groundwater inputs. Similarly, groundwater inputs impact base flow levels in both regulated and unregulated systems. For the sake of simplicity and focus, groundwater is considered an independent input.

Topographic Inputs

The shape of the river channel and floodplain, the location of the levees, the amount and type of vegetation in the channel and on the floodplain, and other structural characteristics comprise the topographical inputs of the conceptual model. They determine the distribution and velocity of any given flow quantity. For example, if one hundred acre-feet of water enter into a river, the water will pass much more quickly and smoothly if the river channel resembles a pipe - smooth and straight. If the channel is small, the water may spill onto the floodplain. If the channel is flat and wide, the water may travel very slowly. If the channel is full of vegetation, it may impede the flow of water or concentrate it between walls of vegetation.

Upstream Sediment Inputs

Upstream sediment inputs refer to and silts, sands, cobbles, gravels or boulders transported in the river system. The quantity and quality of upstream sediment input create the building blocks for depositional processes. Because dams capture most upstream sediment, in regulated rivers sediment inputs are mostly from unregulated tributaries and storage in banks and bars below the reservoir.

3.2.2 Flow Outputs

Regulated flow, unregulated flow, and groundwater establish the amount of water in a river system. The topographic features determine the surface over which the water flows, and how it flows over that surface. Together, they determine the discharge, stage, and velocity of the flows (producing sheer stress). Combined with the frequency of these flows, and the upstream sediment inputs, they drive various geomorphic processes in river systems (described below).

3.2.3 Process Responses

Gravel Bed Mobilization

Gravel bed mobilization refers to the entrainment of D50[1] **(or is it D84?)** gravels. This generally occurs in alluvial rivers during the historic annual or biannual floods or roughly the $Q_{1.5}$ flow (Figure 3.2). The mobilization of the gravels "cleans" them by removing accumulated silt, algae and other fine particulates. (Stillwater Sciences, 2001)

Floodplain Inundation

Floodplain inundation (Figure 3.2) generally occurs during flows at or above the historic biannual flood (Q_2) (Stillwater Sciences, 2001). Floodplain inundation provides temporary access to floodplain habitat for aquatic species, recruits nutrients from the floodplain into the river, and helps to recharge groundwater levels in riparian zones.

Bed Scour and Deposition

Bed scour and deposition refer to the removal of sediment and the corresponding replacement of sediment that occurs during storm events. The bed scour and deposition process discourages the river channel from being "fossilized" by riparian encroachment, maintaining it in a dynamic alluvial state. It is a greater level of mobilization than simply gravel bed mobilization, in that the bed degrades during the ascending limb of the hydrograph and aggrades on the receding limb of the hydrograph. This simplistic view holds when the channel doesn't migrate (e.g., if the river is against a bluff). If the channel does migrate, scour and deposition do not necessarily occur in the same part of the river. Erosion would occur predominantly on the outside of the bend, and deposition would occur predominantly on the inside of bend. In this case, floods "rejuvenate" alternate bar sequences in rivers.

[1] D refers to the length of the intermediate axis of gravels in a gravel bed. The D50 refers to the gravels in the 50th percentile size class, relative to the other gravels in the bed.

Q_5 to Q_{10} floods generally provide the necessary shear stress to scour beds and redeposit with little net change in channel elevation (Trush et al., no date).

Floodplain Sediment Scour and Deposition
Floodplain sediment scour requires greater sheer stress than simply inundation and generally occurs during flows equivalent to the historic Q_{10} (Figure 3.2). By exerting sheer stress, scour prepares floodplain surfaces for recruitment of riparian vegetation by removing existing vegetation, depositing clean sand and transporting new seed across the floodplain. Depositional processes also require higher flows to transport sediment away from the channel onto the floodplain. As flows increase, they spill across the floodplain, velocities slow, and the river deposits its sediments. Most floodplain sediments are the result of this process (Leopold et al., 1964). Deposition on the floodplain further reshapes and prepares the surfaces for recruitment.

Channel Migration
Channel migration requires the greatest amount of stream energy and generally occurs during flows at or greater than the Q_{10} (Figure 3.2). It is a function of stream energy and substate strength. By eroding, channel migration recruits gravels and large woody debris into the system and directly and indirectly creates habitat complexity in the channel and floodplain. By depositing, channel migration prepares surfaces for pioneer species allowing for a diversity of riparian habitats. The process of channel migration is responsible backwater areas, sloughs, oxbow lakes, and secondary or abandoned channels (Bay Institute, 1998).

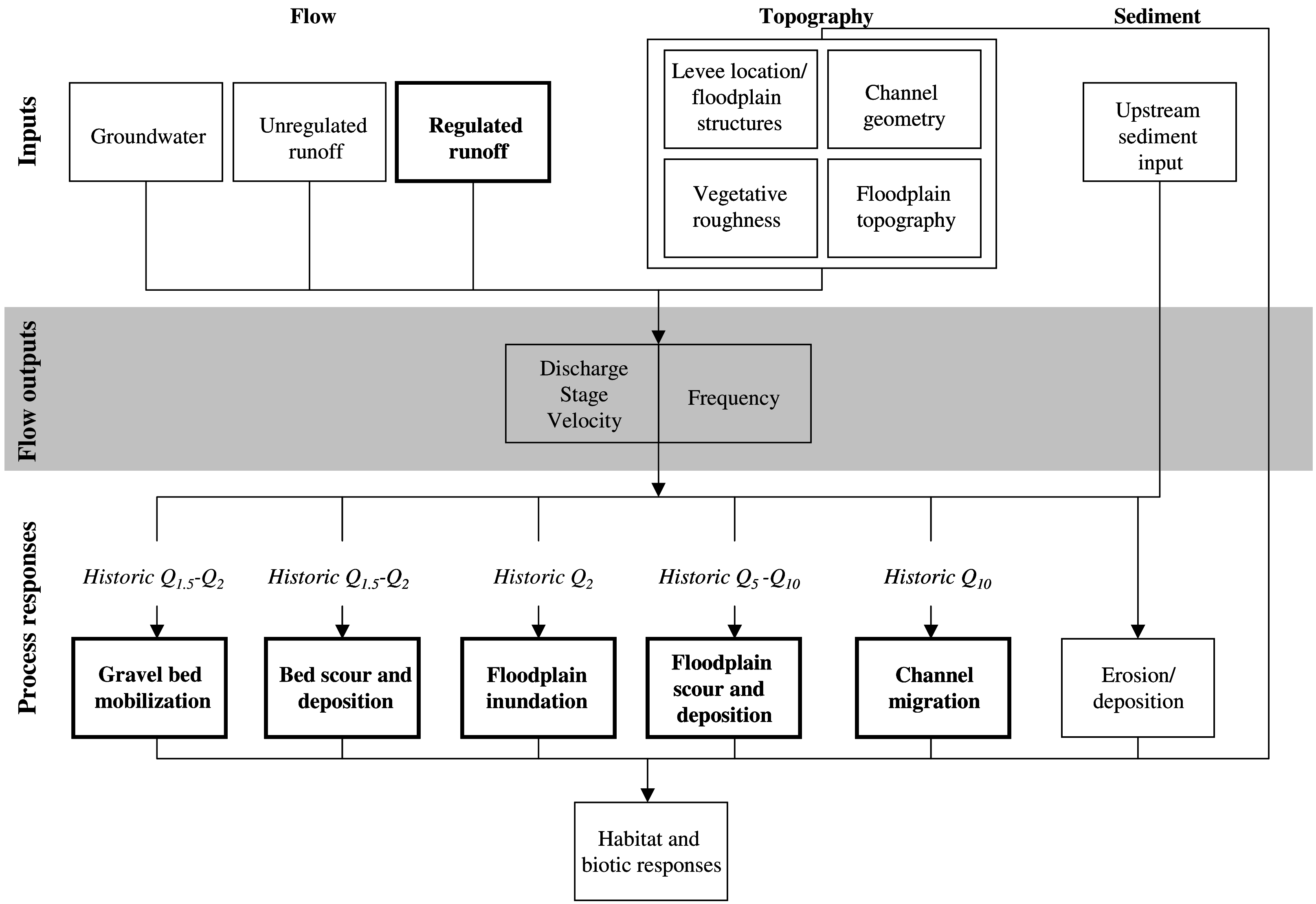


Figure 3.1. Geomorphic Conceptual Model. The figure above illustrates the relationships between flow, sediment, and topographic inputs, and ensuing geomorphic processes. The model has been simplified to focus primarily on restoration objectives of this project and the inputs we propose to modify to achieve these restoration objectives (outlined in bold).

Table 3.1 Uncertainty Table for Geomorphic Processes in the San Joaquin Basin and Tributaries

Inputs/Outputs	Lower San Joaquin	Middle San Joaquin	Merced River	Tuolumne River	Stanislaus River
Inputs					
Flow	⬤	⬤	⬤	⬤	⬤
Topography While well known in certain reaches of the river, comprehensive cross section data may still not be available for much of the tributaries.	⬤	⬤	⬤	⬤	⬤
Upstream Sediments	◯	◯	◯	◯	◯
Process Responses					
Gravel bed mobilization	◯	⬤	⬤	⬤	◯
Floodplain inundation The uncertainty relating to floodplain inundation surrounds what flows are necessary in the varying reaches and sub-reaches of the river to achieve flood plain inundation	◯	◯	◯	◯	◯
Bed scour and deposition	○	○	○	○	○
Floodplain sediment scour and deposition	●	●	●	●	●
Channel migration	○	○	○	○	○

Relative Uncertainty

● Higher

○ Lower

Importance

⬤ High

● Low

NA = Not Applicable

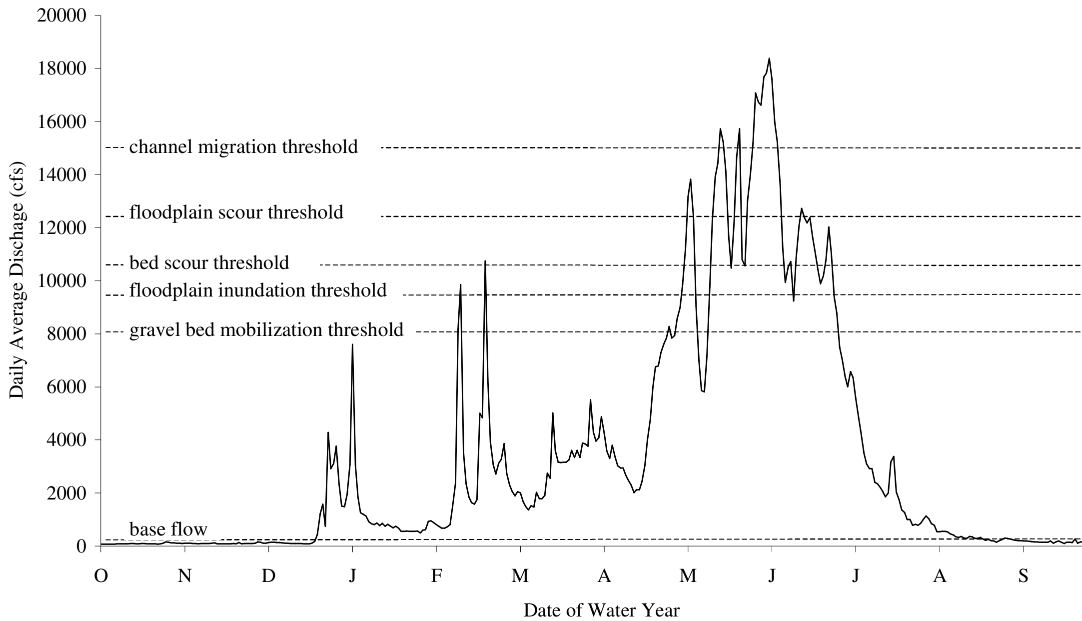


Figure 3.2. Conceptual hydrograph for geomorphic processes. The hydrograph above shows the conceptual thresholds at which certain geomorphic processes occur. The values along the Y axis (flow) are merely for demonstration and do not represent actual flow threshold values. A variety of high flows ($Q_{1.5} - Q_{10}$) to clean sediment, rejuvenate alternate bar sequences, prepare the floodplain for vegetation recruitment and drive channel

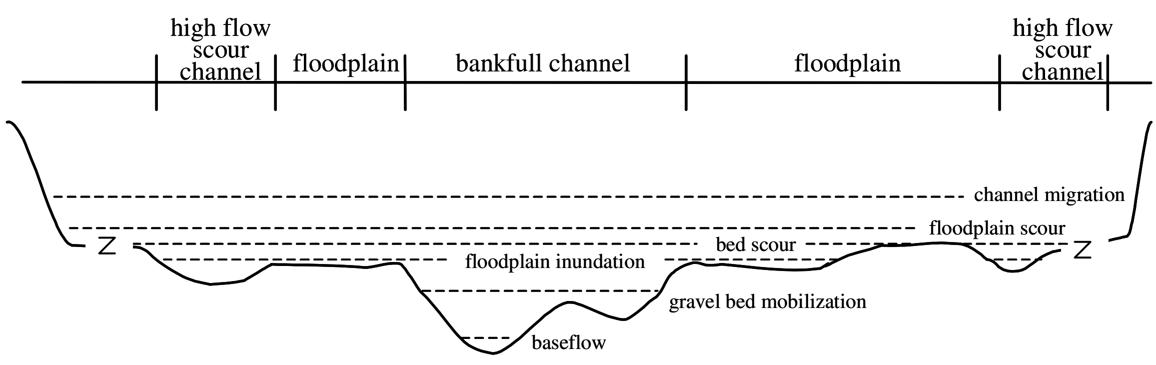


Figure 3.3. Conceptual Cross Section for Geomorphic Processes. The cross section above shows the relative position of flows that result in specified geomorphic processes. Rivers require a variety of high flows ($Q_{1.5} - Q_{10}$) to clean sediment, rejuvenate alternate bar sequences, prepare the floodplain for vegetation recruitment, and drive channel migration.

3.3 COTTONWOOD CONCEPTUAL MODEL

Critical life history stages of cottonwoods and other pioneer riparian species in the San Joaquin Basin are tightly linked with the hydrologic and geomorphic processes described in the previous conceptual model (Section 3.2). Floodplain scour/deposition, channel migration, channel avulsion, and erosion/deposition processes generate new sites for cottonwood seedling establishment. Floodplain inundation provides moist substrates to sustain seedlings through their first growing season. Gravel and sand bed mobilization and bed scour/deposition help define a minimum elevation for cottonwood recruitment. Over time, these processes play a key role in determining the distribution, extent, and age structure of cottonwood communities in the San Joaquin Basin. In turn, as cottonwoods mature, they have the potential to impact sediment deposition processes, channel stability, and channel dynamics. Both geomorphic processes and riparian habitat structure are important determinants of abundance and distribution of aquatic species such as chinook salmon, as described in Section 3.4.

Since 1850, land use activities and managed flow operations have greatly reduced the extent and integrity of riparian forests, particularly cottonwood forests, in the San Joaquin Basin. Most existing cottonwood stands in the basin are mature, exhibiting older age structure than typical under natural conditions (McBain and Trush 2000, Stillwater Sciences 2002a, Jones & Stokes 1998). The absence of sapling cohorts in many reaches of the basin suggests that natural recruitment processes are not occurring under current conditions (McBain and Trush 2000, Jones & Stokes 1998, Stillwater Sciences 2002a). Without younger age classes, senescent trees cannot be replaced as they die, potentially leading to further substantial loss of this once dominant riparian vegetation community.

This conceptual model describes the ecological flows and geomorphic processes that drive establishment and recruitment of cottonwoods under natural conditions (Figure 3.4). The model identifies factors that currently limit cottonwood recruitment in the San Joaquin Basin (Table 3.2), and opportunities for restoring this process through modification of flows and/or channel-floodplain geomorphology. Because channel attributes may differ widely among rivers and reaches of the San Joaquin Basin, flow characteristics for restoration are described qualitatively in this model, with respect to channel and floodplain elevations.

Various species of cottonwoods share the characteristics discussed below. Any discussion specific to the Fremont cottonwood *(Populus fremontii),* the predominant species of the San Joaquin Basin (Stillwater Sciences 2002a, 2002b, McBain and Trush 2000), is noted as such.

3.3.1 Site Preparation

The creation of barren nursery sites through erosional and depositional processes is the first step in cottonwood seedling recruitment. Because cottonwood seeds contain very little endosperm, seedlings require full sunlight to produce photosynthates for growth and development; thus, cottonwood seedlings compete poorly on vegetated sites (Fenner et al. 1984). Under natural flow regimes, moderate 5- to 10-year flood events precipitate channel migration and the creation of point bars suitable for cottonwood seedling establishment (Figure 3.4; McBain and Trush 2000, Trush et al. 2000). Large flows scour away herbaceous plants and/or deposit fine sediments on floodplains, preparing new seed beds for pioneer riparian species (Mahoney and Rood 1998). In addition to point bars and floodplains, cottonwood forests may occur in high flow scour channels, oxbows, and other off-channel backwaters that receive scouring and sediment deposition (Stillwater Sciences 2002a).

Over the past century, continued agricultural and urban encroachment into riparian zones have greatly decreased the landscape area upon which cottonwood recruitment can occur (McBain and Trush 2000, Jones & Stokes 1998). In addition, flow regulation has reduced the intensity and frequency of winter and spring flood flows. The lower flows have led to a significant reduction in the high-energy processes that, in less regulated river systems, create new seedbeds for recruitment—channel migration, point bar accretion, bed scour, and floodplain inundation (Jones & Stokes 1998). Levees and bank stabilization practices have reduced floodplain width and channel migration, in addition to isolating riparian backwaters (Jones & Stokes 1998, Stillwater Sciences 2002a, McBain and Trush 2000). Gravel mining and the large dams have reduced downstream sediment supply and, consequently, the creation of suitable substrates for seedling germination (Stillwater Sciences 2002a). In addition, the loss of upstream sediment supply has facilitated channel incision, requiring greater discharges for flows to inundate adjacent floodplains. The cumulative result of these processes has been a significant reduction in favorable germination sites for cottonwood seedlings.

There are several options for human intervention to increase availability of suitable recruitment sites for cottonwoods. Flood operations can be modified in wet years to allow shorter duration, but higher winter or spring peak flows sufficient to inundate floodplains and mobilize channel sediments (Jones & Stokes 1998). Reservoirs can be operated to release flows that mimic the 5- to 10-year flood events historically associated with cottonwood recruitment. Mechanical approaches include lowering floodplain surfaces for greater inundation frequency at current low flows, setting back or breaching levees to increase floodplain area, restoring the river's connection with abandoned side channels and backwaters, and artificially clearing floodplain sites to reduce plant competition. Along the Merced River, recent grading and clearing of floodplain sites seems to have successfully re-established cottonwood populations in some reaches where natural establishment of cottonwoods is limited (Stillwater Sciences 2002a). Figure 3.5 depicts the relationship between flow discharge and inundation area for a graded/excavated floodplain compared to a main channel.

The changes in hydrology of the San Joaquin Basin have allowed encroachment of more aggressive native riparian species into the formerly active river channel, further limiting cottonwood recruitment (Jones & Stokes 1998). This problem deserves special attention for restoration, as it is one of the most prevalent and lasting effects of regulation and reduction of flows in the San Joaquin Basin (Cain 1997). Under natural hydrologic conditions, surfaces at the edge of low-flow channels were high-scour zones that generally prohibited the establishment of riparian vegetation. Under regulated conditions in the San Joaquin Basin, bed scour has decreased, allowing vegetation—primarily alders and willows—to grow along channel margins that were previously characterized by shifting and exposed gravel or sand bars (Stillwater Sciences 2002a, McBain and Trush 2000, FWUA and NRDC 2002). Vegetation encroachment in many parts of the San Joaquin Basin has resulted in simplified and confined river channels resistant to fluvial geomorphic processes (e.g., channel migration) that create barren seedbeds for cottonwood recruitment. Thus, any cottonwood restoration effort based primarily on flow modification may have limited success unless coupled with mechanical clearing of willows and alders that have encroached into formerly active channels, restricting the river's natural geomorphic processes.

3.3.2 Seedling Establishment

Establishment describes the process of seed release, germination, and growth through the end of the first year. This stage in the life cycle of cottonwoods is marked by high mortality rates, in both natural and regulated river systems (Mahoney and Rood 1998).

Most studies on Fremont cottonwood recruitment have focused on establishment of new stands through seed release, rather than vegetative sprouts (Section 3.3.3). In the San Joaquin Basin, mature female Fremont cottonwoods release hundreds of thousands to millions of seeds between April and June (Table 3.2). Timing and duration of seed release are influenced by photoperiod and temperature, with maximal seed release generally occurring over a three-week period (FWUA and NRDC 2002, Stillwater Sciences 2002a). Seeds are dispersed by wind and water. They may travel up to a couple miles away, but more often they are deposited within a several hundred feet of the parent tree (Braatne et al. 1996). Dry Fremont cottonwood seeds are viable for one to three weeks (Horton et al. 1960). Once they are wet, their viability decreases to a few days (Braatne et al. 1996). Thus, for riparian restoration purposes it is important to understand the mechanisms that influence cottonwood seed release and dispersal, to ensure that timing of spring (snow-melt) pulse flows coincides with cottonwood seed dispersal. The spring pulse flows provide the moist nursery sites necessary for immediate germination of seeds (Mahoney and Rood 1998).

Cottonwoods germinate within 24–48 hours of landing on bare, moist substrates such as silt, sand, or gravel (John Stella, Stillwater Sciences, pers. com., 8 April 2003). For one to three weeks after germination, the upper layer of substrate must maintain moisture as the seedlings' root systems grow. Post-germination decline of river stage, which is presumed to control adjacent groundwater levels (JSA and MEI 2002), should not exceed approximately one inch per day (Mahoney and Rood 1998, Busch et al. 1992). This is the rate at which seedling root growth (0.16–0.47 inches/day; Reichenbacher 1984, Horton et al. 1960) can maintain contact with the capillary fringe of a receding water table in a sandy substrate. Cottonwood root growth and seedling establishment rates are higher in these soils than in coarser textured soils, which are more porous (Kocsis et al. 1991). In reaches with gravelly substrates, slower draw-down rates are necessary to support seedling establishment.

Mahoney and Rood (1998) describe the temporal and spatial window of opportunity for cottonwood seedling establishment as a "recruitment box", defined by timing of spring pulse ("establishment") flows/seed release and by seedling elevation relative to river stage. Optimal timing of seed release for successful establishment is during the gradually declining limb of a spring pulse flow. Optimal elevation relative to river stage is set at the upper end by the seedling's ability to maintain contact with the declining water table, and at the lower end by scouring and inundation flow levels in the first year, especially during the first winter.

The vast majority of cottonwood seedlings in this life stage die of drought stress because root growth is unable to keep pace with the decline in the water table (Mahoney and Rood 1998). In the San Joaquin Basin, regulated ramp-down rates after spring pulse flows are often steep, in order to conserve water for human uses (Stillwater Sciences 2002b). Alternatively, decreased spring flows in regulated systems may cause seedlings to initiate at elevations too low to protect seedlings from flooding and scouring flows later in the growing season or during the winter (Mahoney and Rood 1998). In some rivers, including Merced River, overwinter mortality of cottonwood seedlings is particularly high because flow regulation has reduced spring peak flows relative to winter peak flows (Stillwater Sciences 2002a). Unrelated to flows, grazing and trampling of seedlings by livestock in riparian areas is a relatively small, but documented, source of mortality for cottonwoods during this critical life stage is (Jones & Stokes 1998, McBain and Trush 2000). In the San Joaquin River, high levels of boron and salinity in soils and shallow groundwater are cited as potential limiting factors for cottonwood recruitment (Jones & Stokes 1998). Vegetation removal (channel clearing) for flood control purposes may be another important cause of mortality for cottonwood seedlings in river reaches managed by flood control districts (JSA and MEI 2002).

High seedling mortality rates suggest that opportunities for improving cottonwood recruitment may be greatest in this life stage. In the first year of life, drought stress can be minimized by managing flood release flows for slow ramp-down rates after 5- to 10-year flood releases. Since reservoir spills often occur in wet years, reduced ramp-down rates may be accomplished by reshaping existing flood release flows without reducing water supply deliveries.

Artificial floodplain irrigation, either through flooding or a drip system, can also relieve summer drought stress for newly initiated seedlings. Agricultural irrigation close to the channel during the dry season would achieve similar gains in groundwater level. Grazing and trampling of seedlings by livestock can be minimized through grazing management practices or by building exclosures to protect cottonwood nurseries. To reduce winter mortality due to scouring and inundation, establishment flows can be discharged in spring rather than winter.

3.3.3 Vegetative Reproduction

In addition to seed dispersal and seedling establishment, vegetative reproduction is a potentially significant but commonly overlooked method for cottonwood recruitment along newly formed or previously established floodplains and point bars. Fremont cottonwoods can reproduce clonally through sprouting of buried broken or detached branches, or through development of suckers from shallow roots. This little-studied phenomenon has been alluded to in the riparian literature, and reported anecdotally and in unpublished studies (Tu 2000; Mike Roberts, TNC, pers. com., 27 February 2003). Additional insight into the process can be gained from studies of vegetative reproduction in other cottonwood species (Rood et al. 1994, Reed 1995).

Vegetative reproduction may be particularly important for sustaining Fremont cottonwood populations in altered hydrologic systems such as the San Joaquin Basin. Tu (2000) reported that three years after the floods of 1996 established a new sandbar along the lower Cosumnes River, successful Fremont cottonwood recruits from vegetative branches outnumbered those from seeds by almost six to one. This is especially notable in light of the fact that the original 1996 cohort studied included 7,898 Fremont cottonwood seedlings compared to only 36 vegetative branches. Thus, the greater number of surviving 3-year-old recruits from vegetative branches compared to seedlings was due to their considerably higher survival rates rather than initial predominance. Most of the seedlings in this study died in their first year post-germination as a result of desiccation. Tu (2000) surmised that vegetative branches were better able to survive the critical first year by virtue of their greater nutrient storage, higher competitive ability for light, and greater proximity to declining water tables (most were partially buried in the soil).

In many parts of the San Joaquin Basin, it is possible that the loss of natural recruitment processes under current conditions has increased the importance of vegetative propagation relative to seed propagation for sustaining cottonwood populations. An intervention opportunity based on natural vegetative reproduction is to plant cuttings collected from local cottonwood populations. Although this option would be time and labor intensive, cottonwoods have been successfully re-established by this method in Clear Creek and on the Sacramento and Merced Rivers (Mike Harris, USFWS, pers. com., 26 February 2003; John Stella, Stillwater Sciences, pers. com., 8 April 2003). Once a small number of individuals is successfully recruited to a new site, expansion of the population may subsequently occur via sprouting, suckering, or seed dispersal. Due to the uncertainties of seed dispersal timing, availability of flows, and high cost of flows (unless part of flood release flows), a dual strategy of vegetative reproduction and improved flow management may be the most cost effective option for improving rates of cottonwood recruitment in the San Joaquin Basin.

3.3.4 Recruitment

The recruitment phase occurs from the end of the first year to sexual maturity, at five to ten years of age for Fremont cottonwoods (Reichenbacher 1984). Flow-related mortality is relatively low during this period because a plant has generally developed a sufficient root and shoot system to survive seasonal conditions of drought and flooding. Growth rates are very high in the second year, by the end of which roots may be almost ten feet deep (Ware and Penfound 1949). After the second year, growth rates level. Despite extensive root development during this stage, cottonwoods are still somewhat susceptible to drought stress. Thus, yearly flows must be sufficient to maintain groundwater levels within 10 to 20 feet of ground surface elevations (JSA and MEI 2002).

Groundwater extraction and reduced flows can reduce groundwater levels and induce drought stress in cottonwood saplings (Jones & Stokes 1998). In regulated river systems, low frequency of scouring flows may also allow exotics such as eucalyptus, tamarisk, and giant reed to establish and outcompete early successional native species such as cottonwood (Jones & Stokes 1998, McBain and Trush 2000). Relatively low flow-related mortality during this stage diminishes the importance of flow management opportunities. However, mortality due to herbivory (e.g., beavers, voles, mice) may be significant during this phase (John Stella, Stillwater Sciences, pers. com., 8 April 2003). Density-dependent mortality (self-thinning) may also occur if initial seedling density is high.

3.3.5 Maturity & Senescence

Maturity begins with the first flowering of a sexually mature adult. Senescence begins when reproductive capacity declines. Field studies indicate that a large proportion of existing cottonwood stands in the San Joaquin Basin comprise mature and senescing individuals (McBain and Trush 2000, Stillwater Sciences 2002a, Jones & Stokes 1998). As these cottonwoods die (lifespan >130 years; Shanfield 1983), they are unlikely to be replaced by new generations of cottonwoods. Although cottonwood seedlings are readily germinating on the Tuolomne, Merced, and mainstem San Joaquin Rivers, most cohorts are not surviving to reproductive maturity, for the reasons outlined above. In addition, urban and agricultural conversion of mature cottonwood forests in the San Joaquin Basin further reduces seed sources and threatens future prospects for this once-abundant riparian habitat (McBain and Trush 2000, Jones & Stokes 1998, Stillwater Sciences 2002a).

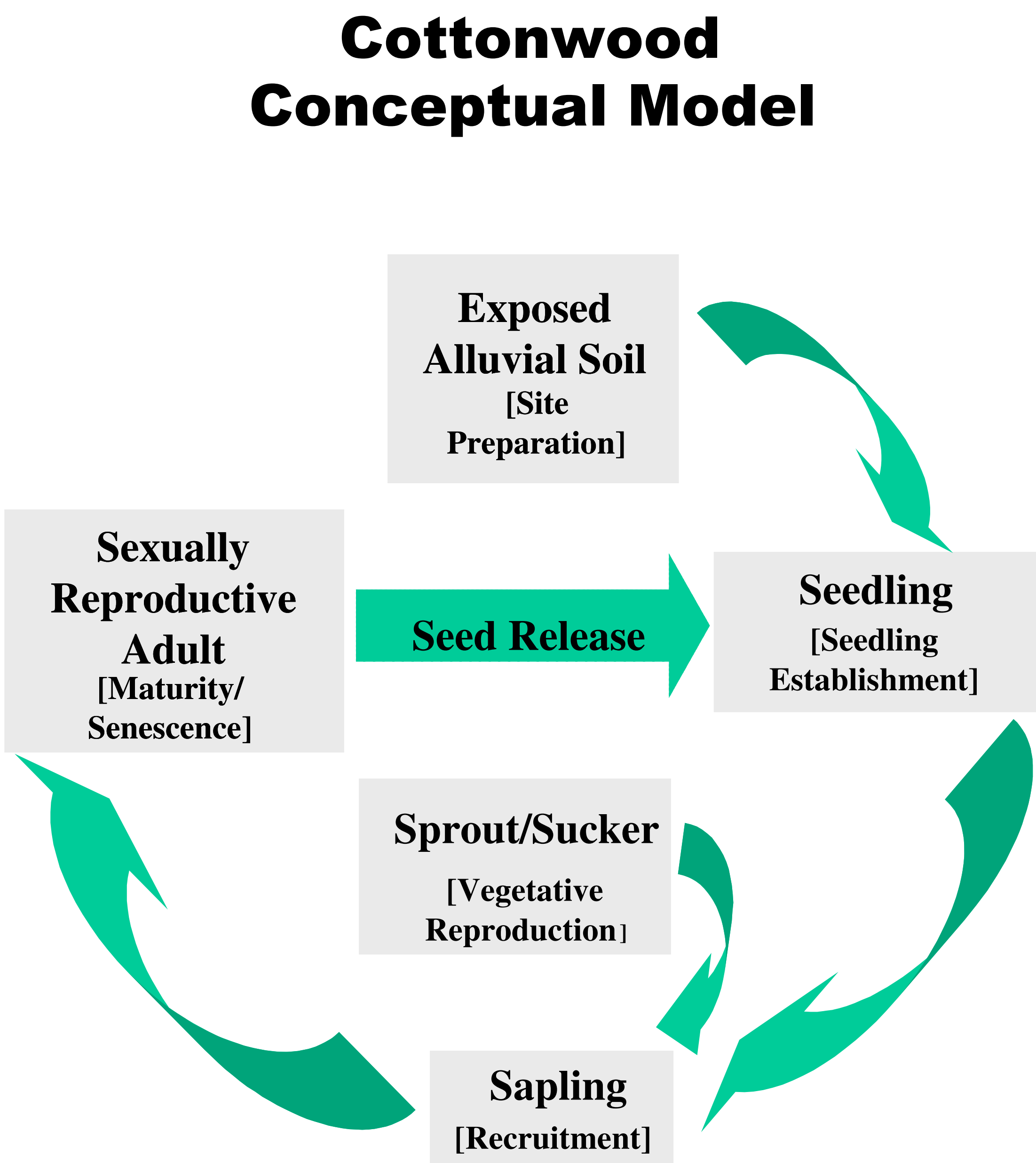


Figure 3.4. Cottonwood Conceptual Model for San Joaquin Basin.

Table 3.2 Cottonwood Conceptual Model

Life Stage	Natural Inputs	Human Impacts	Intervention Opportunities
Site Preparation	▪ **5- to 10-year flood flows** to scour sites ▪ **Sediment deposition** to create new sites	▪ **Reduced flood flows** reduce site exposure and allow encroachment of other vegetation ▪ **Agricultural and urban encroachment** reduce available sites ▪ **Levees and bank stabilization** reduce floodplain width and channel migration, and isolate riparian backwaters ▪ **Gravel mining and dams** reduce downstream sediment deposition ▪ **Vegetation encroachment** (from reduced flows) prevents channel migration and other processes of site preparation for cottonwood recruitment.	▪ **Release flood flows** to scour sites ▪ **Grade and clear floodplains** to create new sites ▪ **Breach / set back levees** to increase site availability ▪ **Restore fluvial connections** with side channels and backwaters to increase site availability ▪ **Mechanically clear** encroached vegetation
Seedling Establishment	▪ **Gradually declining flows** maintain soil moisture (high groundwater table) for seedling ▪ **Occasional high scouring flows** maintain natural distribution of native riparian species.	▪ **High spring ramp-down rates** lower groundwater table and induce drought stress ▪ **Reduced establishment flows** cause seedlings to initiate at low elevations vulnerable to future flooding ▪ **Vegetation removal** for flood control eradicates seedlings	▪ **Reduce spring ramp-down rates** to maintain soil moisture ▪ **Irrigate regeneration sites** to increase soil moisture
Vegetative Reproduction	▪ **High winds or flows** break and bury cottonwood branches at moist establishment sites ▪ **Cottonwoods sucker** from shallow roots		▪ **Plant cuttings** to bypass high mortality of initial seedling stage
Recruitment	▪ **Groundwater levels within 10 to 20 feet** of ground surface reduce drought stress	▪ **Groundwater extraction** reduces groundwater table, inducing drought stress ▪ **Reduced high flows** allow exotics to invade and outcompete cottonwoods	▪ **Protect young trees** from herbivory
Maturity & Senescence		▪ **Agricultural and urban encroachment** clear cottonwood forests, reducing cottonwood seed sources	

Table 3.3 Uncertainty Table for Cottonwood Recruitment in the San Joaquin Basin and Tributaries

Limiting Factors	Lower San Joaquin	Middle San Joaquin (Jones & Stokes 1998; JSA and MEI 2002; FWUA and NRDC 2002)	Merced River (Stillwater Sciences 2002a)	Tuolumne River (McBain & Trush 2000)	Stanislaus River (Schneider 2001)
Site Preparation					
Low frequency/intensity of flood flows	⬤	⬤	⬤	⬤	◯
Loss of upstream sediment supply	⬤	⬤	⬤	⬤	◯
Levees and bank stabilization	⬤	⬤	⬤	⬤	◯
Vegetation encroachment	⬤	⬤	⬤	⬤	◯
Seedling Establishment					
High ramp-down rates	⬤	⬤	⬤	⬤	◯
Low spring pulse flows	⬤	⬤	⬤	⬤	◯
Livestock grazing/trampling	●	●	○	●	○
High boron/salinity levels	◯	◯	○	○	○
Vegetation removal (channel clearing)	◯	◯	◯	◯	◯
Recruitment					
Low water table	●	●	●	●	○
Competition with exotic vegetation	●	●	◯	⬤	○
Maturity & Senescence					
Agricultural and urban encroachment	⬤	⬤	⬤	⬤	⬤

LEGEND:

Relative Certainty
- ● (filled) High Certainty
- ○ (open) Low Certainty

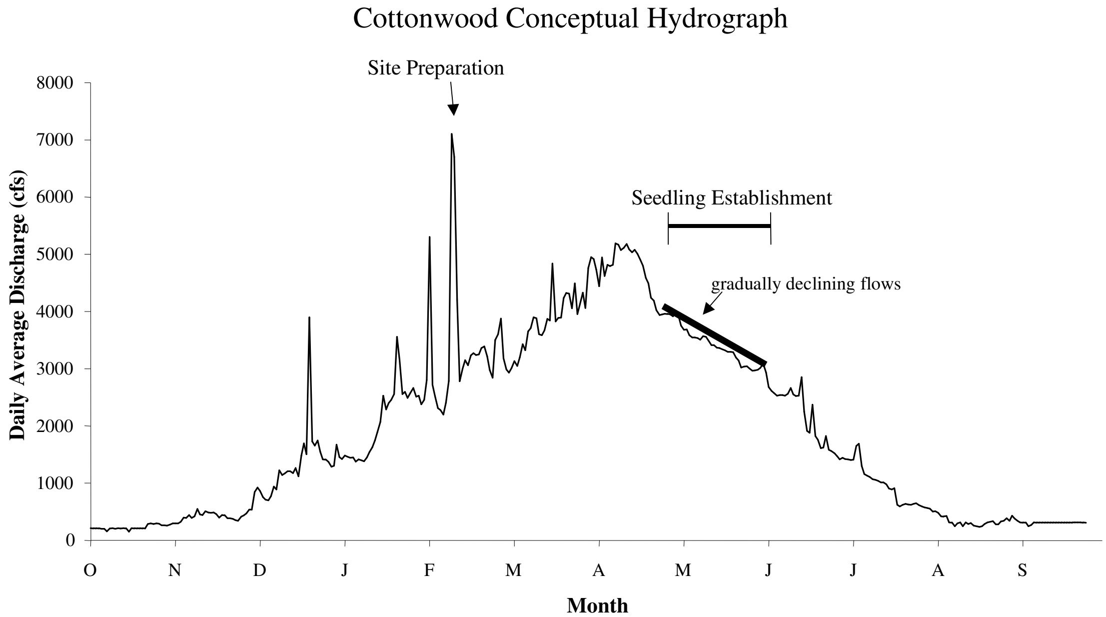
Importance / Vulnerability
- ⬤ (large) High Importance / Vulnerability
- ● (small) Low Importance / Vulnerability

Table 3.4 Life History Traits and Ecological Properties of Fremont Cottonwood *(Populus fremontii)* *(Adapted from Braatne et al. 1996)*

Life history traits/ecological properties	Species characteristics
Reproduction:	
Flowering time	February – March [1]
Seed dispersal time	April – June [2]
Dispersal agents/distance	Wind and water/ max. couple miles [3]
Asexual traits	Branch breakage and flood-related disturbance [4]
Germination/Establishment:	
Seed viability (natural conditions)	1 – 3 wk [5]
Seed germination	24–48 h/bare [6]
Seedling root growth rates	0.16 – 0.47 inches/d [1, 5]
Soil salinity	0 – 1500 mg/L [7]
Recruitment	
Age at reproductive maturity	5 – 10 y r [1]
Lifespan	130+ y r [8]
Mature stand density (trees/ha)	20 – 160+/acre [1]
Rooting depths of mature stands	9 – 16+ ft [9]

[1]Reichenbacher 1984; [2]FWUA and NRDC 2002, Stillwater Sciences 2002a; [3] Braatne et al. 1996; [4]Tu 2000, Mike Roberts, TNC, pers. com., 27 February 2003; [5]Horton et al. 1960; [6]John Stella, Stillwater Sciences, pers. com., 8 April 2003; [7] Jackson et al. 1990; [8] Shanfield 1983; [9] Stromberg et al. 1996

NOTE: This table compiles data from multiple regions. Actual values for the San Joaquin Basin may differ slightly from those reported here.



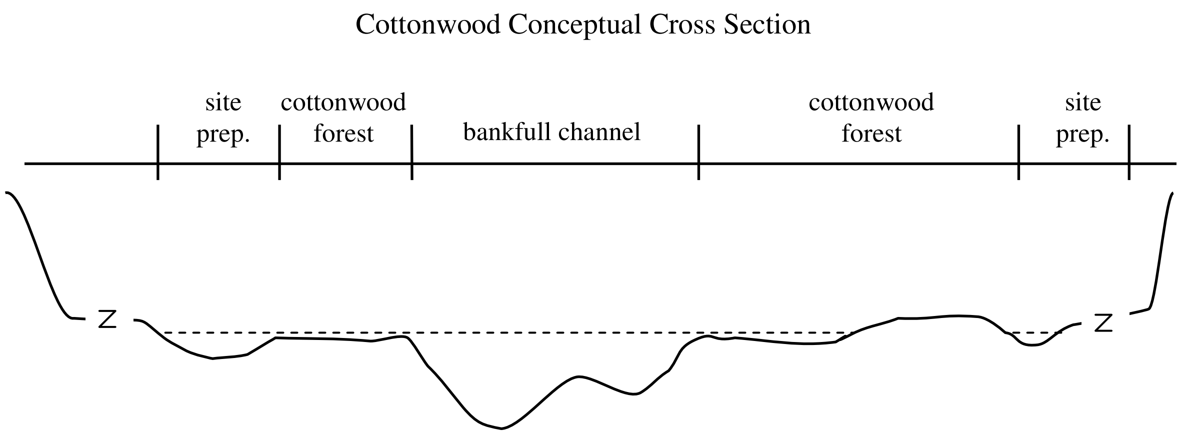
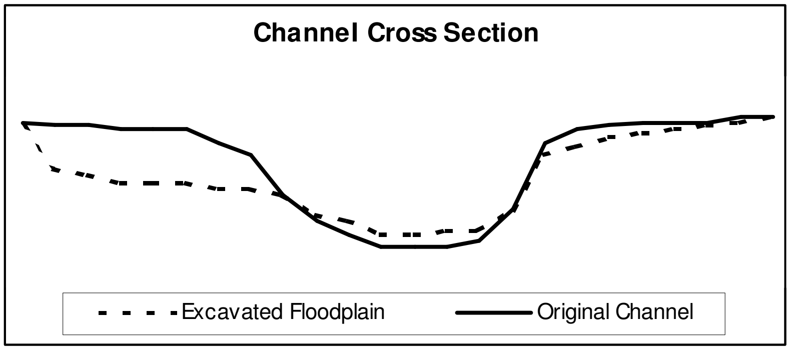


Figure 3.5. Hypothetical Hydrograph and Cross Section for Cottonwood Recruitment.



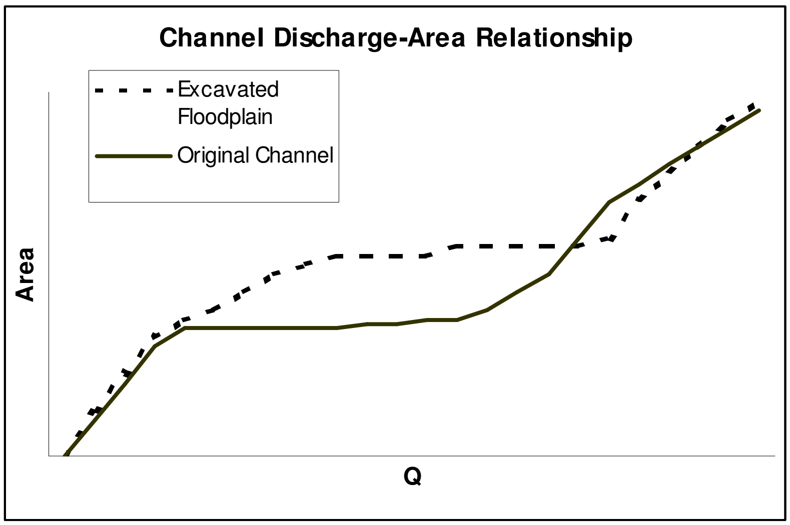


Figure 3.6. Channel Cross Section and Discharge-Inundation Area for Original Channel and Excavated Floodplain. Lowering the elevation of the near-channel floodplain reduces the magnitude of flows necessary to scour and inundate the floodplain and recruit vegetation.

3.4 FALL-RUN CHINOOK SALMON

This conceptual model for fall-run Chinook salmon illustrates the life cycle of the fall run Chinook in the San Joaquin Basin tributaries, factors that increase Chinook mortality during their life cycle, and how restoration can improve the conditions of these fish (Figure 3.7). The model identifies restoration opportunities for Chinook based on the restoration of ecological flows in the San Joaquin Basin. The model begins with Chinook salmon in the ocean, followed by migration through the Delta, the lower San Joaquin (from the Merced River to the Delta) and into the San Joaquin Basin tributaries (the middle San Joaquin (from Friant Dam to the confluence with the Merced), Merced, Tuolumne and Stanislaus Rivers). The life cycle continues with spawning, development of juveniles, and outmigration of smolts into the Ocean. Mortality factors and options for restoration are best shown in the context of the Chinook life cycle because different factors affect Chinook depending on their specific location at different times of their lives.

The primary flow related challenge to restoring large numbers of fall-run salmon in the San Joaquin Basin appears to be the relatively narrow window of time that salmon have to migrate into the system, spawn, rear, and outmigrate before encountering the high water temperatures and major water diversions that characterize the lower San Joaquin and the Delta in the late spring and summer. Fall-run Chinook salmon face numerous challenges from degraded spawning and rearing habitat in the upper reaches to entrainment at the Delta pumps, but even if we can overcome these challenges through better management, salmon will still need adequate water temperatures during the spring months to successfully migrate to the ocean. Adult salmon generally don’t migrate into the tributaries until October and November leaving them only a few months to reproduce and grow large enough to outmigrate successfully to the Ocean before high temperatures set in. Historically, snowmelt maintained high, and presumably cool flows into the early summer in the San Joaquin basin, but today these snowmelt flows are largely impounded and diverted for agriculture.

We hypothesize that high water temperatures during the late spring outmigration period of juveniles and smolts are the primary factor directly related to flow that is currently limiting restoration of fall-run Chinook salmon in the San Joaquin basin. Temperatures are not generally a problem during the incubation and fry stages, because these portions of the lifecycle occur mostly during the winter and early spring months when both ambient and water temperatures are cool. High water temperatures and DO levels at the Stockton Ship Channel in September and October may exacerbate mortality from high water temperatures in the spring by delaying upstream migration of adults to their spawning areas and subsequent growth of juvenile fish. The delay in spawning probably results in later out migration during the spring when temperatures become a problem. Therefore, temperature-induced mortality in the late spring may be related to the timing of adult upstream migration, which may be controlled by temperature and DO levels in the fall.

3.4.1 Life in the Ocean

Chinook salmon spend approximately 1 to 5 years in the ocean before returning to spawn in their natal stream (Moyle, 2002), though historically, most Chinook salmon returning to the Sacramento River have been 4 years old (Clark 1929, in USFWS 1995).

Mortality of salmon in the ocean is based on natural and non-natural factors. Natural stressors include predation by other species, and ocean conditions, such as nutrient flow patterns (CMARP and CALFED Appendix C). The non-natural mortality factor affecting salmon is harvest. From 1967 to 1991, 60-80% of total salmon production was harvested (CMARP).

Changes in river management will do little to decrease natural mortality of salmon in the ocean. This study is not considering restoration of Chinook populations by limiting ocean harvest of salmon at this time. However, it is important to emphasize that large-scale harvesting of salmon in the ocean may be severely limiting salmon populations. If we could manage ocean stocks to increase the number of older fish, it may be possible to increase the ecosystem resilience against drought.

3.4.2 Adult Upstream Migration

Fall-run Chinook salmon headed for San Joaquin tributaries typically leave the Pacific Ocean and enter the Delta at Jersey Point in September, migrate slowly (up to two months) upstream and enter the San Joaquin tributaries in late October or early November, and continue to migrate up the tributaries through December, depending on river conditions (Hallock et al, 1970, CADFG 1993 and 1997, and Carl Mesick Consultants 1998a, in CMARP). In the San Joaquin Basin, fall-run Chinook typically return between October and December (EA Engineering, 1991) and tend to spawn earlier in the season in more northern streams (Healey, 1991 and Yoshiyama, 1996).

Adult migration is greatly dependent on the conditions of the Delta, the lower San Joaquin and Basin tributaries. There are several stressors that affect adult migration. Inadequate attraction flows from the lower San Joaquin increase the chance of salmon straying into the Sacramento basin and other tributaries when Delta export rates are high (Carl Mesick Consultants 1998a in CMARP). Low levels (less than 5mg/l) of dissolved oxygen (DO) during summer and early fall at the Stockton Deep Water Ship Channel and high levels of ammonia from the Stockton wastewater plant in October cause poor water quality to delay adult Chinook migration up the lower San Joaquin, which causes an increase in poaching, lower egg and sperm viability and greater threats to outmigrating juveniles (Hallock et al, 1970 in CMARP). Dewatered reaches on the middle San Joaquin completely prevent salmon from migrating upstream (USFWS 1994 and USGS 1989, Boyle 1986 in Cain draft 1999). Large and small dams on all San Joaquin basin tributaries block upstream migration to historical spawning reaches and drastically reduce or eliminate instream flow, which limits the potential size of the population. Barriers in the South Delta are installed in the spring and removed in the fall of each year to increase water levels in south Delta sloughs, primarily for agriculture diversions. These barriers, such as the Head of the Old River Barrier, may also impede upstream migration. Lastly, high water temperatures can prevent upstream migration, and can cause physiological damage and exhaustion (CALFED C-9). Temperatures above 70°F (21.1°C) prevented the upstream migration of adult Chinook salmon from the Delta to the San Joaquin River, but the Chinook began migrating into the lower San Joaquin as water temperatures fell from 72°F-66°F (22°C-18.9°C) (Hallock 1970 in USFWS, 1995). Temperatures ranging between 50°F and 67°F were found to be suitable for upstream migration of fall-run Chinook (Bell, 1986; Bell, 1973 in USFWS, 1995; and Bell, 1991 in Oroville). Although water temperatures below 38°F are reported to decreases adult survival (Hinze 1959 in USFWS, 1995), temperatures this low are not likely to occur in the San Joaquin Basin tributaries.

Increasing instream flows in the early fall in the San Joaquin basin can improve conditions for migrating adult fall-run Chinook by reducing straying, improving water quality, improving passage barriers, decreasing water temperatures and decreasing the delay in migration. If salmon migration is motivated by major storms, early freshets or pulses after the first rain, and most of the large flows from storm events are trapped behind dams, reservoir operators can simulate pulse events by releasing water from the reservoir. However, "There is [a] concern that pulse flow releases in mid October to attract salmon may cause the fish to enter the rivers earlier than normal, which may expose them to high water temperatures when the pulse flows cease." (CMARP). Therefore, if flows are increased during this mid-fall period, it is important to continue to maintain adequate flows for migrating adults and subsequent spawning.

3.4.3 Spawning

Fall-run Chinook typically spawn in the San Joaquin basin tributaries from late October through December (EA Engineering 1991 and Carl Mesick Consultants 1998b in CMARP). They typically use gravel 6 inches (15 cm) or less in diameter to construct their nests, or redds, and prefer to spawn at the head of riffles (Flosi et al., 1998).

There are a number of limiting factors that decrease spawning habitat. Carl Mesick Consultants (1996) found that extremely low flows (below 50 cfs) due to diversions during the spawning season between 1960 and 1991 in the Tuolumne and Stanislaus Rivers substantially reduced spawning habitat. Insufficient spawning gravel due to blockage of recruitment from upstream dams and direct removal from instream gravel mining, have also limited spawning habitat (CMARP). Gravel mining has also caused channel incision, which in turn has reduced channel complexity and the quality of spawning habitat.

Water diversions and the reduction of peak flow events have reduced both the area and quality of spawning gravel. Historically, high storm flows mobilized gravel and flushed out sand and finer sediments. Dramatic reductions in the frequency of high flows has resulted in higher levels of fines and increased compaction of spawning gravels. Increased fines and compaction have reduced dissolved oxygen and subsurface flows in spawning substrate resulting in lower egg survival (Vaux 1962 and 1968 and McNeil 1969, from Cain draft, 1999).

High water temperatures (greater than 56°F), especially between October and November, due to low reservoir storage, high air temperatures and low flow releases could decrease available spawning habitat and affect sperm and egg viability. High temperatures cause spawners to concentrate in the upper reaches where water temperatures are lower, which increases the rate of superimpostion of redds (CMARP). "Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs" (USFWS, 1995) and water temperatures below 38°F also lower egg viability (Hinze 1959 in USFWS, 1995).

In order to provide quality areas of spawning habitat, adequate flows need to be released from dams into the tributaries during the spawning period. Due to profound channel alteration from gravel mining, artificial gravel habitat construction and enhancement may be necessary. Over the long run, periodic high flows are necessary to mobilize gravels and flush-out fine sediments. However, large peak flow events that occur in channels that have been excessively incised and leveed cause excessive gravel mobilization, which can disrupt spawning and cause egg mortality (CMARP). Therefore, these flows should be released after mid-February so they reduce mortality to incubating salmon eggs (McBain and Trush, 2000). Increased flows may also be needed to decrease water temperatures in late October and early November to prompt earlier spawning, expand the area with suitable temperatures for spawning and incubation, to increase egg viability, and to reduce the probability of superimposition of redds. If flows are increased during this mid-fall period, it is important to continue to maintain adequate flows for spawning and to prevent dewatering of redds.

3.4.4 Egg Development and Emergence

Eggs usually incubate in the gravel for approximately 61-64 days before hatching (Healey 1991) and it takes about 70 days for fry to emerge from the gravel (USFWS 1998 in SP Cramer, 2000). This is consistent with EA Engineering's findings, (1991 in CMARP) which found that eggs incubate for 40-60 days and remain in the gravel for 45-90 days. When fry first emerge from the gravel they are known as alevins and have an attached yolk sac that they depend on for food and nourishment. In most San Joaquin basin tributaries, incubation and alevin development occurs from October through March (CMARP).

The development of eggs into fry appears to be a difficult time for Chinook (Healey, 1991). High water temperatures, fine sediment capping, dewatered redds, poor quality gravel, and low substrate flow may contribute to the high mortality rate during egg and alevin development. High water temperatures (greater than 56°F), particularly in October and early November due to low reservoir storage, high air temperatures and low flow releases (CMARP, Loudermilk 1996) may cause egg mortality and decrease the incubation period (EA Engineering 1993 in CMARP). However, high water temperatures is probably not an important factor affecting Chinook in the San Joaquin Basin because fall-run eggs incubating between October and March are less likely to encounter water temperatures above 14°C (57.2°F) in the Sacramento-San Joaquin Rivers (Myrick and Cech, 2001). The late-fall and winter period of incubation combined with hypolimnetic discharge from the reservoirs generally maintains adequate water temperatures.

Low substrate flow through spawning gravels is known as an important cause of mortality in egg and alevin development. “Adequate water percolation through the spawning gravel is essential for egg and alevin survival. There is no doubt that percolation is affected by siltation and that siltation in spawning beds can cause high mortality” (Shaw and Maga 1943, Wickett 1954, and Shelton and Pollock 1966 in Healey 1991). Fine sediment capping occurs when redds become covered with fine silt (fines) due to small storm events that transport and deposit fines downstream. Shaw and Maga (1943) observed that siltation resulted in greatest mortality when it affected eggs in their early incubation stage (in Healey, 1991). Although common in steep coastal watersheds, fine sediment capping is relatively rare in the San Joaquin basin due to sediment trapping in upstream reservoirs and the general lack of unregulated tributaries upstream of spawning areas.

Dewatering of redds is a known mortality factor effecting development of alevins. (Becker et al., 1982, 1983 in Healey, 1991). Dewatering of redds can be minimized below dams by careful flow regulation. Contaminated groundwater caused by seepage from agricultural or urban areas causes an increase in water temperature and reduces DO within spawning gravel, which may be harmful to incubating salmon eggs (CMARP).

Adequate base flows during the incubation and emergence period combined with periodic flushing flows outside the period should reduce the mortality factor of eggs and alevins. Instream flows, at or above spawning flows, should be maintained throughout the incubation and emergence period to avoid dewatering redds. Siltation and capping from fine sediments could be minimized with small reservoir releases timed to coincide with rainfall induced local run-off. These releases would help convey fine sediments out of the spawning reach.

3.4.5 Juvenile Development/Rearing

Fall-run Chinook usually emerge from the gravel as fry between January and March. Large portions of fry are immediately dispersed downstream to the lower rivers and the Delta, while some fry remain in the tributaries to rear (Kjelson et al. 1982 in Healey 1991, Moyle, 2002, and SP Cramer, 2000). SP Cramer (2000) found that peak migration of fry was associated with an increase in daily average flows. Different studies have found that fry and smolts are more abundant in the Sacramento-San Joaquin Delta at different times, depending on how long they remain in the upstream tributaries, before migrating to the Ocean (Table 3.5) “Most rearing occurs in freshwater habitats in the upper delta area, and the fry do not move into brackish water until they smoltify” (Kjelson et al., 1981, 1982 in Healey, 1991).

Table 3.5 Outmigration timing of fry and smolts to the Delta

Source	Juveniles	Smolt
CMARP	Feb-March	mid April – early June
Kjelson et al. (1981, 1982 in Healey 1991)	Jan-March (Peak: Feb and March)	April – mid-June
Moyle (2002)	March-April	
SP Cramer (2000)	Jan-end of April (Peak: mid Feb)	mid April – end of June

Growth and rearing of juveniles is crucial to ensure that they grow fast enough to smolt before the onset of high temperature stresses common in the late spring. Smolts are typically >70-80mm and are able to survive in saltwater. Larger juveniles have a better chance of succeeding and surviving to the smoltification phase. "The rate of downstream migration of Chinook fingerlings appears to be both time and size dependent and may also be related to river discharge and the location of the Chinook in the river…Larger Chinook traveled downstream faster, and the rate of migration increased with the season" (Healey 1991). Growth is also important for avoiding other sources of stress and mortality such as lack of food, entrainment, predation, and disease. Larger fish are better able to compete for larger prey and avoid entrainment and predation. Larger juveniles have a competitive advantage over smaller fish in selecting prime positions in rearing areas (Fausch 1984 in Myrick and Cech), which can increase feeding rates (Alanara and Brannas 1997 in Myrick and Cech 2001). Larger fish also have more energy stores to withstand stresses imposed by disease.

There is great uncertainty about the suitability of the Delta for juvenile rearing and growth relative to rearing conditions farther upstream in the spawning reaches. The CALFED Strategic Plan for Ecosystem Restoration identified this question as one of the major uncertainties constraining the restoration planning process in the Bay-Delta watershed. Although Chinook salmon use other estuaries for rearing, most research and previous management actions on salmon in the Delta assume that juveniles suffer very high mortality in the Delta and has thus focused on moving smolt through the Delta as quickly as possible. Moyle (2002) found that "juveniles from other runs apparently do not spend as much time in the estuary, but pass through fairly rapidly on their way to sea. Whether or not this rapid passage is a recent phenomenon as the result of drastic changes in estuarine habitat or is the historical pattern is not clear".

Fry appear to develop and grow in the tributaries, on inundated floodplains and in the Delta at different times until they become smolts and are large enough to migrate to the Ocean. There is strong evidence that juveniles rearing on inundated floodplains in the Yolo Bypass, a lowland transition zone between the spawning reaches and the Delta, had significantly higher growth rates than juveniles reared in the mainstem of the Sacramento River (Sommer et al. 2001). Sommer et al. (in preparation) attributed the higher growth rates to the increased area of suitable habitat, increased temperatures and increased food resources. Sommer et al. (2001) found that drift insects (primarily chironomids) were an order of magnitude more abundant in the Yolo Bypass than the adjacent Sacramento River channel during 1998 and 1999 flood events. Seasonally inundated floodplains are also relatively free of exotic predators. "In the Central Valley during high flow periods, these fish historically moved into the floodplain, where they could rear for several months." (Moyle, 2002). Today, however, most of the rivers in the San Joaquin Basin have been cut off from their floodplains, decreasing the available habitat for juveniles to develop and grow.

Less is known about the value of inundated floodplains relative to the gravel bedded reaches of the tributaries, which produce abundant food resources from macro-invertebrate production. Numerous studies indicate that gravel bedded reaches are more productive than sand and clay bottomed reaches that characterize the lower San Joaquin (need citations – suggestions on where to start). The increased food resources in the gravel bedded spawning reaches may be somewhat offset by the constant cold water, hypolimnetic releases from the dams, which may dampen growth. Channel incision, degraded riparian vegetation and degraded streambed complexity have been found to reduce the supply of organic detritus that invertebrates depend on for food, which may limit growth and survival of juvenile salmon that depend on invertebrates (Allan 1995 in CMARP). Incised channels in the San Joaquin basin have cut off the rivers from their floodplains, which further limit access to food supplies (CMARP). These incised channels combined with high flows can result in fry and juveniles being washed down stream into less productive lowland reaches with high predator populations. Despite lower macroinvertebrate production, warmer water temperatures in the low-lying rivers and in the Delta may result in higher growth rates similar to observations from the Yolo bypass. Healey (1991) found that fry grow more rapidly in the Sacramento-San Joaquin estuary than in the rivers. However, others report that "fry that rear in the upper rivers experience a higher survival to smolting than fry that rear in the delta" (Kjelson et al. 1982, Brown 1986 in Healey, 1991).

Temperature has a major impact on growth. High water temperatures were found to stimulate smoltification and growth (Kreeger and McNeil 1992 in CMARP and SP Cramer, 2000 and Castleberry et al., 1991 in Myrick and Cech, 2001). Myrick and Cech (2001) conducted an extensive review of temperature effects on growth of juvenile Chinook in the Central Valley (Table 3.6). Although they found conflicting results, generally temperatures in the 60-66°F (15-19°C) range lead to high juvenile growth rates. When juveniles are rearing in February and March, temperatures in the tributaries are relatively low, cooler than temperatures needed for optimal growth. SP Cramer (2000) found that "higher water years result in cooler river temperatures [in the spring], which in turn can slow growth rates…However, Cramer et al. (1985) concluded from a variety of growth measurements that warmer temperatures, rather than lower flows, were driving growth of juvenile Chinook" (in SP Cramer 2000). Higher growth rates may be a factor of slightly higher temperatures on the floodplains and in the Delta during this early spring period.

Table 3.6 Effects of temperature on growth of Juvenile Chinook in the Central Valley (Myrick and Cech, 2001 and Moyle, 2002)

Source	Location	Maximum Growth
Moyle (2002 referencing Marine)		55-64°F (13-18°C)
Rich (1987)	Nimbus State Fish Hatchery on American River	56-60°F (13-15°C)
Marine (1997)	Coleman National Fish Hatchery on Sacramento River	63-68°F (17-20°C)
Cech and Myrick (1999)	Nimbus State Fish Hatchery on American River	66°F (19°C)

Water temperatures greater than 77°F (25°C) were found to be lethal to juveniles in the Central Valley when exposed to these high temperatures for a long period of time, but they could withstand brief periods of high temperatures up to 84.2°F (29°C) (Myrick and Cech, 2001).

Although the mid water trawl surveys at Chipps Island measure smolt outmigration from the Delta (Baker et al. 1995), there are no measurements that identify where these outmigrating fish reared. Without this information it is impossible to estimate the relative importance to the population of fry reared in the Delta and on lower river floodplains compared with fry that rear in the tributaries before outmigrating. It is fairly clear, however, that the majority of juveniles migrate to the lower river and Delta soon after emergence. Therefore, we hypothesize that improving rearing conditions in the lower river and the Delta should increase overall escapement. Present management seems to foucs on the quality of rearing habitat in the tributaries, but if the majority of young are moving out of the tributaries, it seems prudent to improve conditions for them as well. In order to understand where to focus limited resources where they will have the most impact on successful rearing, we need better information on the relative success of fish rearing in the lower river and Delta relative to fish rearing in the gravel bedded reaches of the tributaries.

Entrainment in water diversion facilities and predation, particularly from non-native bass, are also a major problem for salmon during the juvenile life stage. "Predators are commonly implicated as the principal agent of mortality among fry and fingerlings of chinook…[and] other fish are generally considered to be the most important predators of juvenile salmon" (Healey, 1991). Black bass are especially a problem in captured mine pits on the Stanislaus and Tuolumne Rivers and downstream of small dams and diversion weirs (SP Cramer, 1995 and EA Engineering, 1991 in CMARP). However, entrainment and predation are less related to flow then morality associated with high temperatures during the outmigration period. Juvenile growth rates probably affects mortality from predation and entrainment because smaller juveniles are more susceptible to mortality. Juvenile growth rates may also affect ultimate survival because faster growing juveniles and smolts migrate out of the system earlier in the spring before temperature becomes a major source of mortality and because larger juveniles travel downstream faster (Healey 1991, CMARP).

Contaminated agricultural and urban runoff may also increase outmigrating juvenile salmon's susceptibility to disease, such as *Ceratomyxa*, which causes a high mortality rate in Chinook and flourishes in organic sediments and possibly in mine pits (CMARP p 19 and 20).

We hypothesize that improving juvenile growth rates will improve the rates of successful smolt outmgration and may also reduce mortality from diversions and predation. Based on robust results from research in the Yolo Bypass, it appears providing seasonally inundated floodplain habitat is perhaps the best way to ensure adequate growth before outmigration to the Delta and Ocean. If nothing else, providing seasonally inundated floodplain habitat will provide better habitat for the young that migrate or are washed out of the gravel bedded reaches early.

Increased flows during the rearing period combined with floodplain restoration should help increase overall growth rates and potentially decrease predation. Increased flows during this period should also dilute poor water quality. Increased flow may also decrease negative effects on salmon from contaminants and disease. Agricultural return flow from the west side of the San Joaquin did not cause any detrimental effects on growth and survival of hatchery-born Chinook salmon when the return flows were diluted by 50% or more with water from the San Joaquin (Saiki et al., 1992, from CMARP p 19).

3.4.6 Smolt Outmigration

As mentioned in the previous section, after fry emerge from the gravel the majority disperse downstream, especially during increases in flows or after storm events. Whether young fish migrate out of the tributaries soon after emergence or whether they rear in the tributaries, they eventually undergo smoltification and make their physiological transition to salt water. Several factors were found to trigger smoltification, including changing hormone concentrations, increasing photoperiod, increasing temperature, and increasing body size (Myrick and Cech, 2001). While most of these factors cannot be influenced by changing management actions in the tributaries or the Delta and are not discussed in this report, temperature and body size are affected by flow and can be influenced by reservoir reoperation.

Smolts require lower temperatures than rearing juveniles. While higher temperatures in the 60-66°F (15-19°C) range can optimize growth of juveniles and better prepare them for smoltification earlier, lower temperatures are more optimal during the smoltification process. A comprehensive study by Myrick and Cech (2001) found that Chinook have a better chance of surviving in the Ocean if they undergo smoltification at lower temperatures, ranging from 50-63.5°F (10-17.5 °C). Warmer temperatures in the February –March period (which occur on floodplains) stimulate growth of juveniles so they are larger before they undergo smolification and therefore larger when they enter the Ocean (Myrick and Cech, 2001). Larger juveniles are also able to smolify before harmful high late spring temperatures set in. Cooler temperatures are necessary in the smolt outmigration period of April – June. The need for warmer temperatures in the early spring and cooler temperatures in late spring reflects the historical hydrograph, where large, cold snowmelt flows dominated the San Joaquin Basin later in the spring.

Body size is an important function of the success of outmigrating smolts and the development to smoltification (Dlarke and Shelbourn 1985; Johnssson and Clarke 1988 in Myrick and Cech, 2001). It is important that Chinook reach an appropriate size for smolting before they arrive in saltwater. Relatively warm temperatures can be beneficial for growth provided adequate food supply.

High water temperatures, low flows and entrainment may cause increased mortality rates in outmigrating smolts and affect growth of juvenile Chinook. High water temperatures, particularly in May and June may pose the largest threat to juveniles that remain in the tributaries and in the Delta later in the spring. Baker et al (1995) found that 50% of Chinook smolt that migrate through the Delta from the Sacramento River die when temperatures reach 72-75°F (22-24°C) McCullough (1999 in Moyle) found that few fish can survive temperatures greater than 75.2°F (24°C) even for short periods of time. Temperature data from the middle San Joaquin, the Merced, and the Tuolumne Rivers typically have prolonged temperatures above 77°F (25°C) from the end of May through September (USGS data).

Studies in the Delta found that entrainment rates increase exponentially with increases in diversion rates (no citation in CMARP). "Up to 44% of Chinook salmon juveniles emigrating down the San Joaquin River between 1973 and 1988 dies because of entrainment in CVP and SWP facilitites" (EA Engineering 1996 in McBain and Trush). The CALFED Strategic Plan for Ecosystem Restoration cites flow in the Sacramento River, salinity distribution and the position of the Delta cross-channel as the principal limiting factors affecting smolt survival in the Delta (CALFED App C). The Delta cross-channel and entrainment are recognized as significant barriers to juvenile outmigration, but this study does not address restoration techniques for these mortality factors.

Prolonged periods of high flows from January through June, especially from late February through mid-April, will reduce temperatures and help flush out outmigrating juveniles and smolt (CMARP). There are several programs underway and several measures that could be taken to improve juvenile outmigration and survival. The Vernalis Adaptive Management Plan (VAMP) currently addresses increasing instream flow down the lower San Joaquin over a 31-day period in April and May to improve conditions for Chinook outmigration. Increased flows during outmigration improve juvenile/smolt survival in the San Joaquin basin tributaries and Delta. Studies have shown that survival of fry and smolts passing through the Sacramento-San Joaquin River delta were highly correlated with discharge of the Sacramento River (Healey, 1991 and USFWS, 1998 in SP Cramer). Smolt survival was high (about 78%) when releases from Goodwin Dam, on the Stanislaus River were increased in late April in 1986 and 1988, but were low (28%) when Goodwin releases were lower in April 1989. A substantial increase in migrating juvenile was measured when flows were increased in the Stanislaus River for seven days in April 1995 (SP Cramer 1995 in CMARP).

3.4.7 Conclusion

The importance and availability of data compiled on the mortality factors affecting fall-run Chinook in the San Joaquin Basin is summarized in a table (Table 3.7). The more "important" factors are those known to more severely affect mortality of Chinook, and the "certain" factors are those that have substantial scientific data gathered on the subject. When scientific data was not available, the resource managers reviewing and writing this report made some qualitative judgments about which factors were more important than others. This table provides a coherent summary of where data is lacking and what mortality factors should receive more management and research attention. An "uncertainty" table was created for each conceptual model.

A hydrograph of unimpaired (pre-dam) (Figure 3.8) and regulated (post dam) (Figure 3.9) normal water years for the Tuolumne displays the flow needs of Chinook throughout different months of the year. For example, it is clear that the unimpaired hydrograph provides enough water to meet the needs of migrating adult Chinook in the fall and outmigrating smolts in the spring. The regulated Tuolumne River in 1971 does not adequately provide enough water for juvenile and smolt to migrate to the ocean after the end of April. A cross section of the river displays how unimpaired flows would fill in and flow through a channel and what needs this flow would fulfill for Chinook (Figure 3.10).

Table 3.7 Uncertainty Table for Fall-Run Chinook Salmon in the San Joaquin Basin and Tributaries

Mortality Factors	Lower San Joaquin	Middle San Joaquin	Merced River	Tuolumne River	Stanislaus River
Adult Migration					
Straying	●	○	○	○	○
Water quality	⬤	○	○	○	○
Dewatered reaches	●	⬤	⬤	⬤	⬤
High temperatures	⬤	⬤	⬤	⬤	⬤
Lack of Spawning Habitat					
Decreased channel complexity	NA	⬤	⬤	⬤	⬤
Fine sediment	NA	◯	◯	⬤	◯
Subsurface Flow	NA	◯	◯	◯	◯
Temperature	NA	●	●	●	●
Available gravel	NA	◯	◯	⬤	◯
Egg and Avelin development					
Temperature	NA	●	●	●	●
Low substrate flow	NA	⬤	⬤	⬤	⬤
Fine sediment capping	NA	◯	◯	⬤	⬤
Dewatered redds	NA	⬤	⬤	⬤	⬤
Juvenile growth					
Access to food supplies	◯	◯	◯	◯	◯
Temperature	⬤	⬤	⬤	⬤	⬤
Predation	⬤	⬤	⬤	⬤	⬤
Disease	◯	○	○	○	○
Juvenile & smolt migration					
Temperature	⬤	⬤	⬤	⬤	⬤
Entrainment	⬤	○	○	○	○

LEGEND: **Relative Certainty** — ● High Certainty; ○ Low Certainty. **Importance** — ⬤ High Importance; ● Low Importance. **NA = Not Applicable**

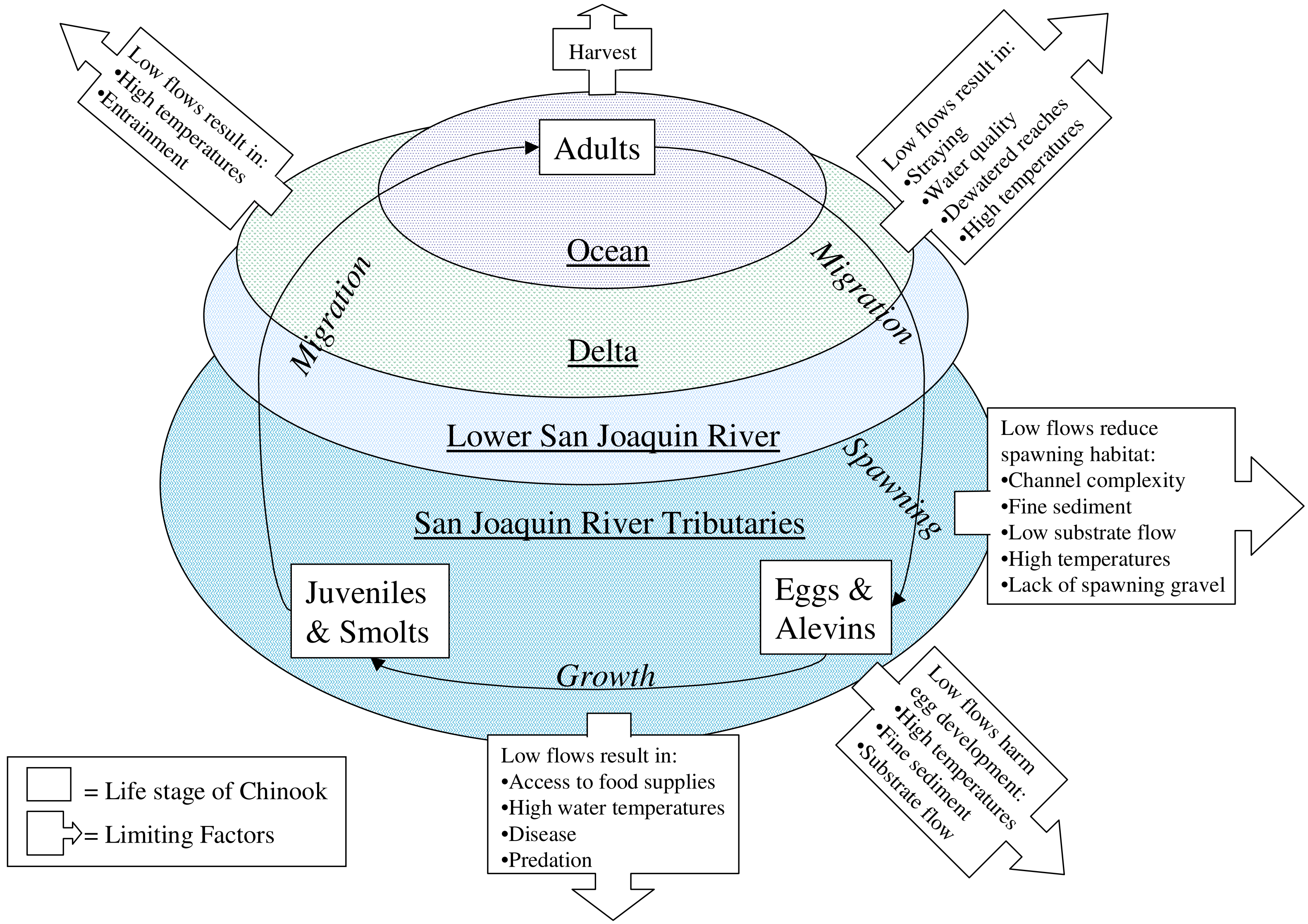


Figure 3.7. Conceptual Model for Fall-run Chinook Salmon in San Joaquin River Basin Tributaries.

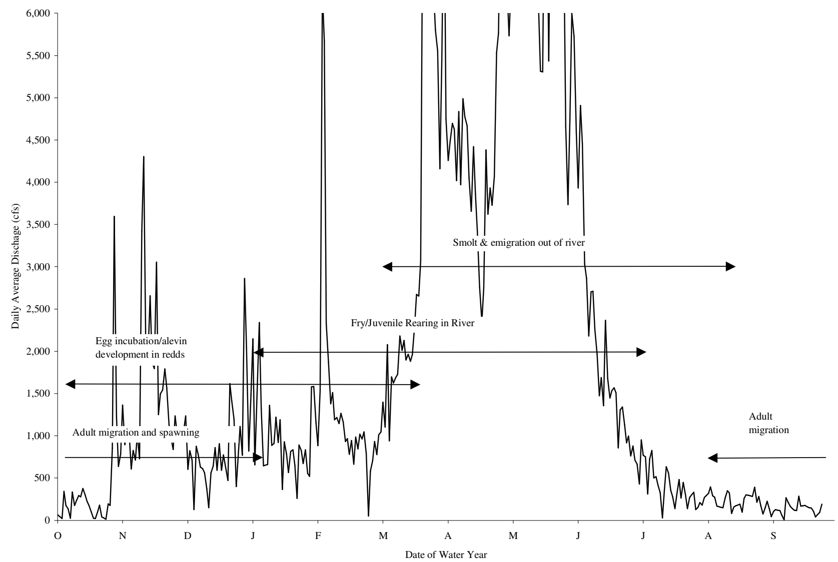


Figure 3.8. **Conceptual 1928 Unimpaired Hydrograph.** Normal water year hydrograph for Tuolumne River at LaGrange showing ecosystem needs of fall-run Chinook salmon.

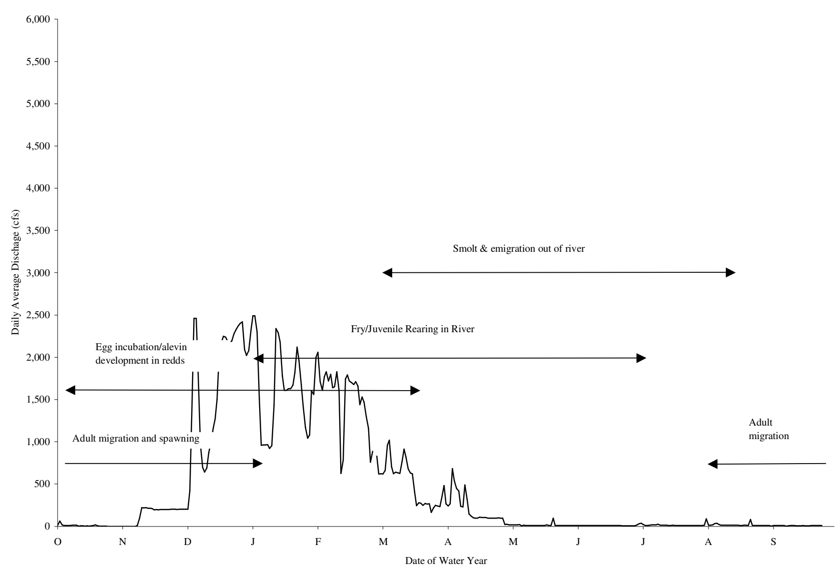


Figure 3.9. Conceptual 1971 Regulated Hydrograph. Normal water year hydrograph for Tuolumne River at LaGrange showing potential mortality factors of fall-run Chinook salmon.

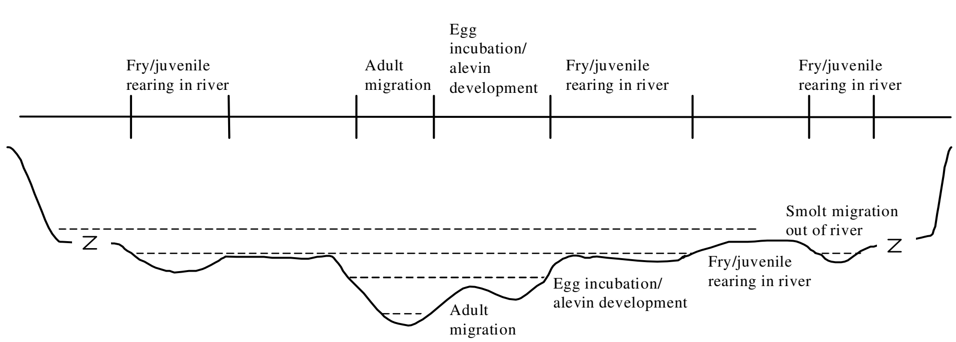


Figure 3.10. Conceptual Cross Section for Fall-Run Chinook Salmon.

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Chapter 4. San Joaquin Basin: Environmental Setting

4.1 OVERVIEW OF SAN JOAQUIN BASIN

The four principal rivers of the San Joaquin Basin and their watersheds share relatively geologic, climactic, hydrologic, and geomorphic characteristics. These similarities have resulted in relatively similar patterns of vegetation and aquatic species. This chapter provides an overview of the geography and geomorphology of the San Joaquin Basin rivers as well as the historical extent and condition of riparian forests, wetlands, and salmonid populations.

4.1.1. Geography and Hydrology

The San Joaquin River Basin drains 13,513.5 mi^2 (35,000 km^2), along the western flank of the Sierra Nevada and eastern flank of the Coast Range in the Central Valley of California. The Merced, Tuolumne, and Stanislaus rivers are the three major tributaries that join the mainstream San Joaquin from the east before it flows northward into the Sacramento-San Joaquin Delta (Figure 4.1). In this document, the middle San Joaquin refers to the San Joaquin River from Friant Dam to the confluence with the Merced River. The lower San Joaquin refers to the San Joaquin River from the confluence with the Merced to the Delta.

Table 4.1. Watershed Characteristics of the San Joaquin Basin.

River	Drainage Area (mi^2)[1]	Annual Runoff (thousand acre feet)[2]	Maximum Elevation (feet)
San Joaquin Mainstem	1,676	1,780	13,986
Merced	1,039	989	13,114
Tuolumne	1,541	1,740	13,057
Stanislaus	900	1,030	11,569

[1] Source: California Department of Water Resources (1988). Drainage area above gauges. [2] Source: US Geological Survey (1988). See Table 5.1.

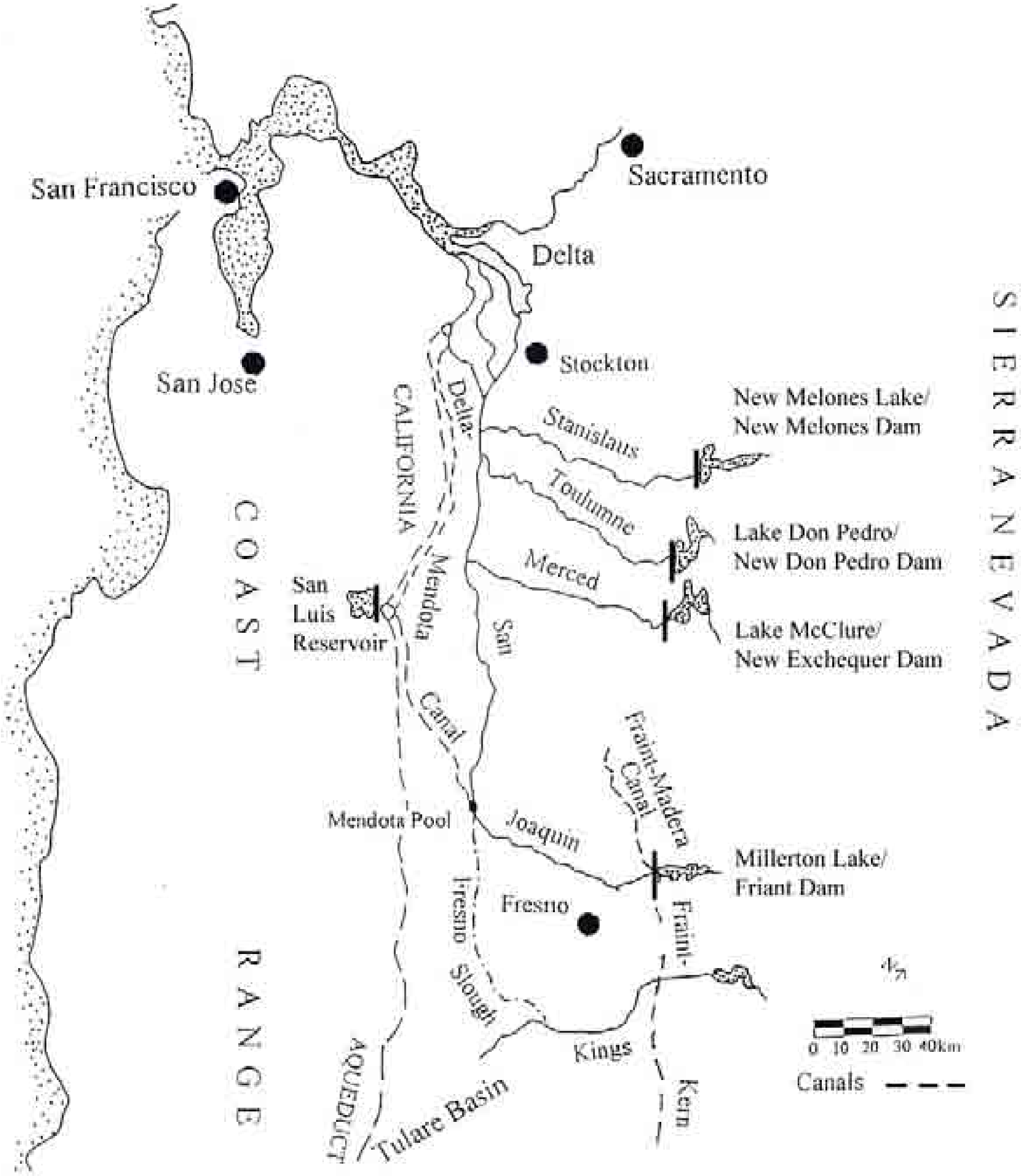

Figure 4.1: Map of the San Joaquin River Basin. Major dams and reservoirs, canals and the California Aqueduct. Diversion dams and canal on the Tuolumne, Merced and Stanislaus not shown.

Precipitation in the Basin is predominantly snow above 3,937 feet (1,200 m) in the Sierra Nevada with rain in the middle and lower elevations and in the Coast Range. As a result, the natural hydrology reflects a mixed runoff regime of summer snowmelt and winter-spring rainfall runoff. Most flow in the Basin is derived from snowmelt from the Sierra Nevada rather than precipitation, as compared with the Sacramento watershed (Figure 4.2).

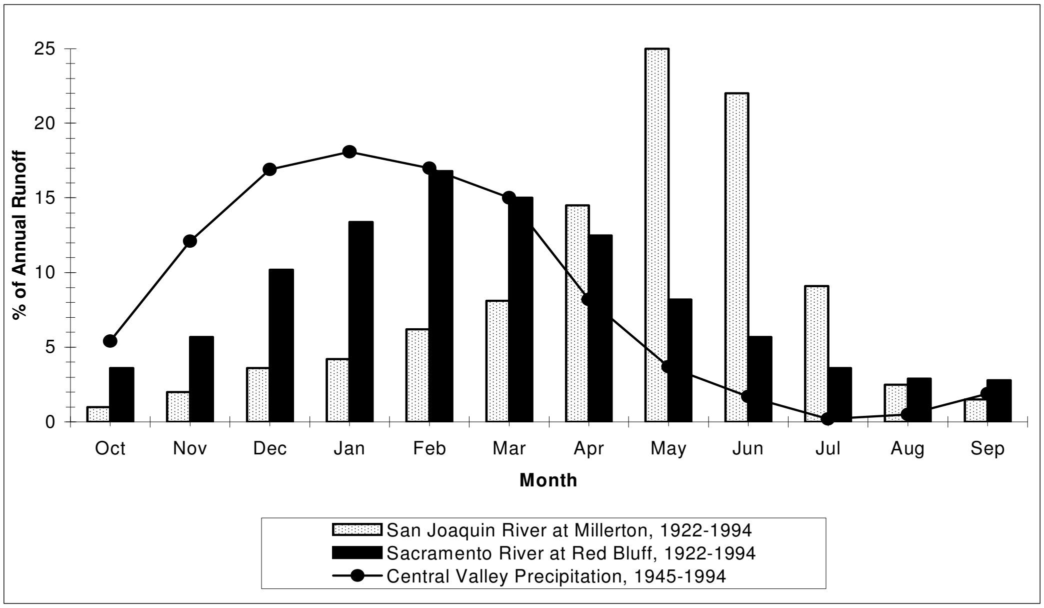

Figure 4.2. Average Monthly Unimpaired Natural Discharge from the Upland Sacramento & San Joaquin River Watersheds. Source: The Bay Institute, 1998.

Typical of Mediterranean climate catchments, flows vary widely seasonally and from year-to-year (Figure 4.3 and 4.4). Although the bulk of the annual flow occurs in the spring, peak channel forming events often occur in the winter, as shown in figure 4.5 depicting the magnitude and timing of the instantaneous peak flow events on the middle San Joaquin River at Friant. Although, figure 4.5 only includes the timing of annual peak flows on the San Joaquin at Friant, it is probably representative of the timing of peak flow events on the other tributaries. Nine of the ten largest peak flow event occurred before February 15 on the San Joaquin at Friant.

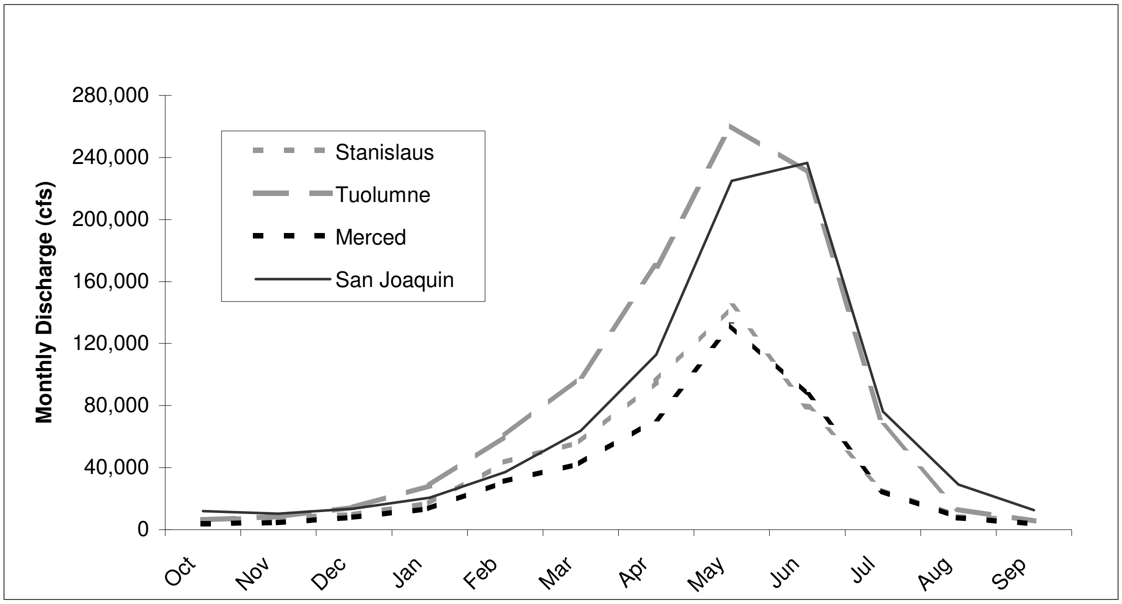

Figure 4.3. Median Monthly Unimpaired Discharge, Water Years 1904 - 1926. Unimpaired median monthly discharge for all San Joaquin basin tributaries. Data from USGS Stations: Stanislaus (Knights Ferry #11-302000); Tuolumne (La Grange, #11-289650); Merced (below Merced Falls Dam near Snelling, #11-270900); San Joaquin (below Friant, #11-251000). Note: Some data missing for Stanislaus (1915 - 1916) and Merced (1915; 1914 for Dec. - Sept.; 1916 for Oct. - Nov.).

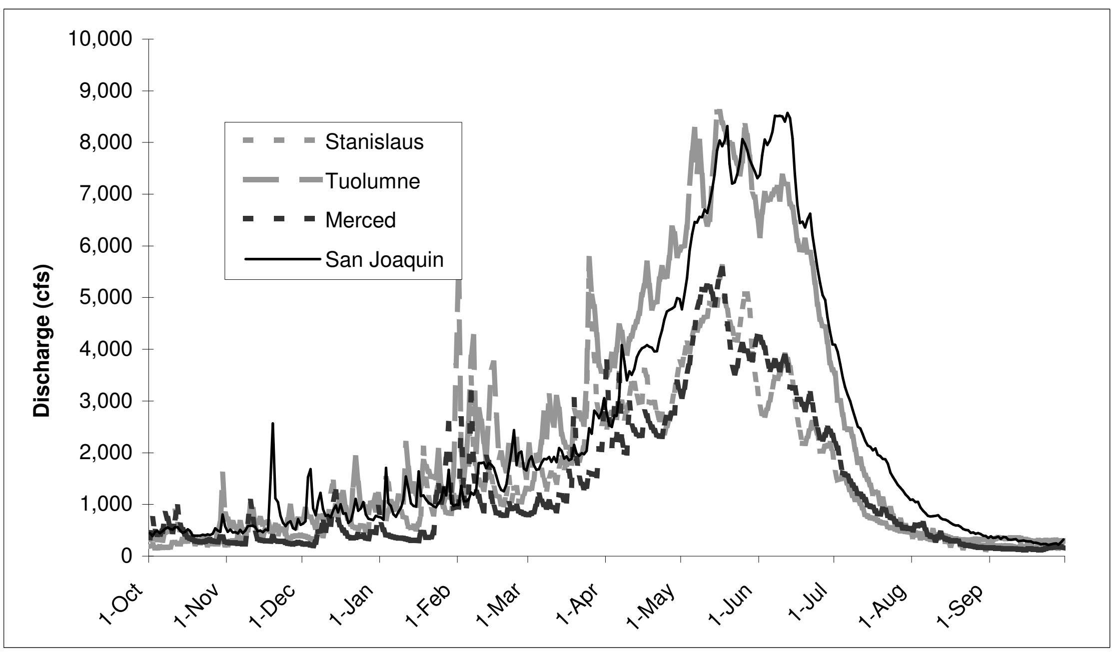

Figure 4.4. Average Hydrographs for Normal Unimpaired Flows in San Joaquin Basin Tributaries. Hydrograph components for unregulated flow conditions in Normal water years for each San Joaquin Basin Tributary, averaged over period of record. Tuolumne (1918-1979, N=15, data from USGS Station at LaGrange #11-289650); Stanislaus (1900-1932, N=7, data from USGS Station at Knights Ferry #11-302000); Merced (1901-1925, N=5, data from USGS Station below Merced Falls near Snelling #11-270900); and San Joaquin (1900-1999, N=21, data from USGS Station below Friant #11-251000).

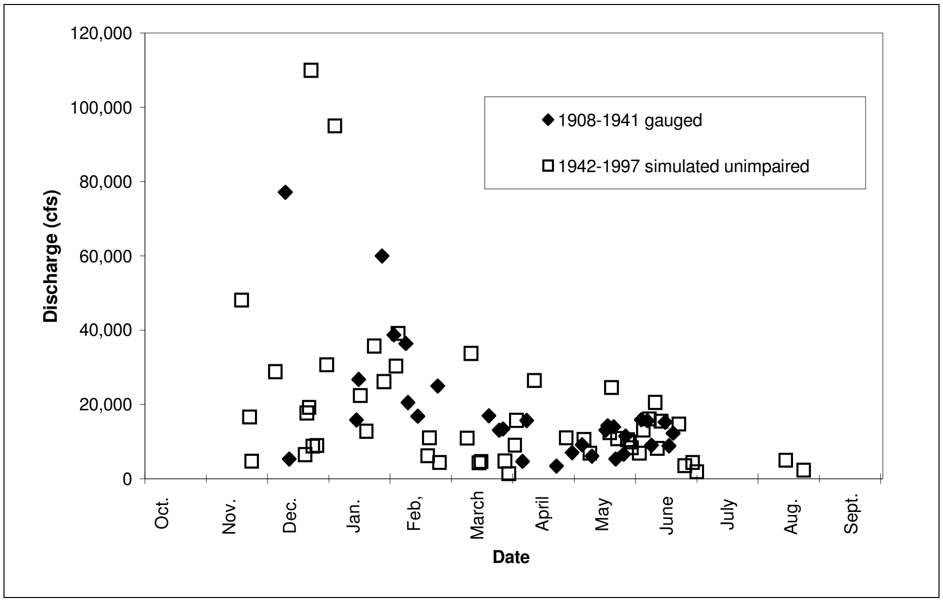

Figure 4.5. Seasonal distribution of annual peak discharges on San Joaquin River at Friant: gauge data WY 1908-1941, simulated unimpaired flows 1942-1997. Note that lower magnitude 1942-1997 simulated unimpaired is lower than actual unimpaired due to simulation error from the confounding effects of upstream hydropower facilities.

4.1.2 San Joaquin Basin Geology and Geomorphology

The San Joaquin, Merced, Tuolumne, and Stanislaus Rivers all originate at the crest Sierra Nevada and flow westward into California's Central Valley. Over the last 3 million years techtonic forces have uplifted the Sierra Nevada fault block has uplifted while the Central Valley grabben has subsided. As the Sierra Nevada rose successive periods of glaciation during the Pleistocene eroded vast quantities sediment and deposited them in the Central Valley. In the upper watersheds, glaciation stripped away the overlying sedimentary and volcanic formations exposing the great granitic batholiths that characterize the upper watersheds today. The exposed, relatively erosion resistant granitic batholiths are most pronounced in the upper watersheds of the Tuolumne and Merced Rivers in Yosemite National Park and in the San Joaquin. Formations of volcanic rock overlying the granitic batholith are more prevalent in the upper watershed of the Stanislaus River.

The alluvial features that characterize the geomorphology of the San Joaquin Basin Rivers in the Central Valley were formed by climate-driven cycles of erosion and deposition during the Pleistocene and Holocene (15,000 years to the present). In colder, wetter periods the glaciers advanced quarrying enormous quantities of sediments from the bedrock in the upper watersheds. During periods of glacial retreat, run-off from the melting glaciers transported these sediments downstream and deposited them in a series of coallesing alluvial fans on the east side of the Central Valley. During interglacial periods when sediment in the upper watershed was less abundant, the rivers entrenched these alluvial fans forming vertical bluffs along their course to the axis of the Valley. During these cycles of glacial advance and retreat, the San Joaquin Basin Rivers underwent several phases of fan construction and dissection (Wahrhaftig and Birman 1965, Marchand andAllwardt 1981, Janda, 1965). Today, 15,000 years after the last glacial retreat began, the valley bottoms of the San Joaquin Basin Rivers are entrenched in these Pleistocene fan formations, which form vertical bluffs of alluvial material 50 to 150 feet above the current river channel. The width of the valley bottom between these bluffs ranges from 0.25 to 4.5 miles wide. The maximum valley bottom width on the middle San Joaquin is 1.2 miles while the maximum width on the Merced River is 4.5 miles. Figure 4.7 depicts a cross section of the San Joaquin River that has entrenched into the Pleistocene alluvial fan 10 miles below Friant Dam.

The bed material of the San Joaquin Basin rivers transition from gravel to sand near the western edge of the entrenched alluvial fan formations. As the rivers entrenched the Pleistocene fan formations, they eroded and transported the finer alluvial materials downstream leaving behind the coarser gravels and cobbles. At the western edge of the fans, where the gradient drops abruptly and the bluffs no longer confine the stream, the rivers have deposited their remaining bed load of sand. Finer suspended sediments are carried farther downstream to the flood basins of the lower river and the Delta. Figure 4.6 shows the abrupt change in stream gradient that generally coincides with the transition from gravel bedded to sand-bedded reaches at the western edge of the entrenched alluvial fan formations.

Figure 4.6 illustrates the similarities and differences in stream gradients between the four rivers between the upstream dams and their confluence with the mainstem San Joaquin River. The gravel bedded reaches of the Merced and Tuolumne Rivers (.0008 – .002) are considerably steeper than the gravel bedded reaches of the San Joaquin and the Stanislaus (.0004 – .0001).

Despite these differences in slope, there are important similarities in the planform of the rivers through the gravel and sand bedded reaches. In the steeper gravel bedded reaches closer to the dams, the valley bottom widths are relatively wide, and the rivers were historically characterized by a multi-branched anastomosing channel form. These systems included numerous channels and “sloughs” paralleling a dominant channel, but channel avulsion during high flow events probably caused dominant channel to alternate between the various multiple channels overtime. Today, the rivers in this zone are generally confined to one main channel due to a lack of frequent flood flows and alterations to the channel from local levees, dredger mining deposits, and channel incision. Downstream of these historically multi-branched channel networks, the valley bottom narrows between the alluvial bluffs and the channel assumes a single threaded meandering form. On the western edge of the Pleistocene alluvial fan where the valley bottom is not longer confined by bluffs, the river historically spread out over broad flood plains dissected by high flow channels and sloughs that drained to the main stem of the San Joaquin. Today these lower reaches are confined by levees that convey flood flows directly to the main stem.

The main stem of the San Joaquin was historically characterized by broad floodplains that were seasonally inundated during winter and spring flood events. The largest flood

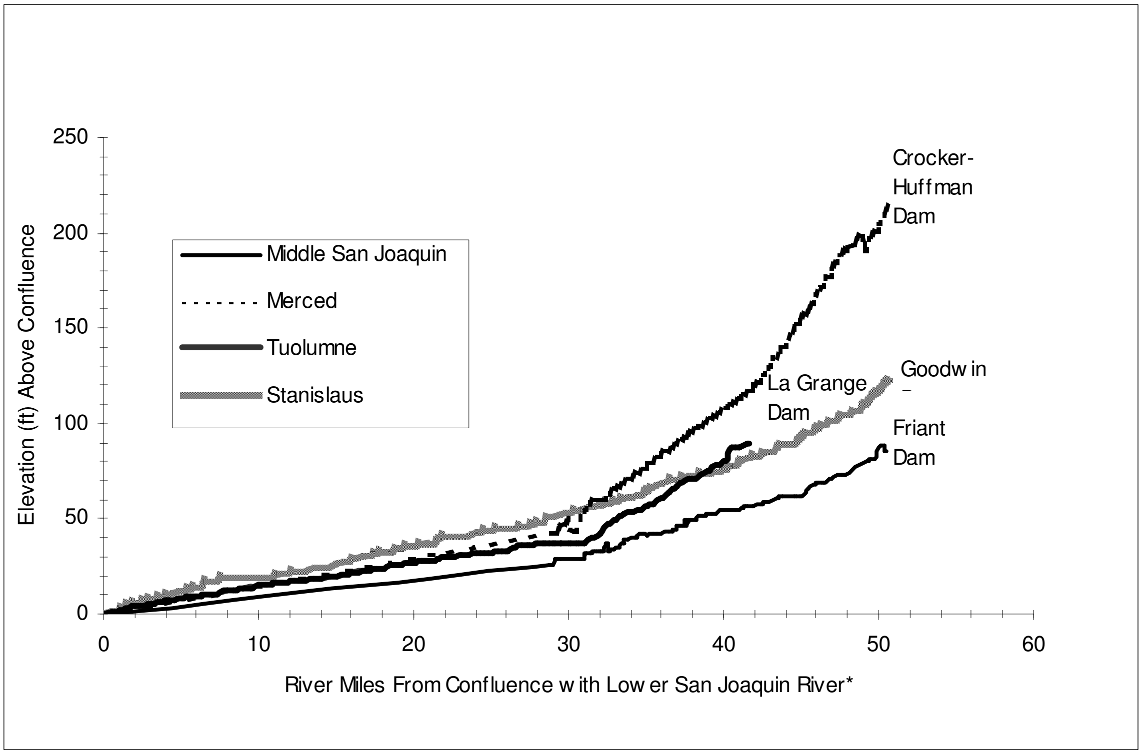

Figure 4.6. Water Surface Profile of San Joaquin Basin Tributaries. San Joaquin 1989 water surface profile from Cain 1997. Merced channel slope data from Vick 1995. Tuolumne River 4,000 cfs water surface profile generated from 1969 USGS channel capacity study in McBain and Trush 2000. Stanislaus water surface profile from Kondolf et al, 2001. Note that La Grange Dam is actually at mile 52.1 on the Tuolumne River. Elevation data from mile 41 to La Grange Dam not shown.
*Distance from Mendota Pool to Friant Dam for middle San Joaquin. Distance from Crocker-Huffman Dam to Cressey for Merced

basin was located upstream of the Merced River where the middle San Joaquin distributed its flows into a complex network of sloughs that branched off both sides of the river. During annual floods, these channels overflowed inundating an area 5-10 miles wide and that encompassed more than 400 square miles (The Bay Institute, McBain and Trush 2002). Downstream of the Merced river, the main stem seasonally flooded smaller, but still significant areas 1-5 miles wide, particularly upstream of the confluences with the Tuolumne and Stanislaus Rivers where floodwaters regularly backed-up.

4.1.3. San Joaquin Basin Historical Riparian and Wetland Conditions

The San Joaquin River and its tributaries were historically flanked by a continuous band of woody riparian vegetation and vast seasonal marshes along their courses in the Central Valley. The species composition and extent of riparian and marsh vegetation varied according to the geomorphology and hydrology of the various reaches. In the upper reaches where the river courses are confined by alluvial bluffs the maximum extent of riparian vegetation is limited to the area between the bluffs. In the steeper gravel bedded reaches, large area of river wash (exposed sand and gravel) bordered the low flow channel interspersed and bordered by patches of willow scrub, cottonwoods, valley oaks, sycamores and other woody riparian species. Today, in the absence of high flood flows below the dam, riparian vegetation has colonized the river wash areas forming narrow bands dominated by alder along the low-flow channel. Historical riparian vegetation more distant from the low-flow channel have been eliminated by agriculture and gravel mining activities.

Downstream of the gravel bedded reaches where the river is no longer confined by bluffs, the river once spread-out from its banks through extensive riparian and marsh areas. Early on, levees were constructed along the river in these unconfined areas, directing all floodwaters downstream and preventing widespread inundation. Forests on the landward side of these levees were cleared to make way for agriculture.

An analysis of early soil maps and a variety of sources done in the Sierra to the Sea report (The Bay Institute 1998 pg 2-30 and figure G-6) estimated the approximately 329,000 acres made up the historical riparian zone in the San Joaquin Valley (below 300 feet elevation). "Available historical documents indicate that under natural conditions, a recognizable riparian zone was present along virtually every minor and major stream in the Central Valley…In the San Joaquin Valley, riparian zones were less extensive, and generally present in narrower bands…and bluffs along the upslope portions of the tributaries confined the floodplain in parts of the San Joaquin River Basin." (The Bay Institute, 1998). In its pristine condition, the natural vegetation of the floor of the San Joaquin Valley was comprised: permanently flooded tule marshes, seasonal marshes in areas that were intermittently inundated, riparian forests along perennial streams, lakes or sloughs, oak woodlands within the 100-year floodplain and in the river deltas of the larger streams, extensive prairie in the upland areas, and the San Joaquin saltbush on more xeric, alkaline sites.

Woody riparian vegetation in the flood basins of the mainstem San Joaquin River was largely confined to relatively narrow bands of coarse soil that formed the natural levees of the river. As the San Joaquin River annually inundated its flood plains and basins, it dropped its coarser sediment loads along its banks forming these levees. These levee formations were more suitable for riparian vegetation both because of their coarser soil texture and their higher elevation relative to the surrounding floodplains and basins. The soils characterizing the flood basins were composed largely of fine clays which combined with long periods of inundation, were not conducive to supporting woody riparian vegetation. Rather they supported the vast tule marshes that once characterized much of the low lying lands of the San Joaquin Basin

4.1.4. San Joaquin Basin Historical Salmonid Populations

Historically, the San Joaquin River and its tributaries supported large runs of both spring- and fall-run Chinook salmon, and steelhead trout (*Oncorhynchus mykiss*) (Clark 1929, Yoshiyama et al, 1998, 2000). The salmon in the San Joaquin Basin are the world's southern-most run of native Chinook salmon (Healey 1991). "In its pristine state, the Sacramento-San Joaquin drainages' production of Chinook salmon rivaled southern Alaska's. In the San Joaquin system alone, the escapement ran upwards of 300,000 to 500,000 Chinook annually (Brown and Moyle 1993, Yoshiyama et all 2000).

The most comprehensive accounts of salmonid populations in the San Joaquin Basin Rivers are descried in a series of articles by Yoshiyama, Fisher, and Moyle (Yoshiyama et al 1996, 1998, 2000). According to these accounts, salmon populations in the San Joaquin Basin were reduced very early due to construction of numerous small dams and irrigation diversions. The major exception was the San Joaquin River upstream of the Merced river where permanent obstruction of salmon did not occur until the construction of Kerckhoff dam in 1920 blocking migration to the upper watershed but still leaving abundant spawning beds downstream. Kerckhoff Dam was followed by the construction of Friant Dam in 1941 and its diversion canals which eventually resulted in the total extirpation of salmon from the middle San Joaquin River.

The following account by Yoshiyama et al. (2000) describes the impacts of early irrigation works on San Joaquin and its tributaries.

> "Dams and diversions were constructed on some tributaries as early as the 1850s (e.g., Tuolumne and Merced rivers; J.B. Snyder, National Park Service, unpublished memorandum). While they were usually small and temporary, the complete lack of allowance for fish passage unquestionably affected the salmon runs to some degree. The California Fish Commission noted that: dams on the headwaters of the Stanislaus, Tuolumne, San Joaquin, and the upper Sacramento Rivers: blocked the salmon from the spawning grounds, which mostly were above the dams, a major cause in the opinion of the Fish Commission, for the decrease of Salmon (CFC 1884:15). The dams and diversion structures on the San Joaquin Valley tributaries for the most part were emplaced relatively early during the period of Euro-American settlement in California, and as a consequence, there was very little documentation, or even historical accounts, of early salmon abundances and distributions in those southern tributaries. By 1988, it was reported that: salmon do not run in the San Joaquin in large numbers" (Collins 1892: 163), in an apparent testimony to the rapid and early demise of most of the large runs in the San Joaquin River Basin. The major exception was the upper San Joaquin River basin. . . "

Yoshiyama (2000) also points out that even where dams did not totally block access to spawning habitat they had a major impact on salmon by altering flows and entraining juvenile salmon.

> "In addition to blocking the upstream migration of salmon, dams of various sizes caused significant degradation of habitat in downstream reaches by restricting streamflows, the consequences of which included elevated water temperatures, hightly variable water levels, increased siltation of streambeds, net loss of gravels

> duc to lack of replenishment from upstream sources, and the exacerbation of pollution effects (Holmberg 1972; Reynolds et al. 1993) . . .
>
> "Entrainment losses of juvenile salmon to irrigation diversions were particularly serious in the San Joaquin River basin, where the earlier irrigation season coincided more closely with the downstream migration period and larger portions (up to 20 – 40%) of the total river flow were diverted during some monts (Hallock and Van Woert 1959; Homberg 1972)

4.2.1 San Joaquin

Geomorphology

The historical channel of the Middle San Joaquin was characterized by a complex maze of secondary and high flow channels. From Friant Dam downstream to Gravely Ford, the San Joaquin River is entrenched (about 98.4 ft or 30 m) in a Pleistocene alluvial fan, composed of cemented sands and gravels overlying pumice layers up to 65.6 ft (20 m) thick (Figure 4.7) (Janda 1965, Marchand and Allwardt 1981). The Friant Pumice Member of the Turlock Formation, dating from approximately 620,000 years before present (y BP)(Janda 1965), is resistant to erosion, forms impressive vertical bluffs, and creates at least one bedrock control in the channel. The Friant Pumice is overlain by the Riverbank Formation, approximately 130-450,000 y BP, and the Modesto Formation, approximately 12-42,000 y BP (Marchand and Allwardt 1981), both cemented gravels that support vertical bluffs but are considerably more erodible than the Friant Pumice. Between the bluffs of older units, the bottomland is mostly floored by modern alluvium, which is easily eroded and redeposited by the present river. The entrenched valley bottom is typically 0.31-.62 miles (500-1000 m or 1,637-3,274 feet) wide. The channel elevation is controlled by granite bedrock outcrops for the first 4.97 ft (8 km) downstream of Friant Dam and by at least one Friant Pumice outcrop 9.3 ft(15 km) downstream of Friant Dam." (Cain, 1997)

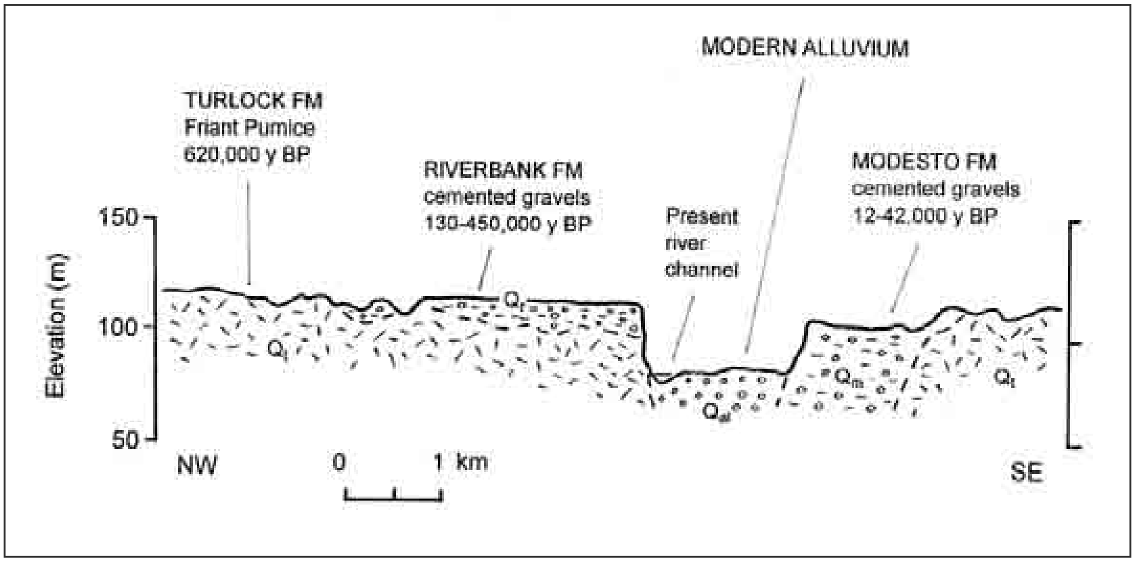

Figure 4.7. Simplified geologic cross section of the San Joaquin River valley bottom and adjacent surfaces of the Pleistocene alluvial fan from Janda (1965). Q_{t},: Friant Pumice Member of the Turlock Formation, Q_{r},: Riverbank Formation, Q_{m}: Modesto Formation, Q_{al}: modern alluvium.

The Bay Institute (1998) provides a detailed description of the geomorphic process of the San Joaquin River: "In its natural state, the San Joaquin River meandered across ancient alluvial fans towards the main axis of the valley floor. Where it first left the Sierra foothills and traversed the intermediate transport zone, the San Joaquin was a gravel-bed, intermediate gradient river. As it approached the main axis of the valley flood, the southwesterly flowing river emerged from confining bluffs into a lower-gradient, depositional topography. Here, the river distributed its high flows into a complex network of sloughs that branched off both sides of the river, and then, near Mendota, made an abrupt right turn to flow northwesterly (towards the Delta) along the main axis of the valley. Near this point (Mendota), the San Joaquin merged with Fresno Slough, a waterway which at that point was wider and deeper than the San Joaquin itself. Fresno Slough was part of an intricate slough system that exchanged water between the Tulare Lake Basin and the San Joaquin River (Farquhar 1932b, Williamson 1853, Davis et al. 1959). Downstream of Mendota, the San Joaquin flowed through a network of large slough channels traversing extensive riparian woodland, tule marshes, and backwater ponds until it joined with the Merced River. After this, the floodplain was more confined and the river adopted a highly sinuous pattern of rapid channel meander migration. This created a rich complex of oxbow lakes, backwater sloughs, ponds, and sand bars in a mosaic of successional states. In its lower reaches just above the Delta, the river formed low natural levees approximately six feet high (Thompson 1957, Atwater and Belknap 1980)" (page 2-25 The Bay Institute 1998).

Riparian vegetation

Information on historical extent of riparian vegetation on the San Joaquin is limited due to the lack of early maps and the early development of agriculture, particularly downstream of Mendota Pool. McBain and Trush et al (2002) provide the most detailed description of historical accounts and maps of early riparian and marsh conditions on the San Joaquin:

> "The general picture of the valley floor is riparian forest and scrub egetation alon the main river channels, especially on elevated surfaces of fine sediment deposited along the channel margins during flood overflow events (when wter leaving the channel would drop sediment as it spread over the land). These localized zones of woody riparian vegetation were flanked by extensive tule marshes that formed where overflow waters spread over the nearly flat flood basin. The outer limit of the tule marshes was flanked by saltbush or grassland (prarie) communities; the tule marsh limits approximately conincided with the boundaries of the natural flood basin (Fox 1987a)"

The California Debris Commission developed detailed maps of the river corridor from highway 99 to the Merced River in 1914, well after much of the lower flood basin had been developed for agriculture. They depict large areas of riparian vegetation, marsh, and riverwash along the river, but it is difficult to discern species composition from these maps and nobody has calculated the total area of vegetation depicted on these maps. The 1914 maps, soils maps, and early accounts indicate that the floodplain of the river between Mendota and the Merced consisted of a large expanse of tule marsh bordered by relatively narrow strips of woody riparian vegetation that was limited to the coarser natural levee soils along the anastomosing river channels.

These vast marshes surrounding linear bands of woody vegetation along the channel are corroborated by Brewer's early description of the valley (Brewer 1949): "From a nearby hill yesterday we could look over an area of at least two hundred square miles and not see a tree as far as the river, where, ten miles off, there is a fringe of timber along the stream." Carson description of the confluences of the Mariposa, Chowchilla, and Fresno Rivers that enter the San Joaquin between Mendota and the Merced River (1950 - as summarized in fox 1987b) provides further evidence of the vast marshes:

> "The Mariposa, Chowchilla, and Fresno Rivers may be classed with the Calaveras, being running streams during the rainy season and spring only. These streams do not enter directly into the San Joaquin, but their united waters form the immense tule marsh between the bend of the San Joaquin and the mouth of the Merced; the water thus collected enters in the San Joaquin at many different points during high water."

It seems fairly obvious that the hydrology, soils, and geomorphology of the vast flood basin between Mendota and the Merced was not conducive to large stands of woody riparian vegetation. Oaks, cottonwoods, willows and other woody species do not tolerate the fine textured clay soils, poor drainage, and prolonged inundation that historically characterized the flood basin. These woody species only occurred where coarser alluvial soils were deposited in long linear deposits on the natural levees of the many parallel channels or at the confluence of these channels with other channels or rivers. Such a riparian and marsh zone was described by Fremont in his memoirs describing his explorations during the 1840's. Describing a days travel along the San Joaquin south of the confluence with the Merced River during April of 1848, he reported:

> "Here the country appears very flat; oak-trees have entirely disappeared, and are replaced by a large willow nearly equal in size. The river is about a hundred yards in breadth, branching into sloughs, and interspersed with islands . . .Late in the afternoon we discovered timber, which was found to be groves of oak-trees on a dry arroyo…Riding on through the timber, about dark we found abundant water in small ponds twenty to thiry yards in diameter, with clear, deep water and sandy beds, bordered with bog-rushes (*Juncus effuses*) and a tall rush twelve feet high (*Scirpus lacustris*), and surrounded near the margin with willow-trees in bloom; among t hem one which resembled *Salix myricoides*." (Freemont, 1887 as cited in Bay Institute 1998)

Upstream of Mendota to Friant Dam woody riparian vegetation was more abundant, but even hear it was confined to the bottomlands between the alluvial bluffs which bordered the river. These bottomlands were up to a mile wide just upstream of highway 41, but were more typically on ¼ of a mile wide (Cain, 1997; see also figures 4.7 and 7.4 of this report). Early maps due not consistently depict riparian vegetation in the reach between Friant and Mendota. Derby's 1850 reconnaissance map of the Tulare Valley does not show any riparian vegetation along the San Joaquin. However, it shows riparian vegetation along the Kings River, but does not show riparian vegetation along the Kaweah where it was and is still abundant (Preston, 1981). Another early map by Nugen (1853) depicts a band of riparian vegetation along the San Joaquin downstream of Friant as well as a very broad band of riparian vegetation on the Kaweah. The field books of the State Engineer, William Hammond Hall, suggest that many large trees were cleared by the time he conducted his survey in 1878. Hall's survey books reference numerous oak stumps that were used as "turning points" in his surveys of 1878. McBain et al (2002) summarize riparian conditions between Friant Dam and the Merced River: "Reach 1 (Friant Dam to Gravelly Ford) and potentially portions of Reach 2 consisted of bands of woody riparian vegetation (alders, willows, cottonwoods, sycamore, and valley oak) along the floodway of the San Joaquin River corridor, typically in dicontiuous patches along high flow scour channels and side channels closer to the groundwater table. Valley oak occurred on the terraces primarily in Reach1."

Salmonids

Yoshiyama et al. 1996 (pg 7-11) compiled a comprehensive overview of historical Chinook salmon populations in the San Joaquin River. This is what they reported:

Figure 4.8. Spring-Run Chinook Salmon from the Middle SanJoaquin River. From files of Eldon Vestal, DFG Region 5 Biologist in 1950's.

"Hatton (1940) considered the upper San Joaquin River in 1939 to possess the 'most suitable spawning beds of any stream in the San Joaquin system'… Clark (1929) stated that 'Fifty or sixty years ago, the salmon in the San Joaquin were very numerous and came in great hordes.'… The former spring run of the San Joaquin River has been described as 'one of the largest Chinook salmon runs anywhere on the Pacific Coast' and numbering 'possibly in the range of 200,000-500,000 spawners annually' (CDFG 1990)…Fry (1961) reported that during the 1940's prior to construction of Friant Dam, the San Joaquin River had an 'excellent spring and small fall run.' At that time the San Joaquin River spring run was considered probably 'the most important' one in the Central Valley (Fry 1961), amounting to 30,000 or more fish in three years of that decade, with a high of 56,000 in 1945 (Fry 1961) and an annual value of 'almost one million dollars' (Hallock and Van Woert 1959)."

4.3 Merced

The Merced River is the first major tributary north of the middle San Joaquin. The Merced drains a 1,039 square mile watershed (Table 4.1). Stillwater Sciences (Baseline Studies Volume II, pg 7 2002) compiled a restoration plan for the Merced River, which summarizes the major features of the watershed. The information presented in this report is summarized from the Stillwater report. The River beings at an elevation of 13,000 feet in Yosemite National Park and flows through the Central Valley, ending at 49 feet at the confluence with the San Joaquin River. The climate and runoff in the Merced River watershed is similar to the other rivers in the San Joaquin basin, summers are dry and winters are wet. Historically, natural flow conditions were driven by late spring and early summer snowmelt, fall and winter rainstorm peaks and low summer baseflows. The annual runoff between 1901 and 1987 from the Merced River averages 989 thousand acre-feet (TAF) (Table 4.1).

Geomorphology

The Merced River Corridor Restoration Plan Baseline Studies summarizes the geomorphic processes and historical geomorphology of the Merced River watershed. The Merced River flows through confined bedrock valleys and steep bedrock gorges of the Sierra Nevada in the upper watershed. The River originates in the batholith of Jurassic-Cretaceous age, flows through granite rocks in the Yosemite Valley and enters metamorphic terrain in the western Sierran foothills. The river drains about 230 square miles of the granitic terrain and about 60 square miles of metamorphic and marine sedimentary terrain.

In the eastern Central Valley, the River flows through an area "characterized by a sequence of steeply sloping, westerly nested Quaternary alluvial fans (Harden 1987). These alluvial fans were sequentially deposited, such that younger fans overlie older fan deposits. The westward shifting of these depositional fans has been linked to progressive uplift and westward tilting of the Sierra Nevada range throughout the Tertiary and Quaternary periods (Bateman and Wahrhaftig 1966). The oldest fans in the Merced River area (the Riverbank Formation and North Merced Gravel) lie at the base of the western Sierra Nevada foothills, and the youngest fan (the Modesto Formation) lies close to the San Joaquin River in the Central Valley.

Historically, the River channel then broadened into a highly dynamic, multiple channel system that occupied the entire width of the valley floor (up to 4.5 miles wide) near the town of Snelling. Downstream of the confluence with Dry Creek, the historical channel was a single-thread, meandering system. "This narrowing and conversion from the braided to the meandering system may have been a response to downstream fining of sediment texture (due to sediment transport-related gravel attrition). With this downstream fining, river bank textures become finer and less erodible, thus driving the conversion to a single-thread channel" (Stillwater, Baseline Studies Volume II, pg 7).

Riparian vegetation

A summary of riparian vegetation along the Merced River is summarized in the Merced River Corridor Restoration Plan Baseline Studies: "The Merced River and its floodplain historically supported a dense riparian woodland. While much of the Central Valley upland and foothills were historically covered by sparsely wooded grasslands, presettlement riparian zones supported dense, multistoried stands of broadleaf trees, including valley oak (*Quercus lobata*), Fremont cottonwood (*Populus fremontii*), western sycamore (*Platanus racemosa*), willow (*Salix* spp.), Oregon ash (*Fraxinus latifolia*), box elder (*Acer negundo*), and other species (Thompson 1961, 1980, Holland and Keil 1995, Roberts et al. 1980, Conard et al. 1980). These riparian forests varied greatly in width, from a narrow strip in confined reaches to several miles wide on broad alluvial floodplains (Thompson 1961). Local accounts of the Merced River describe the rich aquatic and terrestrial fauna supported by riparian habitats (Edminster 1998). Katibah (1984) estimates that the Merced River and the lower San Joaquin River (from the Merced confluence to Stockton) supported over 90,000 acres of riparian forest, part of more than 900,000 acres of historical riparian forest for the whole Central Valley. No historical estimates of riparian forest extent specific to the Merced River are available" (Stillwater, Baseline Studies Volume II, pg 8).

Salmonids

Historical accounts of salmon suggest that salmon were very numerous historically in the Merced River (Yoshiyama et al., 1998; Clark 1929). Chinook may have spawned as far upstream as El Portal on the mainstem, approximately 7 miles upstream of the confluence with the South Fork, and but probably did not migrate farther upstream to Yosemetie Valley due to the steep gradient of that stream reach. (Yoshiyama et al, 1996). Clark reports that "early residents . . . speak of great quantities coming up the river to spawn in the summer and fall. . . They remember the fish being so numerous that it looked as if one could walk across the stream on their backs." A newspaper account from 1882 described by Yoshiyama et al (1998) indicates that salmon were both numerous and perhaps already threatened by water diversions: ". . . the Merced River has become so hot that it has caused all the salmon to die. Tons of dead fish are daily drifting down the river, which is creating a terrible stench, and the like was never known before (Mariposa Gazetter, 26, August 1882). It is unknown whether these high temperatures were caused by upstream irrigation diversions or merely the result of natural conditions, but it is clear from the account that the salmon were numerous. By 1928, Clark (1929) reported " a great deal of the water in the Merced River is used for irrigation during the spring, summer and early fall. The river during this irrigation season is very low, and the salmon find it hard to get up the river until after the rains. This condition has just about killed of the spring and summer runs and now the only fish that come in arrive during the late fall."

Clark also reports that salmon once migrated past the Crocker Huffman and Merced Falls diversion dams, but that the dams greatly contributed to the decline of fish in the Merced.

> "There are three obstructions that affect the salmon (on the Merced). The Crocker Huffman irrigation diversion dam near Snelling is the lowermost. This dam, which was build about 1918, is about 15 feet high and has a good working fishway in high water. There are screens but not over all the ditches. At Merced Falls there is a natural fall an a 20-foot dam has been constructed to form a millpond and to generate power for a sawmill. The dam was build prior to 1913. There is a fishway, but it has been closed and out of order for a number of years. There are screens over the intakes to the power house. The Exchequer Dam is about 20 miles above the Merced Falls and is impassable to fish. . .
>
> "The abundance of salmon in the Merced River now (1929) as compared to the past years tells the same story of depletion as do the other rivers. The reports of the early residents in that section speak of great quantities of fish coming up the river to spawn in the summer and fall. In 1920, a letter received by the Fish and Game Commission from a resident of the country near Merced River states that there were fifty salmon in the past for each one now (1920). In the above mentioned letter the blame for this decrease was attributed to the construction of

dams. Residents along the river in 1928 say that the salmon are so scarce that they rarely see any."

4.1.3 Tuolumne

The Tuolumne River is the largest tributary in the San Joaquin Basin. It originates in the Sierra Nevada at 11,000 feet elevation and drains 1,541 square miles (Table 4.1). The Tuolumne flows into the lower San Joaquin River north of the Merced River and south of the Stanislaus. Typical of other San Joaquin Basin rivers, runoff from the Tuolumne is characterized by late spring and early summer snowmelt. Annual runoff averaged 1,740 TAF per year between 1901 and 1987 (Table 4.1) and 1,906 TAF between 1896 and 1999 (McBain and Trush pg 1). Annual runoff varies widely, from a low of 454,000 acre-feet (WY 1977) to 4.6 acre-feet (WY 1983) (McBain and Trush 2001 pg 13).

Geomorphology

A detailed description of the geomorphic processes and morphology of the Tuolumne River channel downstream of present day LaGrange Dam is provided by McBain and Trush (2001). They divided the river channel into two distinct geomorphic zones based on channel slope and bed material: a sand-bedded zone and a gravel-bedded zone. The transition between these two zones occurs when the slope of the Sierra Nevada decreases and the river valley widens. At this transition "the river was unable to transport gravel and cobble-sized particles. These larger particles deposited in upstream reaches, while sand continued to be transported downstream…[which] caused a noticeable change in planform morphology: in the sand-bedded zone sinuosity increased, amplitude increased, meanders became more tortuous, and channel migration was more continuous than in the upstream gravel-bedded zone. In the gravel-bedded reach, valley walls confined the channel to as narrow as 500 feet near Waterford and the channel downstream of Modesto was virtually unconfined. The channel in the gravel-bedded reach "was a combination of single-thread and split channels (mild braiding). Channel movement appears to have been dominated by a combination of channel avulsion and channel migration." (McBain and Trush 2001). The channel in the sand-bedded zone was almost entirely single thread. The channel bed and banks throughout the River were composed of alluvium (gravel, cobble and boulders). "The critical process for the alluvial river reaches, including both sand and gravel-bedded zones, was that sediment scoured and transported downstream from a particular location was replaced by sediment originating from similar processes upstream. This functional "conveyor-belt" periodically transported sediment, scoured and rebuilt alluvial deposits, and over time, maintained equilibrium in the quantity and quality of in-channel storage deposits throughout the river. This process in turn provided a consistent renewal and maintenance of high quality aquatic and terrestrial habitat in the lower river." (McBain and Trush 2001).

Riparian vegetation

McBain and Trush summarized the historical occurrence of riparian vegetation on the Tuolumne (2001): "Prior to the Gold Rush era, the riparian corridor extended miles wide in places where the river lacked confinement. Pre-settlement riparian vegetation in the sand-bedded reaches was comparable to a lush jungle "gallery forest" where lianas (vines) connected the canopy to dense undergrowth (Bakker 1984). Throughout the corridor, western sycamore, Fremont Cottonwood, Oregon ash and valley oaks grew in profusion on floodplains and terraces, while willows and alders grew along active channel margins. In mature riparian stands, clematis, grape and poison oak lianas draped from the canopy to the ground. An estimated 13,000 acres of riparian vegetation occupied the Lower Tuolumne River from La Grange to Modesto (RM 19-52) before widespread European settlement in the 1850's (Katibah 1984). In gravel-bedded reaches, relatively sparse riparian vegetation was restricted between bluffs, and flourished in high flow scour channels and abandoned main channels where soil moisture conditions were optimal and flood effects minimal".

Salmonids

Historically, the Tuolumne supported populations of spring and fall run Chinook (Yoshiyama 1996 pg 13). These fish occurred as far upstream as Preston Falls, at the boundary of Yosemite National Park and 50 miles upstream of the present day New Don Pedro Dam, and were probably blocked just above the confluence with the Clavey River and the South and Middle forks of the Tuolumne (Yoshiyama 1996 pg 13-14). An early pioneer wrote in his journal "the river of the Towalomes; it is about the size of the Stanislaus, which it generally resembles…and it particularly abounds with salmon" (Bryant 1849 in Yoshiyama 1996 pg 14). The California Fish Commission (1886 in Yoshiyama 1996 pg 15) also noted that the Tuolumne River "at one time was one of the best salmon streams in the State". Yoshiyama (1996 pg 15) reports that "in the past, fall run sizes in the Tuolumne River during some years were larger than in any other Central Valley streams except for the mainstem Sacramento River, reaching as high as 122,000 spawners in 1940 and 130,000 in 1944 (Fry 1961). Tuolumne River fall-run fish historically have comprised up to 12% of the total fall-run spawning escapement for the Central Valley (CDFG 1993). The average population estimate for the period 1971-1988 was 8,700 spawners (EA Engineering 1991)".

4.1.4 Stanislaus

The Stanislaus River begins at an elevation of 11,500 feet in the Sierra Nevada and flows 120 miles until it reaches the confluence with the lower San Joaquin at an elevation of 20 feet (Kondolf et al. 2001 pg 14). The Stanislaus is the northern most San Joaquin Basin tributary studied in this report. The river drains a 900 square mile (Table 4.1) watershed and 40% of the watershed is above the snowline (Kondolf et al. 2001 pg 14). The watershed is 24 miles at the origin in the Sierra and 10 miles at the River's midpoint (Kondolf et al. 2001 pg 14). The Stanislaus Basin has a Mediterranean climate with dry summers and wet winters with heavy rainfall in the winter and large runoff events from snowmelt and rain and snow events in the late spring, similar to the other San Joaquin tributaries. Approximately 90% of the precipitation in the Stanislaus Basin occurs between November and April. Average annual runoff is 1,030 TAF between 1901 and 1987 (Table 4.1). The maximum runoff was 3,580 TAF 1889-90 and the minimum runoff was 260 TAF in 1923-24 (DWR CDEC web data from Kondolf et al. 2001 pg 15).

Geomorphology
The geology of the Stanislaus watershed headwaters consists of glaciated granite, followed by metamorphic rock further downstream, and volcanic rock until a few miles above the present location of New Melones Dam. The upper Stanislaus River is bordered by terraces of late Pleistocene and flows through Holocene alluvial deposits between Knights Ferry and Ripon (Nedeff 1984 in Kondolf et al 2001 pg 14). The lower reaches of the Stanislaus that flow through the Central Valley have wide natural levees and no longer have terraces (Nedeff 1984 in Kondolf et al 1996 pg 14). Historically, "the Lower Stanislaus River was an alluvial river flanked by extensive floodplains; river terraces and natural levees; actively meandering reaches with large gravel bars; sloughs and oxbows; and broad riparian forests and wetlands (Nedeff 1984). The dynamic nature of the river, driven by frequent floods, allowed for frequent changes in morphology, with a migrating channel and significant sediment transport and deposition" (Kondolf et al. 2001 pg 14).

Riparian vegetation
Kondolf et al (2001. pg 15) summarized the historical composition of the riparian vegetation along the Stanislaus River: "Early travelers described the Lower Stanislaus and nearby Central Valley as 'lush jungles of oak, sycamore, ash, willow, walnut, alder, poplar, and wild grapes which comprised almost impenetrable walls of vegetation on both sides of all major valley rivers and their tributaries' (Smith 1980: 1-2, cited by Nedeff 1984). Riverbank and Modesto age river terraces…80 feet above the river were covered with dense belts of valley oak (*Quercus lobata*) stands that stretched for miles across the Stanislaus (Branch 1881). Vegetation composition along the middle and lower reaches of the Stanislaus effectively corresponded to elevation changes and distance from the river channel—reflecting the differences in water table elevations, soil characteristics, and frequency of flooding. Between Knights Ferry and Ripon, dense cottonwood-dominated stands occupied late Pleistocene and Holocene landforms within 20 vertical feet of the water level, while closer to the river channel ash, willow (*Salix spp*.), cottonwood (*Populus fremontii*), boxelder, and other shrubs tend to grow on terraces and floodplains (Nedeff 1984)."

Salmonids
The Stanislaus River historically supported populations of fall and spring-run Chinook. These salmon traveled "considerable distances" up the North and Middle Forks, where there are few natural barriers, but they probably did not use the South Fork (Yoshiyama et al. 1996 pg 15). Historically, the Stanislaus River supported up to 7% of the total salmon spawning escapement in the Central Valley (CDFG 1993 in Yoshiyama et al 1996 pg 16). The California Fish Commission (1886) stated that in the past the Stanislaus had been among the best salmon streams in the state (Yoshiyama et al. 1996 pg 16). Historically, the spring-run Chinook was the primary salmon run in the Stanislaus. Between 1946 and 1959, fall run Chinook averaged 11,100 fish per year and runs were estimated to be between 4,000-35,000 (Yoshiyama et al. 1996 pg 16).

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[2] Source: US Geological Survey (1988

Chapter 5. San Joaquin Basin Water Resources Development

There are over 80 dams with a total storage capacity of over 7.7 million acre-feet on the San Joaquin, Merced, Tuolumne, and Stanislaus Rivers. Combined, these facilities have the capacity to capture and control the entire average annual yield of the rivers they dam for the primary purposes of water supply, flood control, and hydroelectric power generation. This chapter provides and overview of the history, location, capacity, and operation of the dams and diversions on these four rivers (Table 5.1).

Water resources development in the San Joaquin Basin began shortly after the discovery of gold in the Sierra Nevada in 1848 with small-scale diversions to mining districts. Larger scale water diversions did not commence until settlers began to irrigate the alluvial soils of the San Joaquin Basin for agriculture. The earliest dams were small diversion facilities that did not have the capacity to store water or significantly reduce the volume of spring snowmelt run-off. These diversion facilities were large enough, however, to significantly reduce instream flows in the late summer and early fall with implications for the cold water fisheries below them. Beginning in the early twentieth century, irrigation districts and private companies began to develop larger dams with the capacity to store water for both irrigation and hydroelectric power generation. Irrigation districts dammed the Tuolumne, Merced, and Stanislaus Rivers (at the mountain-valley transition) between 1923 and 1926, significantly altering seasonal flow patterns and blocking or impeding passage of anadromous fishes to the upper watershed. During the middle of the twentieth century dozens of dams were constructed for hydro-power, urban and agricultural water supplies, and flood control including four large flood control dams and diversions with the capacity to completely control the flow of the San Joaquin Basin rivers in most years. Today there are over 80 dams large enough to warrant regulation by the California Division of Dam Safety on the four major rivers draining the San Joaquin Basin[1]. Their total combined capacity exceeds 7.7 million acre-feet, more than 135% of the average annual yield of the rivers they dam.

[1] Other dams have also been constructed on lesser known drainages including the Fresno and Chowchilla Rivers and the streams emanating from the interior Coast Range on the western side of the San Joaquin Basin.

Table 5.1. Watershed Characteristics of the San Joaquin Basin.

	Principal Foothill Dams						All Dams in Basin[4]		
					Reservoir Capacity			Total Reservoir Capacity	
River	Dam (Reservoir)[1]	Year[1]	Drainage Area (mi^2)[1]	Annual Runoff (TAF)/yr)[2]	(TAF/ yr)[1]	% Annual Runoff	Number of Dams[1]	(TAF/yr)[3]	% Annual Runoff
San Joaquin Mainstem	Friant (Millerton)	1942	1,676	1,780	520	29%	19	1,150	64%
Merced	Exchequer	1926	1,039	989	280	28%	8	1,050	105%
	New Exchequer (Lake McClure)	1967	1,039	989	1,030	104%			
Tuolumne	Don Pedro	1923	1,541	1,740	250	14%	27	2,730	155%
	New Don Pedro	1971	1,541	1,740	2,030	116%			
Stanislaus	Melones	1926	900	1,030	110	11%	28	2,850	278%
	New Melones	1979	900	1,030	2,420	235%			

[1] Source: California Department of Water Resources (1988). Drainage area above gauges.

[2] Source: US Geological Survey (1988). Thousand acre-feet=TAF. San Joaquin River below Friant (US Geological Survey gauge #11251000) 1907 – 1987, adjusted for evaporation and storage changes in Millerton Reservoir and for diversions to Madera and Friant- Kern Canals. Merced River below Merced Falls Dam near Snelling (#11270900) 1901 – 1987, adjusted for diversion to North Side Canal and change in contents in McSwain Reservoir. Tuolumne River below La Grange Dam near La Grange (#11270900) 1970 – 1987, adjusted for diversion to North Side Canal and change in contents in Lake McClure. Stanislaus River runoff is sum of Stanislaus River below Goodwin Dam (#11302000) 1957 – 1987, Oakdale Canal (#11301000) 1914 – 1987, and South San Joaquin Canal (#11300500) 1914 – 1987, all near Knights Ferry.

[3] Source: Kondolf and Matthews (1993), and California Department of Water Resources (1988), except for New Spicer Meadows, updated based on published data of US Geological Survey.

[4] Includes only dams large enough to be regulated by the California Division of Safety of Dams, i.e. higher than 7.6 m and/or larger than 62,000m^3 in capacity (California Department of Water Resources 1988).

The era of large federally sponsored and licensed flood control dams began in 1941 with the construction of Friant Dam and its associated diversion canals. In the 1960's and 1970's the relatively small water supply dams on the Merced, Tuolumne, and Stanislaus rivers were enlarged nearly ten fold, significantly altering downstream hydrologic patterns. Friant Dam on the middle San Joaquin, New Exchequer on the Merced, New Don Pedro on the Tuolumne, and New Melones on the Stanislaus are all operated, at least in part, for flood control purposes under the authority of the Army Corps of Engineers (Corps). The Corps' water control manual specifies rule curves that govern the operation of the dams. The Corps' rule curves establish maximum controlled dam releases to prevent overbank flooding below the dams, and require that a sizeable volume of the reservoir, the flood reservation, be vacated by the beginning of the rainy season to capture the100-year flood event. The Corps, along with the California Reclamation Board, manages a system of floodways and levees below the major dams to convey the 100-year flood, which is approximately equal to the maximum controlled dam release combined with flood run-off from other smaller drainages in the Basin. Although all of the dams have outlet capacities exceeding the Corps' maximum release rules, dam operators only release more than the Corps' mandated maximum when there is a significant possibility of uncontrolled spills over the dams' spillways. The total controlled release capacity along with the Corps' maximum flow release objectives for each of the four major dams is depicted in Table 5.2.

5.1 MIDDLE AND LOWER SAN JOAQUIN RIVER

From 1910 to 1960, eight major reservoirs were constructed on the San Joaquin River and its tributaries above Friant, with a combined storage capacity of 1.15 million acre-feet, equivalent to 60% of mean annual runoff (Table 5.3 and Figure 5.1). All but Millerton Reservoir (Friant Dam) were built for hydroelectric generation. Friant Dam and its canals (Figures 5.2) are unique among major dams and diversions in the Central Valley of California in that the dam impounds a relatively small percentage of annual runoff, but the canals have an unusually large diversion capacity. The reservoir capacity of Friant Dam is 520,500 acre-feet (equivalent to 30% of mean annual runoff), but the Friant-Kern and Friant-Madera canals can divert 385,000 acre-feet in a single month (Figure 5.3). The maximum capacity of the Friant-Kern Canal is 5,300 cfs, and the maximum capacity of the Friant-Madera Canal is 1,275 cfs (Friant Water Users Authority, 1987). The combined maximum capacity of the canals is equivalent to 80 percent of the median June pre-dam flows. Between 1950 and 1989, the two canals annually diverted an average of 1.5 million acre-feet (McBain and Trush, 2002) roughly 85% of the average annual yield.

Friant Dam, and Millerton Reservoir, which it impounds, were key components of the Central Valley Project (CVP) constructed by the United States Bureau of Reclamation to irrigate the Central Valley. Water impounded at Millerton Reservoir is mostly diverted south in the Firant Kern Canal, with some water diverted north via the Friant-Madera Canal (Figure 5.2). In most years, these diversions take 95% of the river's average annual yield. A small fraction of the water is released according to a 1957 legal settlement to maintain flows (typically 250 cfs or less) during the irrigation season to support agricultural diversions by riparian water right holders in the 36-mile reach

Table 5.2. Maximum Flows in the San Joaquin Basin Tributaries.

River	Dam	Owner	Purpose(s)	Max. power generation flow capacity (cfs)	Low level or other bypass valve (cfs)	Total controlled outlet release capacity (cfs)	Maximum flood release (cfs)	Pre Dam Q1.5 (cfs)	Source
San Joaquin	Friant	Bureau of Reclamation	Flood Control, Navigation, Fire Protection	28-35	17,700	17,700	8,000	8,651	J. Cain, Natural Heritage Institute, pc 7/14/00, USACE, 2000. Post-Flood Assessment.
Merced	New Exchequer Main	Merced Irrigation District	Flood Control and Stormwater Management, Irrigation, Hydroelectric, Recreation, Fish and Wildlife, Fire Protection	3,100	9,300	12,400	6,000 (at Stevinson)	10,062	J. Vick, Stillwater Sciences, pc 7/7/00, Ted Selb, Merced Irrigation District, pc 7/13/00, USACE, 2000. Post-Flood Assessment.
Tuolumne	New Don Pedro	Turlock and Modesto Irrigation Districts	Flood Control and Stormwater Management, Irrigation, Hydroelectric, Recreation, Fish and Wildlife	5,400	9,600	15,000	9,000	8,670	J. Vick, Stillwater Sciences, pc., USACE, 2000. Post-Flood Assessment.
Stanislaus	New Melones	Bureau of Reclamation	Flood Control and Stormwater Management, Irrigation, Hydroelectric, Recreation, Fish and Wildlife	9,000	2,500	19,000	8,000 (at Orange Blossom Bridge)	5,350	G. Cawthorne, USBR New Melones Dam, pc. 3/00, Bill Sanford, USBR, pc 7/5/00, USACE, 2000. Post-Flood Assessment.

Table 5.3. San Joaquin River Dams and Cumulative Storage Capacity

A Year	B Dam Name	C Stream	Capacity (m3)	D Storage Capacity (AF)[1]	E Cumulative Storage (AF)	F Cum. Storage as % annual unimpaired runoff
1896	No. 1 Forebay	Trib. No Fork SJ	85,121	69	69	**0.004%**
1910	Crane Valley Storage (Bass Lk)	NF Willow Creek	55,650,000	45,410	45,479	**2.39%**
1917	Mendota Diversion	Mainstem	3,700,935	3,000	48,479	**2.55%**
1918	Huntington Lake	Big Creek	109,069,000	88,834	137,313	**7.23%**
1920	Kerckhoff Diversion	Mainstem	6,348,000	4,200	141,513	**7.45%**
1923	Big Creek #6	Mainstem	1,225,009	993	142,506	**7.50%**
1926	Florence Lake	So Fork San Joaquin	78,929,000	64,406	206,912	**10.89%**
1927	Shaver Lake	Stevenson Crk	165,441,000	135,283	342,195	**18.01%**
1942	Friant/Millerton	Mainstem	637,255,000	520,500	862,695	**45.41%**
1951	Big Creek #7	Mainstem	42,892,000	35,000	897,695	**47.25%**
1954	Vermillion Valley/Thomas Edison	Mono Creek (~8000 ft elev)	154,205,607	125,000	1,022,695	**53.83%**
1955	Portal Powerhouse Forebay	Trib Sfork SJ River	400,935	325	1,023,020	**53.84%**
1960	Mammoth Pool	Mainstem (~3,500 ft elev.)	153,186,000	123,000	1,146,020	**60.32%**
1961	Reg WW CNT OXID	Trib SJ River	3,543,028	2,872	1,148,892	**60.47%**
	TOTAL LISTED DAMS: 14			TOTAL CAPACITY:	**1,148,892**	AF
					TOTAL:	**60.5%**
					1,900,000	AF

Note: Data on the dams within the San Joaquin River large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.9 maf, Calfed, 2000). The total dam storage capacity in the San Joaquin basin is almost 1.15 maf, or over 60% of average annual unimpaired runoff (Adapted from Richter 2002).

[1]: Division of Safety of Dams, Bulletin 17-00, July 2000.

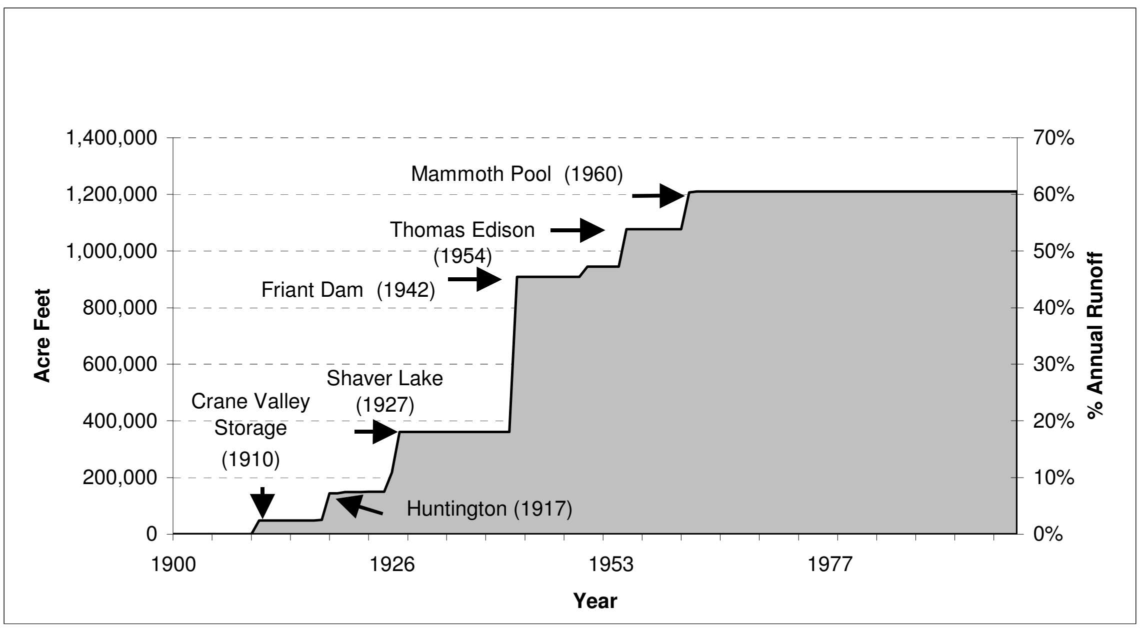

Figure 5.1. Middle San Joaquin River Dams Cumulative Storage Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of San Joaquin River dams is 1.15 maf, relative to annual unimpaired runoff of 1.9 maf (Calfed, 2000). See Table 5.3 for details regarding calculations and data sources (Adapted from Richter 2002)

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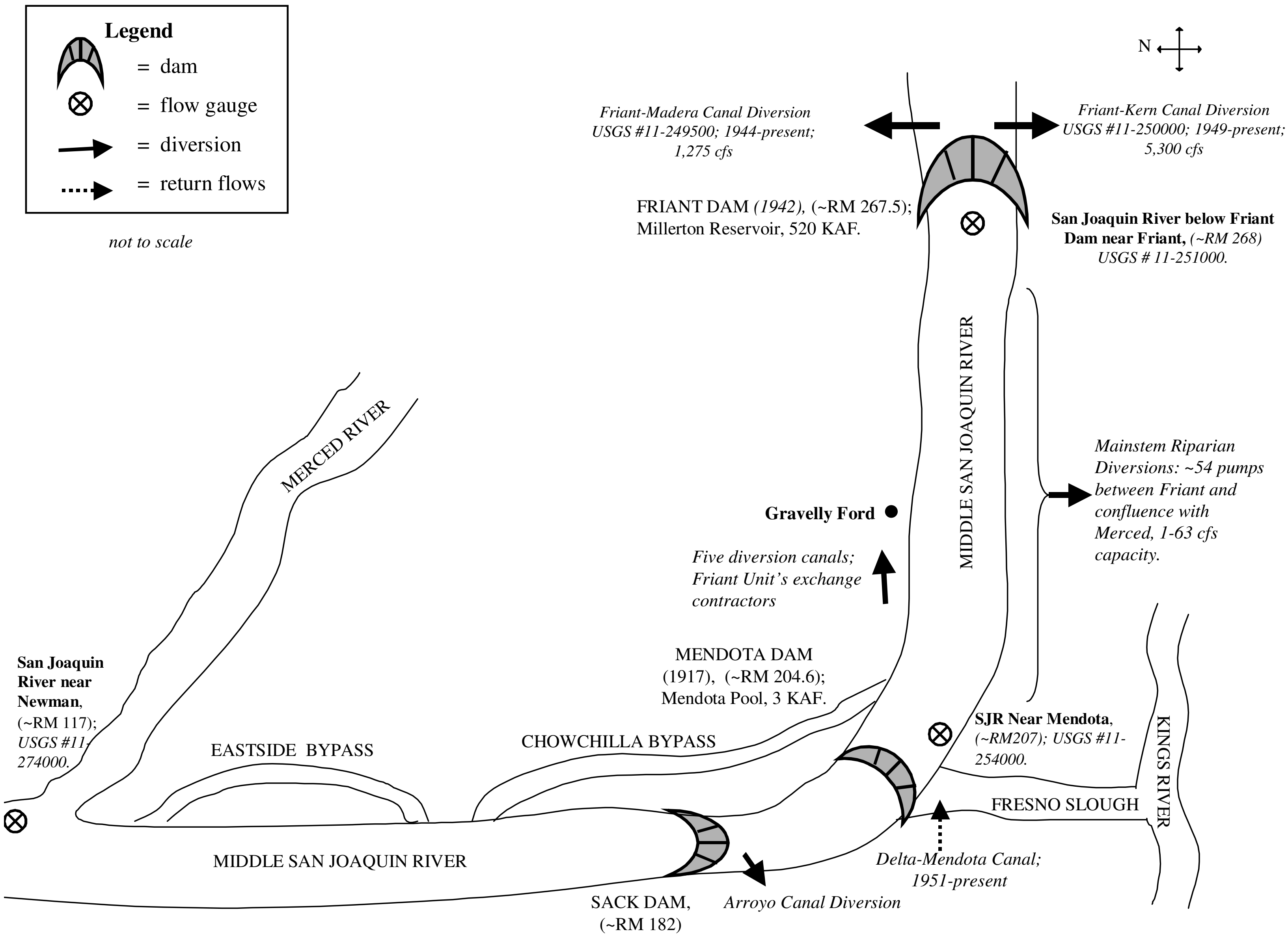

Figure 5.2. Middle San Joaquin River Dams, Diversions, and Gauges

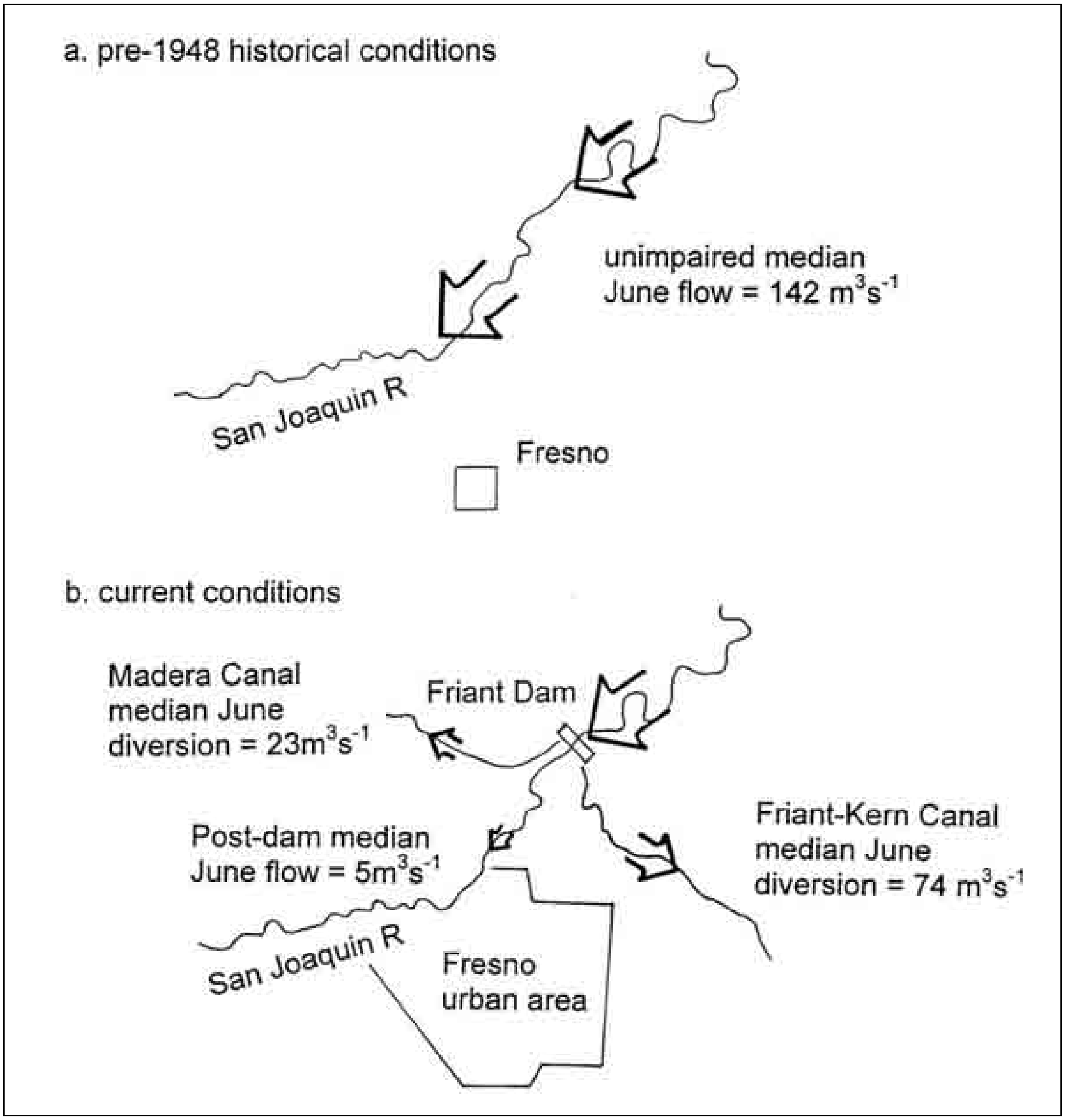

Figure 5.3. Schematic diagram showing flow split between the San Joaquin River and canals under a) pre-dam conditions and b) current conditions, with storage behind Friant and upstream dams. Unimpaired median June flow of 142 m^3s^{-1} based on wy 1908 – 1941. Median June flows in canals based on 1960 – 1997. Data from US Geological Survey published data.

downstream to the Gravelly Ford Canal. As a result, this reach of the river is wetted all year. Below Gravelly Ford, the channel is underlain by highly permeable bed material and high rates of flow losses to infiltration. This reach was allowed to dry up to avoid losing valuable surface water to groundwater infiltration.

Since construction of the CVP, riparian water rights holders downstream of Gravelly Ford have been served by the Delta-Mendota Canal, which delivers water from the Sacramento-San Joaquin Delta to the San Joaquin River at Mendota Pool (Figure 4.1 and Figure 5.2). Mendota Pool is formed behind Mendota Dam and was originally constructed in the nineteenth century to divert irrigation water from the San Joaquin River to several irrigation districts now known as the San Joaquin River Exchange Contractors (Exchange Contractors). The Exchange Contractors gave up their historic rights to the San Joaquin River in exchange for Delta water delivered via the Delta-Mendota Canal. Today, Mendota Pool has a storage capacity of 3,000 acre-feet and distributes Delta water into a system of irrigation canals. Some water is released downstream of Mendota Pool into the historical channel of the San Joaquin River for subsequent diversion into Arroyo Canal at Sack Dam, 22 miles further downstream. Below Sack Dam, the river is often dry for several miles except during flood events.

The Corps flood rules require 180,000 acre-feet of combined flood reservation in Millerton Reservoir and Mammoth Pool, an upstream reservoir, to capture winter flood events. This relatively small flood reservation is buffered by the enormous conveyance capacity of Friant's diversion canals. Corps flood control rules dictate a maximum flood control release of 8,000 cfs, but the dam has the capacity to release 16,400 cfs (Figure 5.4). The floodway below Friant Dam is designed to convey 12,000 cfs to accommodate both maximum controlled release and peak flows from Little Dry Creek, which enters the river a few miles downstream of Friant. At 12,000 cfs, the middle San Joaquin floods roads and housing associated with the Department of Fish and Game fishery. At 14,000 cfs, storm drains at the mobile home near Highway 41 back-up.

The middle San Joaquin River between Gravelly Ford and the Merced River has an unusually complex system of flood bypasses that route most flood flows around the historical channel and flood basin of the San Joaquin (Figure 5.4). Authorized by the Flood Control Act of 1944, the San Joaquin River and Tributaries Project (SJRTP) was constructed in the 1950's and 1960's and includes over 100 miles of levees and bypasses. Starting 35 miles downstream of Friant, a levee-confined floodway between Gravelly Ford and the Chowchilla bypass is designed to convey 12,000 cfs, but due to channel aggradation and levee instability may only be able to safely convey 8,000 cfs. Approximately 45 miles downstream of Friant, large flood releases are diverted into the Chowchilla and Eastside Flood bypass system which routes most of the rivers floodwaters around the historical flood basin downstream of Mendota Pool.

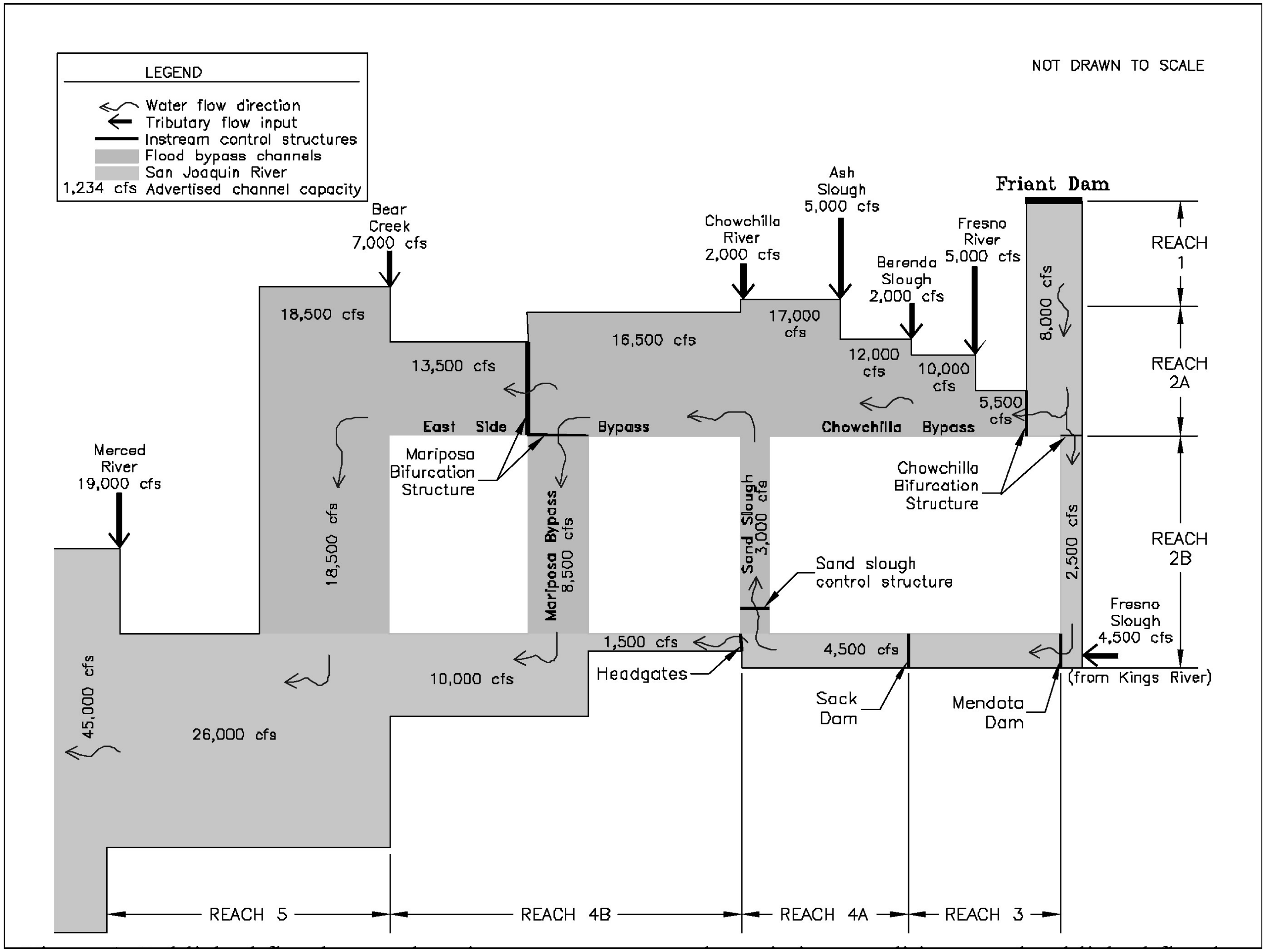

Figure 5.4. Published flood control project conveyance under existing conditions, and published flood control project operations for an example 8,000 cfs release from Friant Dam. McBain and Trush 2002

5.2 MERCED RIVER

Four principal dams control flows on the mainstem of the Merced River (Figure 5.5). Merced Falls diversion dam was constructed in 1901 by Pacific Gas and Electric Company and generates hydroelectric power and diverts flow into the Merced Irrigation District (MID) Northside Canal, which has a capacity of 90 cfs. In 1910, MID constructed Crocker Huffman Dam, which diverts flow into the Main Canal. The Main Canal has a capacity of 1,900 cfs and delivers waters to land south of the Merced River.

Exchequer Dam, the first major storage facility on the Merced River, was constructed in 1926 by the Merced Irrigation District. It stored flows during the high spring run-off period, and then released them downstream during the irrigation season for diversion into the North and Main Canals at Merced Falls and Crocker Huffman Diversion Dams. Due to its limited capacity of 281,000 acre-feet, Exchequer did not capture all of the spring run-off and did not allow for inter annual water storage.

Exchequer Dam, now known as Old Exchequer, was inundated in 1967 by Lake McClure when the Merced Irrigation District constructed New Exchequer Dam immediately downstream (Figure 5.6). New Exchequer and its downstream counterpart, McSwain Dam, are the primary components of the Merced River Development Project, which is owned by the Merced Irrigation District and licensed by the Federal Energy Regulatory Commission (FERC) (Stillwater, 2001). The Merced River Development Project provides agricultural water supply, hydroelectric power, flood control, and recreation, as well as some water to maintain minimum instream flows for fish in the Merced River and wetland habitat at the Merced National Wildlife Refuge (Stillwater, 2001). Lake McClure, the reservoir created by New Exchequer has a storage capacity of 1.032 million acre feet and enables the Merced Irrigation District to store water in wet years for use during subsequent dry years. Lake McSwain, located 6.5 miles downstream of New Exchequer Dam, has a capacity of 9,730 acre feet and is operated as a re-regulation reservoir and hydroelectric facility. Together, New Exchequer and McSwain have a combined storage capacity of 1.04 million acre-feet, which amounts to 102% of the average annual runoff from the Merced River watershed (Table 5.4 and Figure 5.7).

Figure 5.6. The Old Exchequer Dam is curved and shown in front of the New Exchequer Dam (Source: http://www.mercedid.org/_images/water_maincanal_sep02.pdf).

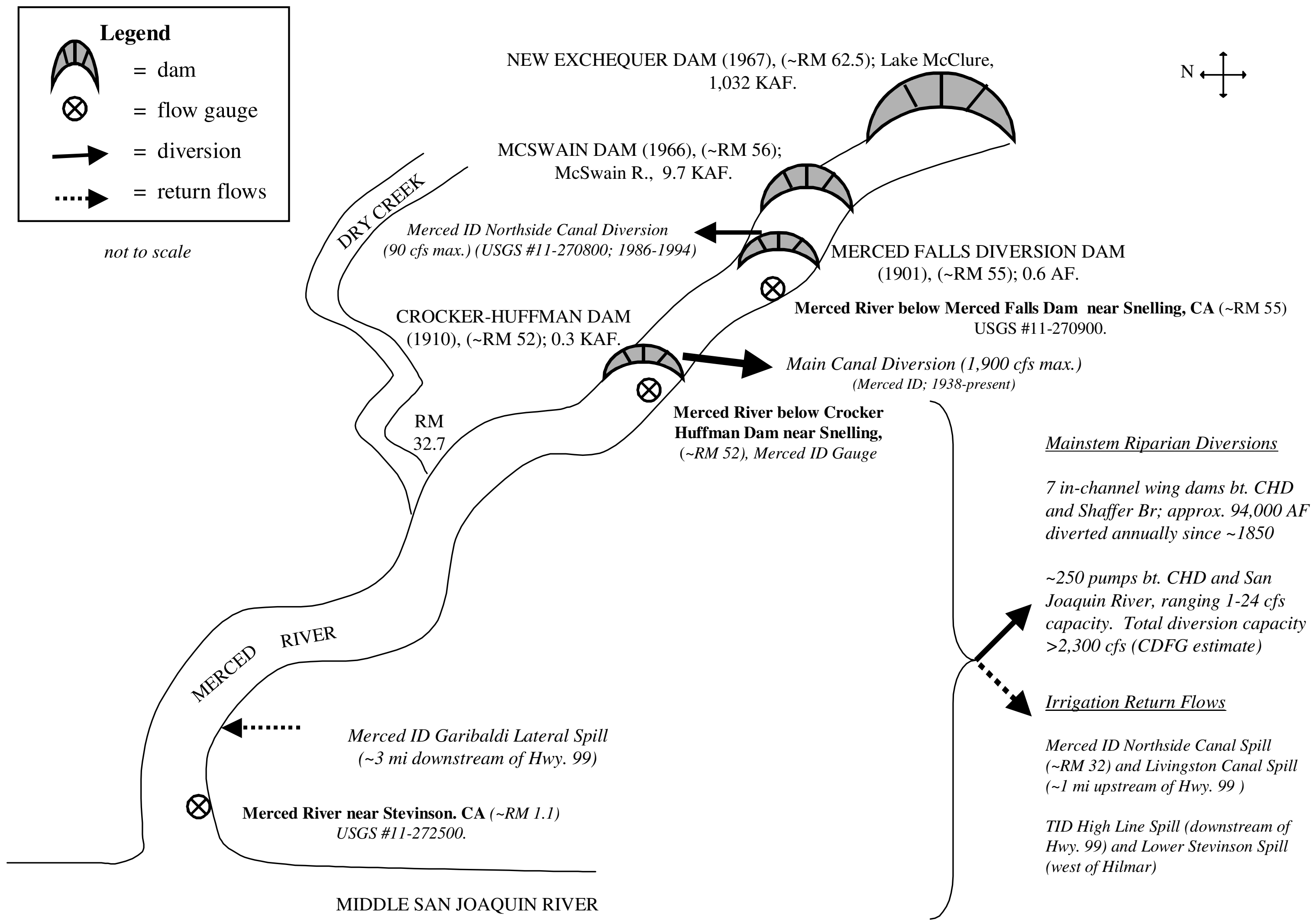

Figure 5.5. Lower Merced River Dams, Diversions, and Gauges
Data sources: USGS and CDEC web sites, CDWR DSD Bulletin17-00, Stillwater Sciences 2001

Table 5.4. Merced River Basin Dams and Cumulative Storage Capacity.

A	B	C		D	E	F
Year	Dam Name	Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1901	Merced Falls	Mainstem Merced River	765,000	620	620	**0.06%**
1910	Crocker-Huffman Diversion	Mainstem Merced River	370,000	300	920	**0.09%**
1926	Exchequer	Mainstem Merced River	347,000,000	281,280	282,200	**27.67%**
1929	Kelsey	Dry Creek (Trib)	1,230,000	1,000	283,200	**27.76%**
1956	Metzger	Dutch Creek (N. Fork)	92,500	75	283,275	**27.77%**
1957	McMahon	Maxwell Creek (Trib)	641,000	520	283,795	**27.82%**
1958	Green Valley	Smith Creek (N. Fork)	296,000	240	284,035	**27.85%**
1966	McSwain	Mainstem Merced River	12,000,000	9,727	293,762	**28.80%**
1967	New Exchequer/McClure [1]	Mainstem Merced River	1,270,000,000	1,032,000	1,044,482	**102.40%**
	TOTAL LISTED DAMS:	9 (Excheq counted twice)		TOTAL CAPACITY:	**1,044,482**	AF
					TOTAL:	**102%**
					1,020,000	AF

Note: Data on the dams within the Merced basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.02 maf, Calfed, 2000). The total dam storage capacity in the Merced basin exceeds 1.04 maf, or over 102 % of average annual unimpaired runoff. (Adapted from Richter's IHA Report) Stillwater reports Exchequer max storage capacity as 1,024,600 AF.

Source: Kondolf G.M. and Matthews, Graham, Management of Course Sediment on Regulated Rivers, Oct. 1993; Calfed, 2000; Kondolf et al, 1996, Water Resources Center Rept. 90; Division of Safety of Dams, Bulletin 17-00, July 2000.

1: Storage from Exchequer was subtracted when New Exchequer was filled.

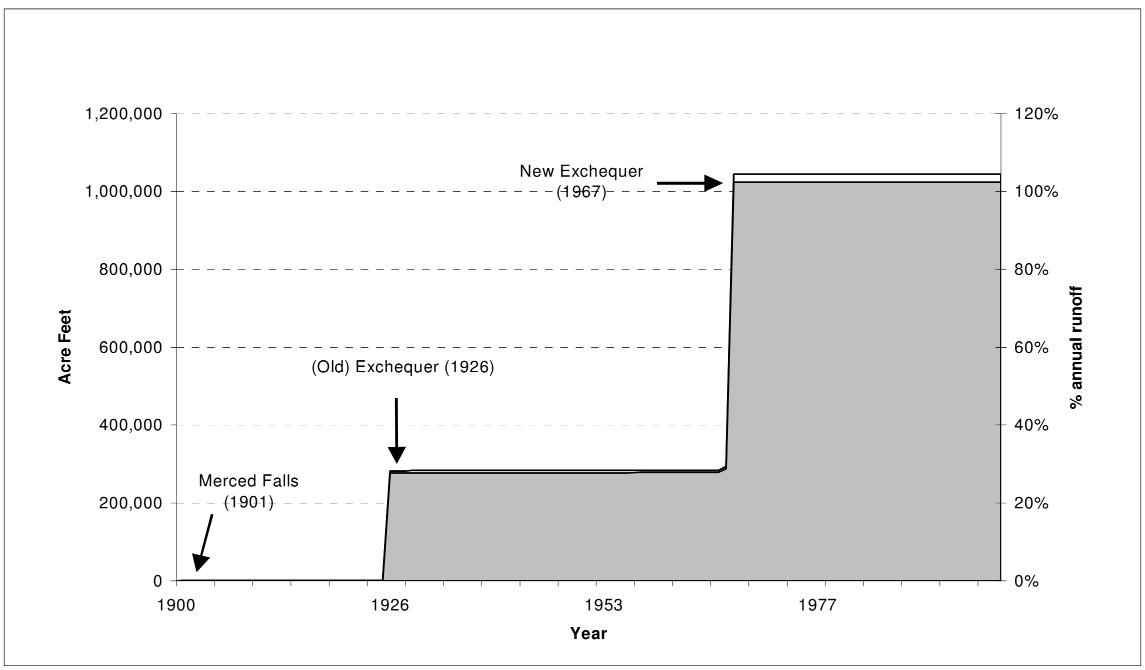

Figure 5.7: Merced River Dams Cumulative Storage Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of Merced River dams is 1.04 maf, relative to annual unimpaired runoff of 1.02 maf (Calfed, 2000). (Adapted from Richter's IHA Report) Source: DWR, Bulletin 17-00, July 2000.

The Merced Irrigation District is required to release between 50 and 250 cfs from its facilities to satisfy the riparian water rights of the Merced River Riparian Water Users. The Merced River Riparian Water Users maintain seven major diversions between Crocker Huffman Dam and Shaffer Bridge. Downstream of Shaffer Bridge, the California Department of Fish and Game (CDFG) identified 238 diversions, generally small pumps that deliver water for agricultural purposes (Stillwater, 2001).

The Army Corps of Engineer regulates flood control operations on the New Exchequer Dam and Reservoir. According to the Corps Water Control Manual that dictates operations of the dam for flood control purposes, a maximum of 400,000 acre-feet of space is dedicated to flood control during the winter run-off season from November 1 – March 15 (Stillwater, 2001).

The Corps limits maximum reservoir releases to 6,000 cfs, measured at Stevinson gauge near the confluence with the San Joaquin. The maximum physical release from the New Exchequer outlet structure is 12,400 cfs (Table 5.2). 350,000 acre-feet of flood reservation storage is reserved for the rain flood pool between October 31 and March 15 and an additional 50,000 acre-feet is reserved for the forecasted spring snowmelt after March 1. During the floods in January 1997, flood flows released 8,000 cfs for 55 days under an emergency variance from the Corps and caused back flooding at the confluence of the San Joaquin, due to simultaneous releases at Friant Dam, and flooded agricultural lands in Stevinson and Hillman.

5.3 TUOLUMNE RIVER

There are over 25 dams on the Tuolumne with a combined storage capacity of over 2.7 million acre feet or 155% of the average annual yield, but five primary dams and several major diversions control flows on the Tuolumne River (Figure 5.8).

Local irrigation districts constructed La Grange Diversion dam in 1893 to divert water into the Turlock Irrigation District (TID) and Modesto Irrigation District (MID) main canals. Today, La Grange continues to serve as the diversion point into these canals. The MID Main canal diverts water to the north and has a capacity of 2,000 cfs and the TID Main Canal, which diverts water to the south, has a capacity of 3,400 cfs. Both canals deliver water to intermediate off-stream storage reservoirs, Modesto Reservoir and Turlock Lake, at the upper end of their canal network to regulate irrigation deliveries (FERC 1996).

The first two major storage reservoirs, Don Pedro and Hetch Hetchy, were both constructed in 1923 to increase storage and control of water for agricultural and municipal uses. The City and County of San Francisco (CCSF) constructed the 360,000 acre-foot Hetch Hetchy Dam (O'Shaughnessy Reservoir) in the upper watershed to provide a more reliable water supply. CCSF diverts 230,000 acre-feet of water directly out of river in the upper watershed for delivery via penstocks and pipelines to water users in the San Francisco Bay Area. Today, the Hetch Hetchy system also includes Lake Eleanor Dam (Lake Eleanor Reservoir) on Eleanor Creek and Cherry Valley Dam (Lake Lloyd Reservoir) on Cherry Creek, both in the upper watershed. The Hetch Hetchy

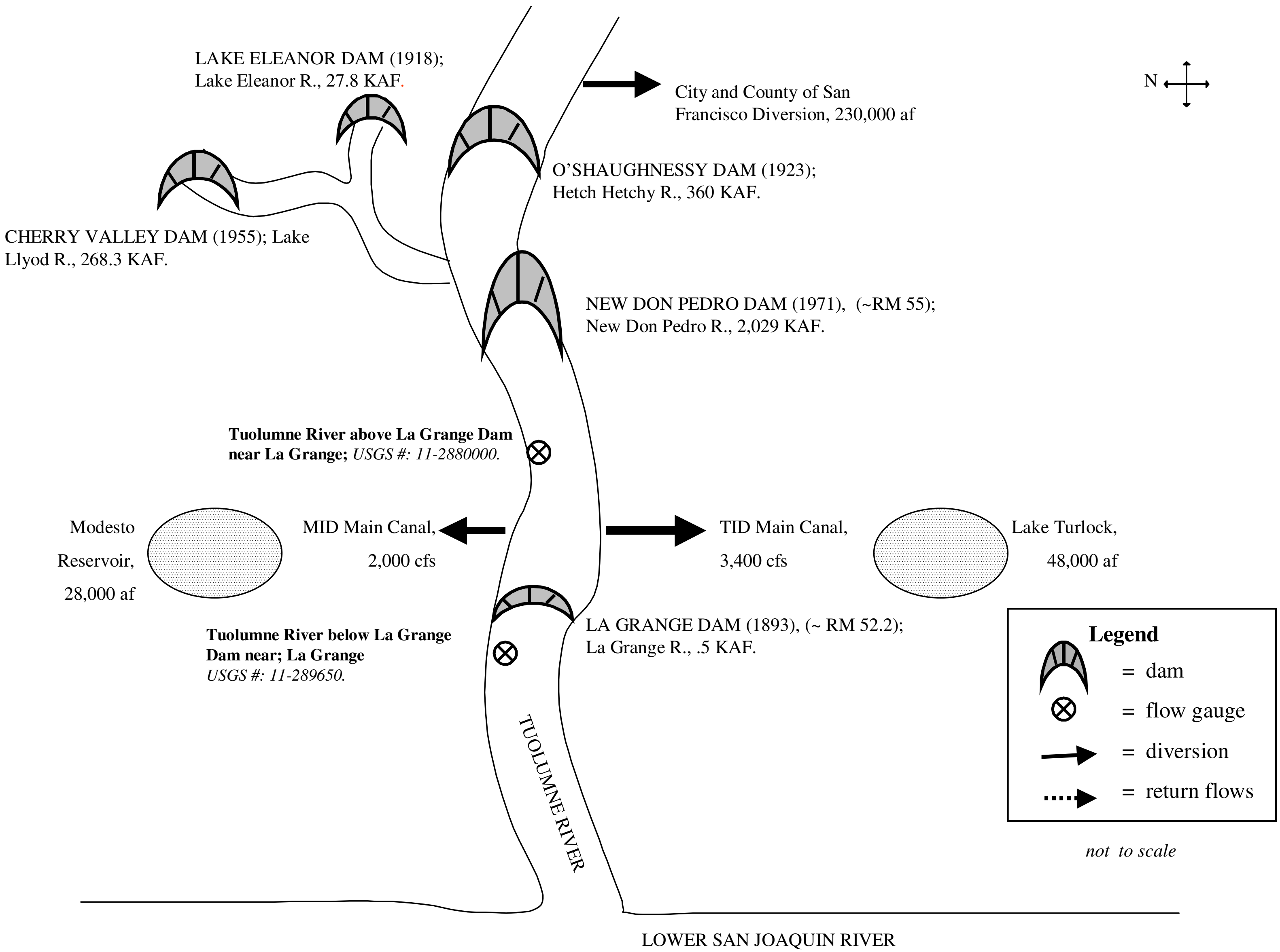

Figure 5.8. Lower Tuolumne River Dams, Diversions, and Gauges

system, which is operated in coordination with, but is not part of, the New Don Pedro Project (discussed later in this section) to meet water rights and flood control agreements.

Local irrigation districts constructed Don Pedro dam and reservoir with a capacity of 290,000. The districts utilized the increased reservoir space to capture spring flows for subsequent release and diversion at La Grange Dam, two miles downstream. In 1971, Don Pedro Dam, now know as Old Don Pedro, was inundated when New Don Pedro Dam was constructed immediately downstream of the old dam to create more reservoir storage space. New Don Pedro Dam (Figure 5.9) is the largest dam on the Tuolumne River with a storage capacity of 2.02 million acre-feet more than 110% of the average annual yield (Table 5.5 and Figure 5.10). The Merced and Turlock Irrigation Districts operate New Don Pedro Reservoir for irrigation, flood control, and hydropower generation. The New Don Pedro Powerhouse is at the base of the dam and is fed by two power tunnels (FERC, 1996). The New Don Pedro Dam, Reservoir and Powerhouse, La Grange Dam, the TID and MID diversion facilities at the La Grange Dam, the TID canal system, TID's Turlock Lake, the MID canal system, and MID's Modesto Reservoir all make up the New Don Pedro Project (NDPP) (FERC, 1996). The NDPP was constructed as a joint project between the MID, TID, CCSF and the Corps (McBain and Trush, 2001), and is owned and operated by MID and TID (FERC, 1996).

Figure 5.9. New Don Pedro Dam. http://www.tid.org/DonPedro /Default.htm

The Corps limits maximum allowable flood releases on the Tuolumne to 9,000 cfs, but the physical release capacity of the Dam outlet structure is 15,000 cfs. State and Federal agencies are working with the irrigation district to expand the floodway below the dam to safely convey 15,000 cfs. The Corps requires the district to maintain 360,000 acre-feet of flood reservation storage between November 1 and May 1 to capture the winter and spring floods.

Table 5.5. Tuolumne River Basin Dams and Cumulative Storage Capacity.

A	B	C		D	E	F
Year	Dam Name	Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1860	Kincaid	Trib. Curtis Crk.	62,000	50	50	0.003%
1860	San Diego Reservoir	Trib. Mormon Crk	49,300	40	90	0.005%
1880	Phoenix	Sullivan Creek	561,000	455	545	0.03%
1894	La Grange	Mainstem	617,000	500	1,045	0.05%
1896	Dawson Lake	Trib. Tuol. River	1,180,000	957	2,002	0.11%
1911	Modesto Reservoir	Trib. Tuol. River	35,800,000	29,020	31,021	1.63%
1912	Tuol. Log Pond	Turnback Crk	148,000	120	31,141	1.63%
1918	Lake Eleanor	Eleanor Creek	34,300,000	27,804	58,945	3.09%
1923	(Old) Don Pedro [1]	Mainstem	419,000,000	290,000	348,945	18.31%
1923	O'Shaughnessy (Hetch Hetchy) [2]	Mainstem	419,000,000	360,000	708,945	37.20%
1923	Priest	Rattlesnake Crk	2,900,000	2,351	711,296	37.32%
1925	Early Intake	Mainstem	141,000	114	711,410	37.32%
1928	Twain Harte	Trib. Sullivan Crk	159,000	129	711,539	37.33%
1930	Moccasin Lower	Moccasin Crk	623,000	505	712,044	37.36%
1931	Bigelow Lake	East Fork Cherry Crk.	580,000	470	712,514	37.38%
1931	Lower Buck Lake	Buck Meadow Crk	444,000	360	712,874	37.40%
1945	Railroad Flat #2	Trib. Dry Crk	117,000	95	712,969	37.41%
1947	Md. Cooperstown	Trib. Dry Creek	112,000	91	713,060	37.41%
1956	Cherry Valley	Cherry Creek	331,000,000	268,311	981,370	51.49%
1956	Gatzman	Trib Dry Creek	95,000	77	981,447	51.49%
1964	Brentwood Park	Trib. Sullivan Crk	98,700	80	981,527	51.50%
1969	Big Creek	Big Creek	9,440,000	7,652	989,179	51.90%
1971	Don Pedro	Mainstem	2,504,004,000	2,029,761	2,728,940	143.18%
1978	Quartz	Trib Woods Crk	1,850,000	1,500	2,730,440	143.25%
1979	Grinding Rock	Trib. Turnback Crk	290,000	235	2,730,675	143.27%
1981	Groveland	Trib. Big Creek	123,000	100	2,730,775	143.27%
Not included above:						
	Wastewater Hi Emig. Lk	No. Fk Cherry Crk	82,600			
	Kilmer	Trib. Dry creek	122,000			
	TOTAL LISTED DAMS:	27		TOTAL CAPACITY:	**2,730,777**	AF
					TOTAL:	**143%**

Note: Data on the dams within the Tuolumne basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.906 MAF, McBain and Trush, 2000). (Adapted from Richter 2002).

Data source:

Kondolf G.M. and Matthews, Graham, Management of Course Sediment on Regulated Rivers, Oct. 1993;

McBain and Trush, Habitat Restoration Plan for the Lower Tuolumne River Corridor, March 2000;

Kondolf et al, 1996, Water Resources Center Rept. 90.

Division of Safety of Dams, Bulletin 17-00, July 2000.

1: Storage from Old Don Pedro was subtracted when New Don Pedro was filled.

Note: Kondolf and Matthews site Old Don Pedro as 250KAF, McBain and Trush site as 290 KAF.

2: Hetch Hetchy/O'Shaughnessy reported as 419 x $10^6 m^3$ in K&M 1993; 363KAF in M&T 2000; and 360 KAF in DSD 2000. Hetch Hetchy originally built in 1923, with a 206,000 AF capacity, and enlarged in 1937 to 360,000 AF accd. To M&T.

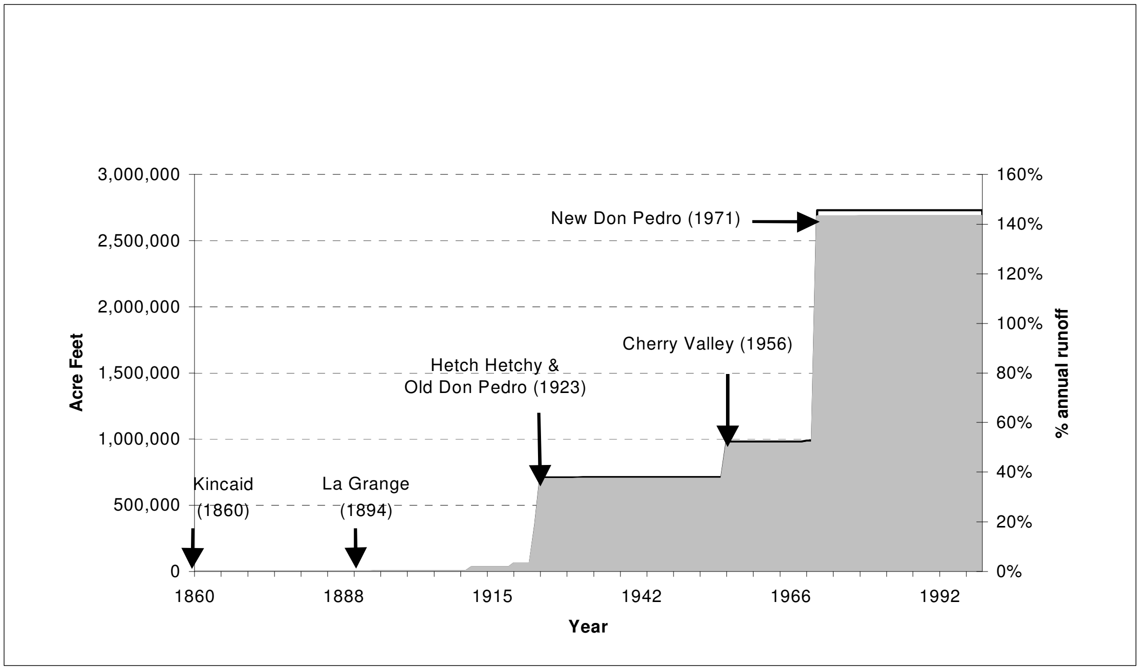

Figure 5.10. Tuolumne River Basin Dams Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of Tuolumne River dams is 2.9 maf, relative to annual unimpaired runoff of 1.906 maf (McBain and Trush, 2000). (Adapted from Richter's IHA Report) Data Source: DWR, Bulletin 17-00, July 2000.

5.4 STANISLAUS RIVER

There are over 30 dams in the Stanislaus watershed with a combined storage capacity of 2,657,241 acre-feet, more than 220% of the average annual runoff. Daming and diversion for both mining and irrigation commenced soon after the Gold Rush. The earliest permanent dam was the original Tulloch Dam constructed in 1858 just downstream of the present dam, but it was a relatively low structure with an opening at one end, and thus may not have had a large impact on Salmon (Tudor-Goodnouogh Engineers 1959 in Yoshiyama 1996). The Oakdale Irrigation District (OID) and the San Joaquin Irrigation District (SJID) built the original 20 foot Goodwin Dam with a fishway in 1913 (Yoshiyama et al 1996) to divert water into the Oakdale and South San Joaquin Irrigation Canals. Oakdale Canal, with a capacity of 560 cfs, diverts water to the south and the South San Joaquin Canal diverts up to 1320 cfs to the north (Figure 5.11). The Goodwin Dam was apparently raised in the late fifties to serve also as a regulating reservoir for the New Tulloch Dam thus eliminating any function the old fishway may have served.

OID and SJID constructed the 156,000 acre-feet Melones Dam and reservoir 15 miles upstream of Goodwin Dam in 1926 to store spring run-off and release it downstream for diversion at Goodwin Dam. In the late 1950's the irrigation districts completed Tri-Dam project in the late 1950's consisting of Tulloch Dam between, Goodwin Dam and Melones, as well as Donnells and Beardsley Dam in the upper watershed. The irrigation districts operate the Tri-Dam Project to store spring snowmelt and release during the irrigation season for diversion at Goodwin Dam.

Melones Dam, now known as Old Melones, was replaced and inundated in 1979 when the Army Corps of Engineers constructed New Melones Dam (Figure 5.12). New Melones is the largest reservoir in the San Joaquin Basin with, and its 2,400,000 acre-feet of storage capacity is 2.4 times greater than the rivers average annual run-off (Table 5.6 and Figure 5.13). The Dam is operated and maintained by the US Bureau of Reclamation for flood control and to maintain water quality in the San Joaquin Delta.

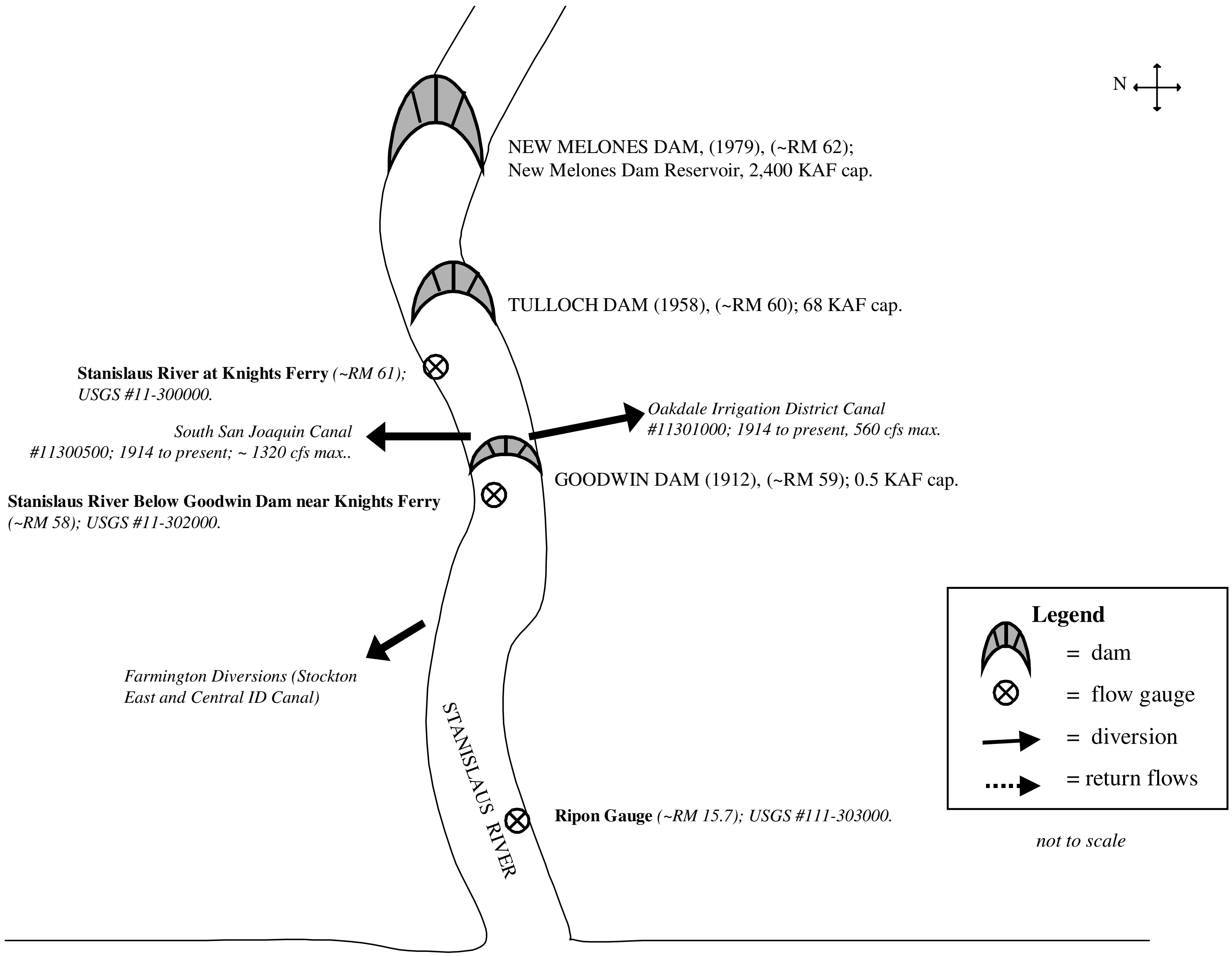

Figure 5.11. Lower Stanislaus River Dams, Diversions, and Gauges.
Data Source: Schneider 1999.

Figure 5.12. New Melones Dam and Reservoir
http://www.usbr.gov/power/data/sites/newmelon/newmelon.htm

The Corps limits the maximum flood releases to 8,000 cfs as measured at Orange Blossom Bridge. When the dam was constructed, the Corps acquired flood easements along the river to maintain a floodway that could convey up to 8,000 cfs. Despite these flood control easements, the Bureau limits flows to 1,500 cfs between March and October to prevent root damage to walnut groves during the growing season.

Figure 5.13. Stanislaus River Basin Dams Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. Note the most noticeable jumps occur in 1926 with the construction of Old Melones Dam, 1957-8 with the Tri-Dams Project, 1979 with New Melones Dam, and 1988 with New Spicer Meadows. The total capacity of Stanislaus River dams is just under 2.85 maf, relative to annual unimpaired runoff of 1.2 maf (Calfed 2000). See Table ST1 for details regarding calculations and data sources. (Adapted from Richter's IHA Report). Data Source: DWR, Bulletin 17-93, June 1993.

Table 5.6. Stanislaus River Basin Dams and Cumulative Storage Capacity.

A	B		C		D	E	F
Year	Dam Name		Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1902	Union	NF	N Fork	2,470,000	2,000	2,000	0.2%
1905	Copperopolis	M	Penney Creek	278,000	225	2,225	0.2%
1906	Alpine	NF	Silver Creek	5,670,000	4,596	6,821	0.6%
1908	Stan FB	M	Trib Stan. River	395,000	320	7,141	0.6%
1908	Utica	NF	N Fork	2,960,000	2,399	9,541	0.8%
1910	Relief	MF	Relief Creek	18,700,000	15,158	24,699	2.1%
1912	Goodwin	M	Mainstem	617,000	500	25,199	2.1%
1916	Rodden Lake	M	Lesnini Creek	469,000	380	25,579	2.1%
1916	Main Strawberry	SF	South Fork	22,900,000	18,312	43,891	3.7%
1926	Old Melones [3]	M	Mainstem	139,000,000	112,674	156,566	13.0%
1928	Hunters	NF	Mill Creek	246,000	199	156,765	13.1%
1930	Lyons - PGE	SF	South Fork	7,680,000	6,228	162,993	13.6%
1938	McCarty	M	Trib Johnny Creek	115,000	93	163,086	13.6%
1953	Murphys Afterbay	M	Trib Angels Creek	49,300	40	163,126	13.6%
1953	Murphys Forebay	M	Trib Angels Creek	66,600	54	163,180	13.6%
1953	Fly in Acres	NF	Moran Creek	123,000	100	163,280	13.6%
1957	Beardsley	MF	Middle Fork	120,000,000	77,600	240,880	20.1%
1958	Tulloch	M	Mainstem	84,400,000	68,400	309,280	25.8%
1958	Beardsley Afterbay	MF	Middle Fork	395,000	320	309,600	25.8%
1958	Donnells	MF	Middle Fork	79,600,000	56,893	366,493	30.5%
1965	Reba	NF	Trib Bloods Creek	296,000	240	366,733	30.6%
1970	Utica	NF	No. Fork Stan	2,960,748	2,400	369,133	30.8%
1975	Forest Meadows	M	Angels Creek	133,000	108	369,241	30.8%
1975	Bear Vly Sewage Hldg	NF	Trib Bloods Creek	427,000	346	369,587	30.8%
1976	Holman	M	Trib Angels Creek	308,000	250	369,836	30.8%
1978	Leland Meadows	MF	Leland Creek	97,000	79	369,915	30.8%
1979	New Melones	M	Mainstem	2,960,000,000	2,400,000	2,657,241	221.4%
1980	Murphy's Wastewater	M	Trib Six-Mile Creek	173,000	140	2,657,381	221.4%
1983	Andrew Cademartori	M	Trib Angels Creek	175,000	142	2,657,523	221.5%
1988	North Fork Diversion	NF	No. Fork Stan	148,037	120	2,657,643	221.5%
1988	New Spicer Meadows	NF	Highland Creek	233,000,000	188,871	2,846,514	237.2%
1989	McKays Pt Div	NF	No. Fork Stan	2,590,654	2,100	2,848,614	**237.4%**
	TOTAL LISTED DAMS:	32			TOTAL CAPACITY:	**2,846,514** AF	
	(including Old Melones)					TOTAL:	**237%**

Note: Data on the dams within the Stanislaus basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the y
dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basir
construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the ba
MAF, Calfed, 1999). Adapted from Richter's IHA Report.
Data source:

[1] Department of Water Resources, Bulletin17-93, Dams Within the Jurisdiction of the State of California, June 1993.

[2] CALFED Bay-Delta Program, ERPP Draft PEIS/EIR Tech. App., Vol. 2 – Ecological Management Zone Visions, 6/99.

[3] Kondolf et al, 1996, Water Resources Center Rept. 90 (for data on Old Melones Reservoir)

Note – storage from Old Melones (built in 1926) was subtracted when New Melones was filled (1979).

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Chapter 6. Hydrologic Changes

6.1 OVERVIEW

This chapter summarizes the hydrologic changes on the San Joaquin Basin that have resulted from the construction and operation of dams and diversions in the basin. We utilized two different analytical approaches, the Indicators of Hydrologic Alteration (IHA) and the Hydrograph Component Analysis, to quantify and characterize hydrologic patterns in the pre and post-dam era. The IHA method (Richter et al, 1996) evaluates changes in 33 biologically significant hydrologic parameters. The HCA evaluates significant changes in components of the annual hydrograph. Although this chapter describes some of the most obvious and interesting results of these analyses, review of the complete analyses and graphs better describes the totality of hydrologic changes on the San Joaquin Basin Rivers. The full results of these analyses are presented in Appendix A and B. In addition to the results of the IHA and HCA analyses, we also present a summary of changes in the magnitude of the instantaneous peak flows, a geomorphically significant hydrologic parameter.

Together these analyses provide valuable insights on each tributary and the San Joaquin Basin as a whole. The measure of hydrologic change in the rivers (as determined in the IHA Analysis) can be compared to the change in the hydrographs (found in the HCA Analysis) to determine which rivers have been most severely affected by dams and diversions and how the hydrographs can be altered to restore valuable geomorphic processes, riparian vegetation and salmon.

Table 6.1 Gauges of the San Joaquin River Basin.

River	Gauge Name	Owner and Number	Years	Drainage Area (sq. mi.)	River Mile	*Website*
Lower San Joaquin	San Joaquin River near Vernalis	USGS # 11-303500	1923- 2001 ?	13536		http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11303500&agency_cd=USGS
	San Joaquin River near Newman	USGS #11-274000	1912-2000			
Middle San Joaquin	San Joaquin River below Friant Dam	USGS # 11-251000	1907-2001	1676	~268	http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11251000&agency_cd=USGS
	SJR Near Mendota	USGS # 11-254000	1940-54; 1999-present **USGS says 1939-2001**	3940	~207	http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11254000&agency_cd=USGS
Merced	Merced River below Merced Falls, near Snelling, CA	USGS #11-270900;	1901-2001	1061	~55	http://waterdata.usgs.gov/ca/nwis/discharge?site_no=11270900
	Merced River below Crocker Huffman Dam near Snelling	Merced Irrigation District	1938-present		52	
	Merced River near Stevinson. CA.	USGS # 11-272500	1940-1995 (note: CDWR #MST gauge, 1999-present)	1273	1.1	http://waterdata.usgs.gov/ca/nwis/discharge?site_no=11272500
Stanislaus	Stanislaus River at Knights Ferry	USGS #11-300000	1915-1932	972	61	http://waterdata.usgs.gov/ca/nwis/discharge?site_no=11300000
	Stanislaus River Below Goodwin Dam near Knights Ferry	USGS #11-302000	1957- 2001	986	~58	http://waterdata.usgs.gov/ca/nwis/discharge?site_no=11302000
	Stanislaus River at Ripon	USGS # 11-303000	1940-2001	1075	15.7	http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11303000&agency_cd=USGS
Tuolumne	Tuolumne River above La Grange dam near La Grange	USGS # 11-2880000	1911-1970	1532		http://waterdata.usgs.gov/ca/nwis/discharge?site_no=11288000
	Tuolumne River below La Grange Dam near La Grange	USGS # 11-289650	1970-2001	1538		http://waterdata.usgs.gov/ca/nwis/nwisman/?site_no=11289650&agency_cd=USGS

6.2 METHODS

Table 6.1 identifies the hydrologic gauges and data used for this analysis. In some cases, the IHA and HCA analysis relied on slightly different data sets or periods of record. In particular, the HCA utilized "unimpaired" data sets from both the Tuolumne and the San Joaquin to describe pre-dam hydrology.[1] On the Merced and Stanislaus, the HCA utilized early hydrologic record to describe "unimpaired" conditions. The IHA conducted a trend analysis of changes over time in relation to water development to identify a relatively unregulated period and then compared it to the full development period. More specifics on the data utilized is described in Appendix A and B. In addition, the HCA and IHA analysis NHI also collected and summarized results from previous reports to describe changes in instantaneous peak flows.

6.2.1 Indicators of Hydrologic Alteration (IHA)

Appendix A, *An Assessment of Hydrologic Alteration in the San Joaquin River Basin* was developed by Brian Richter of the Nature Conservancy for this report. It summarizes the changes to the natural hydrology of the San Joaquin Basin using the "Indicators of Hydrologic Alteration" software developed by The Nature Conservancy. The software analyzes hydrologic changes by looking at 33 ecological parameters (Table 6.2) (i.e. number of zero-flow days, or annual 1-day maxima) and is used to develop hypotheses regarding the ecological impacts of regulated flow regimes.

Because unimpaired daily flows are only available only for the Tuolumne, this IHA analysis was necessarily based upon comparison of different time periods. For each streamgauge site analyzed, hydrologic conditions from at least two decades in the early part of the available record is compared with data from (at least two) recent decades (Table 6.3) Conclusions are based on visual, qualitative observation of fairly obvious changes or patterns. Results summarize major changes in each tributary and are described in this section for each river.

Table 6.3. Periods of record used for IHA analysis

	Early Period	Recent Period
Stanislaus River	1896-1925	1980-2000
Tuolumne River	1896-1922	1972-2000
Merced River	1902-1925	1968-2000
San Joaquin River	1908-1940	1951-2000
Lower San Joaquin	1930-1940	1951-2000

[1] The HCA utilized data from the Kings River, modified by Madeheim, to describe unimpaired conditions on the San Joaquin.

Table 6.2. Summary of 33 hydrologic parameters used in the Indicators of Hydrologic Alteration software, and their characteristics (Richter et al, 1986; Richter, 2002).

IHA Statistics Group	***Hydrologic Parameters***	***Ecosystem Influences***
Group 1: Magnitude of monthly water conditions		
	Mean value for each calendar month	• Habitat availability for aquatic organisms; soil moisture availability for plants; availability of water for terrestrial animals; availability of food/cover for fur-bearing mammals; reliability of water supplies for terrestrial animals; access by predators to nesting sites; influences water temperature, oxygen levels; photosynthesis in water column.
Group 2: Magnitude and duration of annual extreme water conditions		
	Annual 1-day minima	• Balance of competitive, ruderal, and stress- tolerant
	Annual minima, 3-day means	• Creation of sites for plant colonization
	Annual minima, 7-day means	• Structuring of aquatic ecosystems by abiotic vs. biotic
	Annual minima, 30-day means	• Structuring of river channel morphology and physical
	Annual minima, 90-day means	• Soil moisture stress in plants
	Annual 1-day maxima	• Dehydration in animals
	Annual maxima, 3-day means	• Anaerobic stress in plants
	Annual maxima, 7-day means	• Volume of nutrient exchanges between rivers and
	Annual maxima, 30-day means	• Duration of stressful conditions such as low oxygen and
	Annual maxima, 90-day means	• Distribution of plant communities in lakes, ponds,
	Number of zero-flow days	• Duration of high flows for waste disposal, aeration of
Group 3: Timing of annual extreme water conditions		
	Julian date of each annual 1-day maximum	• Compatibility with life cycles of organisms; Predictability/avoidability of stress for organisms
	Julian date of each annual 1-day minimum	• Access to special habitats during reproduction or to avoid predation: Spawning cues for migratory fish; Evolution of life history strategies, behavioral mechanisms
Group 4: Frequency and duration of high and low pulses		
	Number of low pulses within each year	• Frequency and magnitude of soil moisture stress for plants; Frequency and duration of anaerobic stress for plants
	Mean duration of low pulses within each year	• Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain
	Number of high pulses within each year	• Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites
	Mean duration of high pulses within each year	• Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Group 5: Rate and frequency of water condition changes		
	Means of all positive differences between consecutive daily values	• Drought stress on plants (falling levels)
	Means of all positive differences between consecutive daily values	• Entrapment of organisms on islands, floodplains (rising levels)
	Number of hydrological reversals	• Desiccation stress on low-mobility streamedge (varial zone) organisms

6.2.2 Hydrograph Component Analysis (HCA)

Appendix B, The *San Joaquin River Basin Hydrograph Component Analysis Technical Memorandum* was developed for the report by McBain and Trush consultants. It summarizes and describes historical and contemporary streamflow hydrology for the San Joaquin Basin. The hydrograph component analysis describes the variability in magnitude, timing, duration, and frequency of flow of important hydrograph components such as: fall storm pulses, winter and summer baseflows, winter floods, spring snowmelt floods, and snowmelt recession. For each of the four rivers, a period of record was selected that represented (as closely as possible) unimpaired runoff conditions and the contemporary regulated conditions. Table 1 lists the periods of record used for each river.

"Unimpaired" data refers to either (1) natural or unregulated/undiverted streamflow conditions, i.e., empirical data from USGS records prior to major basin impoundments, (2) data from Turlock Irrigation District (TID) as in the case of the Tuolumne River unimpaired flowdata, which is derived from a model of reservoir inflows and basin diversions, and (3) data for the San Joaquin River modeled from the Kings River at Piedra USGS records, and converted based on watershed area at Friant Dam. "Regulated" refers to the period of record after the largest basin reservoir project was completed (Friant Dam, New Exchequer Dam, New Don Pedro Dam, and New Melones Dam). Other regulated periods of record were not included in our analyses because our primary interest was to compare unimpaired conditions with contemporary regulated conditions.

Table 6.3. Periods of record used for IHA analysis

	"Unimpaired"	Fully Regulated
Stanislaus River	1896-1932	1983-1999
Tuolumne River	1896-1999	1972-2000
Merced River	1901-1926	1971-1999
San Joaquin River	1896-1999	1950-2000

Hydrologic analyses included the following:

Water Year Classification: the annual water yields (runoff) for unimpaired and regulated conditions were classified into five different water year types based on the frequency distribution of annual yield. Water yields were plotted as an exceedance probability, then divided symmetrically into five equally weighted classes separated by annual exceedance probabilities (p) of 0.80, 0.60, 0.40, and 0.20 and named "Extremely Wet", "Wet", "Normal", "Dry", and "Critically Dry". This classification system addresses the range of variability in the annual water yield and provides an equal probability for each class that a given water year will fall into that category (equally distributed around the mean), which in turn allows simpler comparisons between water year types. Annual hydrographs grouped into five water year classes were then averaged to produce a single average hydrograph. Average hydrographs illustrate differences among water year classes, but mask actual flow variability within each class. To highlight the annual flow variability, we overlaid the water year average hydrographs with a hydrograph from a single representative water year. Finally, annual yields were plotted as a column chart to illustrate the inter-annual (and cyclical) variation in yield for the period of record, and then plotted as a frequency distribution to illustrate the range in yield for each water year type.

Hydrograph Components:
Each of the important hydrograph components analyzed for each of the four rivers in the Hydrograph Component Analysis is summarized below. Refer to Figure 1 for an illustration of these components.

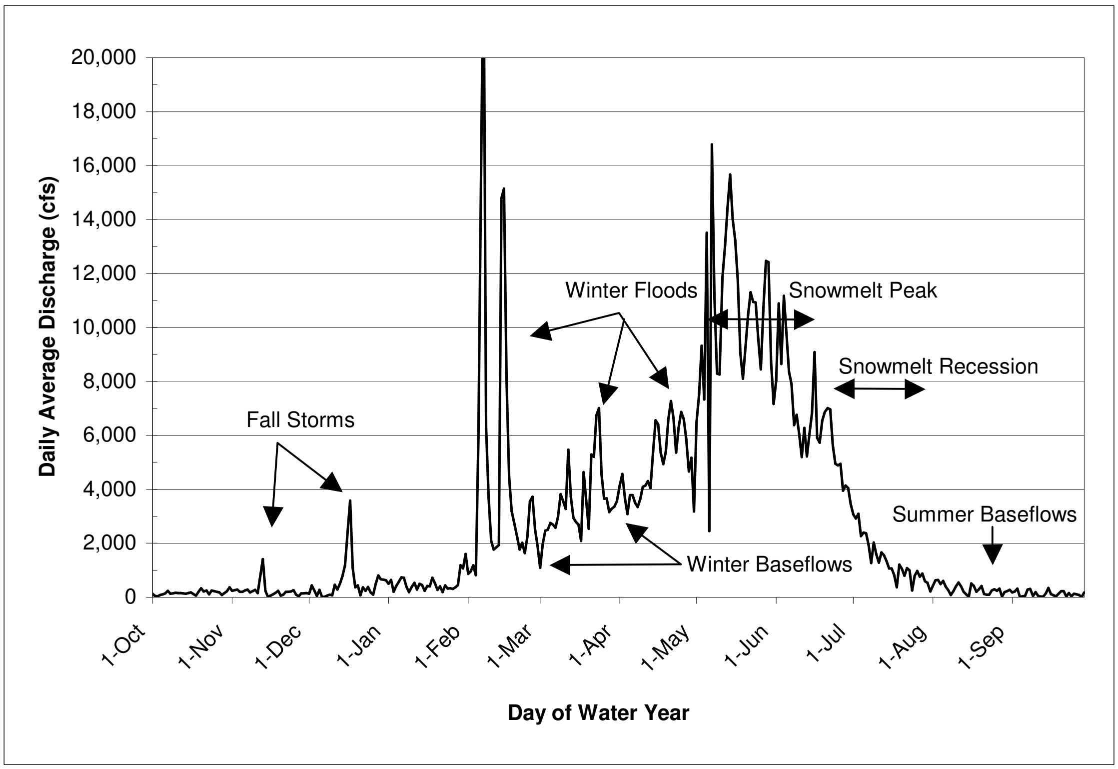

Figure 6.1. Illustration of the important components of the annual hydrograph of daily average flows for a typical San Joaquin Basin Tributary. (Hydrograph from Tuolumne River as measured below La Grange Dam, Normal Unimpaired WY1937).

The dates for each component were chosen to provide a discrete period for analyses that are comparable for each tributary, but do not necessarily capture all the variability in the duration of the component. For example, if no winter storms occur in a particular year, or occur later in the season, then fall baseflows may extend later than the December 20 date used for analyses.

Fall Baseflows: Occurring somewhat variably between October 1 and December 20, these were relatively low flows, frequently the lowest daily average flows of the year. Fall baseflows were the unimpaired flows to which adult Chinook salmon were adapted during the spawning phase of their life history. The magnitude of the fall baseflows were also critical in regulating the temperature regime in the San Joaquin River and tributaries during the spawning period.

Fall Storm Pulses: Typically occurring between October 1 and December 20, these pulses were generally of smaller magnitude than winter floods. These short duration pulse flows may have stimulated or enabled anadromous salmonid upstream migration by providing a more suitable temperature regime in the lower basin rivers, as well as adequate flow volumes to enable upstream fish passage. Fall pulses may have also contributed to maximizing the use of available spawning habitat by providing access to different habitat zones, below the baseflow stage, during short intervals of higher flows.

Winter floods: Typically occurring between mid-December and late-March, winter floods were generated by rainfall or rain-on-snow storm events. Larger magnitude, short duration floods caused by rainfall and rain-on-snow events typically peaked in late December through January, with moderate magnitude events extending through March. Winter floods performed a variety of important ecosystem functions, including the creation and maintenance of channel morphology, scour and transport of bed sediments, bank erosion and channel migration, scour of riparian vegetation along channel margins, scour of alternate bars and other habitat features, and floodplain inundation. The winter flood hydrograph component differed from the annual maximum series flood because it was a daily average flow instead of an instantaneous maximum value.

Winter baseflows: Occurring between December 21 and March 20 (and frequently later into the spring), winter baseflows were low flow periods between winter storms. Winter baseflows were maintained by the receding limbs of storm hydrographs and shallow groundwater discharge, and generally increased in magnitude and duration throughout the winter months as soils became saturated and groundwater tables rose. Flow conditions during winter months are naturally highly variable, so determining winter baseflows is challenging. A close succession of storms, for example, would establish relatively high baseflows, whereas a long, dry spell between storms would lead to lower winter baseflows.

Snowmelt floods: Spring snowmelt floods were usually of smaller magnitude and longer duration than winter floods. Prior to regulation and diversion, this component was the largest contributor to the total annual water yield, with large magnitude and sustained duration floods extending from approximately early May to as late as August during wetter years, and peaking usually in June or July. The spring snowmelt flood had enormous ecological significance, particularly to the native flora and fauna whose life history traits were strongly linked to the seasonal runoff. Native anadromous salmonid juveniles emigrated from up-river rearing grounds through the nutritionally rich Bay-Delta and out to the ocean during the spring snowmelt, conveyed by the large runoff and favorable water temperatures, and protected by increased turbidity resulting from high flows. Numerous native plant species were also dependent on spring floods to inundate higher-elevation channel surfaces and deposit moist, fine sediment seedbeds where successful germination could occur.

Snowmelt recession: Connecting the snowmelt flood to summer baseflows, the snowmelt recession extended into summer, generally declining to baseflow level by August, but often extending into September of Wet and Extremely Wet years. The critical aspect of the snowmelt recession was the rate of recession, the daily decrease in river stage height. This recession rate determined survival or mortality-by-desiccation of germinating plant seedlings.

Summer baseflows: Beginning at the cessation of the spring snowmelt hydrograph, summer baseflows extended through summer and into fall until the first fall storms increased baseflow level. Summer baseflows represented the minimum annual flow conditions.

6.3 RESULTS

The results of the IHA and HCA analyses are first summarized for each of the tributary basins and the middle reach of the San Joaquin River separately. Most of the conclusions drawn from the IHA analysis for these river basins are based upon visual analysis of the graphs of the 18 IHA parameters included in the Appendices. Because such conclusions are based upon visual (qualitative) observation, and comparison of "unimpaired" with "measured" conditions is not yet possible, and thus these conclusions should be regarded as speculative. That being said, the hydrologic changes discussed here are based on rather obvious, fairly abrupt breaks in the annual series associated with the construction of particular dams or diversions.

The "unimpaired" data sets utilized in the HCA analysis for the Merced and Stanislaus are actually derived for the early gauge records. Although these were the best data available to describe natural runoff conditions, they are nevertheless not purely "what the river would have experienced" prior to approximately 1848 when European settlers began manipulating streamflows. For example, small scale diversions began on the Stanislaus as early as 1858. We still classified this period of record as "unimpaired" due to the relatively small scale of the diversions. As with the IHA analysis, most of the changes reported are based on obvious, major alterations in the hydrograph. The notable exception may be late summer and fall base flow which was probably heavily altered even before the period of record commenced. The modeled data used for the San Joaquin and Tuolumne are also an extrapolation of the true unimpaired condition because they are mathematically calculated based on reservoir storage changes, evaporation rates, and diversion volumes, instead of empirically measured streamflows.

6.3.1 Summary of Changes in Instantaneous Peak Flows for all Four Rivers

Table 6.4 provides a comparison of the magnitude of pre and post-dam instantaneous peak flows for various recurrence intervals on the San Joaquin Basin Rivers.

Table 6.4. Comparison of Instantaneous Annual Peak Flows Under Pre-Dam and Regulated Conditions in the San Joaquin Basin.

	Middle San Joaquin (cfs)[2]		**Merced**[3] **(cfs)**		**Tuolumne (cfs)**[4]		**Stanislaus (cfs)**[5]	
	Pre-Dam (1908-1940)	*Post-Dam (1948-1997)*	*Pre-Dam (1902-1925)*	*Post-Dam (1968-2000)*	*Pre-Dam (1918-1970)*	*Post-Dam (1971-1999)*	*Pre-Dam (1904-1979)*	*Post-Dam (1979-2000)*
$Q_{1.5}$	8,651	636	10,062	1,594	8,670	3,020	5,350	1,840
Q_2	11,652	1,059	13,692	2,404			9,430	3,070
Q_5	25,070	3,355	24,006	4,701	25,230	7,569	19,100	5,300
Q_{10}	40,607	7,062	31,526	6,287	37,574	8,429	35,000	6,600
Q_{25}					53,000[6]	13,000[7]	60,000	7,350+[8]
Q_{100}	194,205	77,682						
Q_{MAF}	18,644	4,378	16,200[9]	3,200				

The instantaneous annual peak flows is the maximum peak flow that occurs at a single moment during a given year. It is a different measure than the maximum average daily flow, which as the name implies, averages the flow during the one-day period with the highest discharge. In many cases, the instantaneous annual peak can be twice as much as the maximum average daily flow. The instantaneous peak flow with a recurrence

[2] Data from Cain 1997.
[3] Data from Stillwater Sciences Merced River Corridor Restoration Plan Table 3-2 pg 3-14. Source: USGS gauge Merced River at Exchequer #11-270000 (pre-dam) WY 1902-1925, and CDWR gauge Merced River below Snelling (MSN) #B05 170, WY 1968-1997 (post-dam). Flood magnitudes and recurrence intervals are based on a Log-Pearson III distribution of instantaneous peak flow data.
[4] McBain and Trush 2001Table 2-3 pg 21. Floods described as standard flood frequency analysis of instantaneous peak floods (USGS 1982) Figure 2-9 pg 22 Flood frequency curves for the LaGrange gauging station based on the annual maximum series for pre-NDPD and post-NDPD hydrology, including raw data and a log Pearson Type III distribution fit to log transformed data. Data from USGS gauge at La Grange (#11-289650).
[5] Data from Schneider 2001 table 3.4 pg 59. Data augmented from Knights Ferry Gauge (#11-302000), Melones Dam gauge 1933-1956 (#11-299500) and Stanislaus River at Knight's Ferry 1862, 1904-1932 (#11-300000).
[6] Pre-1970 Log-Pearson III Fit in McBain and Trush 2001 pg 22.
[7] Post 1970 Log-Pearson III Fit in McBain and Trush 2001 pg 22.
[8] Insufficient data to estimate Q_{25} as there are only 21 years of data post NM dam.
[9] Mean annual flood at the Exchequer gauge (1902-1964) and Snelling gauges (1967-2000).

interval of once every 1.5 – 2 years ($Q_{1.5}$ – Q_2) is often referred to as the dominant or effective discharge due to its role in shaping and maintaining channel geomorphology. It is responsible for defining channel geometry (e.g. channel width and cross sectional area) (Leopold et al.1964), mobilizing the bed (Parker et al. 1982), transporting the most sediment over time (Andrews, 1980), and maintaining channel morphology (Rosgen 1986).

In addition to its geomorphic significance, the $Q_{1.5}$ is also biologically significant due to its role in creating inundated floodplain habitat for riparian and aquatic species. The $Q_{1.5}$ constitutes the bankfull discharge to the extent that it has shaped the channel to convey the $Q_{1.5}$. Discharges less than the $Q_{1.5}$ remain within the channel while flows greater than the $Q_{1.5}$ spill over bank and inundated the floodplain. Channels and floodplains shaped over decades to flood at the unimpaired $Q_{1.5}$ do not flood as frequently under regulated hydrologic conditions that reduce the magnitude of the $Q_{1.5}$. Riparian and aquatic species that depend upon floodplain inundation for successful completion of their life cycle may thus be impacted by changes in the $Q_{1.5}$.

Less frequent floods may also be important in shaping channel and floodplain morphology and habitats. Alternate bar morphology characteristic of alluvial river are maintained by periodic and deep scouring that occurs during flood events that exceed the 5-10 year annual flood recurrence (Q_{5} - Q_{10}) (Trush et al. 2000). Even large annual maximum flood on the order of the 10 to 20 year recurrence interval (Q_{10} – Q_{20}) may be necessary to rejuvenate mature riparian stands to early successional stages, form and maintain side channels, scour flood plains, and perpetuate off-channel wetlands, including oxbow lakes (Trush et al. 2000).

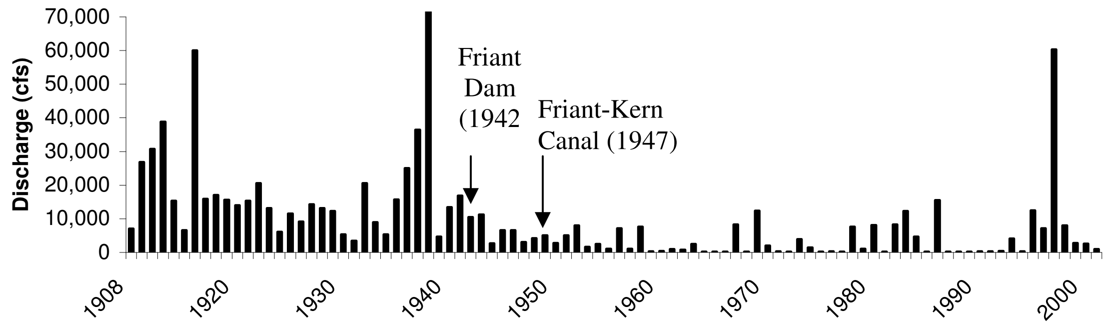

Figure 6.2. San Joaquin River, annual instantaneous maximum flow at Friant gauge below dam.

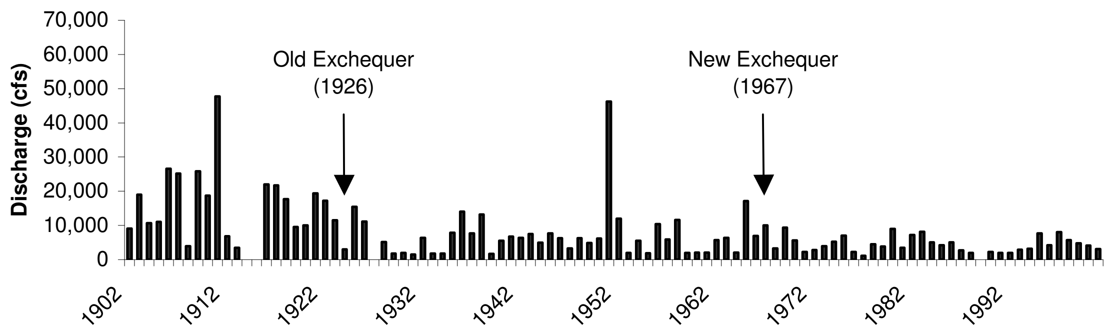

Figure 6. 3. Merced River, annual instantaneous maximum flow at Exchequer (1902- 1964) and Merced Falls (1964-2001).

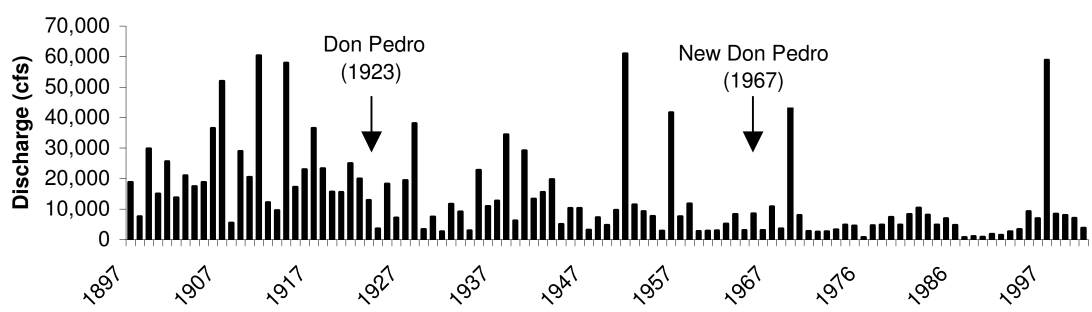

Figure 6.4: Tuolumne River peak annual flow at La Grange.

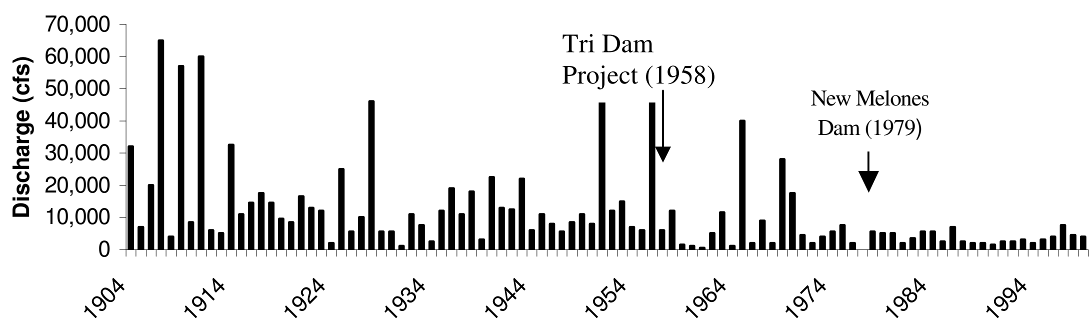

Figure 6.5. Peak Annual Flow, Stanislaus River at Knights Ferry

6.3.2 MIDDLE AND LOWER SAN JOAQUIN

Figure 6.6 presents a summary of changes in median and average monthly flows between the pre-dam and post-dam era. (Note that the y axis is plotted on a log scale.) Reductions were least in the highest percentile values (i.e., infrequent wet periods), and were greatest in lowest percentiles (i.e., dry years). Because storage in the basin is small relative to the annual discharge, and because there is a high inter-annual variability, large flows pass the dam in wet years, while virtually all flow can be stored or diverted in dry years. In the late winter and early spring, while the basin still experiences winter storm-runoff, but prior to irrigation diversions, the 90th percentile flow is virtually unchanged, reflecting the passage of high flows through Friant Dam. Figure 6.5 shows not only a large reduction in median flow, but elongated boxes, indicating a wider variation in flows (between 25th and 75th percentiles) during the post-dam period. While the relative variation in monthly flows (between 25th and 75th percentiles) is greater because of the reductions in dry and "normal" [average] years, the actual range of flows is reduced in some months because the pre-dam flows were much greater. The log scale on Figure 6 exaggerates the apparent variations at the lower end of the scale.

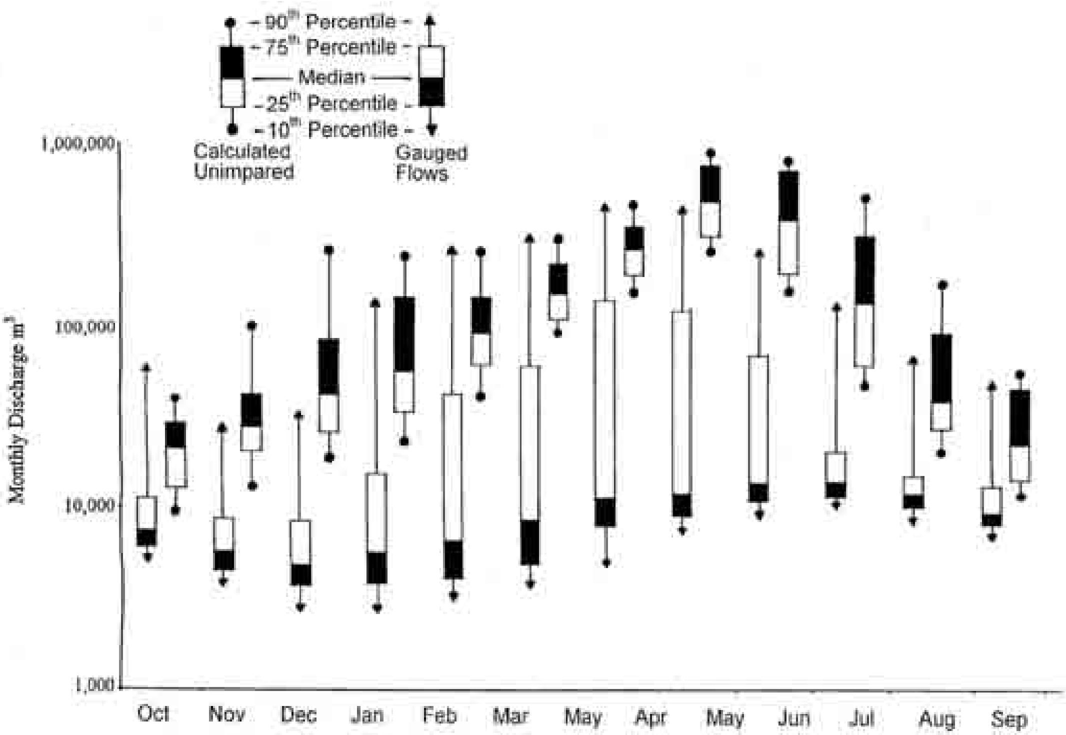

Figure 6.6 Box-and-whisker plots by month for calculated unimpaired and actual gauge flows, San Joaquin River at Friant, based on 1922-1996. (Sources: CDWR, and USGS published data). Note that while 90th percentile flows do not differ greatly, actual median flows do not differ greatly, actual median flows are much lower than unimpaired values. Discharge (y-axis) plotted on log scale.

Friant Dam operations have the greatest effect on flows during the spring and early summer months when diversions into the canal are maximized for irrigation. The effects of Friant Dam and diversions on river flow in June, the month of highest runoff, are illustrated in Figure 5.3. Under pre-dam conditions, the median (unimpaired) June flow of 142 m^3s^{-1} continued downstream largely unchanged until diversions at Mendota Pool. Under current conditions, about two-thirds of the median flow is diverted, and nearly one-third stored in Millerton Reservoir, leaving a median downstream release of only 5 $m^3s^{-1.}$ Under pre-dam conditions, most runoff occurred as snowmelt, from April to June. It is these flows that have been most reduced by Friant Dam and diversions.

Results from IHA Analysis

Middle San Joaquin River (from Friant Dam to Newman)

The largest changes between the early (1908-1940) and recent (1951-2000) periods on the Middle San Joaquin (as measured below Friant Dam) are as follows:

- Monthly average flows throughout the year have been depleted by 82-97% (Figure 6.7).
- 1 to 90-day minima have been reduced by 86-89% (Figure 6.8).
- 1 to 90-day maxima have decreased by 89-94%.
- The average timing of annual low flows is now delayed by more than a month, from early November to late December, and timing of annual high flows is delayed from mid-May to late June.
- Low pulse (flow below 25th percentile) duration has increased 900% from an average of 5 days per year to 54 days. High pulses (flows above 75th percentile) occur far less frequently, but when they do they commonly last longer (Figure 6.7).

Lower San Joaquin River (from Newman to Vernalis)

Hydrologic alterations in the lower San Joaquin are not nearly as severe as in the middle San Joaquin. The largest changes between the early (1930-1940) and recent (1951-2000) periods (as measured at the Newman and Vernalis Gauges):

- Flow depletions of 74-76% in May and June (Figure 6.8).
- Substantial increases in the 1 to 7-day minima (+51-63%) (Figure 6.9).
- Substantial reductions in 1 to 90-day maxima (-45-52%).
- Shift in the timing of annual maxima, from April-May to late December-early January.
- Reductions of 46-48% in high and low pulse durations.

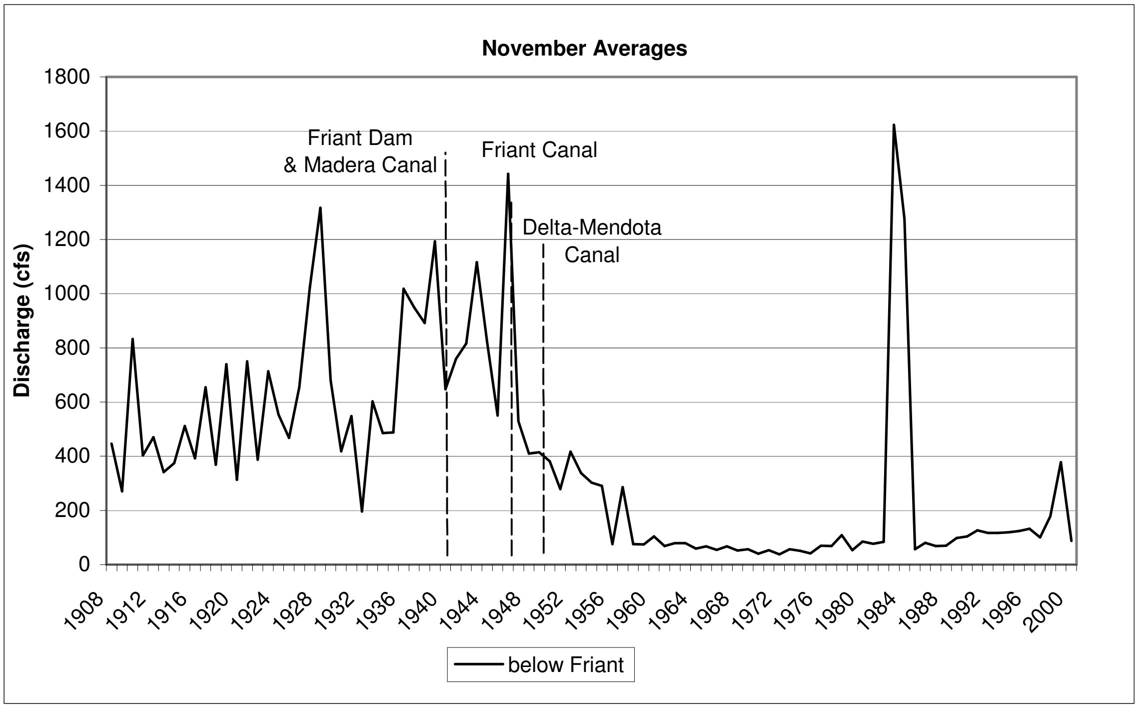

Figure 6.7. November average flow on the middle San Joaquin. An illustration of how monthly average flows have been depleted in November a parameter particularly important to spawning fall-run Chinook.

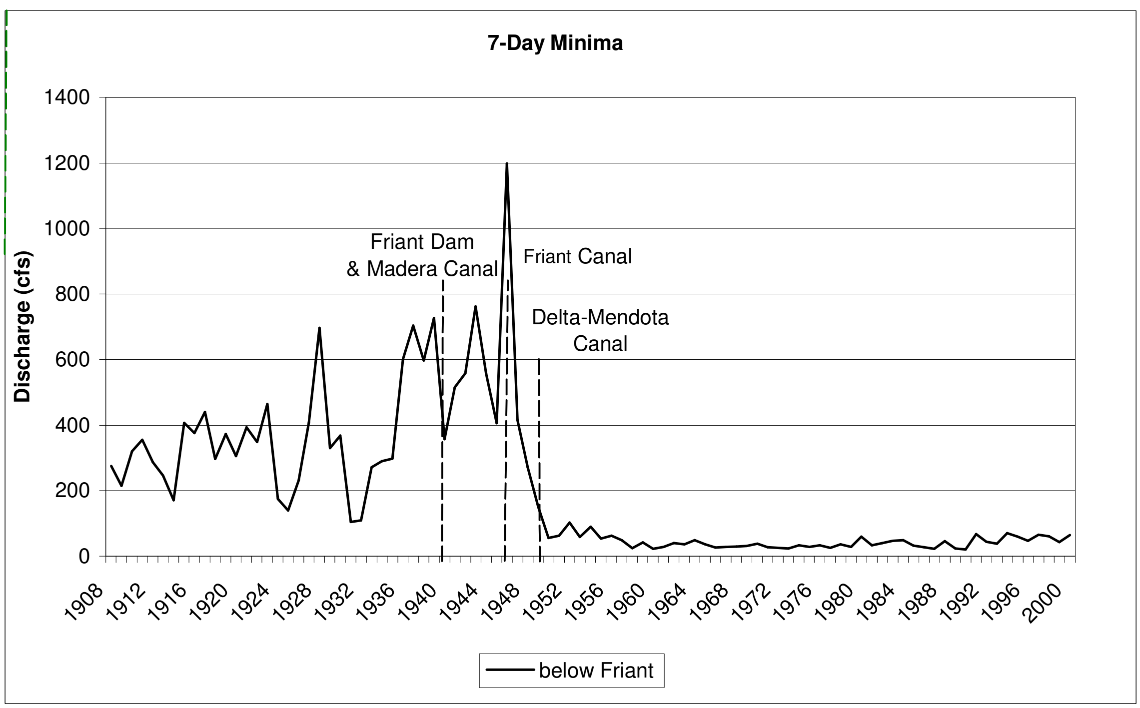

Figure 6.8. 7-day minima flow on the middle San Joaquin. An example of how minimum flows over 7 days have been depleted after the development of dams and canals.

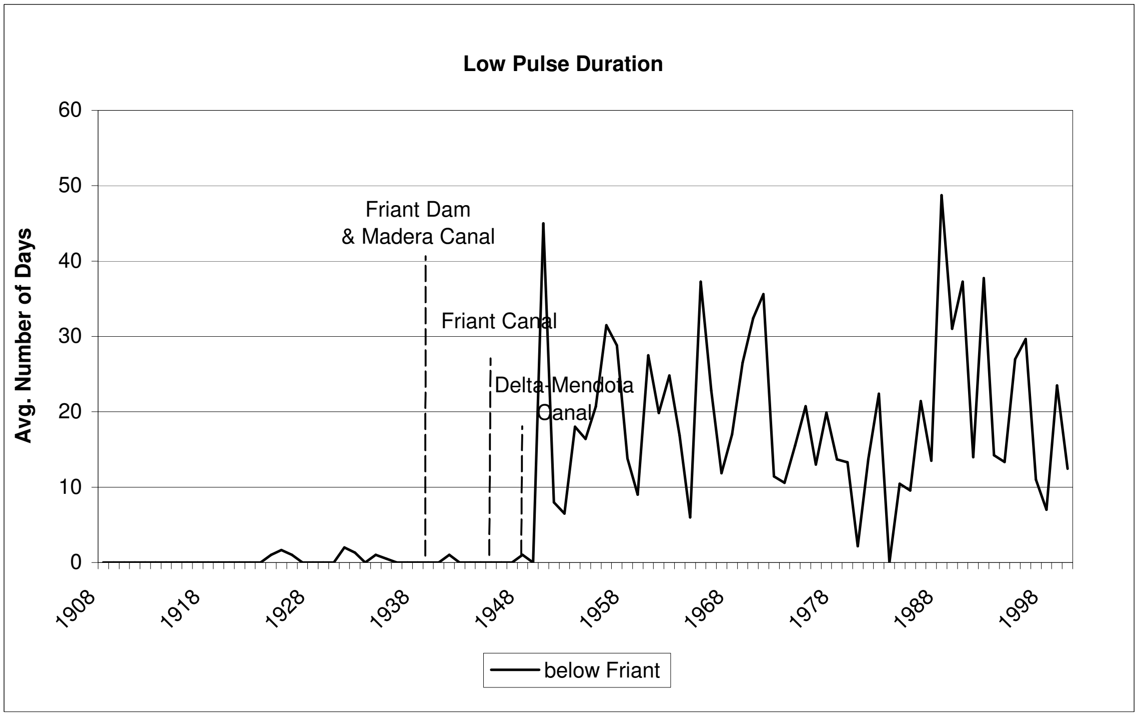

Figure 6.9. Low Pulse Flow Duration on the middle San Joaquin. An example of how the duration of low flow period has dramatically increased after the development of dams and canals.

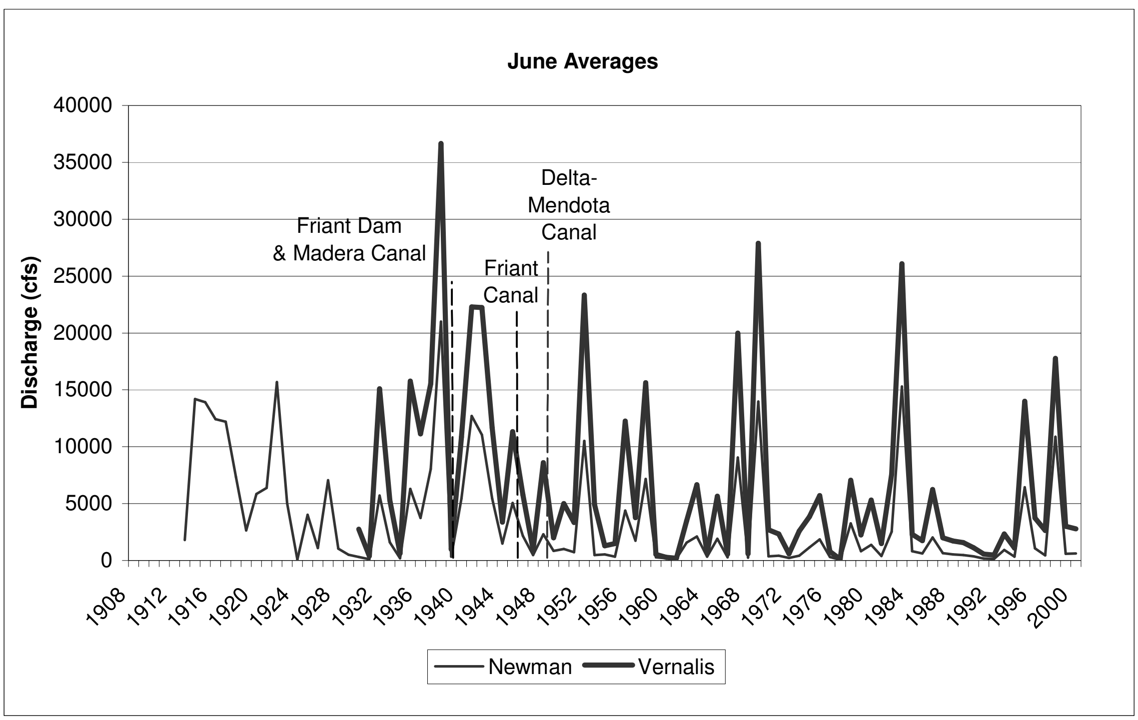

Figure 6.10. June average flow on the lower San Joaquin. Monthly average flows have been depleted by 74-76% in May and June.

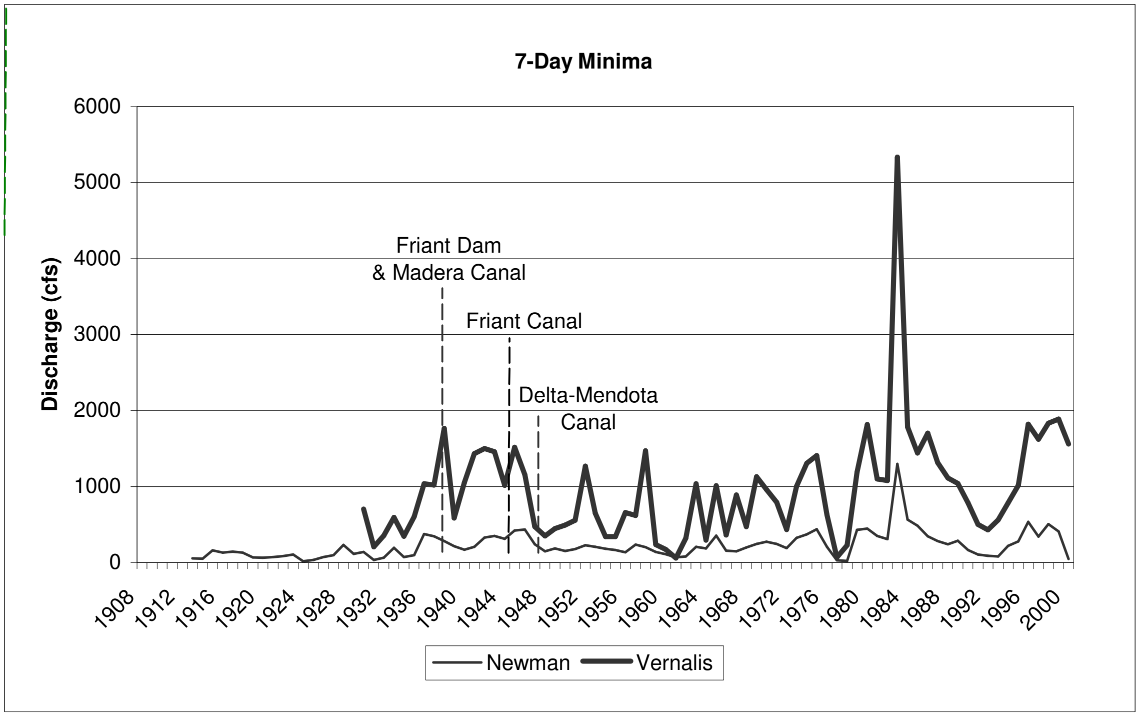

Figure 6.11. 7-day minima flow on the lower San Joaquin. Minimum flows over 7 days have increased 51-63% while maximum flows have decreased 45-52%.

Results from HCA Analysis

Of the four major rivers in the San Joaquin Valley, the San Joaquin River has been the most extensively altered by streamflow regulation and diversion. All regulated streamflow data was measured at the San Joaquin River below Friant USGS gauge and all unimpaired streamflow data was measured at Friant and modeled from the Kings River at Piedra USGS records, and converted based on watershed area at Friant Dam. A summary of the major changes on the San Joaquin River are summarized below:

- The total annual water yield was reduced from 1,813,000 af to 528,000 af, a 71% reduction in yield (Figure 6.12 unimpaired vs regulated annual yield)
- More than half the regulated runoff years analyzed had annual yield less than 125,000 af, which is approximately 7% of the average unimpaired water yield.
- The 1.5-year unimpaired flood was reduced from 10,200 cfs to 850 cfs; the 5-year unimpaired flood of 26,000 cfs was reduced to 6,700 cfs. The smaller magnitude-higher frequency floods were much more severely impacted than were the larger, less frequent floods, likely due to the relatively smaller storage capacity of Millerton Lake.
- The Spring Snowmelt hydrograph component was virtually eliminated in all water year types. Prior to regulation, median spring floods ranged from 6,000 cfs to 18,000 cfs during Dry and Extremely Wet years, respectively, with a duration of several months and occasional flood peaks in excess of 30,000 cfs. Regulated spring floods now range from peaks of 1,800 cfs in Extremely Wet years to as

little as 150 to 200 cfs during Dry and Critically Dry years (Figure 6.13 regulated vs unimpaired wet water year)

- Summer and fall baseflows that historically ranged from 200 to 1000 cfs now rarely exceed 100 cfs under regulated conditions.
- During Dry and Critically Dry years, streamflows remain a static year-round low baseflow of 50 to 200 cfs.
- Two distinct periods of record: from April 1974 to November 1978 (1332 days), and from April 1986 to October 1993 (2350 days) were particularly dry. Compared to the unimpaired daily average flow of approximately 2,500 cfs, these two periods reported daily average flows of 100 cfs and 125 cfs, respectively, with maximum flows for these entire periods of only 236 and 313 cfs, respectively.

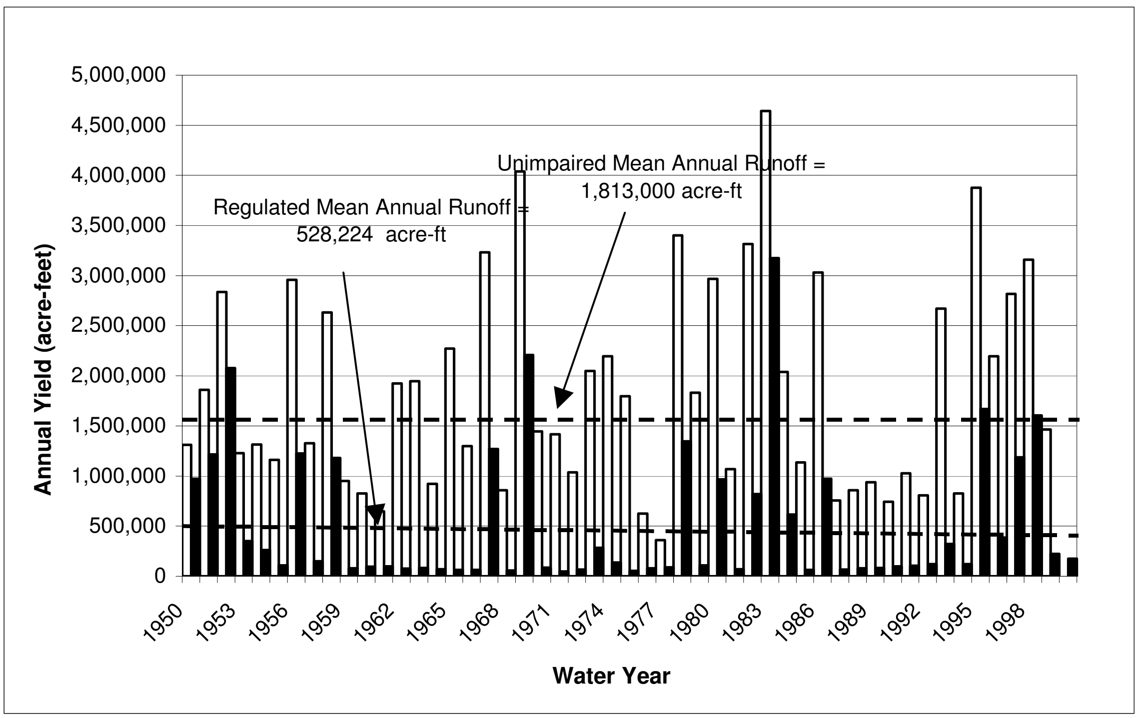

Figure 6.12. Unimpaired and Regulated Annual Water Yield on the middle San Joaquin River as measured at gauge below Friant Dam. The total annual water yield was reduced from 1,813,000 af (unimpaired) to 528,000 af (regulated), a 71% reduction.

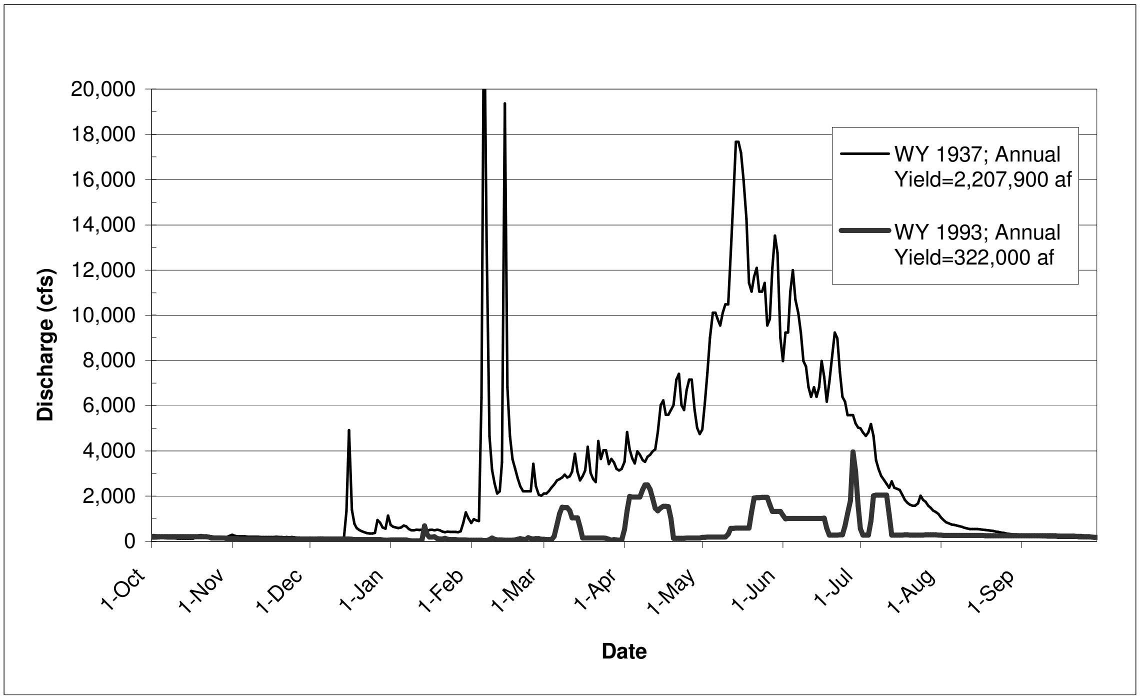

Figure 6.13. Middle San Joaquin River Unimpaired (1937) and Regulated (1993) representative hydrographs for wet years. Unimpaired data modeled from Kings River at Piedra; regulated data measured at gauge below Friant Dam.

6.3.3 RESULTS: MERCED RIVER

Results from IHA Analysis

Construction of Old Exchequer Dam in 1926 added more than 280,000 AF of storage. The effects of this dam on late summer flows are very pronounced, with greatly elevated summer flow conditions resulting from the release of water to storage reservoirs and diversion canals for irrigation purposes especially in August and September, a time when summer baseflows are usually very low (Figure 6.14). November-January flows were substantially lowered (Figure 6.14). The dam also noticeably reduced annual peak flows, and 7-day low flows became more extreme. It also had a pronounced effect on the timing of low flows, which began to be shifted into December and January rather than September-October (Figure 6.16). Both average low pulse (flows below 25th percentile) and high pulse (flows above 75th percentile) duration began to become quite long following dam construction.

The completion of New Exchequer Dam and addition of more than 1 million acre-feet of storage in 1967 began to either accentuate or reverse the hydrologic changes induced by Old Exchequer. For example, Old Exchequer caused substantial depletion of November flows but New Exchequer greatly increased November flows. On the other hand, April-June flows were increasingly depleted by both dams. July-September and annual 7-day low flows were increased after New Exchequer. Annual floods were increasingly curtailed by both Old and New Exchequer dams (Figure 6.17). New Exchequer appears to have brought the average timing of annual low flows and duration of low pulses back closer to the pre-dam character.

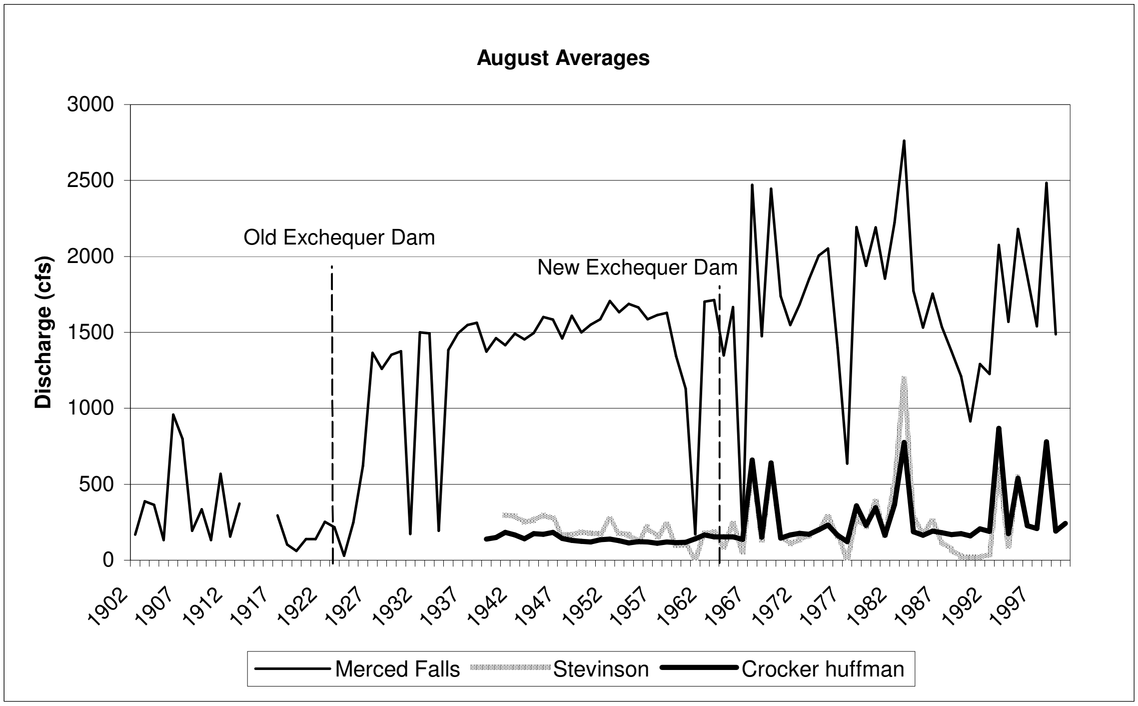

Figure 6.14. Hydrograph of average flows in August on the Merced River. This figure shows the increase of flows in August, probably for irrigation purposes after the construction of Old Exchequer Dam.

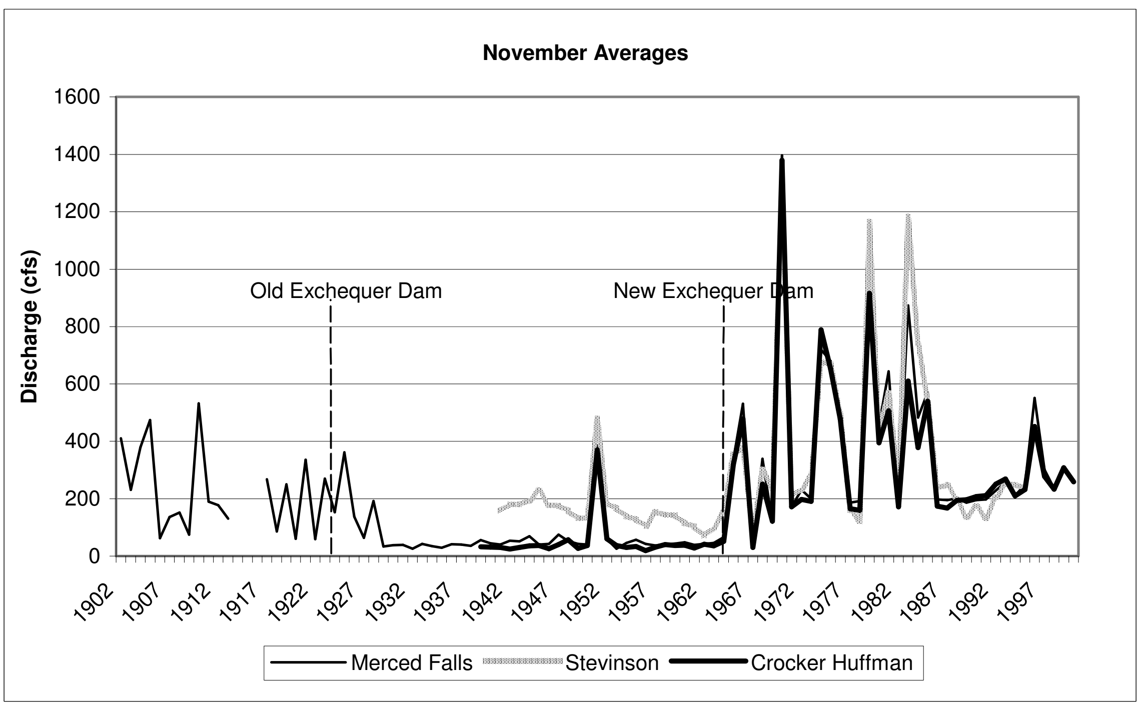

Figure 6.15. Hydrograph of average flows in November on the Merced River. This figure shows the decrease of flows in November after the construction of Old Exchequer Dam and the increase after the construction of New Exchequer Dam.

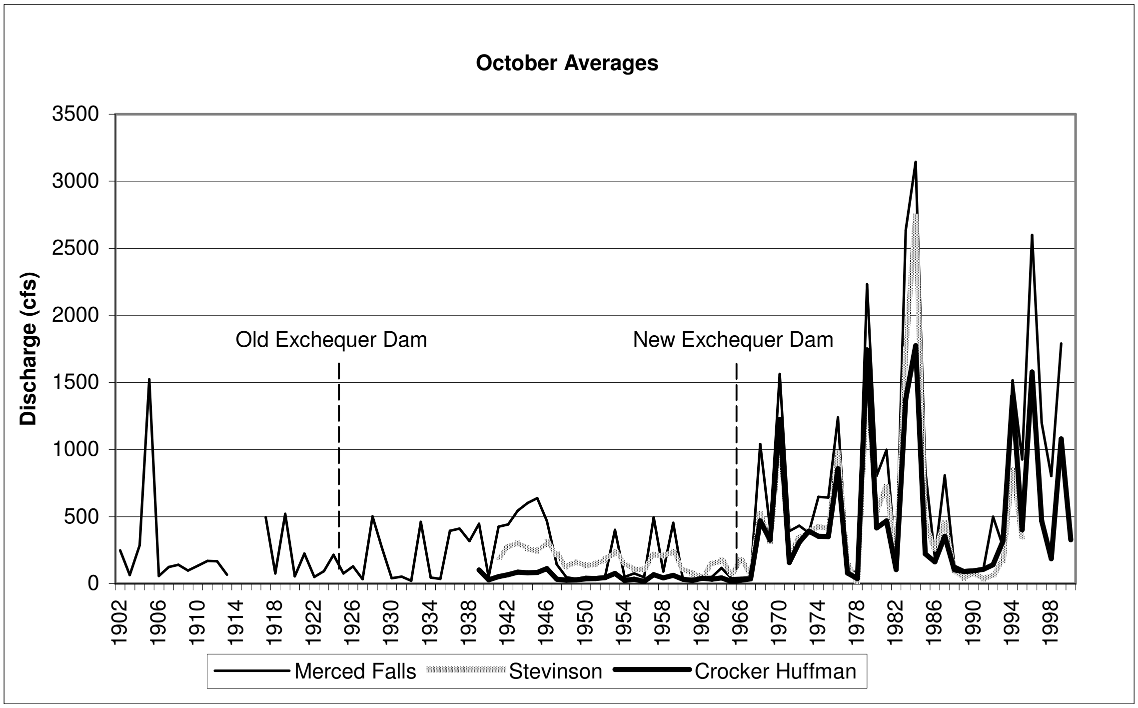

Figure 6.16. Hydrograph of average flows in October on the Merced River. This figure shows the decrease of flows in November after the construction of Old Exchequer Dam and the increase after the construction of New Exchequer Dam.

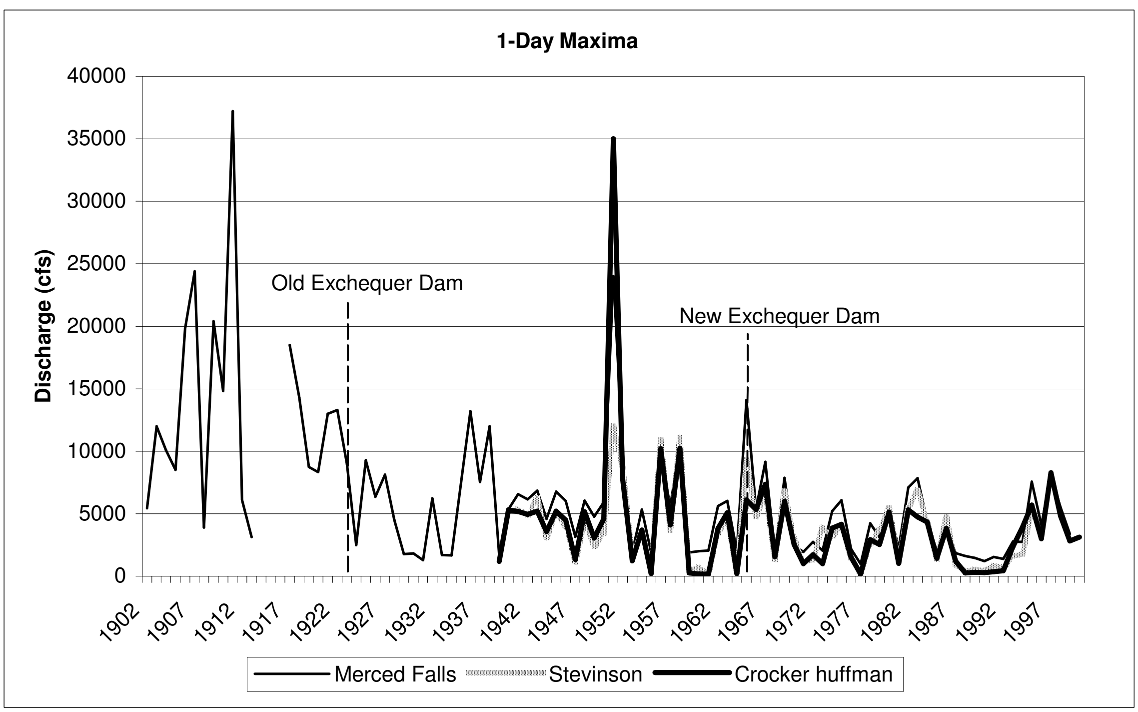

Figure 6.17. 1-day maxima flows on the Merced River from 1902-2001. This figure shows the decrease of annual floods after the construction of Old Exchequer Dam and New Exchequer Dam.

Virtually all aspects of the natural flow regime have been substantially altered on the Merced River. The largest measured changes between the early (1902-1925) (as measured below Merced Falls Dam) and recent (1968-2000) periods (as measured at the gauges at Stevinson, Crocker Huffman and below Merced Falls Dam) are:

- July through October flows have increased substantially, ranging from 160% in July to 961% in September.
- January – June flows have been greatly reduced, ranging from 35% in March to 58% in February.
- 1 to 90-day minimums (low flows) have increased by 146-417%
- 1 to 90-day maximums (large floods) have decreased by 39-72%
- The timing of annual low flows is now delayed by a month, from early October to early November, and timing of annual high flows is delayed from early April to late June.
- Low pulses (flow below 25th percentile) have nearly been eliminated. High pulses (flows above 75th percentile) occur far less frequently but commonly last longer.

Results from HCA Analysis
The unimpaired data was measured at the Merced River below Merced Falls near Snelling USGS gauge and the regulated data was attained at the gauge operated by the Merced Irrigation District on the Merced River below Crocker-Huffman Dam near Snelling.

- The total annual water yield was reduced from 1,038,000 af to 485,000 af, a 54% reduction in yield.
- The 1.5-year unimpaired flood was reduced from 43,170 cfs to 3,142 cfs; the 10-year unimpaired flood of 19,000 cfs was reduced to 7,700 cfs. This trend indicates the smaller magnitude-higher frequency floods were less severely impacted than were the larger, less frequent floods.
- The spring snowmelt hydrograph component was impacted by regulation primarily during Dry and Critically Dry years. The median unimpaired spring flood ranged from 4,000 to 10,900 cfs during Critically Dry and Extremely Wet years, respectively, and was reduced to the 2,000 to 4,000 cfs range during Normal to Extremely Wet years. Dry and Critically Dry years' snowmelt floods were virtually eliminated under regulated conditions (Figure 6.18 – Dry hydrograph).
- The daily average flow was reduced from 1,442 cfs to 653 cfs.
- In addition to reducing the spring snowmelt magnitude, the bulk of the total annual yield was shifted from the spring months under unimpaired conditions to the winter months under regulated conditions (Figure 6.19 – wet hydrograph).

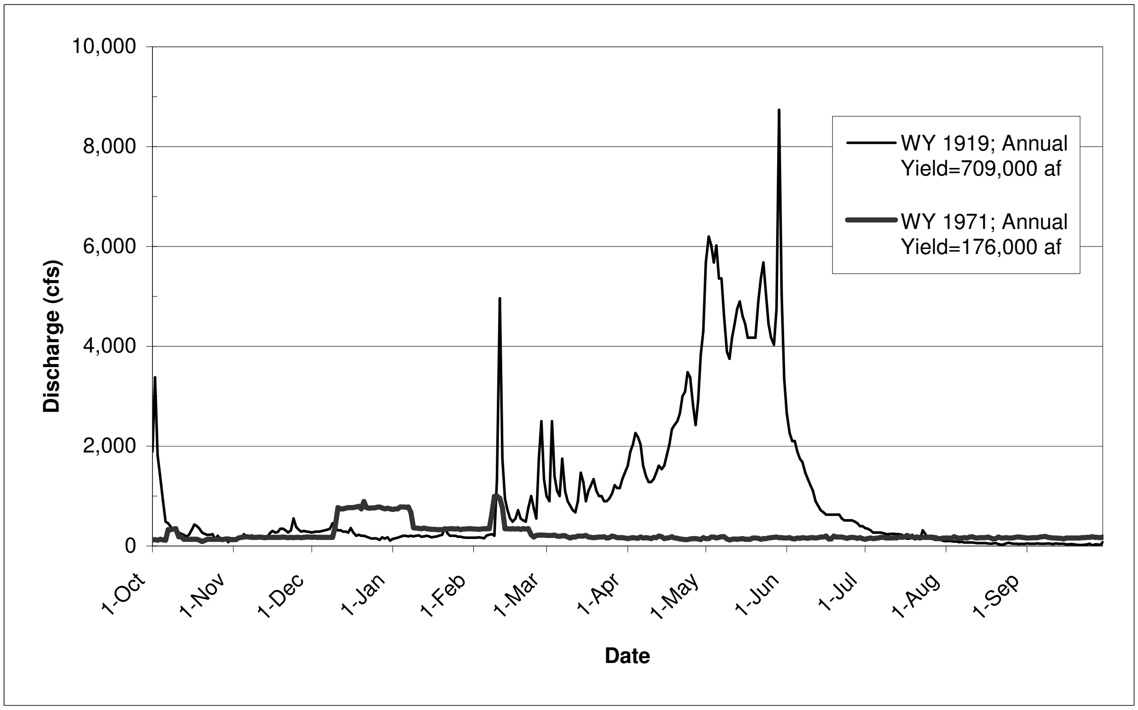

Figure 6.18. Merced River Unimpaired (1919) and Regulated (1971) representative hydrograph for dry years. This figure shows an example of how snowmelt floods were virtually eliminated under regulated conditions, primarily during dry and critically dry years. Unimpaired data from gauge below Merced Fall near Snelling; regulated data from gauge below Crocker-Huffman Dam near Snelling.

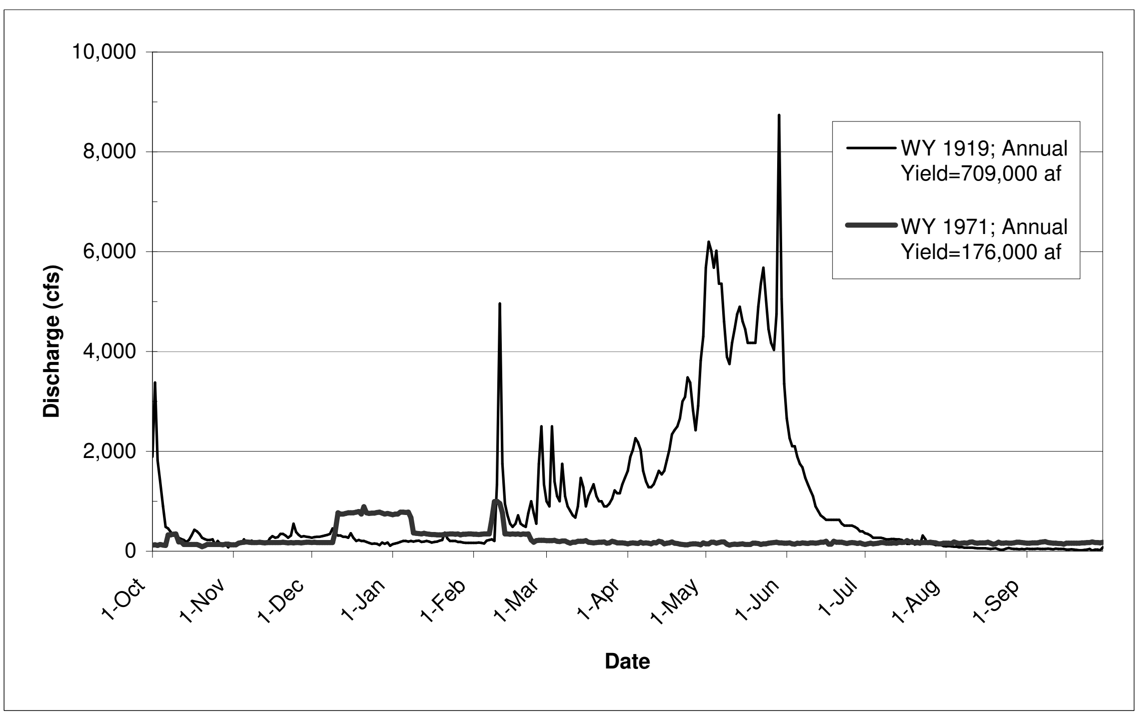

Figure 6.19. Merced River Unimpaired (1904) and Regulated (1974) representative hydrograph for wet years. This figure shows the shift of the bulk of the annual yield of the spring snowmelt from spring, in the unimpaired conditions, to winter in the regulated conditions. Unimpaired data from gauge below Merced Fall near Snelling; regulated data from gauge below Crocker-Huffman Dam near Snelling.

6.3.4 TUOLUMNE

Results from IHA Analysis

With the construction of Hetch Hetchy and Old Don Pedro Dam in 1923, the January-July mean flows were reduced considerably at La Grange following 1923. Annual flood peaks (1-day maximums) and the average duration of high flow pulses (above 75th percentile) were also noticeably reduced after 1923 (Figure 6.20 – 1 day maxima). The construction of Cherry Valley Dam in 1956, with 273 KAF of additional storage, appears to have accentuated some of the changes that began in 1923. In particular, May-August flows were further depleted, 7-day low flows became more extreme, and the river began to be subjected to occasional low pulses of very long duration (Figure 6.21 – low pulse duration), while high pulse durations were noticeably shortened (Figure 6.22 – high pulse duration).

The effects of the New Don Pedro Dam (NDPD) are not clearly distinguishable from the pre-1970 conditions. For some IHA parameters, including November-December and 7-day minimums, operations of NDPD appears to have resulted in a return to conditions similar to pre-1923.

Virtually all aspects of the natural flow regime have been substantially altered on the Tuolumne River. The largest measured changes between the early (1896-1922) (as measured at La Grange) and recent (1972-2000) periods (as measured at La Grange and Modesto):

- September and October flows have increased substantially, by 119% in September and 200% in October
- January – August flows have been greatly reduced, ranging from 36% in February to 99% in June.
- 1 to 90-day minimums have increased by 59-259%
- 1 to 90-day maximums have decreased by 77-81%
- The timing of annual low flows is now much earlier, moving from an average occurrence in early October to late June or early July.
- Low pulses (flow below 25th percentile) now last longer (average low flow duration has changed from 15 days to 21 days). High pulses (flows above 75th percentile) occur far less frequently but when they occur then can last for more than 100 days.

Results from HCA Analysis

Hydrograph components were not analyzed by specific water year class in the post-New Don Pedro Project (NDPP) (regulated) period because the data set was smaller for regulated years and regulation eliminated much variability between water years. All unimpaired and regulated streamflow data were measured below La Grange Dam.

- The total annual water yield in the Tuolumne River has been reduced from 1,906,000 af to approximately 719,000 af, a 62% reduction in yield. The lowest post-New Don Pedro yield was 61,000 af, recorded in 1989 and the highest yield was 3,464,000 af recorded in 1983. The 1995 FERC Settlement Agreement (FSA) increased the minimum streamflow requirements for releases below La Grange from annual minimum releases of 123,000 af and 64,000 af for Normal years and Dry years, respectively, to annual minimum releases ranging from 94,000 af to 300,000 af for Dry and Wet years, respectively.

- Winter floods have been severely diminished by NDPP regulation, with the frequency and magnitude of winter floods reduced. The 1.5-year unimpaired flood of 8,430 cfs was reduced to 2,620 cfs. The annual maximum flood has exceeded 8,400 cfs only three times during the post-NDPP era (since 1971). The January 1997 flood of 60,000 cfs had an unimpaired recurrence interval of 25 years on our flood frequency curve. However, the Army Corp estimated the 60,000 cfs peak discharge had an 80-year recurrence interval.
- Snowmelt floods have been eliminated from the annual hydrograph by NDPP operation and replaced with FERC Settlement Agreement spring pulse-flows intended to stimulate smolt emigration (Figure 6.23 – dry hydrograph). Unimpaired median spring snowmelt floods ranged from 4,500 cfs during Critically Dry years, to 17,000 cfs median flood, with peak spring rain-on-snow floods exceeding 52,000 cfs. The "Outmigration Pulse Flow" in the revised FERC flow schedule provides water volumes ranging from 11,000 to 89,000 af for dry and wet years, respectively, with magnitude-timing-duration decisions the responsibility of the Technical Advisory Committee. Typically, spring pulse releases remain below approximately 5,000 cfs to avoid having to bypass hydropower turbines.
- Daily average flows for May and June at La Grange were reduced from 7,200 cfs unimpaired to 1,370 cfs actual flow (May) and 5,900 cfs unimpaired to 1,370 cfs actual (June).
- Median summer and fall baseflows ranged from 150 to over 1,000 cfs during unimpaired Critically Dry and Extremely Wet years, respectively. These baseflows have been reduced by NDPP regulation and are now determined by the FERC Settlement Agreement. Summer minimum instream flows range from 50 cfs in dry years to 250 cfs during wet years, and begin approximately June 1 each year. Fall baseflows begin October 1, and range from 100 cfs to 300 cfs, depending on water year type.

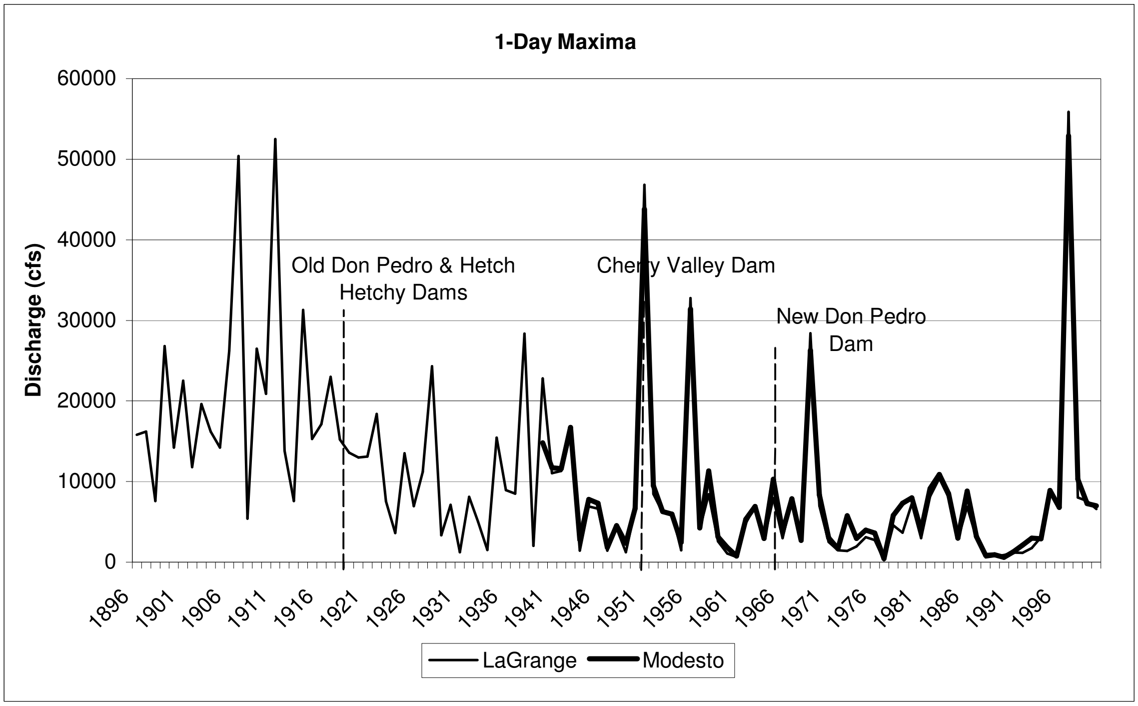

Figure 6.20. 1-day maxima flows on the Tuolumne River. This figure shows the decrease in annual flood peaks after the construction of dams and diversions began in 1923 on the Tuolumne.

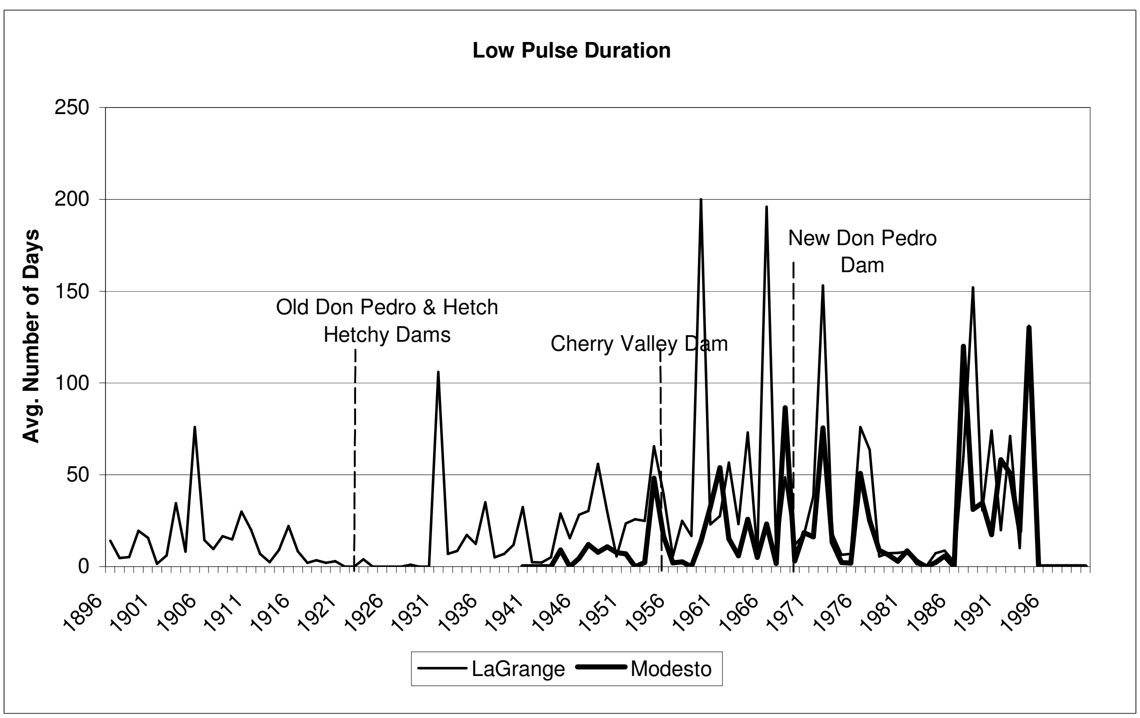

Figure 6.21. Low Pulse Duration on the Tuolumne River. This figure shows the increase of low pulse flows, especially after the construction of Cherry Valley Dam in 1956.

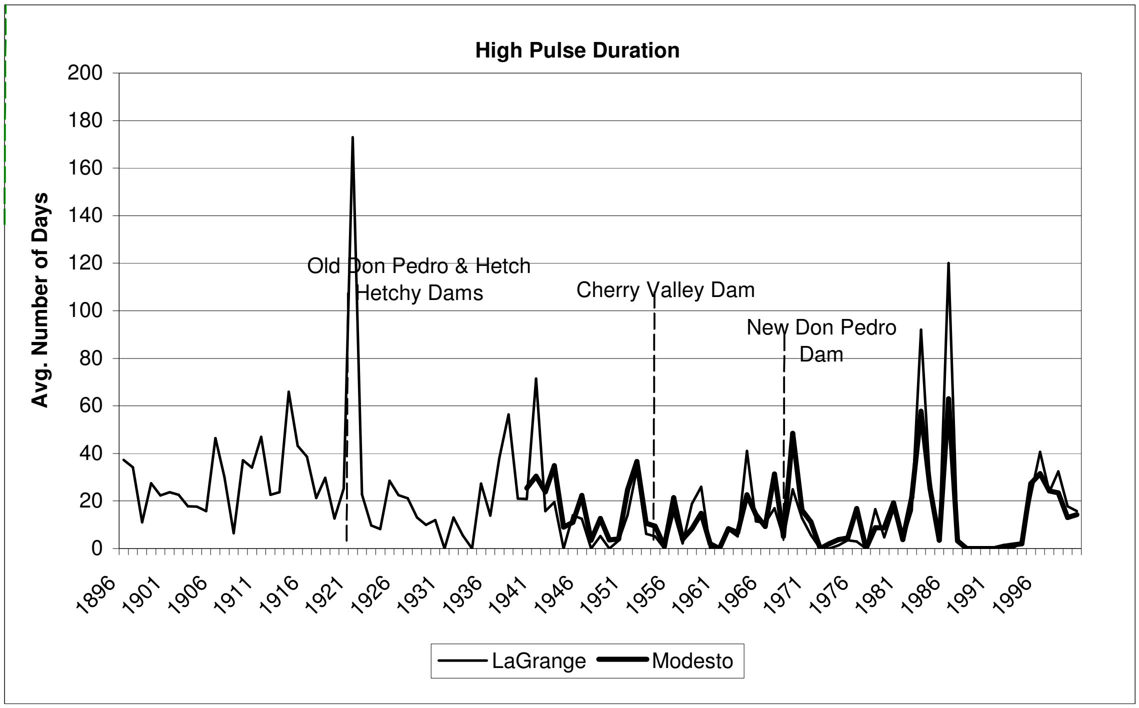

Figure 6.22. High Pulse Duration on the Tuolumne River. This figure shows the reduction of average duration of high flow pulses (above 75th percentile) after 1923.

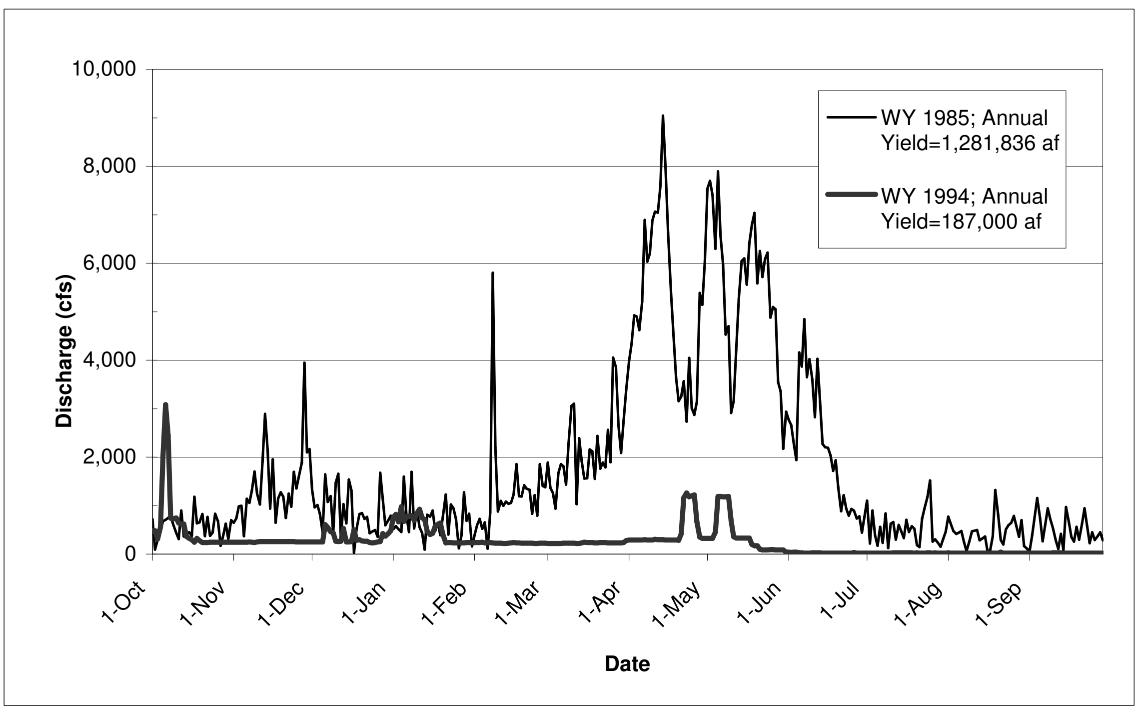

Figure 6.23. Tuolumne River Unimpaired (1985) and Regulated (1994) representative hydrograph for dry years. This figure shows the elimination of snowmelt floods in the spring and the replacement of these floods by FERC spring pulse flows. Data from gauge below La Grange Dam near La Grange.

6.3.5 STANISLAUS

Results From IHA Analysis
Significant changes in hydrologic conditions at Knight's Ferry became apparent with the construction of the Old Melones Dam in 1926. The January mean flows are noticeably suppressed beginning 1926, which may have resulted from Old Melones Dam's ability to capture early snowmelt runoff. Particularly noticeable are changes in August and September flows (Figure 6.24 - August), which begin to increase in 1926, presumably due to the release of water from Old Melones for downstream irrigation use late in the summer growing season.

The effects of the Goodwin Dam and associated diversions (South San Joaquin Canal and Oakdale Irrigation Canal), constructed in 1912-14, do not show up in the graphs of Appendix B until 1957. This is because the data plotted for Knight's Ferry were derived from a number of different gauge sites over time. Prior to 1957, the Knight's Ferry data were obtained from streamgauges lying upstream of the Goodwin Dam and diversions. Beginning in 1957, data obtained from the "Below Goodwin" site are plotted for Knight's Ferry. Thus, the Knight's Ferry graphs reflect the effects of both the Goodwin Dam and diversions and the construction of the "Tri-Dams" project after 1957.

The impact of the Goodwin Dam and diversions is quite detectable in the August and September graphs. The abrupt drop of approximately 1,400 cfs between 1956 and 1957 for the month of August, and of more than 900 cfs between the same years for the month of September, illustrates the impact of these diversions in the river reaches below Goodwin Dam.

Note that the annual traces for the Ripon streamgauge do not show a similar abrupt drop for August or September in 1956-57, suggesting that the construction of the Tri-Dams project did not have much apparent effect on these late summer flows. On the other hand, the Tri-Dams project did have an apparent effect on increasing the average duration of "low pulses" (when flows drop below the 25^{th} percentile), and depressing April and May flows after 1956.

The construction of New Melones Dam in 1978 appears to have had a substantial impact on many of the Stanislaus River's flow characteristics. These effects are most evident on the near-complete curtailment of large floods (Figure 6.25 - 1-day maxima graph), and substantial augmentation of low flows (Figure 6.26 - 7-day minima graph). Not all of the flow changes associated with New Melones Dam are necessarily "bad", however. For instance, flows in May-August appear to have measurably increased, making them more similar to the early decades of record (e.g., 1896-1925). The duration of low pulses has apparently improved (lessened) as well.

The largest measured changes between early (1896-1925) (as measured at Knights Ferry) and recent (1980-2000) periods (as measured at Knights Ferry and Ripon):

- February – June flows have been depressed considerably, ranging from 79% in May to 43% in March.

- September and October flows have increased (106% and 57%, respectively)
- 1 to 90-day minimums have increased (106% and 57% respectively)
- 1 to 90-day maximums have decreased by 74-81%
- High pulses (flows above 75th percentile) occur far less frequently and now last only 1 day on average, as compared to 13 days in the early period.

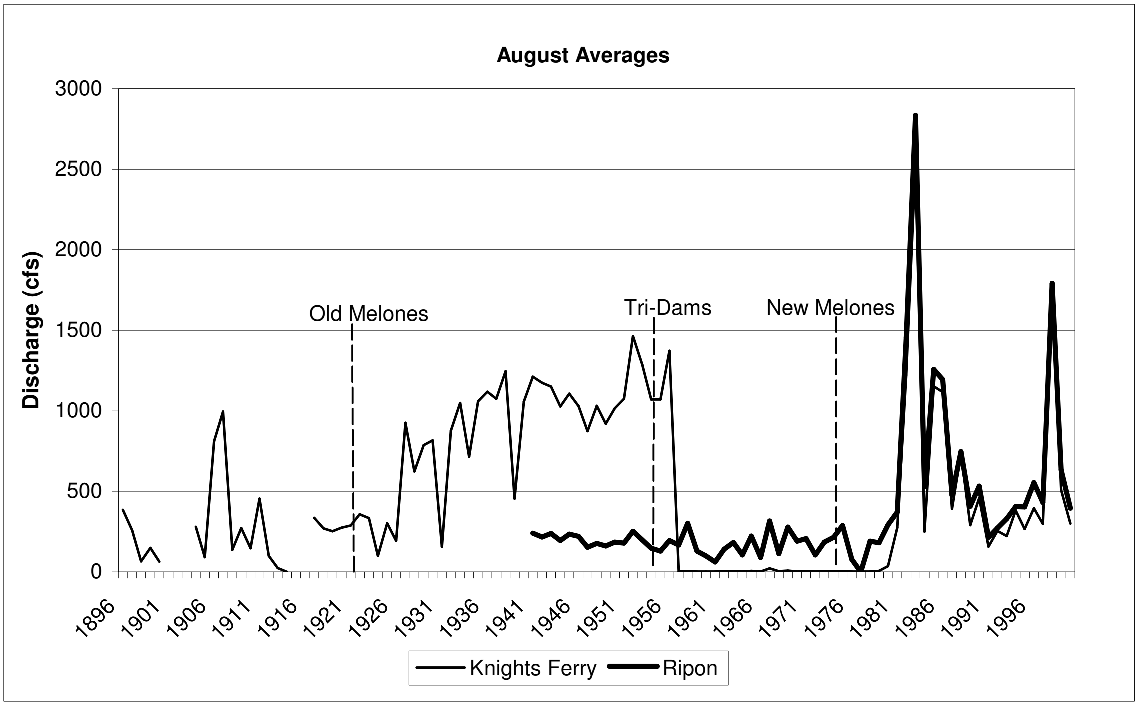

Figure 6.24. August average flows on the Stanislaus River. An example of how monthly average flows have been altered due to construction of dams. August flows increased after the construction of Old Melones Dam and decreased after the construction of the Tri-Dams project.

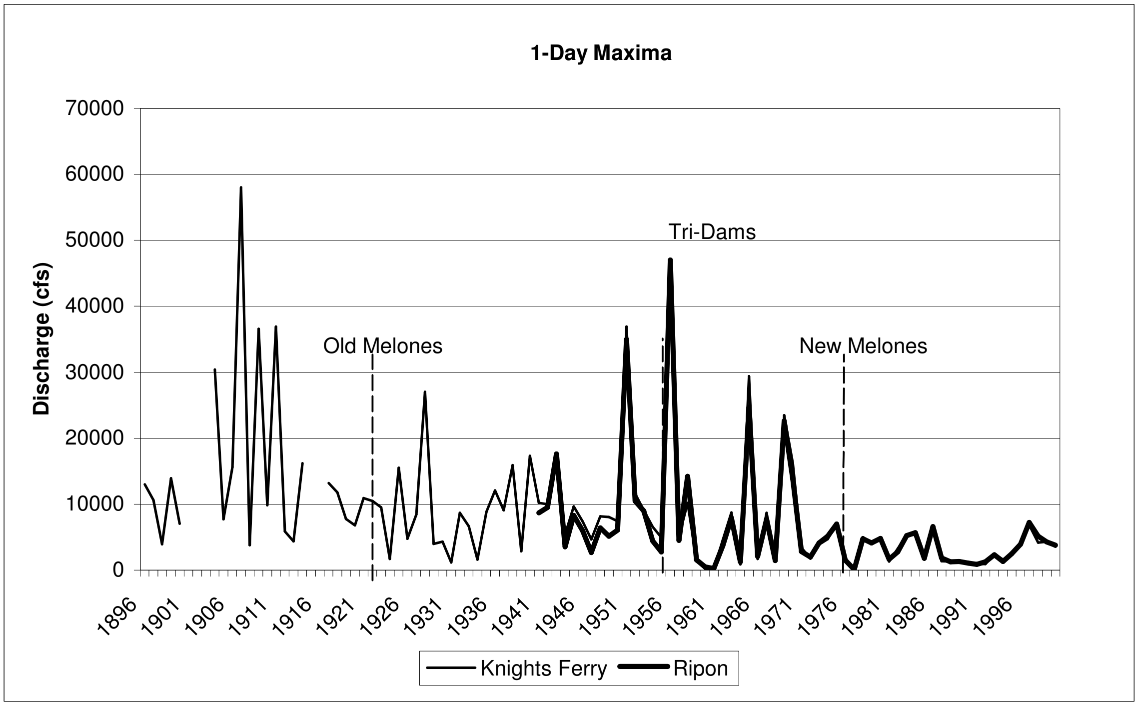

Figure 6.25. 1-day maxima flows on the Stanislaus River. This figure shows the decrease in annual flood peaks after the construction of New Melones Dam in 1977.

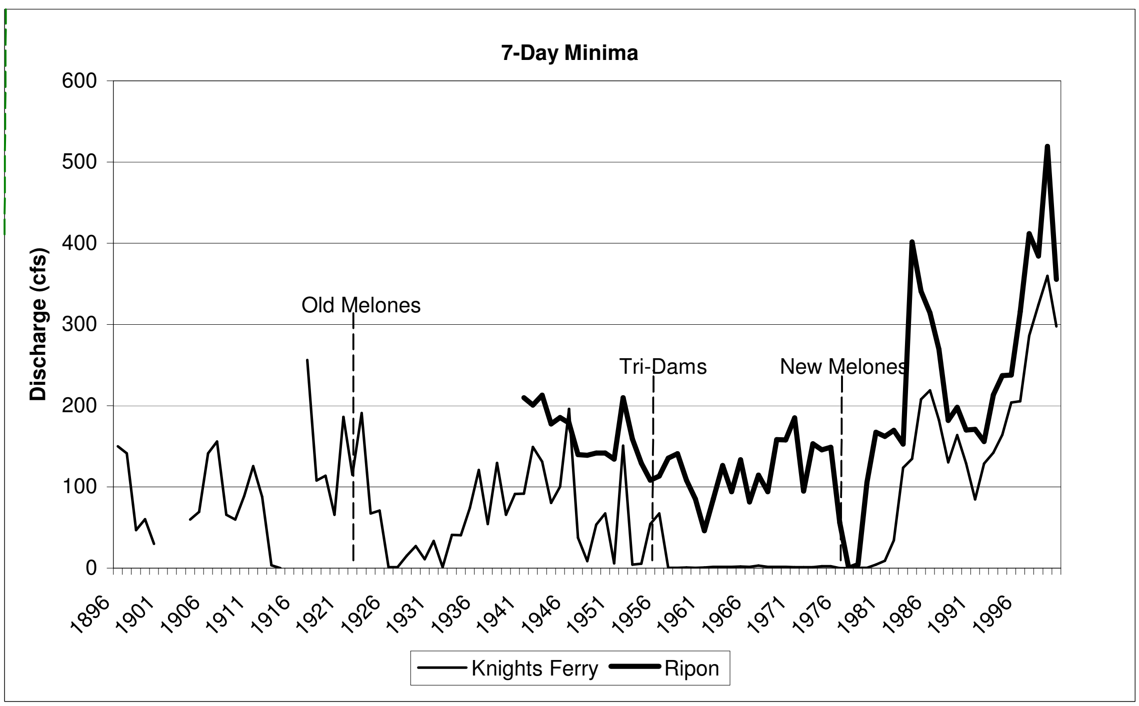

Figure 6.26. 7-day minima flows on the Stanislaus River. This figure shows the increase in low flows after the construction of New Melones Dam in 1977.

Results from HCA Analysis

All unimpaired streamflow data was measured at Knights Ferry, and all regulated streamflow data was measured below Goodwin Dam.

- The total annual water yield in the Stanislaus River has been reduced from 1,146,000 af to approximately 573,000 af, a 50% reduction in yield. Unimpaired annual yield ranged as high as 2,767,000 af. The lowest post-New Melones Dam yield occurred in 1977, when only 4,685 af were released to the Lower Stanislaus. The highest post-New Melones Dam yield was 1,677,000 af recorded in 1983.
- As with most other Central Valley rivers, the winter flood regime was severely reduced by construction of large storage dams in the basin (Figure 6.28). The 1.5-year unimpaired flood of 8,800 cfs was reduced to 1,825 cfs, a 79% reduction. The regulated annual maximum flood has exceeded 8,800 cfs only 7 times since 1956. The largest magnitude winter flood since completion of New Melones Dam in 1983 is 7,350 cfs, with an unimpaired recurrence interval of 1.4 years. The unimpaired (log-Pearson III) 25-year flood was 77,000 cfs, and was reduced to 24,000 cfs, although a flood of this magnitude is unlikely to occur on the Stanislaus.
- The baseflow hydrograph components on the Stanislaus River have not been reduced as severely as in other regulated rivers, and in the case of fall baseflows, are relatively unchanged. The unimpaired fall median baseflow was 182 cfs (all water years analyzed) and was 177 cfs for the regulated period of record analyzed. Summer baseflows increased during the post-New Melones period of record: the unimpaired median summer baseflows ranged from 100 to 300 cfs; the post-New Melones Dam median summer baseflow was 340, and median summer baseflows ranged as high as 1,054 cfs during Extremely Wet years. This general trend is due to sustained baseflow released to meet water quality criteria (conductivity and perhaps others) in the Delta (Vernalis) and the minimum dissolved oxygen requirement at Ripon. In the 25 years prior to completion of New Melones Dam, the minimum summer baseflow fell below 10 cfs during all (regulated) water year types.
- Similar to the winter flood regime, the spring snowmelt peak discharge has been reduced, on average, by approximately 70%. For example, the median unimpaired snowmelt peak for Normal water years was 7,160 cfs, but was only 1,439 cfs during regulated Normal water years.
- During a particularly dry two-year period in WY 1977 and 1978, the mean daily average flow was only 6.6 cfs (compared to unimpaired daily average flow of 1,575 cfs), with a two-year maximum release of only 144 cfs. The post-New Melones flow regime has not been as extremely low as other rivers in the Basin.

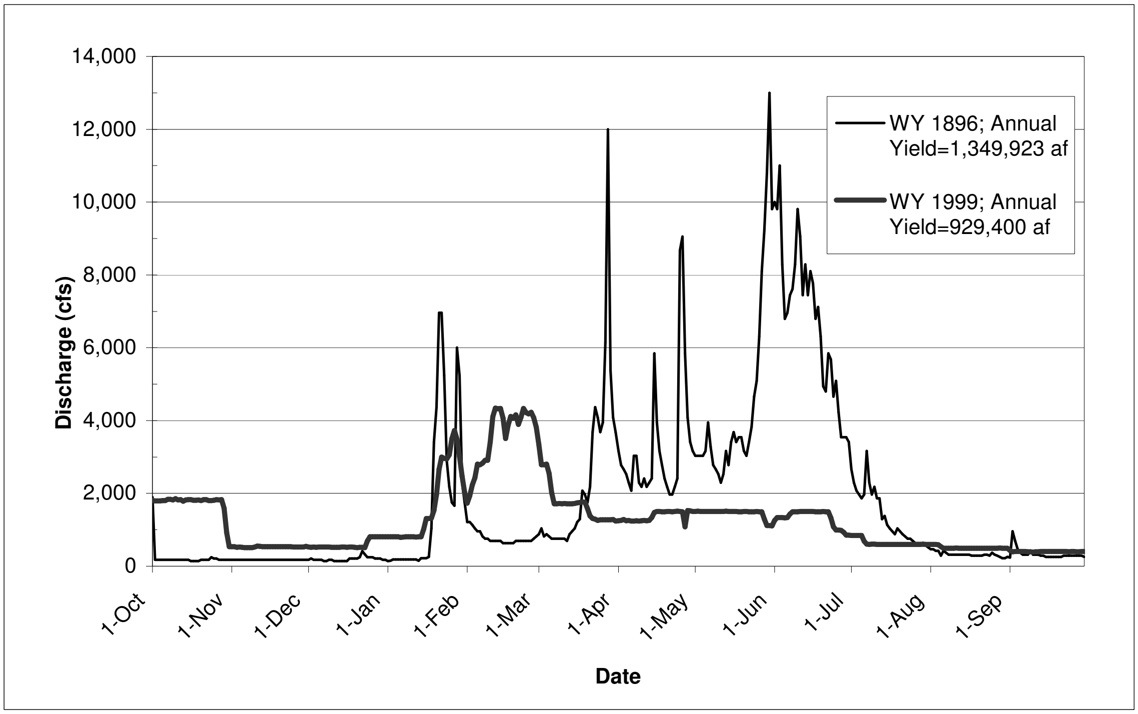

Figure 6.27. Stanislaus River Unimpaired (1896) and Regulated (1999) representative hydrographs for wet years. This figure shows the elimination of snowmelt floods in the spring and the replacement of these floods by FERC spring pulse flows. Unimpaired data from gauge at Knights Ferry; regulated data from gauge below Goodwin Dam near Knights Ferry.

6.6 SAN JOAQUIN BASIN

Results from IHA Analysis

To investigate spatial patterns of hydrologic alteration across the entire San Joaquin Basin, Richter (2002) developed an overall measure of hydrologic alteration based upon six indicators:

1. Wet season flow alteration – an average of deviations in the monthly medians for November-June.
2. Dry season flow alteration – an average of deviations in the monthly medians for July-October.
3. Base flow alteration – deviation in the 7-day low flow.
4. Annual flood flow alteration – deviation in the 1-day maximum flow.
5. Change in duration of high pulses each year – deviation in the average number of days each year with flows > 75th percentile.
6. Change in duration of low pulses each year – deviation in the average number of days each year with flows < 25th percentile.

A summary of the results from this analysis is provided in Table 6.3. Unfortunately, equivalent periods of record are not available for each pair of stations on each of the four rivers. On the Tuolumne, the Modesto gauging station was not installed until after construction of Hetch Hetchy Reservoir. On the Merced, the Stevinson gauging station was not installed until after construction of Old Exchequer Dam. This makes comparison of hydrologic alteration between upstream and downstream gauging stations difficult. However, as described earlier in this report, the relative magnitudes of hydrologic alteration in both the Tuolumne and Merced following construction of the big dams (New Don Pedro on the Tuolumne, New Exchequer Dam on the Merced) was generally much greater than during the years following construction of the smaller and older dams.

Comparing hydrologic changes of the rivers in the basin as measured directly below the dam, the largest changes occur on the Merced (175%) with a 581% increase in flows during the dry season (from July to October) and a 206% increase in baseflows (7-day minimum flows) (Table 6.4). The San Joaquin experienced a 109% change in the watershed with a change of at least 86% in all of the hydrologic indicators and a 184% increase in the number of days that flows are below the 25th percentile. The 87% change within the Tuolumne watershed occurred from a 123% increase in the dry season flows, a 149% increase in baseflows, and a 100% increase in the duration of high pulse flows. The Stanislaus experienced the least amount of hydrologic alteration, according to the IHA, with the largest change of 80% occurring with the increase in low pulse duration. For all rivers except the Stanislaus, hydrologic conditions appear to become considerably better when moving downstream from the dams. This is to be expected, as the rivers gain additional contributions from tributary streams downstream of the dams.

Results from HCA Analysis

The San Joaquin River has experienced the largest decline in annual water yield in the Basin. Although still a 50% decline in water yield, the Stanislaus has experienced the lowest decline compared to other tributaries in the Basin.

Table 6.5. Decrease in Annual Water Yield in the San Joaquin Basin Between Unimpaired and Regulated stream flow.

Tributary	Decrease in Annual Water Yield
San Joaquin	71%
Merced	54%
Tuolumne	62%
Stanislaus	50%

Table 6.6. Hydrologic Alteration Across the San Joaquin Basin.

	Wet Season (Nov-June)	Dry Season (July-Oct)	Baseflow (7-day lows)	Flood Flow (1-day max)	High Pulse Duration	Low Pulse Duration	Average
Stanislaus @ Knights Ferry (1896-25; 1980-2000)	45%	60%	62%	77%	60%	80%	**64%**
Stanislaus @ Ripon (1941-55; 1980-2000)	32%	124%	34%	62%	62%	100%	**69%**
Tuolumne @ LaGrange (1896-55; 1972-2000)	61%	123%	149%	81%	100%	9%	**87%**
Tuolumne @ Modesto (1943-55; 1972-2000)	37%	20%	24%	37%	72%	48%	**40%**
Merced @ Merced Falls (1902-25; 1968-2000)	38%	581%	206%	72%	53%	100%	**175%**
Merced @ Stevinson (1941-65; 1968-2000	62%	36%	5%	54%	107%	72%	**56%**
San Joaquin blw Friant (1908-40; 1951-2000)	104%	86%	89%	90%	100%	184%	**109%**
San Joaquin @ Vernalis (1930-40; 1951-2000)	36%	23%	53%	45%	63%	66%	**48%**

Chapter 7. Ecological Consequences

7.1 INTRODUCTION

Since 1940, salmon populations have plummeted in the San Joaquin Basin (figure 7.1). This period coincides with the construction of large dams on all the major dams in the basin. As discussed in previous chapters, these dams have drastically altered the downstream flow regimes – particularly the peak flow events that shaped channel habitats and the high spring flows that recruited riparian vegetation and maintained cold water temperatures during the juvenile outmigration period. During wet periods such as the mid ninety eighties, salmon populations rebound significantly suggesting that increased stream flow results in larger salmon populations. But changes in streamflow conditions from large dams and the direct impacts on salmon and salmon habitat is only part of a larger story of ecological change to the rivers of the San Joaquin basin over the last century.

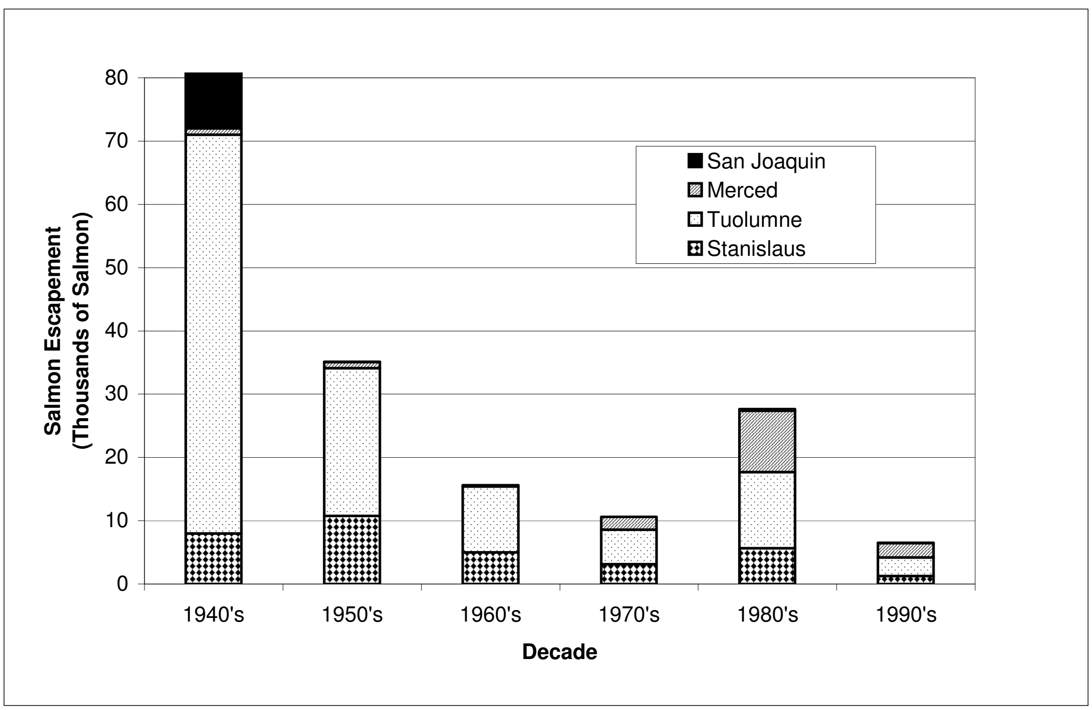

Figure 7.1. Average Annual Salmon Escapement in the San Joaquin Basin by Decade, 1940 to present. Data: CADFG 1961, 1994, AFB ADM. Rpt., Mills & Fisher. 1940 Stanislaus and Merced, and 1941 Stanislaus, Tuolumne, and Merced are partial counts.

Large dams on the San Joaquin Basin rivers have resulted in the near total control of their hydrology which in turn has greatly influenced land use patterns in the river bed and its floodplains. These new land use patterns have caused major changes to the ecology and physical habitat of the rivers and their floodplains. For example, significant reductions in flood flows below the large dam have facilitated large-scale aggregate mining operations in the channel and on nearby floodplains. Similarly, the reduced frequency of floods has facilitated clearing, development, and agriculture on low lying areas that were frequently inundated. Conversely, the impact of many land uses changes may have been exacerbated by changes in hydrology. For example, under natural hydrologic conditions, the clearing of cottonwood forests would have been partially mitigated by the recruitment of new seedlings if the flow regime was conducive to the establishment of cottonwoods. Similarly, the impact of instream gravel mining pits would have been mitigated by large flood flow events that reshape the channel. Although these habitat changes are not directly a result of hydrologic changes, they are made possible exacerbated by changes in hydrology and have significantly altered the ecology of the rivers. Thus it is difficult to identify the cause of several ecological impacts that have occurred in the rivers or to directly link these impacts to changes in hydrology. This chapter provides an overview of the ecological impacts to these rivers with an emphasis on impacts caused by changes in the hydrology.

The ecology of the San Joaquin Basin rivers have been dramatically altered over the last 150 years by a variety of water management and land-use practices including: placer mining, dredger mining, grazing, farming, flood control projects, flow regulation, urbanization, and aggregate mining. These activities have significantly changed the rivers' geomorphology, riparian zone, and salmonid populations. Placer mining in the Tuolumne and Stanislaus River watersheds during the nineteenth century probably increased the sediment load in these rivers changing the channel geomorphology and increasing fine sediment harmful to aquatic species. Early settlers removed riparian trees for fuel wood even before the extent of these areas was accurately described or mapped. Subsequent grazing on these cleared lands undoubtedly limited regeneration of new riparian forests.

Mining in the river channel and floodplain has had one of the most dramatic impacts. During the first half of the twentieth century, dredger mining in the active channel destroyed channel and floodplain habitats to varying degrees on all four rivers. The impacts of these early dredger operations are still prominent on the Tuolumne and Merced rivers where piles of dredged spoils lie unvegetated on thousands of acres of once fertile flood plains. The impacts of aggregate mining are equally dramatic on all four rivers. Large areas of the floodplain and channel have been excavated to a depth of more than 20 feet resulting in large ponded areas that resemble lakes more than rivers. Today these pits provide habitat for exotic fish species that prey on native fish. Moreover these pits have often caused channel incision leading to increased channel velocities, reduced channel complexity, and a reduction in the frequency of floodplain inundation. The flow regulation provided by large dams, enabled large aggregate mining companies to establish permanent operations and mine vast areas that were once frequently inundated. On the middle San Joaquin alone, aggregate miners have mined at least 40 million cubic yards since the construction of Friant Dam – more than 20 times the natural replenishment rate from upstream.

7.2 SAN JOAQUIN

7.2.1 Geomorphic Processes

The geomorphology of the stream below Friant Dam has been altered by intensive gravel mining, the interruption of sediment input from the upper watershed, and the near elimination of annual peak flows by Friant Dam and its associated diversions. Cain (1997) concluded that gravel mining has had a larger impact on the rivers sediment budget and channel morphology than the interruption of sediment from the upstream flows. A schematic sediment budget for the San Joaquin River below Friant Dam (Figure 11) shows estimated pre- (and post-)dam bedload sediment supply (Brown and Thorpe 1947, Janda 1965), minimum estimated extraction by sand and gravel mining for each of the five sub-reaches (see text under methods for sources), and changes in the magnitude of frequent (2-year return period) 10-day maximum running average flows, a surrogate for the river's capacity to transport coarse sediment. Aggregate mining in the active channel during the first 50 years of the post-dam period exceeded the pre-dam sediment supply by an order of magnitude and the post-dam supply by two orders of magnitude. In addition to the approximately 14 million cubic meters mined from the active channel during the half century following the completion of Friant Dam, another 25 million of sand and gravel was mined from the flood plain. In contrast, the pre-dam estimated supply from the upper watershed was only 1.7 million cubic meters. It is important to note, however, that these large reductions in sediment inflow and storage were also accompanied by a large decline in the sediment transport capacity of the river. As depicted in figure 7.1, the 10-day maximum running average flow with a recurrence interval of 2 years has been reduced by a factor of 20 in the post-dam period.

Gravel mining, and to a less extent, interruption of the sediment supply by Friant Dam has caused the channel downstream of Friant Dam to incise significantly. Figure 7.2 depicts changes in channel (thalweg) elevations between 1872 and 1989 in a reach 35 kilometers below Friant Dam and shows that the channel has incised between 3 and 10 feet. It also indicates that the process of incision began before the construction of Friant Dam interrupted the upstream sediment supply. A close examination of figure 7.2 shows presences and expansion of large gravel pits, generally upstream and downstream of road crossings, in the pre-dam period. These pits locally over-steepened the stream gradient, which caused the upstream channel to subsequently cut down. Surveys of the historical spawning reach immediately below Friant Dam (Cain, 1997) also show that incision began before construction of Friant Dam and actually indicate that this reach has incised less that the heavily mined reaches further downstream. The pre-dam incision in this reach is probably a result of pre-dam gravel mining. Furthermore, incision of the reach immediately below is relatively minor due to the presence of bedrock outcrops that preclude further down cutting.

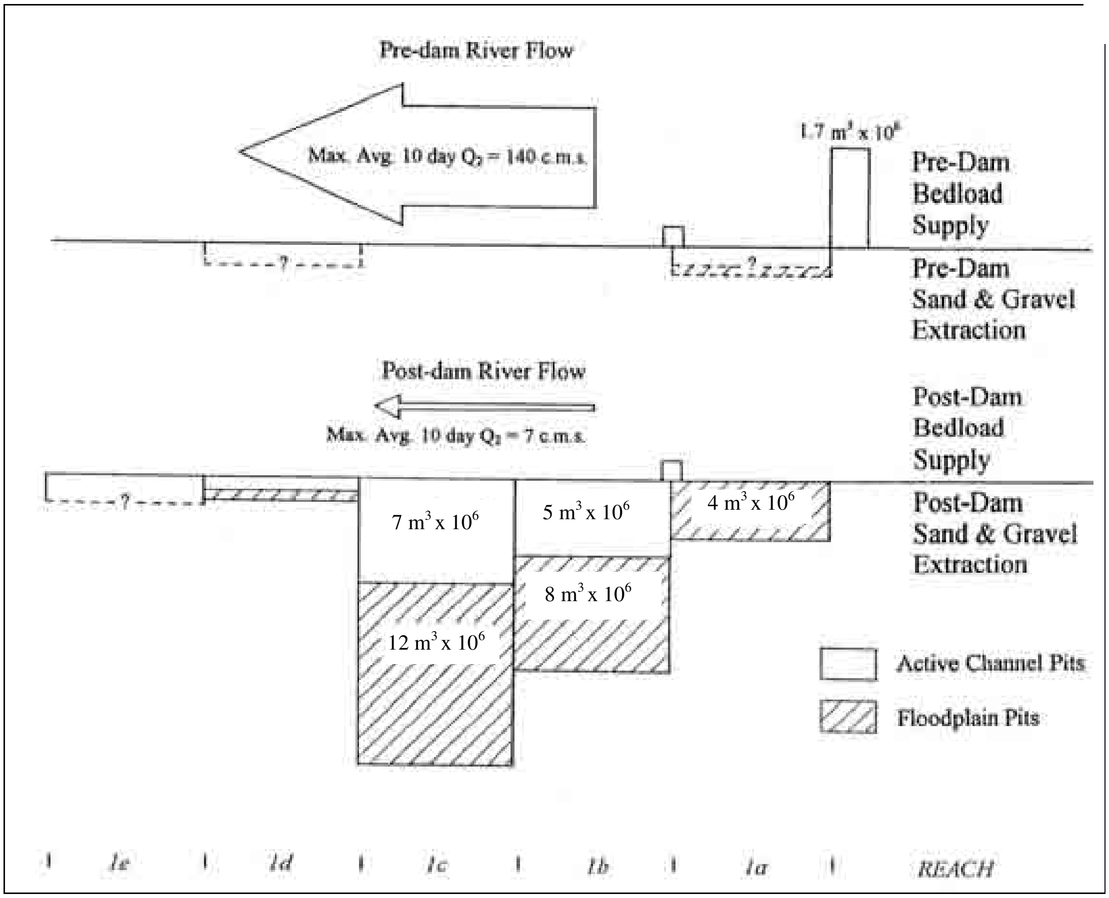

Figure 7.2. Changes in sand and gravel budget for San Joaquin River below Friant Dam. Shown are sediment budgets for fifty-year periods: (a) 1891-1940, and (b) 1941-1990. Construction of Friant Dam eliminated supply of sand and gravel from watershed (about 40,000 m^3y^{-1}) in 1941, while aggregate mining removed over 40 million cubic meters sand and gravel from the channel and floodplain during the 50 year post-dam period.

Channel incision combined with the reduction of peak flows has caused the channel to narrow and has probably reduced the complexity of channel habitat. Figure 7.4 depicts changes in channel width between 1939 and 1989 with valley bottom width shown for comparison. By 1989, the low flow channel was typically half as wide as in 1939, but because flow rarely exceeded the capacity of the 1989 low flow channel, it could also be considered the active channel. Compared to the 1939 active channel, the 1989 channel was an order of magnitude narrower. Comparison of pre- (and post-) dam channel cross sections at nine sites (Cain, 1997) was confounded by the presence of bridges and effects of gravel mining, but analysis of cross section data along with aerial photo mapping and field observations indicate that the channel has narrowed and incised since the dam was constructed, except where instream gravel pits preceded the dam. The channel cross section analysis combined with field observation suggest that channel incision has resulted in more uniform stream habitat characterized by a trapezoidal channel form with relative steep slopes on both sides of the channel. In contrast, the pre-incision channel probably sloped gently down on one side along the point bar with a steep cut-bank on the opposite side. This more diverse channel form characteristic of natural alluvial channels provides a greater diversity of habitat conditions such as substrate type, bank slope, and velocity.

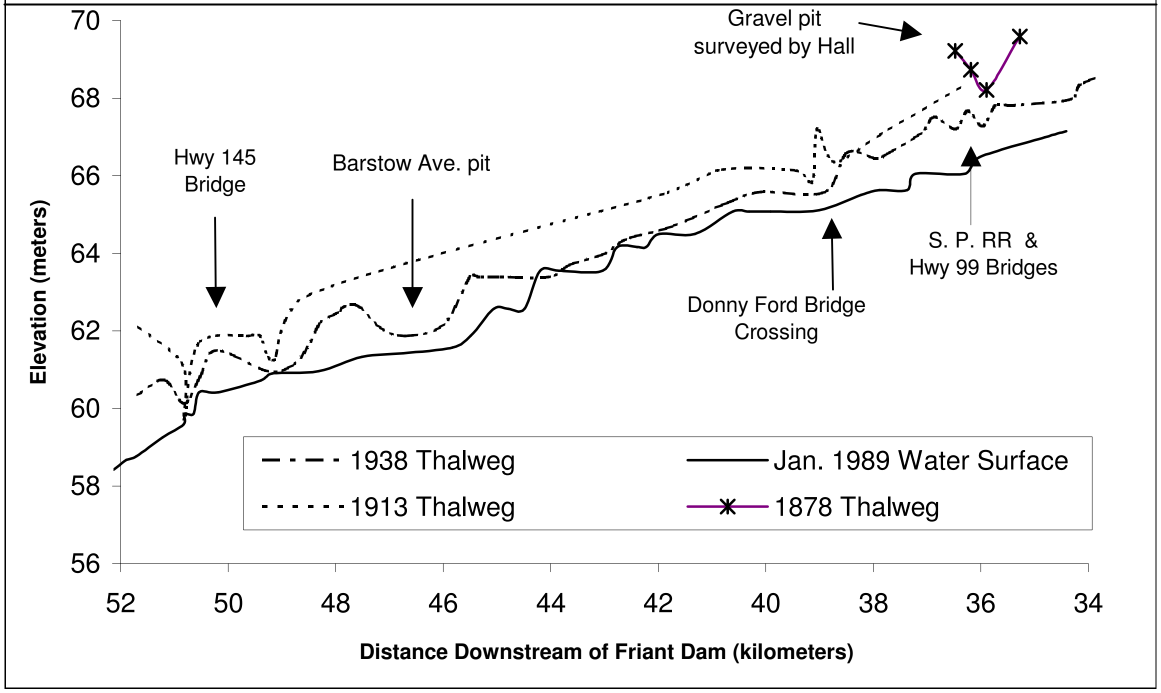

Figure 7.3. Longitudinal profile of reaches 1C-D of the San Joaquin River. 1887 thalweg elevation from Hall, 1887; 1913 thalweg elevation from the California Debris Commission (1913), 1937 thawleg elevation from US Bureau of Reclamation (1938) and 1989 water surface elevation from California State Lands Commission (1993). Presence of aggregate pits evident at approximately kilometers 36, 38, 46, and 50. Note that extraction areas are located both upstream and downstream of bridge crossings, and resulted in bridge failure Highway 145 in 1938.

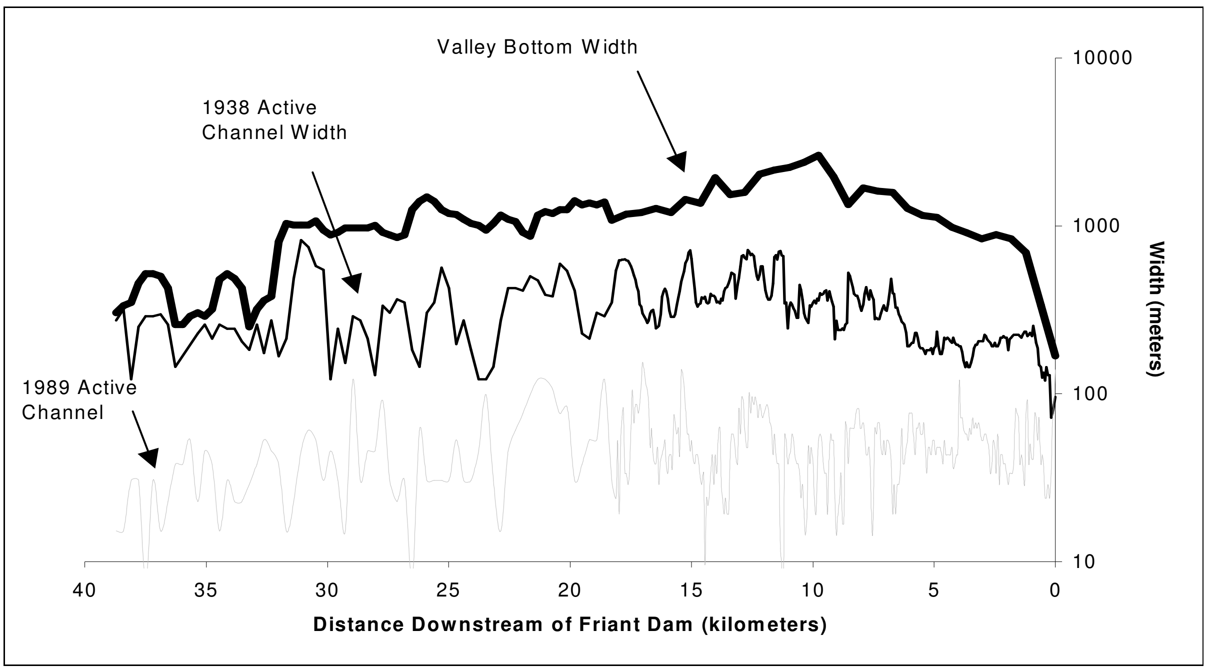

Figure 7.4 Changes in channel width: Widths of San Joaquin River valley bottom, 1939 active channel, and 1989 active channel, between Gravelly Ford and Friant Dam. Valley bottom width and 1989 active channel width are based on 1989 surveys by California State Lands Commission (1993), and 1939 active channel width is measured from aerial photographs. Note that y axis is plotted on logarithmic scale. As a result of reduced flood flows, vegetation established on the bed of the former (1939) active channel, to the edge of the 1989 low flow channel.

Analysis of channel planform changes since the pre-dam period (Cain, 1997) also suggests that the complexity of channel habitat has been significantly reduced. The pre-dam channel was characterized by large gravel bars, mid-channel bars and a complex maze of secondary and high flow channels, which have been abandoned because of reduced flood flows, channel incision, and direct human modifications to the channel, notably gravel mining. Total channel length over the 19 km study reach has been reduced by one quarter from 39 km to 26 km. Bifurcated reaches of the main channel have been reduced to low flow secondary channels while historical secondary channels have been abandoned except during infrequent high flows. Many high flow channels have been abandoned due to incision of the main channel, or have been intentionally blocked at their upstream ends.

Gravel mining has directly and dramatically degraded channel habitats and reduced channel complexity. Figure 7.6 shows the devastating impact that instream and floodplain gravel mining has had on the channel form of the San Joaquin. Although figure 7.6, depicts one of the most dramatically altered reaches of the San Joaquin, it is generally representative of the impacts of gravel mining operations along several reaches of the San Joaquin and its tributaries.

The absence of high flows in the post-dam period has resulted in vegetation encroachment along the low-flow channel. Figure 7.5 diagrammatically depicts channel narrowing, incision, and vegetation encroachement from 1937-1996. The 1937 channel was characterized by gradual sloping, unvegetated point bars and mid-channel bars. By 1996, channel incision, severe dampening of high flows, and corresponding vegetation encroachment had transformed the historically mobile bars into vegetated surfaces infrequently inundated by floods. The pre-dam flood plain has been transformed into an inactive terrace that has been inundated only twice in the post-dam era, by the large floods in 1986 and 1997.

7.1.2 Riparian Vegetation

The extent of riparian and marsh habitat along the San Joaquin was significantly reduced well before the construction of Friant Dam (Bay Institute). Between Mendota Pool and and the Merced River, tens of thousands of acres of tule marshes were converted to agricultural land in the 19^{th} century by the Miller and Lux Company. In the 35 mile reach below Friant Dam, there are no clear and accurate maps of riparian vegetation prior to the aerial photo record which began in 1937. It is probable that large areas of mature riparian vegetation were cleared in the nineteenth century for fuel wood and to make way for agriculture. The field books of the State Engineer, William Hammond Hall, suggest that many large trees were cleared by the time he conducted his survey in 1878. Hall's survey books reference numerous oak stumps that were used as "turning points" in his surveys of 1878.

Instream and floodplain gravel mining pits at San Joaquin River at RM 254 in 1993. .

San Joaquin River at RM 254 before gravel mining in 1938. Note multiple channels, sinuosity, and abundance of exposed riverwash.

Figure 7.5: Ariel photo comparison of San Joaquin River between 1937 and 1993.

Jones and Stokes (2000) and the Department of Water Resources (2002) mapped changes in riparian vegetation since 1937, on of the first aerial photographs of the river corridor (table 7.2). Both of these analyses indicate that the total area of riparian vegetation has not changed significantly between 1937 and 1998, but they found that the type of vegetation and other cover types had changed appreciably. The area of late successional vegetation types such as riparian forest had doubled while the area of riparian scrub was more than halved. The area of riverwash was cut by two thirds. Reductions in the frequency of high flow events that periodically scoured the bed and bars of the river is the primary cause of these measured changes. In the absence of high flows, riparian vegetation encroached to the edge of the low flow channel. Alluvial scrub habitats that had been previously maintained in an early successional stage by seasonal high flows, gradually evolved into riparian forest in the absence of high flows. The areas previously characterized by exposed sand and gravel were colonized by riparian scrub and forest, most notably alder trees that now line much of the low flow channel in the 30 miles of river below Friant Dam. Despite the narrowing of the river channel from reduced flows, the area of open water habitat remained relatively stable to due the increased number of open water areas in instream mining pits.

Table 7.2: Area (acres) of habitat types in the study area over time (Friant Dam to Merced River)

	Year				
Class	**1937**	**1957**	**1978**	**1993**	**1998**
Open water	3,380	3,030	3,300	3,740	3,450
Riverwash	1,080	1,210	1,100	300	350
Riparian forest	2,232	2,680	1,860	2,750	4,610
Riparian scrub	4,540	2,820	3,090	2,160	1,920
Wetland	4,055	320	720	730	1,000
Grassland	19,344	14,380	11,480	12,140	10,670
Agriculture	17,691	27,340	28,840	26,720	25,380
Urban and disturbed	562	1,630	2,840	2,990	6,030
No data	30	0	200	1,880	0
Total	53,413	53,410	53,410	53,410	53,410

Although the areas classified as riparian forest has actually increased since the construction of Friant Dam, the width of the riparian zone and the total area of riparian habitats has actually decreased substantially (figure 7.6). As vegetation encroached on to the river bed, agriculture and urbanization displaced vegetation on the margins of the 1938 riparian zone. Thus, the increase in riparian forest occurred at the expense riverwash and riparian scrub that characterized the channel in 1937. As discussed above (section 7.1.1), vegetation encroachment on historic gravel bars has probably reduced the recruitment, availability, and quality of spawning gravel habitat for Chinook salmon. Reduction in the width of the riparian corridor and the area of scrub and river wash may have also diminished habitat for a number of other riparian species that depend on scrub or open areas for nesting or foraging.

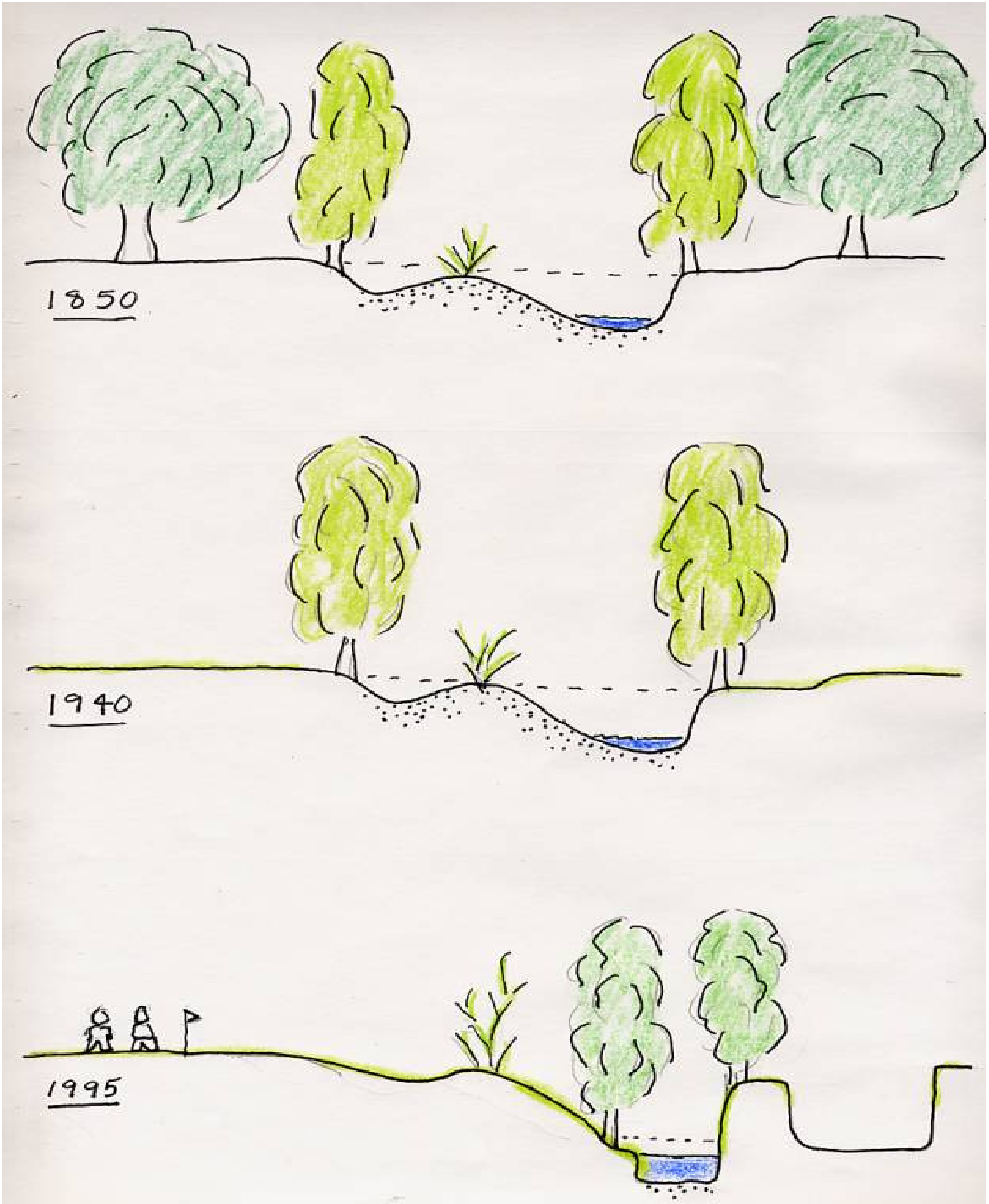

Figure 7.6: Pictograph depicting representative changes in the San Joaquin River channel and riparian zone between 1850 and 1995. Between 1850 and 1940, much of the mature riparian forest was cleared for agriculture and fuel wood. Between 1940 and 1995, channel incised and vegetation dominated herbaceous grasses and alders, encroached on previously unvegetated gravel bars, while agriculture, gravel mining, and golf courses displaced the cottonwoods that once lined the banks of the river.

Table 7.2. Land uses and effects on the middle San Joaquin River from 1848 to present. Source: Cain 1997, McBain and Trush, 2000.

Land Use	Time Period	Location	Disturbance	Effect on Channel
Urban Growth	1980-2000	RM 265-220	Need for commercial lumber, space, and aesthetic value	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution loading into river
Dredger Mining	1920 – 1950	RM 265	Anecdotal accounts of instream dredg-ing for gold and deposition of spoil on bar downstream of Friant Road.	Destroyed ¼ mile of natural channel morphology.
Grazing	1850-1970	Throughout	Young riparian vegetation is grazed, water sources become feces conduits	Destabilized banks, discouraged natural riparian regeneration
Farming	1860-present	Throughout	Mature and establishing riparian vegetation is cleared. Channel location stabilized	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution and fine sediment loading into river. Eliminated vast tule marshes downstream of Mendota Pool
Flow Regulation	1941-present from Friant Dam; c. 1870 to present down-stream of Mendota.	Throughout	Magnitude, dur-ation, frequency, and timing of high flow regime is al-tered , eliminated sediment supply from upstream watershed, early diversions diverted summer and fall base flows at Mendota Pool.	Vegetation encroachment, reduced channel complexity, reduction in area of riverwash and alluvial scrub. Elimination of the vast tule marshes in the floodbasin downstream of Mendota Pool.
Dikes, Levees, and Bypasses	c. 1870 to present below Mendota; Chowchilla floodbypass 1960.	From Gravelly Ford to Merced	Channel increasingly confined by levees; flood flows routed around historic floodbasin via bypass	Near elimination of overbank flows. Increasingly narrowed channel and reduced flooding made way for agriculture in historic wetlands and riparian zone.
Aggregate Mining	1878-present	Friant Dam to Gravelly Ford. RM 265- 230	Large instream and off channel pits, dredger tailing removal	Historic floodplains are left as deep ponds, floodway narrowed by dikes separating ponds from river, riparian vegetation is cleared, regeneration is prevented and mature stands eliminated.

7.1.3 Chinook and Steelhead

Historically, the San Joaquin River and its tributaries supported the world's southern-most run of native chinook salmon (*Oncorhynchus tshawytscha*) as described in chapter 5. Since 1850, human activities such as gold mining, agriculture, reservoir construction and water diversions, urbanization, and flood control have reduced flow and habitat throughout the San Joaquin Basin. Spring-run salmon were extirpated from the major San Joaquin Basin tributaries in 1923-1926 with construction of the first dams that were year-round impassable barriers, cutting off access to their natal spawning grounds upstream. Non-native fish have increased in the San Joaquin River, threatening native fish populations (Table 7.3).

Table 7.3. Changes in the Fish Fauna in the San Joaquin River at Friant, Fresno County. Source: Moyle 2002.

	1898	1934	1941	1971	1985
Native Species					
Splittail	X	---	---	---	---
Hitch	X	X	X	---	---
California roach	X	X	X	---	---
Hardhead	X	X	X	---	---
Sacramento pikeminnow	X	X	X	---	---
Sacramento blackfish	X	X	X	---	---
Chinook salmon	X	X	X	---	---
Tule perch	X	X	X	---	---
Sacramento sucker	X	X	X	X	X
Rainbow trout	X	X	X	X	X
Prickly sculpin	X	X	X	X	X
Threespine stickleback	X	X	X	X	X
Kern brook lamprey	N	N	N	X	X
Pacific lamprey	N	N	N	X	X
Introduced Species					
Brown trout	---	X	X	X	X
Common carp	---	X	X	X	X
Bluegill	---	X	X	X	X
Smallmouth bass	---	X	X	N	X
Brown bullhead	---	---	---	X	X
Mosquitofish	---	---	---	X	X
Green sunfish	---	---	---	X	X
Largemouth bass	---	---	---	X	X
Total Number of Species	14	17	21	14	14
Percent Native Species	100	77	62	43	43

Sources: Based on information from Rutter (1903); Needham and Hanson (1935); Dill (1946); Moyle and Nichols (1974); and Brown and Moyle (1993).
Notes: This was originally a transitional reach between valley floor and foothills, so it had a high diversity of native fishes. After 1941 flow in the reach was regulated by releases from Friant Dam, converting it to a coolwater trout stream containing trout that are mostly of hatchery origin.
Abbreviations: N, probably present but not recorded; X, present.

On the middle San Joaquin River, fall-run salmon were reduced early on by brush dams or other temporary diversion dams (Yoshiyama, 1996). These temporary dams were barriers to migration in the summer and fall, but washed out during winter and spring floods, allowing migration of the spring run. Below Sack Dam, a temporary diversion dam 25 miles below Medota that was seasonally constructed with gunny sacks, flows were less than one c.f.s. during the September through December fall-run immigration period ever year between 1929 and 1933. In 1927, they were below one c.f.s. between August and mid November (Cain, 1997).

Even after construction of Friant Dam tens of thousands of spring-run salmon successfully reproduced during the early-to-mid 1940s, before the major diversions were fully operational (Figure 7.7). Spring-run salmon persisted on the middle San Joaquin, spawning in the reach from Friant Dam downstream to approximately Hwy. 99. Subsequent diversions into the Friant-Kern and Friant Madera canals eventually reduced flows such that, in most years, the river dried up 60 km downstream of the dam, eliminating all fall- and spring-run reproduction by preventing migration of fish into perennial reaches directly below the dam (Figure 7.8).

Today, small remnant populations of fall-run persist on the larger tributaries except for the lower San Joaquin, spawning in lower gradient gravel-bedded reaches downstream of the major dams, and augmented by hatchery production on the Merced River.

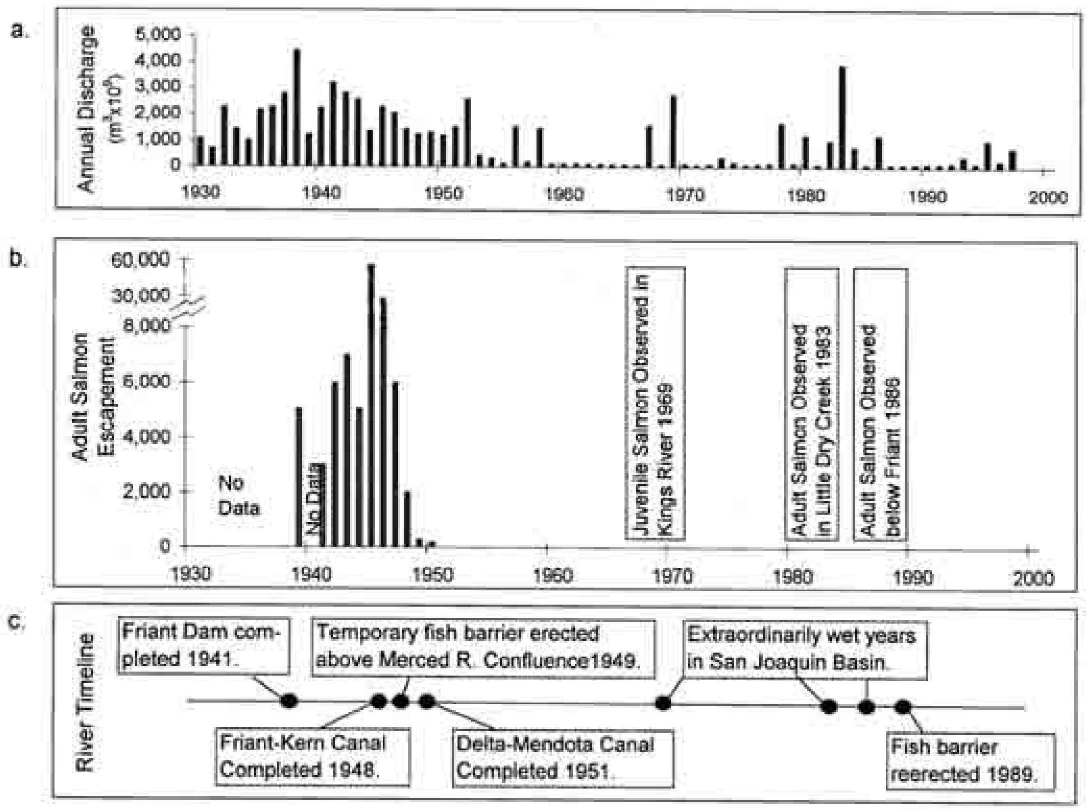

Figure 7.7. Timeline of Salmon population and water development in the San Joaquin River, 1930-1998. a) Mean annual discharge below Friant Dam, b) Adult salmon escapement by year, based on CDFG biennial reports 1940-1952; also shown are more recent observations of salmon in wet years: 1969 (Moyle, 1970) and 1983 and 1986 (CDFG, pers. comm. 1996). c) Timeline of major events potentially influencing salmon populations.

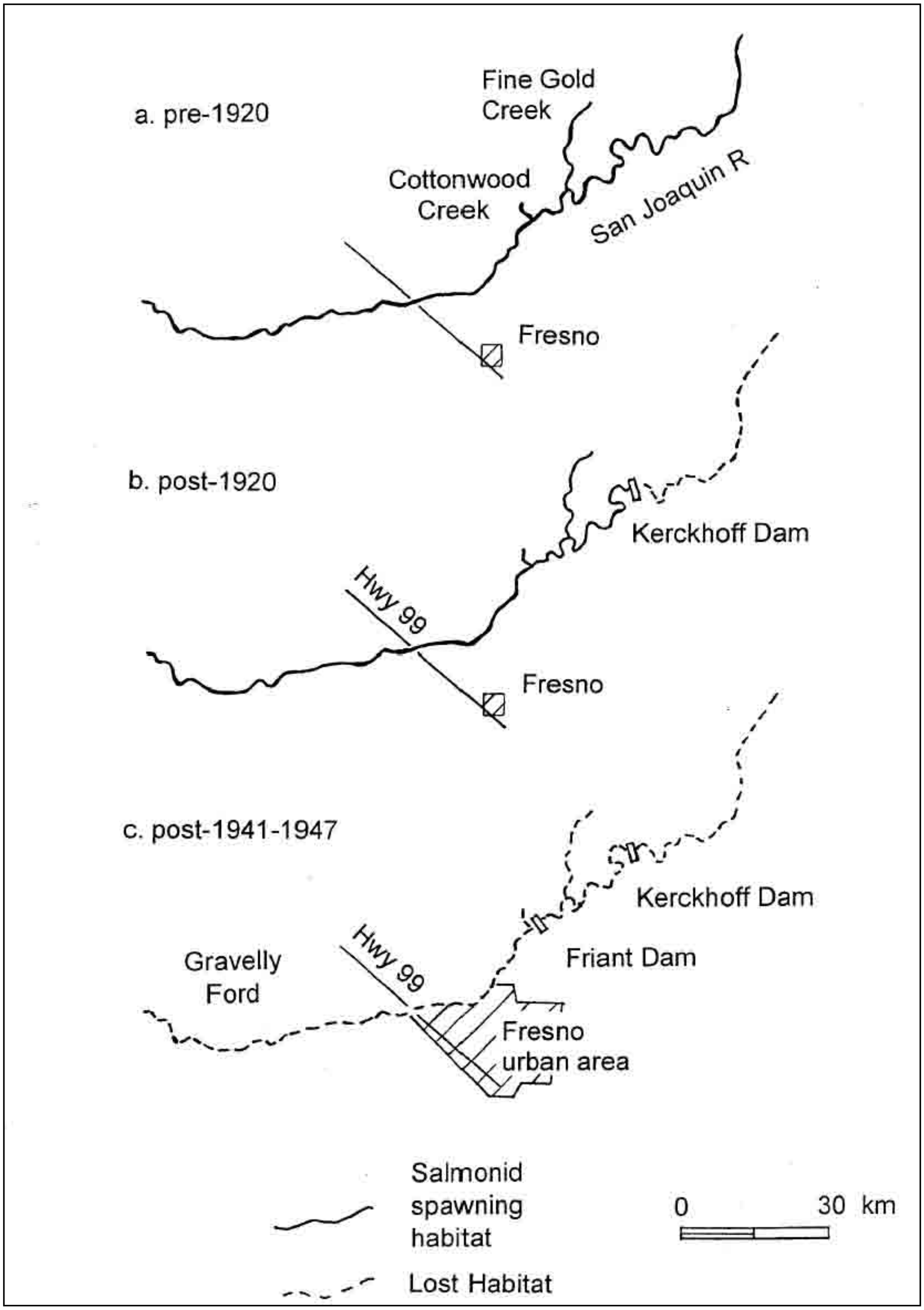

Figure 7.8. Changes in chinook salmon habitat in the San Joaquin River and tributaries above Mendota Pool. (a) Pre-1920: Salmon passed through lower reaches to spawn from the Hwy 99 (and Southern Pacific Railroad) crossing upstream to natural barriers on the San Joaquin River, Fine Gold and Cottonwood Creeks. (b) Post-1920: Kerkhoff Dam cut off access to upper reaches of the San Joaquin River. (c) Post-1941: Friant Dam cut off access to the upper San Joaquin River and Fine Gold Creek, and after 1947, diversions to Friant-Kern Canal reduced flows below Friant Dam eliminated habitat downstream. (Fish distribution data from Yoshiyama et al. 1996).

7.2 MERCED

7.2.1 Geomorphic Processes

The changes in the hydrology of the Merced River have dramatically affected the natural geomorphic processes in the River (Table 7.4). The decrease in peak flows has reduced the width of the channel and adjacent floodplains. The increased sheer-stress from a confined channel scours sediment from the channel, without importing sediment from upstream to replace it. The elimination of peak flows, however, has decreased large flows at least partially offsets the increased sheer stress in a confined channel. But the elimination of these flows has reduced beneficial bank erosion that could provide a source of coarse sediment for spawning habitat. Stillwater Sciences (Stillwater Sciences, 2001b) found that the bed is mobilized at a flow between of 4,800 cfs and 5,500 cfs depending on the location. Before the dam, sediment was believed to be mobilized by the 1.5 to 2 year flood (Q1.5-2) of 10,000 to 13,600 cfs. Since flows of this magnitude are intercepted by the dam, the gravel in the bed of the river are only mobilized on average once every five years. (Stillwater Sciences, 2001b).

In many of the reaches downstream of Crocker-Huffman Dam, extensive dredging for gold and aggregate mining has occurred in the channel and in the floodplain. Dredging in the channel has created large, deep pits or pools in the River. Mining and the upstream dams also intercept the supply of sediment. Vick (1995 in Stillwater Sciences, 2001a) estimated that 7-14 million tons of bedload sediment was removed from the channel and floodplains from mining operations between 1942 and 1993. This is 350-1,350 times the natural annual bedload supply from the upper watershed Vick (1995 in Stillwater Sciences, 2001a).

The combined affects of gravel mining and sediment trapping behind New Exchequer Dam have resulted in channel incision in the historical spawning reach below New Exchequer. Vick (1995) documented up to 5 feet of incision in the gravel mining reach between 1964 and 1995. She surveyed six cross sections in the larger reach downstream of New Exchequer and measured channel degradation ranging from -.15 meters to 6.3 meters at the various cross sections between 1964 and 1995.

The reduction of peak flows and the construction of levees has decreased the extent of the floodplain and has cut off the river from its floodplain. The construction of levees prevents flooding in some reaches and the decrease in large floods limits the frequency of floodplain inundation. Stillwater Sciences (2001a) estimates that a decrease in flow has reduced the floodplain width by an average of 2,140 feet (or 83%) under current conditions, and found that “flood control and subsequent conversion of floodplains to other uses has resulted in a 91 percent reduction in floodplain area throughout the 52-mile corridor (from Crocker-Huffman Dam to the confluence with the Merced).

Mining, reduction in peak flows and reduced sediment supply has converted the river channel from a multiple channel system into a single-threaded channel. The lack of bed scour and the static condition of the channel bed causes a reduction in channel width and the encroachment of vegetation into the active channel. Vick (as reported in Stillwater Sciences 2001a) concluded that vegetation encroachment into the active channel reduced channel width by 33 percent of the historical (1937) width. "As a result, the area of aquatic habitat in the Merced River had been reduced and the river channel is currently characterized by a simplified cross section, with no active bars and no clearly defined low flow channel. In addition, the encroached riparian vegetation is not scoured and new barren surfaces for recruitment of riparian trees are not created, resulting in a relatively even-aged, simplified riparian vegetation community."

Table 7.4. Land uses and effects on the lower Merced River from 1850's to present.
Source: Stillwater Sciences 2002, McBain and Trush, 2000, Vick 1995.

Land Use	Time Period	Location	Disturbance	Effect on Channel
Gold Dredging	1907 - 1952	Near Snelling (RM 45.2 to RM 52)	Excavated channel and floodplain deposits to bedrock; tailings deposited on the floodplains and riparian forests.	Confined channel and floodplain to narrow corridor, removed riparian habitat; coarse sediment replaced by long, deep pools, destroying instream habitat. Destroyed natural channel morphology.
Urban Growth	1950's - present	Snelling (RM 48), Cressey (RM 27.7) and Livingston (RM 22.5)	1% of corridor is zoned residential, commercial, industrial or commercial	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution loading into river
Farming and grazing	1850 - present	San Joaquin confluence to Crocker-Huffman Dam (RM 0 to RM 52)	Mature and establishing riparian vegetation is cleared. Channel location stabilized	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution and fine sediment loading into river
Flow Regulation	1901 - present	Downstrem of New Exchequer Dam (RM 0 to RM 62.5)	Magnitude, duration, frequency, and timing of high flow regime is altered and reduced, reduced/ eliminated sediment supply from upstream watershed	Bed coarsening and downcutting, fine sediments accumulated in channel, channel fossilized by encroaching riparian vegetation, channel migration and bar building virtually eliminated, floodplain construction and deposition reduced, quantity and quality of instream and riparian habitat greatly reduced
Aggregate Mining	1940's - present	Snelling Road bridge to Cressey (RM 46 to 26.8)	Large instream and off channel pits, dredger tailing removal	Historic floodplains are left as deep open-water pits, providing habitat for introduced non-native fish; floodway narrowed by dikes separating ponds from river; riparian vegetation is cleared, regeneration is prevented; sediment transport is interrupted.

7.2.2 Riparian Vegetation

Flow regulation and mining have dramatically affected riparian vegetation on the Merced. Mining on the edge of the bank and in the floodplain has eliminated riparian vegetation and vegetation recruitment due to the creation of steep banks and slopes, which are difficult for seedlings to establish on. Stillwater Sciences compared historical and present day riparian vegetation on the Merced River and reported on the effects of flow regulation on riparian vegetation. Most of the information reported in this section is a summary of that study. Stillwater estimates that the riparian zone has decreased by over 90% since humans settled in the area. The riparian corridor ranges from 50 feet in some reaches to as high as 1,500 at the confluence of the Merced and San Joaquin (Stillwater Sciences, 2001a)

The decrease in flows has caused encroachment of riparian vegetation in the former active channel, the establishment of riparian vegetation at lower bank elevations, and a decrease in the supply of good soil (Stillwater Sciences, 2001a). With a decrease in flows, especially winter floods, flows have not been large enough to scour vegetation along the channel margins since the construction of New Exchequer Dam. This causes riparian vegetation to grow in the channel, which decreases channel width, prevents new riparian species from growing, and stops the natural process of succession. Spring flood flows are not large enough to disperse seeds onto the floodplain so Cottonwoods can establish or deposit fine sediment necessary for their germination and survival. Stillwater Sciences (2001a) reports that “these conditions contribute to the decline of cottonwood dominated forest stands throughout the river corridor.”

7.2.3 Chinook and Steelhead

Historical accounts of salmon suggest that salmon were very numerous historically in the Merced River (Yoshiyama et al., 1998; Clark 1929), but began to decline early on due to water resources development and other human impacts. Chinook may have spawned as far upstream as El Portal on the mainstem, approximately 7 miles upstream of the confluence with the South Fork, and but probably did not migrate farther upstream to Yosemetie Valley due to the steep gradient of that stream reach. (Yoshiyama et al, 1996). Clark reports that “early residents . . . speak of great quantities coming up the river to spawn in the summer and fall. . . They remember the fish being so numerous that it looked as if one could walk across the stream on their backs.” A newspaper account from 1882 described by Yoshiyama et al (1998) indicates that salmon were both numerous and perhaps already threatened by water diversions: “. . . the Merced River has become so hot that it has caused all the salmon to die. Tons of dead fish are daily drifting down the river, which is creating a terrible stench, and the like was never known before (Mariposa Gazetter, 26, August 1882). It is unknown whether these high temperatures were caused by upstream irrigation diversions or merely the result of natural conditions, but it is clear from the account that the salmon were numerous. By 1928, Clark (1929) reported “ a great deal of the water in the Merced River is used for irrigation during the spring, summer and early fall. The river during this irrigation season is very low, and the salmon find it hard to get up the river until after the rains. This condition has just about killed of the spring and summer runs and now the only fish that come in arrive during the late fall.”

Clark also reports that salmon once migrated past the Crocker Huffman and Merced Falls diversion dams, but that the dams greatly contributed to the decline of fish in the Merced.

> "There are three obstructions that affect the salmon (on the Merced). The Crocker Huffman irrigation diversion dam near Snelling is the lowermost. This dam, which was build about 1918, is about 15 feet high and has a good working fishway in high water. There are screens but not over all the ditches. At Merced Falls there is a natural fall an a 20-foot dam has been constructed to form a millpond and to generate power for a sawmill. The dam was build prior to 1913. There is a fishway, but it has been closed and out of order for a number of years. There are screens over the intakes to the power house. The Exchequer Dam is about 20 miles above the Merced Falls and is impassable to fish. . .

"The abundance of salmon in the Merced River now (1929) as compared to the past years tells the same story of depletion as do the other rivers. The reports of the early residents in that section speak of great quantities of fish coming up the river to spawn in the summer and fall. In 1920, a letter received by the Fish and Game Commission from a resident of the country near Merced River states that there were fifty salmon in the past for each one now (1920). In the above mentioned letter the blame for this decrease was attributed to the construction of dams. Residents along the river in 1928 say that the salmon are so scarce that they rarely see any."

Old Exchequer Dam, subsequently replaced by New Exchequerer, created the first insurmountable barrier permanently blocking salmon from their former spawning grounds (CDFG 1921 in Yoshiyama, 1996). Although there are 42 miles of stream potentially available for spawning downstream of New Exchequer Dam, only 24.1 miles is accessible to the fall-run chinook due to the migration barriers and abandoned fishways at Crocker Huffman and Merced Falls dams (Yoshiyama 1996 p. 12).

By 1961, DFG biologists (Fry, 1961) designated the Merced River as a "marginal salmon stream" with a "poor fall run and a poor spring run" due to unnatural barriers to migration (Yoshiyama, 1996). In 1965, a minimum flow regime was established (see chapter 8) that has provided more stable flows for salmon spawning. These flows combined with the construction of the Merced River fish hatchery probably account for the increased escapement levels since the mid 1960's (figure 7.9). The low return rate in dry years, however, suggest that the minimum flow regime may not be adequate. Spawning escapement dropped to dangerous levels in 1990 and 1991 with counts numbering less than 200 individuals, including returns to the Merced River Hatchery (CDFG, 1993, and Fisher unpubl. data in Yoshiyama, 1996) (Figure 7.9). Between 1992 and 1994 spawning levels of 1,000 to 5,000 fish were recorded; a sign of an increase in stock, yet still far below historical numbers.

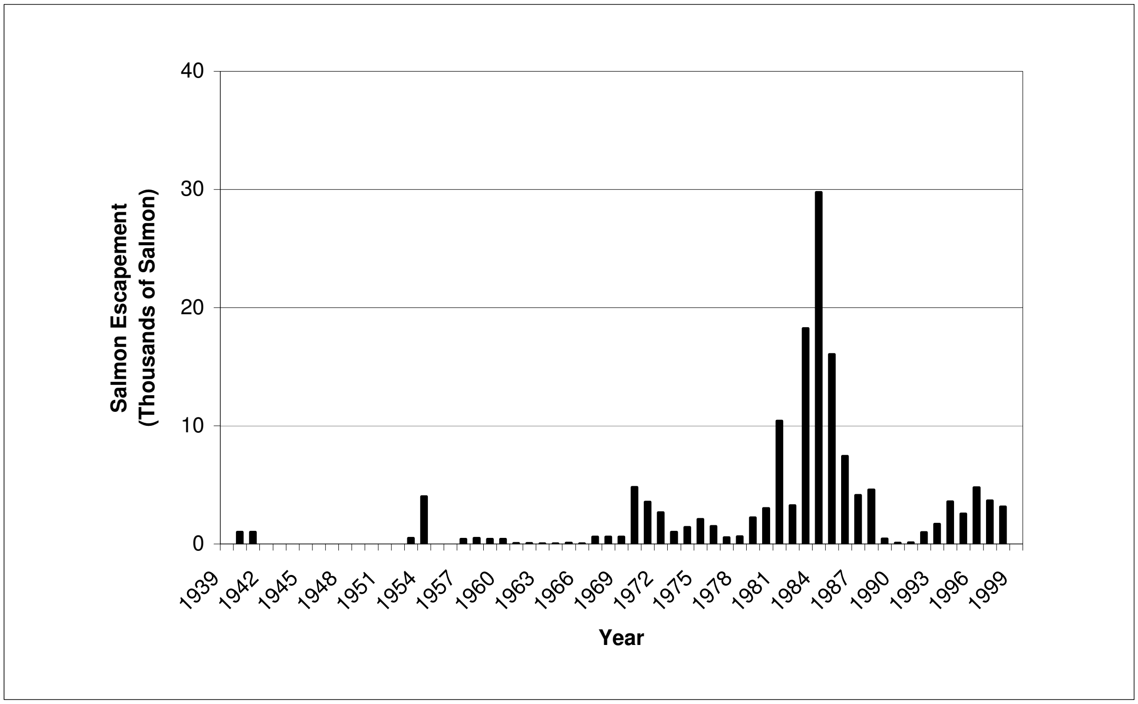

Figure 7.9. Annual Salmon Escapement in the Merced River. Data: CADFG 1961, 1994, AFB ADM. Rpt., Mills & Fisher. 1940 and 1941 are partial counts.

7.3 TUOLUMNE

7.3.1 Geomorphic Processes

The most significant changes to the flow in the Tuolumne River occurred after the construction of the New Don Pedro Project: "with the large watershed storage capacity and minimum instream flow requirements (1971 to present), the New Don Pedro Project (NDPP) severely diminished the magnitude, timing, duration, and frequency of hydrograph components in the post-NDPP era." Although it is the focus of this section, flow regulation is only one among several causes that changed the natural geomorphic processes of the Tuolumne (Table 7.5) McBain and Trush (2000) compiled a Restoration Plan for the Tuolumne River that looked at the historical and current geomorphic processes on the River. The following section (McBain and Trush, 2000) is a summary from the plan of the geomorphic consequences of the changes to the River:

> "After more than a century of cumulative impacts, the river has been transformed from a dynamic alluvial river (capable of forming its own bed and bank morphology) to a river fossilized between either man-made dikes, or agricultural fields, or fossilized within riparian vegetation that has encroached into the low water channel. Riparian forests have been reduced in aerial extent, and natural regenerative processes have been inhibited. Excavation of stored bed material for gold and aggregate mining eliminated active floodplains and terraces and left behind large in-channel and off-channel pits. Off-channel pits are separated from the river by steep-banked dikes and dikes which confine the channel to an unnaturally narrow corridor. The loss of coarse sediment supply that historically provided essential sediment for the formation of alternate bar features and in-

channel and floodplain habitat structure, combined with the dramatic reduction in high flows, has prevented regenerative fluvial processes from promoting river recovery. These changes are largely responsible for the currently degraded state of the river channel. Not only are the ingredients for a healthy channel no longer available to the river (sediment supply), but the processes are handicapped or absent (high flow regime and natural variability within hydrograph components)."

7.3.2 Riparian Vegetation

Flow regulation and land use practices have dramatically reduced riparian habitat. Today on the Tuolumne, less than 15% of the historical riparian forests remain (McBain and Trush, 2000). Large flood flows are trapped behind storage reservoirs and present-day flows aren't sufficient to scour out riparian vegetation that has grown in the channel. The trees that grow in the channel are all the same age, creating an unstable stand that lacks biodiversity. Historically, floods would carry large woody debris that would also help to scour trees from the channel. "Loss of channel migration and clearing of valley oaks and cottonwoods in the riparian corridor decreased large woody debris recruitment, reduced woody plant cover along the river corridor, encouraged exotic plants to infiltrate into the riparian zone and increased ambient temperatures within the river corridor…Riparian encroachment has transformed channel margins from shallow, low velocity exposed cobble habitat (high quality habitat for Chinook [salmon] rearing) to deeper, higher velocity habitat" (McBain and Trush, 2000). The lack of sediment also causes flows to scour away at the channel instead of depositing rich soil for riparian vegetation. The riparian corridor has been reduced to a narrow strip in some reaches and is gone altogether in other places (Figure 7.10) (McBain and Trush, 2000).

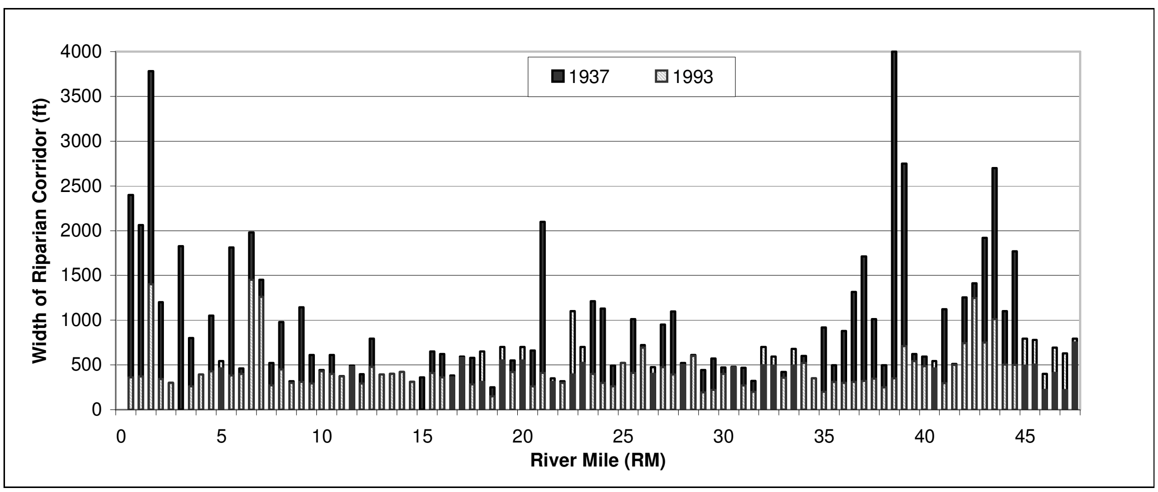

Figure 7.10. Riparian corridor widths in 1937 and 1993, starting at the Tuolumne River's confluence with the San Joaquin River (RM 0.0) and ending just upstream of the New La Grange Dam (RM 51.5). From McBain and Trush, 2000.

Table 7.5. Land uses and effects on the lower Tuolumne River from 1848 to present.
Source: McBain and Trush, 2000.

Land Use	Time Period	Location	Disturbance	Effect on Channel
Placer Mining	1848-1880	La Grange and Upstream (RM 50)	Turned over floodplains and terraces; spoil placement on fertile areas	Destroyed natural channel morphology, increased sediment supply, destroyed instream habitat, removed riparian forests
Urban Growth	1850-present	Modesto to Waterford (RM 15 to 30)	Need for commercial lumber, space, and aesthetic value	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution loading into river
Dredger Mining	1880-1952	Roberts Ferry to La Grange (RM 38 to 50)	Turned over entire riparian corridor valley-wall to valley-wall; spoil placement on fertile areas	Destroyed natural channel morphology, increased sediment supply, destroyed instream habitat, removed riparian habitat
Grazing	1850-present	San Joaquin confluence to La Grange (RM 0 to 50)	Young riparian vegetation is grazed, water sources become feces conduits	Destabilized banks, discouraged natural riparian regeneration
Farming	1860-present	San Joaquin confluence to La Grange (RM 0 to 50)	Mature and establishing riparian vegetation is cleared. Channel location stabilized	Confined river corridor (reduced width), constructed dikes, removed riparian vegetation, increased pollution and fine sediment loading into river
Flow Regulation	1890-present	Downstream of La Grange (RM 0 to 52)	Magnitude, duration, frequency, and timing of high flow regime is altered and reduced, reduced/ eliminated sediment supply from upstream watershed	Bed coarsening and downcutting, fine sediments accumulated in channel, channel fossilized by encroaching riparian vegetation, channel migration and bar building virtually eliminated, floodplain construction and deposition reduced, quantity and quality of instream and riparian habitat greatly reduced
Aggregate Mining	1930-present	Hughson to LaGrange (RM 24 to 50)	Large instream and off channel pits, dredger tailing removal	Historic floodplains are left as deep ponds, floodway narrowed by dikes separating ponds from river, riparian vegetation is cleared, regeneration is prevented and mature stands eliminated.

7.3.3 Chinook and Steelhead

The Tuolumne River, historically remembered as one of the best salmon streams in the state, has suffered a decline in fish numbers since the installation of large dams along the river. While steep topography and formidable waterfalls characterize the upper watershed, a number of fish most likely ascended the mainstem beyond the present day location of New Don Pedro Dam. As with the other tributaries of the San Joaquin River, mining diversions and early irrigation diversion projects on this river undoubtedly had a negative impact on water flow. Major ecological change occurred with the completion of the 120 ft tall La Grange dam in 1894, which blocked continuity of spring- run salmon spawning areas. The main spawning beds are located in a 20 mi stretch from Waterford to La Grange Dam, but the large dams upstream of this site reduce water flows and degrade the quality of the spawning area (Figure 7.11).

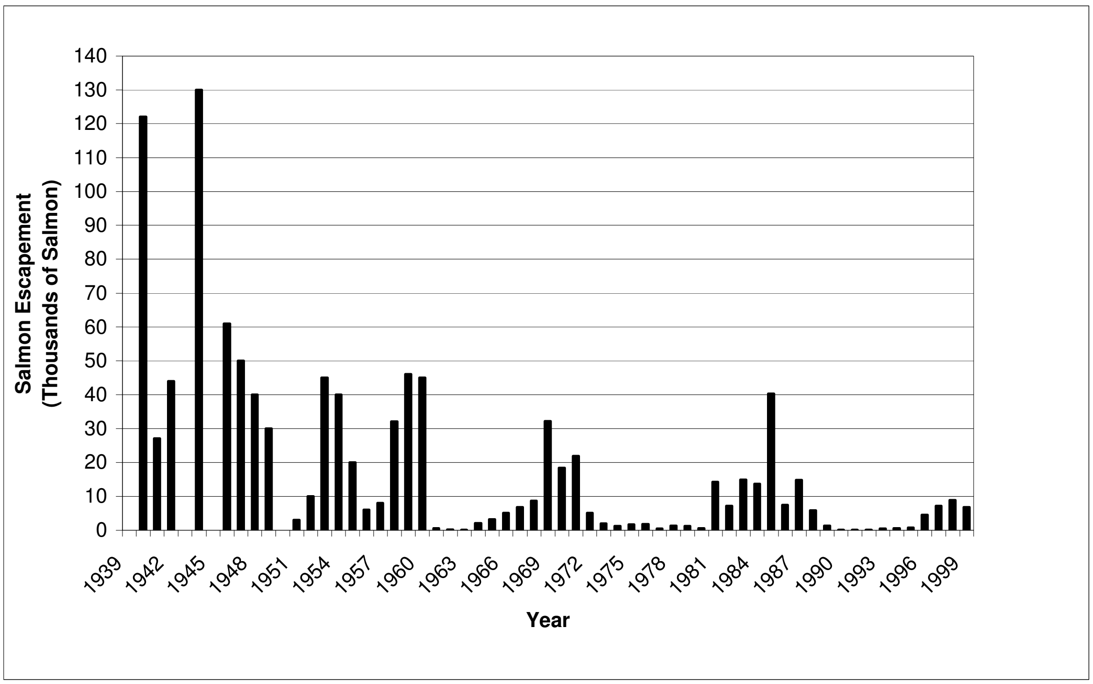

Figure 7.11. Annual salmon escapement in the Tuolumne River. Note difference in scale between Tuolumne and other rivers in the San Joaquin Basin. Data: CADFG 1961, 1994, AFB ADM. Rpt., Mills & Fisher. Partial count in 1941, no estimate in 1943, 1945, and 1950.

Presently, only fall-run salmon persist on the Tuolumne River, whereas in the past both spring and fall-runs utilized the river. Absence of a late fall-run is attributed to hydrological conditions over the past few decades especially the "lack of consistent, cool flows during the summer to support the juveniles" (Yoshiyama, 1996). "Extremely low flows, below 50 cfs, in the Tuolumne and Stanislaus Rivers between 1960 and 1991 have substantially reduced population recruitment (Carl Mesick Consultants, 1996 in CMARP)." A minimum flow regime was established in 1995 (see chapter 8), but prior to 1995 there were many years with flow conditions unsuitable for salmon. For example, in water year 1978 (figure 7.12) flows were insufficient for migration flows in the fall and spawning in the winter despite large releases in the spring. Furthermore, low and eratic flows in the summer would not have been suitable for spring run or steelhead. The hydrograph of water year 1985 illustrates another year when flow conditions may have been detrimental to salmon. Despite a relative abundance of flows in that year, repeated erratic spikes during the spawning and incubation period, presumably for power production were probably detrimental, if not fatal, to salmon eggs and fry. (Figure 7.13).

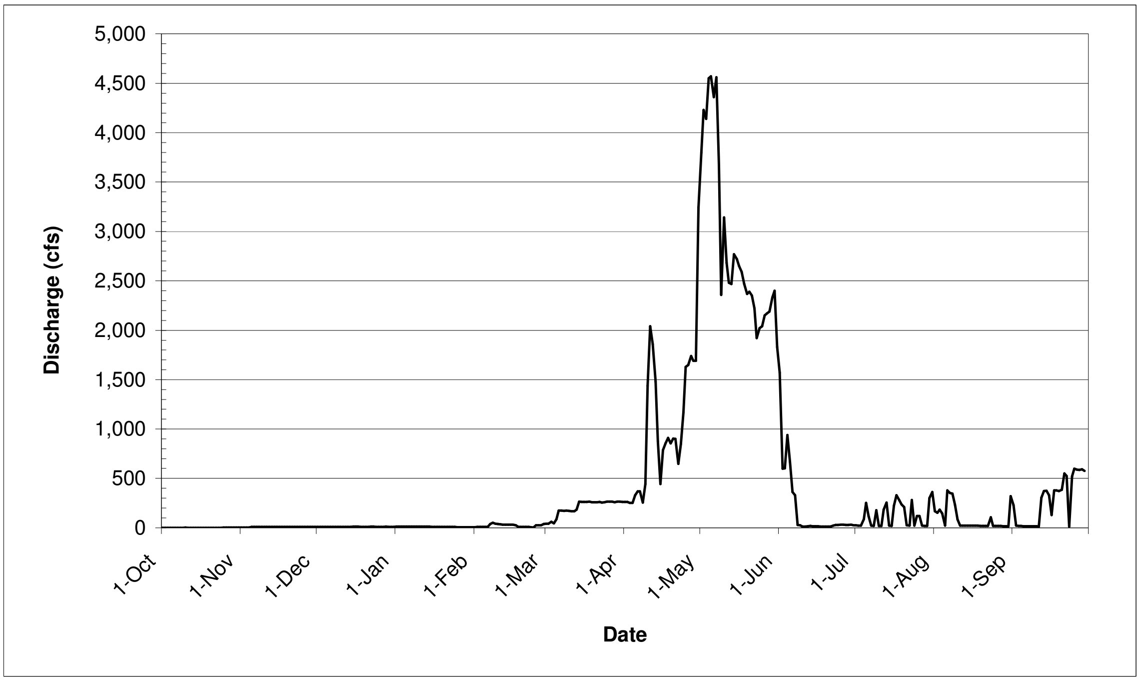

Figure 7.12. Tuolumne River Hydrograph in 1978 (Dry) Regulated Water Year. There are no spawning migration flows in the fall and no spawning flows in the winter. Data from gauge below La Grange Dam near La Grange.

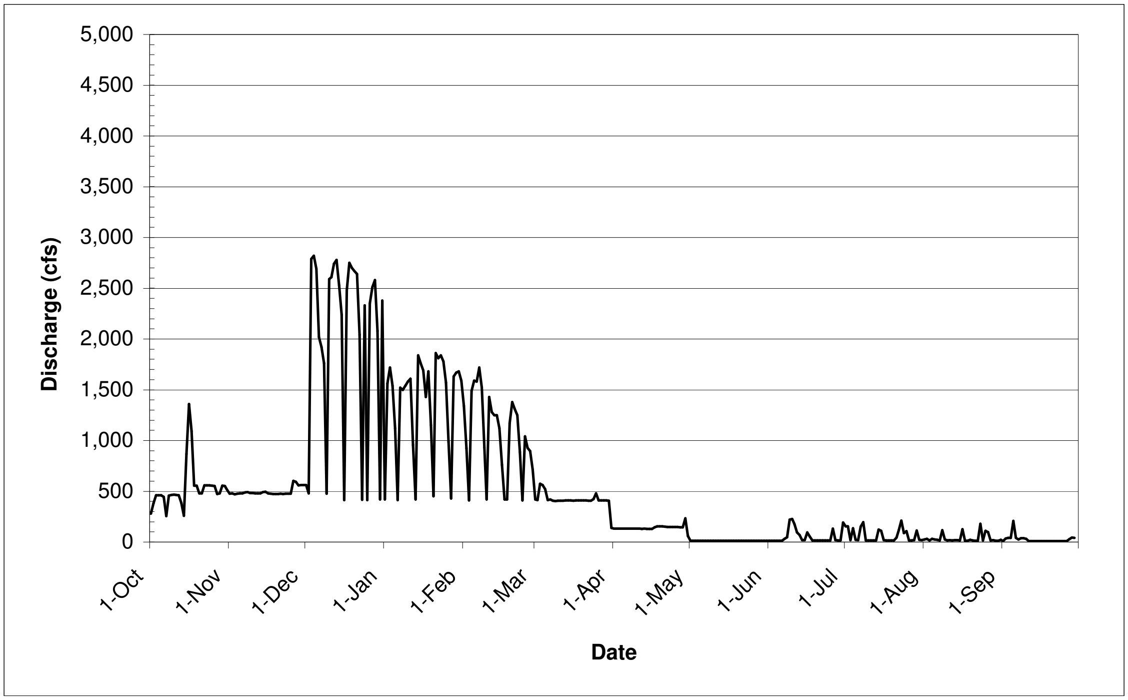

Figure 7.13. Tuolumne River Hydrograph in 1985 (Normal) Regulated Water Year. The pattern of release from December 1 to March 1 is unnatural and may have been harmful to spawning salmon. Data from gauge below La Grange Dam near La Grange. There is no data for November.

7.4 STANISLAUS

7.4.1 Geomorphic Processes

Kondolf et al. (2001) studied aerial photographs and conducted field observations along the lower Stanislaus to determine geomorphic changes in the River. Conclusions reached in the report are summarized in this section. Kondolf et al. (2001) found that historically the river was dynamic, characterized by depositional and scour features and presently the River is characterized as a relatively static and entrenched system. “Changes since construction of New Melones Dam include:

- Reductions in channel diversity through loss of alternating bar sequences;
- Large scale vegetation encroachment in the formerly active channel armoring along channel banks, bars and islands;
- Substantial encroachment in floodplain areas by urban and agricultural development, particularly orchards, thereby altering the natural river channel-floodplain connection;
- Absence of evidence of floodplain scouring flows; and
- An apparently incised river channel that is no longer hydrologically or geomorphologically connected to its floodplain (twice the flow needed to access the floodplain).

Changes ongoing before construction of New Melones Dam but intensified since include:

- Sediment starvation from trapping behind dams of sand and gravel sized sediment supplied from the watershed;
- Mining of sand and gravel at rates nearly ten times greater than pre-dam coarse sediment supply from the catchment" (Kondolf et al., 2001).

Results of Kondolf et al.'s (2001) preliminary estimates of bed mobilization on the Lower Stanislaus suggest: "Flows in excess of 5,000 to 8,000 cfs are needed to mobilize the bed and thereby maintain channel form and gravel quality; and these flows occurred with a pre-dam return period of about 1.5 to 1.8 years, but now occur less than once every 5 to 20 years since construction of New Melones Dam."

7.4.2 Riparian Vegetation

Mining, construction of dams, agricultural development and other impacts from human settlement has dramatically reduced the diversity and regeneration of riparian vegetation on the Stanislaus. "These changes…have cumulatively led to major impacts to native aquatic, terrestrial, and riparian species, and have heavily degraded habitats along the Stanislaus River corridor" (Schneider, 2001). The lack of scouring floods in the Stanislaus has caused woody riparian vegetation to encroach in the channel and colonize gravel bars, as evident in Schneider's (2001 pg 69-70) comparison of 1937 and 1998 aerial photographs. In several reaches, orchards now replace riparian vegetation that once lined the river corridor (Schneider 2001 pg 70) resulting in a reduction of the total corridor width similar to that described on the San Joaquin (figure 7.6).

7.4.3 Chinook and Steelhead

The salmon populations on the Stanislaus have sometimes been compared to the Tuolumne. In the nineteenth century the California Fish Commission reported: "The Tuolumne, a branch of the San Joaquin, at one time was one of the best salmon streams in the State…What has been said of the Tuolune is true of the Stanislaus (CFC1886:20 in Yoshiyama, 2000). More recent patterns of escapement and abundance of salmon on the Stanislaus have also resembled those on the Tuolumne during the last 50 years, although the population levels are somewhat lower on the Stanislaus(Figure 7.14). Both populations plummeted sharply in the early sixties, late seventies, and early nineties, and they rebounded similarly in the late sixties and the mid eighties. Salmon population numbers on the Stanislaus were far smaller in the late forties and fifties then populations on the Tuolumne (Figure 7.11). Whereas escapement on the Tuolumne frequently surpassed 20-30 thousand during the 1940's and 50's, the escapement was closer to ten thousand on the Stanisluas. This may be a result of the disproportionate impact of early water diversions and dams on the Stanislaus compared to the Tuolumne.

In 1940 Hatton reported that the fishway over Goodwin Dam was "seldom passable" and that the "almost complete diversion of water at the dam" made it a "very nearly impassable barrier," and thus the 9.3 miles between Goodwin and the Melones Power House was "only rarely accessible to Salmon (Hatton 1940 in Yoshiyama 1996 p.16). Fry (1961) also attested that Goodwin Dam caused low, warm water flows downstream during the summer and violent water level fluctuations during the fall and winter due to the release of water for hydroelectric purposes (Yoshiyama 1996 p.16). These conditions probably reduced the salmon populations considerably. At some point after the nineteen fifties, the old Goodwin Dam was raised to serve as a regulating reservoir for hydroelectric releases at Tulloch which may have improved downstream conditions for salmonids. The original fish ladder on Goodwin, however, was not raised along with the dam eliminating any potential for salmon to spawn upstream of Goodwin.

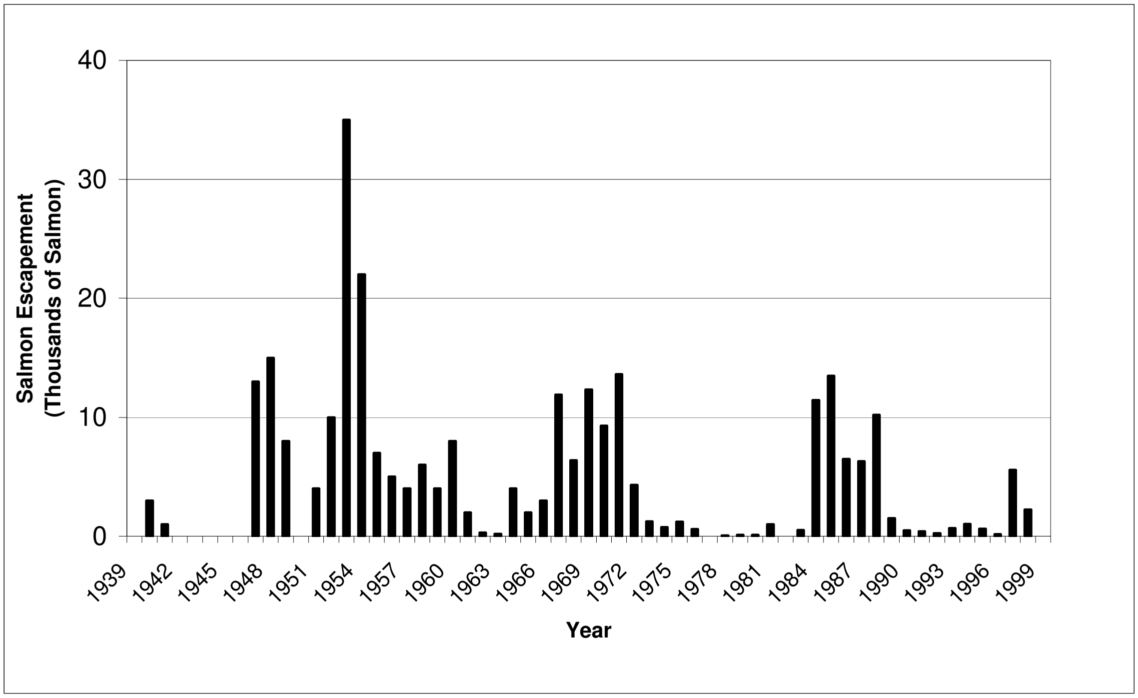

Figure 7.12. Annual Salmon Escapement in the Stanislaus River. Data: CADFG 1961, 1994, AFB ADM. Rpt., Mills & Fisher. 1940 and 1941 are partial counts. No data 1938-39, 1942-1946, and 1950.

The Goodwin Dam, which serves as diversion point to irrigation canals, remains a complete barrier to salmon and has created an upstream limit to their migration patterns. Due to the dramatic water diversion on the Stanislaus prior to the operation of New Melones Dam, the composition of fish type in this river has changed from predominantly spring-run to mostly fall-run fish (Yoshiyama 1996 p. 16 from CDFG 1972 upubl. Report). Large summer flow releases from New Melones to meet water quality objectives in the Delta and fish releases pursuant to the Anadromous Fisheries Restoration Program, have apparently created conditions more favorable for over-summering salmonids. As a result, steelhead and salmon yearlings are now occasionally sampled in the Stanislaus.

Prior to the establishment of minimum flow regimes for fish under the AFRP, flows in some years were clearly unsuitable for salmonids. For example, acutely poor flow conditions in 1959 and 1961 almost certainly contributed to the first recorded, sharp population decline during the early 1960's. In 1959 (Figure 7.14), wildly unnatural flow fluctuations during the spawning and incubation period followed by almost no flow starting in mid March probably reduced spawning success and then subjected surviving juveniles to intolerable, warm low flow conditions. Although, flow fluctuations above a relatively steady base were the norm in pre-dam hydrology, these post-dam fluctuations occasionally cut flow to almost nothing as occurred on several days of January and February of 1959. These poor conditions were followed by even worse conditions during 1961 (Figure 7.15) during which flows were less than 100 c.f.s. during the spawning and incubation period and then fell to near zero by early March dooming any juveniles. Remarkably, some salmon apparently survived and returned to spawn 3 and 4 years latter. Similarly poor flow conditions from 1976-1979 (appendix B) apparently resulted in the population crash of the late seventies and early eighties. New minimum flow regimes under the AFRP will probably reduce the frequency of these dramatic population crashes.

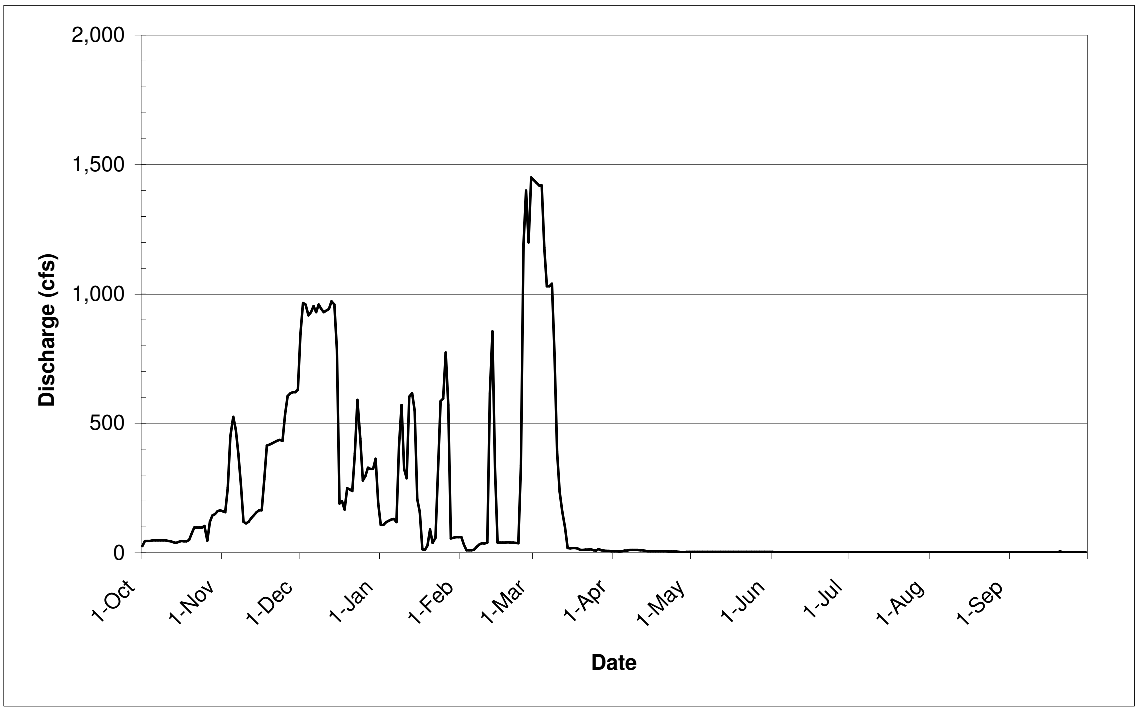

Figure 7.14. Stanislaus River Hydrograph in 1959 (Critically Dry) Regulated Water Year. The sharp fluctuations in flows in January, February and March during critical spawning times can dry up redds and strand spawning Chinook salmon. Data from gauge below Goodwin Dam near Knights Ferry.

Mining, vegetation encroachment and flow regulation have dramatically reduced the distribution and abundance of spawning habitat for Chinook salmon. Instream gravel mining for construction aggregate and gold dredging of the channel has contributed to a 160,000 sq. ft decrease in spawning gravel from Goodwin Dam to Riverbank between 1972 to 1994 (Kondolf et al. 2001 pg 40). Vegetation encroachment has decreased the available spawning habitat by colonizing alluvial bars historically used for spawning (Kondolf et al 2001 pg 40). Between 1972 and 2000, the number of suitable spawning riffles has decreased and is concentrated between Wills Pond and Goodwin Dam (Kondolf et al 2001 pg 40). In-channel mining pits may be contributing to high levels of sand in spawning riffles and providing habitat for exotic warmwater fish that prey on juvenile salmonids (Kondolf et al 2001 pg 41).

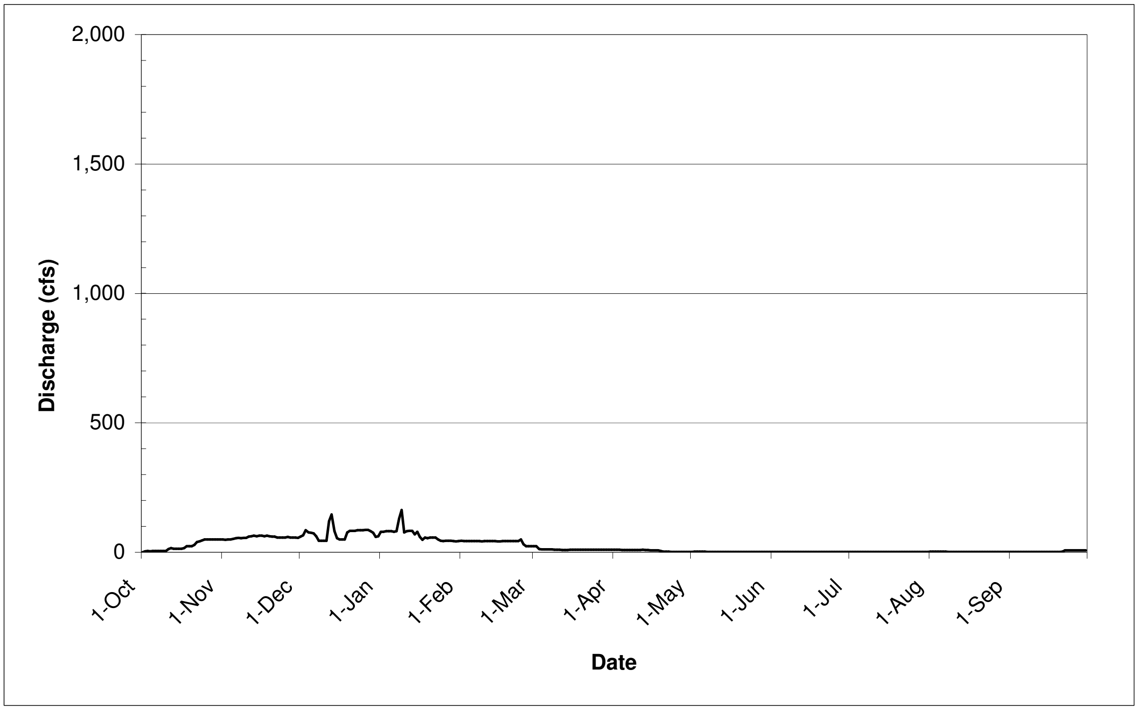

Figure 7.15. Stanislaus River Hydrograph in 1961 (Critically Dry) Water Year. Releasing no flows, even in critically dry years, prevents salmon from successfully spawning, rearing, and migrating. Data from gauge below Goodwin Dam near Knights Ferry.

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Chapter 8. Previous Efforts Establishing Instream Flows

8.1 INTRODUCTION

For decades, managers have established minimum instream flow requirements on tributaries in the San Joaquin basin for the purpose of achieving specific ecological objectives. Nearly all of these efforts have focused on establishing instream flows for anadromous fish, but none of them have specified flow regimes to achieve geomorphic or riparian vegetation objectives. In addition to minimum flow requirements for fish, all of the terminal reservoirs on the four principal tributaries of the San Joaquin Basin release flows to satisfy downstream riparian water rights. Sorting out the specific flow regimes that result from the combination of minimum fish and riparian is surprisingly complicated. This chapter attempts to clarify and summarize the minimum flow regimes on the San Joaquin, Merced, Tuolumne, and Stanislaus River.

8.2 MINIMUM FLOWS

In this chapter, *minimum flows* refer to any required flows that dam operators must meet or exceed at any given time of the year. Minimum flows are established separately on each tributary and reflect differences in dam operators, water use, environmental objectives, and other factors specific to that tributary. *Flow-related requirements* refer to any legal obligation to increase the amount of water in the river for the sake of environmental restoration objectives. These are often quantified as volumes of water (e.g., acre-feet) over a given period of time rather than flow rates (e.g., cubic feet per second). *Recommended minimum flows* refer to previous and current attempts to better quantify the flows necessary to achieve specific ecological functions. Flow recommendations are not legally binding.

Minimum and recommended flows are difficult to represent in any summary form because each year the requirements are different. Year type (e.g. critical, dry, normal, wet), existing flows, reservoir storage, and the specific needs of the fishery all contribute to establishing the minimum flows for any given year. Additionally, because several of the components are set only by the volume of water required, a separate modeling and decision process determines the flow magnitude and duration for a given volume release. The minimum flows will vary every year depending on the outcome of these separate decision-making processes.

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8.2.1 San Joaquin River

Minimum flow requirements

There are no established minimum environmental flow requirements for the San Joaquin River between Friant Dam and the confluence with the Merced River. However, routine river operations maintain flows in much of the river for much of the year. Between approximately October 15 and April 15, at least 35 cfs are released from Friant Dam for operation of the Friant fish hatchery 1.5 miles below Friant Dam (DFG, 1993). After use at the hatchery, some of this water is discharged back into the river. Pursuant to legal settlement in the late 1950's the Bureau of Reclamation is required to release flows to the San Joaquin River for riparian water rights diversions between Friant Dam and Gravelly Ford some 35 miles below the dam. The settlement requires that at least 5 cfs flows past each of the diversions between Friant and Gravelly ford during the irrigation season April 15 and October 15. This requirement generally results in an instream flow through this reach of between 180 and 250 cfs (Figure 8.1). Downstream of Gravelly Ford there are no minimum flow requirements and generally now flow except flood waters and irrigation return flow. Between Mendota Dam and Sack Dam, however, the river is used to convey Delta water from Mendota Pool to Arroyo Canal for irrigation purposes.

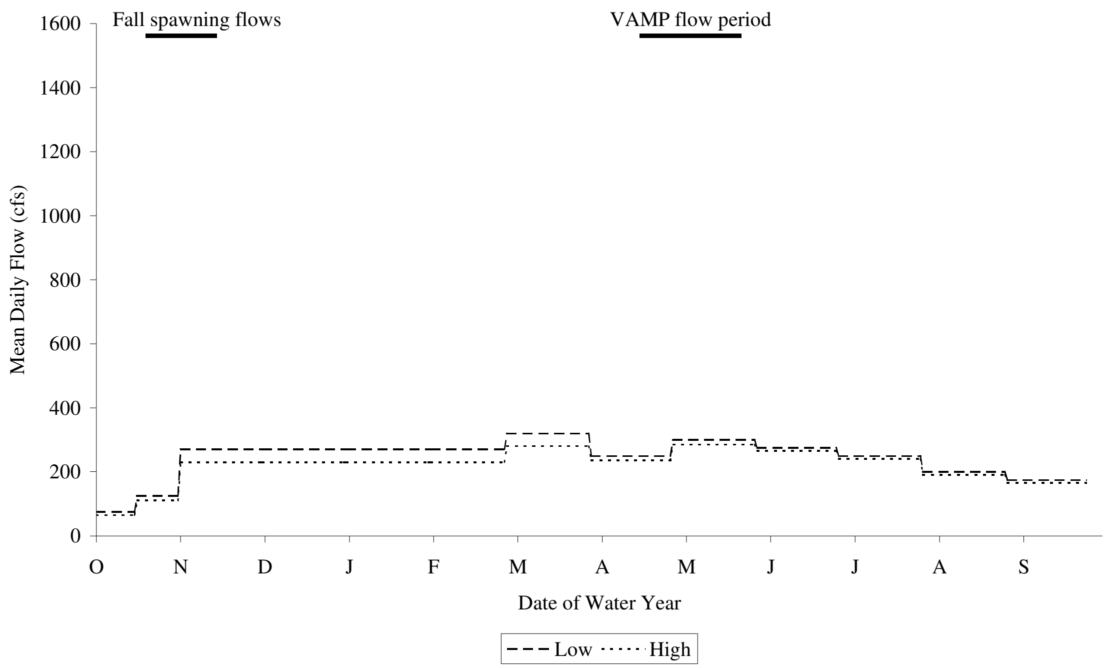

Figure 8.1. Minimum flows on the San Joaquin River downstream of Friant Dam

Minimum flow recommendations

The authorizing legislation of the Central Valley Project Improvement Act explicitly prohibited the Anadromous Fish Restoration Program (AFRP) from developing instream flow requirements for the San Joaquin River between Friant Dam and the confluence with the Merced River. In the 1950's the Department of Fish and Game attempted to implement an instream flow requirement to maintain runs of salmon up to Friant Dam, but they were ultimately unsuccessful. During this effort, fish and game presented minimum fish flow recommendations that were initially developed by noted fish biologist Don Fry (Vestal, 1957) in proceedings before the State Water Resources Control Board. In addition to flows between Friant and Mendota (Table 8.1), DFG recommended flows 100 and 200 cfs be required to flow through to the Merced River confluence.

Table 8.1. Summary of Required Riparian and Recommended Minimum Fish Flow Releases from Friant Dam

Month	Riparian Releases		Fish Hatchery	DFG Recommendation 1957		
	Low (cfs)	High (cfs)	(cfs)	Spring and fall-run (cfs)	Fall-run only (cfs)	Spring-run only (cfs)
October	100	150	35	350	350	350
November			35	350	350	350
December			35	350	350	200
January			35	200	200	200
February			35	200	200	150
March			35	150	150	100
April	100	150	35	100	100	100
May	150	200	35	200	100	200
June	180	250	35	300	0	300
July	180	250	35	350	0	350
August	180	250	35	100	0	100
September	150	200	35	100	0	100
Total annual releases	62,620 AF	87,307 AF	25,288 AF	165,582 AF	108,381 AF	150,529 AF

8.2.2 Merced River

Minimum flow requirements

Minimum flows on the Merced River downstream from New Exchequer Dam are governed by FERC license No. 2179 (1964) and Davis-Grunsky contract No. D-GG17 between DWR and Merced ID (1967). The FERC license requires fairly modest flows between 15 and 100 cfs year round. These flows were based on a 1964 Department of Fish and Game (DFG) memorandum on in-stream fish flows and intended to provide adequate flows for Chinook salmon. The Davis-Grunsky contract requires that MID maintain a continuous flow of 180-220 cfs between November 1 and April 1. In addition to these flows, New Exchequer dam is operated to provide adequate flows for the Merced River Riparian Water Users Association diversions. Though these are not intended for ecological purposes, they can increase flows immediately downstream from the dam by 50-250 cfs. Riparian flows quantities added to either FERC flows or Davis-Grunsky flows, whichever is larger in any particular month (Ted Selb, Merced ID, p.c., June 2002). The combination of these flow requirements creates a range of minimum flows as shown under the header “Approx. Range of Minimum Flows” in the table below (Table 8.2 and Figure 8.2).

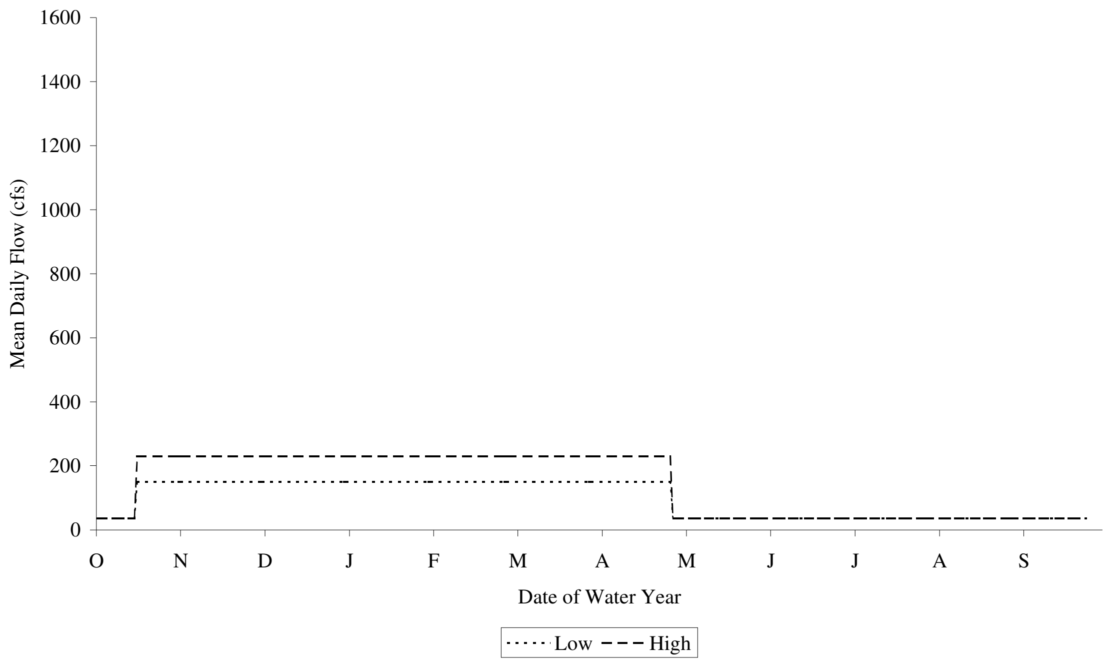

Figure 8.2 Minimum Flows on the Merced River downstream from New Exchequer Dam

Table 8.2 Summary of Merced River Required Minimum Flows by Year Type

Month	FERC (1964)		Davis-Grunsky (1967)		Riparian/ Cowell (1926)	Approx. Range of Minimum Flows	
	Normal (cfs)	Dry (cfs)	Low (cfs)	High (cfs)	(cfs)	Low (cfs)	High (cfs)
October 1-15	25	15	0	0	50	65	75
October 16-31	75	60	0	0	50	110	125
Nov-Dec	100	75	180	220	50	230	270
Jan-Feb	75	60	180	220	50	230	270
March	75	60	180	220	100	280	320
April	75	60	0	0	175	235	250
May	75	60	0	0	225	285	300
June	25	15	0	0	250	265	275
July	25	15	0	0	220	240	250
August	25	15	0	0	175	190	200
September	25	15	0	0	150	165	175
Minimum annual release	30,166 AF	22,624 AF	32,525 AF	39,753 AF	84,073 AF	127,778 AF	139,234 AF

Additional minimum flow-related requirements

The Merced ID has additional flow obligations as established by the Vernalis Adaptive Management Program (VAMP). Merced ID must provide up to 55,000 acre-feet per year during the spring outmigration period and 12,400 acre-feet during the fall migration period. These requirements increase the flow during critical migration periods of the

Chinook salmon, but as they are intended to satisfy objectives on the main stem San Joaquin at Vernalis rather than on the Merced, they are discussed in a later section (SJRGA, 2002)

Minimum flow recommendations

In 1993, Department of Fish and Game identified key deficiencies in the existing in-stream flow requirements and issued recommended in-stream flow schedules for the lower Merced River. In particular, DFG recognized that the high flows did not begin until November 1, a few weeks beyond the onset of the critical fall migration period. Additionally, spring flows during the April-May outmigration were limited to 60-75 cfs. Stream temperatures in the river often exceeded spawning and egg incubation tolerances in the fall and exceeded stressful levels for emigrating smolts in the spring. DFG proposed an alternate flow schedule (Table 8.3) of flows between 200-340 cfs in dry years and 300-1700 cfs in wet years. DFG also recommended a fall attraction flow in October of 15,000 acre-feet (DFG, 1993).

Table 8.3. Summary of Merced River DFG Recommended Minimum Flows by Year Type

Month	Critical (cfs)	Dry (cfs)	Below Normal (cfs)	Above Normal (cfs)	Wet (cfs)
October 1-14	200	225	250	275	300
Oct 15- Dec 31	250	275	300	325	350
January 1-March 31	200	250	300	375	350
April 1-May 31	300	350	400	450	500
June 1-September 30	200	200	250	300	350
Spring outmigration flow (April-May)	2,376 AF	19,602 AF	36,828 AF	54,054 AF	71,280 AF
Fall attraction flow (October)	15,000 AF	15,000 AF	15,000 AF	15,000 AF	15,000 AF
Minimum annual release	181,000 AF	218,000 AF	267,000 AF	320,000 AF	355,000 AF

Additional minimum flow-related recommendations

In 2001, the Anadromous Fish Restoration Program (AFRP) made flow projections for the Merced River based on a water acquisition plan to use federal funds to acquire water for instream flows pursuant to the Central Valley Project Improvement Act. Since the Merced River is not considered part of the CVP, the projections are not binding, but they may serve as the basis for future efforts to purchase water for anadromous fisheries management.

The AFRP recommends purchasing 19,000 acre-feet from willing sellers for the benefit of the Merced NWR and East Gallo Unit and an additional 50,000 acre-feet from willing sellers in April – June for spring outmigration. The resulting impact of these acquisitions is shown in Figure 8.3. Note that this figure does not display minimum flows but rather modifications to predicted flows (AFRP, 2001).

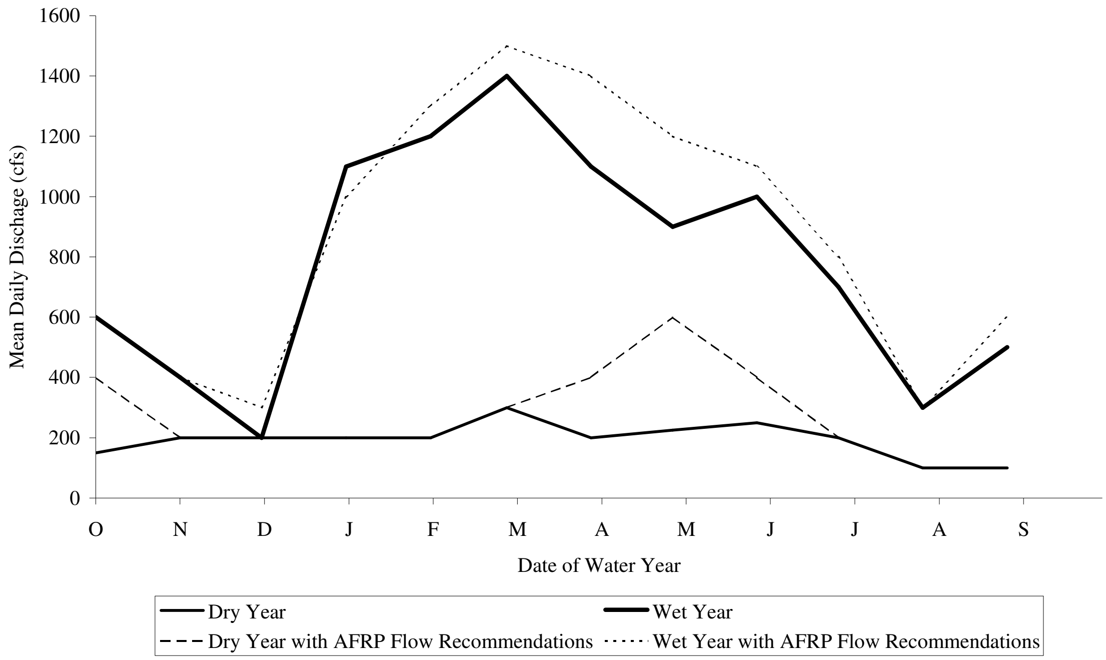

Figure 8.3. Modeled Impact of AFRP Recommended Minimum Flow Acquisitions on Merced River Flows.

8.2.3 Tuolumne River

Minimum flow requirements

The 1995 FERC Settlement agreement established the existing minimum flows on the Tuolumne River downstream from New Don Pedro. The Settlement Agreement sets minimum flows based on year types as described in Table 8.4. The minimum flows provide year round flows between 50-300 cfs to provide and average of 5-15 miles of suitable water temperature for salmon during the summer months, as well as increase invertebrate production and prevent vegetation encroachment on spawning gravels (McBain and Trush, 2001).

Table 8.4. Summary of Tuolumne River Required Minimum Flows by Year Type

Month	Critical (cfs)	Median Critical (cfs)	Inter. Critical-Dry (cfs)	Median Dry (cfs)	Inter. Dry-Below Normal (cfs)	Median Below Normal (cfs)	Above Normal (cfs)
October 1-15	100	100	150	150	180	200	300
October 16-May	150	150	150	150	180	175	300
June-September	50	50	50	75	75	75	250
Other flow requirements							
Fall Attraction Pulse (TAF)	0 TAF	0 TAF	0 TAF	0 TAF	2 TAF	2 TAF	6 TAF
Spring Outmigration Pulse (TAF)	11 TAF	20 TAF	33 TAF	37 TAF	36 TAF	60 TAF	90 TAF
Minimum Annual Release (TAF)	94 TAF	103 TAF	117 TAF	128 TAF	143 TAF	165 TAF	301 TAF

Additional minimum flow-related requirements
In wetter years, as shown in the table above, the 1995 Settlement Agreement requires a specific volume of water to be utilized for fall and spring pulse flows. The Toulumne River Technical Advisory Committee (TRTAC) apportions the pulse flow volumes to optimize conditions for migration, spawning, and rearing. In dry and normal years, the fall pulse flows must have bimodal peaks. Under the 1995 Settlement Agreement spring out-migration pulses are also required for all year types. These range in volume from 11 thousand acre-feet to 90 thousand acre-feet. The TRTAC sets these flows in coordination with the Tuolumne River's 22,000 acre-feet contribution to VAMP flow requirements on the San Joaquin River at Vernalis (McBain and Trush, 2001).

Minimum flow recommendations
In 1993, Department of Fish and Game identified key deficiencies in the then current in-stream flow requirements and issued recommended in-stream flow schedules for the lower Tuolumne River. (In some sense, these flows have been absorbed into and replaced by the 1995 FERC flows, but they are included here for consistency and further clarification.) As with other San Joaquin tributaries, stream temperatures on the lower Tuolumne often exceeded spawning and egg incubation tolerances in the fall and exceeded stressful levels for emigrating smolts in the spring. DFG proposed an alternate flow schedule (Table 8.5) of flows between 80-605 cfs in dry years and 300-1,450 cfs in wet years (DFG, 1993).

Table 8.5. Summary of Tuolumne River DFG Recommended Minimum Flows by Year Type

Month	Critical (cfs)	Dry (cfs)	Below Normal (cfs)	Above Normal (cfs)	Wet (cfs)
October 1-14	80	150	200	250-1,480	300-1,450
Oct 15- Dec 31	80	150	175-1,075	250-1,480	300-1,450
January 1-March 31	80	150	175	250	300
April 1-May 31	50-605	170-985	210-1,428	500-2,520	500-3,000
June 1-September 30	50	75	75	150	200
Minimum Annual Release (TAF)	47 TAF	92 TAF	107 TAF	187 TAF	217 TAF

Additional minimum flow-related recommendations

In 2001, the Anadromous Fish Restoration Program (AFRP) made flow recommendations for the Tuolumne River. Since the Tuolumne River is not considered part of the CVP, the recommendations are not binding. However, the recommendations are relied upon when evaluating flow schedules for anadromous fisheries management.

AFRP recommended purchasing 60,000 acre-feet from willing sellers in April – June for spring outmigration. The resulting impact of these acquisitions is shown in Figure 8.4. Note that this figure does not display minimum flows but rather modifications to predicted flows (AFRP, 2001).

During the FERC relicensing proceedings, the City and County of San Francisco recommended flows between 64 thousand acre-feet in dry years and 250 thousand acre-feet in wet years that include a two day fall attraction pulse, increased outmigration flows in the spring, and summer rearing flows. The USFWS recommended flows that address temperature and physical habitat concerns in the Tuolumne River. The flows range from a minimum of 120 thousand acre-feet to 304 thousand acre-feet but do not include pulse flows for fall or spring migration. These recommendations do not include specific flow rates, only volumes (CALFED, 2001).

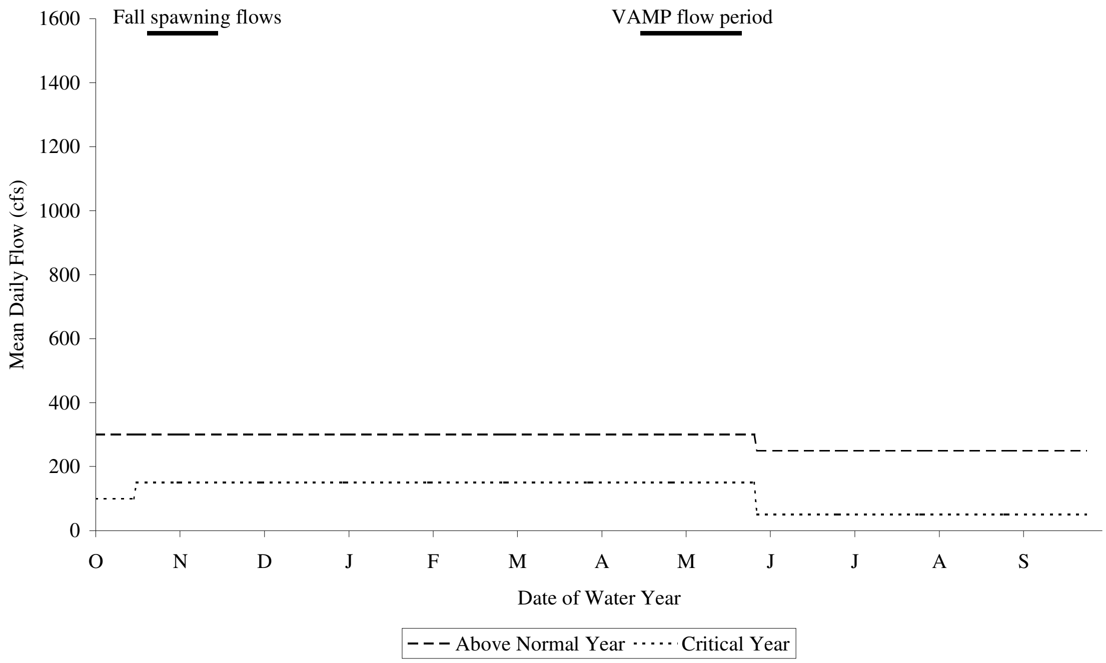

Figure 8.4 Minimum Flows on the Tuolumne River

8.2.4 Stanislaus River

Minimum flow requirements

The 1987 Agreement between CDFG and USBR established minimum flows on the lower Stanislaus River. The agreement prescribes fall minimum flows and spring pulse flows that range in volume between 98.3 to 302.1 thousand acre-feet per year. The minimum flow requirements are intended to benefit Chinook salmon fall spawning, winter rearing, spring out migration, and juvenile steelhead summer rearing (Derek Hilts, USFWS, p.c. July 2002).

The current minimum flow schedule is based on STANMOD, a monthly forecast model used to determine how much flow is allocated to fish for the year. The development of the 1997 New Melones Interim Operations Plan modified the implementation of minimum flows based on STANMOD modeling, New Melones storage, inflow and AFRP flow recommendations. USFWS and USBR define New Melones Interim Operations flows based on storage/inflow. FWS allocates the designated annual quantity using the Interim Operations plan for guidance (and working with DFG and NMFS). This is a very dynamic and iterative process between FWS and USBR that changes monthly as forecasts are compared to actual storage/inflow (Derek Hilts, USFWS, p.c. July 2002).

Table 8.6 shows the initial 1987 Agreement minimum flows. Table 8.7 and Figure 8.5 shows operations in 2001 based on the New Melones Interim Operations Plan and STANMOD.

Table 8.6. Summary of Stanislaus River Required Minimum Flows (cfs) by Year Type

Month	Critical (cfs)	Dry (cfs)	Below Normal (cfs)	Above Normal (cfs)	Wet (cfs)
October	200	250	250	350	350
November-March	250	275	300	350	400
April	300/1500	300/1500	300/1500	1500	1500
May	1500/300	1500/300	1500/300	1500	1500
June	200	200	250	800	1500
July-September	200	200	250	300	300
Minimum Annual Release (TAF)	245 TAF	256 TAF	275 TAF	410 TAF	467 TAF

Table 8.7. Summary of Stanislaus River Minimum Flows (cfs) by Year Type

	Dry Year			→			Wet Year
Month	**(cfs)**	**(cfs)**	**(cfs)**	**(cfs)**	**(cfs)**	**(cfs)**	**(cfs)**
October	0	110	200	250	250	350	350
November-Dec	0	200	250	275	300	350	400
January-March	0	125	250	275	300	350	400
April	0	250	300	300	900	1500	1500
May	0	500	1500	1500	1500	1500	1500
June	0*	0*	200	200	250	800	1500
July-Sept	0*	0*	200	200	250	300	300
Minimum Annual Release (TAF)	70 TAF	99 TAF	245 TAF	256 TAF	311 TAF	410 TAF	467 TAF

*Allocation of zero flow in summer months is based on the assumption that the water required for downstream water quality purposes (70 TAF/yr) in those summer months will assure that flow is not zero.

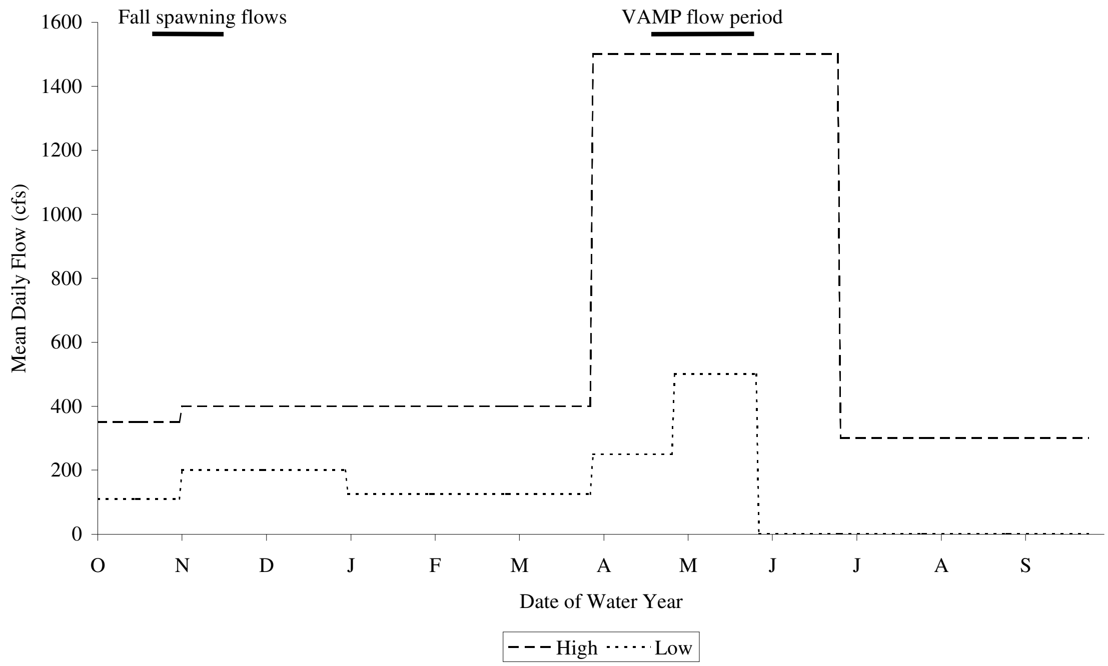

Figure 8.5 Minimum Flows on the Stanislaus River.

Additional minimum flow-related requirements

In addition to the minimum flows governed by the 1987 agreement, New Melones dam also provides 70 thousand acre-feet per year to maintain Delta water quality during the irrigation season under the San Joaquin River Agreement. This water often creates suitable conditions for summer steelhead rearing in the reach below the Goodwin Dam (SJRGA, 2002).

The Oakdale ID and the South San Joaquin ID provide additional flow of up to 22,000 acre-feet per year during the spring outmigration period and 12,400 acre-feet during the fall migration period. The Oakdale ID also provides 15,000 acre-feet plus up to 11,000 acre-feet more for fall attraction flows. These requirements increase the flow during critical migration periods of the Chinook salmon, but as they are intended to satisfy objectives on the mainstem San Joaquin at Vernalis rather than on the Stanislaus, they are discussed in a later section (SJRGA, 2002).

Minimum flow recommendations

DFG (1993) recommended minimum baseflows between 200-500 cfs and spring outmigration flows from 400-2000 cfs (Table 8.8). DFG flows differ from the 1987 flow by allocating as much water as possible during spring outmigration given the observed relationship between outflow at Ripon and adult escapement into the basin 2.5 years later. The Ecosystem Restoration Program Plan, Vol. II (ERPP) recommends maintaining the baseflows below Goodwin Dam of 200-400 cfs with peaks up to 1,500 cfs during the spring outmigration (CALFED, 1998).

Table 8.8. Summary of Stanislaus River DFG Recommended Flows by Year Type

Month	Critical (cfs)	Dry (cfs)	Below Normal (cfs)	Above Normal (cfs)	Wet (cfs)
October 1-14	200	250	250	300	300
Oct 15- Dec 31	250	275	300	350	400
January 1-March 31	200	225	250	300	350
April 1-May 31	300-400	350-800	400-1,200	450-1,600	500-2000
June 1-September 30	200	200	250	300	350
Minimum Annual Release (TAF)	164 TAF	180 TAF	206 TAF	242 TAF	277 TAF

Additional minimum flow-related recommendations

USFWS recommended minimum flows totaling 155 thousand acre-feet irrespective of year type based on and IFIM in-stream Flow Study. The intent of the flow recommendations was to provide adequate spawning, incubation, and rearing habitats for fall-run Chinook salmon. The study did not consider factors such as water quality, temperature, fall attraction flows, or outmigration flows.

8.2.5 Lower San Joaquin

Flow-related requirements

As mentioned above, the Merced, Tuolumne, and Stanislaus rivers all contribute to required minimum flows on the mainstem San Joaquin River as measured at the Vernalis gauge. These flows comprise part of the Vernalis Adaptive Management Plan (VAMP). VAMP outlines "a program of study to gather the best available scientific information on the impact of flows and State Water Project/Central Valley Project (SWP/CVP) export rates on the salmon smolts in the lower San Joaquin River" (SJRGA, 2002).

Table 8.9 outlines the VAMP flow targets. VAMP flows do not set year round minimum flow requirements; rather, they establish flow requirements during the out-migration period during April and May. Depending on the pre-existing hydrologic conditions, the target flow could either increase to the next highest class (e.g. an existing flow of 2,000-3,199 cfs is increased to 4,450 cfs) or it could be eliminated entirely (no increase in flows) (SJRGA, 2002).

Table 8.9. Summary of San Joaquin River (at Vernalis) Minimum Flows

Existing Flow (cfs)	31 day Out-migration Target Flow (cfs)
0-1,999	2,000
2,000-3,199	3,200
3,200-4,449	4,450
4,450-5,699	5,700
5,700-6,999	7,000
7,000 or greater	Provide stable flow to the extent possible

Table 8.10 below summarizes the contribution of the respective tributaries to the spring Vernalis flow target.

In addition to the spring out-migration flows, VAMP also requires fall flows provided by Merced ID and Oakdale ID as detailed below.

Table 8.10. Division of VAMP Spring Out-migration Flow Water

	First 50,000 AF	Next 23,000 AF	Next 17,000 AF	Next 20,000 AF	Total
San Joaquin River (Exchange Contractors)	5,000	2,300	1,700	2,000	11,000
Merced River (Merced ID)	25,000	11,500	8,500	10,000	55,000
Tuolumne River (MID/TID)	10,000	4,600	3,400	4,000	22,000
Stanislaus River (OID/SSJID)	10,000	4,600	3,400	4,000	22,000

Merced VAMP Flows

Merced ID is also responsible for 0 to 55 thousand acre-feet per year of VAMP flows between mid-April and mid-May. These flows vary in intensity and duration based on the needs determined for Vernalis. VAMP flow contributions are determined by the VAMP Division Agreement and the Merced River SIM model. Additionally, Merced ID shall provide, and USBR shall purchase, 12,400 acre-feet water above the existing flow in the Merced River during October of all years. Such water releases shall be scheduled by Merced ID, CDFG, and USFWS (SJRGA 2002).

Tuolumne VAMP Flows

The Modesto and Turlock irrigation districts are responsible for 22 thousand acre-feet of VAMP flows between mid-April and mid-May. These flows vary in intensity and duration based on the needs determined for Vernalis. The TRTAC attempts to coordinate these flow with the Tuolumne River out-migration flows which range from 11 to 90 thousand acre-feet (as required in the 1995 Settlement Agreement).

Stanislaus VAMP Flows

The Oakdale and South San Joaquin irrigation districts are responsible for 22 thousand acre-feet of VAMP flows between mid-April and mid-May. Additional flows of up to 11 thousand acre-feet will be made available to VAMP during any month of the year, though almost always between October and December. This water is used to supplement the fall attraction pulse at Vernalis (SJRGA, 2002).

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Chapter 9: Developing Ecologically Based Flow Regimes for the San Joaquin Basin

9.1 INTRODUCTION

This study identifies hypothetical restoration flow regimes for the San Joaquin River and its tributaries, but recognizes that the most reliable method for developing a restoration flow regime is through a long-term adaptive management program including a series of trials that test the effectiveness of various flow prescriptions. The purpose of developing the hypothetical flow regime is to:

- Test the feasibility of reoperating the terminal reservoirs in the San Joaquin Basin without diverting additional water away from agriculture, and
- Develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the rivers of the San Joaquin Basin.

The assumptions and uncertainties associated with the hypothetical flow regime are as important as the flow regime itself. To cost effectively achieve restoration, managers will ultimately need to test these assumptions and limit the uncertainties through an adaptive management program consisting of a combination of modeling, pilot flow studies, model calibration, and long-term restoration implementation.

Many previous flow restoration efforts have focused on the flow requirements of specific species (AFRP; Mono Lake Tributaries;) often at the direction of a court or legislative body. These efforts have been subjected to criticism of being species specific to the neglect of the larger ecological processes that are needed to maintain habitat for the target species (Stanford, 1994; Castleberry et al., 1996). In response to the criticisms of species specific efforts, many programs including CALFED have embraced a more holistic approach advocating “ecosystem restoration” and reestablishment of ecological, geomorphic, and hydrologic processes. Although this new interest in ecosystem processes may be a step forward, there is a tendency for it to stall-out in vague goal statements about ecosystem health and processes that do not provide the specific guidance necessary to prescribe a restoration flow regime. Efforts to provide more specific measurements of ecosystem health run the risk of bogging down in long lists of ecological indicators, and indicators or processes for one river segment may be different than indicators for a downstream segment.

An evaluation of historical hydrology and habitat conditions can provide a useful reference point for identifying ecosystem restoration goals, but it is simply unrealistic to assume that it is possible to restore historic conditions in highly altered systems such as the San Joaquin. Nevertheless, analyses of historical hydrologic data is useful for describing natural patterns and identifying potential links between hydrology and the requirements necessary to maintain species and precipitate key processes.

Historical hydrologic analysis is useful for identifying patterns in the timing, magnitude, duration, and frequency of flows, but it is less useful in developing specific flow prescriptions. Since it is not possible to restore historical flow regimes in the San Joaquin Basin, we are left with the challenge of identifying what elements of the historical hydrograph are most important for achieving restoration objectives. Only by identifying relatively specific objectives, are we able to identify the range of flows necessary to achieve that objective. Thus, we are once again faced with developing flow prescriptions for a set of objectives rather than based simply on historical patterns.

In this chapter, we have reviewed the literature on methods for establishing environmental flows and developed and applied a method for identifying environmental flow regimes. We have adopted a holistic approach for developing an environmental flow regime that integrates both an analysis of historical hydrology along with a more targeted approach that addresses the specific hydrograph components necessary to achieve a limited set of species specific and ecological objectives. To avoid the pitfalls of species specific flow prescriptions, we have also identified the hydrograph components necessary to achieve keystone ecological and geomorphic processes.

9.2 LITERATURE REVIEW OF ENVIRONMENTAL FLOW METHODOLOGIES

Over the past five decades, the development and application of environmental flow methodologies (EFMs) has rapidly progressed, as a means to help sustain or restore natural aquatic functions and ecosystems in the face of increasing demands for limited water resources. EFMs are science-based processes for assessing and/or recommending instream flows for regulated rivers. Their purpose may be as general as maintaining a healthy riverine ecosystem or as specific as enhancing the survival of targeted aquatic species. The growing prominence of EFMs in river management planning reflects a trend towards more sustainable use of the world's freshwater resources and a shift in focus from water quality to water *quantity* as a major factor in the degradation of rivers (O'Keeffe 2000).

In a comprehensive study of environmental flow methodologies, Tharme (2000) documented the existence of more than 200 EFMs, recorded worldwide. These included various modifications and hybrids of some commonly applied methods, site-specific approaches with limited applications, and procedures that are no longer in use. In actuality there are only a few dozen EFMs that are still widely applied. They can be divided into four major categories: 1) hydrological, 2) hydraulic rating, 3) habitat simulation, and 4) holistic methodologies (Tharme 2000). An overview of each of these categories is provided below, along with general strengths, weaknesses, and associated trends. Table 9.1 at the end of this chapter describes the principal EFMs within each category.

9.2.1 Hydrological Methodologies

Hydrological methodologies make up the largest proportion (30%) of environmental flow methodologies developed (Tharme, 2000). Hydrological methods are usually simple office procedures that recommend a proportion of a river's historical unregulated or naturalized flow regime as the minimum flow to maintain a fishery or other aquatic features. Recommended flows may be given on a monthly, seasonal, or annual basis. For example, the Tennant (Montana) method suggests 20% of mean annual flow (MAF) during the wet season and 40% MAF during the dry season to maintain "good" river conditions (Tennant 1976; Table 9.1). Because of their simplicity and low resolution, Tennant and other hydrological methods are most appropriate for early reconnaissance-level project planning, to provide relatively quick and inexpensive estimates of flows to allocate for environmental purposes. Although biological factors are not explicitly considered in these methods, most were developed with some general biological basis (Caissie and El-Jabi 1995). In addition, hydrological methods assume that a minimum flow within the historic flow range for a river will sustain some proportion of native aquatic biota because the species survived such conditions in the past (Jowett 1997).

Hydrological methods have the primary advantages of being simple, straightforward, and relatively inexpensive to apply. Most require only historical flow records for a site, with little or no additional fieldwork. The simplicity of these methods, however, is also their greatest weakness. Because they do not incorporate site-specific habitat data, their ecological validity is often questionable (King et al. 2000). For example, these methods are frequently applied without regard to artificial changes in channel conditions (due to flow regulation or man-made structures) that may influence the ecological impact of recommended flows. EFMs in this category also should not be applied to river systems that do not approximate in size and type the reference river systems on which they were developed. Many hydrological methods do not address ecologically important intra- and inter annual variations in flows (but see Range of Variability Approach, Table 9.1). And unlike other methods, hydrologically based EFMs usually cannot be used to compare alternative flow regimes. Finally, for some river systems it may be difficult to obtain the unregulated or naturalized flow data necessary to calculate recommended flows.

Despite their many limitations, Tharme (2000) suggested that hydrological methods will continue to be the EFMs of choice for the foreseeable future. However, we can expect to see progress in their development towards more ecologically defensible and sophisticated methodologies. The Range of Variability Approach (RVA) is one such recently developed EFM that is considered to represent a significant advance over earlier hydrological methods. Unlike other EFMs in its category, the RVA captures the complex intra- and interannual variability of natural flow regimes over multiple temporal scales, incorporates a large number of ecologically based hydrologic indices in its analysis, and utilizes an adaptive management program for monitoring and refinement (Richter et al. 1996, 1997; Table 9.1). Since its inception, the RVA has attracted considerable interest among river scientists and managers as a new class of ecologically grounded hydrologically based environmental flow methodologies (King et al. 2000).

9.2.2 Hydraulic Rating Methodologies

Hydraulic rating methodologies comprise 11% of the global total of EFMs. They differ from purely hydrology-based methods in that they incorporate site-specific information on hydraulic parameters, such as wetted perimeter or maximum depth, as measured across riffles or other limiting river cross sections. These parameters are used as surrogates for the habitat available for target biota such as fish or macroinvertebrate communities. Hydraulic rating methods assess changes in the habitat surrogates in response to changes in discharge. Recommended flows are commonly set at a breakpoint in the parameter-discharge curve, interpreted as the flow below which habitat decreases rapidly with a decrease in flow and above which habitat increases slowly with an increase in flow (Loar et al. 1986).

Although they require some fieldwork and data analysis, hydraulic rating methods enable a relatively quick and simple assessment of flows for maintaining habitat of target biota. They are considered more advanced and biologically relevant than hydrological methods. Their inclusion of site-specific field measurements better adapts them to different river systems. Hydraulic rating methods, however, are based on a number of simplistic assumptions that often cannot be verified. Key among these is that the chosen hydraulic variable(s) can be used to determine the flow requirements of the target species. In addition, the validity of results is highly dependent on appropriate sampling of critical river cross sections and proper identification of a breakpoint in the parameter-discharge curve. The latter is frequently complicated by the existence of multiple breakpoints or the lack of any defined breakpoint in the curve. And like most hydrological methods, EFMs in this category generally do not address ecologically important intra- and inter annual variations in flows.

In the past decade there have been few advances in the development or application of hydraulic rating methodologies. Instead, this category of EFMs seems to have been superceded by the more advanced habitat simulation methodologies for which they are precursors. The Wetted Perimeter Approach, the best-known EFM in this category, is still widely applied in North America and globally (Reiser 1989, King et al. 2000). However, it is likely that many other hydraulic rating methods will gradually fall into obsolescence as the science of EFMs advances in alternate directions (Tharme (2000).

9.2.3. Habitat Simulation Methodologies

Habitat simulation methodologies (28%) rank second only to hydrological methods in proportion of total EFMs. This group of flow methodologies includes the U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology (IFIM), which is the most widely used EFM in North America and the world (Reiser 1989, Tharme(2000). IFIM and many other habitat simulation methods comprise systems of highly sophisticated computer modeling techniques that integrate site-specific hydraulic and hydrologic data with species specific habitat preference data (in the form of habitat suitability curves). Computer outputs are usually in the form of habitat usability-flow discharge curves for the various factors of interest, e.g., different life stages of one or two fish species.

Practitioners evaluate these curves and determine flow regimes based on the levels of protection (habitat usability) desired for each factor of interest. Because there is considerable potential for conflicting habitat requirements in this final step, it is necessary to have clear management objectives and a good understanding of the stream ecosystem when using IFIM and other habitat simulation methods to develop flow regimes.

Habitat simulation methods are flexible and adaptable. They incorporate site-specific and species specific information, so can be tailored for particular conditions and management goals. They can be used to analyze flow-related trade offs among multiple species and life stages. They may be modified to recommend flows for riparian vegetation, sediment flushing, recreation, and any number of other instream purposes. They are capable of addressing ecologically important intra- and inter annual variations in flows for target species. Habitat simulation methods are also often perceived as scientifically objective and legally defensible; thus, they may be suitable for allocating instream flows in highly controversial situations (Estes 1996).

The focus of habitat simulation methods on specific target species and/or instream uses raises the risk that other essential components of the stream ecosystem may be overlooked (Prewitt & Carlson 1980). On the other hand, when these methods are used to address multiple management objectives for a river system, there are no set procedures for resolving conflicting flow requirements. The flexibility that habitat simulation methods provide make them among the most difficult EFMs to apply and interpret. Another important consideration, especially for developing countries, is that habitat simulation methods are often time-consuming, costly, and require considerable technical and scientific expertise for proper application. Modeling applications can be run without sufficient understanding of input and output processes; therefore, there is high potential for misuse by improperly trained persons. Other important sources of error or bias for modeling outputs include selection of representative cross sections for collecting hydraulic data, and construction of species-specific habitat suitability curves. Finally, a commonly cited criticism of PHABSIM, the modeling system used with IFIM, is the seeming lack of relation between fish and habitat usability estimates produced by the models (Orth and Maughan 1982).

Habitat simulation models, though the subject of much criticism, are still highly regarded by many river scientists . Current trends in their development are more advanced modeling techniques, multi-dimensional graphics, and integration of GIS display platforms.

9.2.4. Holistic Methodologies

These methods are relatively new to the science of environmental flow management. They were first documented by Tharme (1996) and currently make up 7.7% of total EFMs (Tharme(2002). Holistic approaches rely largely on multidisciplinary expert panels to recommend instream flows (Tharme 2000). They represent a significant departure from earlier environmental flow methods, in that their recommendations are almost wholly subjective. However, more advanced holistic methods, such as the Building Block Methodology (BBM), may utilize several of the analytical tools described for other EFMs to assist in the decision-making process (Tharme 2000; Table 9.1). An early step in the BBM and some other holistic methods is identification of the magnitude, timing, duration, and frequency of important flow events for various ecosystem components and functions. The decision-making process for integrating these flow events may include a number of activities, including workshops, site visits, and limited data collection and analysis. The final output of the consensus process is a recommended flow regime to meet various specific management objectives.

Most holistic methods are relatively quick and inexpensive to apply. They have limited requirements for technical expertise and hydrologic data. And with appropriate interdisciplinary representation, these methods can comprehensively address all major components of the riverine ecosystem, including geomorphological, riparian, biological, water quality, social and other elements. Holistic methods can recommend flows at a variety of temporal scales. They are site-specific and allow for assessment of whole stretches of river rather than extrapolation from sample cross sections. The major weakness of holistic methods is the subjectivity of their approach, which may open their findings to controversy and criticism.

Holistic methods are still very much in the infancy of their development. Most of these methods have their roots in South Africa and Australia. Few have been applied outside of these countries of origin. Application of holistic methods for environmental flow management is expected to grow rapidly over the next decade, as EFMs become better established as river management tools in developing countries. Holistic methods are well suited for use in these countries, where data, finances, and technical expertise are frequently limited.

9.3 METHOD FOR DEVELOPING ENVIRONMENTAL FLOW REQUIREMENTS FOR THE SAN JOAQUIN BASIN RIVERS

We have employed a version of the holistic approach practiced in South Africa and Australia (King et. al. 2000) to identify an environmental flow regime for the San Joaquin Basin rivers. This approach relies heavily on hydrological evaluations, previous studies, and expert opinion to estimate environmental flow requirements and develop a long-term adaptive management plan for implementing and refining an environmental flow regime over time. The results of the holistic approach provide a framework for increasing knowledge regarding the relationship between flow and environmental objectives and refining water management practices over time. The output of the holistic method envisioned here provides not only an estimate of environmental flow requirements, but more importantly, an explicit identification of key assumptions and uncertainties that need to be tested overtime to more accurately describe the flow requirements necessary to achieve environmental objectives.

We made two important assumptions in generally applying this method to all four of the major rivers of the San Joaquin Basin.

- Similarities in both the restoration objectives and the hydrologic, geomorphic, and ecological conditions on the Stanislaus, Tuolumne, Merced, and San Joaquin will result in relatively similar prescriptions for environmental management flows. We believe this assumption is well supported by the environmental conditions, historical alteration, and data described in earlier chapters of this report. Despite these similarities, there are some important differences. The Stanislaus and San Joaquin are lower gradient streams than the Merced and Tuolumne. Additionally, the Merced and San Joaquin are considerably farther from the Delta, requiring anadromous fish to make longer migrations.

- The ongoing restoration programs including the CALFED and AFRP actions will invest heavily in these non-flow actions that will affect the environmental flow requirements of the San Joaquin Basin rivers. The flow necessary to achieve restoration objectives may vary greatly depending on non-flow restoration actions such as improving spawning habitat, reconstructing degraded channel, removing levees to restore floodplain habitat, modifying and screening water diversions, reducing polluted run-off, managing ocean harvest, and other factors. In general, non-flow restoration actions will reduce the amount of water necessary to achieve restoration objectives.

The holistic approach applied in this study consists of the following 6-step process to identify an environmental flow regime:

1. Identify specific environmental objectives (i.e,. target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).
2. Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes.
3. Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.
4. Identify obvious gaps between objective flow requirements and existing flows.
5. Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic patterns, and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives.
6. Design an adaptive management program to further test and refine environmental flows.

1) Identify specific environmental objectives (i.e,. target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).
Well-articulated target ecological conditions and desired species and communities are necessary for establishing environmental flows. Despite the correctly vogue concept of restoring ecosystem processes and avoiding species specific approaches, there is no getting around the fact that key species need specific hydrologic conditions at specific times. This analysis will include both aquatic and riparian communities and the flow parameters necessary to sustain these communities such as floodplain inundation, appropriate water temperature, or creation of structural habitat through geomorphic processes. These specific environmental objectives may vary by region, sub-basin, and reach of the river.

2) Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes.
An environmental flow regime encompasses the adequate timing, magnitude, duration, and frequency of flows necessary to support target species and facilitate specific ecological processes encompassed in the stated environmental objectives. Where we understand the life cycle timing of various target species, it is relatively easy to identify the approximate timing and duration of flows necessary to support different life stages of target species. Estimating the required flow magnitude is far more difficult but can be informed by field data, results of numerical models, and general relationships described in the literature. Most short lived target species require adequate flows each year to reproduce, while longer lived species can sustain their populations with a lower frequency of flow conditions conducive to reproduction. For example, riparian forest species may only require recruitment flows every five to ten years to establish new seedlings.

Estimating the magnitude of flows necessary to support or optimize conditions for target species and processes is by far the most difficult element of the environmental hydrograph to approximate. Environmental engineers and biologists have developed relatively elaborate methods for determining ideal flow regimes such as physical habitat simulation (PHABSIM) and Instream Incremental Flow Methodology (IFIM) to identify optimum flow magnitudes based on known habitat preferences of target species, measured habitat conditions (velocity and depth) at various flows, and numerical models that predict habitat conditions at a range of flows. Numerical models that describe the width, depth, and velocity of the rivers at various discharges are useful for predicting river stage and temperature at various locations, factors that are important considerations for habitat or facilitating geomorphic and hydrologic processes. As discussed above, these models tend to focus on the needs of specific species and can sometimes produce results that are inconsistent with both holistic ecological process restoration and common sense. Furthermore, these models are often not calibrated, particularly at higher flows relevant to riparian recruitment, geomorphic processes, and spring outmigration temperatures. Nevertheless, we utilized the results of these models as a guide combined with other information to develop our environmental flow management hypothesis.

Where possible, we relied on actual data and measurements to estimate the flows necessary to achieve suitable conditions to support biological, riparian, and geomorphic objectives for temperature, floodplain inundation, and bed mobilization. In particular, we relied on USGS temperature gauges on all rivers and at Vernalis to characterize the relationship between temperature and flow. Similarly, we relied on previous studies of the rivers to characterize flows necessary to mobilize bed material and inundate the floodplain.

3) Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.

Analyses of historical hydrologic data is useful for describing natural patterns and identifying potential links between hydrology and the requirements necessary to maintain species and precipitate key processes. An analysis of historical patterns can provide clues about the timing, magnitude, duration, and frequency of flows under which target species have evolved. Identification of major changes between historical and hydrologic patterns combined with the life history requirements of various species can help generate hypotheses about how flow regulation may be limiting target species. We will use the Index of Hydrologic Alteration approach (Richter et al. 1996) and the Hydrograph Component Analysis (HCA) (Trush et al. 2000) to evaluate changes in flow patterns. The IHA provides a quick statistical overview of how several important hydrologic attributes have changed. The Hydrograph Component Analysis (HCA) method developed by McBain and Trush provides a detailed graphical analysis of historical and existing hydrologic conditions. While valid and useful, the statistical analysis in the IHA method is not a substitute for visually comparing and evaluating key components of the pre- and post-dam hydrographs. Similarly, visual comparisons of pre- and post-alteration hydrographs don't always reveal important changes identified by the IHA method.

4) Identify obvious gaps between objective flow requirements and existing flows.

An analysis of historical flow patterns combined with an approximation of the TMDF of flows necessary to achieve objectives compared with the regulated flow regime can help illustrate obvious gaps between regulated flows and flows that may be necessary to achieve environmental objectives. We will plot TMDF flow requirements developed in Step 2 as an annual hydrograph and compare it with average regulated and historical conditions.

5) Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic patterns, and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives. This project identifies hypothetical restoration flow regimes but recognizes that the most reliable method for developing a restoration flow regime is through a long-term adaptive management program including a series of trials that test the effectiveness of various flow prescriptions. The purpose of developing the hypothetical flow regime is to develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the rivers of the San

Joaquin Basin. The assumptions and uncertainties associated with the hypothetical flow regime are as important as the flow regime itself.

6) Design an adaptive management program to further test and refine environmental flows. To cost effectively achieve restoration, managers will ultimately need to test these assumptions and limit the uncertainties through an adaptive management program consisting of a combination of numerical modeling, pilot flow studies, model calibration, and long-term restoration implementation.

9.4 APPLICATION OF HOLISTIC ENVIRONMENTAL FLOW METHOD

9.4.1 Identify Specific Environmental Objectives

The geomorphic, riparian, and salmonid objectives considered in this report are described in greater detail in Chapters 2 and 3 and summarized below:

- Sediment Transport: bed mobilization and bed scour
- Channel Migration
- Floodplain Processes: inundation and fine sediment deposition

Riparian Vegetation

- Fremont cottonwood seedbed preparation
- Fremont cottonwood seed germination
- Fremont cottonwood seedling growth
- Periodic large-scale disturbance of the riparian zone
- Riparian stand structure and diversity

Salmonids

- Chinnook salmon: suitable flow conditions and temperatures for all life stages.
- Steelhead: suitable flow conditions and temperatures for all life stages.

We purposely did not identify population targets for salmonids. The extent and magnitude of restoration actions depends on the size of the population of fish managers are attempting to restore. More fish requires more habitat particularly for spawning and rearing. Creating more habitat may require both physical changes in channel conditions and increases of instream flows. We assumed that spawning and rearing flow levels consistent with or higher than existing base flows during years of good production would yield reasonable escapement levels on all four rivers.

9.4.2 Approximate the Timing, Magnitude, Frequency, and Duration of Flows Necessary to Achieve Objectives

Geomorphic Flow Objectives

Estimating the flows necessary to perform geomorphic processes is difficult, and thus our estimates are coarse approximations for the purpose of evaluating the potential to reoperate the reservoir to achieve these objectives. Human modifications of the channels from their natural state have changed the relationship between flows and geomorphic processes and have therefore complicated the already difficult task of determining the flows necessary for precipitating various geomorphic processes. Gravel and channel restoration projects that are currently planned to change the particle size of gravels and the channel dimensions will further change the relationship between flow and geomorphic processes. Therefore, it is not possible to estimate future flow levels necessary to initiate geomorphic processes, but for the purposes of this study, a rough estimate will be sufficient to evaluate the feasibility of reoperating reservoir releases for the purpose of achieving geomorphic objectives.

There is relatively little information regarding the flows necessary to perform various geomorphic objectives. Geomorphic processes associated with these objectives occur at very high flows, when field measurement is difficult. Hydraulic models that have been developed for all the tributaries provide insight into the flows necessary to mobilize the bed and inundate the floodplain, but in many cases these models have not been adequately calibrated at high flows or do not accurately describe the actual hydraulics at specific cross sections. Empirical observations are generally more reliable, but are often limited to specific study sites. In this study, we have relied on previously reported field measurements, modeling analysis, and general principles from the literature to roughly estimate the magnitude of flows necessary to initiate geomorphic processes.

Geomorphic processes are generally initiated at threshold levels. Bed mobilization and floodplain inundation do not occur until flows reach a threshold level sufficient to flow overbank or create sheer stresses necessary to mobilize gravel. Research from several gravel bedded river systems indicates that a flow with a natural (unregulated) recurrence interval of every 1.5 years is generally needed to mobilize the bed and initiate overbank flows (Leopold et al. 1964). No amount of flows less than the threshold will initiate bed mobilization or floodplain inundation without significant channel modification (i.e., adding smaller gravel or regrading the channel to a smaller size). Similarly, flows that achieve the minimum threshold necessary to mobilize the gravels are generally not adequate to precipitate channel migration.

The threshold flows necessary to initiate geomorphic processes naturally vary from reach to reach depending on channel dimensions, slope, and the size of bed material. In general, sand bedded reaches mobilize at lower flows than gravel bedded reaches with larger particle sizes. Similarly, low gradient reaches flood at lower discharges than steeper reaches, particularly where large woody debris is allowed to accumulate. In this study, we have focused on the flows necessary to mobilize the gravel bedded reaches, because they are more relevant to salmon restoration and because they will also result in mobilization of the sand bedded reaches.

Human perturbations to the channel such as levee construction and gravel mining have altered channel dimensions and therefore probably altered the magnitude of flow necessary to achieve geomorphic objectives. In many cases these channel alterations are local, resulting in a large variability of channel dimension conditions and associated threshold flows necessary to achieve geomorphic objectives among sites. Perturbations such as gravel mining and reduced sediment inflow have caused widespread incision below dams in the San Joaquin Basin rivers. Incision lowers the elevation of the bed relative to the historic floodplain, increasing the discharge necessary to restore the historic floodplain. Incision generally increases the sheer stresses imposed on the channel at a given discharge, increasing the chance of bed mobilization at lower discharges. However, incision accompanied by armoring of the channel with large bed material may reduce the chance of bed mobilization because the larger particles require a greater sheer stress to initiate mobilization.

Sediment Transport: Bed Mobilization, Scour and Channel Migration. For this study, we attempted to estimate the flows necessary to mobilize and scour the bed. Bed mobility and bed scour are two different processes that occur at different flow thresholds. We use the term bed mobility to refer to mobilization of the surface of the channel bed. Bed scour is the process of scouring the bed deeper than its coarse surface layer. Under natural conditions the gravel bedded reaches of the San Joaquin River were theoretically mobilized by peak flows exceeding the 1.5 year recurrence interval of the annual instantaneous peak. Although less is known about the bed scour process, flows exceeding the natural 5–10 year recurrence interval are probably necessary to precipitate bed scour (Trush et al. 2000). There is some information on flows required to initiate bed mobilization, but due to the lack of information on bed scour our estimates of flows necessary for bed scour are relatively speculative.

There are varying degrees of bed mobilization, further complicating the definition of mobility and its distinction with bed scour. Incipient bed mobility is the threshold at which bed material begins to mobilize and occurs when the ratio of the critical sheer stress to the D_{50} equals 1. Incipient mobility can cause small movement of gravel across the top of the riffle without general mobilization of the riffle surface. Relatively frequent (every 1–2 years) incipient motion of gravels on a riffle may be adequate for certain objectives such as flushing fines from the gravels, but is probably not sufficient for certain geomorphic objectives such as restoring sediment transport or maintaining a dynamic, alternating bar sequence (Trush et al. 2000). General bed mobility mobilizes the entire riffle surface and occurs when the ratio of critical sheer stress to particle size D_{50} exceeds 1.3. General bed mobility may be necessary for restoring basic alluvial functions such as transporting coarse sediment from one riffle to the next.

Due to channel incision, interruption of the upstream gravel supply from upstream dams, and associated channel armoring, the 1.5-year recurrence interval may not accurately reflect the flows necessary to mobilize bed material under existing conditions. A limited number of field measurements and modeling analyses during the last decade provide information on the flows necessary to widely mobilize gravels on riffles under existing conditions. Table 9.2 tabulates the results of these measurements and analyses in comparison to the pre-dam 1.5 and 5-year recurrence intervals.

Table 9.2. Bed Mobility Estimates Relative to 1.5 and 5-Year Recurrence Intervals

	Pre-Dam Q 1.5	Pre-Dam Q 5	Field studies	Modeling Analyses
San Joaquin	8,650	25,063	12,000	> 12,000
Merced	10,060	24,000	3,200	4,800 - 5,500
Tuolumne	8,670	25,230	>6,880	7,000 - 9,000
Stanislaus	5,350	19,130		5,000 - 8,000

Gravel tracer studies were conducted by various groups on the Tuolumne, Merced, and San Joaquin, but gravel movement was only measured on the Merced and San Joaquin. On the Tuolumne, McBain and Trush set up a gravel tracer study at over a half dozen cross sections across riffles in water year 1995–96, but they did not observe movement of the tracer rocks at discharges up to the peak of 6,880 cfs. On the basis of subsequent modeling analysis, McBain and Trush estimated that the threshold of incipient gravel mobilization of the D_{84} at these riffles would occur at 7,000–8,000 cfs, but noted that these flows would not cause wholesale bed scour.

Stillwater Sciences conducted gravel tracer studies at several cross sections in two different representative reaches of the Merced River, the Shaffer Bridge reach and the Snelling reach below the Crocker-Huffman Diversion Dam. A peak flow of 3,250 cfs mobilized tracer rocks at all of the transects in the Shaffer Bridge reach, but the peak flow of 1,345 did not mobilize tracer rocks at the Snelling cross sections. Modeling analysis predicted incipient mobilization for the Shafer and Snelling cross sections at 4,800 and 5,500 cfs respectively. Stillwater suggested that the tracer rock study might have underestimated the flows necessary to mobilize the bed since the tracer rocks sat on top of the bed and protruded into the flow.

Cain conducted a gravel tracer study in water year 1994-95 on the San Joaquin on a bar 1.5 miles below Friant Dam on the San Joaquin River. The gravels, which had a large D_{84} of between 100 and 150 mm, did not move at discharges of 8,000 cfs during March of 1995, but over 70% of them moved after flows of 12,000 cfs later in the spring. Subsequent modeling analysis (JSA 2002, Stillwater 2003) evaluated flows necessary for incipient motion and general bed mobility at over a dozen riffles in the gravel bedded reach below Friant Dam. They predicted that flows of 8,000 cfs would trigger incipient motion of D_{50} on some riffles including a few near Cain's study site 1.5 miles below Friant Dam, but their overall modeling analysis indicated that flows of more than 16,000 cfs may be necessary to cause general bed mobility and scour in the gravel bedded reach below Friant Dam (Figure 9.1).

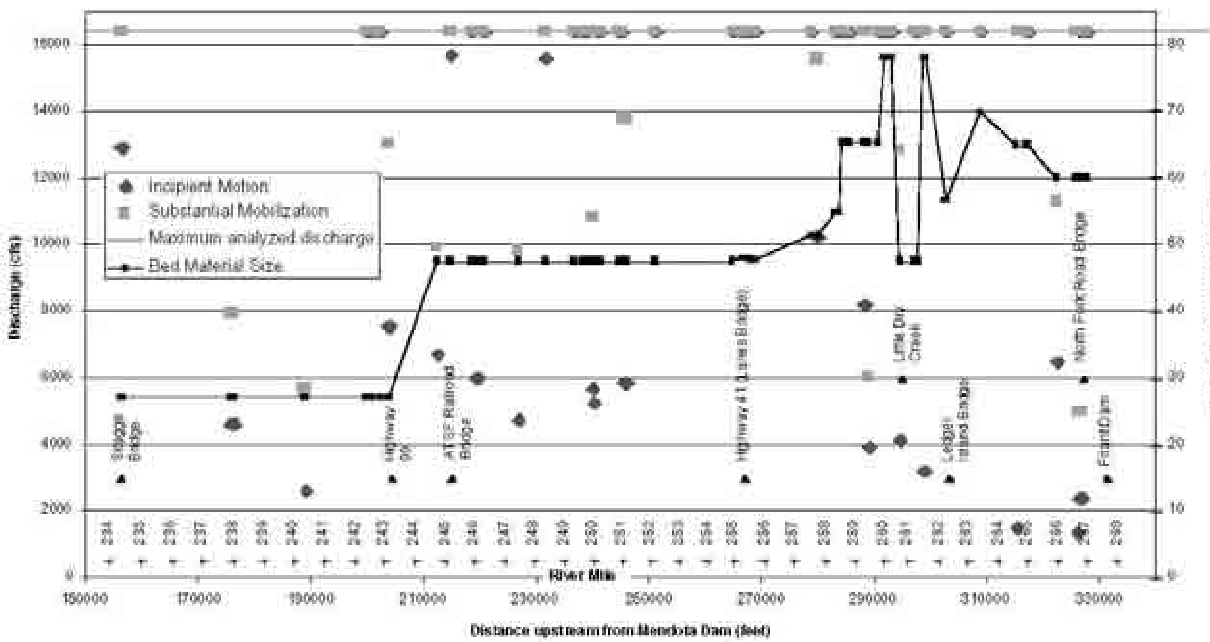


Figure 9.1. Modeling Results from Jones & Stokes/Musseter. Discharge required for initiation of motion (π*'=1.0) and substantial bed-material transport (π*'=1.3) in Reach 1*(From McBain and Trush, 2002).* Also shown is the existing median bed-material size that was used in the computations at each riffle.

Floodplain Inundation

This analysis evaluates the flows necessary to inundate the modern floodplain surface, not the historic floodplain. The flows necessary to currently inundate the historic floodplains are considerably more than the flows that historically inundated the floodplain before the dams, due to the significant channel incision that has occurred on all of the San Joaquin Basin rivers since construction of the dams. Figure 9.2 depicts the changes in a representative cross section and illustrates how the relationship to the channel and floodplain have changed as a result of incision. Due to the combination channel incision and flow regulation, the historic floodplain is currently a terrace that is only inundated, if at all, in the largest flood events. Even in the absence of flow regulation, the historic floodplain would be inundated far less frequently than historically due to channel incision. Due to incision much of the historic gravel bar formations that were once part of the channel now function as a new floodplain that is only inundated periodically. This analysis evaluates the flows necessary to inundate this new floodplain surface.

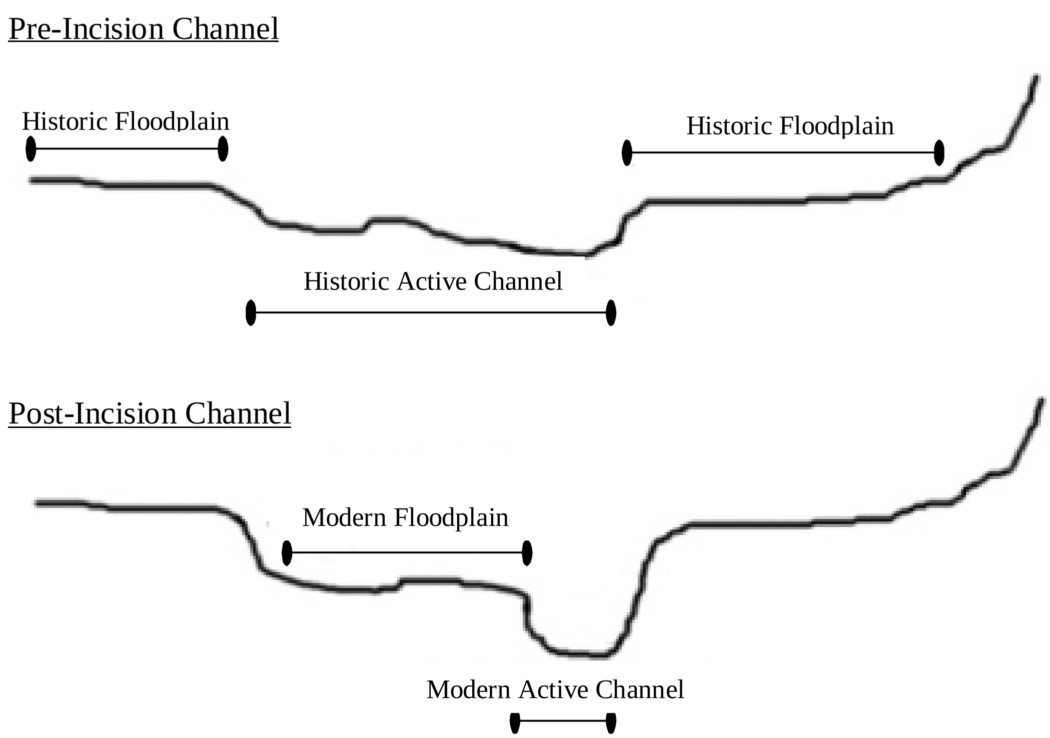


Figure 9.2. Changes in a Representative Channel Cross Section as a Result of Incision.

Flows necessary to inundate the floodplain vary from reach to reach. Hypothetically, relatively little area beyond the channel is inundated until the river discharge exceeds bank capacity and then large areas of floodplain become inundated as depicted in curve A in figure 9.3. In reality, different floodplain surfaces and back bar channels become inundated at different flow thresholds, and flows that don't inundate the floodplain in steeper reaches are more than sufficient to inundate floodplains in lower reaches. For this analysis, we estimated the flows necessary to inundate low floodplains in the steeper upper reaches on the assumption that they would be sufficient to also inundate large areas of floodplain surfaces in the lower gradient reaches.

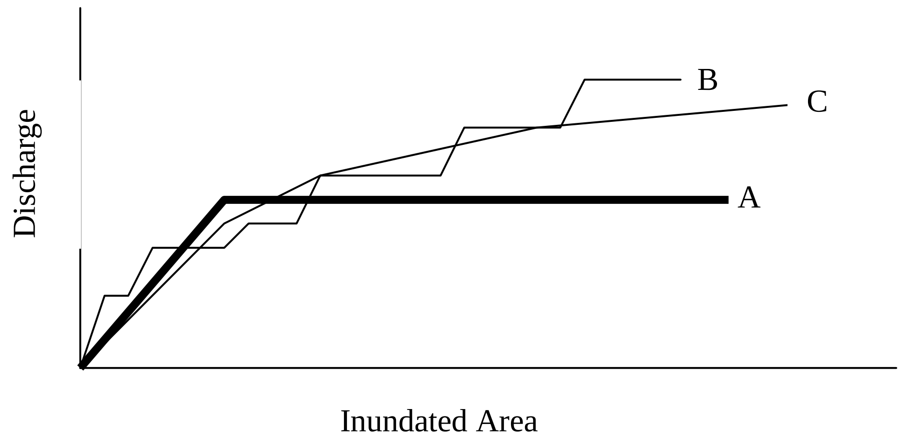


Figure 9.3. Alternative models for the relationship between flow and inundated area.

Different floodplain surfaces and backwater channels become inundated at different flows even within a given reach, particularly on geomorphically altered systems like the San Joaquin and its tributaries as depicted in curve B figure 9.3. Under the classic floodplain inundation model illustrated with curve A, the area of floodplain inundation is small until flows exceed bankfull capacity when the area of inundated floodplain rises sharply across an entire reach. In reality, however, the area of inundated floodplain across several reaches may increase linearly with flow because of the diversity of surfaces inundated at different flows as illustrated with curve C. The variability in floodplain elevations and threshold flows necessary to inundate these various floodplain surfaces in a given reach and across reaches makes it difficult to target a single flow that precipitates widespread floodplain inundation. For the purposes of this study, however, we have identified a single floodplain inundation flow for each river based on measurements and analysis of present channel capacity in the steeper, less flood prone reaches.

Some data is available to determine the flows necessary to inundate the low floodplain areas in the steeper spawning reaches. Field surveys conducted by NHI staff on an alluvial bar 1.5 miles below Friant Dam indicate that the low floodplain (historic bar surface) becomes inundated at flows between 4,000 and 4,500 cfs. This is consistent with observations of the operators at Friant Dam who report that they begin to receive complaints about flooding from downstream landowners when releases exceed 4,000 cfs (Duncan, pers. com., 1998). These observations are also consistent with riparian area inundation analysis conducted by Jones and Stokes (2002) and Stillwater Sciences (2003) that found that area of inundation began to level out in the spawning reach of the San Joaquin at flows of between 4,000 and 5,000 cfs.

On the Merced River, Stillwater (2002) measured and modeled flows necessary to inundate the floodplain in two representative reaches, Snelling and Shaffer Bridge. At the Snelling site, the floodplain is approximately 7 feet above the channel bed and is inundated at flows exceeding 3,055 cfs. At the Shaffer Bridge site, the floodplain is 6–

7.5 feet above the channel bed and is inundated at flows exceeding 3,330 cfs. On the Stanislaus, an analysis of the stage-discharge relationship at two cross sections, Lover's Leap and Russian Rapids, estimated that the incised channel inundates the new floodplain at flows of 2,450 and 3,500 cfs respectively (Kondolf et al. 2002). A study of riparian vegetation relationships and flood inundation on the Tuolumne River (TRTAC 2000) concluded that extensive channel disturbance and low sediment supply have prevented any distinct post-dam floodplains from forming, making it difficult to identify a floodplain inundation flow. NHI's analysis of several cross sections in the TAC report indicate that low floodplain inundation occurs at several cross sections between flows of 3,000 and 6,500 cfs. The TAC report recommended that channel restoration projects reconstruct floodplains and terraces at an elevation exceeding 4,000–6,000 cfs, but several channel reconstruction projects currently under design or implementation have proposed grading floodplain surfaces at elevations inundated by flows exceeding 2,600 cfs, the post-dam 1.5 annual peak flow.

Riparian Vegetation Recruitment Flows

As described in detail in the cottonwood riparian conceptual model section of Chapter 3, successful recruitment and maintenance of cottonwoods requires several actions including preparation of a relatively barren mineral soil seedbed, a recruitment flow at a relatively high river stage during the germination period to avoid scour and inundation during subsequent high flow events in their first two years of growth, a gradually receding hydrograph after germination to allow root growth to keep pace with the declining water table, and adequate base flows to provide moisture during early growth and mature life stages.

Preventing or limiting riparian encroachment of riparian vegetation on the low flow channel edge is also important for maintaining conditions suitable for cottonwoods and maintaining riparian stand structure and diversity. Reductions in spring and early summer flows on regulated rivers, in the San Joaquin Basin and elsewhere, has resulted in encroachment of riparian vegetation on the low flow channel. On the middle San Joaquin River, reductions in peak flow combined with static summer base flows have resulted in colonization of the low flow channel edge by alders and button willow, limiting the potential for recruitment of shade intolerant cottonwoods (Cain 1997). Moreover, encroachment of riparian vegetation may increase channel incision (Tsujimoto,1999) and reduce the availability of spawning gravels by reducing recruitment of gravels underlying the vegetation.

The first step in developing flow targets for cottonwood regeneration is determining the timing of cottonwood seed release. We assumed that maximum number of viable cottonwood seeds would be available between April 15 and May 15 and therefore targeted the timing of the cottonwood establishment flow for this window. This assumption is supported by the results of previous studies on the San Joaquin (Stillwater Objectives report—McBain and Trush 2002, and DeFlitch and Cain 2002). Germination and seedling growth conditions for seeds released after this establishment flow window, including those of cottonwoods, black willow, and narrow-leaf willow would still be good due to the gradually declining target hydrograph, but seedlings from these trees would establish on surfaces below the initial establishment flow.

The second step and perhaps the most difficult challenge is determining the magnitude of establishment flows necessary for cottonwood regeneration. The magnitude of these flow targets depends on the elevation of the surface that one is trying to establish cottonwood seedlings upon. If seedbed conditions are suitable, it is possible to establish cottonwoods at any flow, but seedlings established on a low surface are not likely to survive into mature trees because they will be vulnerable to mortality from subsequent inundation and scour by high-flow events. Seedlings established on high surfaces require a higher magnitude establishment flow and are more prone to desiccation during hot summer months when base flows are generally low. Mahoney and Rood (Mahoney and Rood, 1998) estimated that the vertical zone between 5 and 8 feet above the low flow channel is the optimal zone for establishment of cottonwoods to assure adequate moisture and prevent mortality associated with scour and inundation during high flows.

Ideally, it is possible to identify a seedling establishment elevation that optimizes water and recruitment area. In this analysis, we assumed that the optimum cottonwood recruitment elevation occurs at the elevation of the modern floodplain and assumed the floodplain inundation flow targets identified above in the floodplain inundation section. Establishment flows that inundate the floodplain theoretically create a broad area suitable for recruitment both on the floodplain and the upper banks. Establishment flows greater than the floodplain inundation threshold require more scarce water, but do not necessarily create more area suitable for riparian recruitment. Establishment flows below the floodplain elevation only create suitable recruitment conditions in a relatively narrow vertical zone along the bank and thus result in a significantly smaller area suitable for recruitment.

The third step in determining flow targets for cottonwood regeneration is determining a sufficiently gradual recession flow after the seeds have germinated. Based on the literature, the stage of the river should decline at a rate of 2cm /day from the elevation of the germination surface to the elevation of the summer base flow to assure healthy riparian seed growth. We relied on analyses conducted by Jones and Stokes (2002) and Stillwater Sciences (2003) to calculate the flow recession rate that would result in a 2cm/day decline on the middle San Joaquin River. Their analyses utilized the output of a hydrologic model to calculate the stage-discharge relationship at over 1,000 cross sections on the San Joaquin between Friant Dam and the Merced River. Stillwater's analysis indicated that 100 cfs step-down rates yielded the maximum modeled recruitable area. They observed a small decrease in recruitable area as the step-down rate increased to 200 cfs per day and fairly substantial reductions in recruitable area when the step-down rate increased to 500 cfs per day. Jones and Stokes analyses predicted that step-down rates of approximately 150 cfs per day during high flows and 30 cfs per day during low flows resulted in the target stage decline rate of 2 cm per day at nearly all of the 1,000 cross sections. For purposes of this analysis we used the more conservative step-down rates identified by Jones and Stokes.

On the Merced, Tuolumne, and Stanislaus Rivers, we used stage-discharge relationships from USGS gauges to determine the flow recession rates necessary to achieve a stage decline of 2 cm per day. We used data from “Merced below Merced Falls”, “Tuolumne below La Grange”, and “Stanislaus below Orange Blossom” to develop an equation describing the stage-/discharge relationship. Based on this analysis we determined that a step-rate of 130 cfs per day at higher discharges and 40 cfs at lower discharges would achieve the target of less than 2 cm per day decline in stage. This method assumes that using stage tables for a specific location (Merced Falls, La Grange, and Orange Blossom) is appropriate for other reaches of the rivers, specifically where riparian establishment would occur. Although this assumption is not necessarily true, it is supported by the results of the far more detailed analysis for the San Joaquin River described above.

Fall-Run Chinook Salmon Flow Requirements

Fall-Run Chinook Salmon Migration

During the upstream migration period for the fall-run adult salmon, adequate flows are necessary to provide suitable water temperature, depth, and dissolved oxygen conditions. Fall-run Chinook salmon in the San Joaquin Basin migrate upstream starting in late October (Hallock et al, 1970), but the majority of migration occurs from late October to mid-November in the tributaries of the San Joaquin River (Miyamoto and Hartwell 2001, Mesick 2001)

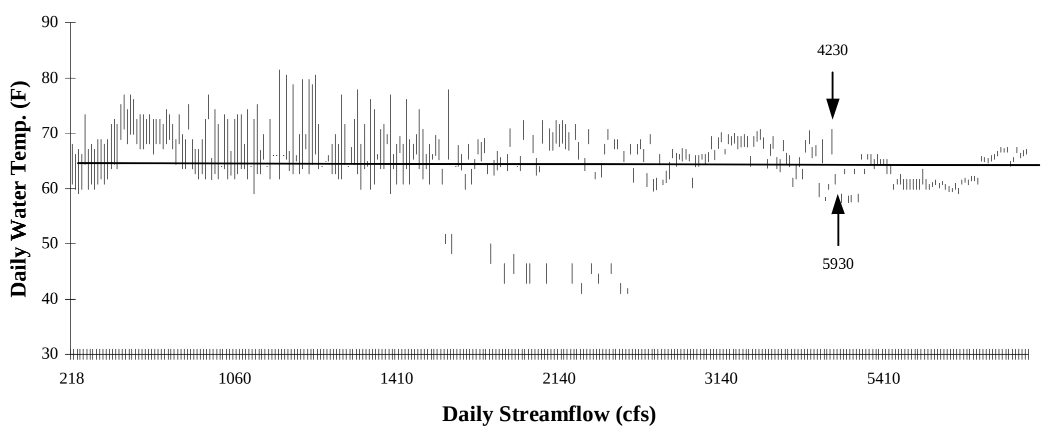


Figure 9.4. Water Temperature vs. Flow at Vernalis, Oct. 1–Oct. 15.

- Numerous studies suggest that water temperatures of greater than 65 degrees impede upstream migration of adult Chinook salmon (Hallock et al. 1970, Macdonald et al. in press, Becker and Fujihara 1978). Under historical conditions, fall-run Chinook salmon may have migrated upstream when monthly temperatures exceeded 70 degrees (Yoshiyama et al. 1996). NHI's analysis of water temperature at Vernalis between October 1 and 15 (Figure 9.4) indicate that water temperatures do not fall below 65 degrees until flows past Vernalis are in excess 4,000-5,000. It may not be economically feasible or cost effective to release such a large volume of water to accommodate fish passage in early October. One option is do manage for a less ambitious water temperature target of 70 degrees which can generally be achieved with half as much water. Another option is to shift the target for the beginning of the migration period until after October 15, when water temperatures are generally far less of a problem due to a decrease in ambient air temperatures.

- Published estimates of depths necessary for passage include a minimum depth of 0.8 feet over at least 25% of the channel (Thompson 1972) to 1 foot over the entire passageway (Evans and Johnston 1980). Without detailed models of stage, discharge, and bathymetry for the reaches that salmon migrate through, it is difficult to predict the exact amount of flow necessary to achieve these conditions. Passage conditions are perhaps most problematic on the middle San Joaquin between Friant Dam and the Merced River. To evaluate flows necessary to provide adequate upstream passage, USFWS (1994) surveyed the river between Friant Dam and Mendota Pool to determine the shallowest cross sections and then measured depths at various discharges at four cross sections between Gravelly Ford and Mendota Pool that represented the worst passage conditions. They concluded that a migration flow of 150 cfs was sufficient to allow passage of adult salmon. Assuming that 80 cfs (Flitch and Cain, 2002) of the flow is lost to seepage between Gravelly Ford and Mendota Pool and 5% of releases from Friant Dam are lost between the Dam and Gravelly Ford due to evaporation, illegal diversion, or percolation (Vorster, pers. com. 1999), a release of 250 cfs would be sufficient to allow passage of salmon between Mendota Pool and Gravelly Ford. Flows in the range of 150 to 200 cfs appear to create adequate depth conditions to allow passage on the tributaries.

- Low dissolved oxygen levels (DO) at the Stockton ship channel below Vernalis may delay upstream migration in October. Hallock and others (1970) showed that radio tagged adult Chinook salmon delayed their migration at Stockton whenever DO levels were less than 5 mg/l in October, but reported that DO levels near Stockton usually increased to suitable levels by November. DO levels could be influenced by temperature, flow, nutrients from agricultural return flows, the presence of a barrier at the head of Old River, and hydraulic conditions at the Stockton ship channel. Messick reported that DO levels in the early and mid-nineties were unsuitably low during early October until higher flows in the range of 3,000 cfs flowed past Vernalis. Due to the number of variables affecting DO, however, it is difficult to determine precisely the flow magnitude necessary to create suitable DO conditions in early to mid-October.

Fall-Run Spawning and Egg Incubation
During the spawning and incubation period of late October to mid-February, flows must be sufficient to provide an adequate area of spawning habitat and assure suitable water temperature, velocity, and depth for spawning and egg incubation.

- High water temperatures are seldom a problem during the cooler months when spawning and incubation occurs, unless low reservoir levels result in warm epilimnetic releases.

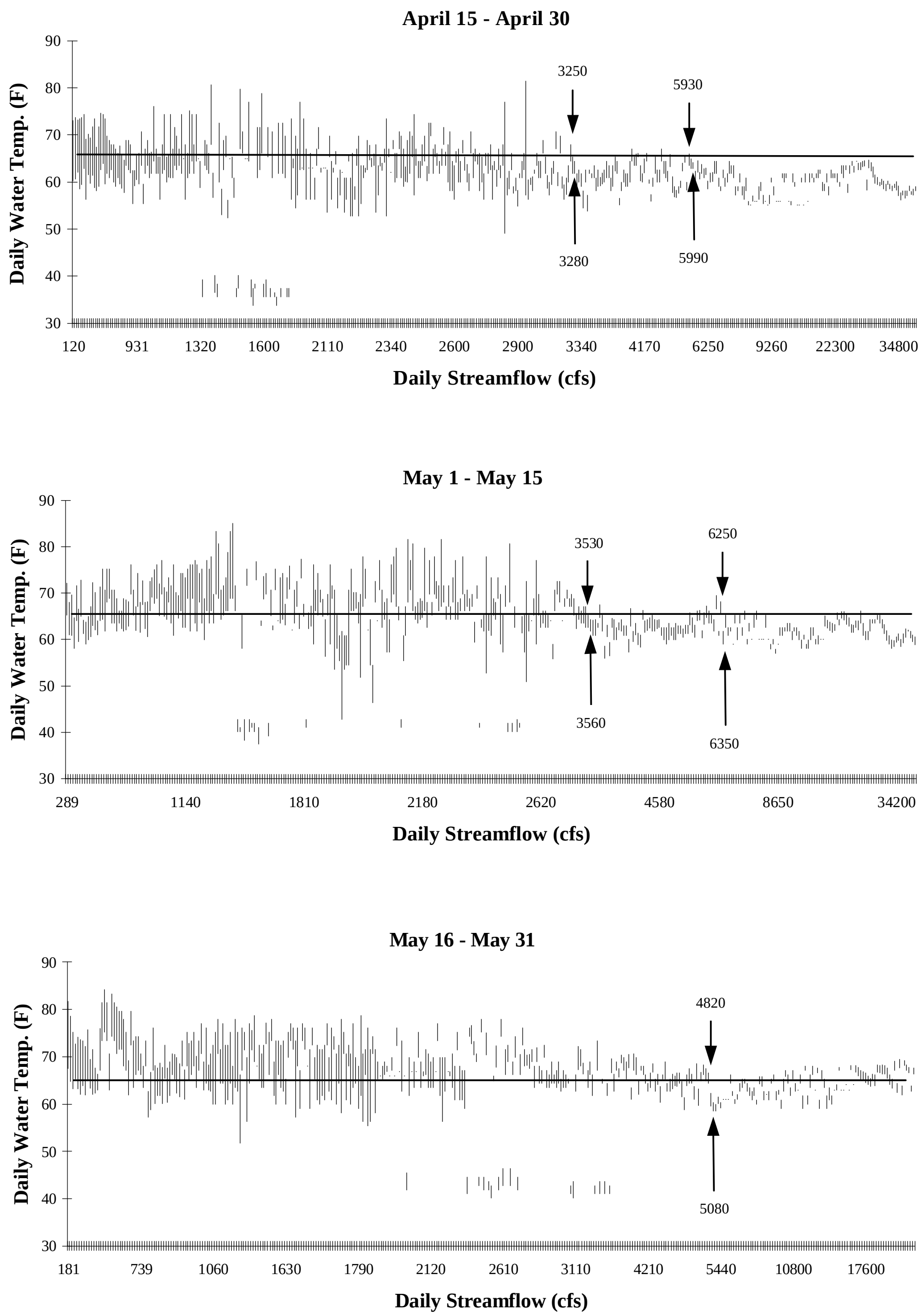


Figure 9.5. Water Temperature vs. Flow at Vernalis, April 15–May 31. The few data points for very high flows between May 16 and May 31 appear to be associated with very wet years when large scale inundation of floodplains and warm water contributions from the James Bypass occur, thus explaining the apparent rise in water temperatures at very high flows.

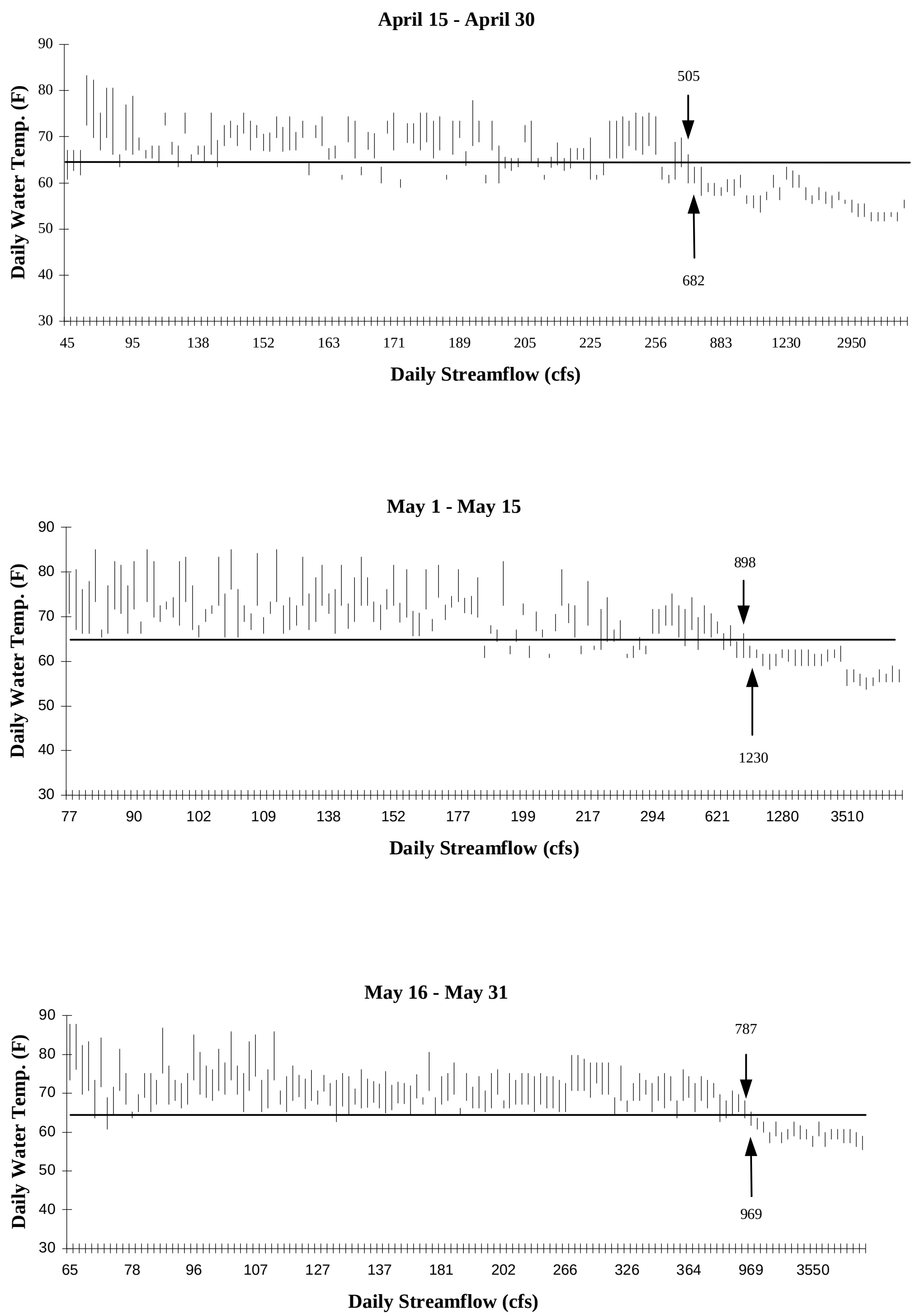


Figure 9.6. Water Temperature vs. Flow on Merced at Stevinson, April 15–May 31. These graphs should be interpreted with caution due to the relatively small number of data points, particularly at high flows.

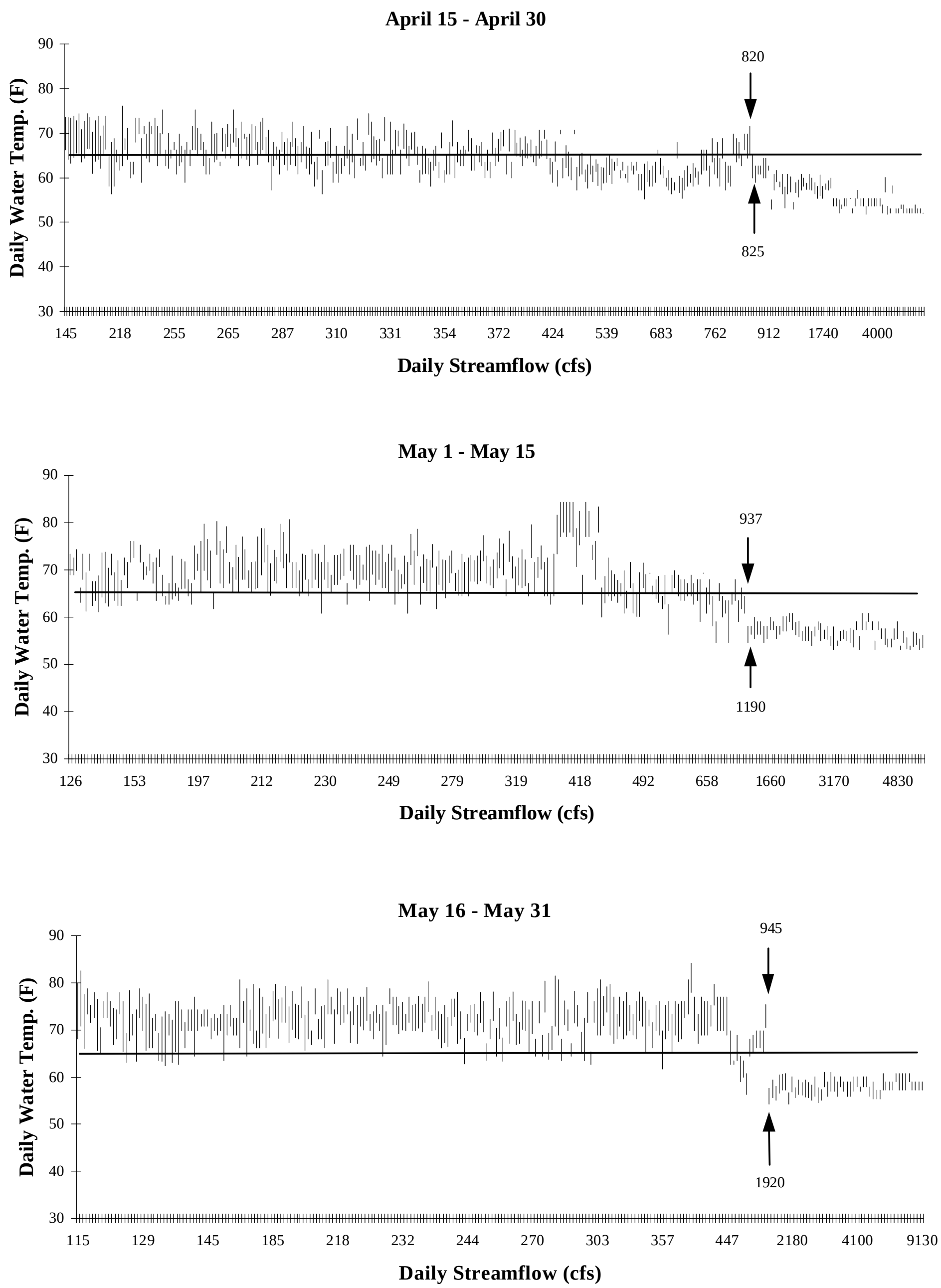


Figure 9.7. Water Temperature vs. Flow on Tuolumne, April 15–May 31.

- The area of spawning habitat is a function of suitable depth, velocities, and spawning gravel availability. IFIM (PHABSIM) studies of the Tuolumne indicate that flows of 200–300 cfs optimize spawning habitat in these rivers (CMARP) but the CMARP paper questioned whether the PHABSIM studies underestimated the amount of suitable habitat for spawning Chinook salmon at higher flows. Spawning surveys (DFG, 1957 unpublished) on the San Joaquin in the 1950's suggest that flows of between 250 and 500 cfs created ample spawning habitat. A recent study on restoration flow requirements for the San Joaquin River estimated that flows of 500 cfs would be adequate during the spawning and incubation period.

Fall-Run Rearing
The quality and quantity of rearing habitat conditions is related to flow. At a minimum, flows similar to the magnitude of spawning and incubation flows are necessary to maintain a wetted channel. Recent research from the Consumnes and Yolo Bypass indicate that salmon rearing and growth are enhanced by inundated floodplain conditions. Inundated floodplain areas apparently increase food supply and provide good depth and water temperatures for rearing salmon. Inundated floodplain areas also appear to provide refuge from predators due to dispersion of juvenile salmon, the presence of vegetative cover, and the lack of predators on ephemerally inundated floodplains. There is some risk, however, that floodplain inundation could strand juvenile salmon on the floodplain when flows recede. Ideally, floodplain inundation for weeks rather than days would provide a longer duration of optimal rearing habitat and reduce the potential for stranding. Shorter term inundation of several days, however, may also provide benefits by enhancing nutrient levels, food supply, and temperature conditions for rearing juveniles.

Creating prolonged inundated floodplain habitat would require both a large magnitude and volume of water without structural change to the channel conveyance capacity. On the Tuolumne and Merced, channel reconstruction projects have regarded the channel and floodplain to allow for floodplain inundation at lower discharges. In the Yolo Bypass, the Department of Water Resources is analyzing opportunities to create inundated floodplain at relatively low discharges by placing flow constriction barriers in the low flow channel. More detailed discussion on the magnitude of water necessary to create floodplain inundation is discussed above in the geomorphic section. It may be possible to reduce the volume of water necessary to create floodplain inundation with a series of flood pulses rather than one prolonged high pulse. Under such a scenario, the floodplain would become inundated and gradually drain before subsequent pulses reflooded it.

Smolt Outmigration
Velocity and temperature appear to be the main flow-related factors affecting successful smoltification and outmigration. Higher velocity flows (higher flows) theoretically help

salmon move out of the rivers and Delta faster and help avoid entrainment at irrigation diversions and the Delta pumps. High temperatures, above 65 degrees F, are primarily a problem during the later portions of the spring outmigration period (April–May), when air and water temperatures increase.

Juveniles that rear in the tributaries migrate out of the tributaries and begin smoltification from April to mid-June. NHI analyzed stream temperature data from the lower tributaries and at Vernalis (Figures 9.5–9.7; Appendix C). At low flows (300 cfs), water temperatures in the lower tributaries are often above 65 degrees in late April and May. Temperatures at Vernalis typically rose above 65 degrees in April and early May when flows were below 3,500 cfs. In late May, flows of over 5,000 cfs generally resulted in water temperatures at or near 65 degrees F.

Steelhead Trout Flow Requirements
Stream flow requirement for steelhead trout overlap with Chinook salmon with a few important exceptions. Steelhead juveniles require cool water temperatures in the upper reaches below the dams to over-summer. Additionally, steelhead require winter freshets to trigger upstream migration during January through March. We assumed that flows of 250-300 c.f.s. would provide adequate temperatures in the 5-10 mile reaches below the dams due to cool water releases from the dam. We assumed that flows of 500 c.f.s combined in combination with unregulated winter run-off would suffice for upstream migration.

9.4.3 Compare Historical and Existing Hydrology
An analysis comparing existing and historical hydrologic regimes, together with an understanding of flow requirements for specific objectives, is useful for identifying specific hydrologic alterations that may be limiting the attainment of environmental objectives. We used two approaches to compare existing and historical hydrologic patterns.

An analysis of existing (regulated) and historical (unimpaired) hydrology enables water managers to better understand the natural flow regime and how it may relate to the restoration or enhancement of target species. An analysis of historical patterns can provide clues about the timing, magnitude, duration, and frequency of flows under which target species historically survived or adapted. An analysis of historical hydrology may also reveal important patterns such as annual magnitude of floods and the timing of annual low flows that may have historically shaped the ecosystem in a manner that is not obvious from a species-specific analysis of environmental flow requirements. Major hydrologic alterations, particularly during critical life stages of target species, may help generate hypotheses regarding how target species are limited by the existing hydrologic regime. Comparison of existing and historical hydrology may also provide insight into when regulated instream flows can be reduced or reallocated to more efficiently achieve ecosystem targets within the context of existing water demand.

We evaluated pre- and post-dam hydrology using IHA and HCA methods to generate hypotheses regarding the causal links between historical hydrograph components and ecological conditions relevant to our restoration objectives. The Index of Hydrologic Alteration (IHA) method (Richter et al. 1996) provides a quick statistical overview of how several important hydrologic attributes have changed. The Hydrograph Component Analysis (HCA) method developed by McBain and Trush hydrograph provides a detailed graphical analysis of historical and existing hydrologic conditions. While valid and useful, the statistical analysis in the IHA method is not a substitute for visually comparing and evaluating key components of the pre- and post-dam hydrographs. Similarly, visual comparisons of pre- and post-alteration hydrographs don't always reveal important changes identified by the IHA method. Results of the IHA and HCA analysis are described in greater detail in Chapter 6 and Appendices A and B. Below is a summary of changes most significant to the environmental objectives.

The five most significant hydrologic differences between historical and regulated flows in the San Joaquin Basin that are relevant to the environmental objectives are:

- Reductions in peak flood events
- Reduced spring and early summer flows
- Reduced frequency of winter rainfall storm events
- A truncated spring and early summer recession limb, particularly in wet years
- Erratic fall and winter spawning and incubation flows
- A general decline in hydrologic variability

Figure 9.8 is a composite of unimpaired and regulated annual hydrographs for the "normal" year classification and depicts the dramatic changes caused by flow regulation.[1] The most obvious changes are the dramatic reduction in the peak flood events and the volume of spring snowmelt flows.

[1] Figure 9.8 should not be used to compare discharge volumes between the various rivers because data are based on different periods of record. The more important information is the differences between regulated and unimpaired hydrology on each of the different rivers.

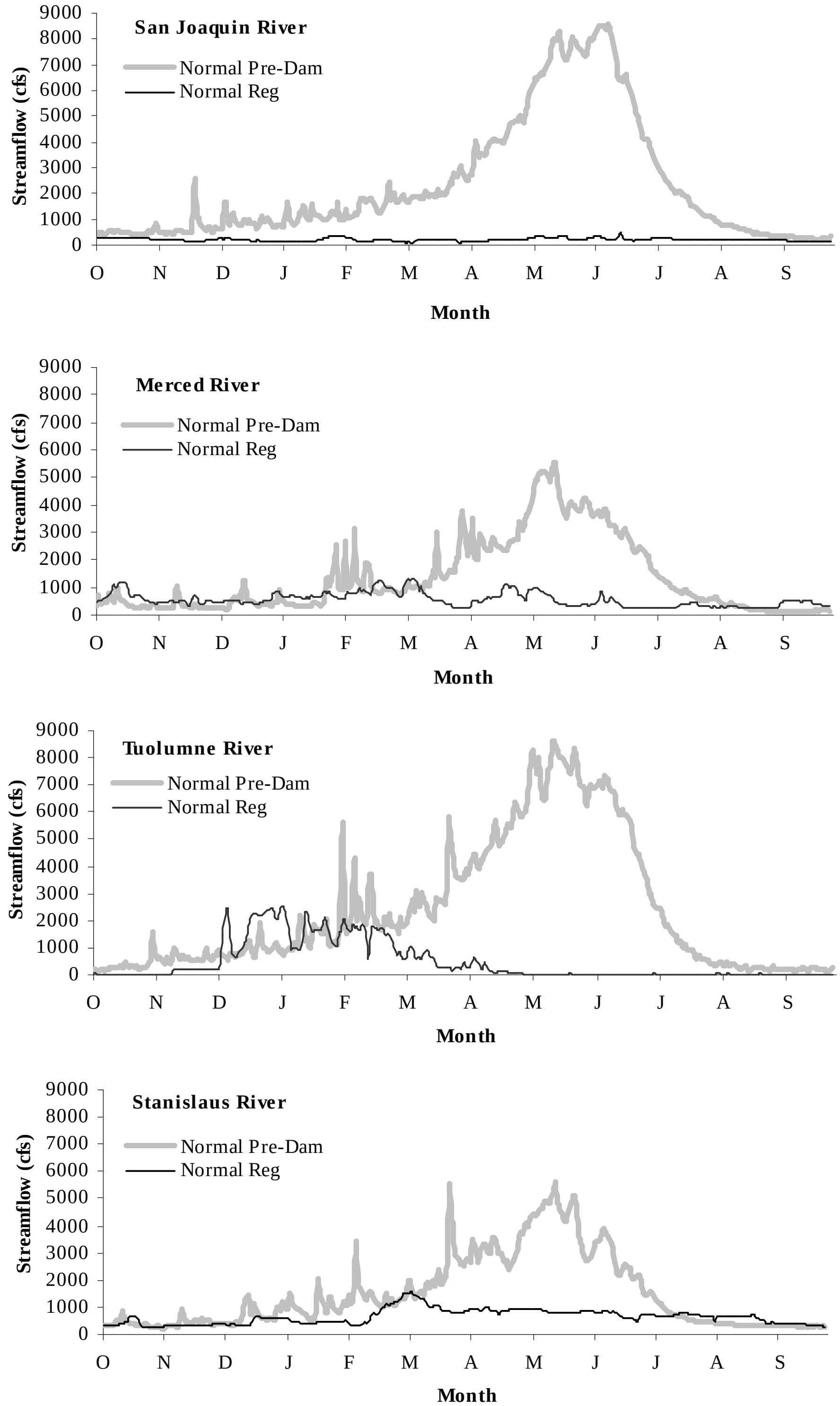


Figure 9.8. Comparison of Unimpaired and Regulated Annual Hydrographs for Normal Water Years.

9.4.4. Identify Obvious Gaps between Objective Flow Requirements and Existing Flows

In many cases, post-dam regulated flow conditions are different than the existing environmental flow requirements now mandated by state and federal laws and regulations. The minimum environmental flow requirements for the San Joaquin Basin rivers are discussed in the previous chapter. In earlier decades, minimum environmental flows were not always mandated or required below the terminal reservoirs in the San Joaquin Basin. Recently implemented minimum flow requirements on the Tuolumne and Stanislaus Rivers are a large improvements over earlier regulated flow regimes. Similarly, the Davis-Grunsky flows mandated on the Merced with the construction of New Exchequer in the late 1960's eliminated some of the most obvious flow impediments to salmon that existed prior to New Exchequer. Despite the improvements resulting from these minimum flow regimes, they are not necessarily enough to achieve the environmental objectives under consideration in this analysis. This section identifies the major gaps between the regulated minimum flow requirements and the flows necessary to achieve the environmental objectives.

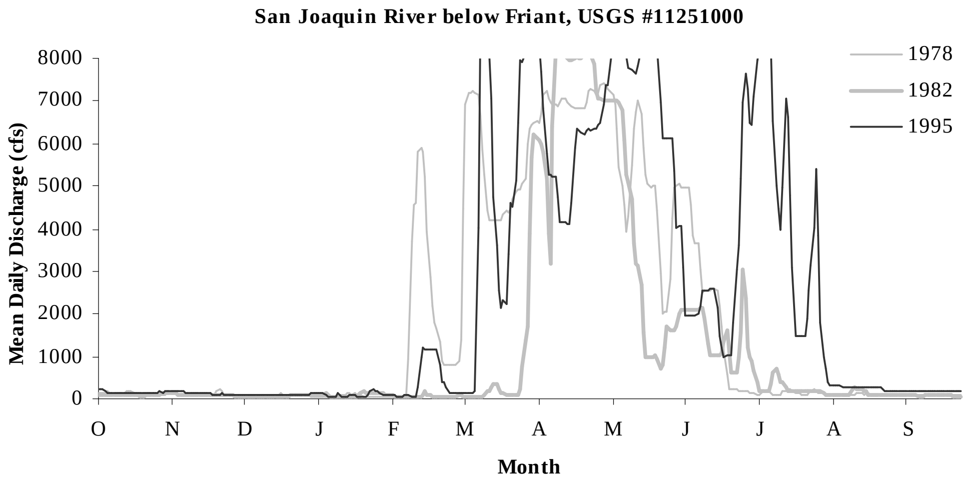
Geomorphic Objectives

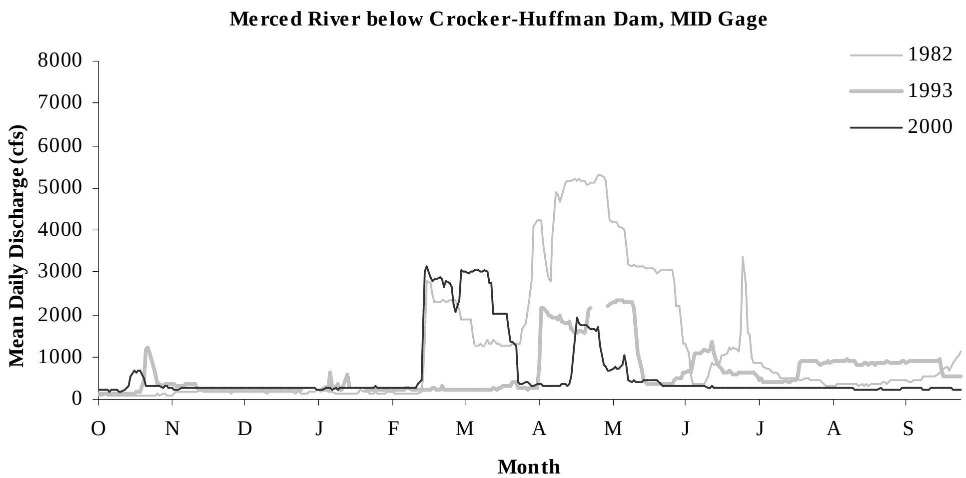
As discussed above and in the conceptual model chapter, peak flows trigger geomorphic processes that shape and maintain channel habitat conditions. The peak flows in post-dam regulated hydrographs for normal years are not high enough to trigger any of the geomorphic processes. Equally important, the regularity of peak flows from year to year is highly variable due to upstream regulation. Although, adequate peak flows may occur on a 5-year recurrence interval under regulated conditions. There may be periods of up to ten years when adequate flows due not occur. The long intervals of low flow conditions result in vegetation encroachment and bed armoring that inhibit bed mobilization when large flows do occur.

Riparian Vegetation Objectives

Changes in the recession of the spring and early summer hydrograph have also been significant. As discussed above, a gradually declining spring hydrograph is important for recruitment of riparian vegetation. Widespread recruitment of riparian vegetation probably did not occur in all years, but rather only in years when the spring hydrograph receded coincident to the germination and recruitment requirements of riparian vegetation species. Changes in the rate of the spring snowmelt recession are not obvious from the composite hydrographs depicted in Figure 9.8 because it averages spring flows over several years. The recession rate is more directly controlled by reservoir release operations in specific wet and above normal years. Generally, releases from the reservoir are characterized by abrupt changes in flow during the period of riparian vegetation germination and recruitment. Figure 9.9 depicts flow release patterns during some representative years on the Merced and Tuolumne Rivers and illustrates the abrupt changes that often occur in the post-dam era.

Abrupt changes in reservoir releases during germination and initial seedling establishment period can limit recruitment by abruptly desiccating recently germinated seedlings before their roots reach the water table or by scouring and inundating newly established seedlings with high summer flows shortly after germination. Both of these processes occur on the regulated rivers of the San Joaquin Basin, although abrupt desiccation appears to be the more prevalent process. For example, reservoir releases dropped abruptly in early June of 1982 on the Merced River just after the germination period of cottonwood seeds, almost certainly desiccating any cottonwood seedlings that may have become established. The 1993 hydrograph from the San Joaquin illustrates the potential for scour and inundation by high releases after germination. Any seedling that might have become established in May and June with a more gently receding hydrograph would have succumbed to inundation or scour during the 5,000 cfs release in early July.





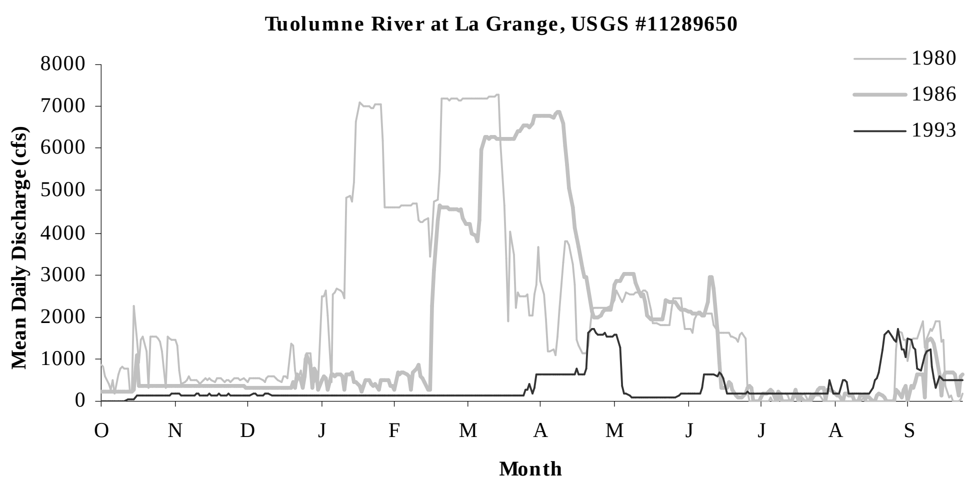


Figure 9.9. Representative Post-Dam Flow Release Patterns for Merced, Tuolumne, and San Joaquin.

Fall-Run Chinook Salmon Objectives

Large volumes of spring snowmelt may have been important for juvenile salmon rearing and smolt-outmigration as well as steelhead adult upstream migration. High flow volumes in the early spring inundated large areas of floodplain habitat, particularly in the lower river, that would have provided excellent floodplain rearing habitat for juvenile salmon. These spring flows also would have provided ample flows to allow for upstream migration of steelhead. Later in the spring and early summer, as ambient air temperature increased, high flows probably maintained suitable water temperatures through the lower river during the primary smoltification and outmigration life stage of Chinook salmon.

Erratic fall and winter spawning flows due to reservoir regulation were historically a problem before minimum instream flow standards were adopted and enforced. Figures 7.12-7.15 illustrate some of the poor flow conditions that characterized stream flows before minimum regulations. These very low base flows and abrupt transitions in flow while the eggs are in the gravel can dewater redds, resulting in likely failure of the cohort. These erratic winter timer releases are now generally precluded by the existing minimum flow requirements.

Relatively high winter flood peaks induced by rainfall run-off were quite common historically. When these events happened in early winter, they may have scoured redds and reduced survival of eggs and fry. When these events occurred in late winter after the eggs had hatched, these flows may have provided excellent floodplain rearing habitat for young fry.

9.5 RESULTS OF HOLISTIC METHOD: A HYPOTHETICAL ENVIRONMENTAL FLOW REGIME

9.5.1 Geomorphic Flow Requirements

Table 9.3 presents a summary of geomorphic flow target thresholds for each river that was used in the reservoir reoperation component of this study. Many of these flows exceed the current flood control guidelines of the Army Corps of Engineers and in some cases exceed the capacity of the floodway below the dams. The flows in Table 9.3 are not flow recommendations, but rather estimates of the flows necessary to achieve geomorphic objectives for the purpose of modeling reservoir reoperation.

Table 9.3. Summary of Geomorphic Flow Target Thresholds

	Pre-Dam Q 1.5	Bed Mobility	Channel Scour and Migration	Floodplain Inundation
San Joaquin	8,650	12,000	16,000	4,000
Merced	10,060	6,000	10,000	3,500
Tuolumne	8,670	8,000	12,000	4,500
Stanislaus	5,350	6,000	10,000	3,500

The ratio between bed mobilization flows and floodplain inundation is far greater than anticipated from a review of the literature. Normally, flows necessary to initiate bed mobility are only slightly greater than flows required for inundation of the floodplain. Inundation flows depicted in Table 9.3 are far below bed mobility flows because we analyzed the flows necessary to inundate the modern floodplain rather than the historic floodplain, which is now a terrace too high to practically inundate frequently. These modern floodplain surfaces are actually the historical bars of the pre-incision channel. The channel scour and migration flows identified in Table 9.3 may be too low. Generally, the flows required for scour and migration are two to three times larger than bed mobilization flows (Trush et al 2000). Because of the increased sheer stresses resulting from widespread channel incision as well as gravel augmentation and channel reconstruction strategies designed to reduce scour and migration thresholds, however, these flows may be adequate to achieve their geomorphic objectives and are reasonable approximations for the reservoir reoperation component of this study.

Table 9.4. Timing of Environmental Flow Requirements for the San Joaquin River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
Fall-run salmon upstream migration	■	■										
Fall-run salmon spawning and incubation		■	■	■	■							
Fall-run salmon rearing base					■	■	■	■				
Fall-run salmon smolt out-migration			■	■	■							
Steelhead trout adult migration				■	■	■	■					
Steelhead trout over-summering								■	■	■	■	■
Cottonwood seedling establishment							▒	▒				
Riparian maintenance flow	■							■	■	■	■	■
Geomorphic objectives	■					■	■	■	■	■		

9.5.2 San Joaquin

The hypothetical flow environmental flow hydrographs used to depict the modeling analysis described in volume 2 are depicted in figures 9.10, 9.12, 9.14, and 9.16. Tables 9.5 – 9.8 provide a summary of the assumed flow requirements used to develop the hypothetical flow regime for each of the four rivers. Different hydrographs were selected for four different year types – wet, normal wet, normal dry and dry. Flow volumes are different for each water year classification, in recognition that certain restoration objectives requiring high flow magnitudes and volumes would be achieved during wetter years when there is more water available in the San Joaquin Basin. Figures 9.11, 9.13, 9.14, and 9.15 provide a comparison between the wet and normal wet hypothetical hydrographs with unimpaired wet year conditions, the AFRP wet year flow assumptions, and the existing minimum wet year required flows on each river. These later figures show that the exiting flow requirements do not achieve geomorphic and riparian objectives.

Water Year	**Exceedence Probability**
WET	0% to 20%
NORMAL-WET	20% to 50%
NORMAL-DRY	50% to 80%
DRY	80% to 100%

The hypothetical environmental hydrographs for each river are designed to achieve the following objectives during different year types.

Wet Years

- Significant cobble/gravel bed mobilization
- Channel migration
- Significant riparian regeneration
- Adequate flows and temperatures for smolt outmigration for all species
- Adequate fish passage flows
- Attractant pulse flows for adult Chinook salmon and steelhead

Normal-wet Years

- Marginal cobble/gravel bed mobilization
- Limited channel migration
- Limited riparian regeneration
- Adequate flows and temperatures for smolt outmigration for all species
- Adequate fish passage flows
- Attractant pulse flows for adult Chinook salmon and steelhead

Normal-dry Years

- Adequate flows and temperatures for smolt outmigration for all species
- Adequate fish passage flows
- Attractant pulse flows for adult Chinook salmon and steelhead

Dry Years

- Adequate flows and temperatures for smolt outmigration for all species
- Marginal fish passage flows
- Attractant pulse flows for adult Chinook salmon and steelhead

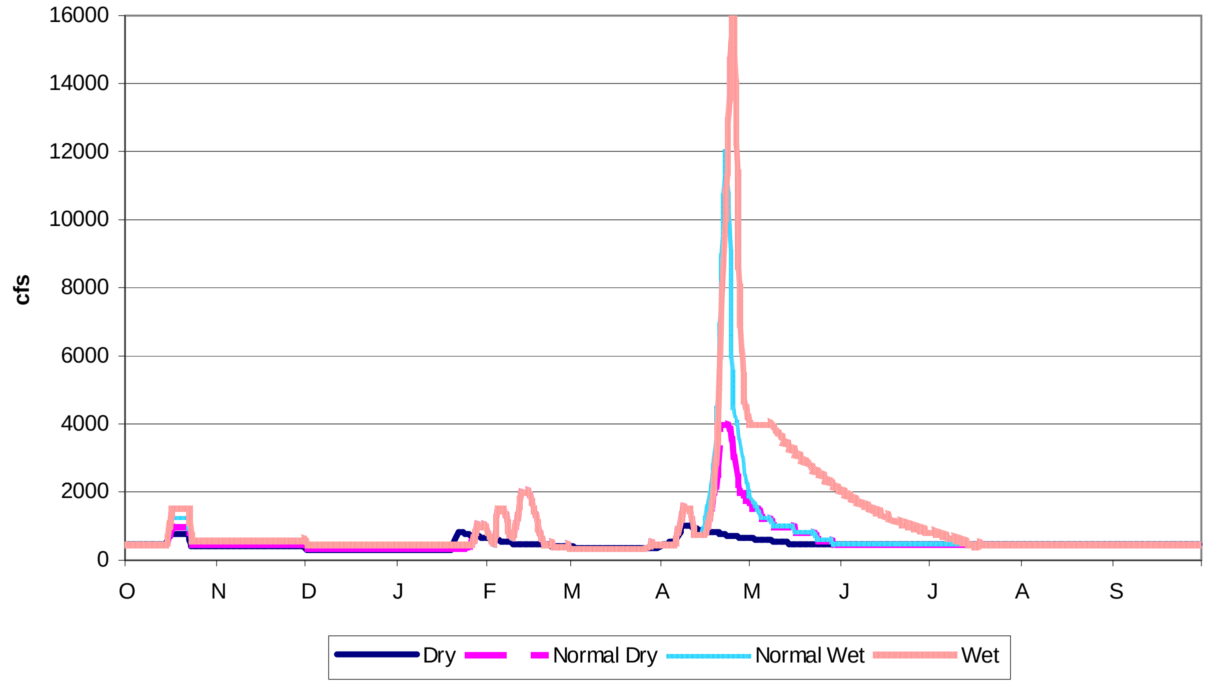


Figure 9.10. Middle San Joaquin River hypothetical environmental flow hydrographs for four different year classes.

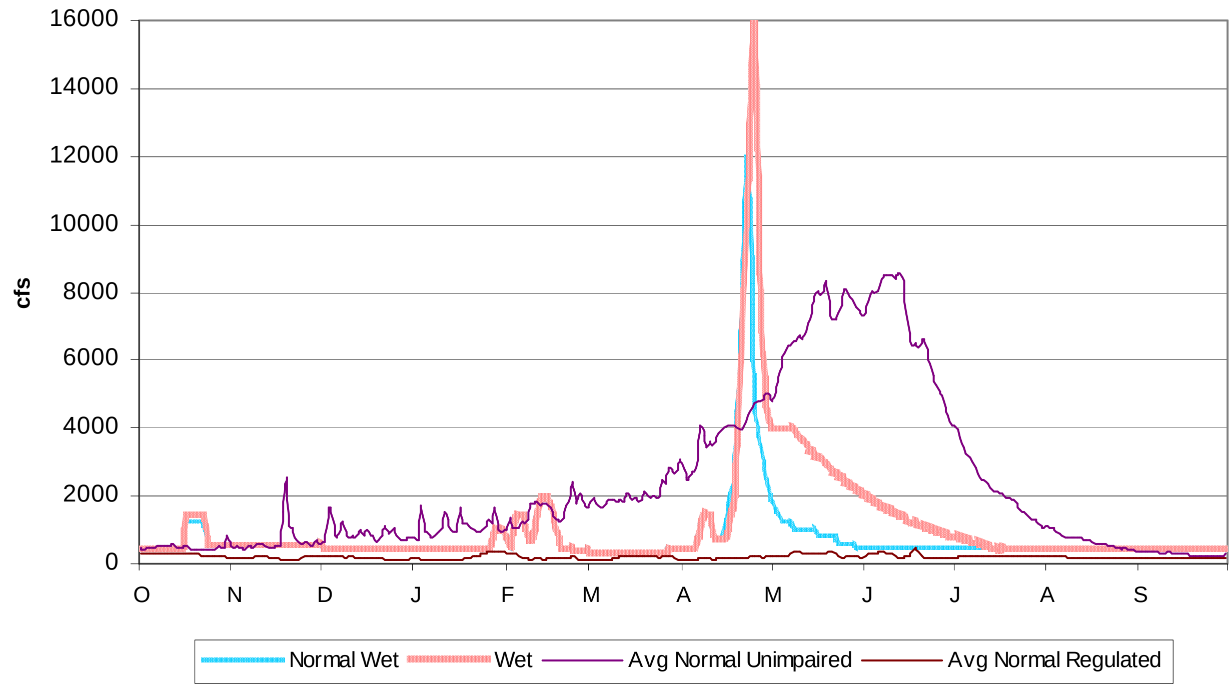


Figure 9.11. Middle San Joaquin River comparison of hypothetical environmental flow hydrograph with average normal unimpaired and average normal regulated hydrographs which are both composites of severa normal year classes in the pre and post dam era.

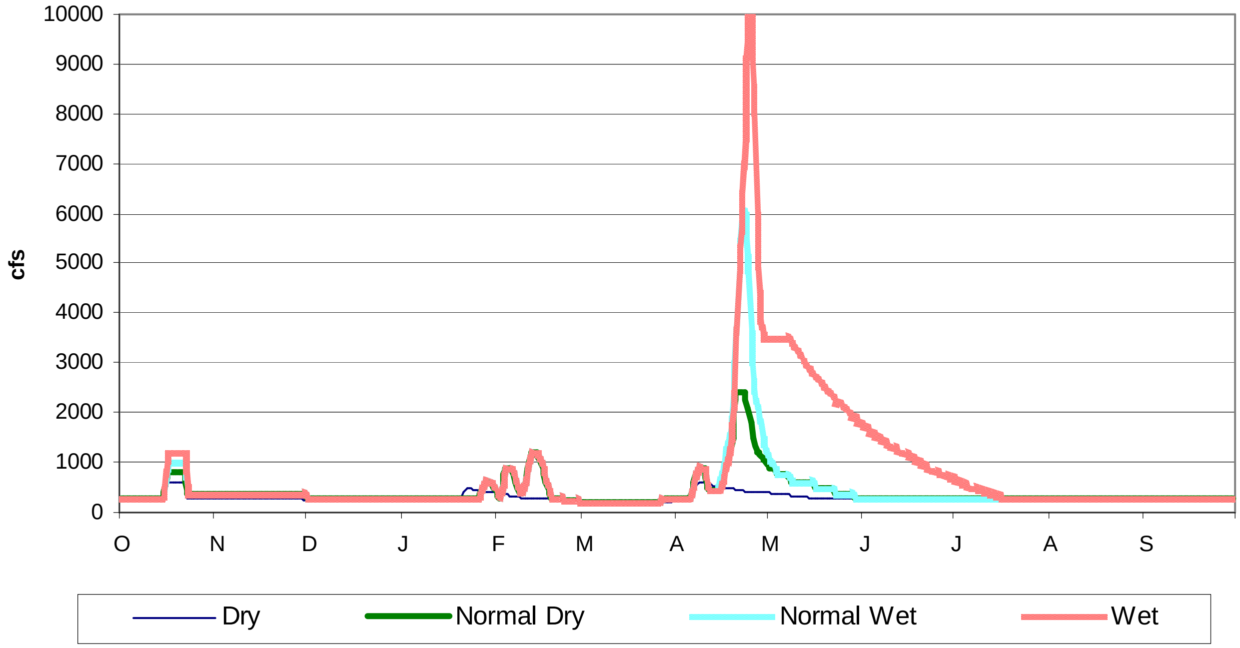


Figure 9.14. Merced River hypothetical environmental flow hydrographs for four different year classes.

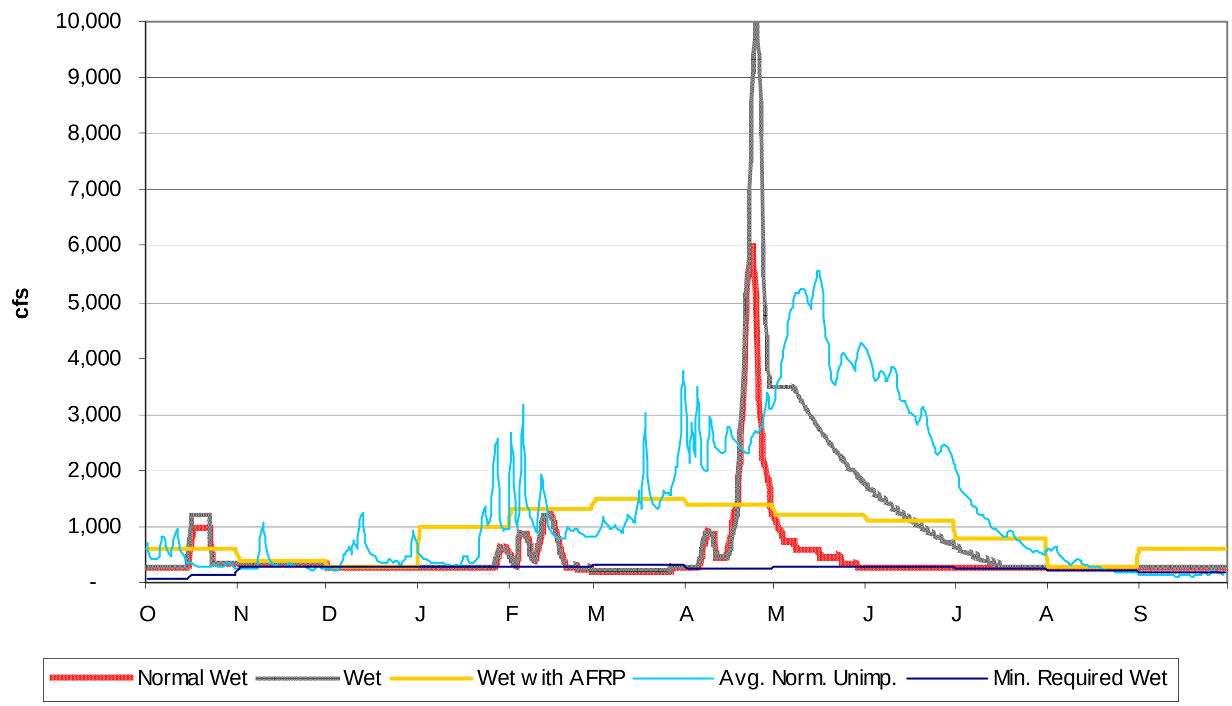


Figure 9.15. Merced River hypothetical environmental flow regime for normal-wet and wet years compared with minimum required wet year flow, AFRP wet, and average normal unimpaired which is an average of several normal year classes.

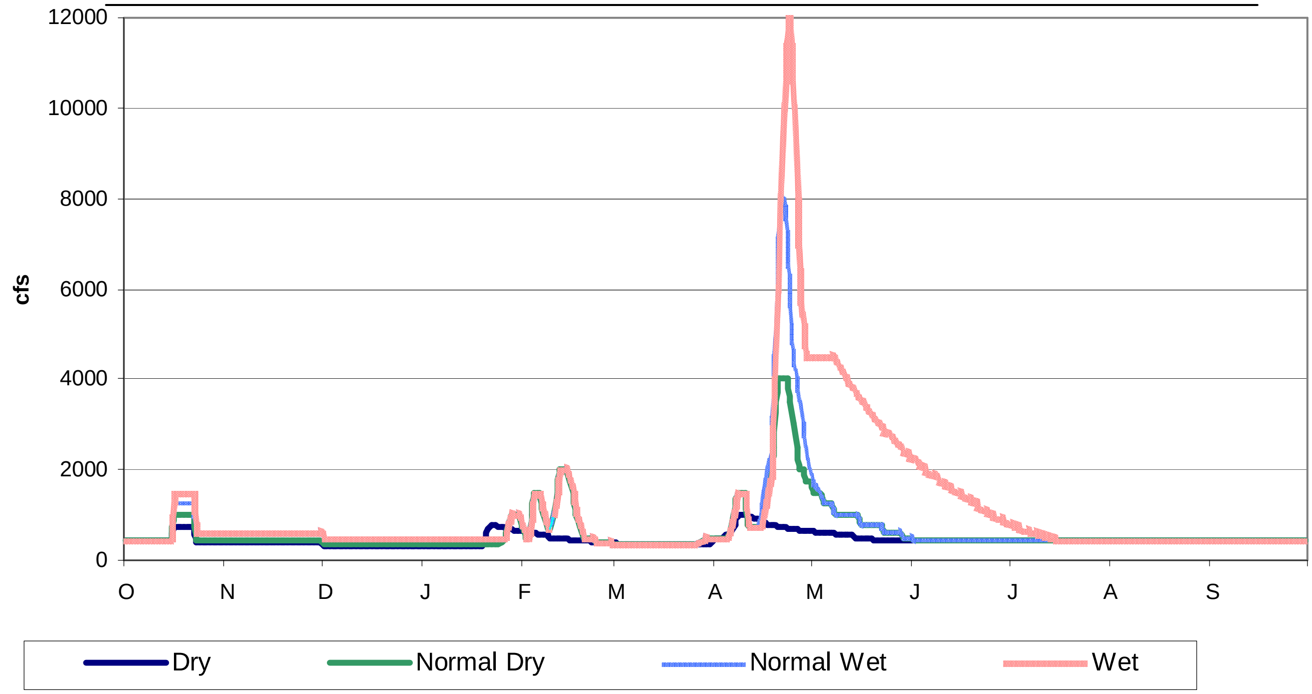


Figure 9.12. Tuolumne River River hypothetical environmental flow hydrographs for four different year classes.

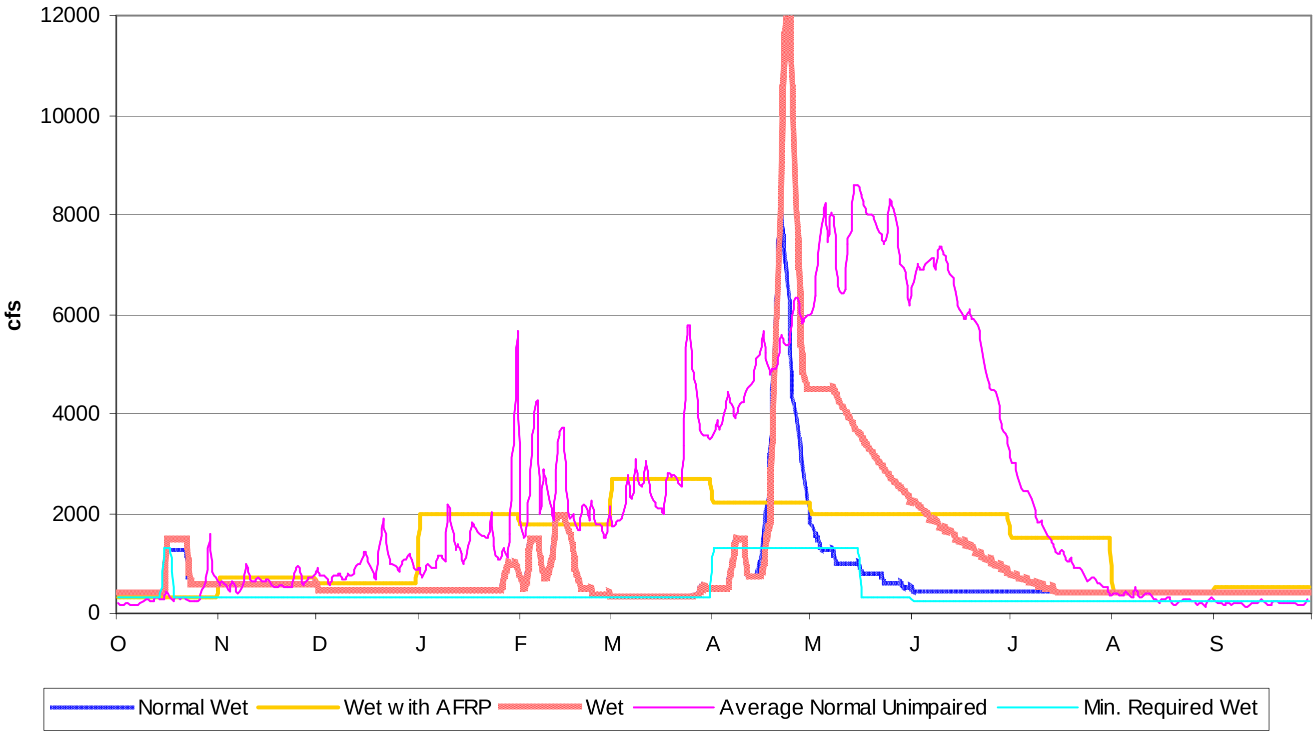


Figure 9.13. Tuolumne River hypothetical environmental flow regime for normal-wet and wet years compared with minimum required wet year flow, AFRP wet, and average normal unimpaired which is an average of several normal year classes. Minimum required flow is an interpretation of more complex requirement. See Table 8.4.

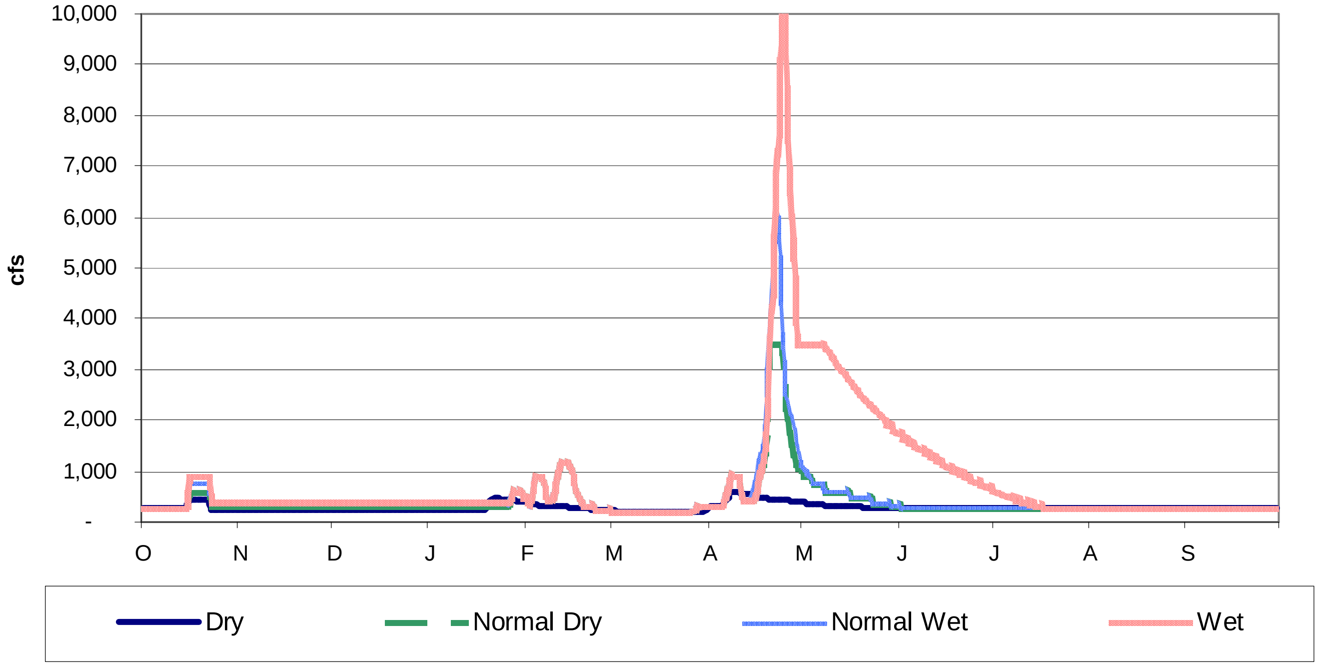


Figure 9.16. Stanislaus River River hypothetical environmental flow hydrographs for four different year classes.

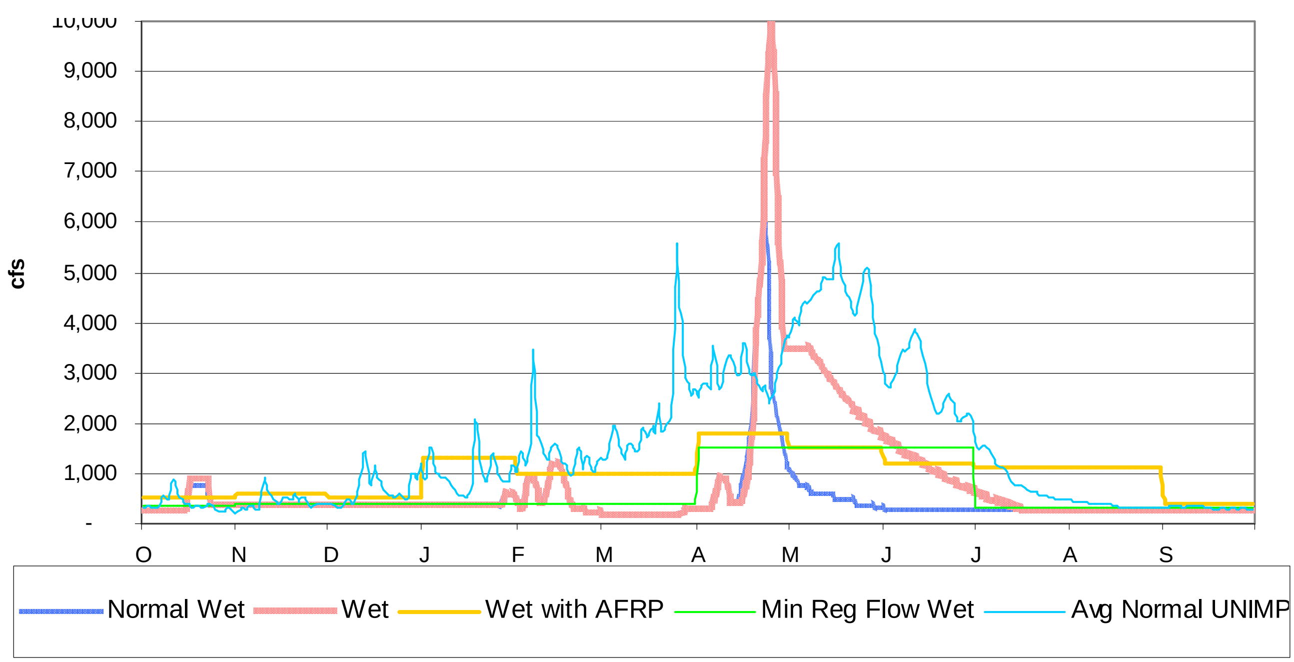


Figure 9.17. Stanisluas River hypothetical environmental flow regime for normal-wet and wet years compared with minimum required wet year flow, AFRP wet, and average normal unimpaired which is an average of several normal year classes.

Table 9.5: SAN JOAQUIN: Multi-Objective Ecological Flow Management

ECOSYSTEM INDICATOR	Objective/Notes	Magnitude (cfs)	Timing	Duration (days)	Frequency	Max Rate of Change (cfs)	NOTES
Fall Run Chinook Salmon							
<u>Population Targets</u>							
long-term average escapement	specify escapement target (e.g., AFRP, etc.): not specified for this study.						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
annual smolt production	specify production target (what all management should aim towards), could use recruitment ratio (Mossdale smolts/spawning pairs)						Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
<u>Streamflow Objectives</u>							
Adult migration							
baseflow	provide suitable temperature and eliminate migratory barriers	1,000-4,000 (depends on time and flow in other tribs)	Oct 1-15 (maybe earlier)	2-3 weeks	annually	N/A	Phyical barriers in channel assumed not to be problem at flows above 150 c.f.s. Analysis of Vernalis temperature data indicates that very high flows are necessary to achieve temperatures of 65-70 degrees. May require flows of 1,000 - 4,000 cfs. See figure 9.4)
attraction pulse flow	stimulate upstream movement into spawning grounds	1,000-2,500	Oct 15-19	2-5	annually depending on water year type	N/A	pulse flows should provide several short (2-3 day) windows of good water quality (temp and DO) in the Delta and lower SJR to allow passage into lower tributaries; need additional experimentation to confirm that fish actually respond to "attraction pulse flows";
Spawning/Incubation	assume same flow for each life history stage; may eventually differentiate;				annually		
temperature flow	provide suitable temperature range during spawning		Oct 19-Dec 15		annually		Assumed that temperature not a problem in spawning reach after at flows of > 250 cfs due to hypolimnetic discharge from dam. Needs to be assessed with temperature model
habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);	250-500	gradually increasing Oct 19 to Dec 15	4 flow stages, two weeks at each flow from Oct 15 to Dec 15	annually, although may not achieve higher range in dry years	shouldn't matter going up, but needs to descend slowly	Habitat area not analyzed in this study. Assumed to be adequate between 250-500 cfs. Staged releases of progressively higher flows during the spawning season, would provide lower temperatures progressively downstream later in the year (from lowering ambient and from higher releases), encouraging spawning further downstream as the season progresses, reducing superimposition. The staged increases in flows should be modeled with the cumulative spawning curve (not WUA curve) and peak timing of spawning to determine the highest use of the best habitat, and to redistribute spawning downstream to reduce superimposition
Incubation Baseflow	Flow after last spawning occurs to keep incubating eggs in good condition	80% of max spawning habitat flow	Dec 15-March 15	90 days for egg incubation	Annually		The 80% number is a rough estimate. This number could be refined by evaluating spawning locations on a cross section and lower flows to see when the redd begins to de-water.
Fry/juvenile rearing							
upstream baseflows	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat	100-250; 600+	winter baseflow-Mar 15 to April 31	45 days	annually		the PHABSIM WUA curve from Tuolumne shows the lowest available rearing habitat in the 200-600 range, for all three habitat types. Only rearing in deep pools (not riffles, runs) improves above 600 cfs;
Floodplain inundation rearing	seasonal, short-duration pulse flow to allow rearing on inundated floodplains	1000-4500	Feb-Apr (better earlier)	5-30 days	Annually if possible		Inundated floodplains have been shown to provide excellent rearing habitat. Costly to provide long duration, but it may be possible to provide series of pulse flows to periodically wet low floodplains/veg. and also prevent stranding. This component needs to be evaluated to determine the strategy that achieves the highest growth rates and lowest mortality from predation
delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta	not estimated	May	all month, punctuated by pulse flows (VAMP flows)			This component not evaluated in this study. Needs study or literature review to determine suitable flows for rearing in delta, not sure if this is appropriate here, did not use in hydrographs
Outmigration (juvenile/smolt)	Provide suitable temperatures in lower San Joaquin for juveniles and smolts (65 degrees or less for smolts).	1,500-5,000 (depends on flow in other tribs)	May 1-June 15	steep ascending limb, 4-8 day peak, gradual descending limb	Annually if possible	gradual descending for riparian germination	Flows of 3,000 to 5,000 cfs required to maintain temp at 65 degrees during April-May. Flows should be coordinated with other tributaries. Idealy the peak flow and descending limb should extend into June 15 (not June 1) to allow additional time for late emergent fry to get out, also may allow springers to get upstream, but may be water prohibitive to provide suitable water temperatures past May 31. The unimpaired snowmelt usually extended into July (and sometimes August)
Yearling rearing	specify temperature range, and length of stream along which to provide suitable habitat	150-350					Requires better data and temperature model, should provide suitable habitat as far downstream as Basso Bridge (5 miles) in all years, downstream to Roberts Ferry Bridge in Extremely Wet years
Steelhead							
<u>Streamflow Targets</u>							Other flow requirments for steelhead presumed achieved with flows for fall-run salmon above.
Adult migration	provide suitable flow to trigger migration and allow passage of adults in late winter and early spring						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
Over-Summering Habitat	provide suitable water temperatures (65 degrees) during spring summer and fall in reach below dam. Length of reach with suitable temperature depens on year type.	150-350	May 1-Oct. 15				Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Riparian Vegetation							
<u>Cottonwood</u>							
Seedbed preparation	Clear away weeds, expose mineral soil, deposit fines.	16,000	prior to establishement	2-5	Wet and Ext Wet		Even high flows may not be enough to prepare nursery be for seedling germination due to the existing presence of well established hebaceous species. Target surfaces may need to be mechanically scoured to facilitate scour and deposition at reasonable flows. Deposition of fines may be impossible due to trapping at dam.
seed germination (cottonwood)	use cottonwood as target indicator species	4,000	April 15 - May 15	7	Wet and Ext Wet		
seedling growth/establishment	establish target floodplain elevations relative to channel thalweg for cottonwood establishment	gradually decending limb from estabishment stage	April 15 - mid July	15-30	Wet and Ext Wet	50 -100 cfs/day	2 cm/day, which is a variable change in cfs/day, so estimate 50 -100 cfs for now, need rating curves for target site
periodic large-scale disturbance	infrequent "resetting flow" to scour vegetation, create barren areas, and maintain age-class diversity	16,000	winter-spring, but best for fish after March	2-5	Ext Wet		
<u>Stand Structure and Diversity</u>							
age/species assemblage diversity	Re-introduce flood disturbance and hydrologic variability to achieve diversity objective	4,000 to 16,000	Mar 15-June 1	2-5	Normal, wet, ext wet		
Geomorphic Processes							
<u>Sediment Transport</u>							
bed mobilization in gravel bedded reach	target 75-90 mobilization of the D84 in riffle habitats	12,000	Mar 15-June 1	2	Wet and Ext Wet		Any time, but best for fish after mid March
bed scour in gravel bedded reach	scour point bar units to approx twice depth of D84	16,000	Mar 15-June 1	2	Ext Wet		Any time, but best for fish after mid March
<u>Channel Morpohology</u>							
channel migration	define and quantify in terms of lateral bank erosion	16,000	Mar 15-June 1	2	Ext Wet		Unknown magnitude, assume 12000 begins to cause migration in gravel reach
<u>Floodplain Processes</u>							
floodplain inundation	Wet the floodplain	4,000	Mar 15-June 1	2	Normal, wet, ext wet		Based on Basso floodplains and new channel restoration designs
floodplain fine sediment deposition	Inundate the floodplain by greater than 1 foot depth	8000	Mar 15-June 1	2	Wet and Ext Wet		8000-4500 is estimated 1 ft depth, needs checking

Table 9.6: MERCED: Multi-Objective Ecological Flow Management

ECOSYSTEM INDICATOR	Objective/Notes	Magnitude (cfs)	Timing	Duration (days)	Frequency	Max Rate of Change (cfs)	NOTES
Fall Run Chinook Salmon							
Population Targets							
long-term average escapement	specify escapement target (e.g., AFRP, etc.): not specified for this study.						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
annual smolt production	specify production target (what all management should aim towards), could use recruitment ratio (Mossdale smolts/spawning pairs)						Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Streamflow Objectives							
Adult migration							
baseflow	provide suitable temperature and eliminate migratory barriers	1,000-4,000 (depends on time and flow in other tribs)	Oct 1-15 (maybe earlier)	2-3 weeks	annually	N/A	Phyical barriers in channel assumed not to be problem at flows above 150 c.f.s. Analysis of Vernalis temperature data indicates that very high flows are necessary to achieve temperatures of 65-70 degrees. May require flows of 1,000 - 4,000 cfs. See figure 9.4)
attraction pulse flow	stimulate upstream movement into spawning grounds	1,000-2,500	Oct 15-19	2-5	annually depending on water year type	N/A	pulse flows should provide several short (2-3 day) windows of good water quality (temp and DO) in the Delta and lower SJR to allow passage into lower tributaries; need additional experimentation to confirm that fish actually respond to "attraction pulse flows";
Spawning/Incubation	assume same flow for each life history stage; may eventually differentiate;				annually		
temperature flow	provide suitable temperature range during spawning		Oct 19-Dec 15		annually		Assumed that temperature not a problem in spawning reach after at flows of > 250 cfs due to hypolimnetic discharge from dam. Needs to be assessed with temperature model
habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);	250-500	gradually increasing Oct 19 to Dec 15	4 flow stages, two weeks at each flow from Oct 15 to Dec 15	annually, although may not achieve higher range in dry years	shouldn't matter going up, but needs to descend slowly	Habitat area not analyzed in this study. Assumed to be adequate between 250-500 cfs. Staged releases of progressively higher flows during the spawning season, would provide lower temperatures progressively downstream later in the year (from lowering ambient and from higher releases), encouraging spawning further downstream as the season progresses, reducing superimposition. The staged increases in flows should be modeled with the cumulative spawning curve (not WUA curve) and peak timing of spawning to determine the highest use of the best habitat, and to redistribute spawning downstream to reduce superimposition
Incubation Baseflow	Flow after last spawning occurs to keep incubating eggs in good condition	80% of max spawning habitat flow	Dec 15-March 15	90 days for egg incubation	Annually		The 80% number is a rough estimate. This number could be refined by evaluating spawning locations on a cross section and lower flows to see when the redd begins to de-water.
Fry/juvenile rearing							
upstream baseflows	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat	300	winter baseflow-Mar 15 to April 31	45 days	annually		the PHABSIM WUA curve from Tuolumne shows the lowest available rearing habitat in the 200-600 range, for all three habitat types. Only rearing in deep pools (not riffles, runs) improves above 600 cfs;
Floodplain inundation rearing	seasonal, short-duration pulse flow to allow rearing on inundated floodplains	1000-4500	Feb-Apr (better earlier)	5-30 days	Annually if possible		Inundated floodplains have been shown to provide excellent rearing habitat. Costly to provide long duration, but it may be possible to provide series of pulse flows to periodically wet low floodplains/veg. and also prevent stranding. This component needs to be evaluated to determine the strategy that achieves the highest growth rates and lowest mortality from predation
delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta	not estimated	May	all month, punctuated by pulse flows (VAMP flows)			This component not evaluated in this study. Needs study or literature review to determine suitable flows for rearing in delta, not sure if this is appropriate here, did not use in hydrographs
Outmigration (juvenile/smolt)	Provide suitable temperatures in lower San Joaquin for juveniles and smolts (65 degrees or less for smolts).	1,500-5,000 (depends on flow in other tribs)	May 1-June 15	steep ascending limb, 4-8 day peak, gradual descending limb	Annually if possible	gradual descending for riparian germination	Flows of 3,000 to 5,000 cfs required to maintain temp at 65 degrees during April-May. Flows should be coordinated with other tributaries. Idealy the peak flow and descending limb should extend into June 15 (not June 1) to allow additional time for late emergent fry to get out, also may allow springers to get upstream, but may be water prohibitive to provide suitable water temperatures past May 31. The unimpaired snowmelt usually extended into July (and sometimes August)
Yearling rearing	specify temperature range, and length of stream along which to provide suitable habitat	150-350					Requires better data and temperature model, should provide suitable habitat as far downstream as Basso Bridge (5 miles) in all years, downstream to Roberts Ferry Bridge in Extremely Wet years
Steelhead							
Streamflow Targets							Other flow requirments for steelhead presumed achieved with flows for fall-run salmon above.
Adult migration	provide suitable flow to trigger migration and allow passage of adults in late winter and early spring						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
Over-Summering Habitat	provide suitable water temperatures (65 degrees) during spring summer and fall in reach below dam. Length of reach with suitable temperature depens on year type.	150-350	May 1-Oct. 15				Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Riparian Vegetation							
Cottonwood							
Seedbed preparation	Clear away weeds, expose mineral soil, deposit fines.	6,000	prior to establishement	2-5	Wet and Ext Wet		Even high flows may not be enough to prepare nursery be for seedling germination due to the existing presence of well established hebaceous species. Target surfaces may need to be mechanically scoured to facilitate scour and deposition at reasonable flows. Deposition of fines may be impossible due to trapping at dam.
seed germination (cottonwood)	use cottonwood as target indicator species	3,500	April 15 - May 15	7	Wet and Ext Wet		
seedling growth/establishment	establish target floodplain elevations relative to channel thalweg for cottonwood establishment	gradually decending limb from estabishment stage	April 15 - mid July	15-30	Wet and Ext Wet	50 -100 cfs/day	2 cm/day, which is a variable change in cfs/day, so estimate 50 -100 cfs for now, need rating curves for target site
periodic large-scale disturbance	infrequent "resetting flow" to scour vegetation, create barren areas, and maintain age-class diversity	10,000	winter-spring, but best for fish after March	2-5	Ext Wet		
Stand Structure and Diversity							
age/species assemblage diversity	Re-introduce flood disturbance and hydrologic variability to achieve diversity objective	3,500 - 10,000	Mar 15-June 1	2-5	Normal, wet, ext wet		
Geomorphic Processes							
Sediment Transport							
bed mobilization in gravel bedded reach	target 75-90 mobilization of the D84 in riffle habitats	6,000	Mar 15-June 1	2	Wet and Ext Wet		Any time, but best for fish after mid March
bed scour in gravel bedded reach	scour point bar units to approx twice depth of D84	10,000	Mar 15-June 1	2	Ext Wet		Any time, but best for fish after mid March
Channel Morpohology							
channel migration	define and quantify in terms of lateral bank erosion	10,000	Mar 15-June 1	2	Ext Wet		Unknown magnitude, assume 12000 begins to cause migration in gravel reach
Floodplain Processes							
floodplain inundation	Wet the floodplain	3,500	Mar 15-June 1	2	Normal, wet, ext wet		Based on Basso floodplains and new channel restoration designs
floodplain fine sediment deposition	Inundate the floodplain by greater than 1 foot depth	6,000	Mar 15-June 1	2	Wet and Ext Wet		8000-4500 is estimated 1 ft depth, needs checking

Table 9.7: TUOLUMNE: Multi-Objective Ecological Flow Management

ECOSYSTEM INDICATOR	Objective/Notes	Magnitude (cfs)	Timing	Duration (days)	Frequency	Max Rate of Change (cfs)	NOTES
Fall Run Chinook Salmon							
Population Targets							
long-term average escapement	specify escapement target (e.g., AFRP, etc.): not specified for this study.						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
annual smolt production	specify production target (what all management should aim towards), could use recruitment ratio (Mossdale smolts/spawning pairs)						Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Streamflow Objectives							
Adult migration							
baseflow	provide suitable temperature and eliminate migratory barriers	1,000-4,000 (depends on time and flow in other tribs)	Oct 1-15 (maybe earlier)	2-3 weeks	annually	N/A	Phyical barriers in channel assumed not to be problem at flows above 150 c.f.s. Analysis of Vernalis temperature data indicates that very high flows are necessary to achieve temperatures of 65-70 degrees. May require flows of 1,000 - 4,000 cfs. See figure 9.4)
attraction pulse flow	stimulate upstream movement into spawning grounds	1,000-2,500	Oct 15-19	2-5	annually depending on water year type	N/A	pulse flows should provide several short (2-3 day) windows of good water quality (temp and DO) in the Delta and lower SJR to allow passage into lower tributaries; need additional experimentation to confirm that fish actually respond to "attraction pulse flows";
Spawning/Incubation	assume same flow for each life history stage; may eventually differentiate;				annually		
temperature flow	provide suitable temperature range during spawning		Oct 19-Dec 15		annually		Assumed that temperature not a problem in spawning reach after at flows of > 250 cfs due to hypolimnetic discharge from dam. Needs to be assessed with temperature model
habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);	250-800	gradually increasing Oct 19 to Dec 15	4 flow stages, two weeks at each flow from Oct 15 to Dec 15	annually, although may not achieve higher range in dry years	shouldn't matter going up, but needs to descend slowly	Habitat area not analyzed in this study. Assumed to be adequate between 250-500 cfs. Staged releases of progressively higher flows during the spawning season, would provide lower temperatures progressively downstream later in the year (from lowering ambient and from higher releases), encouraging spawning further downstream as the season progresses, reducing superimposition. The staged increases in flows should be modeled with the cumulative spawning curve (not WUA curve) and peak timing of spawning to determine the highest use of the best habitat, and to redistribute spawning downstream to reduce superimposition
Incubation Baseflow	Flow after last spawning occurs to keep incubating eggs in good condition	80% of max spawning habitat flow	Dec 15-March 15	90 days for egg incubation	Annually		The 80% number is a rough estimate. This number could be refined by evaluating spawning locations on a cross section and lower flows to see when the redd begins to de-water.
Fry/juvenile rearing							
upstream baseflows	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat	100-250; 600+	winter baseflow-Mar 15 to April 31	45 days	annually		the PHABSIM WUA curve shows the lowest available rearing habitat in the 200-600 range, for all three habitat types. Only rearing in deep pools (not riffles, runs) improves above 600 cfs;
Floodplain inundation rearing	seasonal, short-duration pulse flow to allow rearing on inundated floodplains	1000-4500	Feb-Apr (better earlier)	5-30 days	Annually if possible		Inundated floodplains have been shown to provide excellent rearing habitat. Costly to provide long duration, but it may be possible to provide series of pulse flows to periodically wet low floodplains/veg. and also prevent stranding. This component needs to be evaluated to determine the strategy that achieves the highest growth rates and lowest mortality from predation
delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta	not estimated	May	all month, punctuated by pulse flows (VAMP flows)			This component not evaluated in this study. Needs study or literature review to determine suitable flows for rearing in delta, not sure if this is appropriate here, did not use in hydrographs
Outmigration (juvenile/smolt)	Provide suitable temperatures in lower San Joaquin for juveniles and smolts (65 degrees or less for smolts).	1,500-5,000 (depends on flow in other tribs)	May 1-June 15	steep ascending limb, 4-8 day peak, gradual descending limb	Annually if possible	gradual descending for riparian germination	Flows of 3,000 to 5,000 cfs required to maintain temp at 65 degrees during April-May at Vernalis. Flows should be coordinated with other tributaries. Idealy the peak flow and descending limb should extend into June 15 (not June 1) to allow additional time for late emergent fry to get out, also may allow springers to get upstream, but may be water prohibitive to provide suitable water temperatures past May 31. The unimpaired snowmelt usually extended into July (and sometimes August)
Yearling rearing	specify temperature range, and length of stream along which to provide suitable habitat	150-350					Requires better data and temperature model, should provide suitable habitat as far downstream as Basso Bridge (5 miles) in all years, downstream to Roberts Ferry Bridge in Extremely Wet years
Steelhead							
Streamflow Targets							Other flow requirments for steelhead presumed achieved with flows for fall-run salmon above.
Adult migration	provide suitable flow to trigger migration and allow passage of adults in late winter and early spring		Feb. - April	5-10	Annually		Pulse flows associated with floodplain rearing should be adequate in timing and magnitude.
Over-Summering Habitat	provide suitable water temperatures (65 degrees) during spring summer and fall in reach below dam. Length of reach with suitable temperature depens on year type.	150-400	May 1-Oct. 15	165	Annually		Assumed that hypolimnetic discharge from dam would maintain water temperatures at below 65 degrees for 5-10 miles at flows of 150-400 cfs respectively.
Riparian Vegetation							
Cottonwood							
Seedbed preparation	Clear away weeds, expose mineral soil, deposit fines.	12,000	prior to establishement	2-5	Wet and Ext Wet		Even high flows may not be enough to prepare nursery be for seedling germination due to the existing presence of well established hebaceous species. Target surfaces may need to be mechanically scoured to facilitate scour and deposition at reasonable flows. Deposition of fines may be impossible due to trapping at dam.
seed germination (cottonwood)	use cottonwood as target indicator species	4500	April 15 - May 15	7	Wet and Ext Wet		
seedling growth/establishment	establish target floodplain elevations relative to channel thalweg for cottonwood establishment	gradually decending limb from estabishment stage	April 15 - mid July	15-30	Wet and Ext Wet	50 -100 cfs/day	2 cm/day, which is a variable change in cfs/day, so estimate 50 -100 cfs for now, need rating curves for target site
periodic large-scale disturbance	infrequent "resetting flow" to scour vegetation, create barren areas, and maintain age-class diversity	12000	winter-spring, but best for fish after March	2-5	Ext Wet		
Stand Structure and Diversity							
age/species assemblage diversity	Re-introduce flood disturbance and hydrologic variability to achieve diversity objective	4500 to 12000	Mar 15-June 1	2-5	Normal, wet, ext wet		Timing and magnitude of flows should vary to provide recruitment flows for a variety of species.
Geomorphic Processes							
Sediment Transport							
bed mobilization in gravel bedded reach	target 75-90 mobilization of the D84 in riffle habitats	8000	Mar 15-June 1	2	Wet and Ext Wet		Based on Tuolumne River Restoration Plan. Anytime but best for fish after March 15.
bed scour in gravel bedded reach	scour point bar units to approx twice depth of D84	12000	Mar 15-June 1	2	Ext Wet		Based on Tuolumne River Restoration Plan. Anytime but best for fish after March 15.
Channel Morpohology							
channel migration	define and quantify in terms of lateral bank erosion	12000	Mar 15-June 1	2	Ext Wet		Unknown magnitude, assume 12000 begins to cause migration in gravel reach
Floodplain Processes							
floodplain inundation	Wet the floodplain	4500	Mar 15-June 1	2	Normal, wet, ext wet		Based on Basso floodplains and new channel restoration designs
floodplain fine sediment deposition	Inundate the floodplain by greater than 1 foot depth	8000	Mar 15-June 1	2	Wet and Ext Wet		8000-4500 is estimated 1 ft depth, needs checking

Table 9.8: STANISLAUS: Multi-Objective Ecological Flow Management

ECOSYSTEM INDICATOR	Objective/Notes	Magnitude (cfs)	Timing	Duration (days)	Frequency	Max Rate of Change (cfs)	NOTES
Fall Run Chinook Salmon							
Population Targets							
long-term average escapement	specify escapement target (e.g., AFRP, etc.): not specified for this study.						Not specified for this study. Historical populations below Goodwin as high as 35,000
annual smolt production	specify production target (what all management should aim towards), could use recruitment ratio (Mossdale smolts/spawning pairs)						Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Streamflow Objectives							
Adult migration							
baseflow	provide suitable temperature and eliminate migratory barriers	1,000-4,000 (depends on time and flow in other tribs)	Oct 1-15 (maybe earlier)	2-3 weeks	annually	N/A	Phyical barriers in channel assumed not to be problem at flows above 150 c.f.s. Analysis of Vernalis temperature data indicates that very high flows are necessary to achieve temperatures of 65-70 degrees. May require flows of 1,000 - 4,000 cfs. See figure 9.4.
attraction pulse flow	stimulate upstream movement into spawning grounds	1,000-2,500	Oct 15-19	2-5	annually depending on water year type		pulse flows should provide several short (2-3 day) windows of good water quality (temp and DO) in the Delta and lower SJR to allow passage into lower tributaries; need additional experimentation to confirm that fish actually respond to "attraction pulse flows";
Spawning/Incubation	assume same flow for each life history stage; may eventually differentiate;				annually		
temperature flow	provide suitable temperature range during spawning	200-300	Oct 19-Dec 15		annually		Assumed that temperature not a problem in spawning reach after at flows of > 250 cfs due to hypolimnetic discharge from dam. Needs to be assessed with temperature model
habitat flow	specify minimum, optimal, and range of spawning flows based on habitat criteria, then assign different spawning flows to different water year types (inter-annual variation), and provide variation within each water year (intra-annual variation);	250-500	gradually increasing Oct 19 to Dec 15	4 flow stages, two weeks at each flow from Oct 15 to Dec 15	annually, although may not achieve higher range in dry years	shouldn't matter going up, but needs to descend slowly	Habitat area not analyzed in this study. Assumed to be adequate between 250-500 cfs. Staged releases of progressively higher flows during the spawning season, would provide lower temperatures progressively downstream later in the year (from lowering ambient and from higher releases), encouraging spawning further downstream as the season progresses, reducing superimposition. The staged increases in flows should be modeled with the cumulative spawning curve (not WUA curve) and peak timing of spawning to determine the highest use of the best habitat, and to redistribute spawning downstream to reduce superimposition
Incubation Baseflow	Flow after last spawning occurs to keep incubating eggs in good condition	80% of max spawning habitat flow	Dec 15-March 15	90 days for egg incubation	Annually		The 80% number is a rough estimate. This number could be refined by evaluating spawning locations on a cross section and lower flows to see when the redd begins to de-water.
Fry/juvenile rearing							
upstream baseflows	minimum flows to provide suitable rearing conditions in relative vicinity of spawning habitat	100-250; 600+	winter baseflow-Mar 15 to April 31	45 days	annually		the PHABSIM WUA curve from Tuolumne shows the lowest available rearing habitat in the 200-600 range, for all three habitat types. Only rearing in deep pools (not riffles, runs) improves above 600 cfs;
Floodplain inundation rearing	seasonal, short-duration pulse flow to allow rearing on inundated floodplains	1000-4500	Feb-Apr (better earlier)	5-30 days	Annually if possible		Inundated floodplains have been shown to provide excellent rearing habitat. Costly to provide long duration, but it may be possible to provide series of pulse flows to periodically wet low floodplains/veg. and also prevent stranding. This component needs to be evaluated to determine the strategy that achieves the highest growth rates and lowest mortality from predation
delta	moderate to high (?) baseflows to provide suitable rearing habitat in Delta	not estimated	May	all month, punctuated by pulse flows (VAMP flows)			This component not evaluated in this study. Needs study or literature review to determine suitable flows for rearing in delta, not sure if this is appropriate here, did not use in hydrographs
Outmigration (juvenile/smolt)	Provide suitable temperatures in lower San Joaquin for juveniles and smolts (65 degrees or less for smolts).	1,500-5,000 (depends on flow in other tribs)	May 1-June 15	steep ascending limb, 4-8 day peak, gradual descending limb	Annually if possible	gradual descending for riparian germination	Flows of 3,000 to 5,000 cfs required to maintain temp at 65 degrees during April-May. Flows should be coordinated with other tributaries. Idealy the peak flow and descending limb should extend into June 15 (not June 1) to allow additional time for late emergent fry to get out, also may allow springers to get upstream, but may be water prohibitive to provide suitable water temperatures past May 31. The unimpaired snowmelt usually extended into July (and sometimes August)
Yearling rearing	specify temperature range, and length of stream along which to provide suitable habitat	150-350					Requires better data and temperature model, should provide suitable habitat as far downstream as Basso Bridge (5 miles) in all years, downstream to Roberts Ferry Bridge in Extremely Wet years
Steelhead							
Streamflow Targets							Other flow requirments for steelhead presumed achieved with flows for fall-run salmon above.
Adult migration	provide suitable flow to trigger migration and allow passage of adults in late winter and early spring						TRTAC does not specify targets. AFRP escapement target is 8,900 long term average. This is low relative to what could be achieved with good management. Several 1940's escapements exceeded 100,000 fish.
Over-Summering Habitat	provide suitable water temperatures (65 degrees) during spring summer and fall in reach below dam. Length of reach with suitable temperature depens on year type.	150-350	May 1-Oct. 15				Not specified. Should be a product of the salmon population model with attainable production, mortality, predation parameters
Riparian Vegetation							
Cottonwood							
Seedbed preparation	Clear away weeds, expose mineral soil, deposit fines.	10,000	prior to establishement	2-5	Wet and Ext Wet		Even high flows may not be enough to prepare nursery be for seedling germination due to the existing presence of well established hebaceous species. Target surfaces may need to be mechanically scoured to facillitate scour and deposition at reasonable flows. Deposition of fines may be impossible due to trapping at dam.
seed germination (cottonwood)	use cottonwood as target indicator species	3,500	April 15 - May 15	7	Wet and Ext Wet		
seedling growth/establishment	establish target floodplain elevations relative to channel thalweg for cottonwood establishment	gradually decending limb from estabishment stage	April 15 - mid July	15-30	Wet and Ext Wet	50 -100 cfs/day	2 cm/day, which is a variable change in cfs/day, so estimate 50 -100 cfs for now, need rating curves for target site
periodic large-scale disturbance	infrequent "resetting flow" to scour vegetation, create barren areas, and maintain age-class diversity	10,000	winter-spring, but best for fish after March	2-5	Ext Wet		
Stand Structure and Diversity							
age/species assemblage diversity	Re-introduce flood disturbance and hydrologic variability to achieve diversity objective	3,500 to 10,000	Mar 15-June 1	2-5	Normal, wet, ext wet		
Geomorphic Processes							
Sediment Transport							
bed mobilization in gravel bedded reach	target 75-90 mobilization of the D84 in riffle habitats	6,000	Mar 15-June 1	2	Wet and Ext Wet		Any time, but best for fish after mid March
bed scour in gravel bedded reach	scour point bar units to approx twice depth of D84	10,000	Mar 15-June 1	2	Ext Wet		Any time, but best for fish after mid March
Channel Morpohology							
channel migration	define and quantify in terms of lateral bank erosion	10,000	Mar 15-June 1	2	Ext Wet		Unknown magnitude, assume 12000 begins to cause migration in gravel reach
Floodplain Processes							
floodplain inundation	Wet the floodplain	3,500	Mar 15-June 1	2	Normal, wet, ext wet		Based on Basso floodplains and new channel restoration designs
floodplain fine sediment deposition	Inundate the floodplain by greater than 1 foot depth	6,000	Mar 15-June 1	2	Wet and Ext Wet		8000-4500 is estimated 1 ft depth, needs checking

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Table 9.1. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Hydrological Flow Methods (aka Historical Flow, Fixed-Percentage, Standard-Setting, Discharge, Desktop, or Office Methods)					
Montana (Tennant) Method--Associates different river conditions with different percentages of mean annual flow (MAF) for a high- and low-flow season. The most widely used of the hydrological flow methods. References: Annear and Conder 1984; Caissie and El-Jabi 1995; IFC 2002; Orth and Maughan 1982; Railsback 2001; Tennant 1976; Tharme 2000, 2002	Recommend Flows / Ecosystem-level / Seasonal	Tennant developed this method by studying changes in widths, depths, and velocities in relation to changes in % MAF for 11 moderate-sized streams in Montana, Wyoming, and Nebraska. A river condition was assigned to each level of flow based on the quality of the physical habitat it provided for fish (trout), wildlife, recreation and related environmental resources***. Different percentages are provided for low- and high-flow periods, the timing of which may differ among regions. It is generally recommended that practitioners conduct site evaluations to determine if the percentages assigned to these classifications require modification for the basin of interest.	1) Habitat quality is similar in most streams when they carry the same percentage of their average annual flow	1) Requires little or no field work 2) Relatively fast and inexpensive	1) Generally limited to reconnaissance-level planning (rather than meeting species- or resource-specific objectives) 2) Does not consider the effects of changes in channel shape, e.g., due to flow regulation or recommended flow regime 3) Never produces a zero flow recommendation, so may not be applicable for rivers that naturally dry out in some months 4) Generally does not incorporate site-specific biological or geomorphological information in the decision-making process 5) Method was designed for fast-water fish (trout), so may not be appropriate for some non-salmonid species, e.g., fish that require inundation of floodplains for spawning 6) Method was developed based on moderate-sized rivers, so may not be applicable to all sizes of streams 7) Provides for little, if any, intra- or interannual variation in flow 8) Typically requires unimpaired or naturalized hydrologic records 9) Biological assumptions have not yet been proven 10) Does not explicitly consider floodplain flows, which are critical for spawning by some fish species

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
New England Aquatic Base Flow (ABF)-- Recommends August median flow for a minimum summer flow value; February median flow for fall/winter; and April/May median flow for the spring period. For ungaged streams, where historical monthly medians are unknown, the recommended minimum flows are 0.5 cubic feet per second per square mile of drainage area (cfsm) in the summer, 1.0 cfsm in fall/winter, and 4.0 cfsm in spring. In some applications, the August median flow is used as a year-round minimum flow. References: Caissie and El-Jabi 1995; IFC 2002; Railsback 2001	Recommend Flows / Community-level / Seasonal	This method was developed by the U.S. Fish and Wildlife Service to provide minimum streamflow guidelines for the New England region, where August low flows represented a natural limiting period for aquatic organisms. The rationale behind this method is that species evolved to survive these low flow conditions, so such flows should be suitable base flows. Different (higher) monthly medians are recommended for spring and fall/winter to provide for spawning, migration, and other biological needs. Default values for ungaged streams were determined from a survey of minimally impacted streams and rivers in New England.	1) Fish are adapted to survive the historical low-flow month	1) Requires little or no field work 2) Relatively fast and inexpensive	1) Generally limited to reconnaissance-level planning (rather than meeting species- or resource-specific objectives) 2) Does not consider the effects of changes in channel shape, e.g., due to flow regulation or recommended flow regime 3) Generally does not incorporate site-specific biological or geomorphological information in the decision-making process 4) Provides for little, if any, intra- or interannual variation in flow 5) Typically requires unimpaired or naturalized hydrologic records 6) Based on New England hydrology, so may not be applicable outside of this region (e.g., in regions with greater hydrologic variability, low flow months may have flows near zero) 7) Generally does not provide for the necessary regime of flows critical to maintaining natural riverine functions and processes 8) Biological assumptions have not yet been proven 9) Does not explicitly consider floodplain flows, which are critical for spawning by some fish species

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Flow Duration Curve Methods--A class of methods in which flow exceedence percentiles or proportions of monthly medians are recommended for application within specific regions, often by season. References: Caissie and El-Jabi 1995; IFC 2002	Recommend Flows / Community-level / Depends on method, but generally monthly	A number of region-specific approaches have been developed for recommending environmental flows based on flow duration curves, each with its own rationale for flow selection. Flow duration curves are derived from hydrologic records and display the relationship between flow discharge and the percentage of time that it is exceeded. Some professional judgment is used in determining specific flow percentiles for maintaining suitable river conditions for a region. Moderate field effort may be required with some methods. For ungaged streams, recommended flows may be determined using hydrologic statistics and gage data from nearby reference streams. Some flow duration curve methods are outlined below: > Hoppe Method--Recommends Q40 (flow that is exceeded 40% of the time) for spawning, Q80 for food production and cover, and Q17 for 48 hours as a flushing flow. > Northern Great Plains Resource Program Method--Recommends monthly Q90 as the minimum instream flow for each month. > Lyon's Method--For habitat maintenance Oct.-March, recommends 40% of the monthly median (Q50). For spawning and hot summer months (April-Sept.), recommends 60% of Q50.	1) The specific percentiles or percentages recommended by each method are appropriate for maintaining habitat and biological functions of aquatic biota	1) Requires little or no field work 2) Relatively fast and inexpensive	1) Generally limited to reconnaissance-level planning (rather than meeting species- or resource-specific objectives) 2) Most do not consider the effects of changes in channel shape, e.g., due to flow regulation or recommended flow regimes 3) Most do not incorporate site-specific biological or geomorphological information in the decision-making process 4) Most provide for little, if any, interannual variation in flow 5) Typically require unimpaired or naturalized hydrologic records 6) Many do not provide for the necessary regime of flows critical to maintaining natural riverine functions and processes 7) Recommended flows are difficult to justify biologically, particularly when site-specific information is not incorporated 8) Most do not explicitly consider floodplain flows, which are critical for spawning by some fish species

Range of Variability Approach (RVA)-- Identifies an appropriate range of variation (typically 1 standard deviation from the mean) for each of 33 hydrologic parameters, at multiple time scales. Monitoring and adaptive management are used to regularly evaluate effects of flow releases and revise flow targets as necessary. References: IFC 2002; Railsback 2001; Richter et al. 1996, 1997; Tharme 2000, 2002	Recommend Flows, Monitor Conditions / Ecosystem-level / Daily (for some parameters)	A relatively new methodology developed by The Nature Conservancy based on the notion that natural variation in flow is critical to protecting the integrity of river ecosystems. The natural range of flow variation is characterized using 33 hydrological parameters (collectively called "Index of Hydrologic Alteration" or IHA) that describe the magnitude, timing, duration, frequency, and rate of change of a river's natural flow regime, as calculated from a river's hydrologic records. Initial target ranges are defined for each of the parameters (e.g., duration of low flow periods should fall within 1 standard deviation of historic durations), and flows are managed to meet these target ranges every year. RVA emphasizes restoration of natural flow variation to support ecosystem (including riparian) processes and biodiversity, rather than particular fish species.	1) Maintaining a fraction of natural flow variability will protect or restore aquatic ecosystems 2) The 33 hydrologic parameters adequately capture elements of the flow regime necessary to maintain or restore important ecosystem processes	1) Requires little or no field work 2) Adaptive management approach allows flow targets and river management strategies to be refined over time 3) Accounts for natural intra-annual variation in flow 4) Parameters are relatively easy to calculate from hydrologic records 5) Incorporates wide range of hydrologic parameters 6) Through monitoring and adaptive management, incorporates site-specific information in the decision-making process	1) Generally limited to reconnaissance-level planning (rather than meeting species- or resource-specific objectives) where objective is restoration of historic ecosystem processes and biodiversity 2) Typically requires unimpaired or naturalized hydrologic records 3) Although provides for intra-annual variation in flow, may not adequately address ecosystem processes that occur over longer time frames 4) Biological assumptions have not yet been proven 5) Adaptive management approach may be expensive to implement (due to monitoring costs, etc.) and result in long-term uncertainty in flow release requirements 6) In practical terms, may be difficult to schedule annual flow releases to meet complex target flows recommended by method

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Hydraulic Rating Methods					

Wetted-Perimeter Approach--Sets minimum flow near the inflection point of a wetted perimeter-discharge curve, i.e., below which an increase in flow results in a large increase in wetted stream perimeter and above which it produces only a minor increase in wetted perimeter. This point usually occurs at a discharge level that inundates much of the streambed to the bottom of the bank. The most widely used of the hydraulic rating methods. References: Annear and Conder 1984; Gippel and Stewardson 1998; IFC 2002; Orth and Maughan 1982; Tharme 2002	Compare and Recommend Flows / Community-level / None	This method seeks to maximize area of wetted streambed, which is assumed to provide critical fish rearing and benthic invertebrate production habitat. Transects are typically placed in riffles because these areas are early affected by reductions in flow discharge. Along each transect, wetted perimeter is measured as the length of wetted channel perpendicular to flow. Field data are used to develop a wetted perimeter-discharge curve, from which an inflection point (curve breakpoint) can be determined. Minimum flows for fish rearing are generally set near the inflection point of the wetted-perimeter-discharge curve.	1) Wetted channel area is the primary limiting factor for aquatic communities, particularly fish	1) Requires relatively little field work 2) Incorporates site-specific information in the decision-making process 3) Does not require unimpaired or naturalized hydrologic records	1) Generally limited to reconnaissance-level planning (rather than meeting species- or resource-specific objectives) 2) Provides for little, if any, intra- or interannual variation in flow 3) Generally does not provide for the necessary regime of flows critical to maintaining natural riverine functions and processes 4) Biological assumptions have not yet been proven 5) Determination of inflection point may be somewhat subjective, particularly when none or multiple points exist 6) Never produces a zero flow recommendation, so may not be applicable for rivers that naturally dry out in some months 7) Number and placement of sample transects will affect wetted perimeter-discharge curves (and, consequently, flow recommendations) 8) Does not consider the effects of changes in channel shape (and therefore wetted perimeter-discharge curve) due to recommended flow regime 9) Does not explicitly consider floodplain flows, which are critical for spawning by some fish species

R-2 Cross Hydraulic Model--Calculates minimum flow as the discharge necessary to meet certain hydraulic requirements of wetted perimeter, depth, and water velocity (for aquatic organisms) in habitats vulnerable to low flow conditions. References: Skinner (http://cwcb.state.co.us/isf/V2IS1_R2CROSS.htm)	Compare and Recommend Flows / Community-level / Seasonal	This method is based on the biological assumption that protecting certain critical habitats vulnerable to low-flow conditions will produce the greatest relative benefit for fish and other aquatic organisms. In most streams, riffles are one of the first habitat types lost as flows diminish. These shallow areas connecting pools are important habitat for fish and aquatic insects. The R2Cross computer model analyzes measurement data collected from representative riffles or other low-flow habitats and produces a table of hydraulic characteristics (including wetted perimeter, depth, and water velocity) at various levels of flow from almost no flow to bankfull conditions. Recommended flows are those necessary to maintain, in these critical habitats, the hydraulic characteristics necessary to support fish and other aquatic life.	1) Fish and other aquatic organisms are limited by suitability of certain habitats, such as riffles, during low-flow conditions	1) Incorporates site-specific information in the decision-making process 2) Does not require unimpaired or naturalized hydrologic records 3) Incorporates multiple biologically-based hydraulic parameters	1) Provides for little, if any, intra- or interannual variation in flow 2) Generally does not provide for the necessary regime of flows critical to maintaining natural riverine functions and processes 3) Number and placement of representative low-flow habitats will affect flow recommendations 4) Never produces a zero flow recommendation, so may not be applicable for rivers that naturally dry out in some months 5) Does not consider the effects of changes in channel shape (and therefore hydraulic characteristics of low-flow habitats) due to recommended flow regime 6) Does not explicitly consider floodplain flows, which are critical for spawning by some fish species 7) Biological assumptions have not yet been proven

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Habitat Simulation Methods (aka Habitat Rating, Habitat Modeling, or Microhabitat Methods)					

Instream Flow Incremental Methodology (IFIM)--Computer-intensive method that recommends flows based on the amount of usable habitat, defined by some combination of depth, velocity, and substrate, provided for life stages of target species at different stream flows. The most widely used of the habitat simulation methods. References: Annear and Conder 1984; Castleberry et al. 1976; Gore and Nestler 1988; IFC 2002; Orth 1987; Orth and Maughan 1982; Poff et al. 1997; Railsback 2001; Reiser et al. 1989; Scott and Shirvell 1987; Tharme 2000	Compare and Recommend Flows / Species-level / Seasonal	A technically advanced, complex methodology developed by the U.S. Fish and Wildlife Service. At the heart of IFIM is the Physical Habitat Simulation Model (PHABSIM), a system of 240 computer programs housed within five different hydraulic and five habitat simulation models. Habitat data (depth, velocity, substrate) are collected along several transects in one or more representative stream reaches. One of PHABSIM's hydraulic simulation models is used to establish depth/velocity relations to discharge for a stream reach. The model results, habitat data, and habitat suitability curves (developed based on knowledge of target species' microhabitat preferences at particular life stages) are input into a habitat simulation model for each discharge, target species, and life stage of interest. For each target species and life stage, results are graphed in a weighted usable area (WUA) versus discharge curve showing changes in habitat availability with increases in discharge. Breakpoints on these curves are often used in recommending environmental flows.	1) Depth, velocity, and substrate are the most important variables for describing habitat suitability for target species or activities 2) Depth, velocity, and substrate independently influence habitat use by target species or for target activities 3) Weighted usable area is an effective predictor of target species standing stock or habitat use	1) Incorporates site-specific information in the decision-making process 2) Does not require unimpaired or naturalized hydrologic records 3) Incorporates multiple biologically-based hydraulic and habitat parameters 4) Can be used or adapted to meet management objectives targeting specific recreational uses, resources, species assemblages (including riparian), species, or critical life stages 5) Can be used to evaluate trade offs for various management objectives in relation to changes in discharge 6) Its apparent scientific objectivity, technical sophistication, and widespread acceptance make it appropriate for resolving highly contentious water use conflicts	1) Provides for little, if any, interannual variation in flow 2) Generally does not provide for the necessary regime of flows critical to maintaining natural riverine functions and processes 3) Number and placement of sample transects will affect flow recommendations 4) May be difficult to develop habitat suitability curves for little-studied species, including most warmwater stream fishes 5) PHABSIM results are highly dependent on which models are used 6) No scientifically defensible method for combining model outputs for different species and life stages into a single recommended flow regime. 7) Uses various spatial resolutions throughout the method, causing errors that are not easily defined 8) Never produces a zero flow recommendation, so may not be applicable for rivers that naturally dry out in some months 9) Changes in WUA have not been explicitly linked to changes in target species populations 10) Relatively expensive and complex 11) As with many computer-based modeling applications, there is a high risk of "incorrect" outputs when used by practitioners who don't understand assumptions and theory of methodology 12) Method's assumptions may not hold for larger, warmer, and more turbid rivers 13) Habitat selection models predict fish distribution rather than abundance; there are no direct implications for most management concerns 14) Does not consider the effects of changes in channel shape (and therefore habitat suitability at various discharge levels) due to recommended flow regime 15) Development of habitat suitability curves prone to measurement and sampling errors 16) Biological assumptions have not yet been proven

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Riverine Community Habitat Assessment and Restoration Concept (RCHARC)--Compares alternative instream flow schedules based on their ability to match the monthly frequency distribution of depths and velocities observed in a target (typically unimpaired) reference river. References: IFC 2002; Railsback 2001	Compare and Recommend Flows / Community-level / Monthly	Developed by the U.S. Army Corps of Engineers for assessment of large, warm rivers. A river system with desired habitat conditions (e.g., one that supports a desired aquatic community) is selected for reference. Data collected along 4 to 8 sample transects are modeled to produce a target frequency distribution of depths and velocities by month. Alternative flow regimes are evaluated, on a month-by-month basis, to determine which are likely to produce a distribution of depths and velocities (in the study site) similar to the target distribution.	1) Monthly distribution of depth and velocity are the most important flow-related factors determining the health and composition of river communities 2) Depth and velocity independently influence health and composition of river communities	1) Incorporates site-specific information in the decision-making process 2) Does not require unimpaired or naturalized hydrologic records 3) Accounts for natural intra-annual variation in flow	1) Number and placement of sample transects will affect flow recommendations 2) Does not consider the effects of changes in channel shape (and therefore distribution of depths and velocities) due to recommended flow regime 3) Provides for little, if any, interannual variation in flow 4) Relatively expensive 5) Ability to meet ecological and other objectives depends on selection of suitable reference site 6) Does not explicitly consider floodplain flows, which are critical for spawning by some fish species 7) Methods for statistical comparison of depth/velocity distributions between reference and study site are not yet well developed 8) Biological assumptions have not yet been proven
Holistic Methods (aka Professional Judgement Methods)					

Method Summary	Purpose / Scope* / Timestep**	Description/Implementation Steps	Assumptions	Advantages	Limitations
Building Block Methodology--Experts in various fields of riverine ecology (including fish, aquatic invertebrates, riparian vegetation, fluvial geomorphology, local hydraulics, water chemistry and social dependence) combine existing knowledge in workshop settings to recommend an environmental flow regime. References: IFC 2002; King and Louw 1998; Tharme 2000, 2002	Compare and Recommend Flows / Ecosystem-level / Monthly	The BBM originated in South Africa as a means to address the country's river management needs while acknowledging limitations on available hydrologic data, technical expertise, and financial resources. The BBM provides a structured workshop process for river scientists to utilize available hydrological baseflow and flood data and existing knowledge on flow-related needs of ecosystem components, to identify specific flow elements critical to maintaining natural riverine functions and processes. These flow elements are described in terms of magnitude, duration, timing, and frequency, and incorporated into recommended flow regimes for both maintenance and drought conditions. During the workshop, hydrological and hydraulic modelers analyze data to answer questions posed by workshop participants. Limited new data may also be collected to inform the process. The output is a target environmental flow regime, quantitatively detailed over space and time.	1) Environmental flow regimes based primarily on professional knowledge of critical flows can be effectively used to maintain natural riverine functions and processes	1) Incorporates site-specific information in the decision-making process 2) Requires little or no field work 3) Accounts for natural intra- and inter-annual variation in flow 4) Comprehensive ecosystem approach for whole-river management 5) Relatively fast and inexpensive 6) Requires minimal unimpaired or naturalized hydrologic records 7) Directly incorporates professional knowledge from various fields of river science in decision-making process 8) Flows benefiting specific river uses, resources, species assemblages (including riparian), species, etc., can be incorporated in recommended flow regime 9) Findings and recommendations from other environmental flow methodologies can be utilized in decision-making process	1) Subjective approach--recommended flows may be vulnerable to challenge and difficult to defend 2) Biases and skills of workshop participants will affect flow recommendations 3) No scientifically defensible method for combining critical flows (for different species, processes, etc.) into a single recommended flow regime.

Table 9.1 cont'd. Summary of Instream Flow Methodologies

Expert Panel Assessment Method (EPAM)--A panel of experts in river science observes trial flow releases at multiple sites downstream of a reservoir and recommends a flow regime based on the suitability of trial flows for riverine processes, and primarily for abundance and survival of native fish species. References: Swales and Harris 1995	Compare and Recommend Flows / Ecosystem-level / Seasonal	One or two expert panels--each comprising specialists in the fields of freshwater fish ecology, river invertebrate ecology, and fluvial geomorphology--are set up to observe flows from each of several inspection sites 3 - 8 km downstream of a dam. Four experimental flows representing 80%, 50%, 30%, and 10% flow percentiles are released. Panels evaluate suitability of each discharge for ecological processes, especially native fish communities. Panels decide on a consensus suitability score (1 - 5, where 5=excellent) for each flow on a seasonal and non-seasonal basis. Primary considerations include fish spawning and rearing requirements and fish passage.	1) Flows can be visually assessed by a group of experts in a reasonably objective way that lends itself to repeatability over space and time	1) Incorporates site-specific information in the decision-making process 2) Requires little or no field work 3) Relatively fast and inexpensive 4) To a certain degree, may account for natural intra- and inter-annual variation in flow 5) Does not require unimpaired or naturalized hydrologic records 6) Directly incorporates professional knowledge from various fields of river science in decision-making process 7) Although primary emphasis is typically on fish, flows benefiting specific river uses, resources, species assemblages (including riparian), species, etc., can be incorporated in recommended flow regime 8) Entire stream reach can be assessed, rather than a limited number of representative transects	1) Subjective approach--recommended flows may be vulnerable to challenge and difficult to defend 2) Biases and skills of participants will affect flow recommendations 3) Not well-suited for assessment of intra- or inter-annual variations in flow 4) In some cases, there may be legal, economic, or other impediments to experimental flow releases, particularly at the 10% (high flow) flow percentile

* Scope--General (highest level) flow targets. "Species-level" means flows are designed to benefit a single or a few species; "Community-level", a single or a few communities, e.g., fish and/or macroinvertebrate communities; "Ecosystem-level", a wide range of aquatic and riparian elements.

** Timestep--The minimum timestep for which flows are generally recommended. None=not applicable (single value recommended)

*** The table below is reproduced from Tennant (1976).

Description	Oct - Mar (% of MAF)	Apr - Sept (% of MAF)
Flushing or maximum	200	200
Optimum	60 - 100	60 - 100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	<10	<10

Table 9.1. Summary of Environmental Flow Methodologies
[INSERT TABLE 9.1 HERE—Ellen needs to finish cites]

An Assessment of Hydrologic Alteration in the San Joaquin River Basin, CA

performed by Brian Richter
for the Natural Heritage Institute
February 2002

An Assessment of Hydrologic Alteration in the San Joaquin River Basin, CA

Background

This report summarizes a comprehensive assessment of hydrologic alteration in the San Joaquin River basin (Figure 1). The analysis focuses on each of the three main tributaries (Stanislaus, Tuolumne, and Merced) as well as the mainstem of the San Joaquin River.

The natural hydrologic conditions of the San Joaquin watershed began to be altered as early as the mid-1800's due to mining activities and timber clearing in the upper watershed and agricultural activities on the valley floor. These early hydrologic changes, however, pale in comparison to the alterations associated with the construction of major storage dams and associated water diversion beginning around the turn of the century (refer to table in Appendix 1). Fairly large storage dams were built for irrigation water supply on each of the four rivers during 1893-1942, but the storage capacities of those earlier reservoirs are rather small compared to the "new generation" of dams built in the late 1960's and 70's. The construction of New Exchequer Dam on the Merced River enabled the storage of more than a full year's worth of runoff; New Don Pedro Dam enabled capture of nearly a year and a half's worth of runoff; and New Melones Dam on the Stanislaus enabled capture of nearly two-and-a-half year's worth of runoff. Each of these mega-dams also provides flood control and some hydroelectric power generation. The operations of these facilities for these multiple purposes has resulted in drastic changes to the natural hydrologic regimes of the tributaries and mainstem San Joaquin, to the point that flows in these rivers now bear little resemblance to natural flow patterns.

The history of hydrologic alteration in the San Joaquin watershed can thus be viewed as three distinct phases of water development: alterations associated primarily with land use activities in the mid- to late-1800's; development of small dams and diversions in the first half of the 1900's; and the big dam era beginning in 1967. As will be illustrated in this report, the latter two phases left distinctive marks on the hydrologic regimes of rivers in the San Joaquin basin.

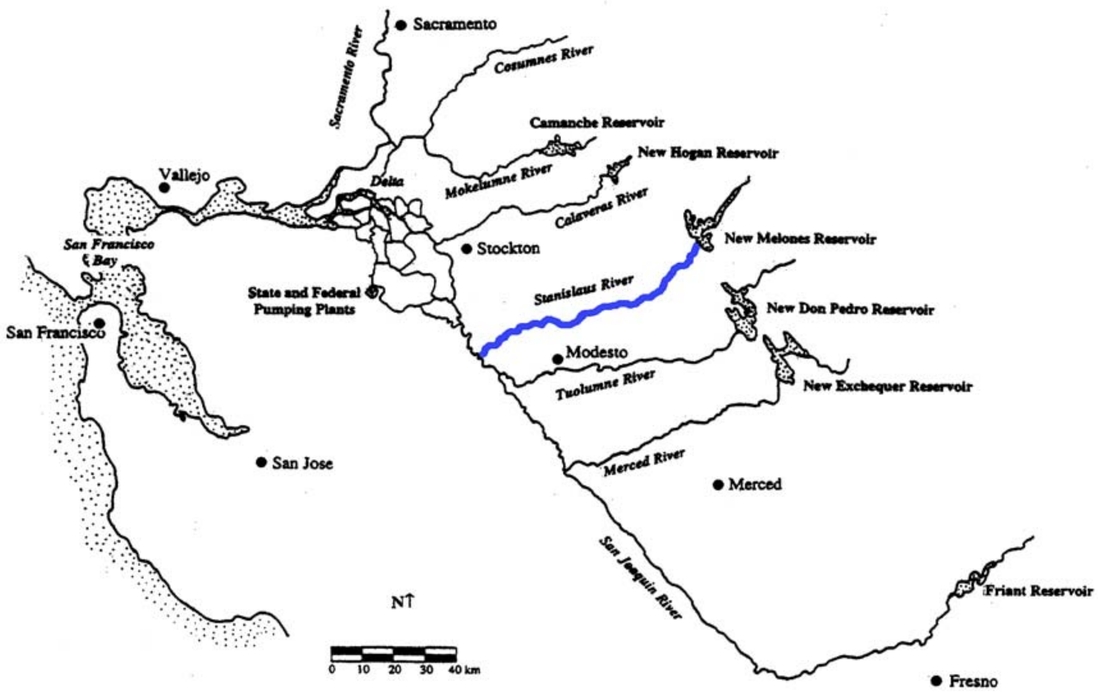

Figure 1. San Joaquin River and Tributaries Location Map, California.
(Map adapted from Kondolf et al, 1996).

Methods

The primary tool used in this analysis is the "Indicators of Hydrologic Alteration" (IHA) software developed by The Nature Conservancy.[1] This software enables assessment of changes in 33 different hydrologic parameters (Table I). While the IHA parameters have been designed to assist investigators in analyzing ecologically-relevant hydrologic changes, the results of an IHA analysis provide no direct information about ecological changes in the river(s) being assessed. However, IHA results do provide an excellent basis upon which to develop hypotheses of ecological impacts, as described in Richter et al. 1997.[2]

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[1] 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.
[2] 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.

Table I. Summary of 33 hydrologic parameters used in the Indicators of Hydrologic Alteration software, and their characteristics.

IHA Statistics Group	*Hydrologic Parameters*	*Ecosystem Influences*
Magnitude of monthly water conditions	Mean value for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
Magnitude and duration of annual extreme water conditions	Annual 1-day minima	• Balance of competitive, ruderal, and stress- tolerant organisms
	Annual minima, 3-day means	• Creation of sites for plant colonization
	Annual minima, 7-day means	• Structuring of aquatic ecosystems by abiotic vs. biotic factors
	Annual minima, 30-day means	• Structuring of river channel morphology and physical habitat conditions
	Annual minima, 90-day means	• Soil moisture stress in plants
	Annual 1-day maxima	• Dehydration in animals
	Annual maxima, 3-day means	• Anaerobic stress in plants
	Annual maxima, 7-day means	• Volume of nutrient exchanges between rivers and floodplains
	Annual maxima, 30-day means	• Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments
	Annual maxima, 90-day means	• Distribution of plant communities in lakes, ponds, floodplains
	Number of zero-flow days (zero flow)	• Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
Timing of annual extreme water conditions	Julian date of each annual 1-day maximum	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms
	Julian date of each annual 1-day minimum	• Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms

Table I, continued

IHA Statistics Group	*Hydrologic Parameters*	*Ecosystem Influences*
Frequency and duration of high and low pulses	Number of low pulses within each year	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants
	Mean duration of low pulses within each year	• Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain
	Number of high pulses within each year	• Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites
	Mean duration of high pulses within each year	• Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Rate and frequency of water condition changes	Means of all positive differences between consecutive daily values	• Drought stress on plants (falling levels)
	Means of all positive differences between consecutive daily values	• Entrapment of organisms on islands, floodplains (rising levels)
	Number of hydrological reversals	• Desiccation stress on low-mobility streamedge (varial zone) organisms
	Grand total 33 parameters	

The IHA software provides a number of different options for assessing hydrologic changes. A user may choose to compare two data sets of daily flows, such as before and after construction of a dam. Alternatively, gradual trends in hydrologic conditions can be evaluated using regression analysis, which is useful in assessing hydrologic trends in watersheds undergoing progressive land use conversion over time. One of the most powerful capabilities of the IHA software is the ability to plot and view graphs of the annual series of values for each of the 33 parameters.

The results of an IHA analysis are most informative when human-altered daily flow conditions can be compared with "unimpaired" daily flow conditions simulated using a hydrologic model. When unimpaired flows are not available for comparison, the investigator is left to compare different periods of record, such as before and after dam construction, to assess human influences. Such a comparison is not as reliable because climatic differences between the two periods can induce another source of variability. Furthermore, because the operational protocols at any particular dam may be modified over time, the measured impacts of a dam may vary over time.

Because unimpaired daily flows are available only for the Tuolumne, this IHA analysis was necessarily based upon comparison of different time periods. For each streamgauge site analyzed, hydrologic conditions from at least two decades in the early part of the available record is compared with data from (at least two) recent decades (Table II). Graphs of annual values of 18 different IHA parameters are also provided for each tributary and the mainstem San Joaquin, for the entire period of available record, which enable visual assessment of changes over time in each river associated with construction of dams and diversions.

Table II. Periods of record used for IHA analysis

	Early Period	Recent Period
Stanislaus River	1896-1925	1980-2000
Tuolumne River	1896-1922	1972-2000
Merced River	1902-1925	1968-2000
San Joaquin River	1908-1940	1951-2000

Results

The results of the IHA analysis are first summarized for each of the tributary basins and the middle reach of the San Joaquin River separately. Most of the conclusions drawn from the IHA analysis for these river basins are based upon visual analysis of the graphs of the 18 IHA parameters included in the Appendices. Because such conclusions are based upon visual (qualitative) observation, and comparison of “unimpaired” with “measured” conditions is not yet possible, these conclusions should be regarded as speculative. That being said, the hydrologic changes discussed here are based on rather obvious, fairly abrupt breaks in the annual series associated with the construction of particular dams or diversions.

After discussing river-specific patterns of alteration, the overall spatial patterns of hydrologic alteration in the whole San Joaquin basin are discussed.

Stanislaus River

Three phases of water development in the Stanislaus River basin are quite evident in Figure 2 and Table III. Prior to construction of Old Melones Dam in 1926, less than 4% of the average annual runoff of the river could be stored in the nine reservoirs regulated by the Division of Safety of Dams. After construction of New Melones Dam in 1978, more than 220% of average annual runoff could be stored.

Significant changes in hydrologic conditions at Knight's Ferry became apparent with the construction of the Old Melones Dam in 1926 (see Stanislaus graphs in Appendix 2). The January mean flows are noticeably suppressed beginning 1926, which may have resulted from Old Melones Dam's ability to capture early snowmelt runoff. Particularly noticeable are changes in August and September flows, which begin to increase in 1926, presumably due to the release of water from Old Melones for downstream irrigation use late in the summer growing season.

The effects of the Goodwin Dam and associated diversions (South San Joaquin Canal and Oakdale Irrigation Canal), constructed in 1912-14, do not show up in the graphs of Appendix 2 until 1957. This is because the data plotted for Knight's Ferry were derived from a number of different gauge sites over time (see Appendix 1). Prior to 1957, the Knight's Ferry data were obtained from streamgauges lying upstream of the Goodwin Dam and diversions. Beginning in 1957, data obtained from the "Below Goodwin" site are plotted for Knight's Ferry. Thus, the Knight's Ferry graphs reflect the effects of both the Goodwin Dam and diversions and the construction of the "Tri-Dams" project after 1957.

The impact of the Goodwin Dam and diversions is quite detectable in the August and September graphs. The abrupt drop of approximately 1,400 cfs between 1956 and 1957 for the month of August, and of more than 900 cfs between the same years for the month of September, illustrates the impact of these diversions in the river reaches below Goodwin Dam.

Note that the annual traces for the Ripon streamgauge do not show a similar abrupt drop for August or September in 1956-57, suggesting that the construction of the Tri-Dams project did not have much apparent effect on these late summer flows. On the other hand, the Tri-

Dams project did have an apparent effect on increasing the average duration of “low pulses” (when flows drop below the 25th percentile), and depressing April and May flows after 1956.

The construction of New Melones Dam in 1978 appears to have had a substantial impact on many of the Stanislaus River’s flow characteristics. These effects are most evident on the near-complete curtailment of large floods (see 1-day maxima graph), and substantial augmentation of low flows (7-day minima graph). Not all of the flow changes associated with New Melones Dam are necessarily “bad”, however. For instance, flows in May-August appear to have measurably increased, making them more similar to the early decades of record (e.g., 1896-1925). The duration of low pulses has apparently improved (lessened) as well.

Overall, the largest measured changes between the early (1896-1925) and recent (1980-2000) periods are as follows (see “IHA Scorecard” in Appendix 2):

- February – June flows have been depressed considerably, ranging from 79% in May to 43% in March.
- September and October flows have increased (106% and 57%, respectively)
- 1- to 90-day minimums have increased by 44-128%
- 1- to 90-day maximums have decreased by 74-81%
- High pulses (flows above 75th percentile) occur far less frequently and now last only 1 day on average, as compared to 13 days in the early period.

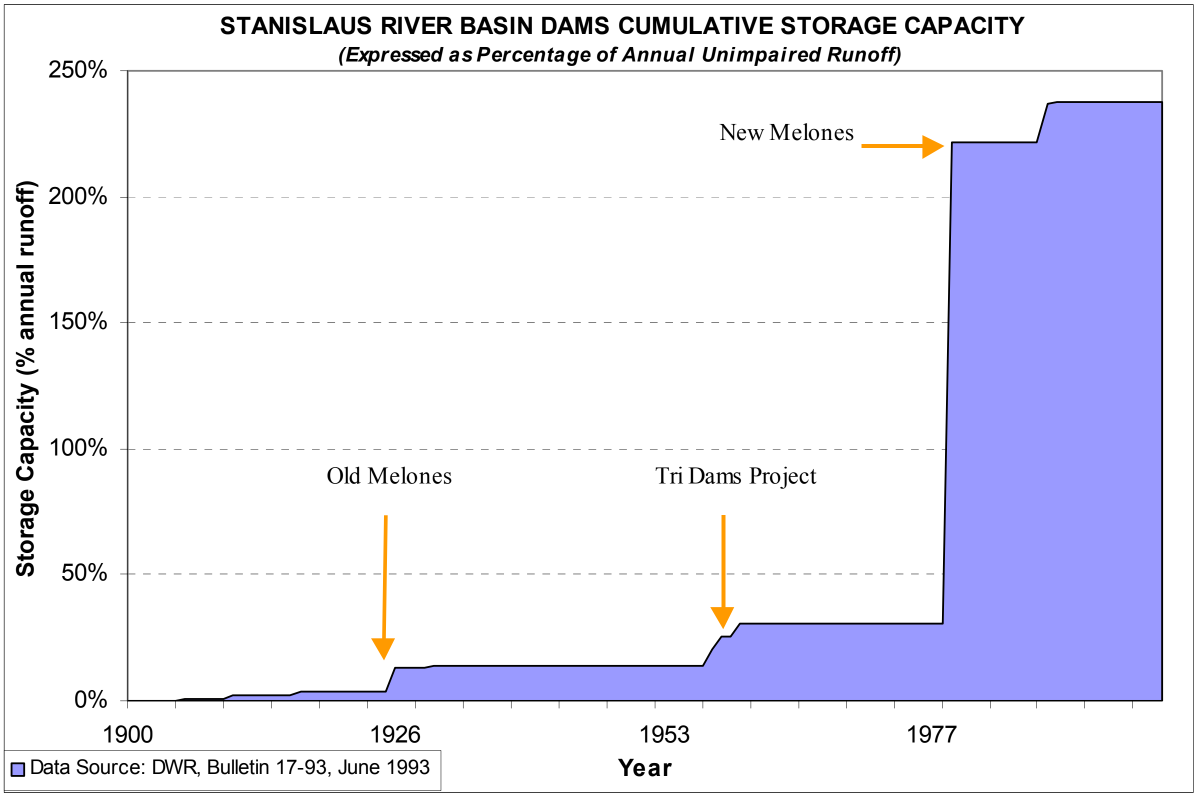

Figure 2: Stanislaus River Basin Dams Capacity.
Incremental increase in storage capacity expressed as a percentage of mean annual runoff. Note the most noticeable jumps occur in 1926 with the construction of Old Melones Dam, 1957-8 with the Tri-Dams Project, 1979 with New Melones Dam (see photo below), and 1988 with New Spicer Meadows. The total capacity of Stanislaus River dams is just under 2.85 maf, relative to annual unimpaired runoff of 1.2 maf (Calfed 2000). See Table ST1 for details regarding calculations and data sources.

Table III: Stanislaus River Basin Dams and Cumulative Storage Capacity. Data on the dams within the Stanislaus basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.2 MAF, Calfed, 1999).

A	***B***		***C***		***D***	***E***	***F***
Year	Dam Name		Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1902	Union	NF	N Fork	2,470,000	2,000	2,000	0.2%
1905	Copperopolis	M	Penney Creek	278,000	225	2,225	0.2%
1906	Alpine	NF	Silver Creek	5,670,000	4,596	6,821	0.6%
1908	Stan FB	M	Trib Stan. River	395,000	320	7,141	0.6%
1908	Utica	NF	N Fork	2,960,000	2,399	9,541	0.8%
1910	Relief	MF	Relief Creek	18,700,000	15,158	24,699	2.1%
1912	Goodwin	M	Mainstem	617,000	500	25,199	2.1%
1916	Rodden Lake	M	Lesnini Creek	469,000	380	25,579	2.1%
1916	Main Strawberry	SF	South Fork	22,900,000	18,312	43,891	3.7%
1926	Old Melones [3]	M	Mainstem	139,000,000	112,674	156,566	13.0%
1928	Hunters	NF	Mill Creek	246,000	199	156,765	13.1%
1930	Lyons - PGE	SF	South Fork	7,680,000	6,228	162,993	13.6%
1938	McCarty	M	Trib Johnny Creek	115,000	93	163,086	13.6%
1953	Murphys Afterbay	M	Trib Angels Creek	49,300	40	163,126	13.6%
1953	Murphys Forebay	M	Trib Angels Creek	66,600	54	163,180	13.6%
1953	Fly in Acres	NF	Moran Creek	123,000	100	163,280	13.6%
1957	Beardsley	MF	Middle Fork	120,000,000	77,600	240,880	20.1%
1958	Tulloch	M	Mainstem	84,400,000	68,400	309,280	25.8%
1958	Beardsley Afterbay	MF	Middle Fork	395,000	320	309,600	25.8%
1958	Donnells	MF	Middle Fork	79,600,000	56,893	366,493	30.5%
1965	Reba	NF	Trib Bloods Creek	296,000	240	366,733	30.6%
1970	Utica	NF	No. Fork Stan	2,960,748	2,400	369,133	30.8%
1975	Forest Meadows	M	Angels Creek	133,000	108	369,241	30.8%
1975	Bear Vly Sewage Hldg	NF	Trib Bloods Creek	427,000	346	369,587	30.8%
1976	Holman	M	Trib Angels Creek	308,000	250	369,836	30.8%
1978	Leland Meadows	MF	Leland Creek	97,000	79	369,915	30.8%
1979	New Melones	M	Mainstem	2,960,000,000	2,400,000	2,657,241	221.4%
1980	Murphy's Wastewater	M	Trib Six-Mile Creek	173,000	140	2,657,381	221.4%
1983	Andrew Cademartori	M	Trib Angels Creek	175,000	142	2,657,523	221.5%
1988	North Fork Diversion	NF	No. Fork Stan	148,037	120	2,657,643	221.5%
1988	New Spicer Meadows	NF	Highland Creek	233,000,000	188,871	2,846,514	237.2%
1989	McKays Pt Div	NF	No. Fork Stan	2,590,654	2,100	2,848,614	**237.4%**
	TOTAL LISTED DAMS:	32			TOTAL CAPACITY:	**2,846,514** AF	
	(including Old Melones)					TOTAL:	**237%**

Data source:

[1] Department of Water Resources, Bulletin17-93, Dams Within the Jurisdiction of the State of California, June 1993.

[2] CALFED Bay-Delta Program, ERPP Draft PEIS/EIR Tech. App., Vol. 2 – Ecological Management Zone Visions, 6/99.

[3] Kondolf et al, 1996, Water Resources Center Rept. 90 (for data on Old Melones Reservoir)

Note – storage from Old Melones (built in 1926) was subtracted when New Melones was filled (1979).

Tuolumne River

Three distinct phases of water development in the Tuolumne River basin are evident in Figure 3 and Table IV. Prior to construction of Old Don Pedro Dam in 1923, storage capacity in the basin was about 3% of average annual runoff. After construction of New Don Pedro Dam in 1971, more than 140% of annual runoff could be stored.

The La Grange Dam was constructed in 1893, but streamflow measurements at La Grange did not commence until 1896. La Grange Dam diverts water into two large diversion canals (MID Main Canal and TID Main Canal), which together have a capacity exceeding 5,000 cfs. Therefore, considerable depletion of flow at these canals is not detected in this IHA analysis of the Tuolumne.

With the construction of Hetch Hetchy and Old Don Pedro in 1923, approx. 650 KAF of new storage became available. The January-July mean flows were reduced considerably at La Grange following 1923 (see graphs in Appendix 3). Annual flood peaks (1-day maximums) and the average duration of high flow pulses (above 75th percentile) were also noticeably reduced after 1923.

The construction of Cherry Valley Dam in 1956, with 273 KAF of additional storage, appears to have accentuated some of the changes that began in 1923. In particular, May-August flows were further depleted, 7-day low flows became more extreme, and the river began to be subjected to occasional low pulses of very long duration, while high pulse durations were noticeably shortened.

New Don Pedro Dam (NDPD) added over 2,000 KAF of additional storage beginning in 1970, enabling cumulative storage of more than 140% of average annual runoff. However, the effects of NDPD are not clearly distinguishable from the pre-1970 conditions in the graphs in Appendix 3. For some IHA parameters, including November-December and 7-day minimums, operations of NDPD appears to have resulted in a return to conditions similar to pre-1923.

Virtually all aspects of the natural flow regime have been substantially altered on the Tuolumne River. Overall, the largest measured changes between the early (1896-1922) and recent (1972-2000) periods are as follows (see "IHA Scorecard" in Appendix 3):

- September and October flows have increased substantially, by 119% in September and 200% in October
- January-August flows have been greatly reduced, ranging from 36% in February to 99% in June.
- 1- to 90-day minimums have increased by 59-250%
- 1- to 90-day maximums have decreased by 77-81%
- The timing of annual low flows is now much earlier, moving from an average occurrence in early October to late June or early July
- Low pulses (flow below 25th percentile) now last longer (average low flow duration has changed from 15 days to 21 days). High pulses (flows above 75th percentile) occur far less frequently but when they occur they can last for more than 100 days.

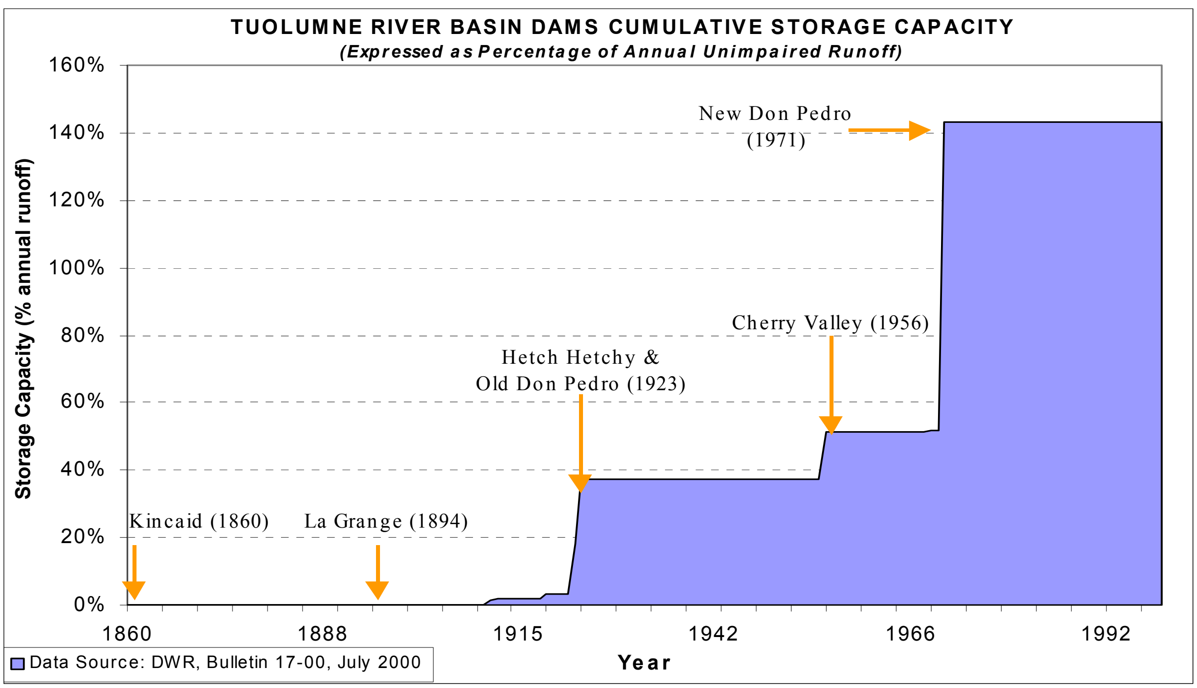

Figure 3: Tuolumne River Basin Dams Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of Tuolumne River dams is 2.9 maf, relative to annual unimpaired runoff of 1.906 maf (McBain and Trush, 2000).

Table IV: Tuolumne River Basin Dams and Cumulative Storage Capacity. Data on the dams within the Tuolumne basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.906 MAF, McBain and Trush, 2000).

A	*B*	*C*		*D*	*E*	*F*
Year	Dam Name	Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1860	Kincaid	Trib. Curtis Crk.	62,000	50	50	0.003%
1860	San Diego Reservoir	Trib. Mormon Crk	49,300	40	90	0.005%
1880	Phoenix	Sullivan Creek	561,000	455	545	0.03%
1894	La Grange	Mainstem	617,000	500	1,045	0.05%
1896	Dawson Lake	Trib. Tuol. River	1,180,000	957	2,002	0.11%
1911	Modesto Reservoir	Trib. Tuol. River	35,800,000	29,020	31,021	1.63%
1912	Tuol. Log Pond	Turnback Crk	148,000	120	31,141	1.63%
1918	Lake Eleanor	Eleanor Creek	34,300,000	27,804	58,945	3.09%
1923	(Old) Don Pedro [1]	Mainstem	419,000,000	290,000	348,945	18.31%
1923	O'Shaughnessy (Hetch Hetchy) [2]	Mainstem	419,000,000	360,000	708,945	37.20%
1923	Priest	Rattlesnake Crk	2,900,000	2,351	711,296	37.32%
1925	Early Intake	Mainstem	141,000	114	711,410	37.32%
1928	Twain Harte	Trib. Sullivan Crk	159,000	129	711,539	37.33%
1930	Moccasin Lower	Moccasin Crk	623,000	505	712,044	37.36%
1931	Bigelow Lake	East Fork Cherry Crk.	580,000	470	712,514	37.38%
1931	Lower Buck Lake	Buck Meadow Crk	444,000	360	712,874	37.40%
1945	Railroad Flat #2	Trib. Dry Crk	117,000	95	712,969	37.41%
1947	Md. Cooperstown	Trib. Dry Creek	112,000	91	713,060	37.41%
1956	Cherry Valley	Cherry Creek	331,000,000	268,311	981,370	51.49%
1956	Gatzman	Trib Dry Creek	95,000	77	981,447	51.49%
1964	Brentwood Park	Trib. Sullivan Crk	98,700	80	981,527	51.50%
1969	Big Creek	Big Creek	9,440,000	7,652	989,179	51.90%
1971	Don Pedro	Mainstem	2,504,004,000	2,029,761	2,728,940	143.18%
1978	Quartz	Trib Woods Crk	1,850,000	1,500	2,730,440	143.25%
1979	Grinding Rock	Trib. Turnback Crk	290,000	235	2,730,675	143.27%
1981	Groveland	Trib. Big Creek	123,000	100	2,730,775	143.27%
Not included above:						
	Wastewater Hi Emig. Lk	No. Fk Cherry Crk	82,600			
	Kilmer	Trib. Dry creek	122,000			
	TOTAL LISTED DAMS:	27		TOTAL CAPACITY:	**2,935,375**	AF
					TOTAL:	**143%**

Data source:

Kondolf G.M. and Matthews, Graham, Management of Course Sediment on Regulated Rivers, Oct. 1993;

McBain and Trush, Habitat Restoration Plan for the Lower Tuolumne River Corridor, March 2000;

Kondolf et al, 1996, Water Resources Center Rept. 90.

Division of Safety of Dams, Bulletin 17-00, July 2000.

1: Storage from Old Don Pedro was subtracted when New Don Pedro was filled.

Note: Kondolf and Matthews site Old Don Pedro as 250KAF, McBain and Trush site as 290 KAF.

2: Hetch Hetchy/O'Shaughnessy reported as $419 \times 10^6 m^3$ in K&M 1993; 363KAF in M&T 2000; and 360 KAF in DSD 2000.

Hetch Hetchy originally built in 1923, with a 206,000 AF capacity, and enlarged in 1937 to 360,000 AF accd. To M&T.

Merced River

Three distinct phases of water development in the Tuolumne River basin are evident in Figure 4 and Table V. Prior to construction of Old Exchequer Dam in 1926, storage capacity in the basin was inconsequential (Table V). After construction of New Exchequer Dam in 1967, more than 100% of annual runoff could be stored.

The Merced Falls Dam, constructed in 1901, diverts water into the Merced Irrigation District's Northside Canal (cap: 90 cfs). However, due to the early onset of these diversions, they are not visible in the hydrograph traces in Appendix 4. Beginning in 1910, the Crocker-Huffman began diverting Merced River flows into the Main Canal. The impacts of these diversions are quite evident in April-September (Appendix 4). The Main Canal has a capacity of 1,900 cfs; depletion of approximately this amount is apparent in July and August.

Construction of Old Exchequer Dam in 1926 added more than 280,000 AF of storage. The effects of this dam on late summer flows are very pronounced, with greatly elevated flow conditions resulting from the release of water for irrigation purposes in these months. November-January flows were substantially lowered. The dam also noticeably reduced annual peak flows, and 7-day low flows became more extreme. It also had a pronounced effect on the timing of low flows, which began to be shifted into December and January rather than September-October. Both average low pulse (flows below 25th percentile) and high pulse (flows above 75th percentile) duration began to become quite long following dam construction. (see Appendix 4).

The completion of New Exchequer Dam and addition of more than 1 million acre-feet of storage in 1967 began to either accentuate or reverse the hydrologic changes induced by Old Exchequer. For example, Old Exchequer caused substantial depletion of November flows but New Exchequer greatly increased November flows. On the other hand, April-June flows were increasingly depleted by both dams. July-September and annual 7-day low flows were increased after New Exchequer. Annual floods were increasingly curtailed by both Old and New Exchequer dams. New Exchequer appears to have brought the average timing of annual low flows and duration of low pulses back closer to the pre-dam character.

Virtually all aspects of the natural flow regime have been substantially altered on the Merced River. Overall, the largest measured changes between the early (1902-1925) and recent (1968-2000) periods are as follows (see "IHA Scorecard" in Appendix 3):

- July through October flows have increased substantially, ranging from 160% in July to 961% in September.
- January-June flows have been greatly reduced, ranging from 35% in March to 58% in February.
- 1- to 90-day minimums have increased by 146-417%
- 1- to 90-day maximums have decreased by 39-72%
- The timing of annual low flows is now delayed by a month, from early October to early November, and timing of annual high flows is delayed from early April to late June.
- Low pulses (flow below 25th percentile) have nearly been eliminated. High pulses (flows above 75th percentile) occur far less frequently but when they commonly last longer.

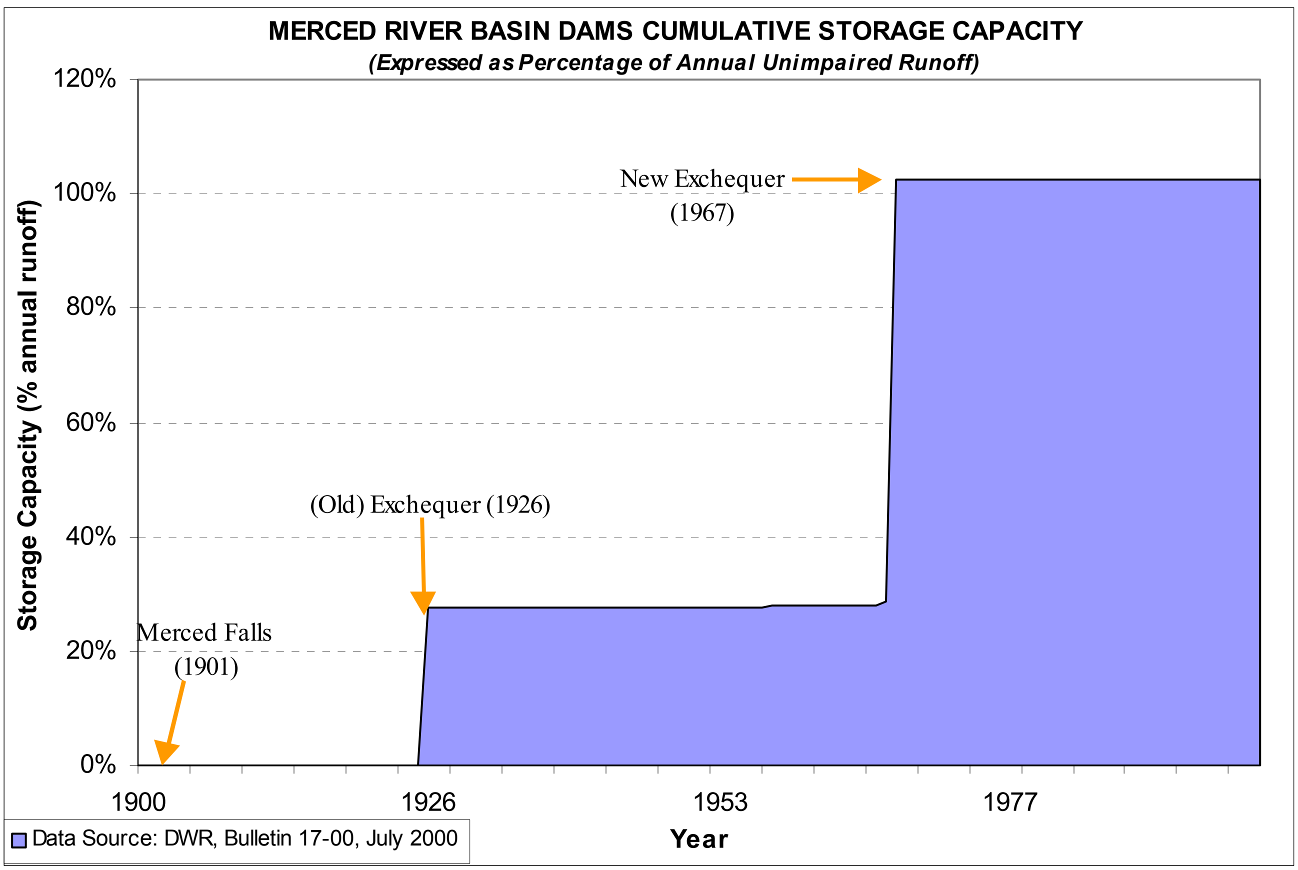

Figure 4: Merced River Basin Dams Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of Merced River dams is 1.04 maf, relative to annual unimpaired runoff of 1.02 maf (Calfed, 2000).

Table V: Merced River Basin Dams and Cumulative Storage Capacity. Data on the dams within the Merced basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.02 maf, Calfed, 2000). The total dam storage capacity in the Merced basin exceeds 1.04 maf, or over 102 % of average annual unimpaired runoff.

A	*B*	*C*		*D*	*E*	*F*	
Year	Dam Name	Stream	Capacity (m3)	Storage Capacity (AF)	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff	
1901	Merced Falls	Mainstem Merced River	765,000	620	620	**0.06%**	
1910	Crocker-Huffman Diversion	Mainstem Merced River	370,000	300	920	**0.09%**	
1926	Exchequer	Mainstem Merced River	347,000,000	281,280	282,200	**27.67%**	
1929	Kelsey	Dry Creek (Trib)	1,230,000	1,000	283,200	**27.76%**	
1956	Metzger	Dutch Creek (N. Fork)	92,500	75	283,275	**27.77%**	
1957	McMahon	Maxwell Creek (Trib)	641,000	520	283,795	**27.82%**	
1958	Green Valley	Smith Creek (N. Fork)	296,000	240	284,035	**27.85%**	
1966	McSwain	Mainstem Merced River	12,000,000	9,727	293,762	**28.80%**	
1967	New Exchequer/McClure [1]	Mainstem Merced River	1,270,000,000	1,032,000	1,044,482	**102.40%**	
	TOTAL LISTED DAMS:	9 (Excheq counted twice)		TOTAL CAPACITY:	**1,044,482**		AF
					TOTAL:	**102%**	
					1,020,000		AF

Data source:

Kondolf G.M. and Matthews, Graham, Management of Course Sediment on Regulated Rivers, Oct. 1993; Calfed, 2000; Kondolf et al, 1996, Water Resources Center Rept. 90; Division of Safety of Dams, Bulletin 17-00, July 2000.

1: Storage from Exchequer was subtracted when New Exchequer was filled.
Note: Stillwater reports Exchequer max storage capacity as 1,024,600 AF.

San Joaquin River

Three phases of water development are apparent in the San Joaquin River basin (see Figure 5 and Table VI), although they are not as distinctive as in the Tuolumne and Merced basins. Reservoir storage capacity in the San Joaquin basin did not exceed 20% until after construction of Friant Dam in 1942. After construction of Friant and two other sizeable dams in 1954 and 1960, total storage in the basin reached 60% of annual runoff. This total storage capacity stands in stark contrast to the three tributary basins discussed previously, in which 100-240% of annual runoff can be stored.

The major hydrologic alterations in the San Joaquin basin are related to construction of Friant Dam and associated diversion canals, including the Madera (1944) and Friant (1948) canals. The construction of each of these canals led to increasing hydrologic alteration in the middle San Joaquin.

Virtually all aspects of the natural flow regime have been substantially altered in the middle San Joaquin River. Overall, the largest measured changes between the early (1908-1940) and recent (1951-2000) periods are as follows (see "IHA Scorecard" in Appendix 5):

- Monthly average flows throughout the year have been depleted by 82-97%.
- 1- to 90-day minima have been reduced by 86-89%.
- 1- to 90-day maxima have decreased by 89-94%.
- The average timing of annual low flows is now delayed by more than a month, from early November to late December, and timing of annual high flows is delayed from mid-May to late June.
- Low pulse (flow below 25th percentile) duration has increased 900%, from an average of 5 days per year to 54 days. High pulses (flows above 75th percentile) occur far less frequently but when they commonly last longer.

By contrast, hydrologic alterations in the lower San Joaquin are not nearly as severe as in the middle San Joaquin, as measured at Vernalis. The largest measured changes between the early (1930-1940) and recent (1951-2000) periods are as follows (see "IHA Scorecard" in Appendix 5):

- Flow depletions of 74-76% in May and June.
- Substantial increases in the 1- to 7-day minima (+51-63%)
- Substantial reductions in 1- to 90-day maxima (-45-52%)
- Shift in the timing of annual maxima, from April-May to late December-early January.

- Reductions of 46-48% in high and low pulse durations.

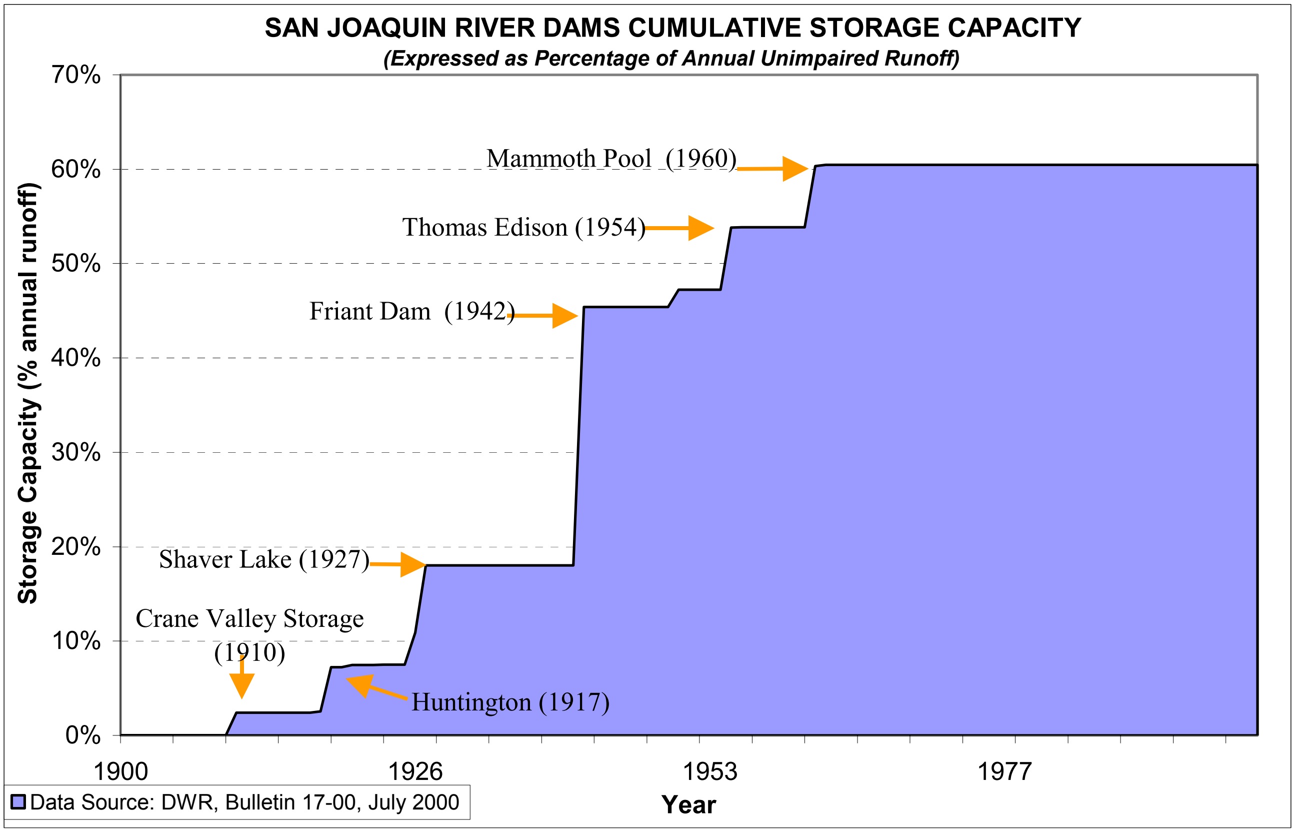

Figure 5: San Joaquin River Dams Capacity. Incremental increase in storage capacity expressed as a percentage of mean annual runoff. The total capacity of San Joaquin River dams is 1.15 maf, relative to annual unimpaired runoff of 1.9 maf (Calfed, 2000). See Table VI for details regarding calculations and data sources.

Table VI: San Joaquin River Dams and Cumulative Storage Capacity. Data on the dams within the San Joaquin River basin large enough to be regulated by the Division of Safety of Dams (DOSD), including the year the dam was built (col. A), watershed location (C.), and its storage capacity (D). Col. E details the cumulative storage capacity within the basin after the construction of each additional dam. Col. F expresses this cumulative storage as a percentage of total average unimpaired runoff in the basin (1.9 maf, Calfed, 2000). The total dam storage capacity in the San Joaquin basin is almost 1.15 maf, or over 60% of average annual unimpaired runoff.

A	*B*	*C*		*D*	*E*	*F*
Year	Dam Name	Stream	Capacity (m3)	Storage Capacity (AF)[1]	Cumulative Storage (AF)	Cum. Storage as % annual unimpaired runoff
1896	No. 1 Forebay	Trib. No Fork SJ	85,121	69	69	**0.004%**
1910	Crane Valley Storage (Bass Lk)	NF Willow Creek	55,650,000	45,410	45,479	**2.39%**
1917	Mendota Diversion	Mainstem	3,700,935	3,000	48,479	**2.55%**
1918	Huntington Lake	Big Creek	109,069,000	88,834	137,313	**7.23%**
1920	Kerckhoff Diversion	Mainstem	6,348,000	4,200	141,513	**7.45%**
1923	Big Creek #6	Mainstem	1,225,009	993	142,506	**7.50%**
1926	Florence Lake	So Fork San Joaquin	78,929,000	64,406	206,912	**10.89%**
1927	Shaver Lake	Stevenson Crk	165,441,000	135,283	342,195	**18.01%**
1942	Friant/Millerton	Mainstem	637,255,000	520,500	862,695	**45.41%**
1951	Big Creek #7	Mainstem	42,892,000	35,000	897,695	**47.25%**
1954	Vermillion Valley/Thomas Edison	Mono Creek (~8000 ft elev)	154,205,607	125,000	1,022,695	**53.83%**
1955	Portal Powerhouse Forebay	Trib Sfork SJ River	400,935	325	1,023,020	**53.84%**
1960	Mammoth Pool	Mainstem (~3,500 ft elev.)	153,186,000	123,000	1,146,020	**60.32%**
1961	Reg WW CNT OXID	Trib SJ River	3,543,028	2,872	1,148,892	**60.47%**
	TOTAL LISTED DAMS:	14		TOTAL CAPACITY:	**1,148,892**	AF
					TOTAL:	**60.5%**
					1,900,000	AF

Data source:

[1]: Division of Safety of Dams, Bulletin 17-00, July 2000.

[2]: Kondolf et al, 1996, Water Resources Center Rept. 90; Division of Safety of Dams, Bulletin 17-00, July 2000.

[3]: Cain, John, personal communication, August 2001.

Spatial Patterns of Hydrologic Alteration in the San Joaquin Watershed

To investigate spatial patterns of hydrologic alteration across the entire San Joaquin watershed, I developed an overall measure of hydrologic alteration based upon six indicators:

1. Wet season flow alteration – an average of deviations in the monthly medians for November-June.

2. Dry season flow alteration – an average of deviations in the monthly medians for July-October.

3. Base flow alteration – deviation in the 7-day low flow.

4. Annual flood flow alteration – deviation in the 1-day maximum flow.

5. Change in duration of high pulses each year – deviation in the average number of days each year with flows > 75^{th} percentile.

6. Change in duration of low pulses each year – deviation in the average number of days each year with flows < 25^{th} percentile.

A summary of the results from this analysis is provided in Table VII. Unfortunately, equivalent periods of record are not available for each pair of stations on each of the four rivers. On the Tuolumne, the Modesto gaging station was not installed until after construction of Hetch Hetchy Reservoir. On the Merced, the Stevinson gaging station was not installed until after construction of Old Exchequer Dam. This makes comparison of hydrologic alteration between upstream and downstream gaging stations difficult. However, as described earlier in this report, the relative magnitudes of hydrologic alteration in both the Tuolumne and Merced following construction of the big dams (New Don Pedro on the Tuolumne, New Exchequer Dam on the Merced) was generally much greater than during the years following construction of the smaller and older dams.

For all rivers except the Stanislaus, hydrologic conditions appear to become considerably better when moving downstream from the dams. This is to be expected, as the rivers gain additional contributions from tributary streams downstream of the dams.

Table VII. Hydrologic Alteration Across the San Joaquin Watershed

	Wet Season (Nov-June)	Dry Season (July-Oct)	Baseflow (7-day lows)	Flood Flow (1-day max)	High Pulse Duration	Low Pulse Duration	Average
Stanislaus @ Knights Ferry (1896-25; 1980-2000)	45%	60%	62%	77%	60%	80%	**64%**
Stanislaus @ Ripon (1941-55; 1980-2000)	32%	124%	34%	62%	62%	100%	**69%**
Tuolumne @ LaGrange (1896-55;1972-2000)	61%	123%	149%	81%	100%	9%	**87%**
Tuolumne @ Modesto (1943-55; 1972-2000)	37%	20%	24%	37%	72%	48%	**40%**
Merced @ Merced Falls (1902-25; 1968-2000)	38%	581%	206%	72%	53%	100%	**175%**
Merced @ Stevinson (1941-65; 1968-2000	62%	36%	5%	54%	107%	72%	**56%**
San Joaquin blw Friant (1908-40; 1951-2000)	104%	86%	89%	90%	100%	184%	**109%**
San Joaquin @ Vernalis (1930-40; 1951-2000)	36%	23%	53%	45%	63%	66%	**48%**

Appendix 1. Summary of Watershed Characteristics, Dams, and Flow Information

	Stanislaus	Tuolumne	Merced	Middle San Joaquin	Mainstem San Joaquin
WATERSHED CHARACTERISTICS:					
Watershed Drainage Area [1]	1,075 mi^2 (headwaters >11,500 ft. elevation, 40% basin above snowline)	1,540 mi^2 (1,900 mi^2 in M&T[2])	1,273 mi^2 (top elev. ~13,000 ft; min. elev. 49 ft)	13,537 mi^2 Drainage area above Friant: 1,560 mi^2 (4340 km^2).	
Watershed Dimensions	River length[3]: 161 mi *River length below New Melones Dam: ~62 mi.; Below Goodwin Dam: 59 mi.* Max. width: 24 mi. at Sierra crest (~10 mi at midpoint). [4] (Joins SJ River at RM ____)	River length[2]: ~155mi ? *River length below New Don Pedro Dam: ~55 mi Below La Grange: ~52 mi.* Max width: ______? (Joins SJ River at RM 83.0)	River length[3]: 135 mi *River length below New Exchequer: 62.5 mi; Below Crocker Huffman Dam: 52 mi.* Max width: 26 miles [5] (Joins SJ River at RM 118)	River length[3]: 330 mi *River length below Friant Dam: 266 mi* Valley width: 130 mi. wide [6]	
Avg. unimpaired flow	**1.2 maf/yr** [6] Avg. unimpaired inflow to New Melones: **1,600 cfs**; Historical avg. flow at Ripon (near mouth): **950cfs**.[1]	**1.906 maf/yr** [3] Avg. unimpaired inflow to New Don Pedro: **2,500 cfs**; Historical avg. flow at La Grange: **880 cfs**.[1]	**1.02 maf/yr** [6] Avg. unimpaired inflows at McClure (New Exchequer dam): **1,325 cfs**; Historical avg. flow at Stevenson (near the mouth): **650 cfs**.[1]	**1.9 maf/yr** [6] *(Note: 2.2 maf/yr committed to water contracts).* *Avg. unimpaired inflow at Friant?* *Historical avg. flow nr. Mouth Merced?*	*~ 7 maf/yr?* *Historical avg. flow at/near Vernalis – 2,294 cfs?*
Primary flow source	Snowmelt runoff	Snowmelt runoff	Snowmelt runoff	Snowmelt runoff	Tributary inflow
Peak Flow (cfs, date)	64,500 cfs; 3/19/1907; below Goodwin Dam. (Post New Melones: 7,350 cfs; 1/3/1997).	58,900 cfs; 1/3/1997; below La Grange Dam	47,700 cfs; 1/31/1911; below Merced Falls Dam (Post New Exchequer: 8,020; 1/4/1997).	77,200 cfs; 12/11/1947; at Friant. (Post Friant: 60,300cfs; 1/3/97).	79,000 cfs; 12/9/1950; at Vernalis.
DAMS AND DIVERSIONS:					
Downstream barrier to fish migration	**Goodwin Dam**, RM 59 (1912; 500AF); salmon and steelhead spawn in 23 mi. reach below Goodwin	**LaGrange Dam**, RM 52.2 (1894; 500AF); salmon and steelhead spawn in 25 mi. reach below LaGrange.	**Crocker-Huffman Dam**, RM 52 near Snelling (1910; 200AF); salmon spawn in 24-mile reach below the dam and the town of Cressey.	**Friant Dam,** RM 260 (1942; 520,000 AF); Streamflow releases below Friant dam are insufficient to support salmon passage, spawning, or rearing and no water passes through the Gravelly Ford (RM 229) to Mendota Pool reach except during high runoff periods.[1]	

	Stanislaus	**Tuolumne**	**Merced**	Middle San Joaquin	**Mainstem**
Major dams -- Completed; capacity (KAF); (Drainage area; River mile)	**New Melones -- 1978; 2,400 KAF**; (DA ~904 mi^2; RM: ~62). [Replaced Old Melones – 1926; 113KAF]. **Tri-dams project – 1957-8; 203KAF** [Tulloch: DA ~980 mi^2, RM ~60; Beardsley: DA ~315mi^2; Donnells: DA ~230 mi^2). **New Spicer Meadows** – **1988; 189 KAF.**	**New Don Pedro – 1970; 2,030 KAF**; (DA ~ 1,542 mi^2; RM 55 to 75). [Replaced Old Don Pedro – 1923; 290KAF]. **Hetch Hetchy** – **1923; 360 KAF**; (DA ~456 mi^2). **Cherry Valley – 1956; 273 KAF**; (DA: ~117 mi^2).	**New Exchequer (Lake McClure) – 1967; 1,024 KAF**; (DA ~1,037 mi^2; RM 62.5). (Replaced Exchequer – 1926; 281 KAF) *McSwain Dam (afterbay to New Exch.) – 1966; 9.7KAF; (RM 56).*	Friant Dam (Millerton Lake) – 1942; 520KAF; **(DA < 1,638mi^2; RM ~266).** Shaver Lake – 1927; 135 KAF. Thomas Edison Lake – 1965; 125 KAF. **Mammoth Pool -- 1960; 123KAF.**	*Mendota Diversion Dam – 1917; 3 KAF; (DA: ~ ____; RM ______)*
Dam Stats[7] *(DSD dams are those > 50 ft in height and > 50 AF).*	28 DSD dams (12 non DSD); 90.3% basin upstream of major dam[7]; Total reserv. cap: 2.85 maf (3,542x10^6m^3)	27 DSD dams; 81.8% basin upstream of major dam[7]; Total reservoir capacity: 2.94 maf (3,343 x 10^6m^3)	8 DSD dams; 81.7% basin upstream of major dam[7]; Total reservoir capacity:1.04 maf (1,288 x 10^6m^3)	19 DSD dams; [7] 90.3% basin upstream of major dam[8]; Total reservoir capacity: 1.149 maf (1,415 x 10^6m^3)	
% cumulative capture of unimpaired runoff	**237%** See Table St1 & Figure St1	**143%** See Table T1 & Figure T1	**102%** See Table M1 & Figure M1	**60.5%** See Table SJ1 & Figure SJ1	
Main flow diversions	Goodwin Dam (1912; 500 AF) diverts flow into **South San Joaquin Canal** (1914, ~1,320 cfs max) and **Oakdale Irrigation District Canal** (1914, ~560 cfs max). [Previous to Goodwin Dam, Stan. & SJ Water Co. Canal diverted ~3 mi upstream of Knights Ferry (1899).] Any stat on how much diverted at Goodwin?? *44 small pump diversions identified on lower Stanislaus.*[6]	La Grange Dam (1893; 500 AF; owned by TID and MID) diverts flow into the **MID Main Canal** (~1910; ____cfs cap, max diversion 1,820 cfs; avg. 310KAF/yr) and **TID Main Canal** (~1899; ___cfs cap., max diversion 3,400 cfs; avg. 575KAF/yr). **900KAF/yr** diverted at La Grange.[2] Inflow to La Grange: 1,670 KAF; downriver: 785 KAF. [2] *36 small irrigation pump diversions identified on lower Tuolumne.*[6]	Merced Falls Dam (1901; 620AF; PG&E; RM 55) diverts flow into **Merced ID Northside Canal** (___yr: 90 cfs cap.) and Crocker-Huffman dam (1910; 300AF; Merced ID; RM 52) diverts into **Main Canal** (____yr: 1,900 cfs cap.). Approx **500KAF/yr** diverted at Merced Falls and Crocker-Huffman dams. *68 small irrig pump diversions identified in the lower Merced by DFG surveys.* [6]	Friant Dam (1942; 520,000 AF) diverts flow into the **Friant-Kern Canal** (1948; 5,300 cfs cap.), **Madera Canal** (1944; 1,275 cfs cap.), and other **CVP facilities**. Almost all of the mainstem flow is diverted at Friant dam into the Friant-Kern Canal.[6] Except during spill conditions at Friant dam, the Friant to Gravelly Ford reach receives a 35-230 cfs flow release to support riparian water diversions.[6] (Note: Delta Mendota Canal (1951) delivers water from the Delta to Mendota reservoir for downstream water rights holders).	

	Stanislaus	**Tuolumne**	Merced	**Middle San Joaquin**	**Mainstem San Joaquin**
FLOW DATA SOURCES FOR IHA MODEL:					
STATUS OF IHA FLOW DATA:	Complete. Use assembled file cited below for Knights Ferry (see notes); download USGS data for Ripon. *[Files & Memo sent 8/25/01]*	Complete. Use assembled file cited below for La Grange; download USGS data for Modesto. ***[Files & Memo sent 9/20/01]***	Complete. Use assembled file cited below for Crocker Huffman Gauge; download USGS Merced Falls data; download USGS Stevenson data. *[Files & Memo sent 9/14/01 and 9/18/01]*	Complete. Download data from web. *[Files & Memo sent 8/25/01]*	Complete. Download data from web. *[Files & Memo sent 8/25/01]*
Regulated flow data **<Rim Stations>** *(near upstream barrier to fish migration)*	**<File: STANatKF>** Knights Ferry Compilation; 1895-2000; (DA: 905-1,032 mi^2; ~RM 58-61) [Source: Schneider]. *Compiled from:* **1895-1900: "OAKDALE" #11302500* **1903-1914 "AT KNIGHTS FERRY" #11302000 (manually entered data)* **1915-1932 "NEAR KNIGHTS FERRY" #11300000 (NOTE: ABOVE SSJID and OID diversions).* **1932-1957 "BELOW MELONES" #11299500 (NOTE: ABOVE SSJID and OID diversions).* **1957-2000 "BELOW GOODWIN" #11302000*	**<File: Tuol@LG1896-2001 forIHA.xls>** Compilation at La Grange Dam; (DA: 1,532-1,538mi^2) *Compiled from:* **1896-1917: "ABV LA GRANGE #112888000* **1918-1930: "ABV LA GRANGE #112888000 (NOTE: ABOVE TID and MID diversions)* **1930-1960: Synthetical produced data -- below diversions from McBain & Trush* **1961-2001: "BELOW LA GRANGE" #11289650*	**<File: MercedFlowData@ CH&MFforIHA.xls>** augmented by **<File: Merced IHAFormattedCH.xls>** **Crocker Huffman Gauge below CH Dam; 1938 -2000.** [Source: Merced ID] & **USGS #11270900** "MERCED R BL MERCED FALLS DAM NR SNELL"; **1901-2000**; (DA: ~ 1,061 mi^2; RM ~55).	**<WEB> USGS #11251000** "SAN JOAQUIN R BL FRIANT CA"; **1907-2000**; (DA: ~1,676 mi^2; RM 268.	**<WEB> USGS #11274000** "SAN JOAQUIN R NR NEWMAN CA"; **1912-2000**; (DA: ~ _____; RM: ~ 117).
Regulated flow data -- <Confluence> *(near confluence with SJ River)*	**WEB:** USGS#11303000 "STAN R A RIPON" (RM 15); 1940-2000.	**WEB:** USGS#11290000 "TUOL. R A MODESTO, CA" (RM ~16; 0.2 mi below Dry Crk); DA: 1,884 mi^2. 1895-6; 1940-2000.	**WEB:** USGS#11272500 "MERCED R NR STEVINSON" (RM 1.1); 1940-1995.	**Limited Data. Priority 2.** USGS#11254000 "SAN JOAQUIN NR MENDOTA CA" (RM ~207); 1939-1954; 1999-2000.	**WEB:** USGS#11303500 "SAN JOAQUIN R NR VERNALIS CA" **(RM ___)**; 1923-2000.
Unimpaired flow data source	***Do not have yet***	**<File:TuolUnimpaired1897-1999.xls>** (Source: McBain & Trush from TID).	***Do not have yet***	*M&T have data set via Hux, will send.*	***Do not have yet***

Proposed Pre and Post Impact Periods	Pre: Before 1926 (Old Melones Dam) Post: After 1979 (New Melones Dam) (Note: NM filled closer to ~1983).	Pre: Before 1923 (Hetch Hetchy and Old Don Pedro) Post: After 1971 (New Don Pedro Dam)	Pre: Before 1926 (Old Exchequer Dam) Post: After 1967 (New Exchequer Dam)	Pre: Before 1941 (Friant Dam) Post: After 1951 (when Delta Mendota Canal completed, allows for full operation of Friant for water deliveries) (the canal delivers water from the Delta to Mendota reservoir for downstream water rights holders).	
	Stanislaus	**Tuolumne**	Merced	**Middle San Joaquin**	**Mainstem SJ**
OTHER INFORMATION:					
Anadromous fish species	Fall-run Chinook salmon, steelhead, and perhaps late-fall-run Chinook.[6] (Spring-run extirpated).	Fall-run Chinook salmon, steelhead, and perhaps late-fall-run Chinook.[6] (Spring-run extirpated).	Fall-run chinook; perhaps steelhead and late-fall run chinook. [6] (Spring-run chinook extirpated).	Spring-run (extirpated 1949 with closure Friant) and fall-run Chinook (extirpated 1949). Steelhead.	
River avail. to anadr. fish [1]	Historical: 113 mi. Current: 46 mi.	Historical: 99 mi. Current: 47 mi.	Historical: 99 mi. Current: 43 mi.	Historical: 231 mi. Current: 50mi (toMerced)	
Calfed Identified Stressors[6] *(and/or other land use information)*	**RE: SJ Tribs:** Dams that hinder or block fish migration; legal and illegal fish harvest; water diversions that result in insufficient flow in the lower portion of most streams; high water temperature during salmon and steelhead spawning and rearing; poor water quality; hatchery stocking of salmon and steelhead; gravel mining in the stream channel; poor livestock grazing practices; high predation levels on juvenile salmon by non-native fish; salmon and steelhead harvest; unscreened or poorly screened water diversion. **RE: San Joaquin System Overall:** Artificial confinement of the river channel w/in levees; dams that block access to historical habitat; poor land use and livestock grazing practices on riparian lands; lack of flood flows, which alters the natural sediment balance and reduces riparian vegetation growth; reservoir management and diversions on the mainstem and tributary streams that significantly reduce streamflow and alter stream temperature; entrainment of fish and other aquatic organisms in diversions, direct removal and fragmentation of riparian habitat for agricultural and urban development and floodway maintenance; in channel and floodplain gravel extraction, which alters channel forms.				
Other notes		Irrigation return flow near Modesto increase river flow by about 100 cfs[6].	15-25 cfs legally required flow releases in summer usually depleted before reaching river mouth due to small diversions throughout the lower river. [6]		
Attachments	Dams: Table St1; Figure St1. Gauges: Table ST2; Figure ST2	Dams: Table T1; Figure T1. Gauges: Table T2; *DRAFT* Figure of gauges from M&T	Dams: Table M1; Figure M1. Gauges: Table M2; Figure M2.	Dams: Table SJ1; Figure SJ1 Gauges: Table SJ2; Figure SJ2	

[1]: Dept. Fish and Game, AFRP, www.delta.dfg.ca.gov/afrp/ ; [2]: McBain and Trush. 2000; [3]: Mount, Jeffrey F. California Rivers and Streams, 1995; [4]: Schneider, Katrina S. 2001; [5]: Stella, John. Personal Communication. July 2001; [6]: Calfed EIS/EIR Technical Appendix, July 2000; [7]: Kondolf et. al. 1996 (adapted from Kondolf and Matthews, 1993); [8]: Cain, John. Personal Communication. August 2001.

Note: Basin overall: SJ River basin averages 27.3 in/yr precipitation with snowmelt runoff dominant water source and peak flows historically around May and June. (Calfed 2000). Mean annual precipitation totals 21.8 maf (Stella 2001 citing CDWR 1998).

San Joaquin River Basin Hydrograph Component Analysis
Technical Memorandum

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Table 6. Summary of important hydrograph components for five different water year types for the Stanislaus River, unimpaired and regulated conditions.

1 Introduction

This Technical Memorandum summarizes and describes historical and contemporary streamflow hydrology for the San Joaquin River and it's three major tributaries: the Merced River, Tuolumne River, and Stanislaus River. Hydrologic analyses were performed independently for each tributary, and were based almost exclusively on annual hydrographs of daily average flows. To evaluate unimpaired conditions, we used pre-dam streamflow records as well as computed-unimpaired estimates during post-dam periods when available. Regulated conditions were based exclusively on USGS gaging data after the largest storage reservoir was completed (Table 1). We also completed log-Pearson Type III flood frequency analyses for each tributary using the annual maximum flood series from USGS records (USGS 1982). Analyses are based on evaluation of annual hydrographs and observation of characteristic "intra-annual" patterns of flow, which we termed "hydrograph components." Hydrograph components are seasonal patterns of daily average flow that tend to recur from year to year, but at varying magnitudes and durations (Trush et al. 2000). The "Hydrograph Component Analysis" (HCA) method was originally developed during the *Trinity River Channel Maintenance Flow Study* (McBain and Trush 1997; USFWS and HVT 1999) and later expanded and incorporated into the *Habitat Restoration Plan for the Lower Tuolumne River Corridor* (McBain and Trush 2000).

Table 1. Streamflow data used in hydrologic analyses.

	UNIMPAIRED	REGULATED
San Joaquin River	San Joaquin River at Friant, CA Modeled from Kings River at Piedra (USGS #11222000) WY 1896 – 1999; Source: Hux Madeheim	San Joaquin R blw Friant CA (USGS Stn 11-251000) WY 1950 – 2000; Source: USGS data
Merced River	Merced River blw Merced Falls nr Snelling (USGS 11270900) WY 1901 – 1926; Source: USGS data	Merced River blw Crocker-Huffman Dam nr Snelling (Merced Irrigation District Gage) WY 1966 – 2000; Source: MID data
Tuolumne River	Tuolumne River blw La Grange Dam, nr La Grange, CA (USGS 11289650) WY 1896 – 1999; Source: TID Modeling and USGS data	Tuolumne River blw La Grange Dam, nr La Grange, CA (USGS 11289650) WY 1971 - 1999; Source: USGS data
Stanislaus River	Stanislaus River at Knights Ferry, CA (USGS 11300000) WY 1896 – 1932; Data Source: USGS data	Stanislaus River blw Goodwin Dam nr Knights Ferry, CA (USGS 11302000) WY 1983 – 1999; Source: USGS data

The distinct hydrograph components observed for the San Joaquin River basin are similar for all tributaries, and included fall storm pulses, winter and summer baseflows, winter floods, spring snowmelt floods, and snowmelt recession (Figure 1). While these hydrograph components have been evident to hydrologists prior to the HCA methods, this approach describes the *variability* in magnitude, timing, duration, and frequency of flow of the important hydrograph components, and allows us to better link biological and geomorphic roles to these hydrograph components. This inter-annual variability is captured by grouping annual hydrographs into different water year types. We utilized five different water year types, each with equal (20%) exceedance probability to facilitate comparisons within and among different water year types. Water year types are labeled "Extremely Wet", "Wet", "Normal", "Dry", and "Critically Dry". The HCA analyses should complement the Indicators of Hydrologic Alteration (IHA) analyses being conducted independently by Brian Richter.

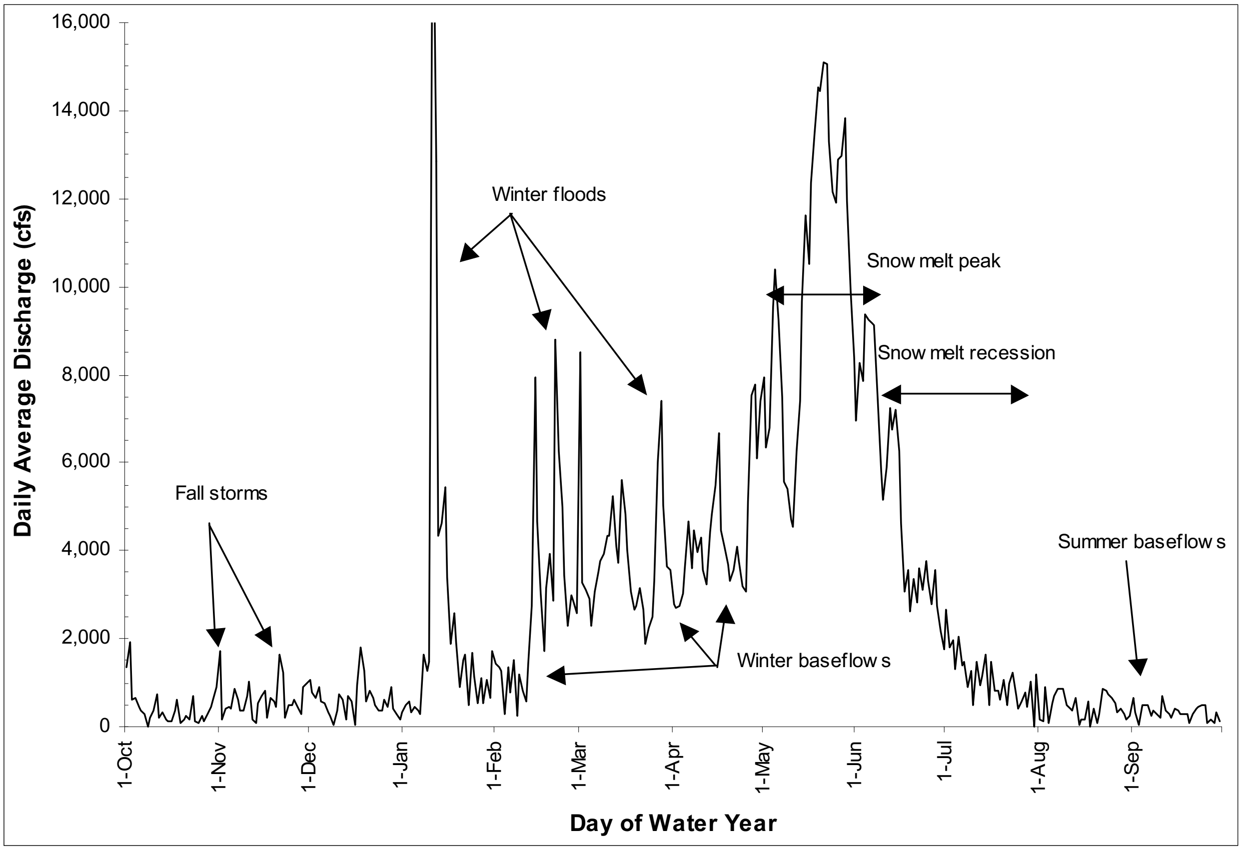

Figure 1. Illustration of the important components of the annual hydrograph of daily average flows for a typical San Joaquin Basin Tributary.

The fundamental supposition (hypothesis) underlying development of the HCA methods is that annual hydrograph components collectively provide the impetus for processes that shape and sustain alluvial river ecosystems. Each hydrograph component accomplishes specific ecologically significant functions in driving geomorphic processes, promoting and sustaining natural riparian vegetation patterns, and determining species' life history characteristics. A clear example of this concept is the role played by the spring snowmelt flood in promoting cottonwood (*Populus fremontii*) regeneration. The magnitude of the snowmelt flood, timing of the peak, and rate of the recession, all in conjunction with the timing of cottonwood seed dispersal, are the overriding factors determining not only the *success* of germination, but equally importantly, the *location* of germination relative to river stage height and zones of channelbed scour. Other hydrograph components play equally vital roles in governing ecosystem processes.

Quantifying the inter-annual variability of hydrograph components provides river policy makers and resource managers an important foundation for management decisions and actions aimed at restoring ecosystem processes. Traditional methods (e.g., PHABSIM) used to establish regulated streamflow regimes often ignore the role of specific annual hydrograph components and the importance of variability in the hydrograph components, invariably to the detriment of the health of the river ecosystem. The most fundamental approach available today to achieve meaningful river restoration is therefore to restore flows that target re-activating key hydrograph components and the associated physical processes they govern.

2 Geographical Setting

The 290-mile long San Joaquin Valley occupies the southern half of the California Central Valley, and drains the southern half of the Sierra Nevada range to the San Francisco Bay-Delta (Figure 2). The arid west side of the valley supports relatively small, intermittent streams, but the east side supports several streams and three major rivers which drain from the Sierra Nevada Mountains into the mainstem San Joaquin River at the valley floor, including the Merced, Tuolumne, and Stanislaus Rivers. Precipitation in the San Joaquin River basin averages about 27 inches per year (CALFED ERP 1999) and snowmelt runoff is the major source of water to the upper San Joaquin River and tributaries. The unimpaired flow regime of the principle rivers is dominated by large winter rain-driven and rain-on-snow floods, and the large spring snowmelt runoff. Summer/fall dry periods are characterized by low baseflows.

The San Joaquin River basin is now regulated by numerous large reservoirs and diversions that store and deliver the majority of streamflow for agricultural irrigation and hydropower production. In the San Joaquin River and three tributaries, the four large reservoirs alone (Millerton Lake, Lake McClure, New Don Pedro Reservoir, New Melones Reservoir) account for nearly 6 million acre feet (af) of water storage capacity, slightly more than the combined average annual yield from these four rivers of 5.9 million acre feet. Table 2, "San Joaquin River Basin Draft Watershed Overview Table" (prepared by Katrina Schneider) presents a wealth of relevant information and statistics for each of the four major rivers of the San Joaquin River basin.

3 Hydrograph Component Analysis

Methods

For each of the four rivers, a period of record was selected that represented (as closely as possible) unimpaired runoff conditions and the contemporary regulated conditions. Table 1 lists the periods of record used for each river.

"Unimpaired" data refers to either (1) natural or unregulated/undiverted streamflow conditions, i.e., empirical data from USGS records prior to major basin impoundments, (2) data from Turlock Irrigation District (TID) as in the case of the Tuolumne River unimpaired flowdata, which is derived from a model of reservoir inflows and basin diversions, and (3) data for the San Joaquin River modeled from the Kings River at Piedra USGS records, and converted based on watershed area at Friant Dam. These unimpaired data sets were the best data available to describe natural runoff conditions, but are nevertheless not purely "what the river would have experienced" prior to approximately 1848 when European settlers began manipulating streamflows. For example, some disruption of natural streamflow patterns on the Tuolumne River began in the 1850's with early gold mining diversion ditches, followed by larger-scale mining diversions in the early 1870's. This period of record, however, is still considered "unimpaired" due to the relatively small scale of the diversions. The modeled data are also an extrapolation of the true unimpaired condition because they are mathematically calculated based on reservoir storage changes, evaporation rates, and diversion volumes, instead of empirically measured streamflows.

"Regulated" refers to the period of record after the largest basin reservoir project was completed (Friant Dam, New Exchequer Dam, New Don Pedro Dam, and New Melones Dam). Other regulated periods of record were not included in our analyses because our primary interest was to compare unimpaired conditions with contemporary regulated conditions.

Hydrologic analyses included the following:
Water Year Classification: the annual water yields (runoff) for unimpaired and regulated conditions were classified into five different water year types based on the frequency distribution of annual yield. Water yields were plotted as an exceedance probability, then divided symmetrically into five equally

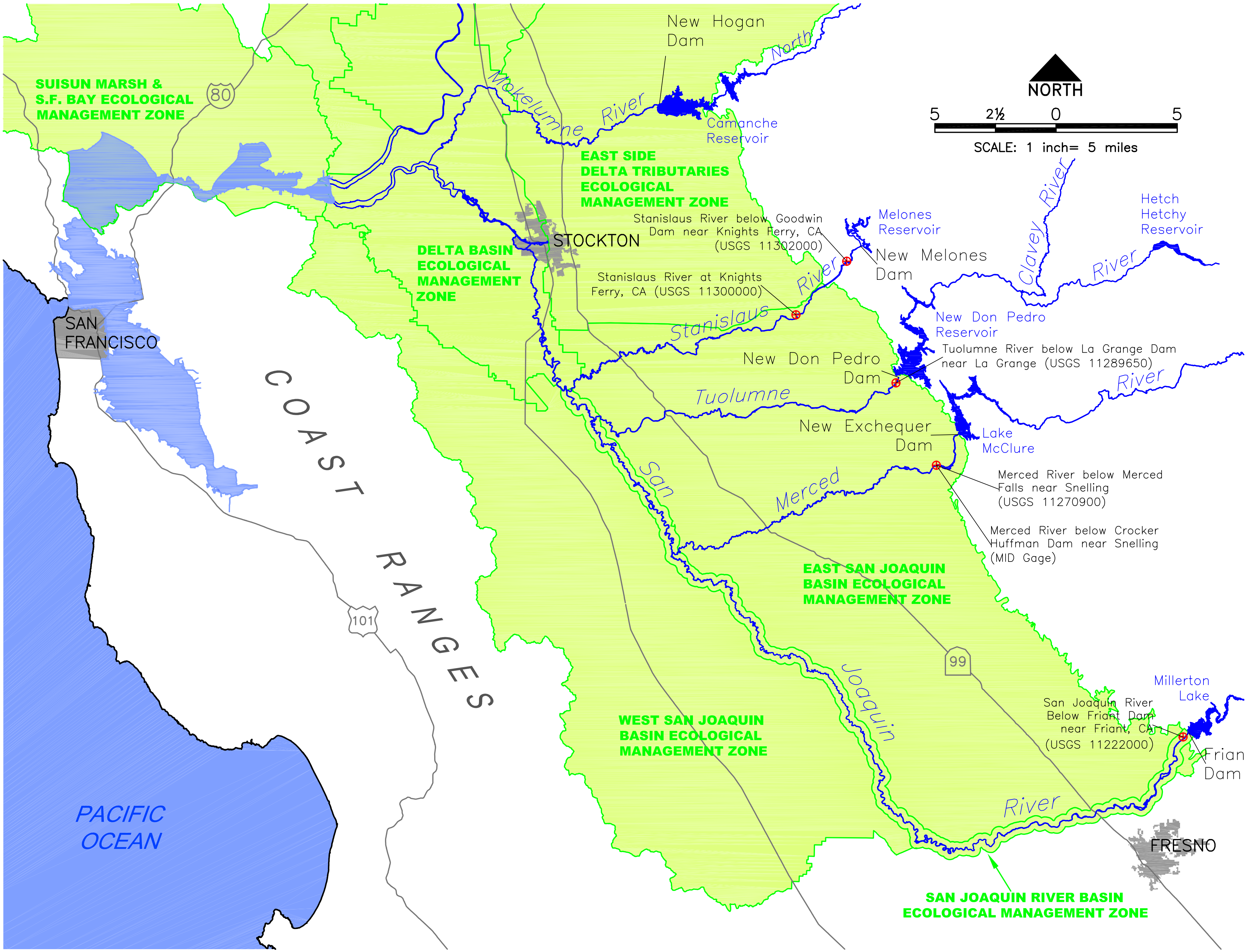

FIGURE 2. SAN JOAQUIN RIVER AND MAJOR TRIBUTARIES

Table 2. San Joaquin River Basin
Watershed Overview Table

	Stanislaus	Tuolumne	Merced	Middle San Joaquin	Mainstem San Joaquin
WATERSHED CHARACTERISTICS:					
Watershed Drainage Area [1]	1,075 mi^2 (headwaters >11,500 ft. elevation, 40% basin above snowline)	1,540 mi^2 (1,900 mi^2)[2]	1,273 mi^2 (top elev. ~13,000 ft; min. elev. 49 ft)	13,537 mi^2 Drainage area above Friant: 1,560 mi^2 (4340 km^2).	
Watershed Dimensions	River length[3]: 161 mi *River length below New Melones Dam: ~62 mi.; Below Goodwin Dam: 59 mi.* Max. width: 24 mi. at Sierra crest (~10 mi at midpoint). [4]	River length[2]: ~155mi *River length below New Don Pedro Dam: ~55 mi Below La Grange: ~52 mi.* (Joins SJ River at RM 83.0)	River length[3]: 135 mi *River length below New Exchequer: 62.5 mi; Below Crocker Huffman Dam: 52 mi.* Max width: 26 miles [5] (Joins SJ River at RM 118)	River length[3]: 330 mi *River length below Friant Dam: 266 mi* Valley width: 130 mi. wide [6]	
Avg. unimpaired flow	**1.2 maf/yr** [6] Avg. unimpaired inflow to New Melones: **1,600 cfs**; Historical avg. flow at Ripon (near mouth): **950cfs**.[1]	**1.906 maf/yr** [3] Avg. unimpaired inflow to New Don Pedro: **2,500 cfs**; Historical avg. flow at La Grange: **880 cfs**.[1]	**1.02 maf/yr** [6] Avg. unimpaired inflows at McClure (New Exchequer dam): **1,325 cfs**; Historical avg. flow at Stevenson (near the mouth): **650 cfs**.[1]	**1.9 maf/yr** [6] *(Note: 2.2 maf/yr committed to water contracts).*	~ 7 maf/yr (estimate) *Historical avg. flow at/near Vernalis – 2,294 cfs*
Primary flow source	Snowmelt runoff	Snowmelt runoff	Snowmelt runoff	Snowmelt runoff	Tributary inflow
Peak Flow (cfs, date)	64,500 cfs; 3/19/1907; below Goodwin Dam. (Post New Melones: 7,350 cfs; 1/3/1997).	58,900 cfs; 1/3/1997; below La Grange Dam	47,700 cfs; 1/31/1911; below Merced Falls Dam (Post New Exchequer: 8,020; 1/4/1997).	77,200 cfs; 12/11/1947; at Friant. (Post Friant: 60,300cfs; 1/3/97).	79,000 cfs; 12/9/1950; at Vernalis.
DAMS AND DIVERSIONS:					
Downstream barrier to fish migration	**Goodwin Dam**, RM 59 (1912; 500AF); salmon and steelhead spawn in 23 mi. reach below Goodwin	**LaGrange Dam**, RM 52.2 (1894; 500AF); salmon and steelhead spawn in 25 mi. reach below LaGrange.	**Crocker-Huffman Dam**, RM 52 near Snelling (1910; 200AF); salmon spawn in 24-mile reach below the dam and the town of Cressey.	**Friant Dam,** RM 260 (1942; 520,000 AF); Streamflow releases below Friant dam are insufficient to support salmon passage, spawning, or rearing and no water passes through the Gravelly Ford (RM 229) to Mendota Pool reach except during high runoff periods.[1]	

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Table 2. San Joaquin River Basin Watershed Overview Table

	Stanislaus	Tuolumne	Merced	Middle San Joaquin	Mainstem
Major dams **--** Completed; capacity (KAF); (Drainage area; River mile)	**New Melones -- 1978; 2,400 KAF**; (DA ~904 mi^2; RM: ~62). [Replaced Old Melones – 1926; 113KAF]. **Tri-dams project – 1957-8; 203KAF** [Tulloch: DA ~980 mi^2, RM ~60; Beardsley: DA ~315mi^2; Donnells: DA ~230 mi^2). **New Spicer Meadows** – **1988; 189 KAF.**	**New Don Pedro – 1970; 2,030 KAF**; (DA ~ 1,542 mi^2; RM 55 to 75). [Replaced Old Don Pedro – 1923; 290KAF]. **Hetch Hetchy** – **1923; 360 KAF**; (DA ~456 mi^2). **Cherry Valley – 1956; 273 KAF**; (DA: ~117 mi^2).	**New Exchequer (Lake McClure) – 1967; 1,024 KAF**; (DA ~1,037 mi^2; RM 62.5). (Replaced Exchequer – 1926; 281 KAF) *McSwain Dam (afterbay to New Exch.) – 1966; 9.7KAF; (RM 56).*	**Friant Dam (Millerton Lake) – 1942; 520KAF**; (DA < 1,638mi^2; RM ~266). **Shaver Lake – 1927; 135 KAF.** **Thomas Edison Lake – 1965; 125 KAF.** **Mammoth Pool -- 1960; 123KAF.**	*Mendota Diversion Dam – 1917; 3 KAF.*
Dam Stats[7] *(DSD dams are those > 50 ft in height and > 50 AF).*	28 DSD dams (12 non DSD); 90.3% basin upstream of major dam[7]; Total reserv. cap: 2.85 maf (3,542x10^6m^3)	27 DSD dams; 81.8% basin upstream of major dam[7]; Total reservoir capacity: 2.94 maf (3,343 x 10^6m^3)	8 DSD dams; 81.7% basin upstream of major dam[7]; Total reservoir capacity:1.04 maf (1,288 x 10^6m^3)	19 DSD dams; [7] 90.3% basin upstream of major dam[8]; Total reservoir capacity: 1.149 maf (1,415 x 10^6m^3)	
% cumulative capture of unimpaired runoff	**237%** See Table St1 & Figure St1	**143%** See Table T1 & Figure T1	**102%** See Table M1 & Figure M1	**60.5%** See Table SJ1 & Figure SJ1	
Main flow diversions	Goodwin Dam (1912; 500 AF) diverts flow into **South San Joaquin Canal** (1914, ~1,320 cfs max) and **Oakdale Irrigation District Canal** (1914, ~560 cfs max). [Previous to Goodwin Dam, Stan. & SJ Water Co. Canal diverted ~3 mi upstream of Knights Ferry (1899).] *44 small pump diversions identified on lower Stanislaus.*[6]	La Grange Dam (1893; 500 AF; owned by TID and MID) diverts flow into the **MID Main Canal** (~1910; max diversion 2,000 cfs; avg. 310KAF/yr)[2] and **TID Main Canal** (~1899; max diversion 3,400 cfs; avg. 575KAF/yr).[2] **900KAF/yr** diverted at La Grange.[2] Inflow to La Grange: 1,670 KAF; downriver: 785 KAF. [2] *36 small irrigation pump diversions identified on lower Tuolumne.*[6]	Merced Falls Dam (1901; 620AF; PG&E; RM 55) diverts flow into **Merced ID Northside Canal** (90 cfs cap.) and Crocker-Huffman dam (1910; 300AF; Merced ID; RM 52) diverts into **Main Canal** (1,900 cfs cap.). Approx **500KAF/yr** diverted at Merced Falls and Crocker-Huffman dams. *68 small irrig pump diversions identified in the lower Merced by DFG surveys.* [6]	Friant Dam (1942; 520,000 AF) diverts flow into the **Friant-Kern Canal** (1948; 5,300 cfs cap.), **Madera Canal** (1944; 1,275 cfs cap.), and other **CVP facilities**. Almost all of the mainstem flow is diverted at Friant dam into the Friant-Kern Canal.[6] Except during spill conditions at Friant dam, the Friant to Gravelly Ford reach receives a 35-230 cfs flow release to support riparian water diversions.[6] (Note: Delta Mendota Canal (1951) delivers water from the Delta to Mendota reservoir for downstream water rights holders).	

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Table 2. San Joaquin River Basin Watershed Overview Table

	Stanislaus	**Tuolumne**	**Merced**	**Middle San Joaquin**	**Mainstem San Joaquin**
FLOW DATA SOURCES FOR IHA MODEL:					
STATUS OF IHA FLOW DATA:	Complete. Use assembled file cited below for Knights Ferry (see notes); download USGS data for Ripon. *[Files & Memo sent 8/25/01]*	Complete. Use assembled file cited below for La Grange; download USGS data for Modesto. *[Files & Memo sent 9/20/01]*	Complete. Use assembled file cited below for Crocker Huffman Gauge; download USGS Merced Falls data; download USGS Stevenson data. *[Files & Memo sent 9/14/01 and 9/18/01]*	Complete. Download data from web. *[Files & Memo sent 8/25/01]*	Complete. Download data from web. *[Files & Memo sent 8/25/01]*
Regulated flow data **<Rim Stations>** *(near upstream barrier to fish migration)*	**<File: STANatKF>** Knights Ferry Compilation; 1895-2000; (DA: 905-1,032 mi^2; ~RM 58-61) [Source: Schneider]. *Compiled from:* **1895-1900: "OAKDALE" #11302500* **1903-1914 "AT KNIGHTS FERRY" #11302000 (manually entered data)* **1915-1932 "NEAR KNIGHTS FERRY" #11300000 (above divs).* **1932-1957 "BELOW MELONES" #11299500 (above diversions).* **1957-2000 "BELOW GOODWIN" #11302000*	**<File: Tuol@LG1896-2001 forIHA.xls>** Compilation at La Grange Dam; (DA: 1,532-1,538mi^2) *Compiled from:* **1896-1917: "ABV LA GRANGE #112888000* **1918-1930: "ABV LA GRANGE #112888000 (above diversions)* **1930-1960: Synthetical produced data -- below diversions from McBain & Trush* **1961-2001: "BELOW LA GRANGE" #11289650*	**<File: MercedFlowData@ CH&MFforIHA.xls>** augmented by **<File: Merced IHAFormattedCH.xls>** **Crocker Huffman Gauge below CH Dam; 1938 -2000.** [Source: Merced ID] & **USGS #11270900** "MERCED R BL MERCED FALLS DAM NR SNELL"; **1901-2000**; (DA: ~ 1,061 mi^2; RM ~55).	**<WEB> USGS #11251000** "SAN JOAQUIN R BL FRIANT CA"; **1907-2000**; (DA: ~1,676 mi^2; RM 268.	**<WEB> USGS #11274000** "SAN JOAQUIN R NR NEWMAN CA"; **1912-2000**; (RM: ~ 117).
Regulated flow data -- <Confluence> *(near confluence with SJ River)*	**WEB:** USGS#11303000 "STAN R A RIPON" (RM 15); 1940-2000.	**WEB:** USGS#11290000 "TUOL. R A MODESTO, CA" (RM ~16; 0.2 mi below Dry Crk); DA: 1,884 mi^2. 1895-6; 1940-2000.	**WEB:** USGS#11272500 "MERCED R NR STEVINSON" (RM 1.1); 1940-1995.	**Limited Data. Priority 2.** USGS#11254000 "SAN JOAQUIN NR MENDOTA CA" (RM ~207); 1939-1954; 1999-2000.	**WEB:** USGS#11303500 "SAN JOAQUIN R NR VERNALIS CA"; 1923-2000.
Unimpaired flow data source		**<File:TuolUnimpaired1897-1999.xls>** (Source: McBain & Trush from TID).			
Proposed Pre and Post Impact Periods	Pre: Before 1926 (Old Melones Dam) Post: After 1979 (New Melones Dam) (Note: NM filled closer to ~1983).	Pre: Before 1923 (Hetch Hetchy and Old Don Pedro) Post: After 1971 (New Don Pedro Dam)	Pre: Before 1926 (Old Exchequer Dam) Post: After 1967 (New Exchequer Dam)	Pre: Before 1941 (Friant Dam) Post: After 1951 (when D-M Canal completed - allows for full operation of Friant for deliveries. The canal delivers water from Delta to Mendota reservoir for downstream water rights holders).	

Table 2. San Joaquin River Basin
Watershed Overview Table

	Stanislaus	Tuolumne	Merced	Middle San Joaquin	Mainstem SJ
OTHER INFORMATION:					
Anadromous fish species	Fall-run Chinook salmon, steelhead, and perhaps late-fall-run Chinook.[6] (Spring-run extirpated).	Fall-run Chinook salmon, steelhead, and perhaps late-fall-run Chinook.[6] (Spring-run extirpated).	Fall-run chinook; perhaps steelhead and late-fall run chinook. [6] (Spring-run chinook extirpated).	Spring-run (extirpated 1949 with closure Friant) and fall-run Chinook (extirpated 1949). Steelhead.	
River avail. to anadr. fish [1]	Historical: 113 mi. Current: 46 mi.	Historical: 99 mi. Current: 47 mi.	Historical: 99 mi. Current: 43 mi.	Historical: 231 mi. Current: 50mi (toMerced)	
Calfed Identified Stressors[6]	**RE: SJ Tribs:** Dams that hinder or block fish migration; legal and illegal fish harvest; water diversions that result in insufficient flow in the lower portion of most streams; high water temperature during salmon and steelhead spawning and rearing; poor water quality; hatchery stocking of salmon and steelhead; gravel mining in the stream channel; poor livestock grazing practices; high predation levels on juvenile salmon by non-native fish; salmon and steelhead harvest; unscreened or poorly screened water diversion. **RE: San Joaquin System Overall:** Artificial confinement of the river channel w/in levees; dams that block access to historical habitat; poor land use and livestock grazing practices on riparian lands; lack of flood flows, which alters the natural sediment balance and reduces riparian vegetation growth; reservoir management and diversions on the mainstem and tributary streams that significantly reduce streamflow and alter stream temperature; entrainment of fish and other aquatic organisms in diversions, direct removal and fragmentation of riparian habitat for agricultural and urban development and floodway maintenance; in channel and floodplain gravel extraction, which alters channel forms.				
Other notes		Irrigation return flow near Modesto increase river flow by about 100 cfs[6].	15-25 cfs legally required flow releases in summer usually depleted before reaching river mouth due to small diversions throughout the lower river. [6]		
Attachments	Dams: Table St1; Figure St1. Gauges: Table ST2; Figure ST2	Dams: Table T1; Figure T1. Gauges: Table T2; Figure of gauges from M&T	Dams: Table M1; Figure M1. Gauges: Table M2; Figure M2.	Dams: Table SJ1; Figure SJ1 Gauges: Table SJ2; Figure SJ2	

[1]: Dept. Fish and Game, AFRP, www.delta.dfg.ca.gov/afrp/ ; [2]: McBain and Trush. 2000 and personal communications; [3]: Mount, Jeffrey F. California Rivers and Streams, 1995; [4]: Schneider, Katrina S. 2001; [5]: Stella, John. Personal Communication. July 2001; [6]: Calfed EIS/EIR Technical Appendix, July 2000; [7]: Kondolf et. al. 1996 (adapted from Kondolf and Matthews, 1993); [8]: Cain, John. Personal Communication. August 2001.
Note: Basin overall: SJ River basin averages 27.3 in/yr precipitation with snowmelt runoff dominant water source and peak flows historically around May and June. (Calfed 2000). Mean annual precipitation totals 21.8 maf (Stella 2001 citing CDWR 1998).

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weighted classes separated by annual exceedance probabilities (p) of 0.80, 0.60, 0.40, and 0.20 and named "Extremely Wet", "Wet", "Normal", "Dry", and "Critically Dry". This classification system addresses the range of variability in the annual water yield and provides an equal probability for each class that a given water year will fall into that category (equally distributed around the mean), which in turn allows simpler comparisons between water year types. Annual hydrographs grouped into five water year classes were then averaged to produce a single average hydrograph. Average hydrographs illustrate differences among water year classes, but mask actual flow variability within each class. To highlight the annual flow variability, we overlaid the water year average hydrographs with a hydrograph from a single representative water year. Finally, annual yields were plotted as a column chart to illustrate the inter-annual (and cyclical) variation in yield for the period of record, and then plotted as a frequency distribution to illustrate the range in yield for each water year type. A table presents each water year, water year type, and yield used in the analysis.

Flow Duration Curve: a flow duration curve ranks all the daily average flow values for the period of record and plots the discharge magnitude as an exceedance probability. This relationship provides information such as "the 10% exceedance flow for the San Joaquin River at Friant Dam was 7,000 cfs (i.e., the streamflow exceeded 7,000 cfs ten percent of the days over the long-term, on average), and was reduced to 2,040 cfs under contemporary regulated conditions." The flow duration curve is a useful tool to estimate the frequency of flow at a given station, as well as flow reductions due to streamflow diversion, but does not provide any seasonal information.

Flood Frequency Curve: the flood frequency curve, based on the annual maximum flood series, is a useful tool to hydrologists and geomorphologists because it describes the flows responsible for geomorphic work. A probability distribution is fitted to the record of instantaneous annual maximum floods at a given station, and the estimated parameters of the distribution are then used to predict the average recurrence interval of floods of a given magnitude (Dunne and Leopold 1978). In our analyses, we plot the raw data for the annual maximum series, and then fit a log-Pearson Type III distribution to the raw data. We present flood frequency curves and report the flood magnitudes with recurrence intervals of 1.5, 5, 10, and 25 years for both the unimpaired and regulated periods of record.

Hydrograph Components: The following list summarizes the important hydrograph components analyzed for each of the four rivers. Refer to Figure 1 for an illustration of these components. The dates for each component were chosen to provide a discrete period for analyses that are comparable for each tributary, but do not necessarily capture all the variability in the duration of the component. For example, if no winter storms occur in a particular year, or occur later in the season, then fall baseflows may extend later than the December 20 date used for analyses.

- Fall Baseflows: Occurring somewhat variably between October 1 and December 20, these were relatively low flows, frequently the lowest daily average flows of the year. Fall baseflows were the unimpaired flows to which adult chinook salmon were adapted during the spawning phase of their life history. The magnitude of the fall baseflows were also critical in regulating the temperature regime in the San Joaquin River and tributaries during the spawning period. Fall baseflows were estimated by computing the median of the daily average flows for the October to December period for each water year, and reporting the median, maximum and minimum value for each water year type.
- Fall Floods: Typically occurring between October 1 and December 20, these floods were generally of smaller magnitude than winter floods. These short duration pulse flows may have stimulated or enabled anadromous salmonid upstream migration by providing a more suitable temperature regime in the lower basin rivers, as well as adequate flow volumes to enable upstream fish passage. Fall floods may have also contributed to maximizing the use of available spawning

habitat by providing access to different habitat zones during short intervals of higher flows. Fall floods were estimated by computing the maximum daily average flow for the October to December period for each water year, then reporting the median and maximum value.

- Winter floods: Typically occurring between mid-December and late-March, winter floods were generated by rainfall or rain-on-snow storm events. Larger magnitude, short duration floods caused by rainfall and rain-on-snow events typically peaked in late December through January, with moderate magnitude events extending through March. Winter floods performed a variety of important ecosystem functions, including the creation and maintenance of channel morphology, scour and transport of bed sediments, bank erosion and channel migration, scour of riparian vegetation along channel margins, scour of alternate bars and other habitat features, and floodplain inundation. The winter flood hydrograph component differed from the annual maximum series flood because it was a daily average flow instead of an instantaneous maximum value. In addition to the flood frequency analysis, winter floods were estimated by computing the maximum daily average flow for each water year and reporting the median, maximum, and minimum value for each water year type.
- Winter baseflows: Occurring between December 21 and March 20 (and frequently later into the spring), winter baseflows were low flow periods between winter storms. Winter baseflows were maintained by the receding limbs of storm hydrographs and shallow groundwater discharge, and generally increased in magnitude and duration throughout the winter months as soils became saturated and groundwater tables rose. Flow conditions during winter months are naturally highly variable, so determining winter baseflows is challenging. A close succession of storms, for example, would establish relatively high baseflows, whereas a long, dry spell between storms would lead to lower winter baseflows. Winter baseflows were estimated by ranking the daily average flows for the December to March period for each water year, eliminating the approximately 15% exceedance flows from this group of data which represented the higher peak winter flows, then computing the median, maximum and minimum value from the remaining group of data for each water year type.
- Snowmelt floods: Spring snowmelt floods were usually of smaller magnitude and longer duration than winter floods. Prior to regulation and diversion, this component was the largest contributor to the total annual water yield, with large magnitude and sustained duration floods extending from approximately early May to as late as August during wetter years, and peaking usually in June or July. The spring snowmelt flood had enormous ecological significance, particularly to the native flora and fauna whose life history traits were strongly linked to the seasonal runoff. Native anadromous salmonid juveniles emigrated from up-river rearing grounds through the nutritionally rich Bay-Delta and out to the ocean during the spring snowmelt, conveyed by the large runoff and favorable water temperatures, and protected by increased turbidity resulting from high flows. Numerous native plant species were also dependent on spring floods to inundate higher-elevation channel surfaces and deposit moist, fine sediment seed beds where successful germination could occur. Snowmelt floods were computed in the same manner as were the winter floods, but for the spring months from April through July. The median, maximum, and minimum values were then reported for each water year type.
- Snowmelt recession: Connecting the snowmelt flood to summer baseflows, the snowmelt recession extended into summer, generally declining to baseflow level by August, but often extending into September of Wet and Extremely Wet years. The critical aspect of the snowmelt recession was the rate of recession, the daily decrease in river stage height. This recession rate determined survival or mortality-by-desiccation of germinating plant seedlings. Snowmelt recession was not analyzed in this hydrograph component analysis because this analysis requires fairly extensive hydraulic geometry data (stage-discharge relationship) made available from cross section surveys.

- Summer baseflows: Beginning at the cessation of the spring snowmelt hydrograph, summer baseflows extended through summer and into fall until the first fall storms increased baseflow level. Summer baseflows represented the minimum annual flow conditions. Summer baseflows were estimated for each water year by computing the median daily average flow for the August through September period, then reporting the medial, maximum, and minimum values for each water year type.

Results

The following results reference Tables 3-6 which are summary tables of the hydrograph components for the unimpaired and regulated periods of record for each river. Additional tables and figures are presented for unimpaired and regulated hydrograph analyses in Appendix A, including: (a) table of annual water yields, exceedance probability, and water year classification, (b) bar chart of annual water yield, and (c) frequency distribution of annual water yield, (d) flow duration curve, (e) flood frequency curve, (f) average and representative hydrographs, and (g) annual hydrograph for each year of record used in the analyses. The following bulleted summary is not meant to report all the hydrograph components for each of the rivers for each of the periods of record analyzed, nor to provide comparisons among the different rivers, but is instead intended to summarize the salient components and the major changes that have occurred for each river. We may present changes in the magnitude of the 1.5-year recurrence winter flood for one tributary but discuss the 10-year recurrence flood for another. All the hydrologic information we analyzed for each river is contained in the appendices.

San Joaquin River (Table 3)

Of the four major rivers in the San Joaquin Valley, the San Joaquin River has been the most extensively altered by streamflow regulation and diversion.

- The total annual water yield was reduced from 1,812,000 af to 528,000 af, a 71% reduction in yield.
- More than half the regulated runoff years analyzed had annual yield less than 125,000 af, which is approximately 7% of the average unimpaired water yield.
- The 1.5-year unimpaired flood was reduced from 10,200 cfs to 850 cfs; the 5-year unimpaired flood of 26,000 cfs was reduced to 6,700 cfs. The smaller magnitude-higher frequency floods were much more severely impacted than were the larger, less frequent floods, likely due to the relatively smaller storage capacity of Millerton Lake (Table 2).
- The Spring Snowmelt hydrograph component was virtually eliminated in all water year types. Prior to regulation, median spring floods ranged from 6,000 cfs to 19,000 cfs during Critically Dry and Extremely Wet years, respectively, with a duration of several months and occasional flood peaks in excess of 25,000 cfs (1906, 1983, 1996). Regulated spring floods now range from (median) peaks of 8,000 and 4,000 cfs in Extremely Wet and Wet years respectively, to as little as 180 to 400 cfs during Critically Dry and Dry years, respectively.
- Unimpaired summer and fall baseflows that historically ranged from 200 to 1000 cfs now range between approximately 150 to 250 cfs under regulated conditions during summer irrigation season, and fall to 60 to 130 cfs in autumn when irrigation diversions cease.
- During Dry and Critically Dry years, streamflows remain at a static year-round low baseflow of 50 to 200 cfs, with no higher flow releases.
- Two distinct periods of record: from April 1974 to November 1978 (1332 days), and from April 1986 to October 1993 (2350 days) were particularly dry. Compared to the unimpaired daily average flow of approximately 2,500 cfs, these two periods reported daily average flows of 100 cfs and 125 cfs, respectively, with maximum flows for these entire periods of only 236 and 313 cfs, respectively.

Merced River (Table 4)

- The total annual water yield was reduced from 1,038,000 af to 485,000 af, a 54% reduction in yield.
- The 1.5-year unimpaired flood was reduced from 4,317 cfs to 3,142 cfs; the 10-year unimpaired flood of 19,000 cfs was reduced to 7,700 cfs. This trend indicates the smaller magnitude-higher frequency floods were less severely impacted than were the larger, less frequent floods.
- The spring snowmelt hydrograph component was impacted by regulation primarily during Dry and Critically Dry years. The median unimpaired spring flood ranged from 4,000 to 10,900 cfs during Critically Dry and Extremely Wet years, respectively, and was reduced to the 2,000 to 4,000 cfs range during Normal to Extremely Wet years. Dry and Critically Dry years' snowmelt floods were virtually eliminated under regulated conditions.
- The daily average flow was reduced from 1,442 cfs to 653 cfs.
- In addition to reducing the spring snowmelt magnitude, the bulk of the total annual yield was shifted from the spring months under unimpaired conditions to the winter months under regulated conditions.

Tuolumne River (Table 5)

Hydrograph components were not analyzed by specific water year class in the post-NDPP (regulated) period because the data set was smaller for regulated years and regulation eliminated much variability between water years. In general, minimum instream flows (baseflows) were determined by the 1971 FERC license flow schedule (Table 5B) and the revised flow schedule resulting from the FERC Settlement Agreement (Table 5C).

- The total annual water yield in the Tuolumne River has been reduced from 1,906,000 af to approximately 719,000 af, a 62% reduction in yield. The lowest post-New Don Pedro yield was 61,000 af, recorded in 1989 and the highest yield was 3,464,000 af recorded in 1983. The 1995 FERC Settlement Agreement (FSA) increased the minimum streamflow requirements for releases below La Grange from annual minimum releases of 123,000 af and 64,000 af for Normal years and Dry years, respectively, to annual minimum releases ranging from 94,000 af to 300,000 af for Dry and Wet years, respectively.
- Winter floods have been severely diminished by NDPP regulation, with the frequency and magnitude of winter floods reduced. The 1.5-year unimpaired flood of 8,430 cfs was reduced to 2,620 cfs. The annual maximum flood has exceeded 8,400 cfs only three times during the post-NDPP era (since 1971). The January 1997 flood of 60,000 cfs had an unimpaired recurrence interval of 25 years on our flood frequency curve. However, the Army Corp estimated the 60,000 cfs peak discharge had an 80-year recurrence interval.
- Snowmelt floods have been eliminated from the annual hydrograph by NDPP operation and replaced with FERC Settlement Agreement spring pulse-flows intended to stimulate smolt emigration. Unimpaired median spring snowmelt floods ranged from 4,500 cfs during Critically Dry years, to 17,000 cfs median flood, with peak spring rain-on-snow floods exceeding 52,000 cfs. The "Outmigration Pulse Flow" in the revised FERC flow schedule (Table 5C) provides a water volumes ranging from 11,000 af to 89,000 af for dry and wet years, respectively, with magnitude-timing-duration decisions the responsibility of the Technical Advisory Committee. Typically, spring pulse releases remain below approximately 5,000 cfs to avoid having to bypass hydropower turbines.
- Daily average flows for May and June at La Grange were reduced from 7,200 cfs unimpaired to 1,370 cfs actual flow (May) and 5,900 cfs unimpaired to 1,370 cfs actual (June).
- Median summer and fall baseflows ranged from 150 to over 1,000 cfs during unimpaired Critically Dry and Extremely Wet years, respectively. These baseflows have been reduced by NDPP regulation and are now determined by the FERC Settlement Agreement. Summer minimum

instream flows range from 50 cfs in dry years to 250 cfs during wet years, and begin approximately June 1 each year. Fall baseflows begin October 1, and range from 100 cfs to 300 cfs, depending on water year type.

Stanislaus River (Table 6)

- The total annual water yield in the Stanislaus River has been reduced from 1,146,000 af to approximately 573,000 af, a 50% reduction in yield. Unimpaired annual yield ranged as high as 2,767,000 af. The lowest post-New Melones Dam yield occurred in 1977, when only 4,685 af were released to the Lower Stanislaus. The highest post-New Melones Dam yield was 1,677,000 af recorded in 1983.
- As with most other Central Valley rivers, the winter flood regime was severely reduced by construction of large storage dams in the basin. The 1.5-year unimpaired flood of 8,800 cfs was reduced to 1,825 cfs, a 79% reduction. The regulated annual maximum flood has exceeded 8,800 cfs only 7 times since 1956. The largest magnitude winter flood since completion of New Melones Dam in 1983 is 7,350 cfs, with an unimpaired recurrence interval of 1.4 years. The unimpaired (log-Pearson III) 25-year flood was 77,000 cfs, and was reduced to 24,000 cfs, although a flood of this magnitude is unlikely to occur on the Stanislaus.
- The baseflow hydrograph components on the Stanislaus River have not been reduced as severely as in other regulated rivers, and in the case of fall baseflows, are relatively unchanged. The unimpaired fall median baseflow was 182 cfs (all water years analyzed) and was 177 cfs for the regulated period of record analyzed. Summer baseflows increased during the post-New Melones period of record: the unimpaired median summer baseflows ranged from 100 to 300 cfs; the post-New Melones Dam median summer baseflow was 340, and median summer baseflows ranged as high as 1,054 cfs during Extremely Wet years. This general trend is due to sustained baseflow released to meet water quality criteria (conductivity and perhaps others) in the Delta (Vernalis) and the minimum dissolved oxygen requirement at Ripon. In the 25 years prior to completion of New Melones Dam, the minimum summer baseflow fell below 10 cfs during all (regulated) water year types.
- Similar to the winter flood regime, the spring snowmelt peak discharge has been reduced, on average, by approximately 70%. For example, the median unimpaired snowmelt peak for Normal water years was 7,160 cfs, but was only 1,439 cfs during regulated Normal water years.
- During a particularly dry two year period in WY 1977 and 1978, the mean daily average flow was only 6.6 cfs (compared to unimpaired daily average flow of 1,575 cfs), with a two-year maximum release of only 144 cfs. The post-New Melones flow regime has not been as extremely low as

Table 3a. San Joaquin River below Friant CA (Modeled UNIMPAIRED water yield from Kings River)

	WATER YEAR TYPE					
Hydrograph Component	***Extremely Wet***	***Wet***	***Normal***	***Dry***	***Critically Dry***	***All Water Years***
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Water Years	20	21	21	21	21	104
Average Daily Flow (cfs)	4,597 cfs	3,022 cfs	2,307 cfs	1,635 cfs	1,063 cfs	2,506 cfs
Average Annual Yield (af)	3,328,190 ac-ft	2,187,744 ac-ft	1,670,032 ac-ft	1,183,424 ac-ft	769,731 ac-ft	1,812,000 ac-ft
Maximum Annual Yield (af)	4,641,537 ac-ft	2,672,303 ac-ft	1,936,172 ac-ft	1,321,069 ac-ft	949,591 ac-ft	2,304,134 ac-ft
Minimum Annual Yield (af)	2,755,032 ac-ft	1,945,119 ac-ft	1,326,827 ac-ft	1,026,184 ac-ft	361,178 ac-ft	1,482,868 ac-ft
Fall Baseflows (Oct 1 - Dec 20)						
Median	380 cfs	318 cfs	432 cfs	295 cfs	274 cfs	340 cfs
Minimum	115 cfs	114 cfs	194 cfs	97 cfs	100 cfs	124 cfs
Maximum	1,705 cfs	1,547 cfs	895 cfs	666 cfs	610 cfs	1,085 cfs
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	2,118 cfs	2,368 cfs	2,066 cfs	1,315 cfs	909 cfs	2,066 cfs
Maximum	45,728 cfs	19,677 cfs	42,352 cfs	11,734 cfs	8,294 cfs	45,728 cfs
Winter Baseflows (Dec 21 - Mar 20)						
Median	1,712 cfs	875 cfs	564 cfs	450 cfs	310 cfs	782 cfs
Minimum	989 cfs	160 cfs	200 cfs	250 cfs	154 cfs	350 cfs
Maximum	3,202 cfs	1,975 cfs	1,512 cfs	867 cfs	627 cfs	1,637 cfs
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	31,256 cfs	15,560 cfs	9,719 cfs	6,655 cfs	3,797 cfs	13,397 cfs
Median Peak Magnitude	28,345 cfs	12,822 cfs	8,489 cfs	5,734 cfs	3,735 cfs	11,825 cfs
Minimum	11,248 cfs	6,407 cfs	3,548 cfs	2,078 cfs	1,486 cfs	4,953 cfs
Maximum	77,467 cfs	40,982 cfs	23,908 cfs	27,292 cfs	7,928 cfs	35,515 cfs
Snowmelt Floods (Mar 21 - June 21)						
Average Peak Magnitude	18,925 cfs	15,361 cfs	12,162 cfs	9,640 cfs	5,942 cfs	12,406 cfs
Median Peak Magnitude	19,275 cfs	14,467 cfs	11,740 cfs	9,641 cfs	5,742 cfs	12,173 cfs
Minimum	11,645 cfs	10,512 cfs	8,583 cfs	6,635 cfs	3,549 cfs	8,185 cfs
Maximum	25,316 cfs	32,217 cfs	16,941 cfs	13,986 cfs	10,092 cfs	19,711 cfs
Snowmelt Recession						
Median Date of Peak	31-May	23-May	27-May	19-May	12-May	22-May
Earliest Peak	28-Apr	26-Apr	6-May	25-Apr	22-Apr	27-Apr
Latest Peak	21-Jun	30-Jun	13-Jun	15-Jun	16-Jun	19-Jun
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	1,013 cfs	583 cfs	389 cfs	284 cfs	212 cfs	496 cfs
Minimum	453 cfs	302 cfs	200 cfs	133 cfs	114 cfs	241 cfs
Maximum	2,105 cfs	1,049 cfs	582 cfs	664 cfs	584 cfs	997 cfs

Daily Average Discharge	=	2,506 cfs
Total Annual Runoff	=	1,812,000 ac-ft

Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	10,227 cfs	850 cfs
Q_5	=	26,195 cfs	6,749 cfs
Q_{10}	=	36,758 cfs	13,644 cfs
Q_{25}	=	53,000 cfs	28,727 cfs

Table 3b. San Joaquin River below Friant CA 1950 - 2000 REGULATED (post-Friant) water yeild (USGS Stn 11-251000

	WATER YEAR TYPE					
Hydrograph Component	**Extremely Wet**	**Wet**	**Normal**	**Dry**	**Critically Dry**	**All Water Years**
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Water Years	10	10	10	10	11	51
Average Daily Flow (cfs)	2,345 cfs	950 cfs	208 cfs	121 cfs	88 cfs	730 cfs
Average Annual Yield (af)	1,697,624 ac-ft	687,662 ac-ft	150,839 ac-ft	87,888 ac-ft	63,570 ac-ft	528,224 ac-ft
Maximum Annual Yield (af)	3,174,569 ac-ft	1,180,140 ac-ft	262,264 ac-ft	99,816 ac-ft	75,116 ac-ft	3,174,569 ac-ft
Minimum Annual Yield (af)	1,187,252 ac-ft	285,118 ac-ft	104,426 ac-ft	79,474 ac-ft	48,424 ac-ft	48,424 ac-ft
Fall Baseflows (Oct 1 - Dec 20)						
Median	117 cfs	105 cfs	127 cfs	81 cfs	62 cfs	105 cfs
Minimum	52 cfs	71 cfs	54 cfs	44 cfs	36 cfs	36 cfs
Maximum	480 cfs	1,050 cfs	495 cfs	125 cfs	87 cfs	1,050 cfs
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	299 cfs	196 cfs	194 cfs	126 cfs	93 cfs	194 cfs
Maximum	5,020 cfs	3,130 cfs	1,020 cfs	693 cfs	120 cfs	5,020 cfs
Winter Baseflows (Dec 21 - Mar 20)						
Median	1,095 cfs	65 cfs	86 cfs	54 cfs	36 cfs	65 cfs
Minimum	49 cfs	52 cfs	56 cfs	26 cfs	24 cfs	24 cfs
Maximum	5,720 cfs	110 cfs	173 cfs	71 cfs	61 cfs	5,720 cfs
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	10,313 cfs	5,777 cfs	684 cfs	361 cfs	165 cfs	3,460 cfs
Median Peak Magnitude	7,985 cfs	4,900 cfs	711 cfs	172 cfs	117 cfs	711 cfs
Minimum	4,030 cfs	936 cfs	146 cfs	106 cfs	66 cfs	66 cfs
Maximum	36,800 cfs	14,900 cfs	1,380 cfs	1,950 cfs	580 cfs	36,800 cfs
Snowmelt Floods (Mar 21 - June 21)						
Average Peak Magnitude	7,320 cfs	4,212 cfs	888 cfs	418 cfs	183 cfs	2,604 cfs
Median Peak Magnitude	7,960 cfs	3,890 cfs	583 cfs	229 cfs	171 cfs	583 cfs
Minimum	291 cfs	168 cfs	198 cfs	121 cfs	136 cfs	121 cfs
Maximum	12,400 cfs	8,080 cfs	2,370 cfs	2,110 cfs	217 cfs	12,400 cfs
Snowmelt Recession						
Median Date of Peak	8-Jun	8-May	18-Jun	5-Jul	10-Jul	15-Jun
Earliest Peak	26-Apr	21-Apr	20-May	1-May	25-Apr	30-Apr
Latest Peak	12-Jul	4-Jul	15-Aug	11-Aug	17-Aug	30-Jul
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	245 cfs	148 cfs	175 cfs	162 cfs	135 cfs	162 cfs
Minimum	76 cfs	86 cfs	107 cfs	82 cfs	90 cfs	76 cfs
Maximum	2,090 cfs	1,750 cfs	267 cfs	201 cfs	144 cfs	2,090 cfs

Daily Average Discharge	=	730 cfs	
Total Annual Runoff	=	528,224 ac-ft	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	10,187 cfs	771 cfs
Q_5	=	25,177 cfs	5,885 cfs
Q_{10}	=	35,111 cfs	11,922 cfs
Q_{25}	=	50,650 cfs	25,379 cfs

Table 4A. Merced River Below Merced Falls Dam Near Snelling CA, Unimpaired water yield 1901-1926 (USGS Stn 11-270900)

	WATER YEAR TYPE					
Hydrograph Component	***Extremely Wet***	***Wet***	***Normal***	***Dry***	***Critically Dry***	***All Water Years***
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Years in Water Year Type	5	5	5	5	5	
Daily Average Discharge (cfs)	2,625	1,593	1,416	1,000	577	1,442
Total Annual Runoff (af)	1,837,129	1,153,363	923,696	723,820	433,069	1,014,215
Maximum Annual Runoff (af)	2,126,503	1,418,394	947,302	843,755	525,295	1,172,250
Minimum Annual Runoff (af)	1,441,928	1,011,156	887,637	607,408	251,814	839,988
Fall Baseflows (Oct 1 - Dec 20)						
Median	129	287	195	139	140	178
Minimum	64	56	142	61	61	77
Maximum	220	318	520	324	168	310
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	694	1,000	2,480	1,050	280	1,101
Maximum	3,190	14,800	3,970	3,380	730	5,214
Winter Baseflows ((Dec 21 - Mar 20)						
Median	1,430	900	676	202	228	687
Minimum	620	240	604	126	191	356
Maximum	1,530	1,300	810	288	405	866
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	22,880	13,228	8,426	7,384	1,868	10,757
Median Peak Magnitude	20,400	13,300	8,980	6,320	1,530	10,106
Minimum	12,600	6,740	3,370	4,960	1,330	5,800
Maximum	37,200	18,500	12,000	14,300	3,080	17,016
Snowmelt Floods (Apr 21 - Jul 21)						
Average Peak Magnitude	10,972	8,358	7,136	6,180	3,905	7,310
Median Peak Magnitude	10,500	8,870	6,920	5,420	3,515	7,045
Minimum	8,040	5,940	5,900	3,600	2,490	5,194
Maximum	15,400	10,500	8,820	8,740	6,100	9,912
Snowmelt Recession						
Median Data of Peak	2-Jun	5-Jun	16-May	28-May	13-May	25-May
Earliest Peak	6-May	26-Apr	6-May	26-Apr	1-May	1-May
Latest Peak	13-Jun	11-Jun	17-May	12-Jun	4-Jun	5-Jun
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	300	151	162	78	110	160
Minimum	198	85	78	41	24	85
Maximum	424	192	309	100	232	251

Daily Average Discharge (cfs)	=	1,442	
Total Annual Runoff (af)	=	1,038,334	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	4,317	3,142
Q_5	=	13,110	6,194
Q_{10}	=	19,385	7,756
Q_{25}	=	29,550	9,807

Table 4B. Merced River below Crocker-Huffman Dam, CA 1966-2000 (Regulated) (MID Gage)

	WATER YEAR TYPE					
Hydrograph Component	***Extremely Wet***	***Wet***	***Normal***	***Dry***	***Critically Dry***	***All Water Years***
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Years in Water Year Type	7	7	7	7	7	35
Daily Average Discharge (cfs)	1,580	697	553	258	177	653
Total Annual Runoff (af)	1,143,914	503,731	397,210	186,720	127,741	471,863
Maximum Annual Runoff (af)	1,671,221	648,014	463,018	246,222	147,901	1,671,221
Minimum Annual Runoff (af)	845,167	172,858	274,126	155,883	78,932	78,932
Fall Baseflows (Oct 1 - Dec 20)						
Median	229	165	267	224	188	224
Minimum	116	33	192	38	165	33
Maximum	1,272	1,355	1,446	489	249	1,446
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	1,519	1,002	1,815	1,149	227	1,149
Maximum	3,110	2,800	3,925	5,323	1,201	5,323
Winter Baseflows ((Dec 21 - Mar 20)						
Median	765	157	258	154	184	184
Minimum	162	16	218	27	78	16
Maximum	5,497	963	539	339	242	5,497
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	5,368	2,598	2,026	1,525	286	2,361
Median Peak Magnitude	5,135	2,529	2,139	1,002	274	2,139
Minimum	4,114	294	434	415	178	178
Maximum	8,279	4,325	3,130	4,880	424	8,279
Snowmelt Floods (Apr 21 - Jul 21)						
Average Peak Magnitude	4,052	2,682	1,756	234	253	1,795
Median Peak Magnitude	4,739	2,655	1,930	220	264	1,930
Minimum	1,412	282	182	209	144	144
Maximum	6,002	7,365	3,843	294	315	7,365
Snowmelt Recession						
Median Data of Peak	8-Jun	5-Jun	7-Jun	14-Jun	19-May	7-Jun
Earliest Peak	27-Apr	22-Apr	21-Apr	1-May	2-May	21-Apr
Latest Peak	16-Jul	26-Jun	28-Jul	18-Jul	2-Aug	2-Aug
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	663	252	195	154	146	195
Minimum	200	168	145	103	93	93
Maximum	1,029	750	874	178	199	1,029

Daily Average Discharge (cfs)	=	653	
Total Annual Runoff (af)	=	484,871	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	4,317	3,142
Q_{5}	=	13,110	6,194
Q_{10}	=	19,385	7,756
Q_{25}	=	29,550	9,807

Table 5A. Tuolumne River at La Grange 1896-1999 (USGS11-289650) USGS data and modeled Unimpaired water yield data from TID

	WATER YEAR TYPE					
Hydrograph Component	**Extremely Wet**	**Wet**	**Normal**	**Dry**	**Critically Dry**	**All Water Years**
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Years in Water Year Type	15	16	16	16	16	
Daily Average Discharge (cfs)	4,536	3,143	2,377	1,666	1,164	2,577
Total Annual Runoff (af)	3,049,559	2,275,486	1,720,878	1,206,287	842,446	1,818,931
Maximum Annual Runoff (af)	4,639,714	2,544,881	2,045,209	1,362,947	454,334	4,639,714
Minimum Annual Runoff (af)	2,581,784	2,066,348	1,397,742	893,100	1,098,414	893,100
Fall Baseflows (Oct 1-Dec 20)						
Average	542	380	366	352	332	366
Minimum	230	90	88	131	121	88
Maximum	1,668	1,576	856	842	780	1,668
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	5,287	6,393	2,697	1,797	1,422	2,697
Maximum	74421	66959	15773	10587	8308	74,421
Winter Baseflow (Dec 21-Mar 20)						
Average	2,838	2,089	1,316	933	775	1,316
Minimum	1,370	1,518	430	571	263	263
Maximum	4,463	2,831	2,593	1,710	1,280	4,463
Winter Floods (Dec 21-Mar 20)						
Average Peak Magnitude	23,736	21,236	13,956	7,342	3,409	13,936
Median Peak Magnitude	11,800	19,400	9,955	6,050	2,940	9,955
Minimum	8,450	10,300	5,100	2,860	2,610	2,610
Maximum	47,600	61,000	38,100	15,600	6,210	61,000
Snowmelt Floods (Mar 21-Aug 5)						
Average Peak Magnitude	13,363	11,174	8,646	6,768	4,538	8,898
Median Peak Magnitude	17,484	15,387	12,630	9,617	6,766	12,630
Minimum	12,219	11,623	9,964	7,388	5,130	5,130
Maximum	52,118	38,425	43,351	14,427	15,279	52,118
Snowmelt recession						
Median Date of Peak	1-Jun	16-May	19-May	29-May	3-May	19-May
Summer Baseflow (July 15 - Oct 15)						
Average	637	284	220	222	152	222
Minimum	447	174	117	129	82	82
Maximum	2,259	420	565	403	274	2,259

Daily Average Discharge (cfs)	=	2,577	
Total Annual Runoff (af)	=	1,906,505	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	8,430	2,620
Q_5	=	26,310	8,770
Q_{10}	=	39,240	13,500
Q_{25}	=	60,340	21,580

Table 5B. Tuolumne River at La Grange, CA regulated water yield 1971- 2001 (USGS Stn 11-289650)

Hydrograph Component	Extremely Wet	Wet	Normal	Dry	Critically Dry	All Water Years
			WATER YEAR TYPE			
Probabilty of Exceedence	20%	40%	60%	80%	100%	
Number of Years in Water Year Type	6	6	6	6	6	
Mean Annual Yield (cfs)	2,062	908	478	226	93	753
Average Annual Yield (af)	2,136,869	1,016,937	410,102	221,380	75,741	772,206
Maximum Annual Yield (af)	3,464,878	1,376,458	561,473	292,052	84,964	
Minimum Annual Yield (af)	1,493,029	657,186	345,889	163,878	61,029	
Fall Baseflows (Oct 1 - Dec 20)						
Median	376	348	507	272	167	334
Minimum	174	314	196	8	93	157
Maximum	2,910	3,120	860	410	213	1,503
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	1,650	2,120	2,615	1,410	247	1,608
Maximum	5,880	4,710	2,870	3,080	861	3,480
Winter Baseflows ((Dec 21 - Mar 20)						
Median	3,960	1,317	792	264	116	1,290
Maximum	1,160	295	501	10	92	412
Minimum	6,240	4,610	1,310	364	149	2,535
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	14,467	6,258	2,643	1,007	179	4,911
Median Peak Magnitude	8,150	6,450	2,685	888	174	3,669
Maximum	4,600	3,480	1,940	130	97	2,049
Minimum	50,100	8,010	3,080	2,750	290	12,846
Snowmelt Floods (Mar 21 - June 21)						
Average Peak Magnitude	6,798	4,403	830	1,575	750	2,871
Median Peak Magnitude	7,400	3,725	596	1,108	683	2,702
Maximum	2,860	2,200	328	383	207	1,196
Minimum	10,400	6,870	1,800	4,570	1,190	4,966
Snowmelt Recession						
Median Data of Peak	23-Apr	13-Apr	27-Mar	25-Apr	28-Apr	17-Apr
Earliest Peak	23-Mar	22-Mar	21-Mar	29-Mar	31-Mar	25-Mar
Latest Peak	23-May	18-May	6-Apr	15-May	2-May	6-May
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	1,096	208	19	17	22	272
Maximum	88	15	8	8	6	25
Minimum	3,070	565	536	476	46	938

Daily Average Discharge (cfs)	=	753
Total Annual Runoff (af)	=	772,206

Annual Maximum Flood Frequency		Unimpaired	Regulated
$Q_{1.5}$	=	8,430	2,620
Q_{5}	=	26,310	8,770
Q_{10}	=	39,240	13,500
Q_{25}	=	60,340	21,580

Figure 6a. Stanislaus River at Knights Ferry unimpaired water yield (USGS 11-302000)

	WATER YEAR TYPE					
Hydrograph Component Probabilty of Exceedence	***Extremely Wet*** 20%	***Wet*** 40%	***Normal*** 60%	***Dry*** 80%	***Critically Dry*** 100%	***All Water Years***
Number of Years in Water Year Type	6	6	7	6	7	32
Daily Average Discharge	2,942 cfs	1,865 cfs	1,488 cfs	986 cfs	591 cfs	1,575 cfs
Total Annual Runoff	2,130,261 ac-ft	1,349,923 ac-ft	1,077,573 ac-ft	714,105 ac-ft	427,868 ac-ft	1,146,284 ac-ft
Maximum Annual Runoff	2,767,666 ac-ft	1,398,908 ac-ft	1,287,742 ac-ft	793,938 ac-ft	548,897 ac-ft	2,767,666 ac-ft
Minimum Annual Runoff	1,583,572 ac-ft	1,300,637 ac-ft	883,021 ac-ft	576,026 ac-ft	249,197 ac-ft	249,197 ac-ft
Fall Baseflows (Oct 1 - Dec 20)						
Median of Oct 1-Dec 20 median flow	157 cfs	182 cfs	297 cfs	161 cfs	202 cfs	182 cfs
Minimum of Oct 1-Dec 20 median flow	60 cfs	10 cfs	98 cfs	17 cfs	125 cfs	10 cfs
Maximum of Oct 1-Dec 20 median flow	320 cfs	309 cfs	550 cfs	279 cfs	264 cfs	550 cfs
Fall Floods (Oct 1 - Dec 20)						
Average Peak Magnitude	2,571 cfs	2,806 cfs	2,987 cfs	423 cfs	659 cfs	1,889 cfs
Median Peak Magnitude	672 cfs	1,099 cfs	2,130 cfs	423 cfs	504 cfs	672 cfs
Minimum of daily peak values	212 cfs	246 cfs	580 cfs	165 cfs	380 cfs	165 cfs
Maximum of daily peak values	11,110 cfs	9,830 cfs	5,740 cfs	705 cfs	1,520 cfs	11,110 cfs
Winter Baseflows ((Dec 21 - Mar 20)						
Median of Dec 21-Mar 20 median flow	1,848 cfs	809 cfs	892 cfs	217 cfs	241 cfs	809 cfs
Minimum of Dec 21-Mar 20 median flow	160 cfs	550 cfs	180 cfs	156 cfs	89 cfs	89 cfs
Maximum of Dec 21-Mar 20 median flow	2,660 cfs	1,680 cfs	1,510 cfs	265 cfs	415 cfs	2,660 cfs
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	32,283 cfs	9,675 cfs	11,756 cfs	7,655 cfs	1,981 cfs	12,670 cfs
Median Peak Magnitude	33,500 cfs	9,300 cfs	9,500 cfs	5,615 cfs	1,440 cfs	9,300 cfs
Minimum of daily peak values	15,600 cfs	6,950 cfs	4,640 cfs	4,250 cfs	1,090 cfs	1,090 cfs
Maximum of daily peak values	58,000 cfs	13,200 cfs	27,000 cfs	13,900 cfs	3,785 cfs	58,000 cfs
Snowmelt Floods (Apr 21 - Jul 21)						
Average Peak Magnitude	11,503 cfs	9,830 cfs	6,887 cfs	5,540 cfs	3,530 cfs	7,458 cfs
Median Peak Magnitude	11,495 cfs	9,695 cfs	7,160 cfs	5,310 cfs	3,920 cfs	7,160 cfs
Minimum of daily peak values	8,060 cfs	7,630 cfs	4,380 cfs	3,740 cfs	1,170 cfs	1,170 cfs
Maximum of daily peak values	14,400 cfs	13,000 cfs	8,820 cfs	7,740 cfs	5,880 cfs	14,400 cfs
Snowmelt Recession						
Median Data of Peak	3-Jun	17-May	17-May	8-May	10-May	17-May
Earliest Peak	15-May	28-Apr	5-May	30-Apr	21-Apr	21-Apr
Latest Peak	13-Jun	10-Jun	7-Jun	22-May	4-Jun	13-Jun
Summer Baseflows (July 15 - Sep 30)						
Median of July 15 - Sep 30 median flow	197 cfs	293 cfs	284 cfs	249 cfs	99 cfs	249 cfs
Minimum of July 15 - Sep 30 median flow	0 cfs	129 cfs	50 cfs	90 cfs	15 cfs	0 cfs
Maximum of July 15 - Sep 30 median flow	443 cfs	825 cfs	847 cfs	781 cfs	748 cfs	847 cfs

Daily Average Discharge	=	1,575 cfs	
Total Annual Runoff	=	1,146,284 ac-ft	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	8,089 cfs	2,089 cfs
Q_5	=	29,886 cfs	10,099 cfs
Q_{10}	=	47,192 cfs	16,391 cfs
Q_{25}	=	77,081 cfs	24,769 cfs

Table 6b. Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED (USGS Stn 11-302000)

	WATER YEAR TYPE					
Hydrograph Component	***Extremely Wet***	***Wet***	***Normal***	***Dry***	***Critically Dry***	***All Water Years***
Probabilty of Exceedence	*20%*	*40%*	*60%*	*80%*	*100%*	
Number of Years in Water Year Type	4	3	4	4	3	18
Daily Average Discharge (cfs)	1,817	1,128	643	412	271	854
Total Annual Runoff (af)	1,315,121	816,700	465,365	298,059	196,473	573,216
Maximum Annual Runoff (af)	1,677,531	929,423	552,847	389,397	268,677	1,677,531
Minimum Annual Runoff (af)	1,063,632	663,493	406,467	187,035	133,706	133,706
Fall Baseflows (Oct 1 - Dec 20)						
Median	745	270	303	239	206	270
Minimum	352	231	207	205	161	161.0
Maximum	1,580	536	414	407	208	1,580
Fall Floods (Oct 1 - Dec 20)						
Median Peak Magnitude	2,570	1,250	823	1,034	734	1,034
Maximum	5,340	1,850	1,610	1,330	989	5,340
Winter Baseflows ((Dec 21 - Mar 20)						
Median	1,825	525	384	195	85	384
Minimum	928	275	137	130	8	8
Maximum	5,020	1,710	506	283	155	5,020
Winter Floods (Dec 21 - Mar 20)						
Average Peak Magnitude	5,393	4,823	1,863	1,538	698	2,863
Median Peak Magnitude	5,290	4,340	1,325	1,270	917	1,325
Minimum	4,150	3,800	1,270	917	158	158
Maximum	6,840	6,330	3,530	2,430	1,020	6,840
Snowmelt Floods (Apr 21 - Jul 21)						
Average Peak Magnitude	2,419	1,443	1,232	1,266	833	1,439
Median Peak Magnitude	1,855	1,530	1,230	1,415	882	1,415
Minimum	694	1,240	956	734	734	694
Maximum	5,270	1,560	1,510	1,590	884	5,270
Snowmelt Recession						
Median Data of Peak	2-May	2-May	18-Jun	10-May	16-May	10-May
Earliest Peak	24-Apr	28-Apr	21-May	27-Apr	30-Apr	24-Apr
Latest Peak	19-Jun	12-Jun	14-Jul	10-Jun	10-Jun	14-Jul
Summer Baseflows (July 15 - Sep 30)						
Baseflow Median	1,054	489	346	273	273	346
Minimum	317	337	285	203	154	154
Maximum	1,780	1,240	705	327	327	1,780

Daily Average Discharge (cfs)	=	854	
Total Annual Runoff (af)	=	573,216	
Annual Maximum Flood Frequency		***Unimpaired***	***Regulated***
$Q_{1.5}$	=	8,089	2,089
Q_5	=	29,886	10,099
Q_{10}	=	47,192	16,391
Q_{25}	=	77,081	24,769

4 Literature Cited

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5 Appendices

Appendix A: San Joaquin R blw Friant CA 1896-1999 (Modeled UNIMPAIRED from Kings River)

Appendix B: San Joaquin R blw Friant CA 1950-2000 REGULATED (USGS Stn 11-251000)

Appendix C: MERCED R BL MERCED FALLS DAM NR SNELLING CA, UNIMPAIRED 1901-1926 (USGS Stn 11-270900)

Appendix D: Merced River blw Crocker-Huffman Dam, CA 1966-2000 (REGULATED) (MID Gage)

Appendix E: Tuolumne River at La Grange 1896-1999 (USGS11-289650) USGS data and modeled UNIMPAIRED data from TID

Appendix F: Tuolumne River at La Grange, CA REGULATED 1971-2001 (USGS Stn 11-289650)

Appendix G: Stanislaus R at Knights Ferry UNIMPAIRED 1896-1932 (USGS 11-302000)

Appendix H: Stanislaus River blw Goodwin Dam nr Knights Ferry, CA REGULATED 1958-2000 (USGS Stn 11-302000)

APPENDIX A.

UNIMPAIRED HYDROLOGIC DATA FOR THE

- SAN JOAQUIN RIVER

INCLUDING:

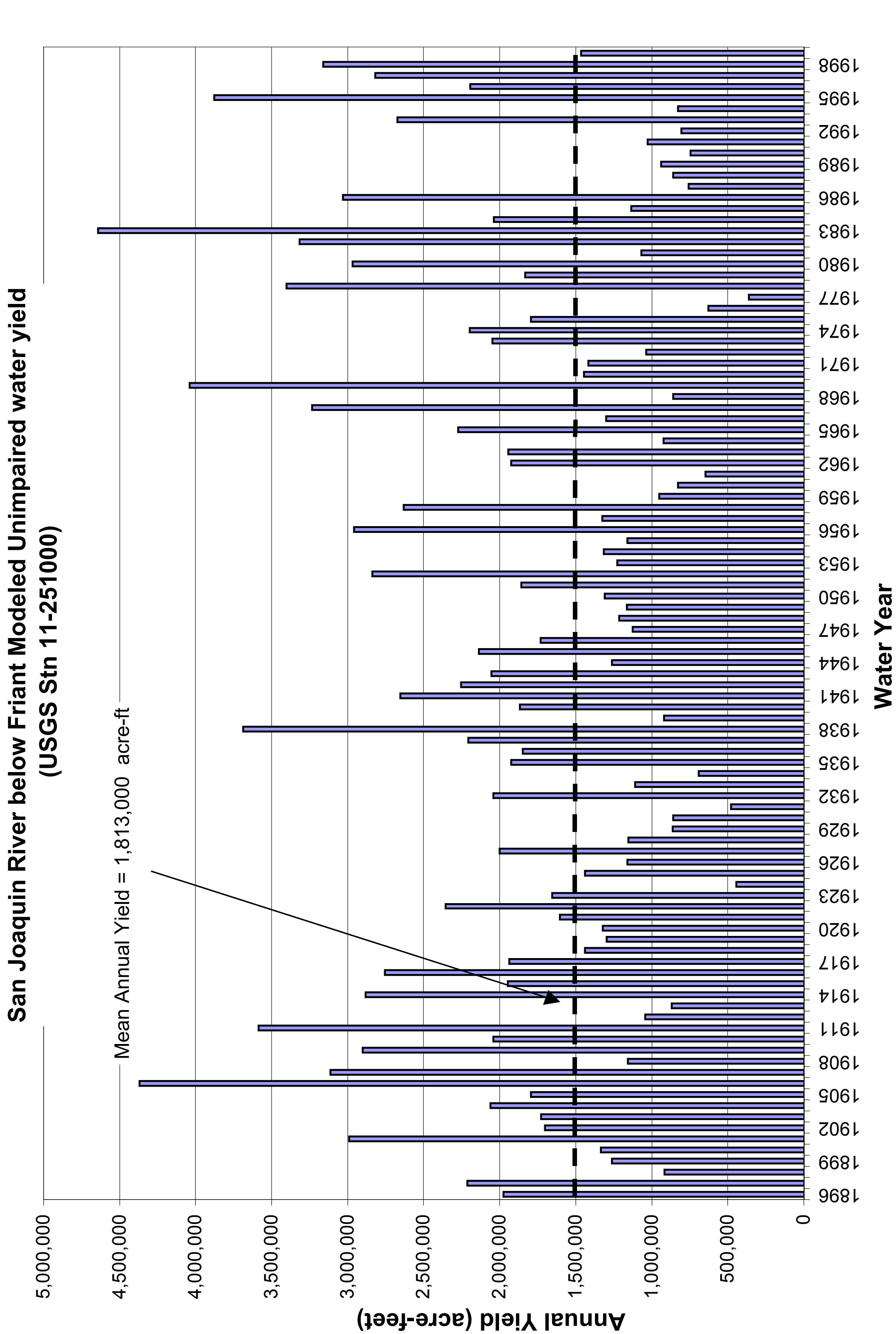
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

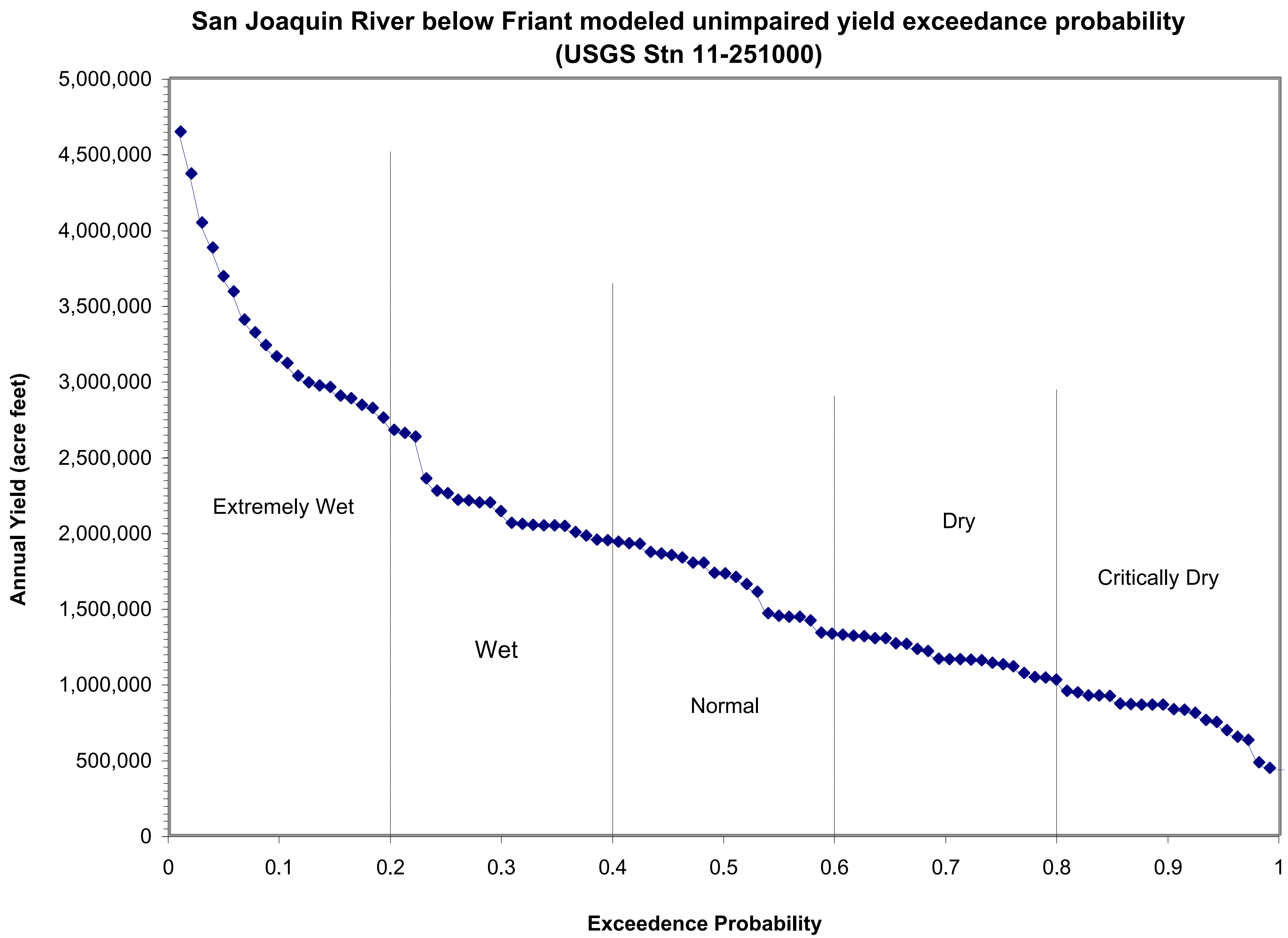
San Joaquin River blw Friant CA (Modeled UNIMPAIRED water yield from Kings River)

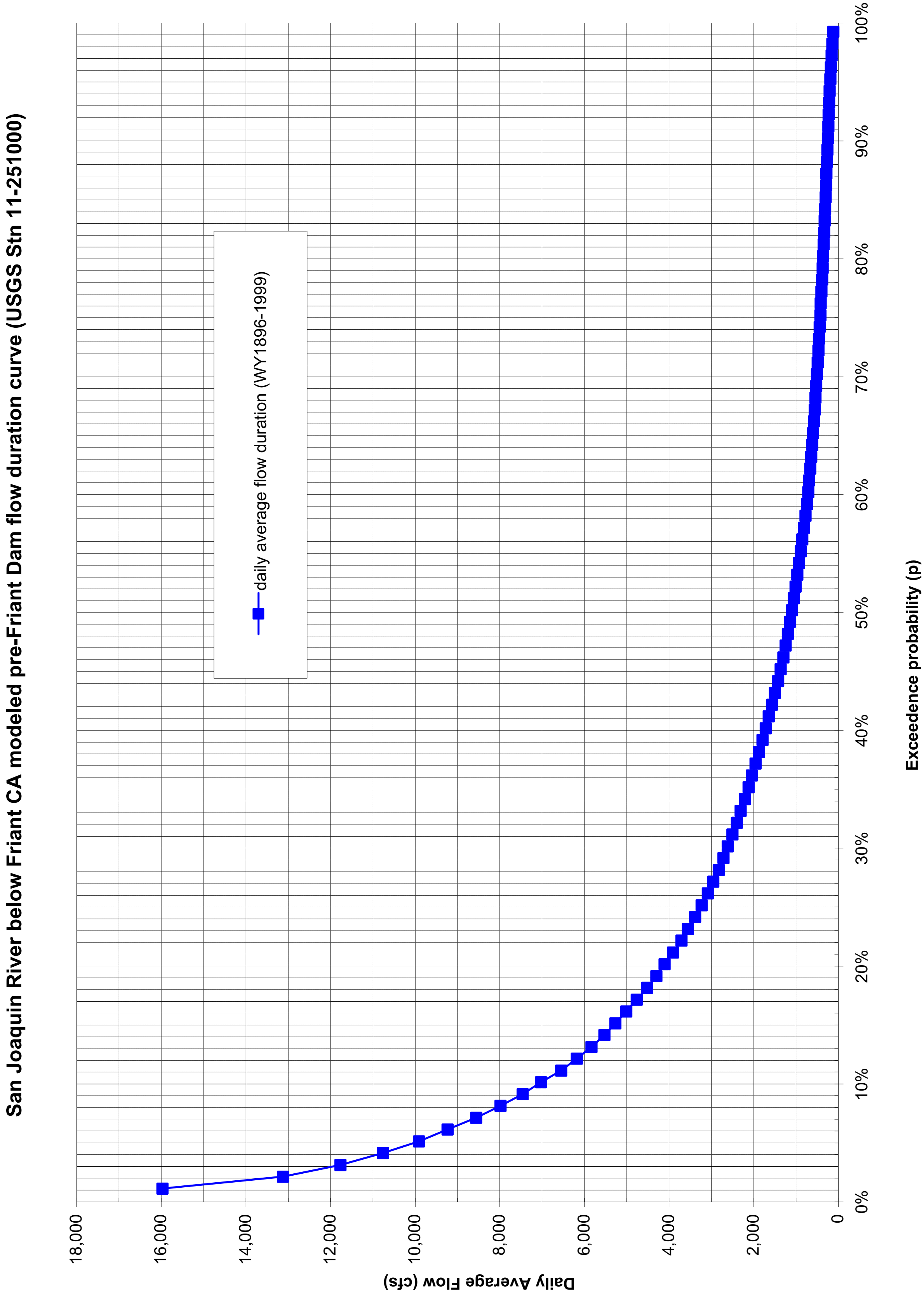
WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1896	1,975,854	WET	37.50%	39
1897	2,213,268	WET	25.96%	27
1898	915,687	CRITICALLY DRY	84.62%	88
1899	1,262,882	DRY	65.38%	68
1900	1,336,191	NORMAL	58.65%	61
1901	2,988,756	EXTREMELY WET	12.50%	13
1902	1,703,975	NORMAL	50.96%	53
1903	1,726,975	NORMAL	50.00%	52
1904	2,059,433	WET	30.77%	32
1905	1,795,374	NORMAL	48.08%	50
1906	4,367,736	EXTREMELY WET	1.92%	2
1907	3,113,855	EXTREMELY WET	10.58%	11
1908	1,157,378	DRY	72.12%	75
1909	2,900,658	EXTREMELY WET	15.38%	16
1910	2,041,470	WET	34.62%	36
1911	3,585,948	EXTREMELY WET	5.77%	6
1912	1,043,090	DRY	77.88%	81
1913	867,687	CRITICALLY DRY	85.58%	89
1914	2,883,358	EXTREMELY WET	16.35%	17
1915	1,947,072	WET	38.46%	40
1916	2,755,032	EXTREMELY WET	19.23%	20
1917	1,936,172	NORMAL	40.38%	42
1918	1,440,179	NORMAL	55.77%	58
1919	1,297,481	DRY	64.42%	67
1920	1,321,069	DRY	60.58%	63
1921	1,603,977	NORMAL	52.88%	55
1922	2,354,966	WET	23.08%	24
1923	1,653,976	NORMAL	51.92%	54
1924	443,271	CRITICALLY DRY	99.04%	103
1925	1,438,979	NORMAL	56.73%	59
1926	1,160,983	DRY	71.15%	74
1927	2,000,971	WET	36.54%	38
1928	1,152,519	DRY	73.08%	76
1929	861,987	CRITICALLY DRY	86.54%	90
1930	858,987	CRITICALLY DRY	88.46%	92
1931	479,993	CRITICALLY DRY	98.08%	102
1932	2,042,522	WET	33.65%	35
1933	1,110,984	DRY	75.96%	79
1934	690,990	CRITICALLY DRY	95.19%	99
1935	1,922,972	NORMAL	42.31%	44
1936	1,848,838	NORMAL	45.19%	47
1937	2,207,968	WET	26.92%	28
1938	3,687,946	EXTREMELY WET	4.81%	5
1939	920,987	CRITICALLY DRY	83.65%	87
1940	1,867,531	NORMAL	43.27%	45
1941	2,652,961	WET	21.15%	22
1942	2,253,967	WET	25.00%	26
1943	2,053,970	WET	31.73%	33
1944	1,261,727	DRY	66.35%	69
1945	2,137,969	WET	29.81%	31
1946	1,729,975	NORMAL	49.04%	51
1947	1,125,984	DRY	75.00%	78
1948	1,214,171	DRY	68.27%	71
1949	1,164,065	DRY	69.23%	72
1950	1,310,563	DRY	62.50%	65
1951	1,859,105	NORMAL	44.23%	46
1952	2,837,455	EXTREMELY WET	17.31%	18
1953	1,227,344	DRY	67.31%	70
1954	1,314,573	DRY	61.54%	64

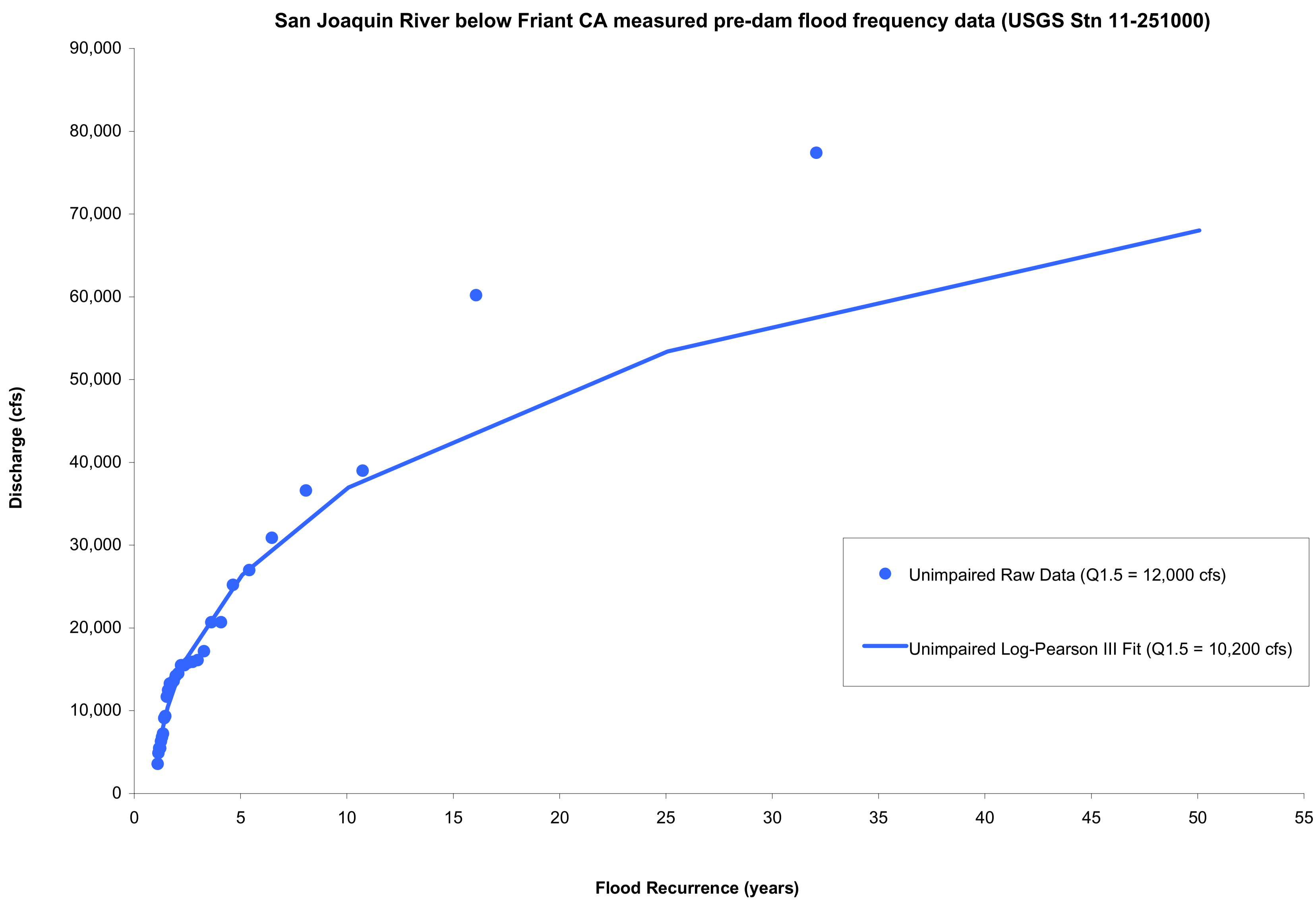
San Joaquin River blw Friant CA (Modeled UNIMPAIRED water yield from Kings River)

WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1955	1,161,166	DRY	70.19%	73
1956	2,956,903	EXTREMELY WET	14.42%	15
1957	1,326,827	NORMAL	59.62%	62
1958	2,631,449	WET	22.12%	23
1959	949,591	CRITICALLY DRY	80.77%	84
1960	827,875	CRITICALLY DRY	90.38%	94
1961	647,639	CRITICALLY DRY	96.15%	100
1962	1,924,026	NORMAL	41.35%	43
1963	1,945,119	WET	39.42%	41
1964	921,423	CRITICALLY DRY	82.69%	86
1965	2,272,370	WET	24.04%	25
1966	1,298,910	DRY	63.46%	66
1967	3,232,508	EXTREMELY WET	8.65%	9
1968	858,992	CRITICALLY DRY	87.50%	91
1969	4,040,894	EXTREMELY WET	2.88%	3
1970	1,445,790	NORMAL	54.81%	57
1971	1,417,250	NORMAL	57.69%	60
1972	1,037,276	DRY	78.85%	82
1973	2,047,472	WET	32.69%	34
1974	2,196,444	WET	27.88%	29
1975	1,795,682	NORMAL	47.12%	49
1976	626,656	CRITICALLY DRY	97.12%	101
1977	361,178	CRITICALLY DRY	100.00%	104
1978	3,402,809	EXTREMELY WET	6.73%	7
1979	1,832,091	NORMAL	46.15%	48
1980	2,966,426	EXTREMELY WET	13.46%	14
1981	1,068,369	DRY	76.92%	80
1982	3,316,816	EXTREMELY WET	7.69%	8
1983	4,641,537	EXTREMELY WET	0.96%	1
1984	2,039,500	WET	35.58%	37
1985	1,135,196	DRY	74.04%	77
1986	3,031,273	EXTREMELY WET	11.54%	12
1987	757,194	CRITICALLY DRY	93.27%	97
1988	858,655	CRITICALLY DRY	89.42%	93
1989	939,125	CRITICALLY DRY	81.73%	85
1990	743,956	CRITICALLY DRY	94.23%	98
1991	1,026,184	DRY	79.81%	83
1992	806,045	CRITICALLY DRY	92.31%	96
1993	2,672,303	WET	20.19%	21
1994	826,423	CRITICALLY DRY	91.35%	95
1995	3,876,313	EXTREMELY WET	3.85%	4
1996	2,195,587	WET	28.85%	30
1997	2,817,622	EXTREMELY WET	18.27%	19
1998	3,159,958	EXTREMELY WET	9.62%	10
1999	1,464,794	NORMAL	53.85%	56

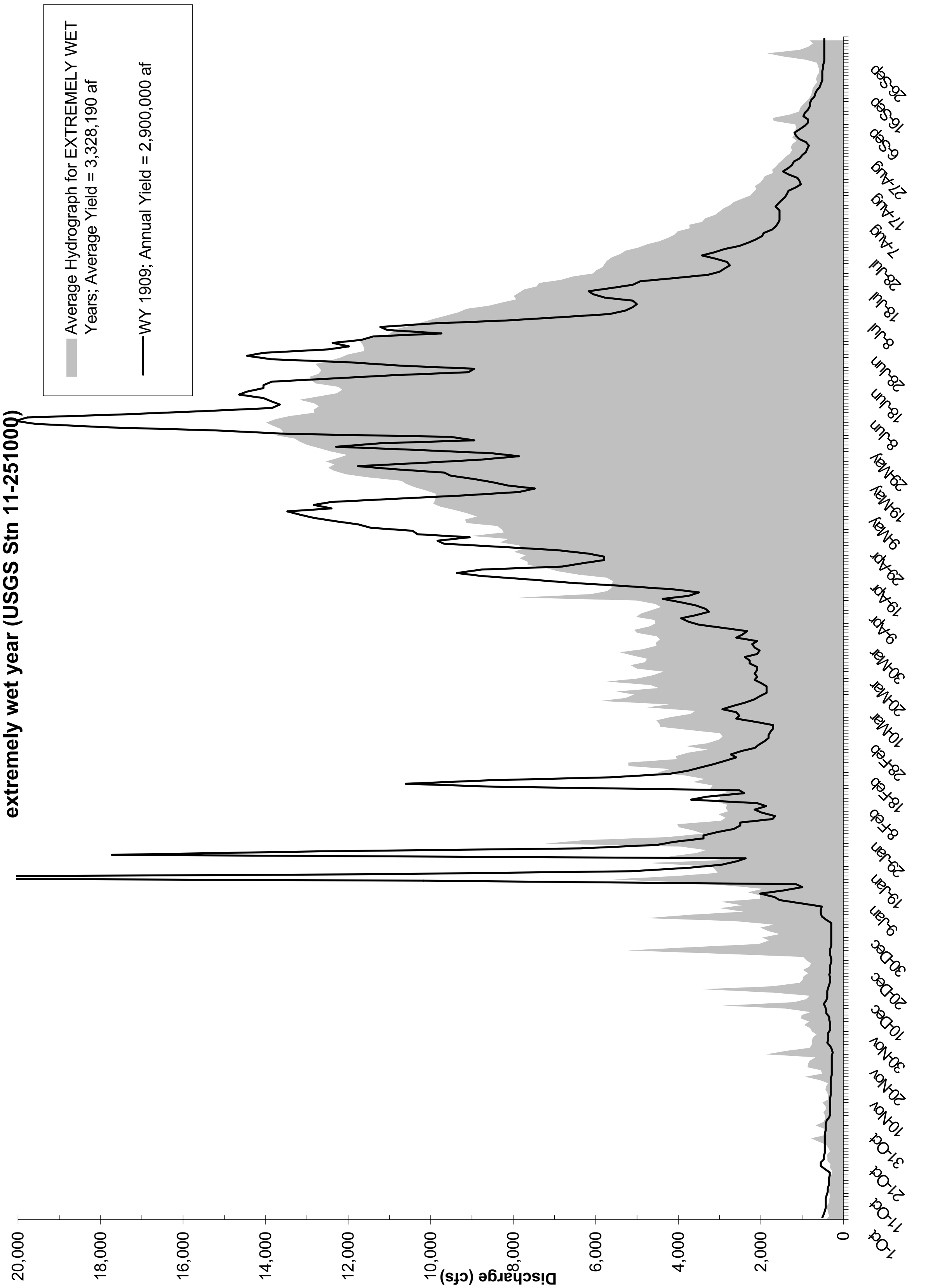

San Joaquin River below Friant Modeled Unimpaired water yield
(USGS Stn 11-251000)
Mean Annual Yield = 1,813,000 acre-ft
Annual Yield (acre-feet)
5,000,000
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Water Year
1896
1899
1902
1905
1908
1911
1914
1917
1920
1923
1926
1929
1932
1935
1938
1941
1944
1947
1950
1953
1956
1959
1962
1965
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998

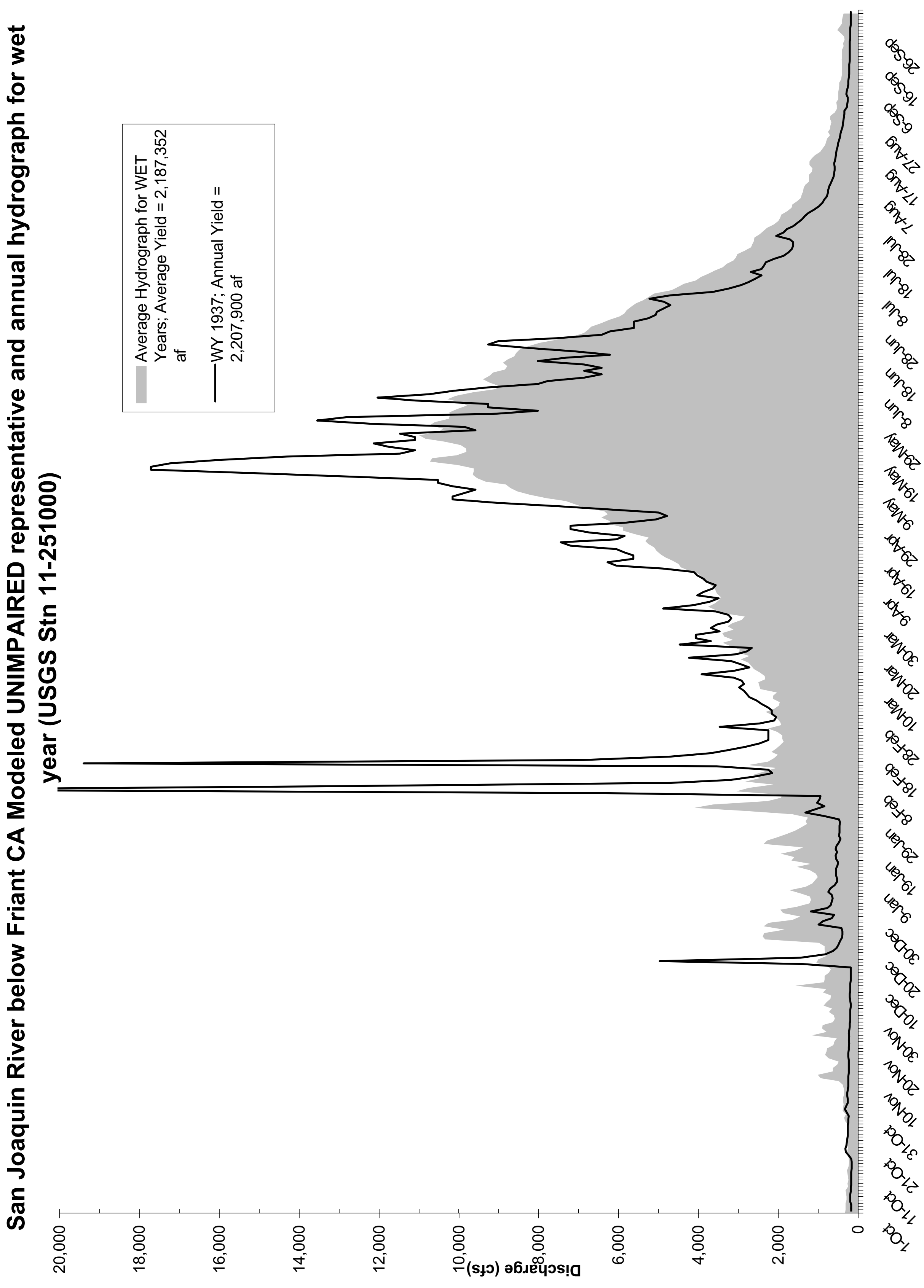

San Joaquin River below Friant modeled unimpaired yield exceedance probability
(USGS Stn 11-251000)
Annual Yield (acre feet)
5,000,000
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Exceedence Probability
Extremely Wet
Wet
Normal
Dry
Critically Dry


San Joaquin River below Friant CA modeled pre-Friant Dam flow duration curve (USGS Stn 11-251000)
daily average flow duration (WY1896-1999)
Daily Average Flow (cfs)
Exceedence probability (p)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


San Joaquin River below Friant CA measured pre-dam flood frequency data (USGS Stn 11-251000)
Discharge (cfs)
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5
10
15
20
25
30
35
40
45
50
55
Flood Recurrence (years)
Unimpaired Raw Data (Q1.5 = 12,000 cfs)
Unimpaired Log-Pearson III Fit (Q1.5 = 10,200 cfs)

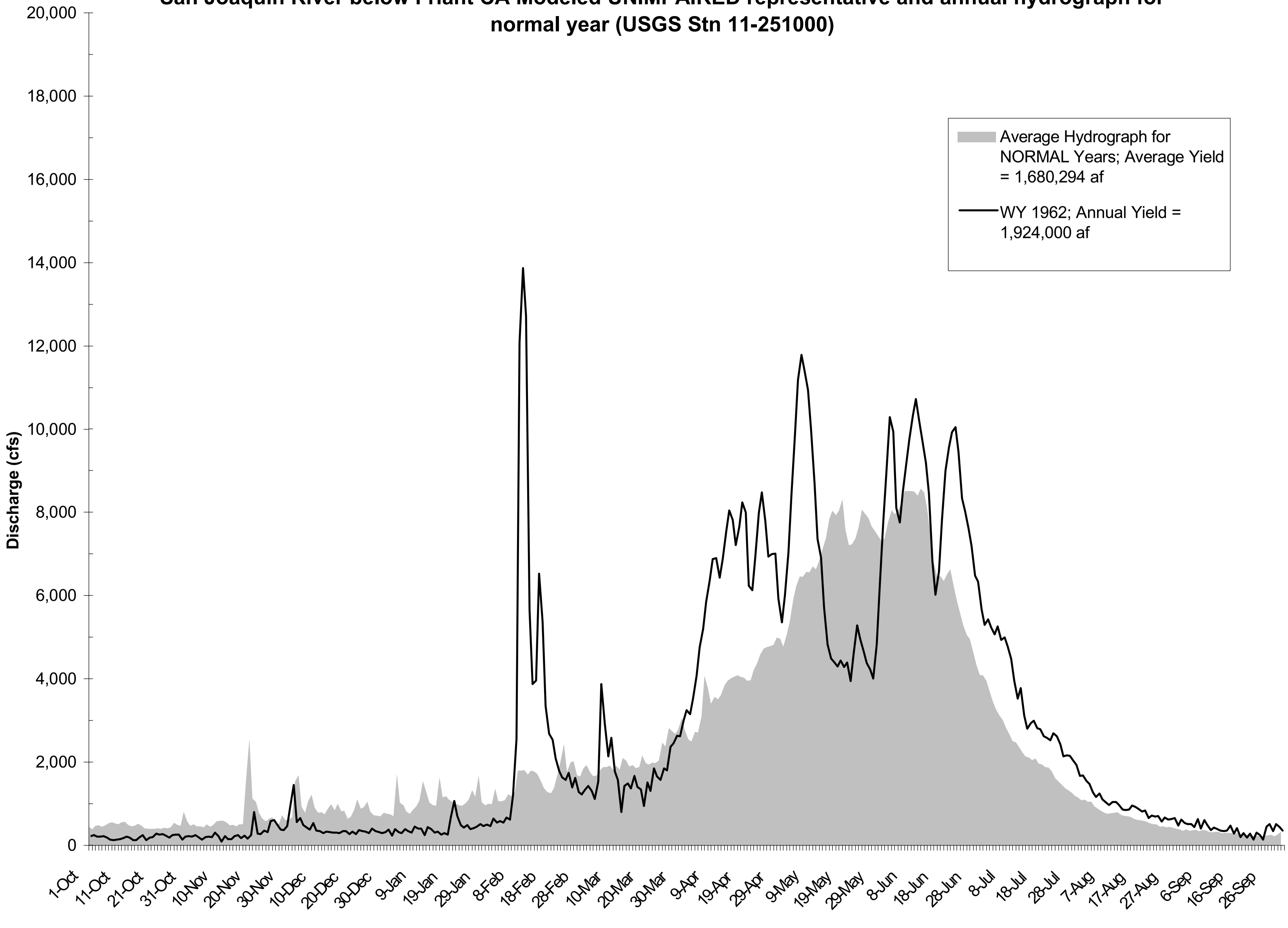
San Joaquin River below Friant CA Modeled UNIMPAIRED representative and annual hydrograph for extremely wet year (USGS Stn 11-251000)



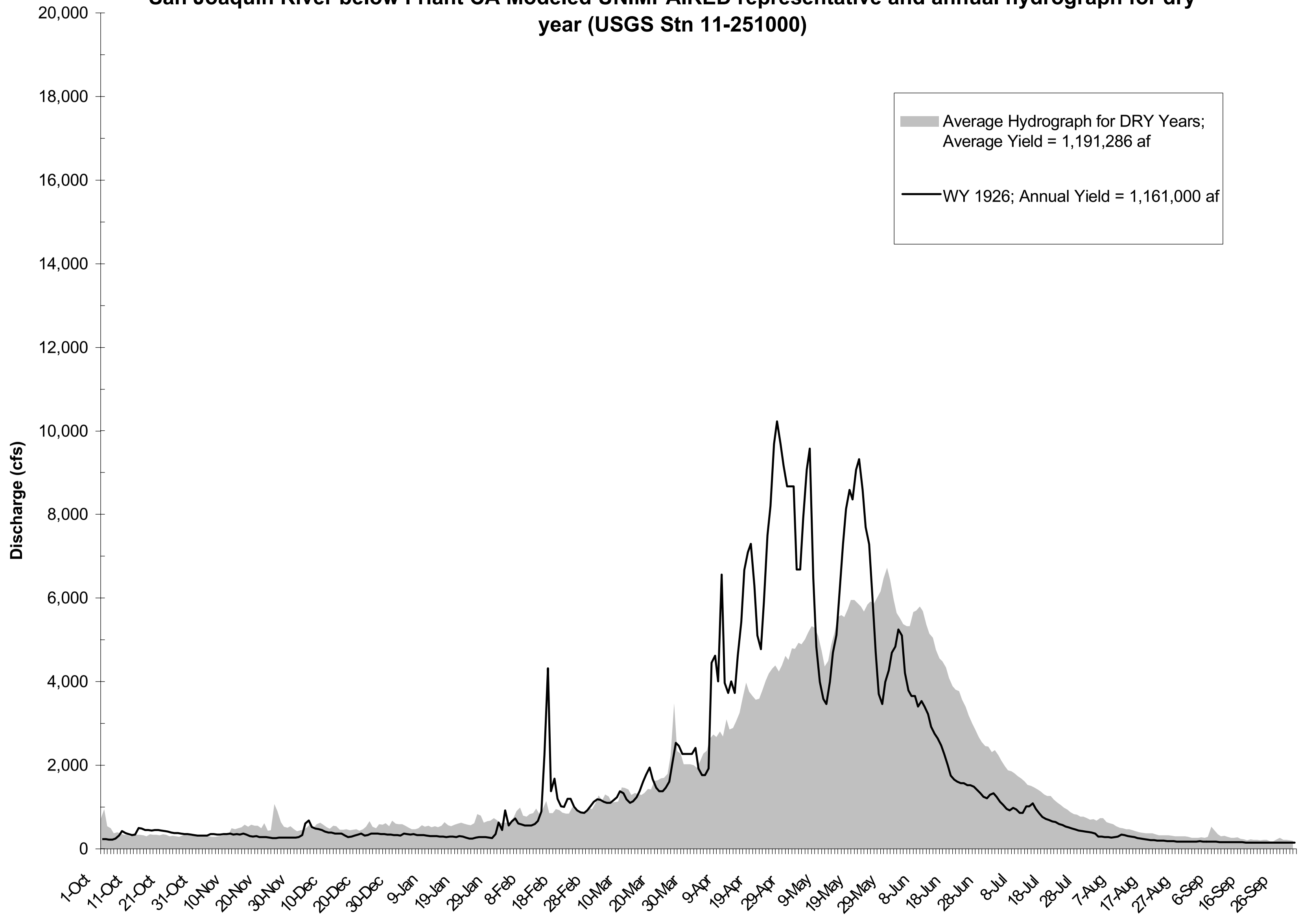


San Joaquin River below Friant CA Modeled UNIMPAIRED representative and annual hydrograph for wet year (USGS Stn 11-251000)
Discharge (cfs)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
8-Jul
18-Jul
28-Jul
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep
Average Hydrograph for WET Years; Average Yield = 2,187,352 af
WY 1937; Annual Yield = 2,207,900 af

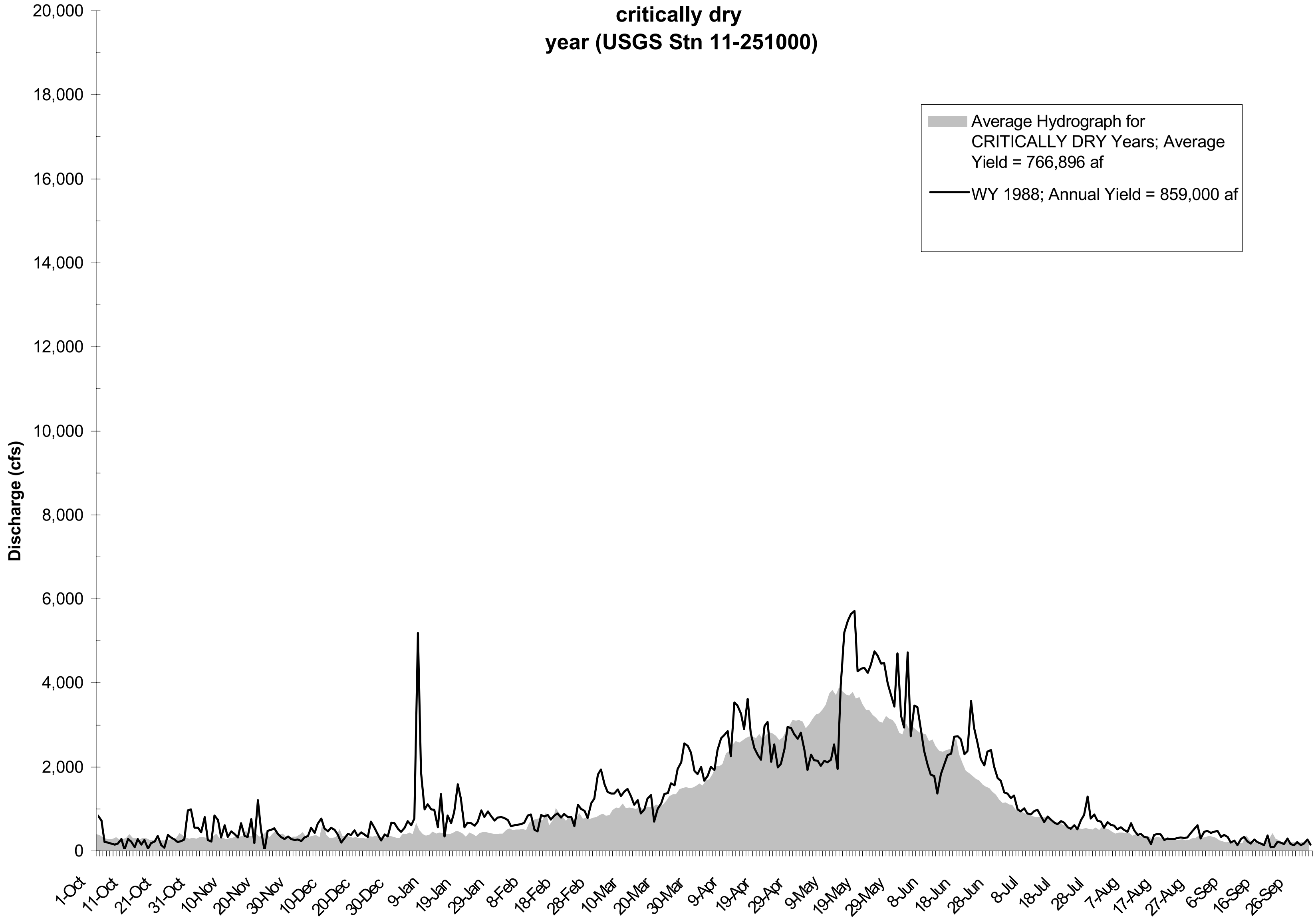
San Joaquin River below Friant CA Modeled UNIMPAIRED representative and annual hydrograph for normal year (USGS Stn 11-251000)

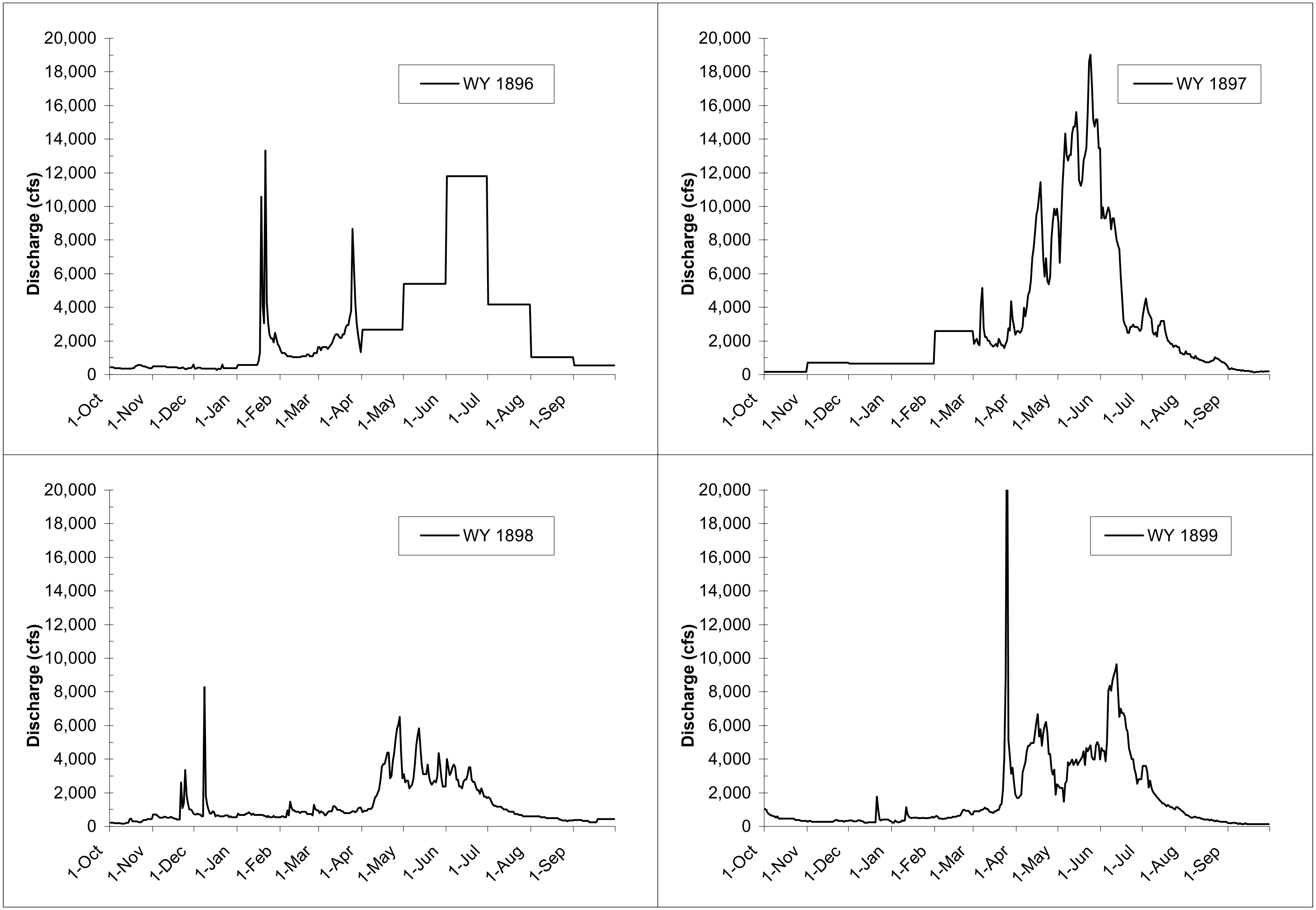


San Joaquin River below Friant CA Modeled UNIMPAIRED representative and annual hydrograph for dry year (USGS Stn 11-251000)

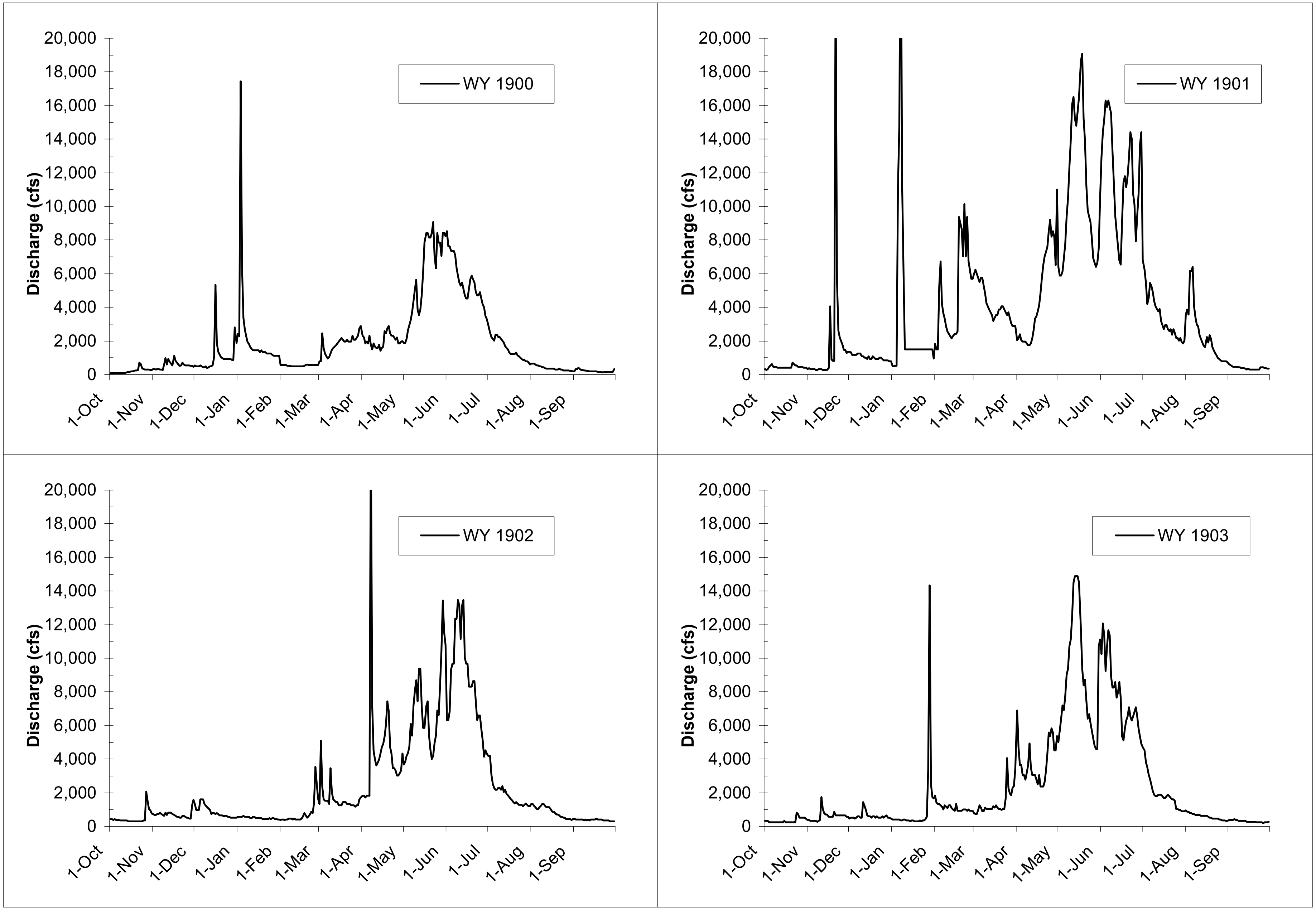


San Joaquin River below Friant CA Modeled UNIMPAIRED representative and annual hydrograph for critically dry year (USGS Stn 11-251000)

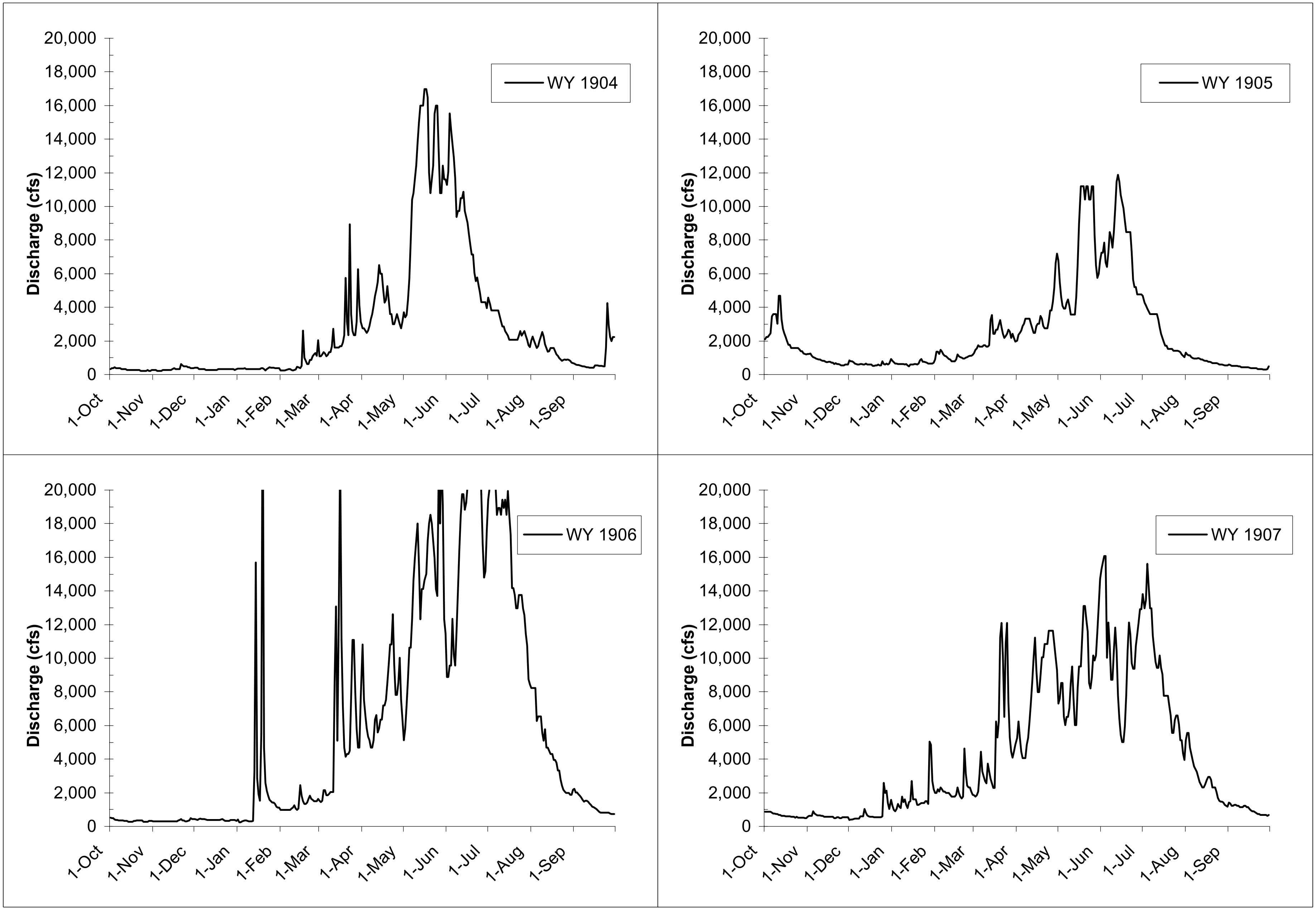




San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



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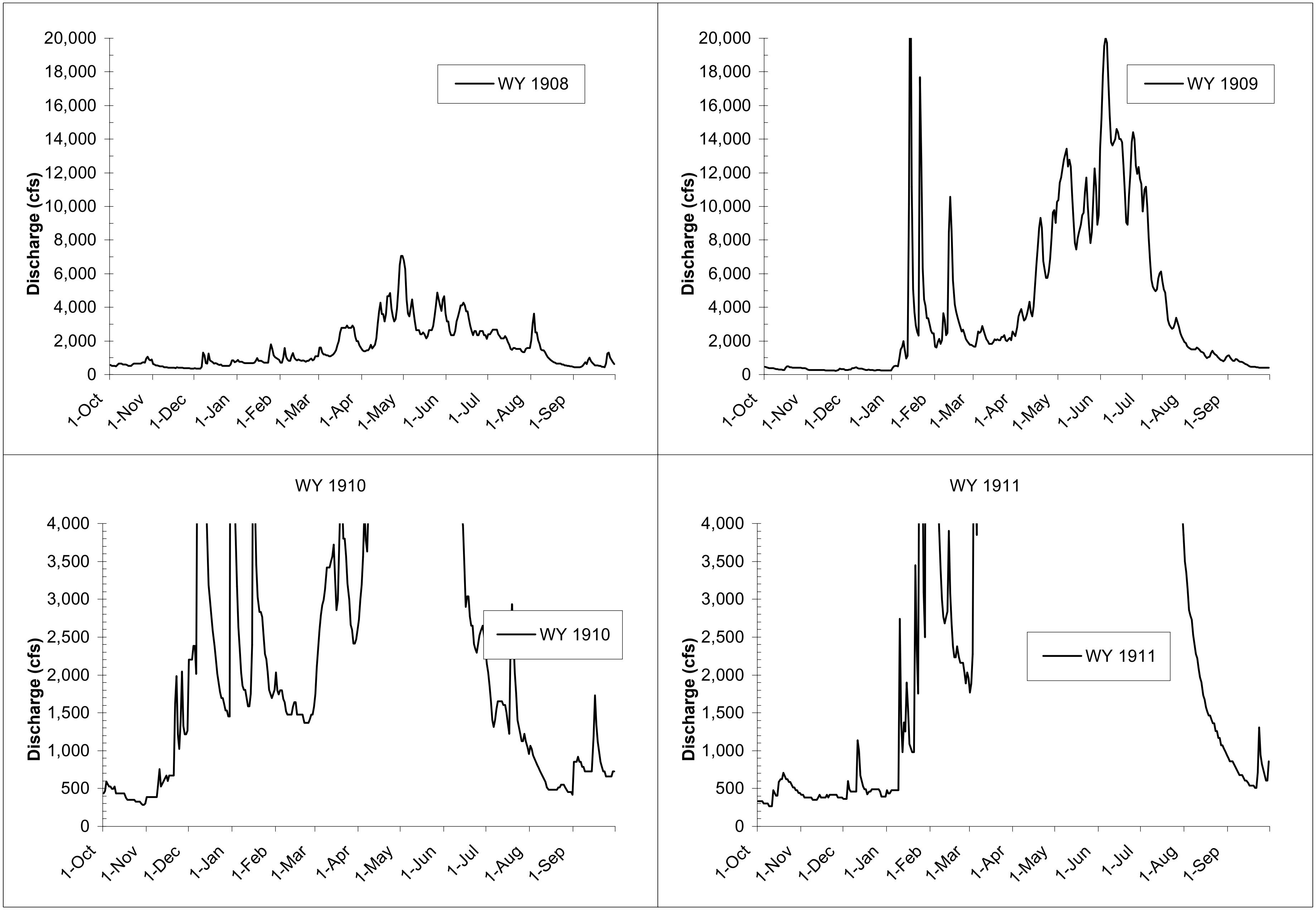

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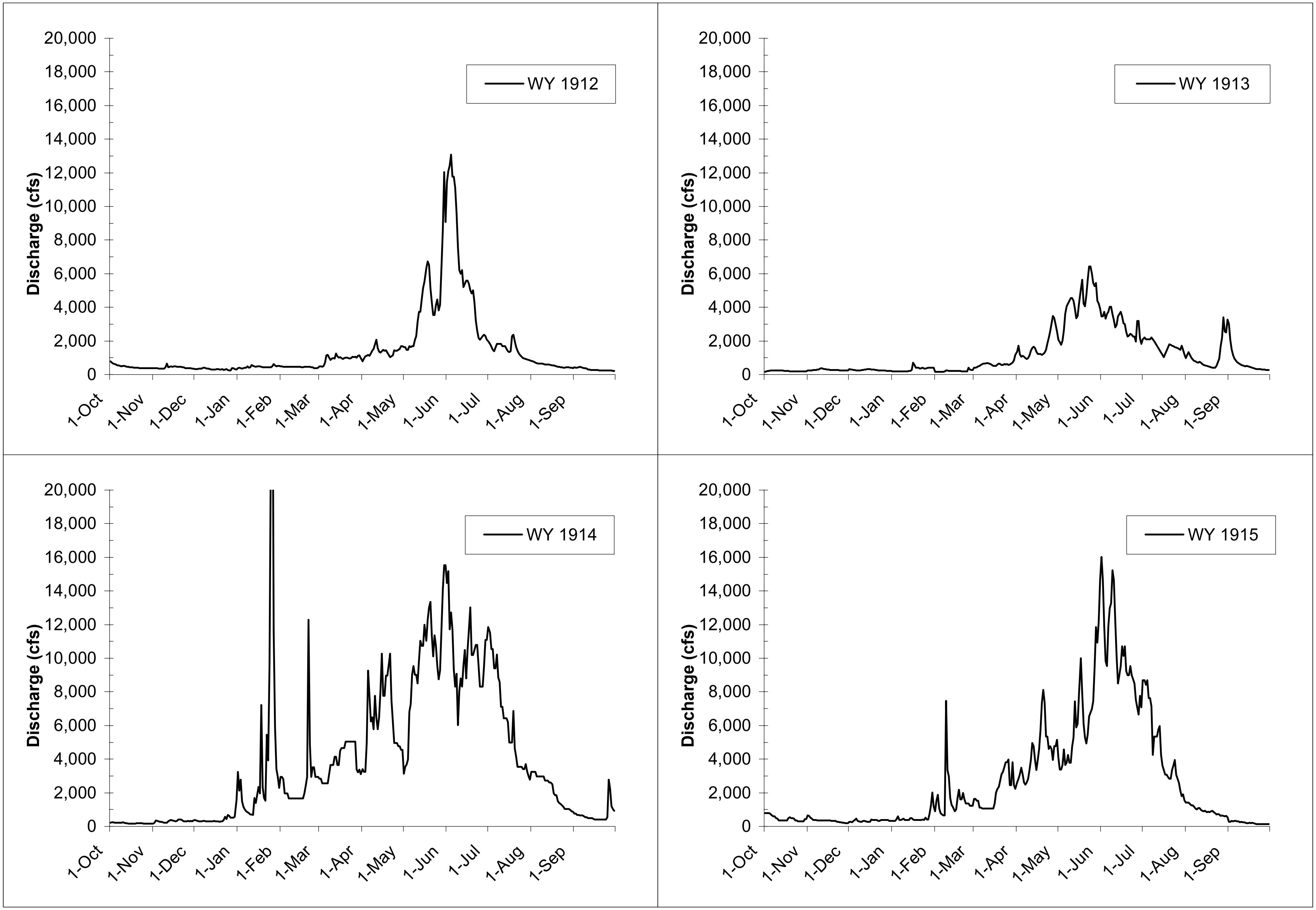

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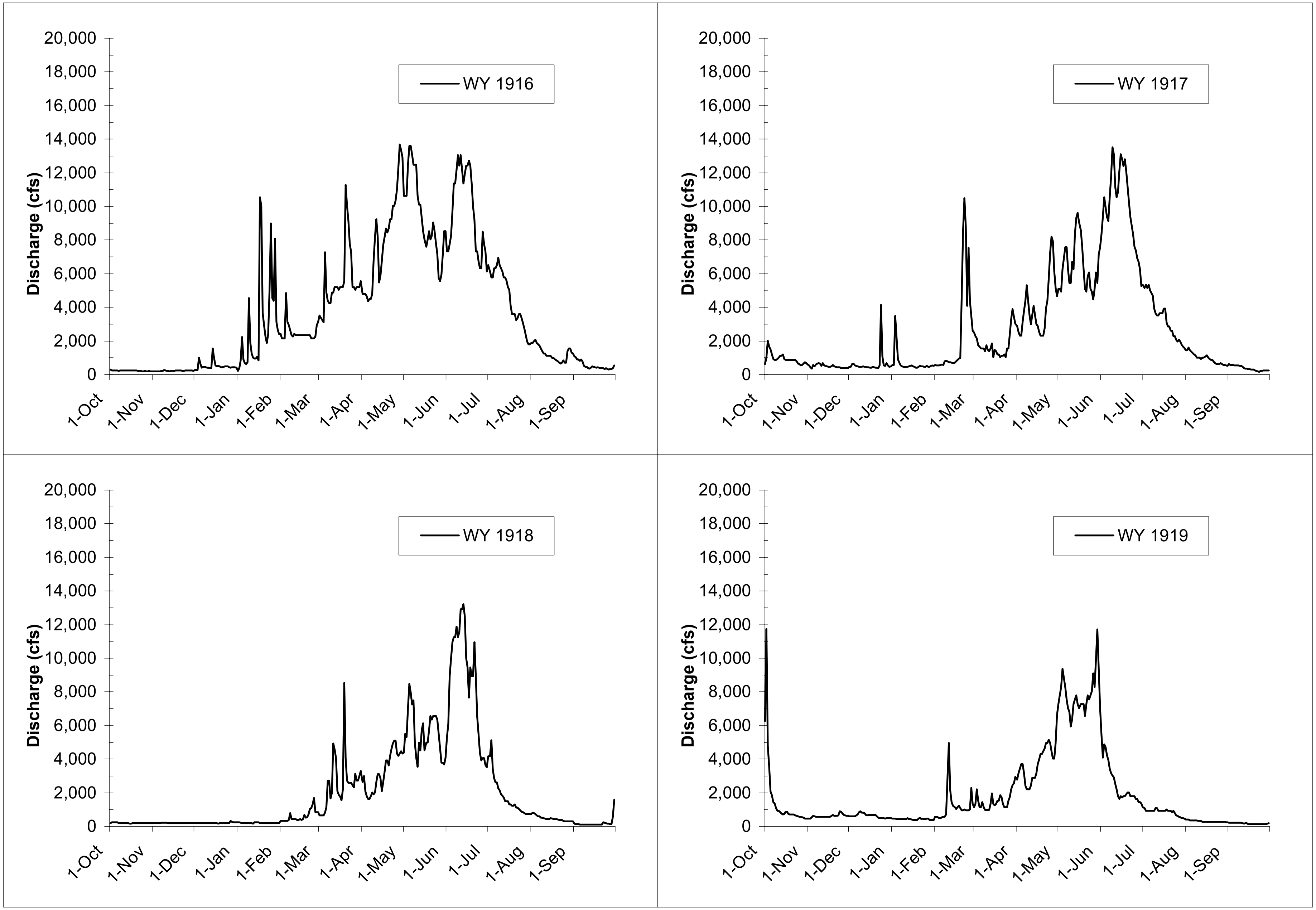

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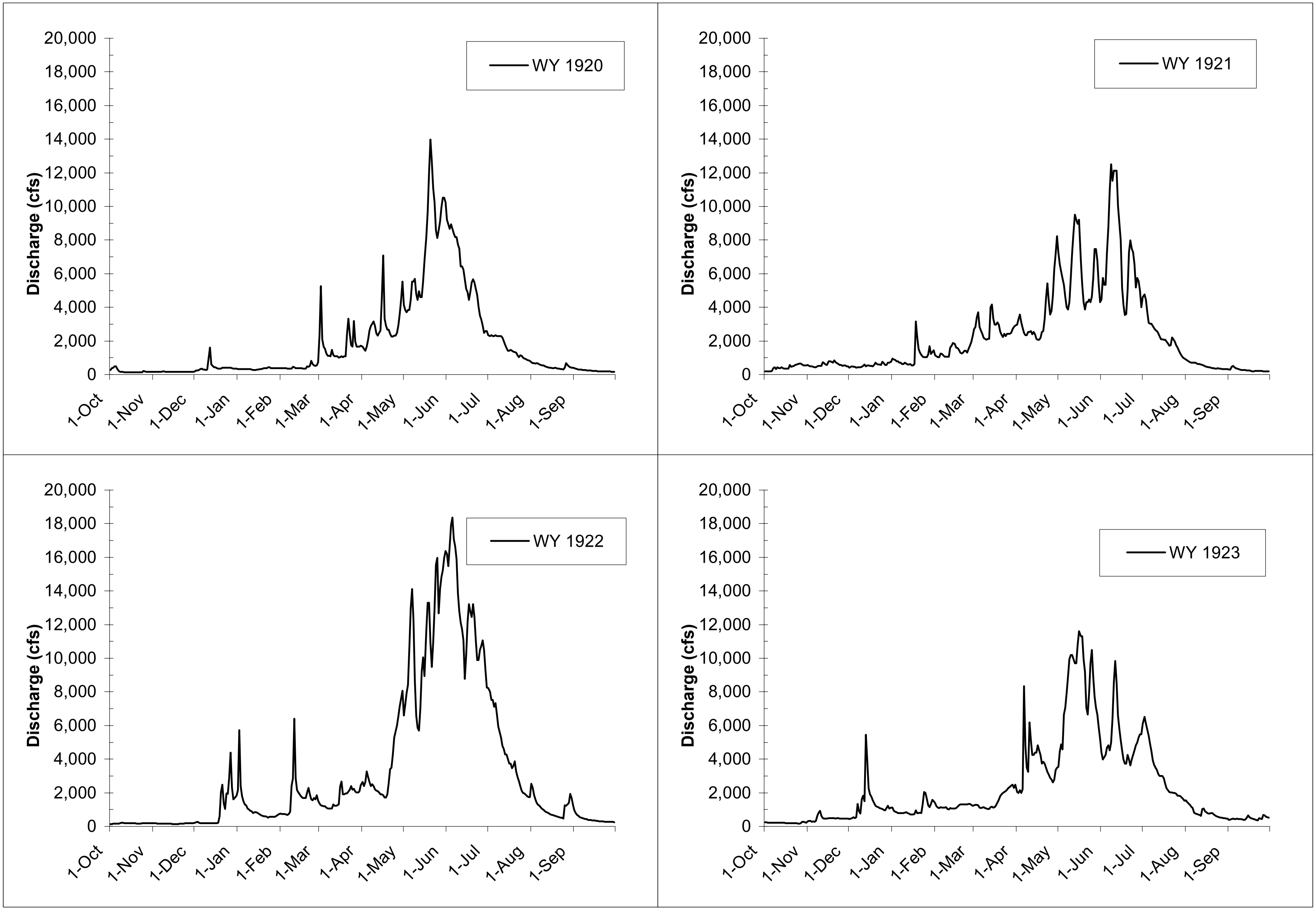

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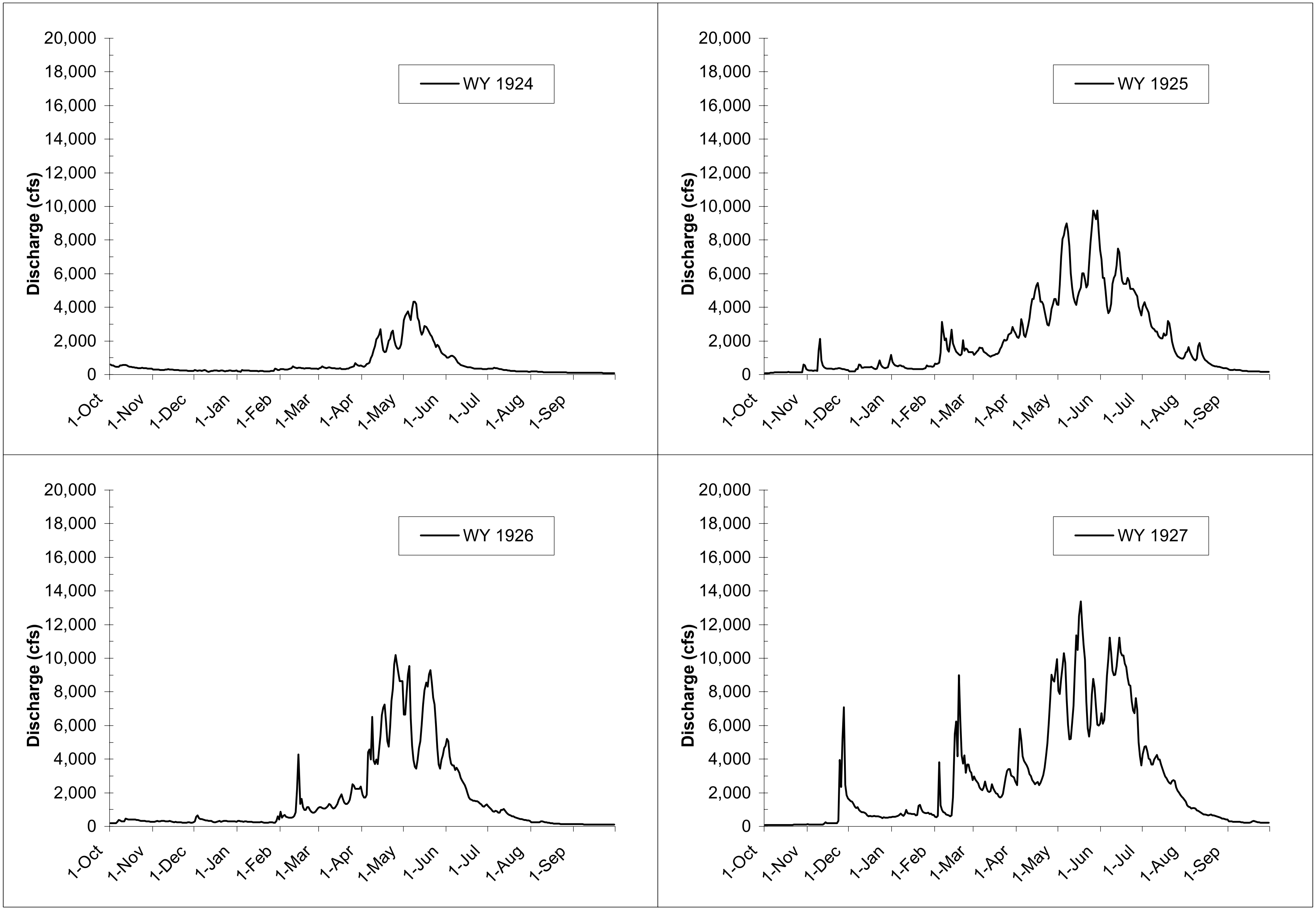

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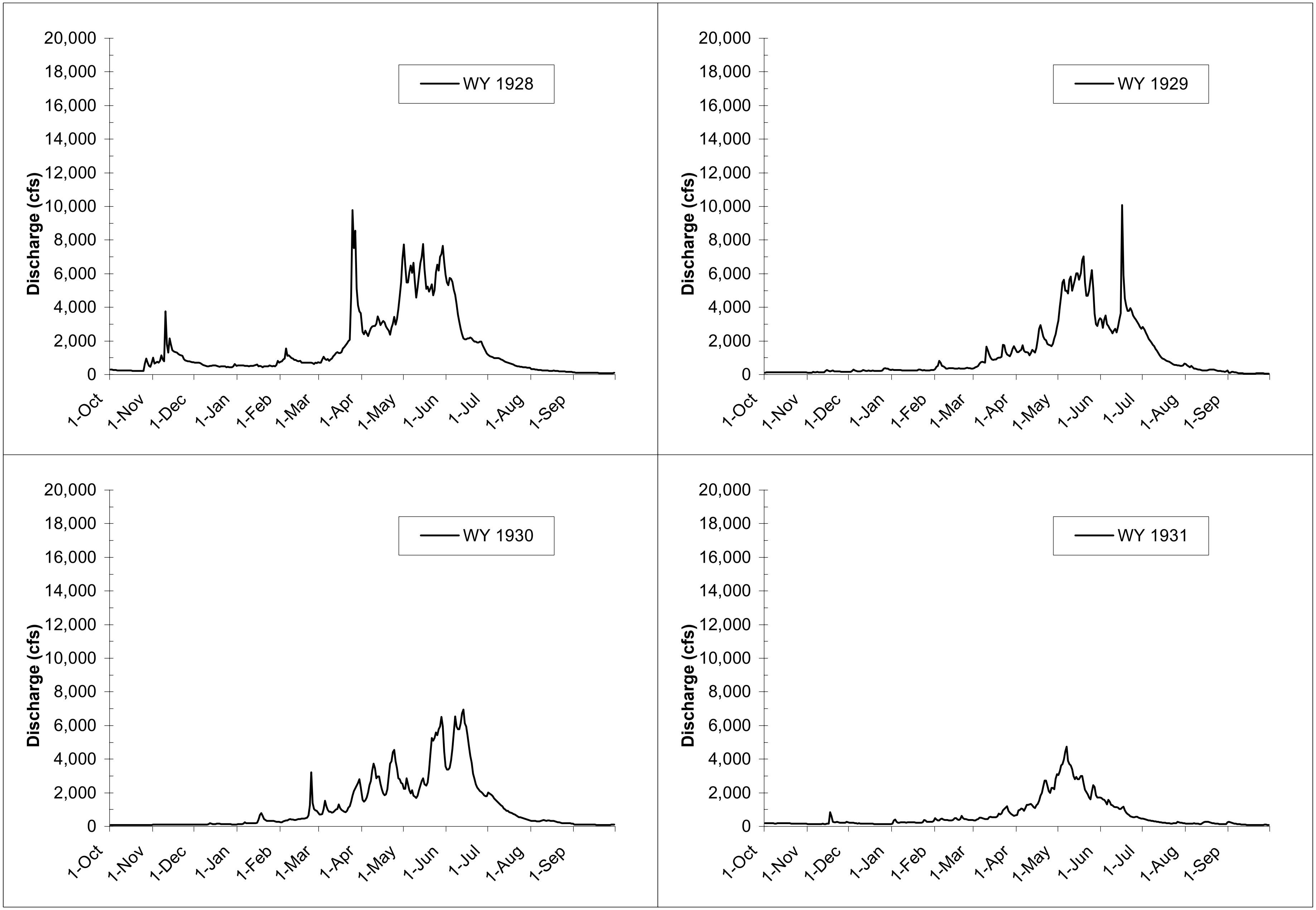

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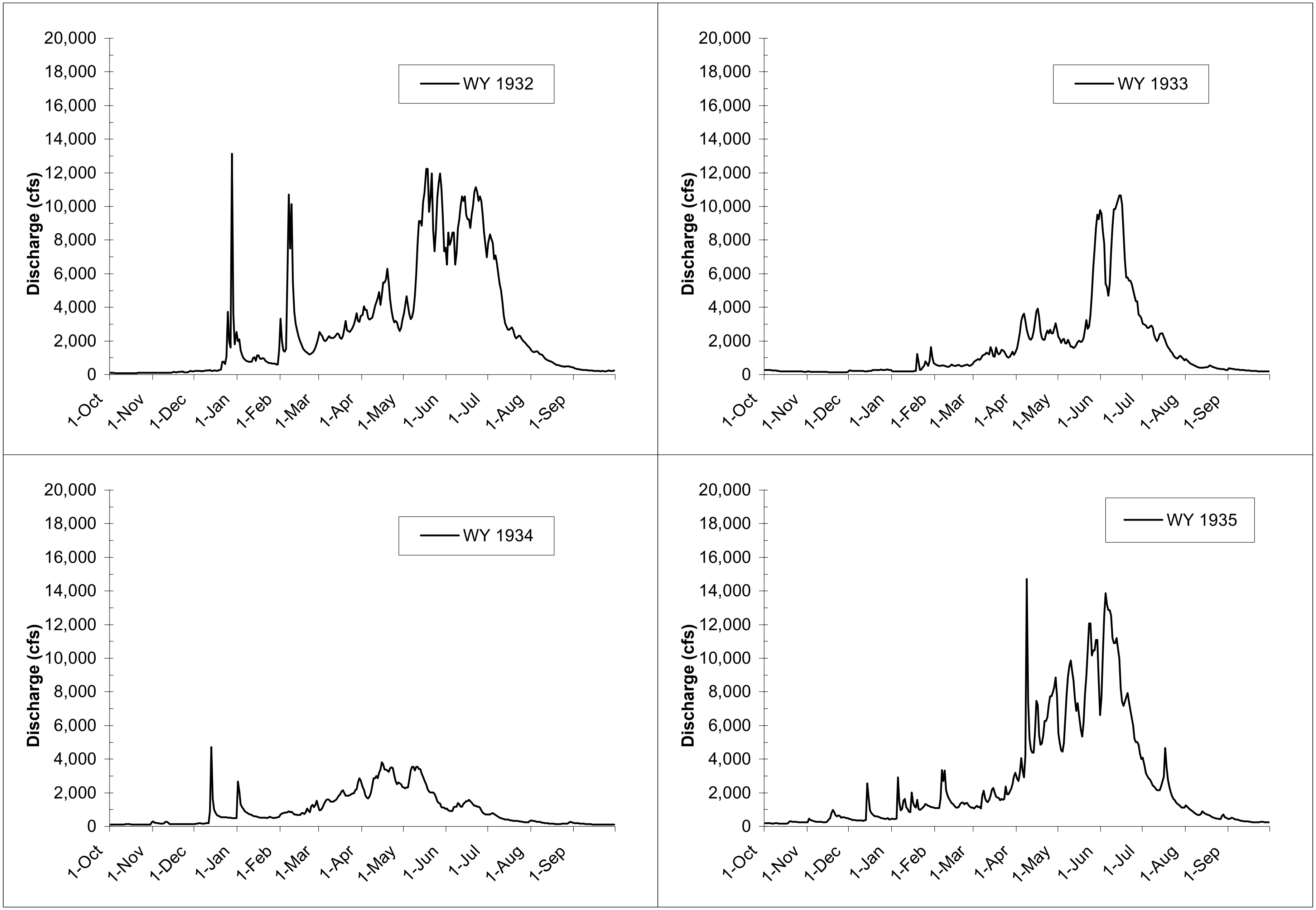

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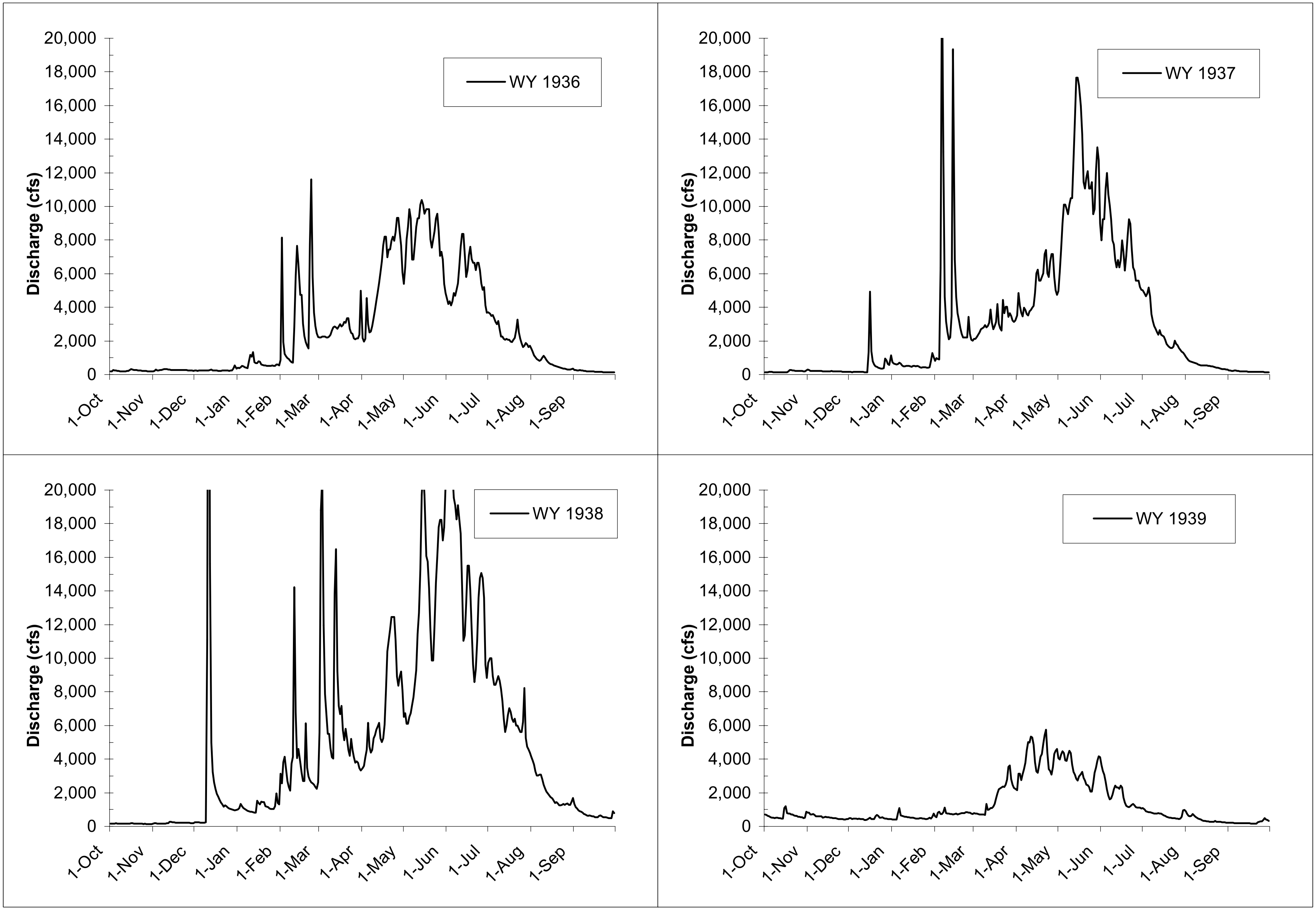

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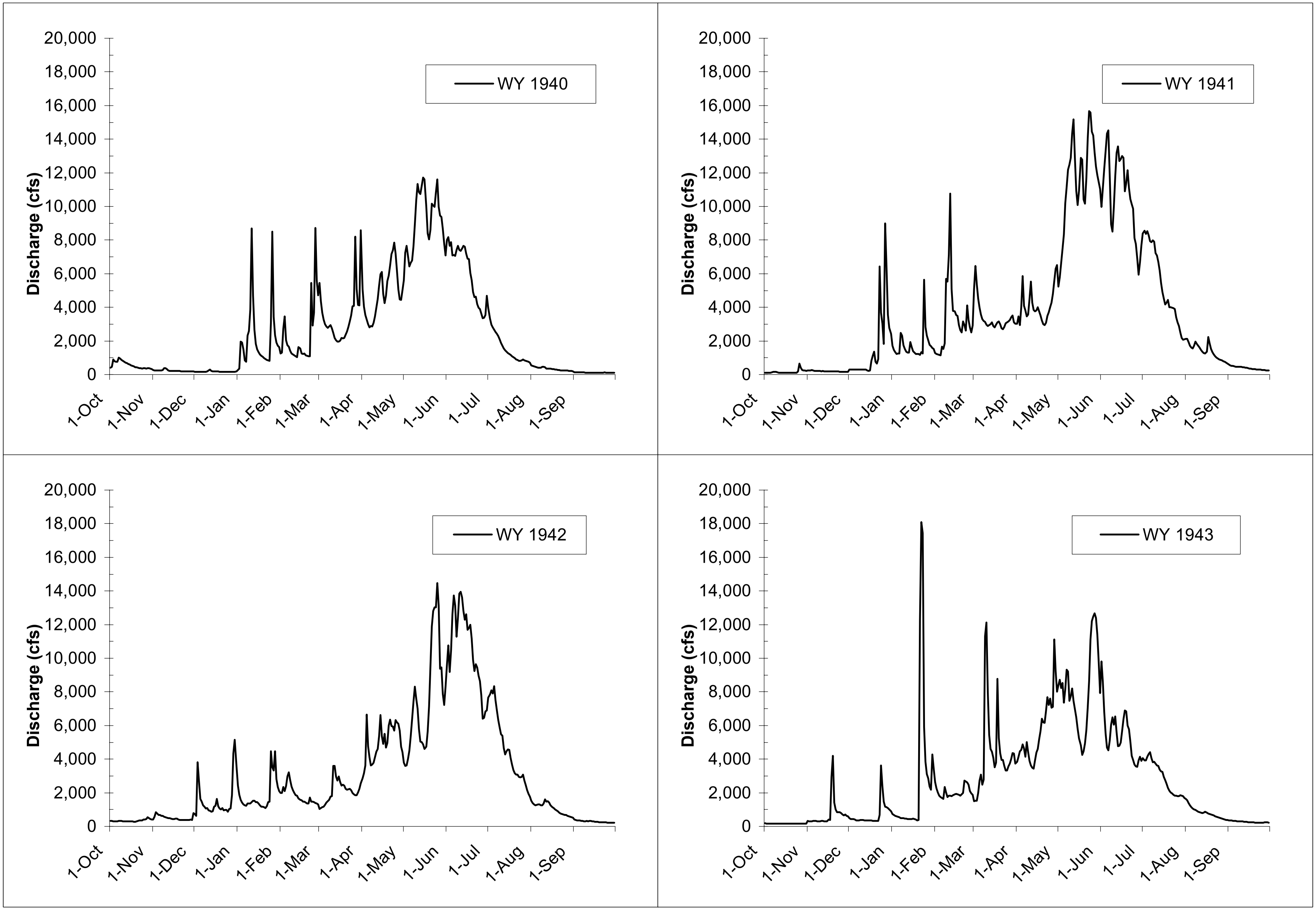

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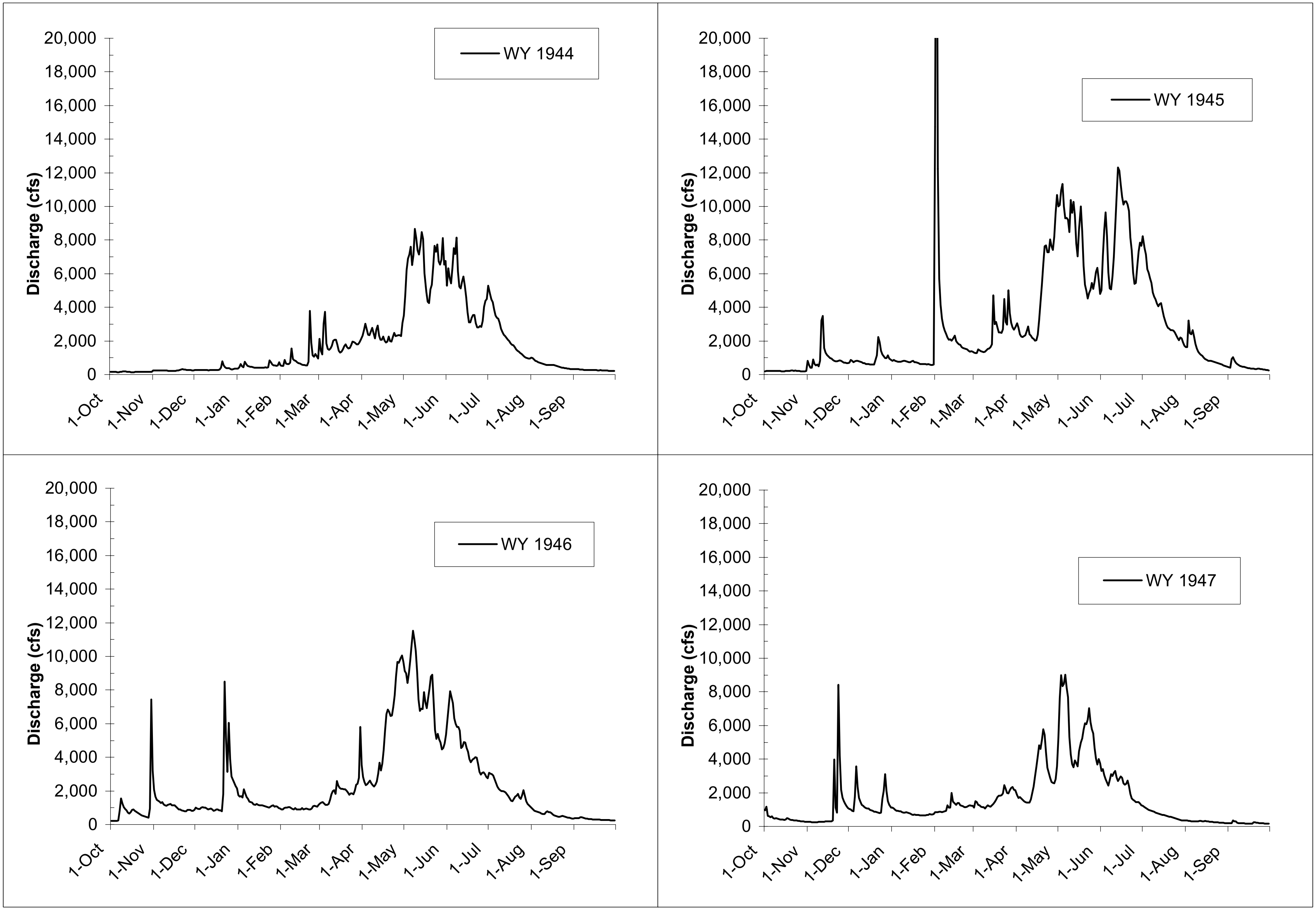

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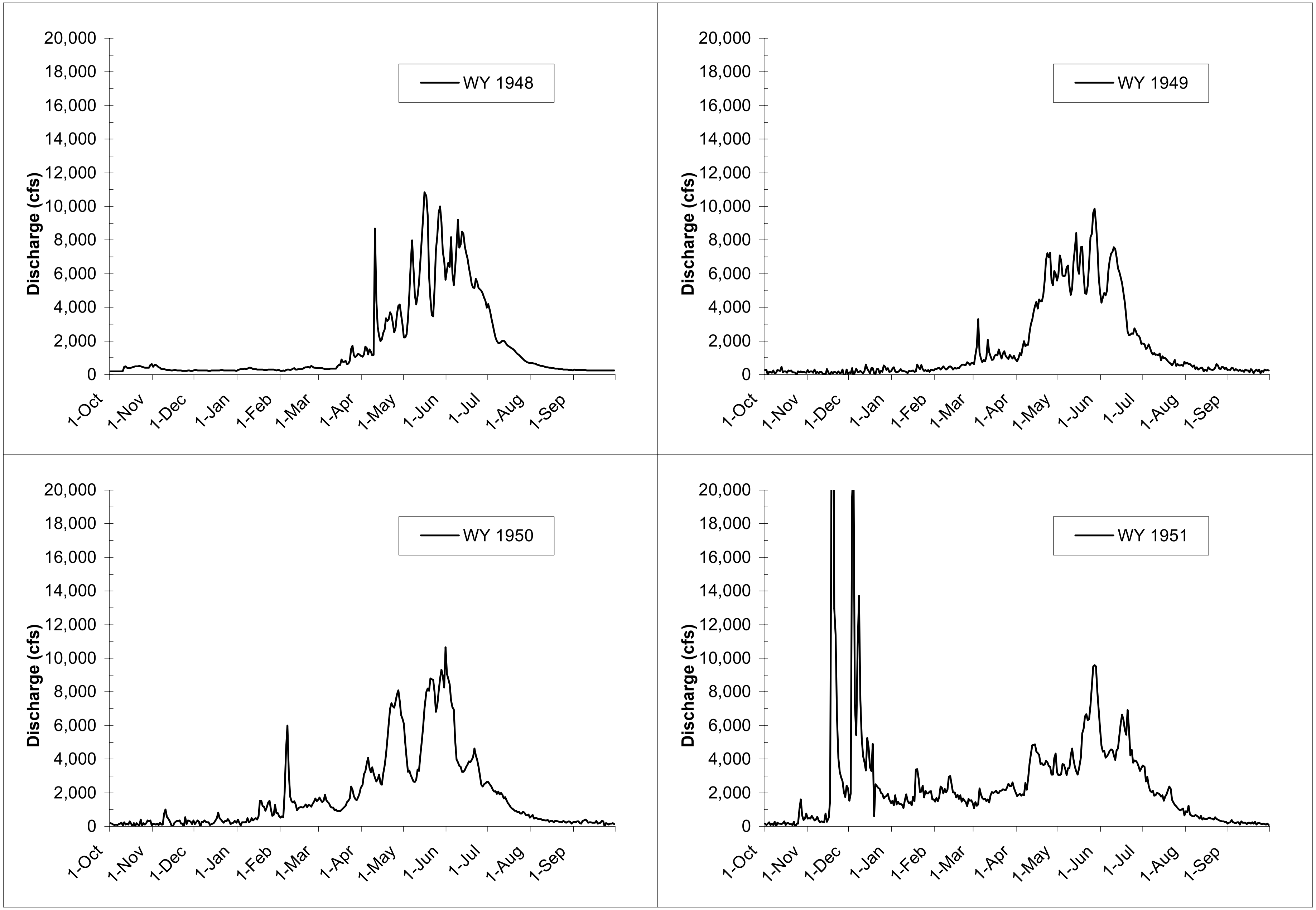

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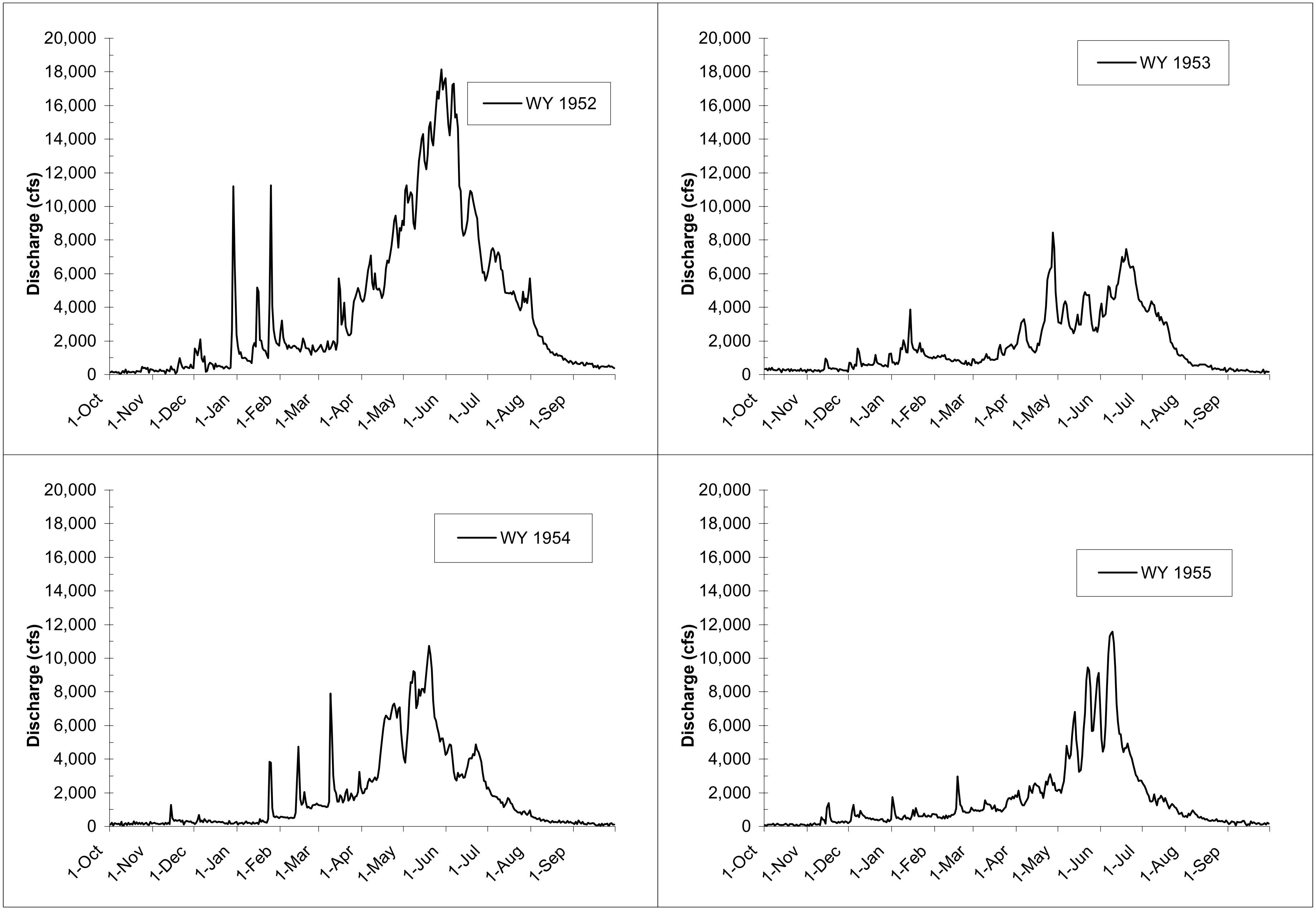

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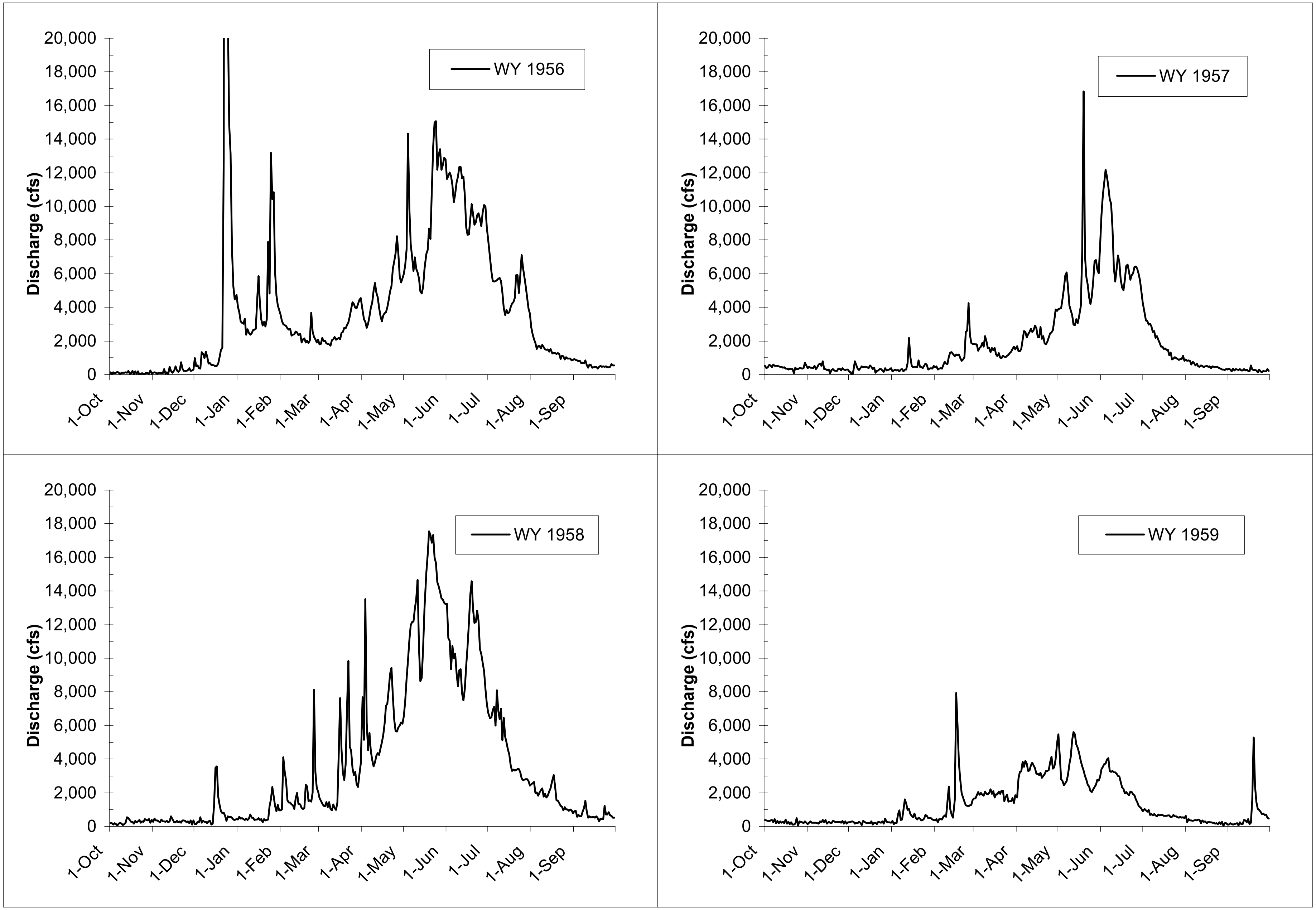

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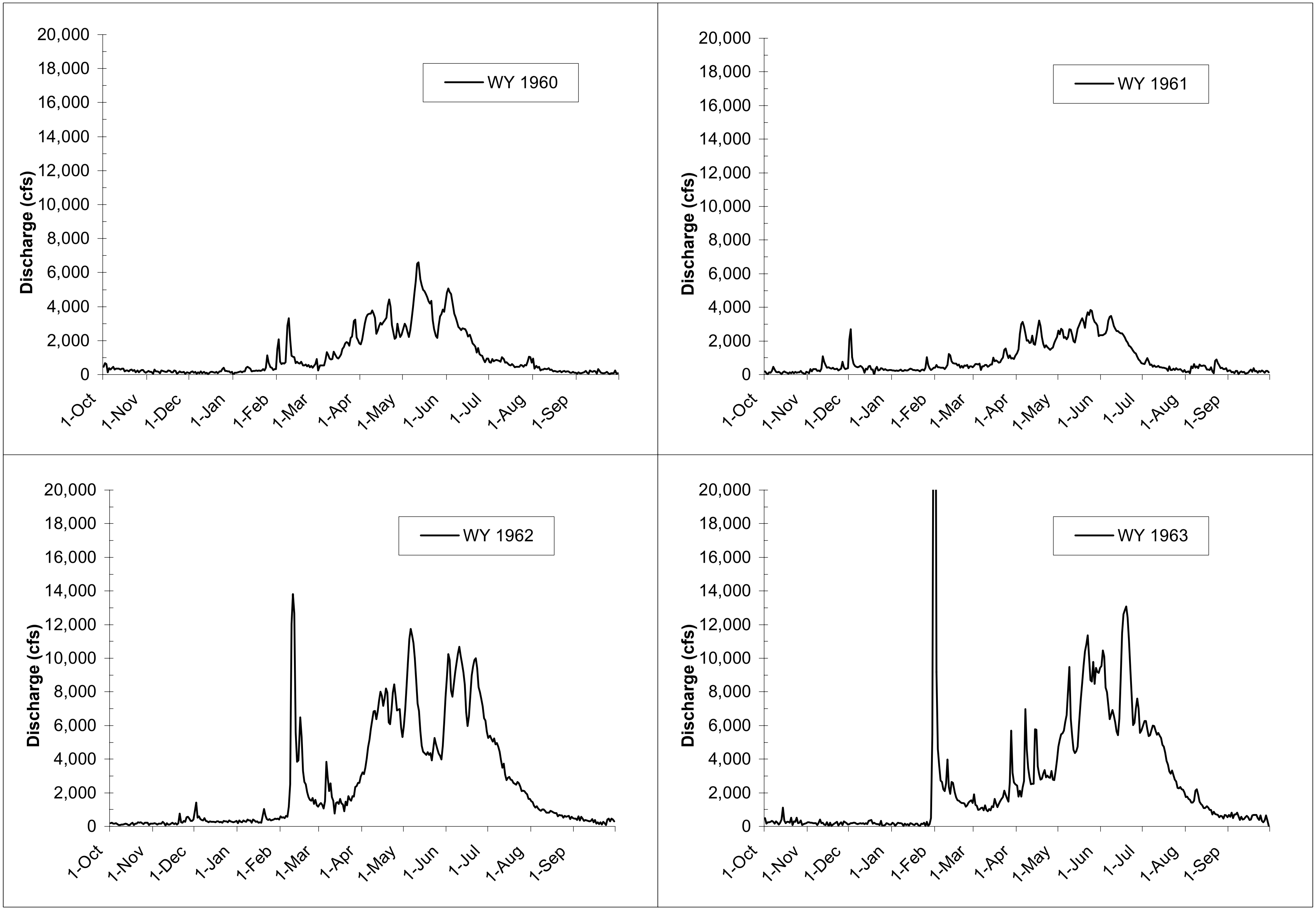

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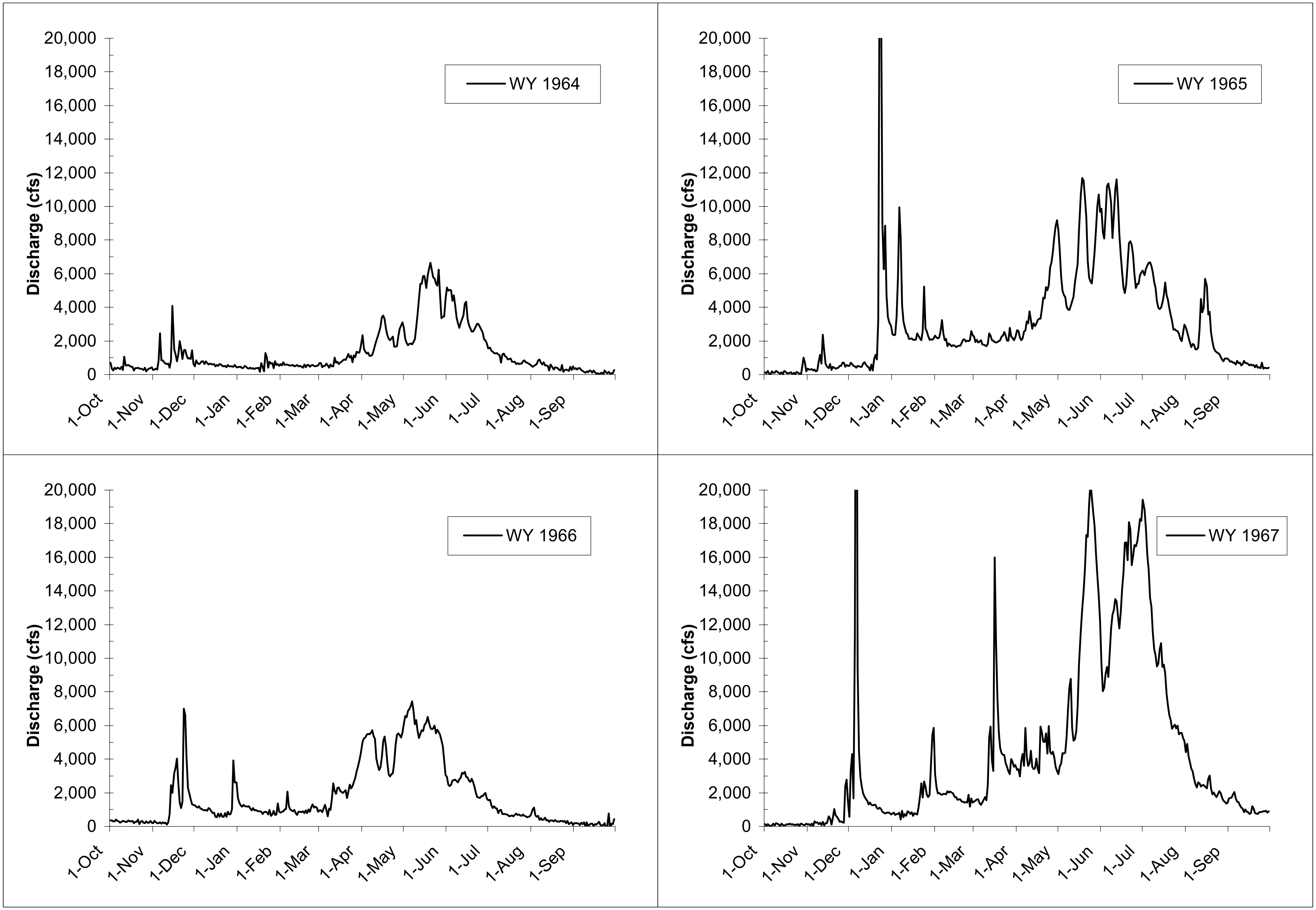

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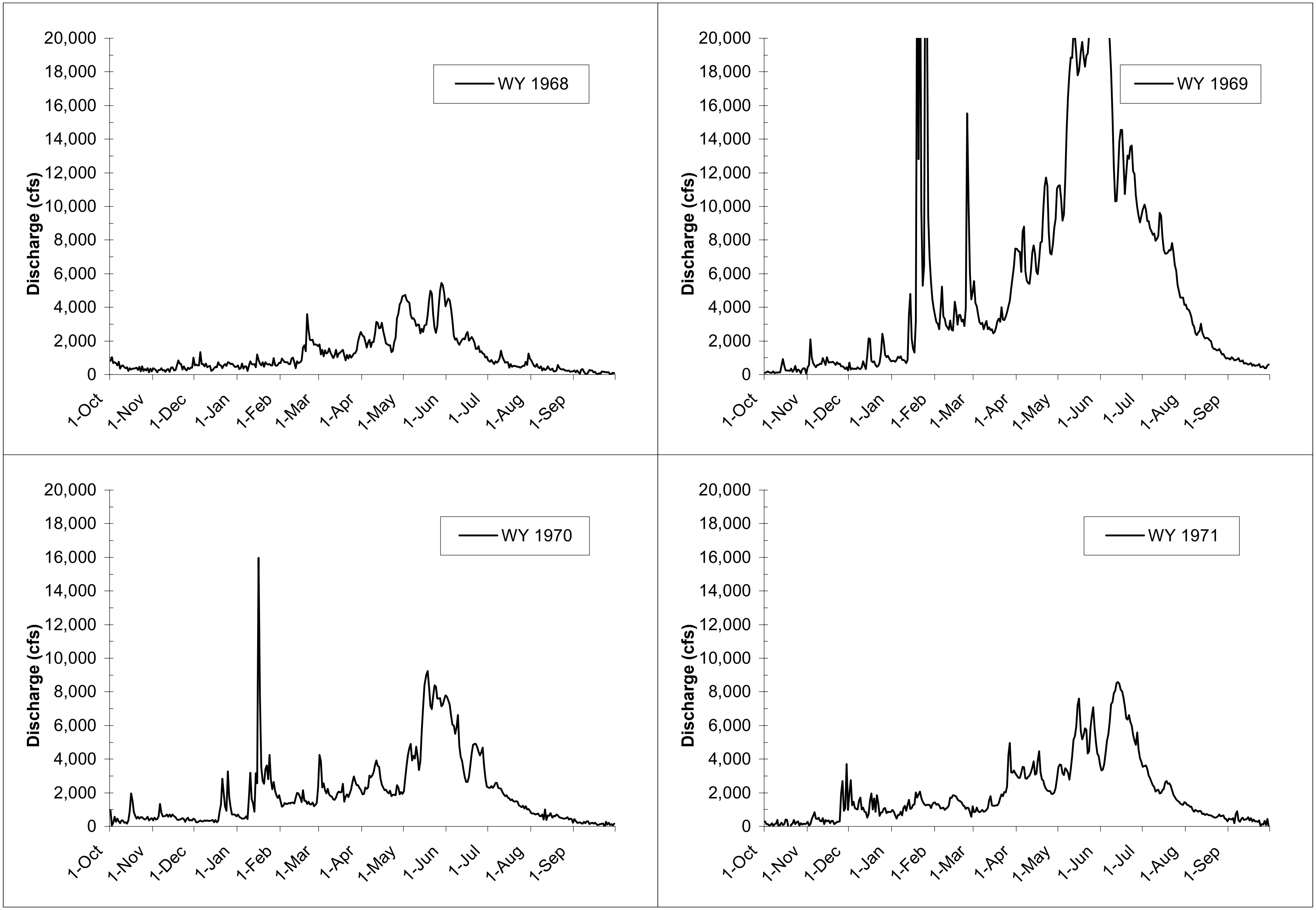
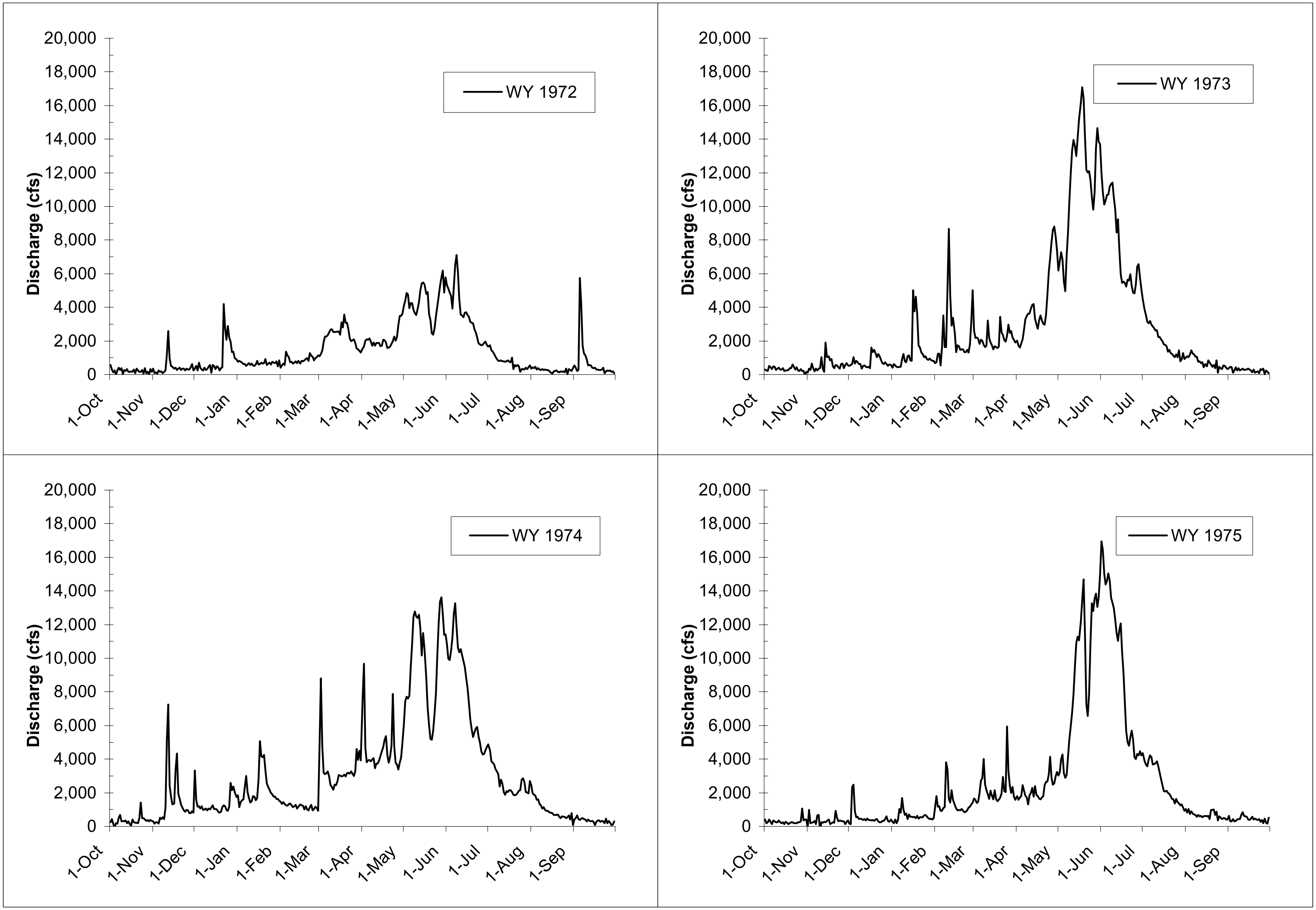
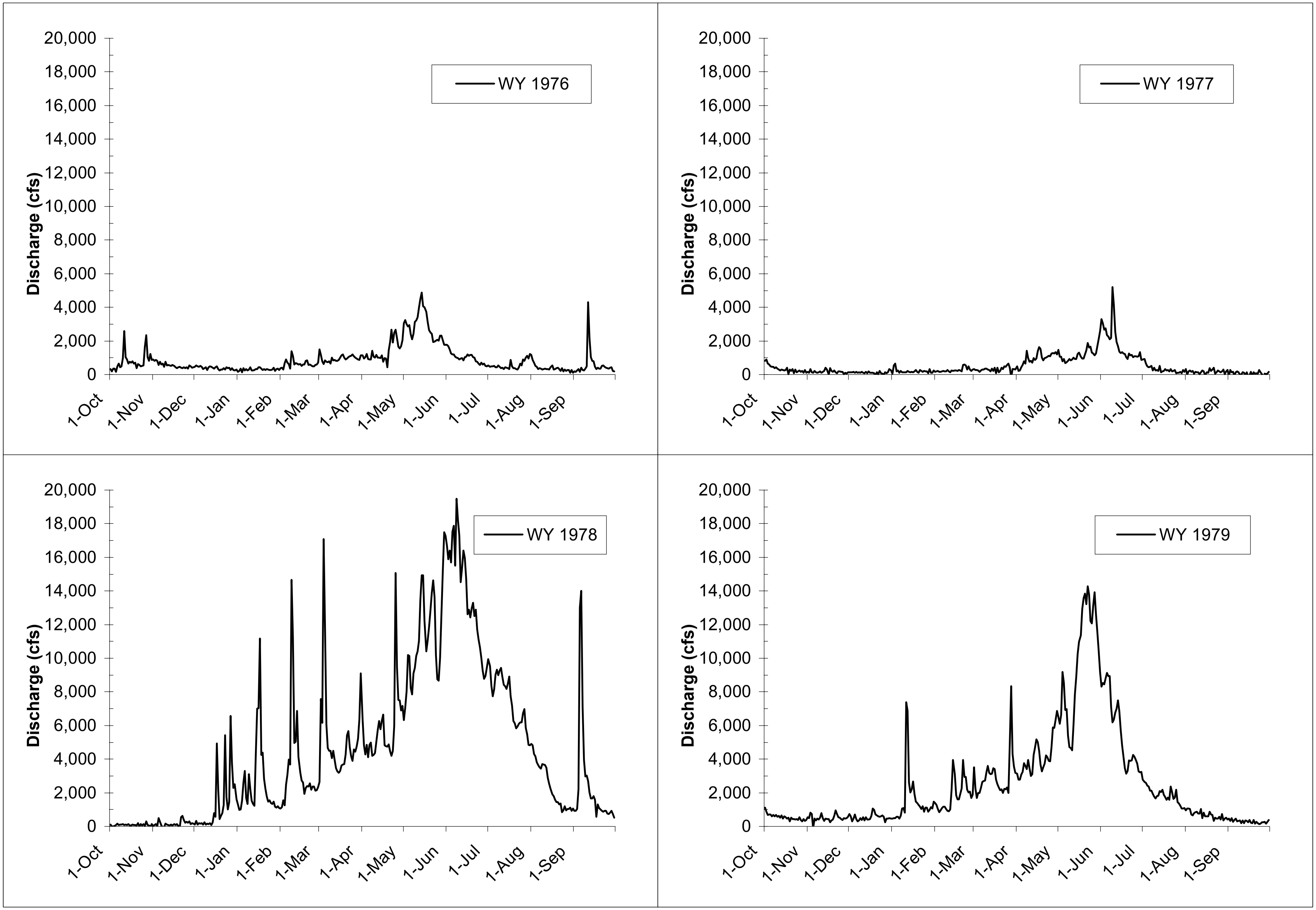


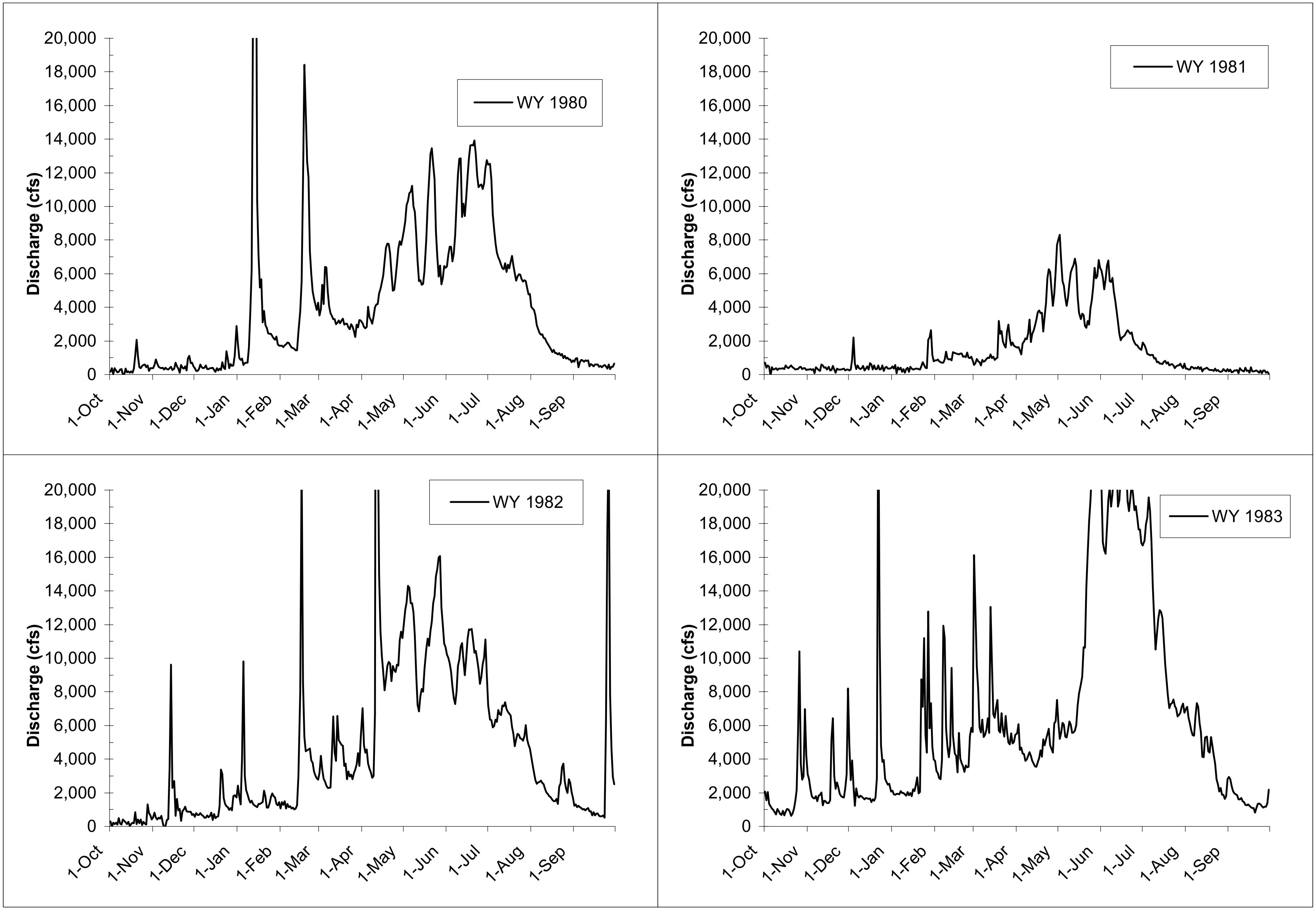
San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



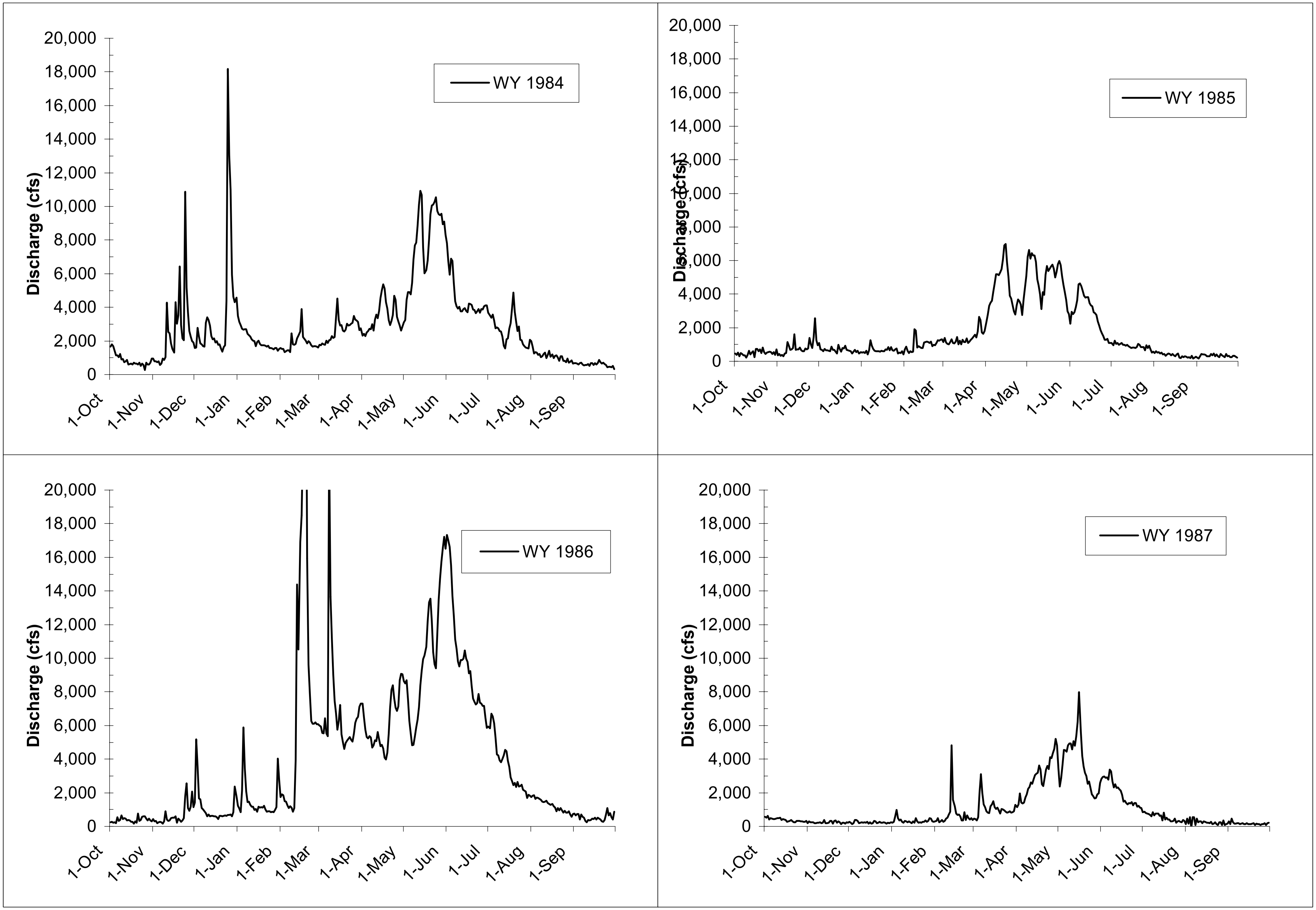
San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



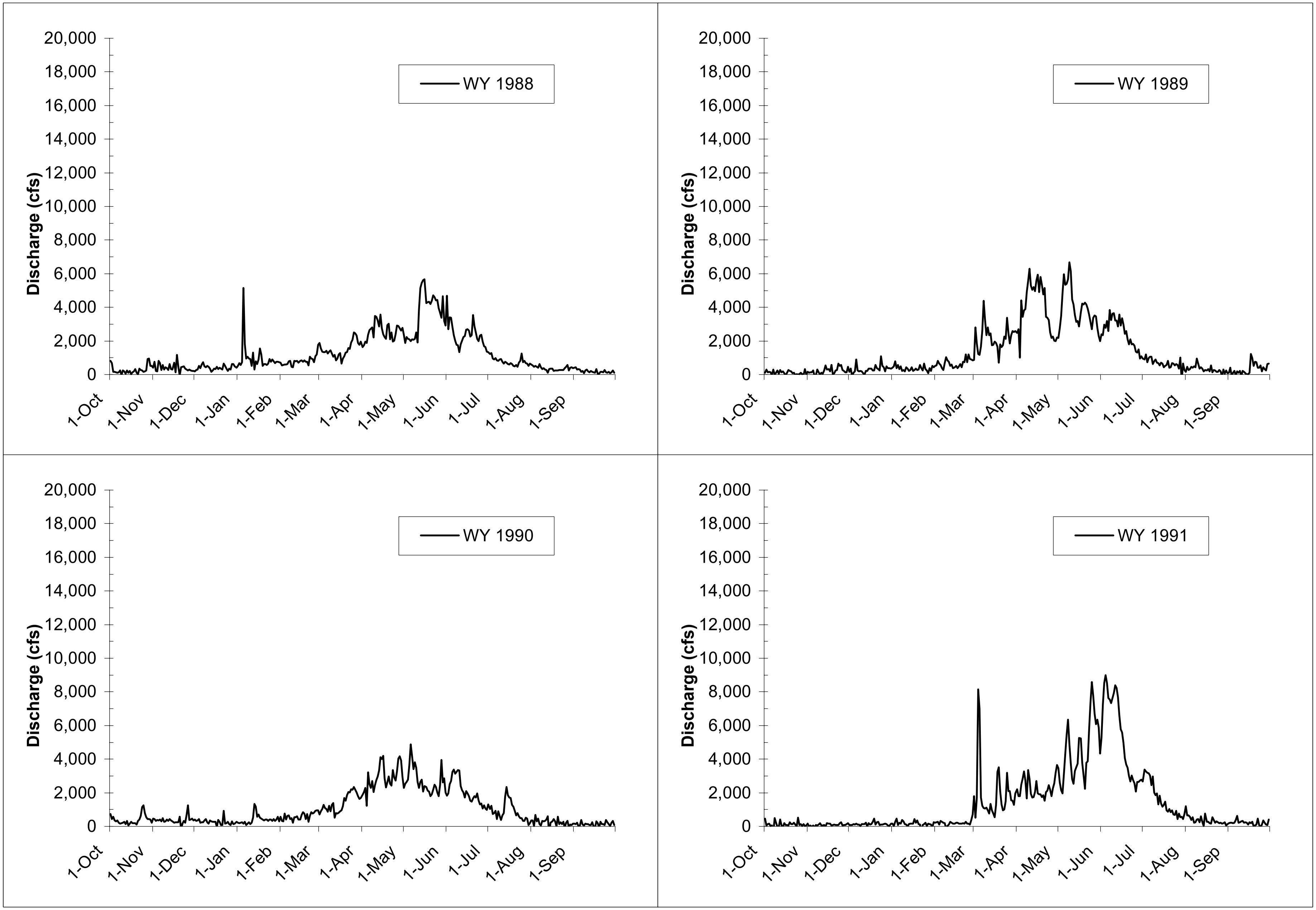
San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



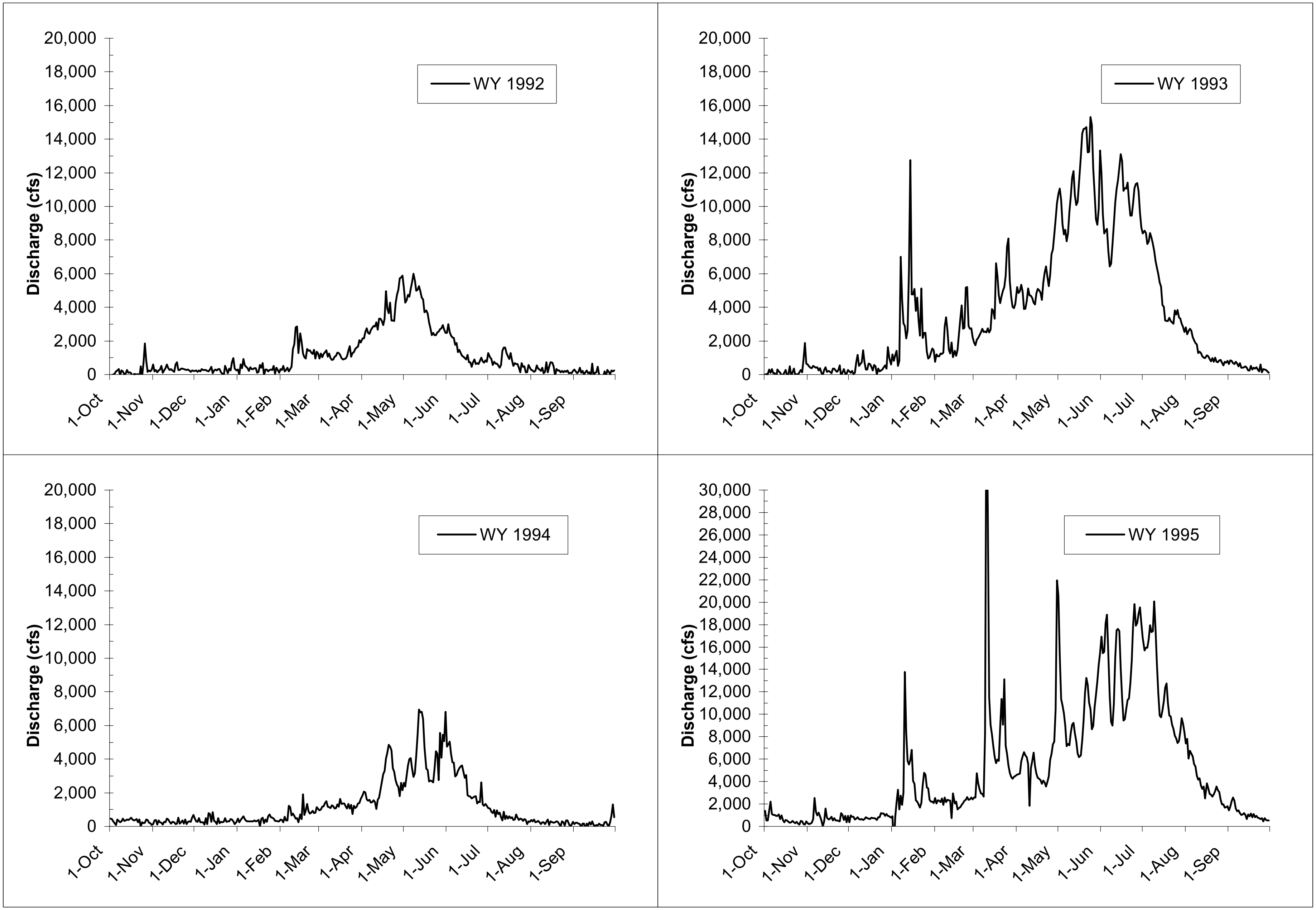
San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



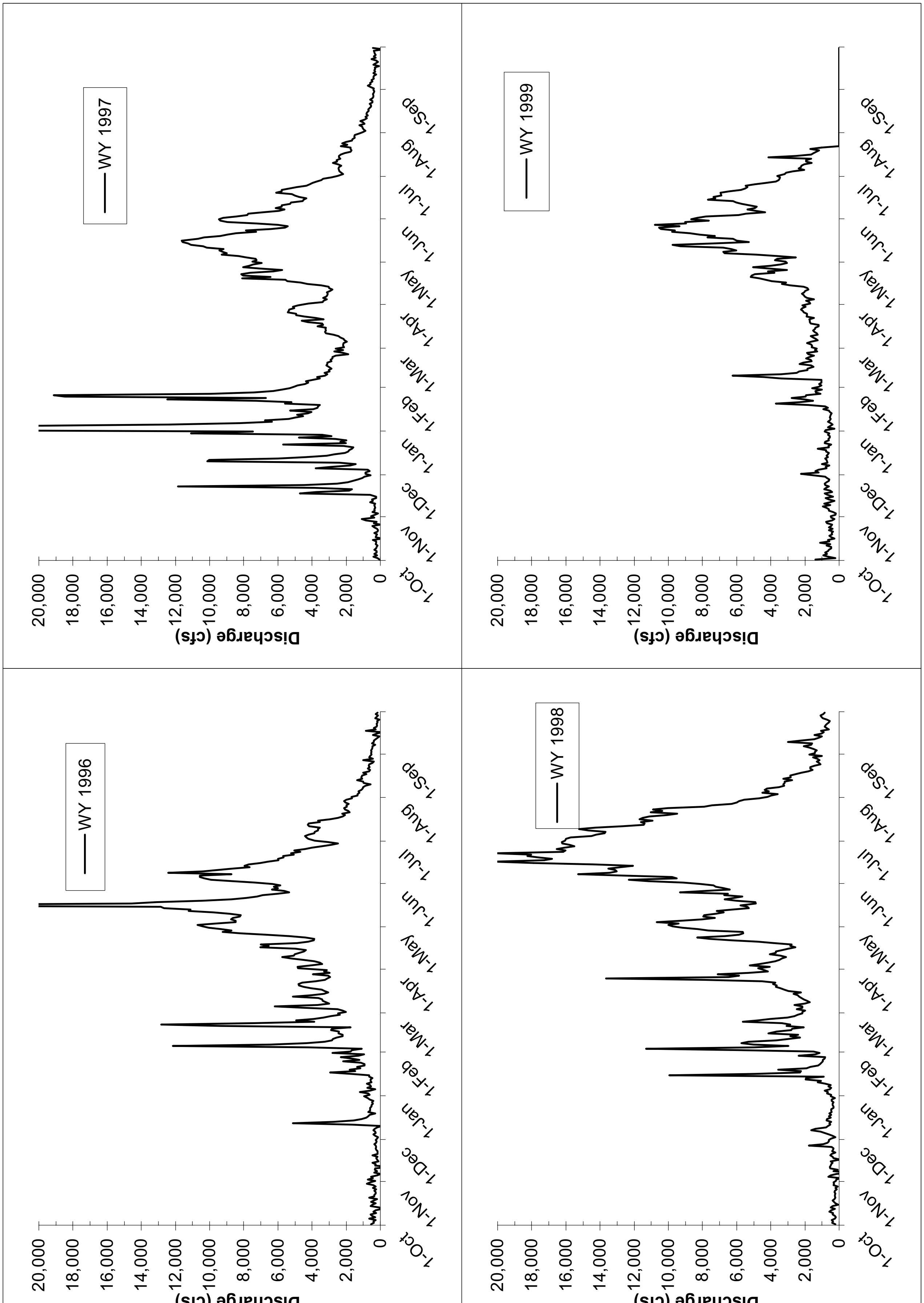
San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)



San Joaquin River blw Friant CA UNIMPAIRED hydrographs for WY 1896-1999 (USGS 11-251000)

APPENDIX B.

REGULATED HYDROLOGIC DATA FOR THE

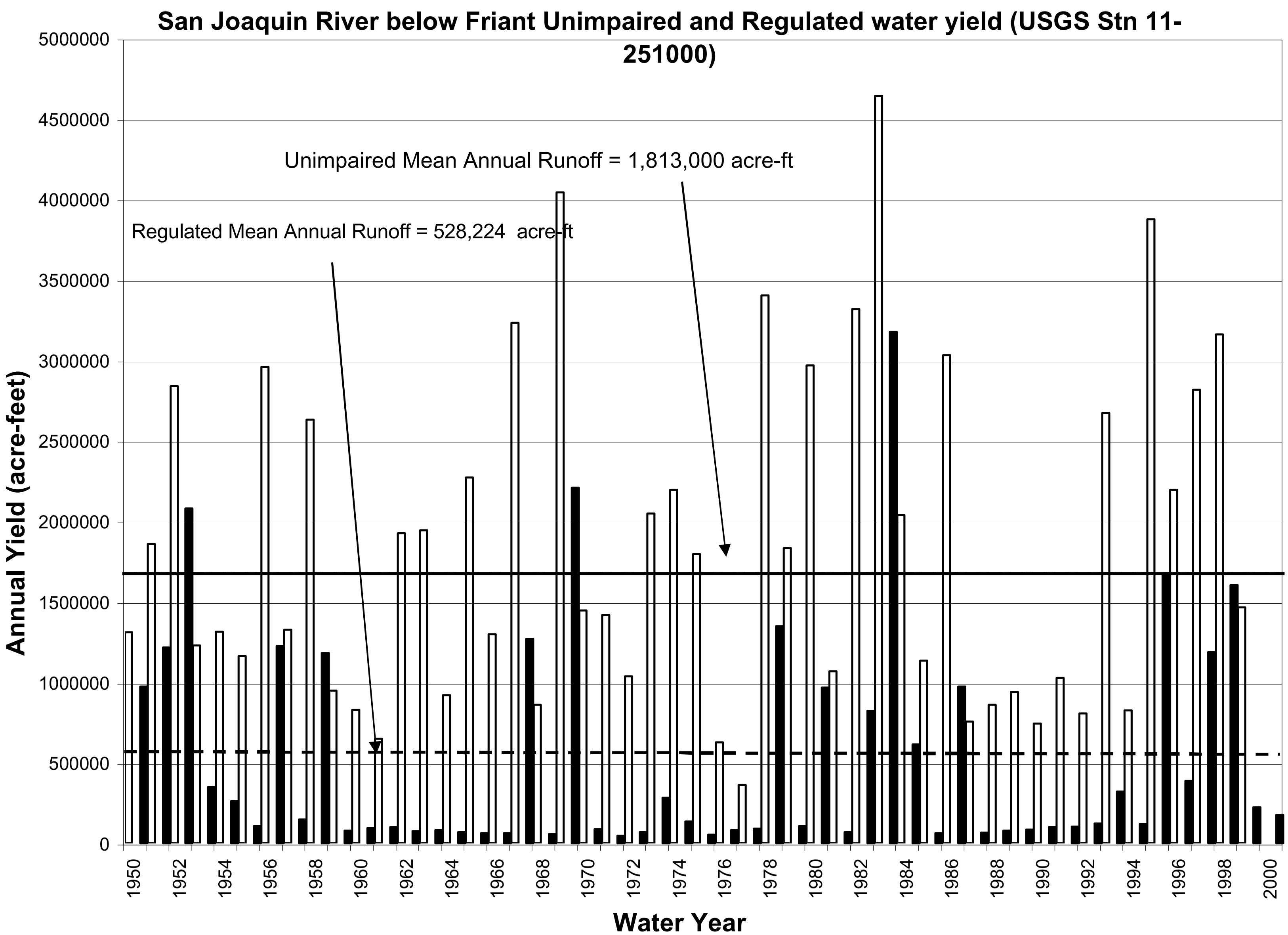
- SAN JOAQUIN RIVER

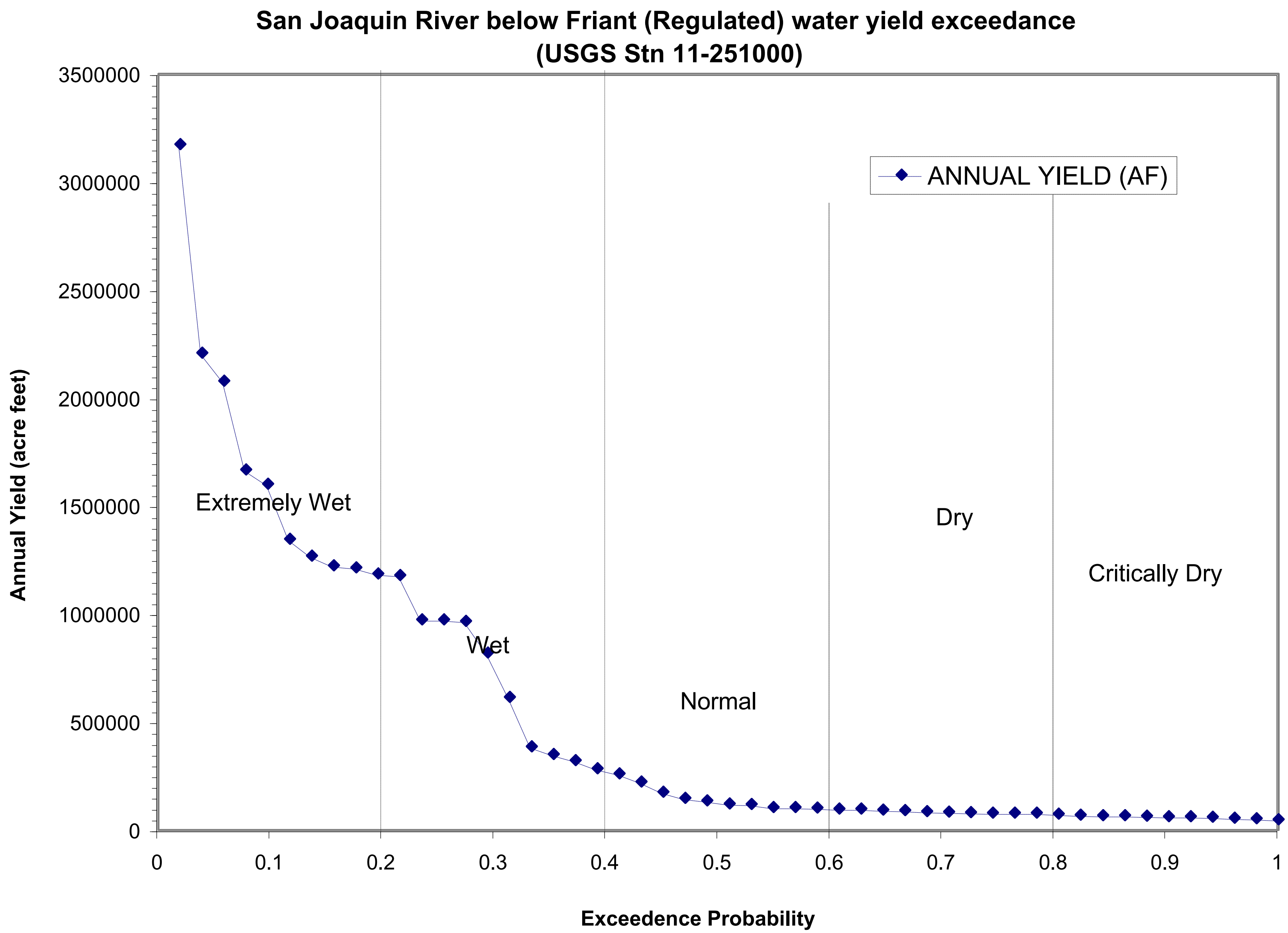
INCLUDING:

- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

San Joaquin River below Friant CA 1950-2000 REGULATED (post-Friant) water yield (USGS Stn 11-251000)

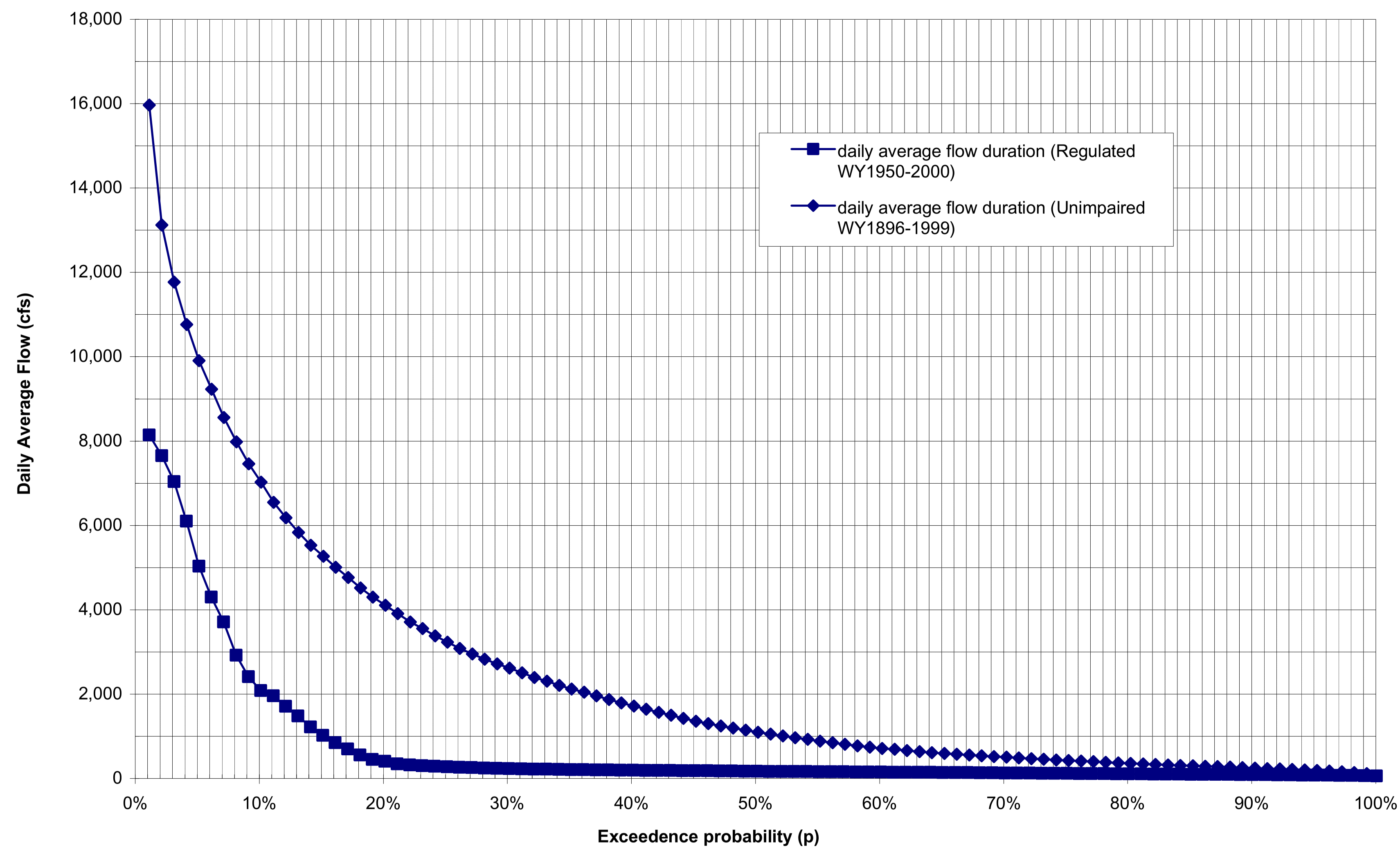
WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1950	973,696	WET	25.49%	13
1951	1,215,858	EXTREMELY WET	17.65%	9
1952	2,078,340	EXTREMELY WET	5.88%	3
1953	350,995	WET	35.29%	18
1954	262,264	NORMAL	41.18%	21
1955	107,328	NORMAL	54.90%	28
1956	1,224,163	EXTREMELY WET	15.69%	8
1957	149,411	NORMAL	47.06%	24
1958	1,180,140	WET	21.57%	11
1959	79,474	DRY	78.43%	40
1960	95,490	DRY	64.71%	33
1961	99,816	DRY	60.78%	31
1962	75,116	CRITICALLY DRY	80.39%	41
1963	82,852	DRY	72.55%	37
1964	70,217	CRITICALLY DRY	82.35%	42
1965	63,306	CRITICALLY DRY	92.16%	47
1966	62,390	CRITICALLY DRY	94.12%	48
1967	1,269,086	EXTREMELY WET	13.73%	7
1968	57,616	CRITICALLY DRY	96.08%	49
1969	2,207,875	EXTREMELY WET	3.92%	2
1970	86,805	DRY	68.63%	35
1971	48,424	CRITICALLY DRY	100.00%	51
1972	67,985	CRITICALLY DRY	86.27%	44
1973	285,118	WET	39.22%	20
1974	136,179	NORMAL	49.02%	25
1975	53,829	CRITICALLY DRY	98.04%	50
1976	80,672	DRY	74.51%	38
1977	90,881	DRY	66.67%	34
1978	1,347,765	EXTREMELY WET	11.76%	6
1979	106,913	NORMAL	56.86%	29
1980	967,620	WET	27.45%	14
1981	69,435	CRITICALLY DRY	84.31%	43
1982	820,903	WET	29.41%	15
1983	3,174,569	EXTREMELY WET	1.96%	1
1984	615,213	WET	31.37%	16
1985	64,064	CRITICALLY DRY	90.20%	46
1986	974,283	WET	23.53%	12
1987	66,889	CRITICALLY DRY	88.24%	45
1988	79,517	DRY	76.47%	39
1989	84,117	DRY	70.59%	36
1990	99,261	DRY	62.75%	32
1991	104,426	NORMAL	58.82%	30
1992	122,616	NORMAL	50.98%	26
1993	322,389	WET	37.25%	19
1994	119,921	NORMAL	52.94%	27
1995	1,667,853	EXTREMELY WET	7.84%	4
1996	386,263	WET	33.33%	17
1997	1,187,252	EXTREMELY WET	19.61%	10
1998	1,603,480	EXTREMELY WET	9.80%	5
1999	223,186	NORMAL	43.14%	22
2000	176,148	NORMAL	45.10%	23


San Joaquin River below Friant Unimpaired and Regulated water yield (USGS Stn 11-251000)
Unimpaired Mean Annual Runoff = 1,813,000 acre-ft
Regulated Mean Annual Runoff = 528,224 acre-ft
Annual Yield (acre-feet)
0
500000
1000000
1500000
2000000
2500000
3000000
3500000
4000000
4500000
5000000
Water Year
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000

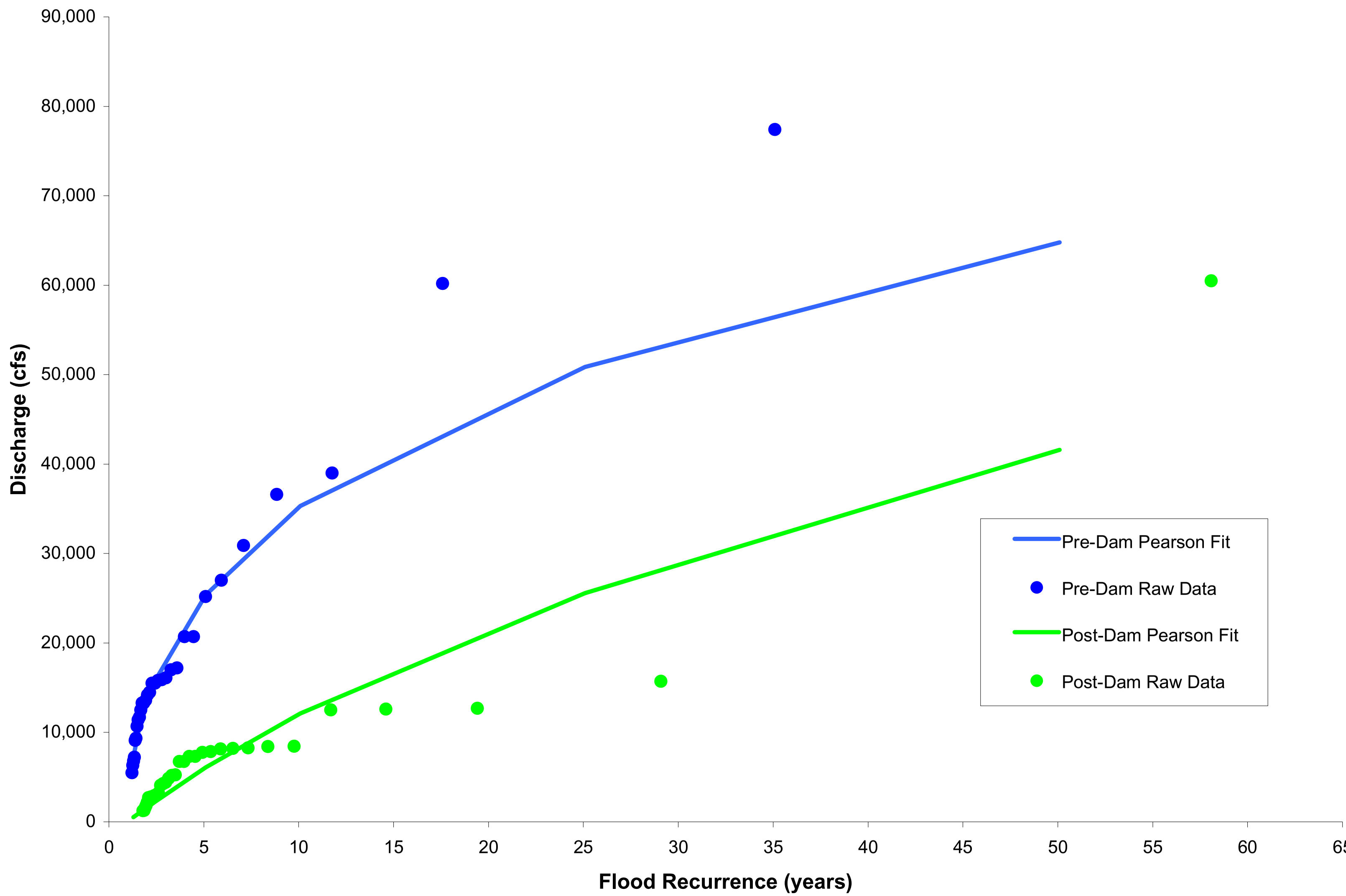


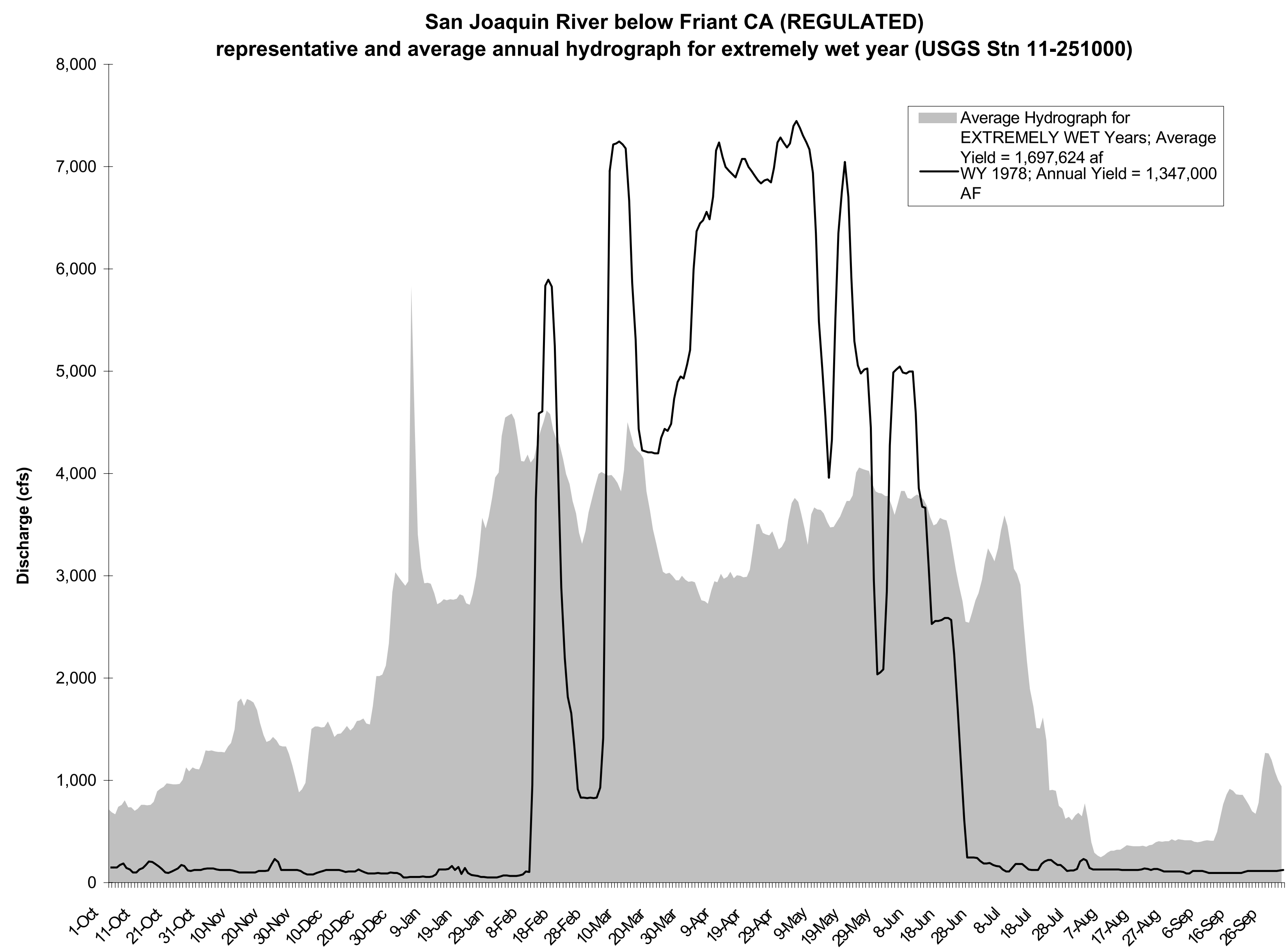
San Joaquin River below Friant (Regulated) water yield exceedance
(USGS Stn 11-251000)
Annual Yield (acre feet)
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Exceedence Probability
ANNUAL YIELD (AF)
Extremely Wet
Wet
Normal
Dry
Critically Dry

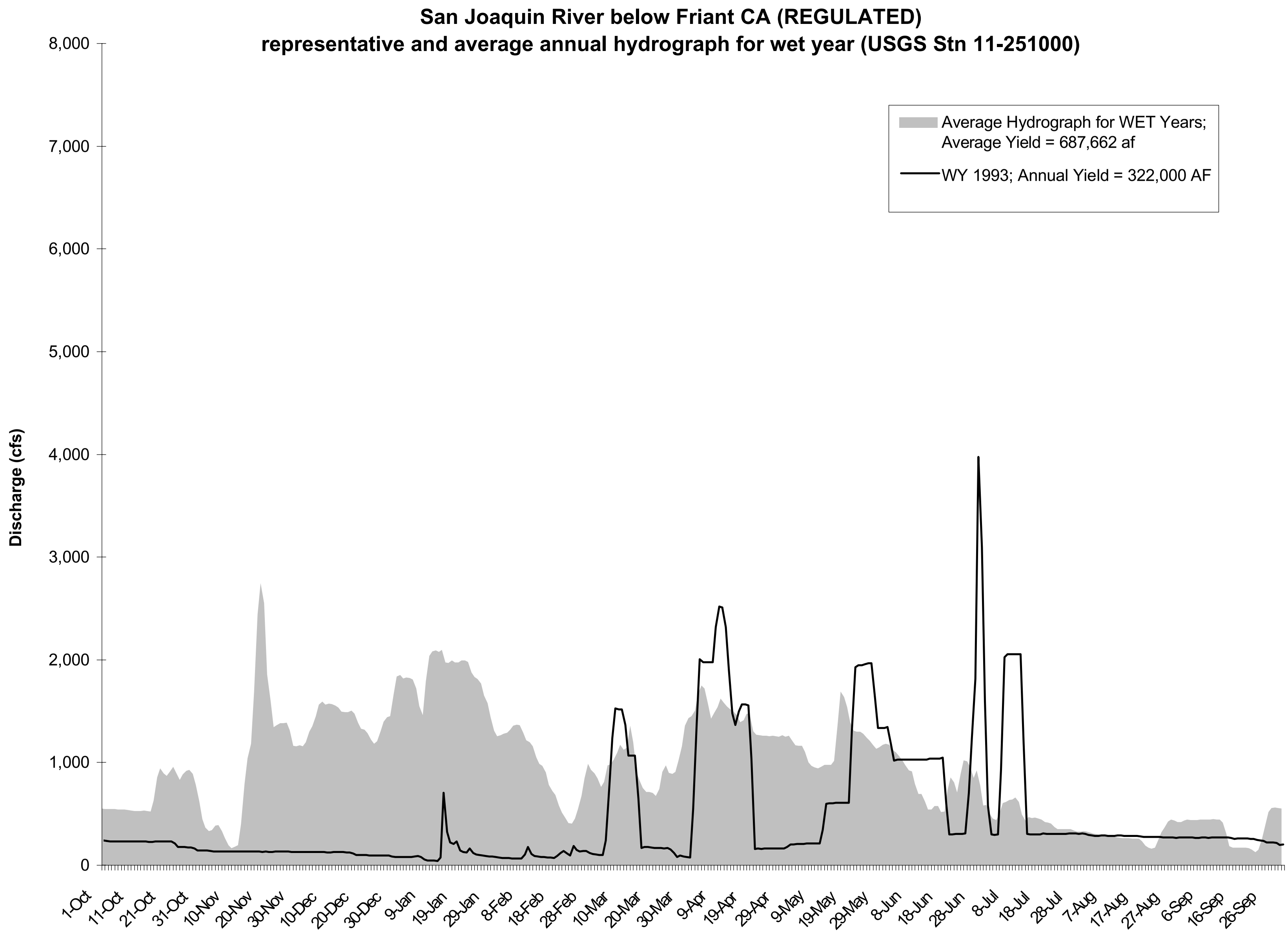
San Joaquin River below Friant CA UNIMPAIRED (modeled) and REGULATED post-Friant Dam flow duration curves (USGS Stn 11-251000)



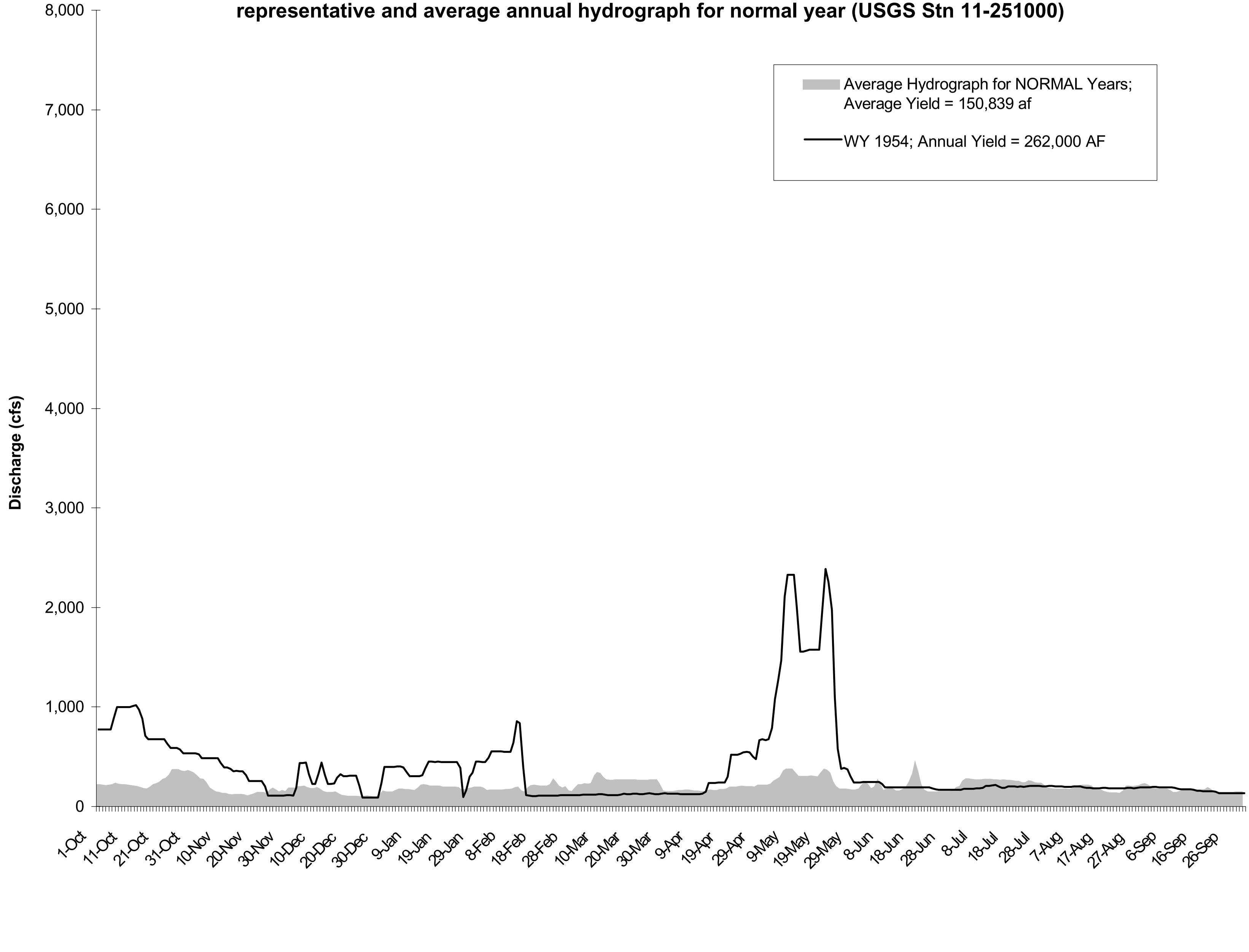
San Joaquin River Below Friant CA measured pre- and post-dam flood frequency data (USGS Stn 11-251000)

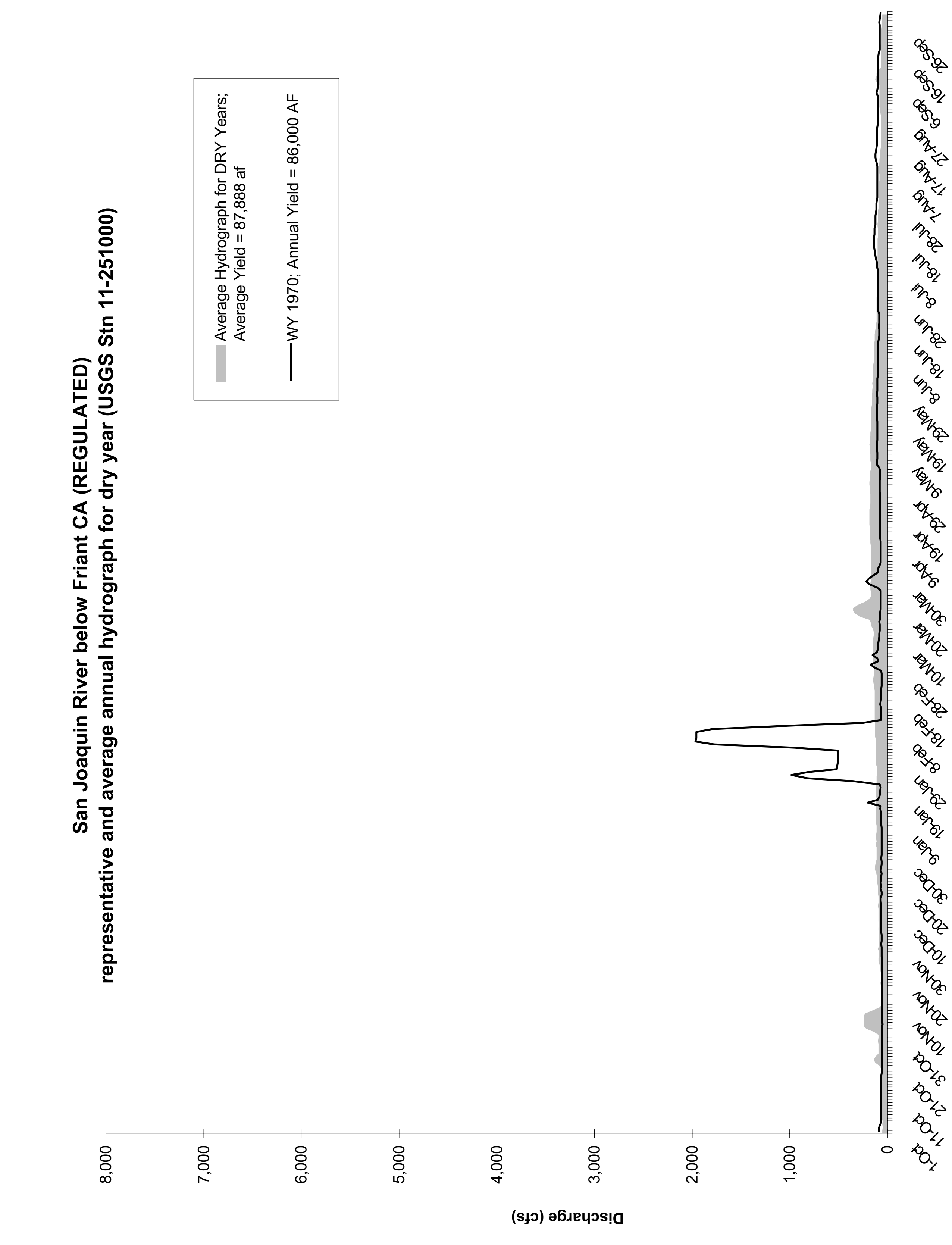



San Joaquin River below Friant CA (REGULATED)
representative and average annual hydrograph for extremely wet year (USGS Stn 11-251000)
Average Hydrograph for EXTREMELY WET Years; Average Yield = 1,697,624 af
WY 1978; Annual Yield = 1,347,000 AF
Discharge (cfs)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
8-Jul
18-Jul
28-Jul
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep


San Joaquin River below Friant CA (REGULATED)
representative and average annual hydrograph for wet year (USGS Stn 11-251000)
Average Hydrograph for WET Years; Average Yield = 687,662 af
WY 1993; Annual Yield = 322,000 AF
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
8-Jul
18-Jul
28-Jul
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep

San Joaquin River below Friant CA (REGULATED)
representative and average annual hydrograph for normal year (USGS Stn 11-251000)




San Joaquin River below Friant CA (REGULATED)
representative and average annual hydrograph for dry year (USGS Stn 11-251000)
Average Hydrograph for DRY Years; Average Yield = 87,888 af
WY 1970; Annual Yield = 86,000 AF
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
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8-Jul
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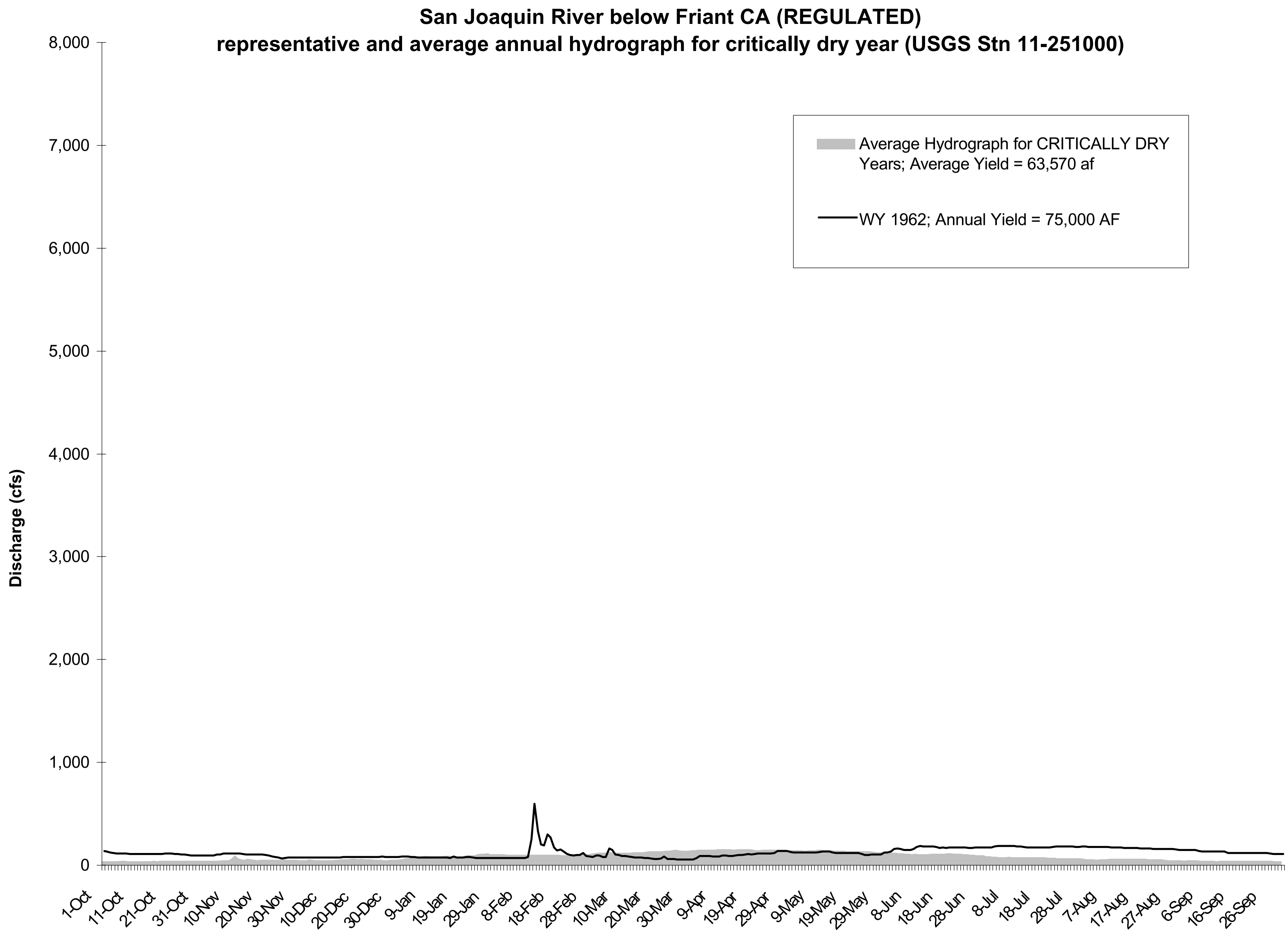
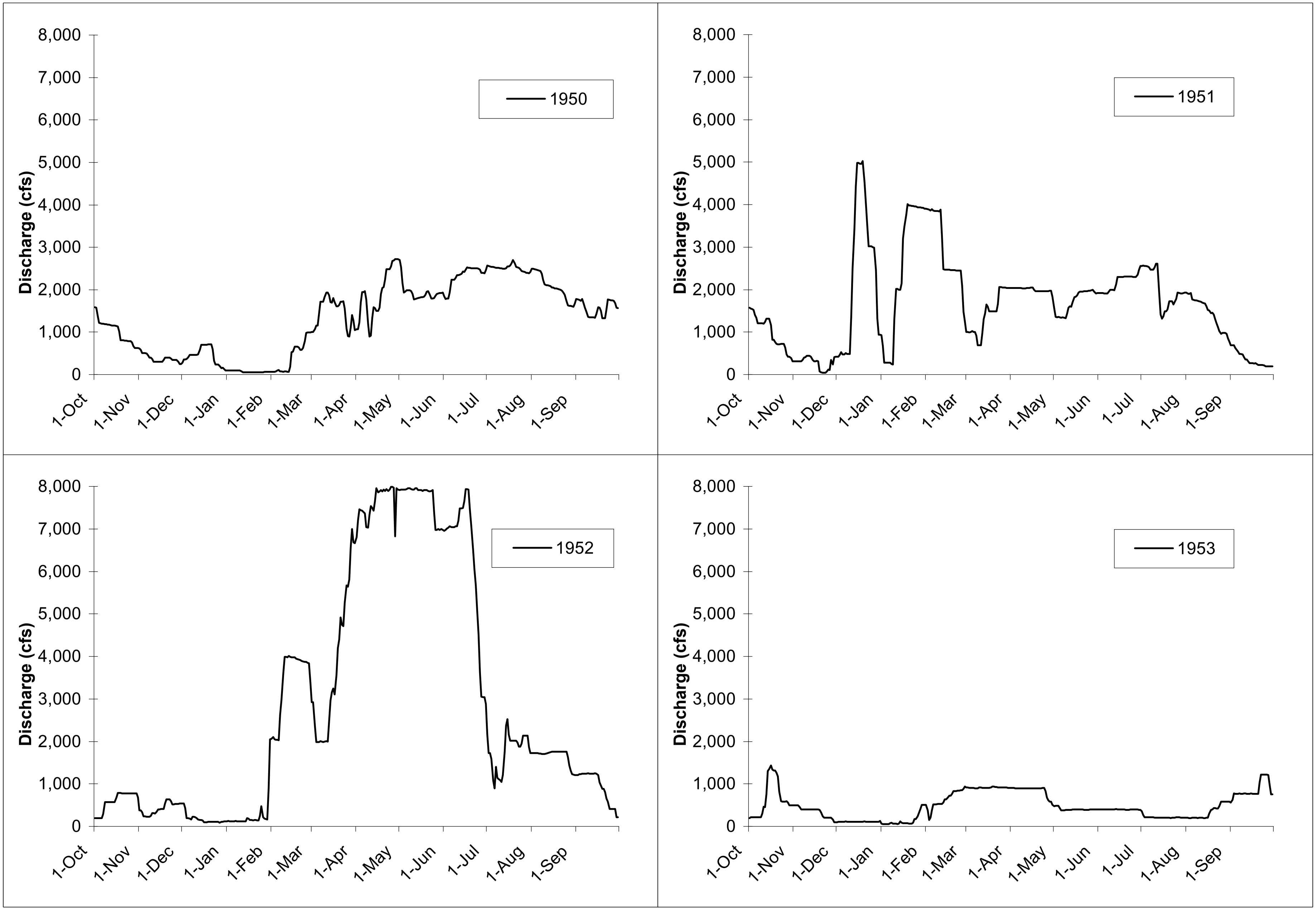
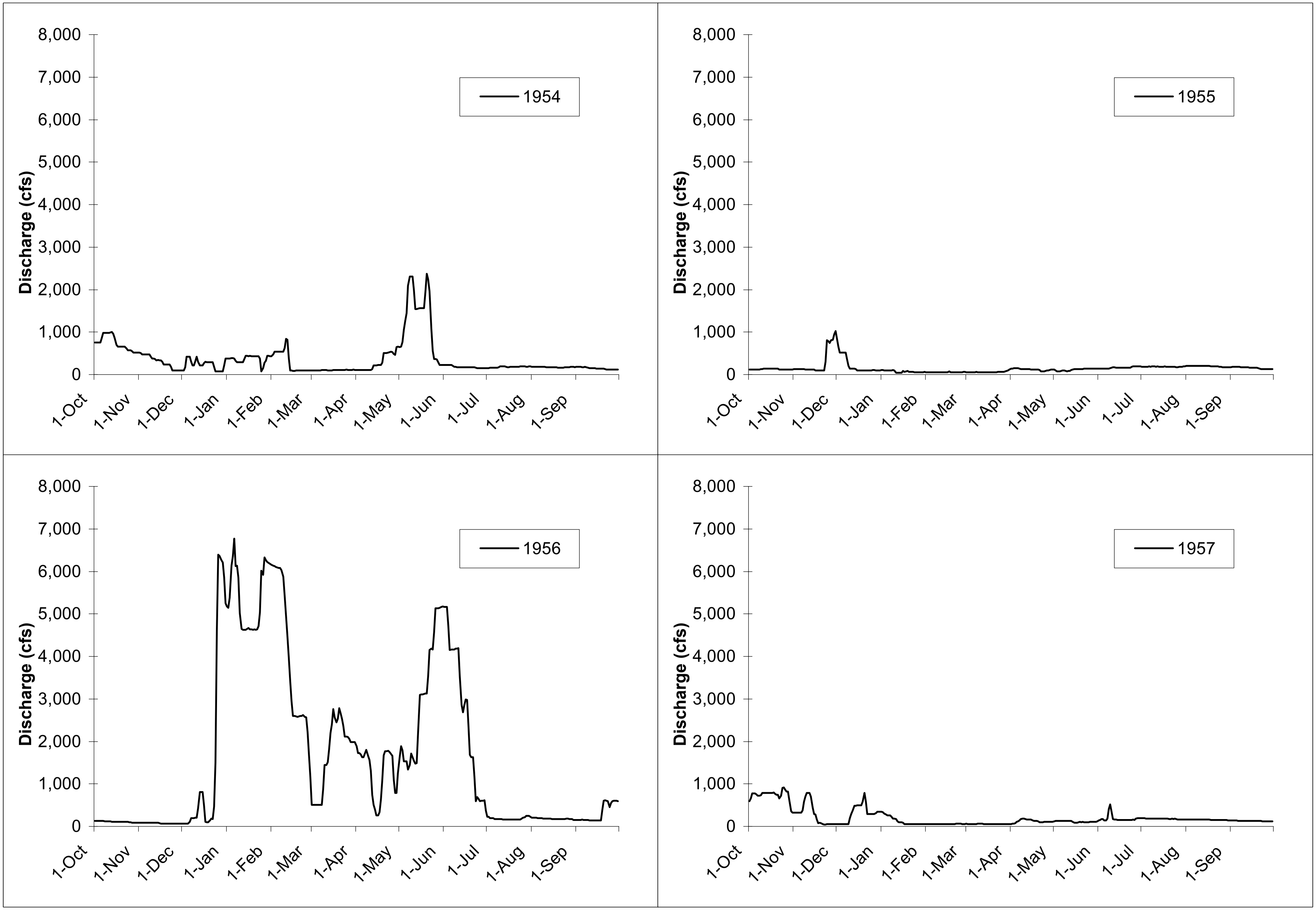
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep

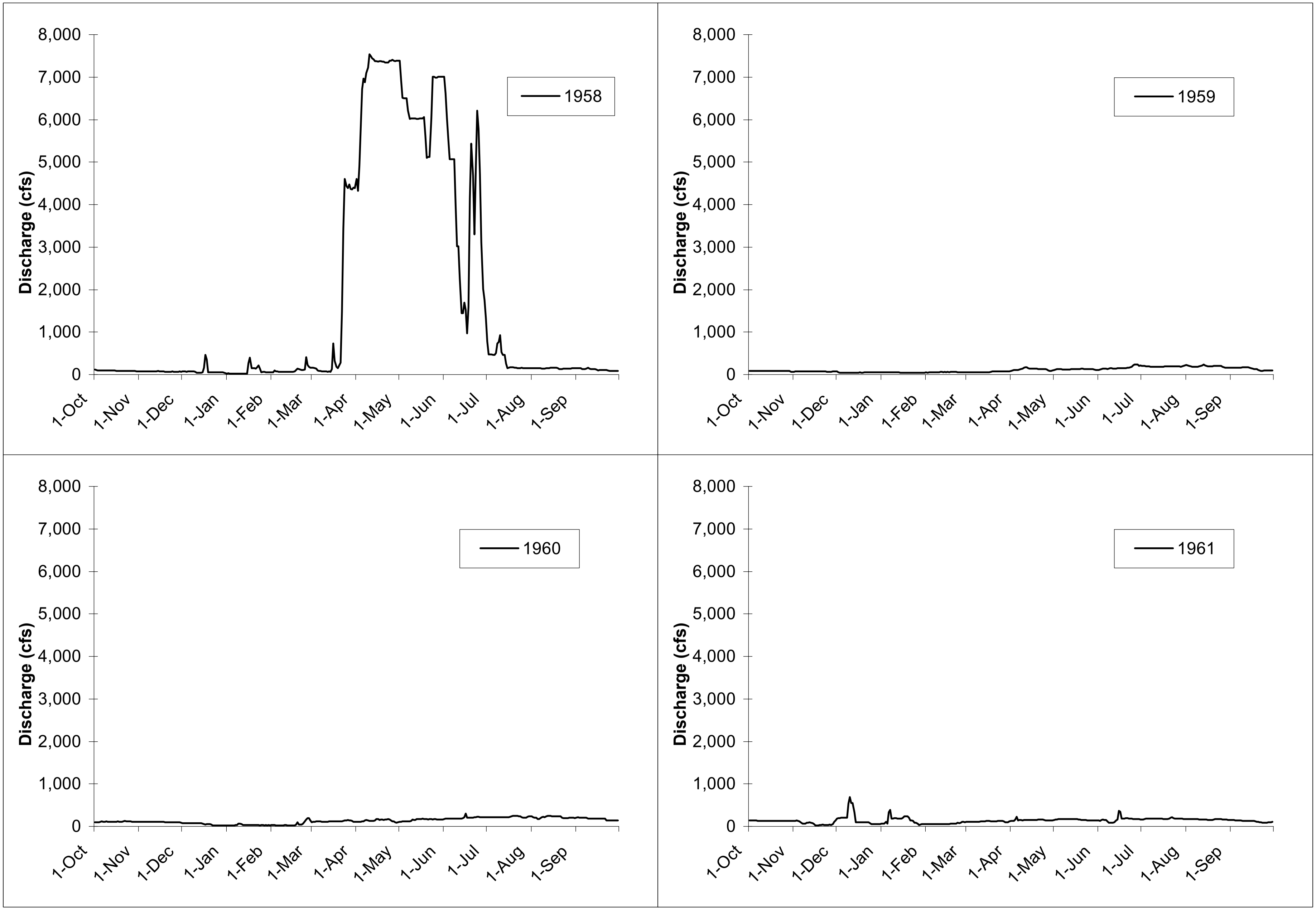

San Joaquin River below Friant CA (REGULATED)
representative and average annual hydrograph for critically dry year (USGS Stn 11-251000)
Average Hydrograph for CRITICALLY DRY Years; Average Yield = 63,570 af
WY 1962; Annual Yield = 75,000 AF
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
8-Jul
18-Jul
28-Jul
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep



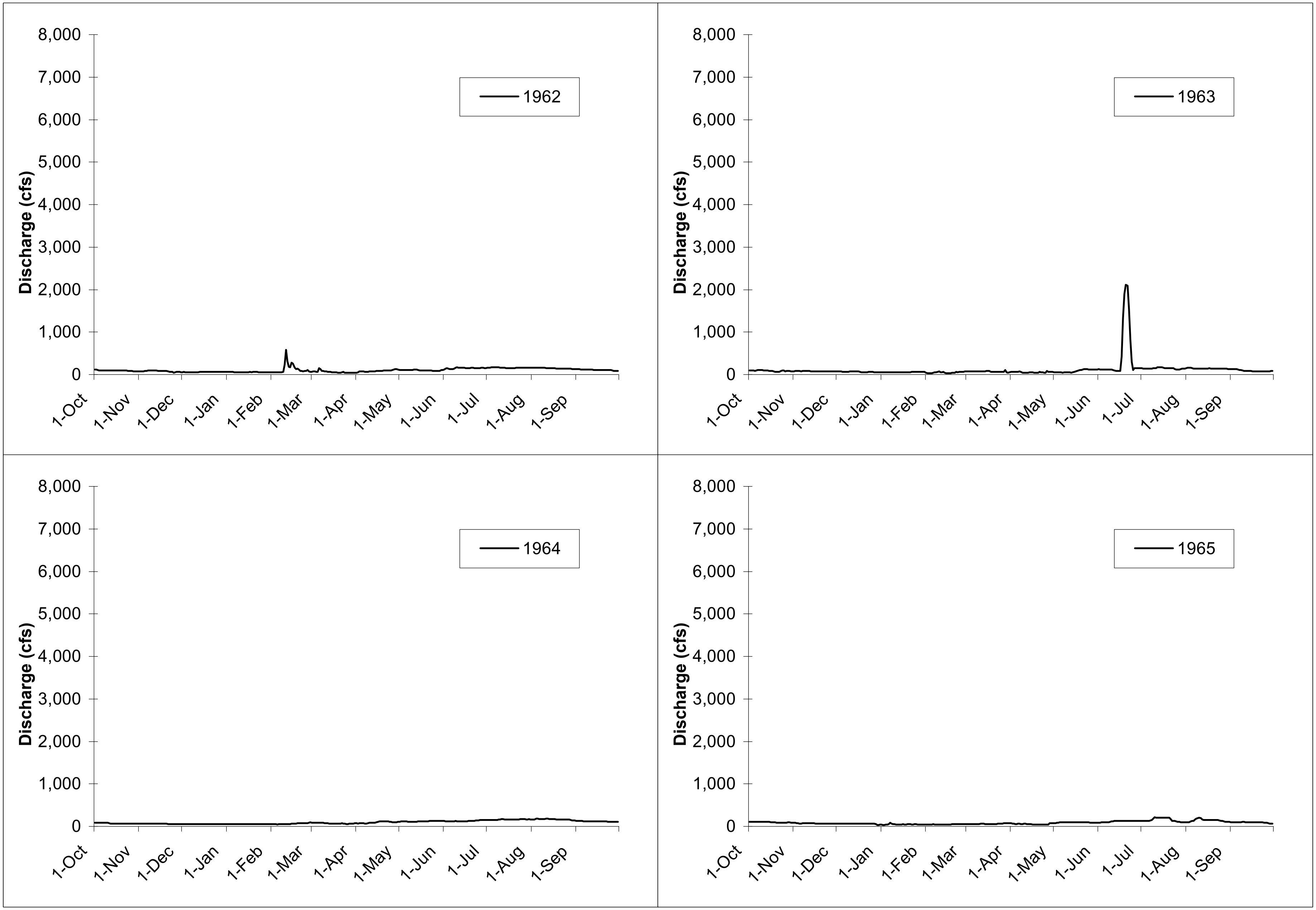
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



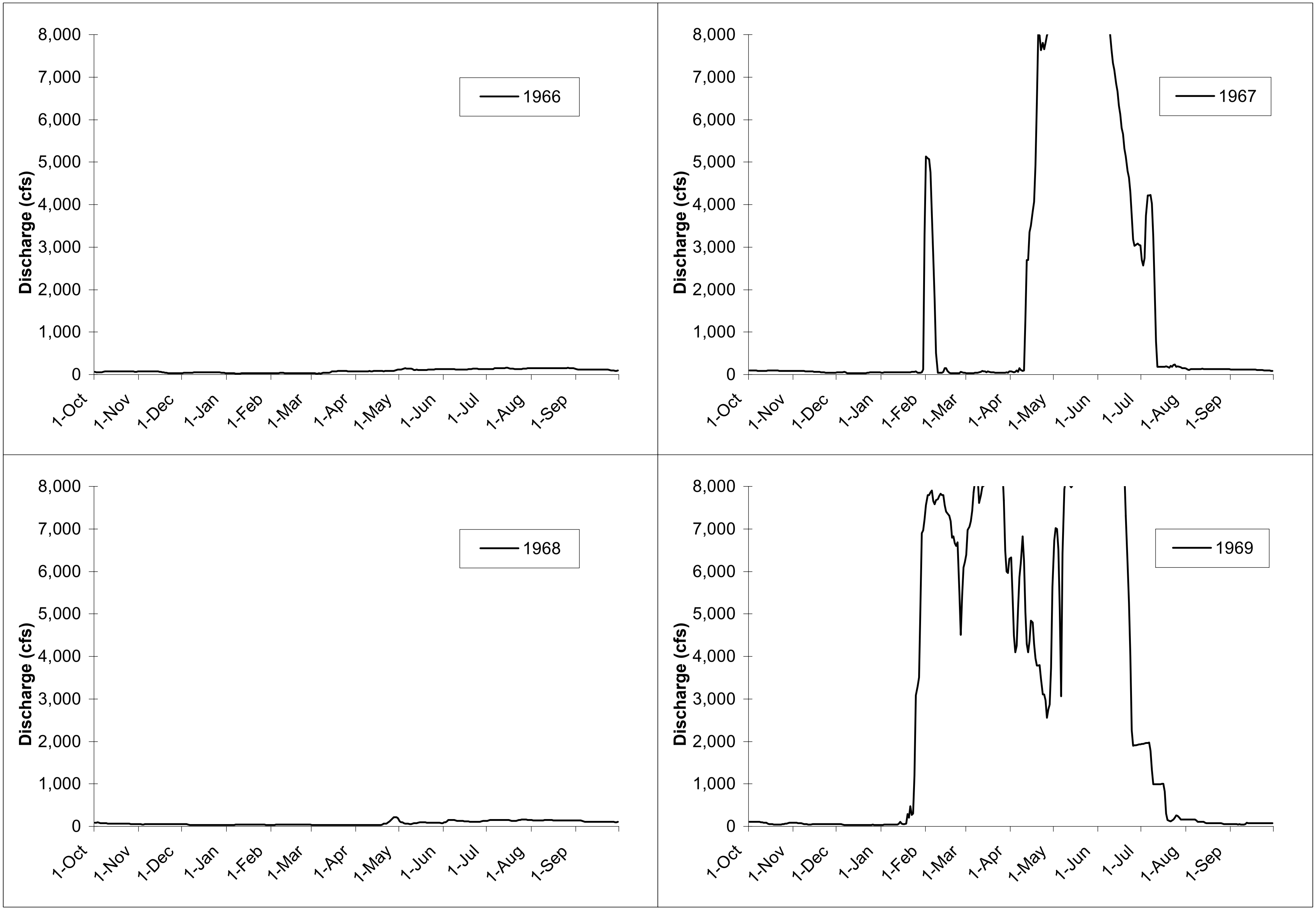
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



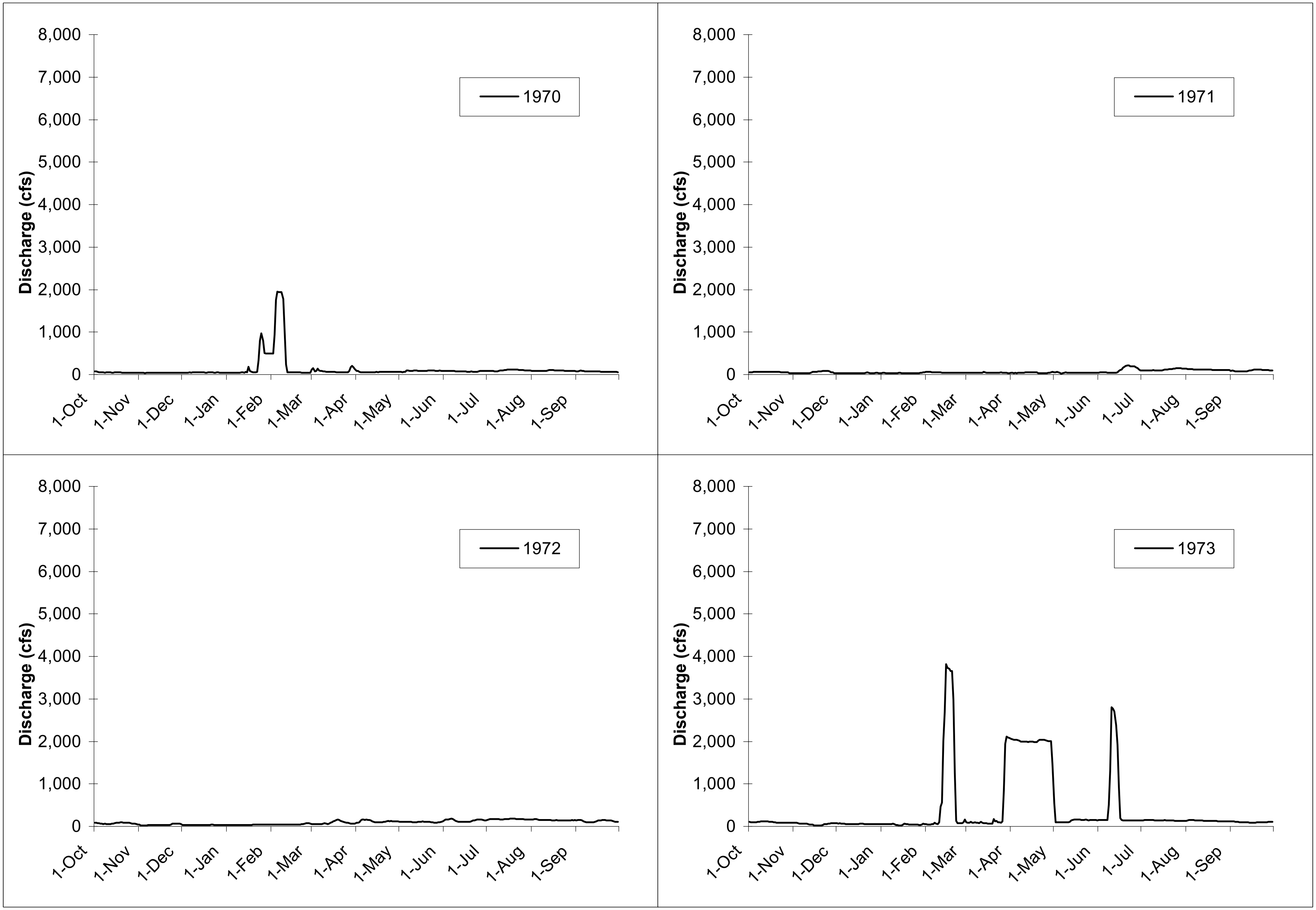
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



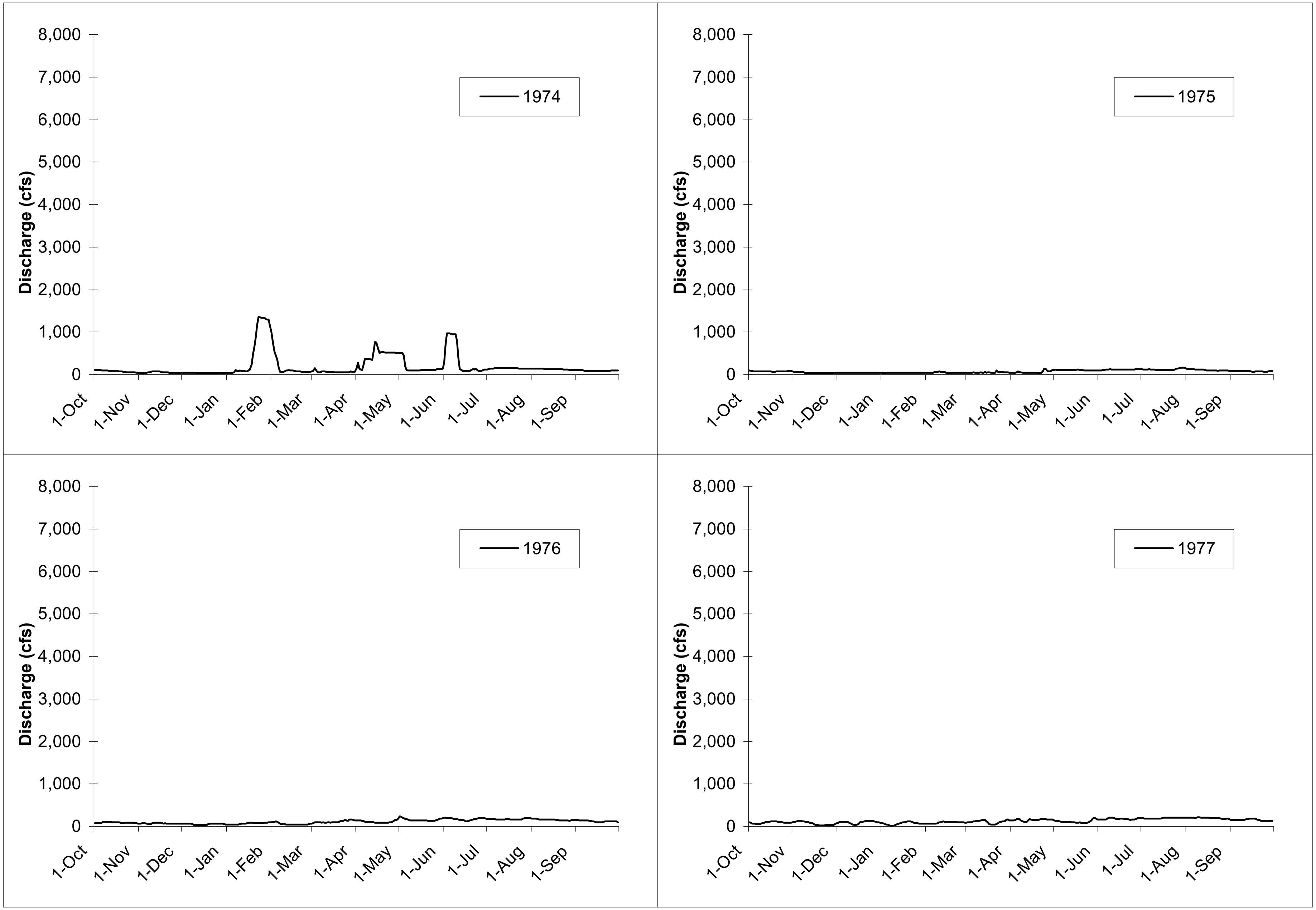
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



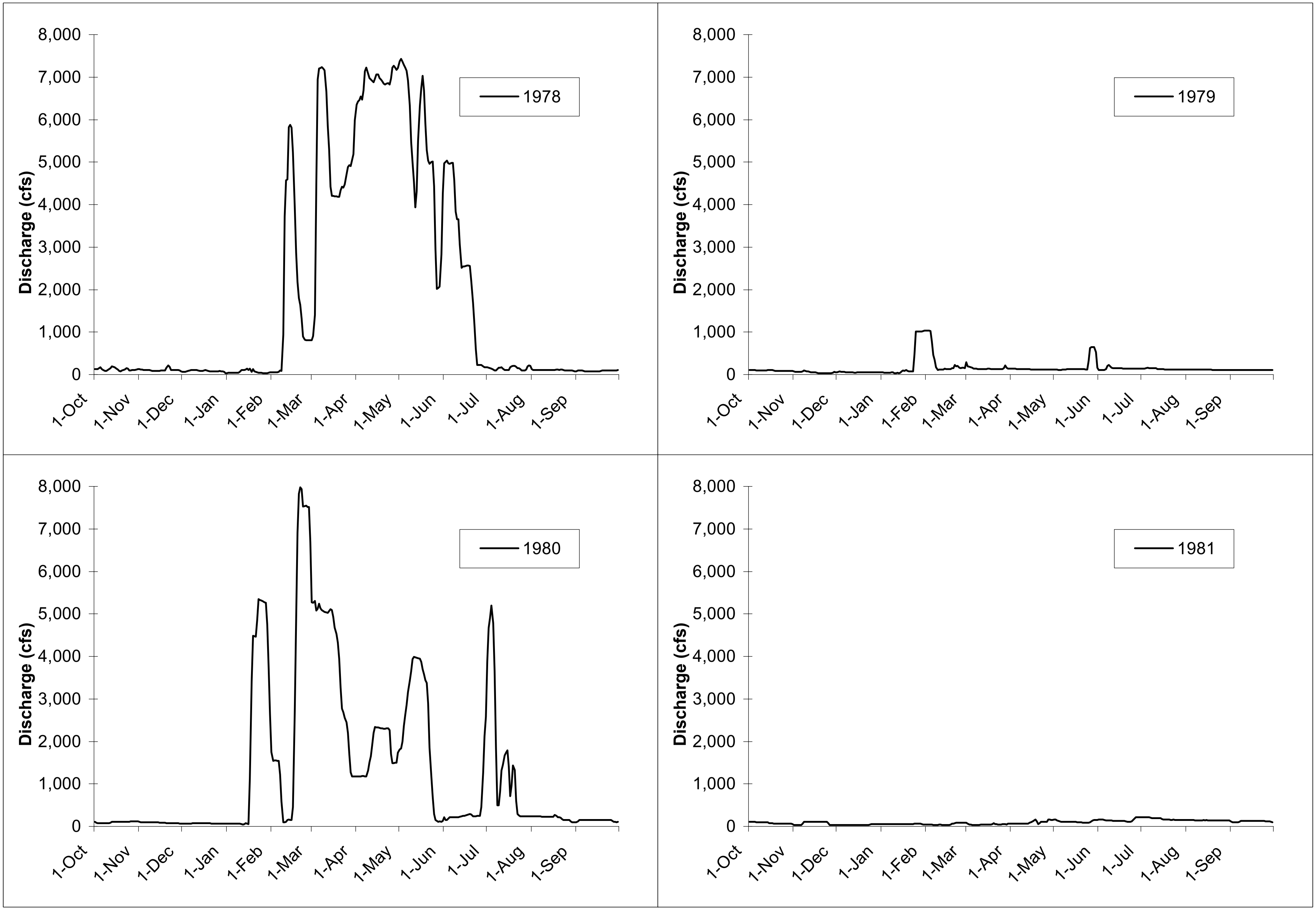
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



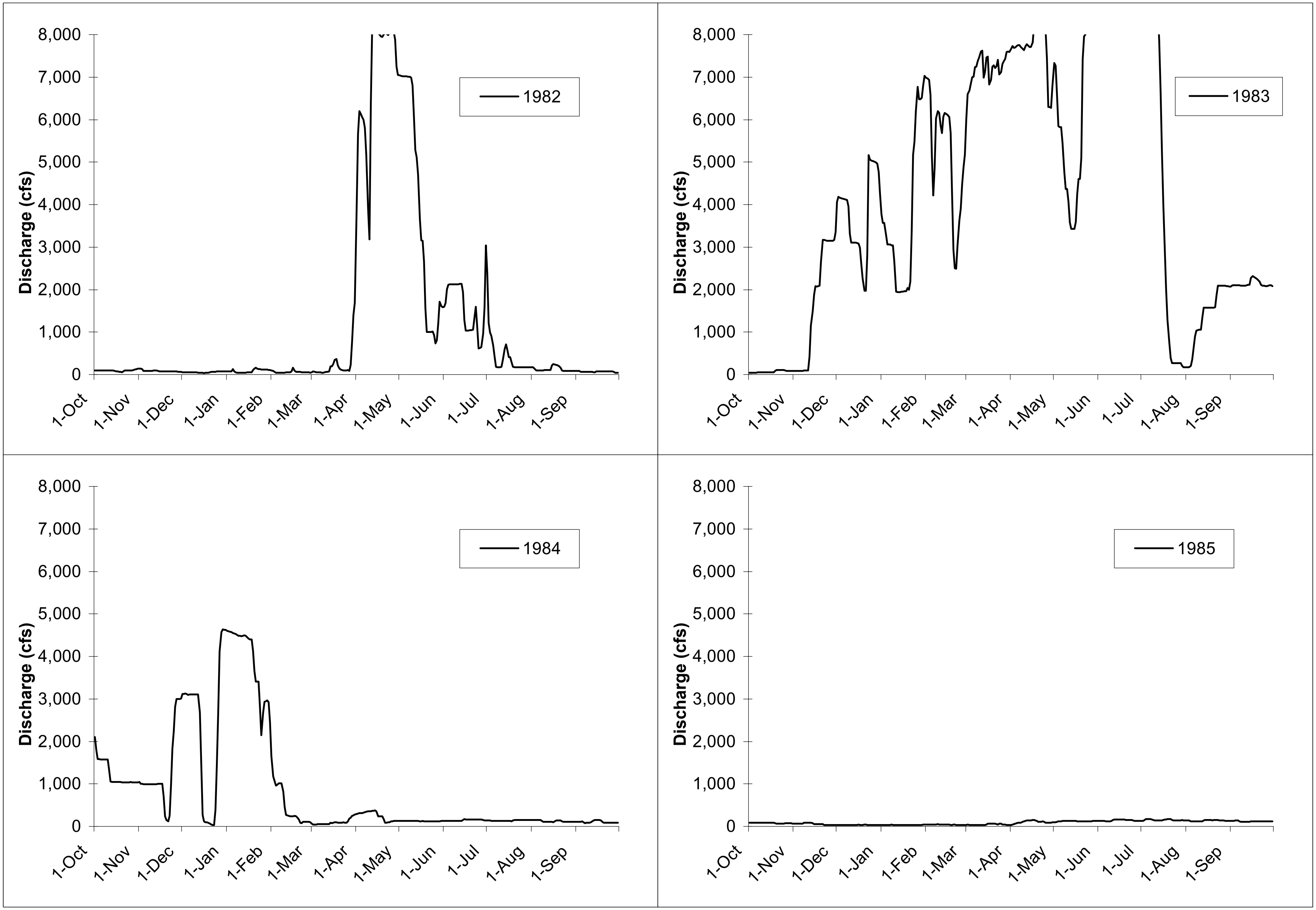
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



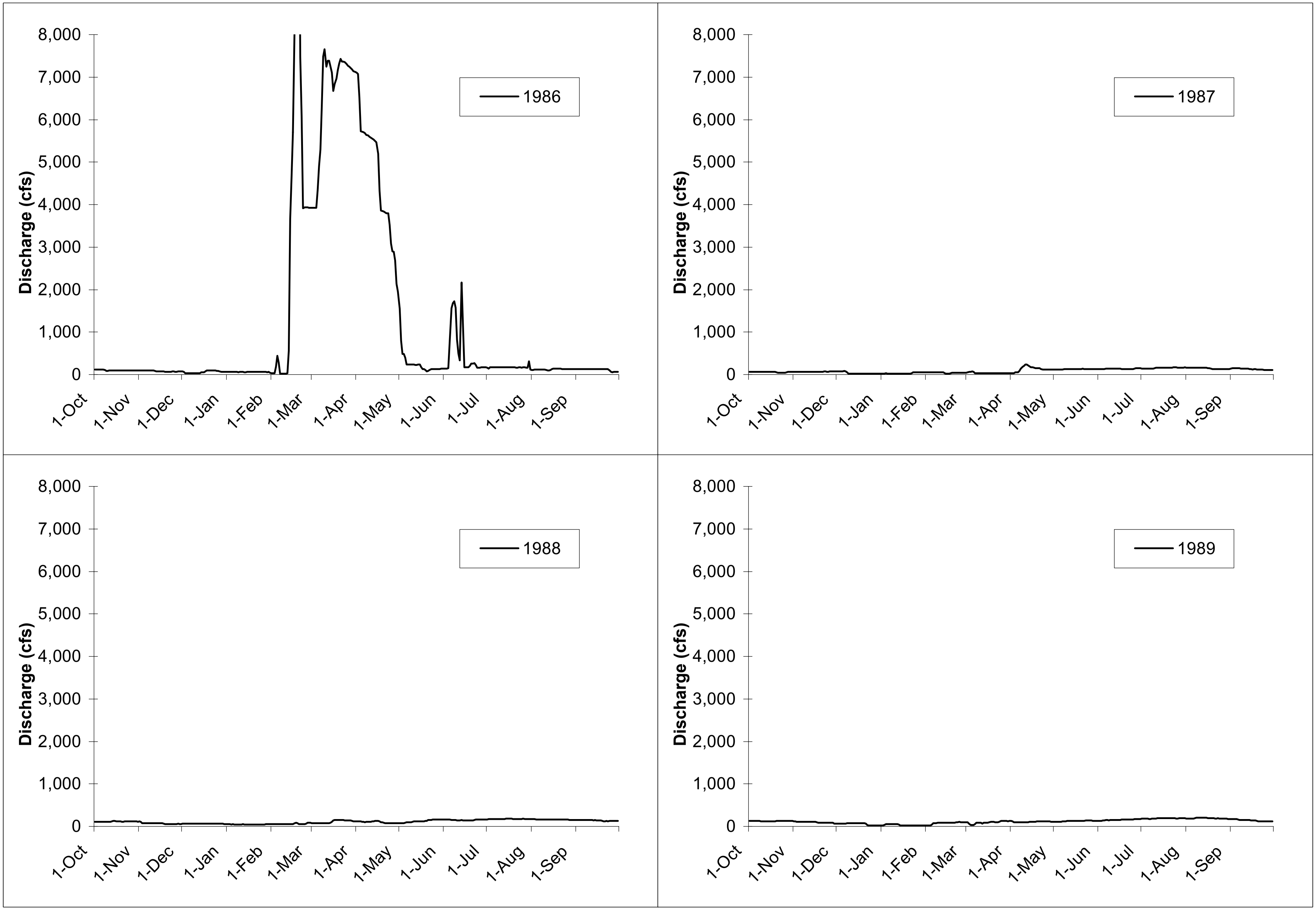
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



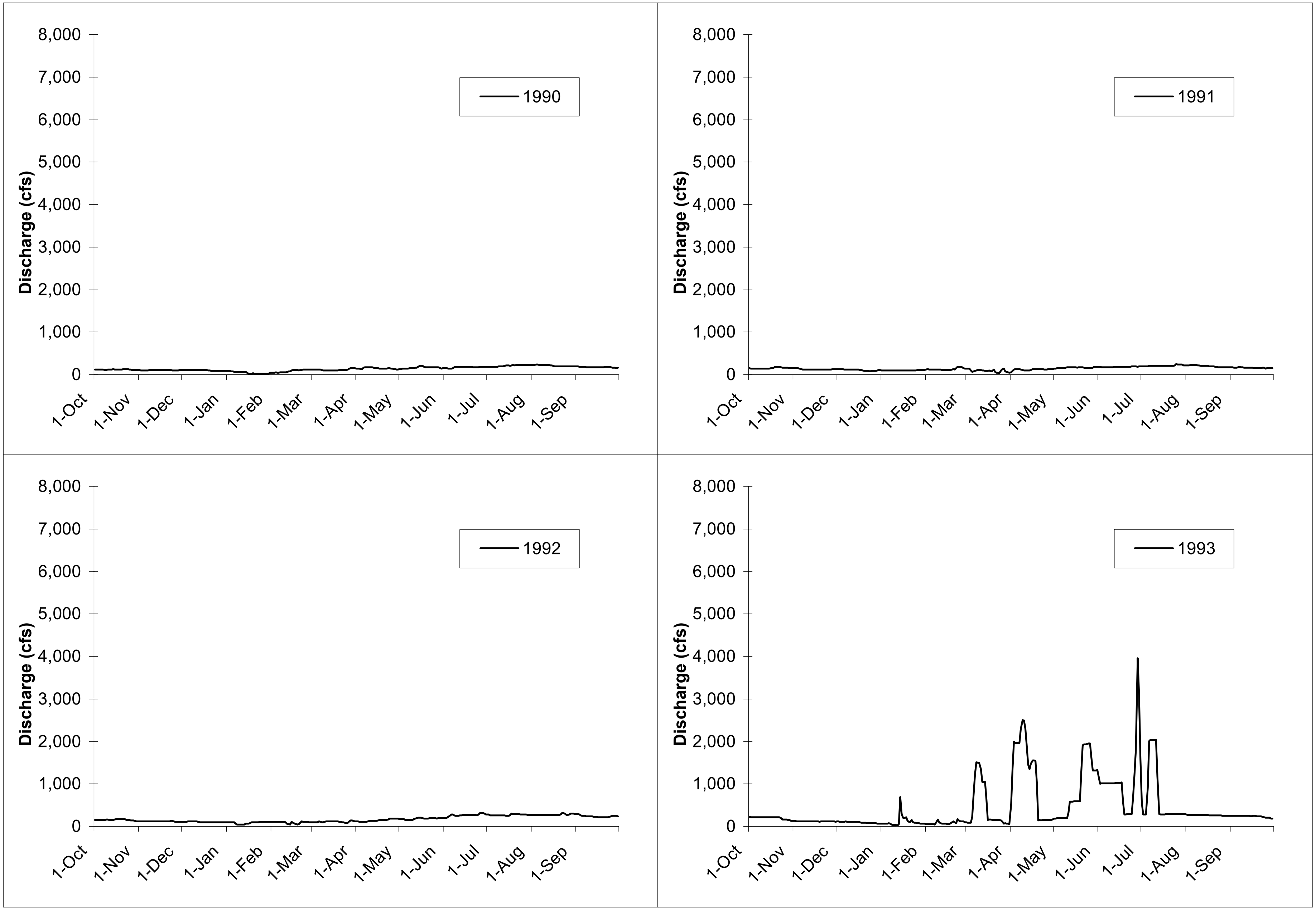
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



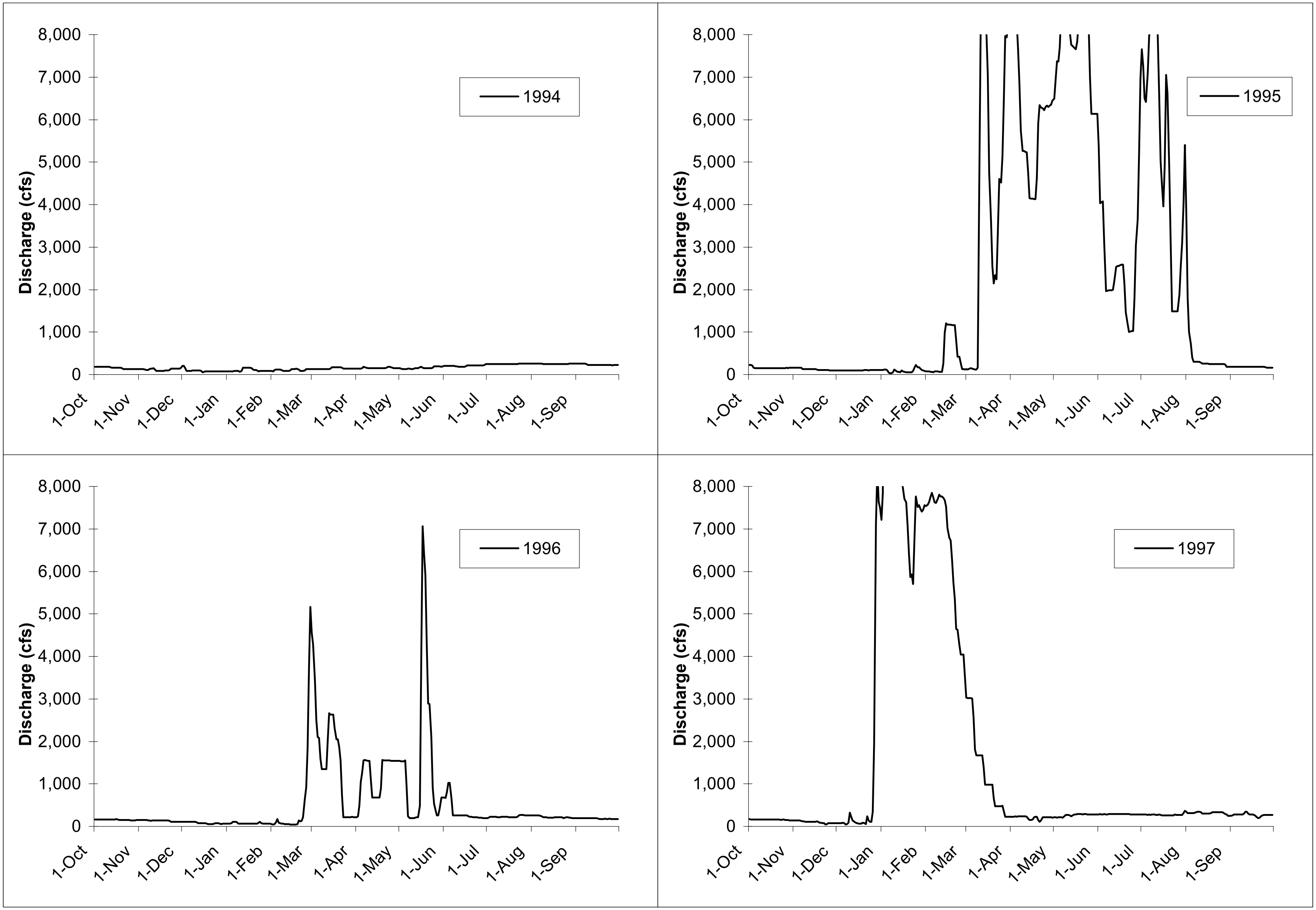
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



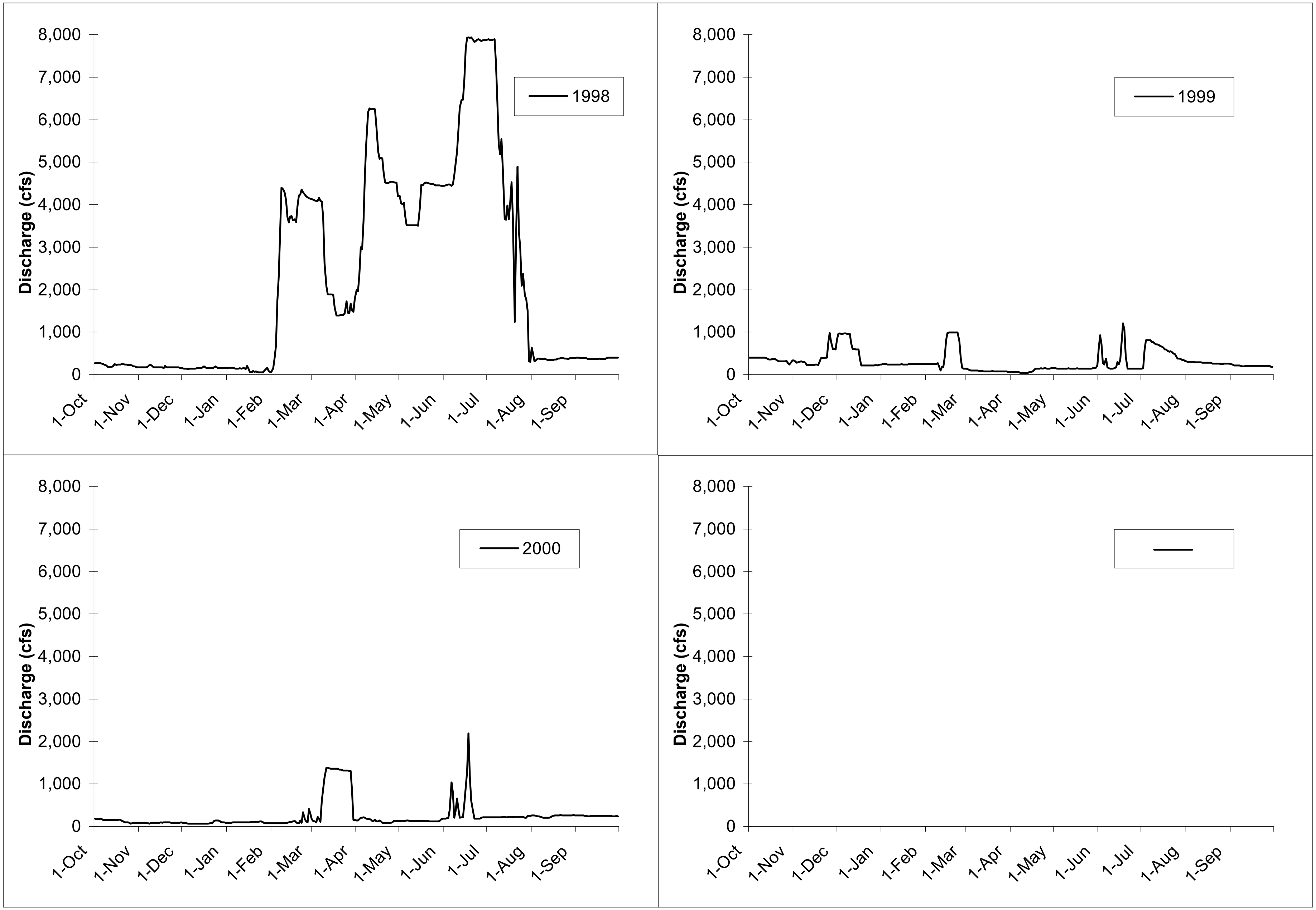
San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)



San Joaquin River below Friant CA REGULATED hydrographs for WY1950-2000 (USGS Stn 11-251000)

APPENDIX C.

UNIMPAIRED HYDROLOGIC DATA FOR THE

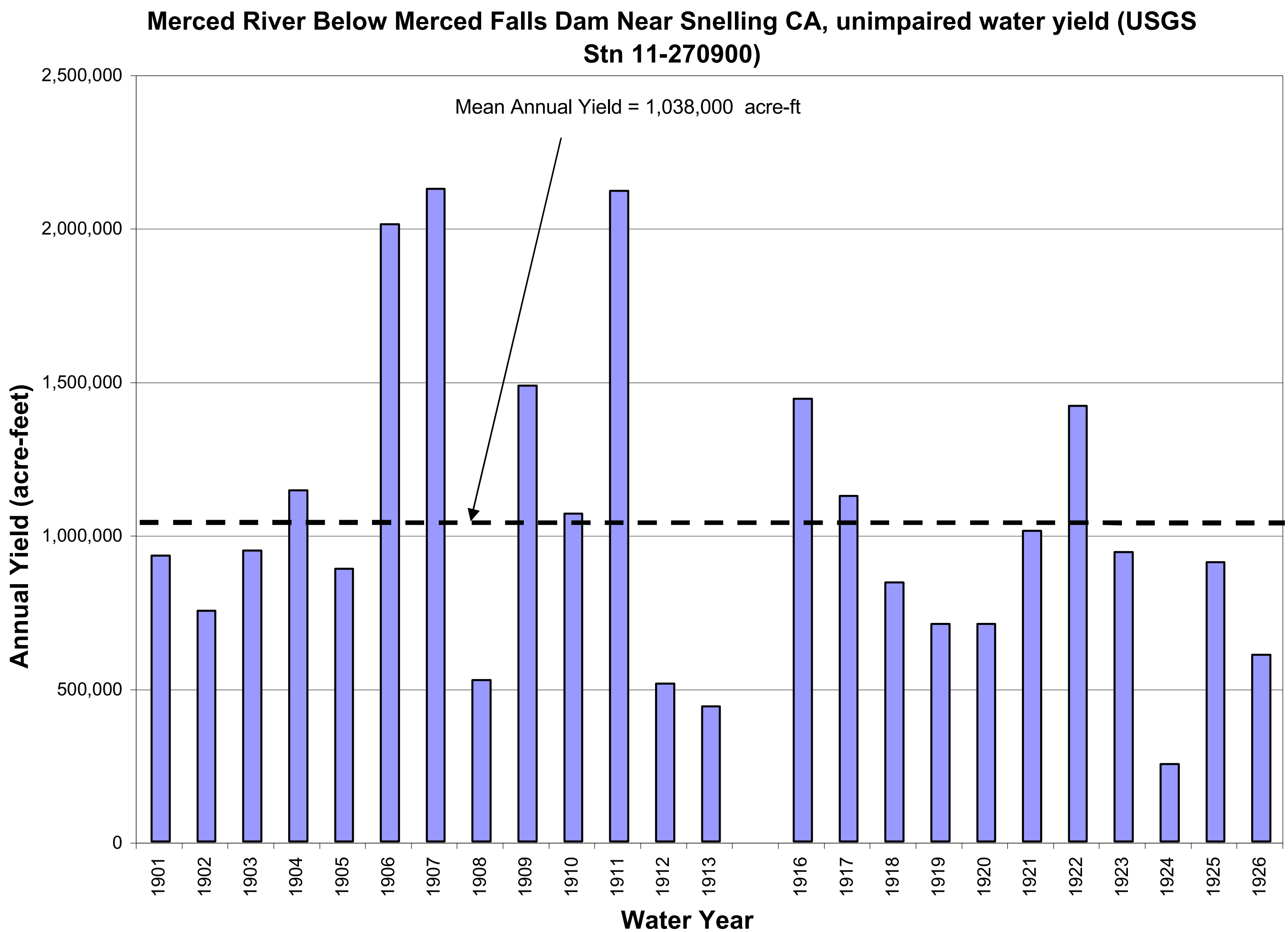
- MERCED RIVER

INCLUDING:

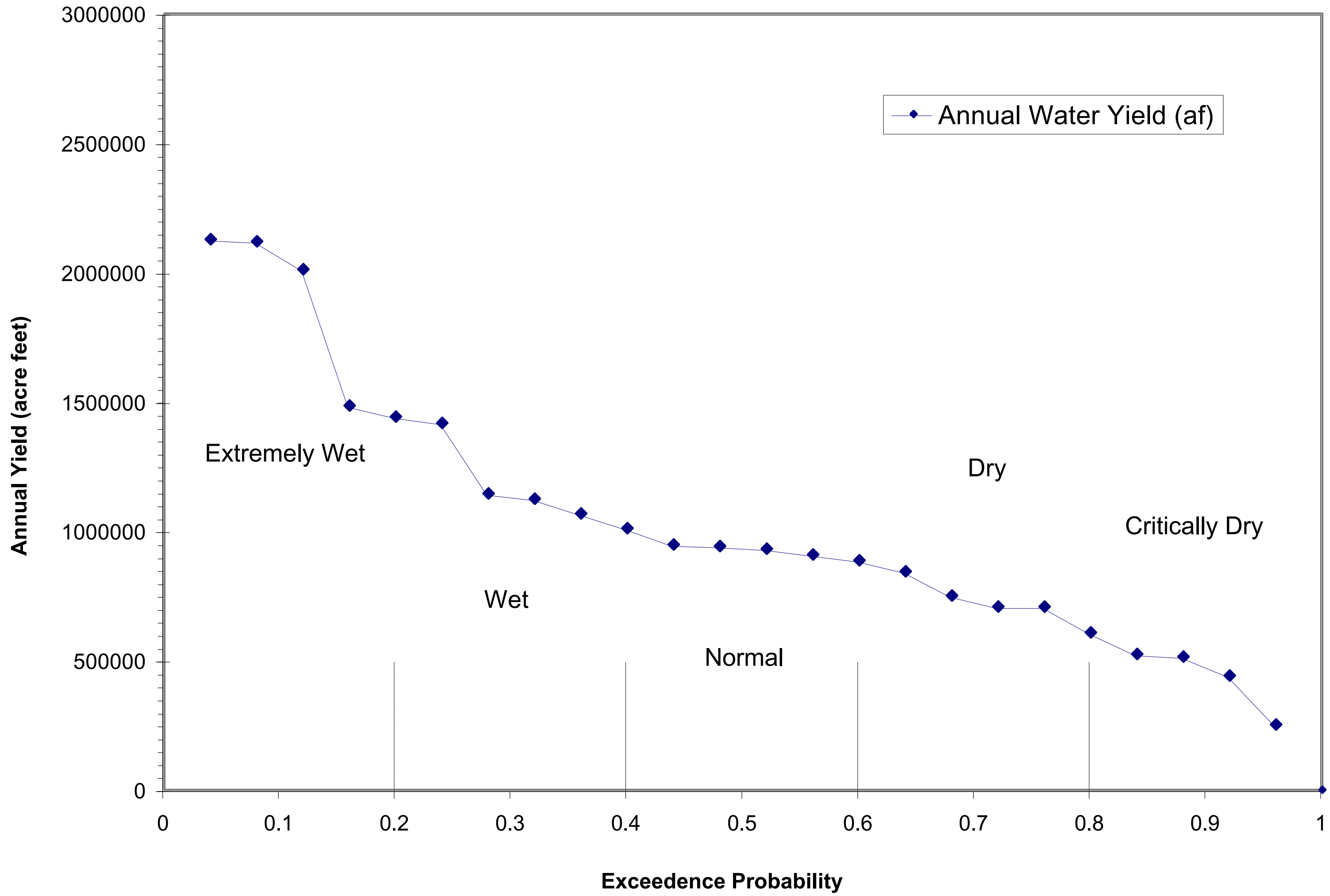
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

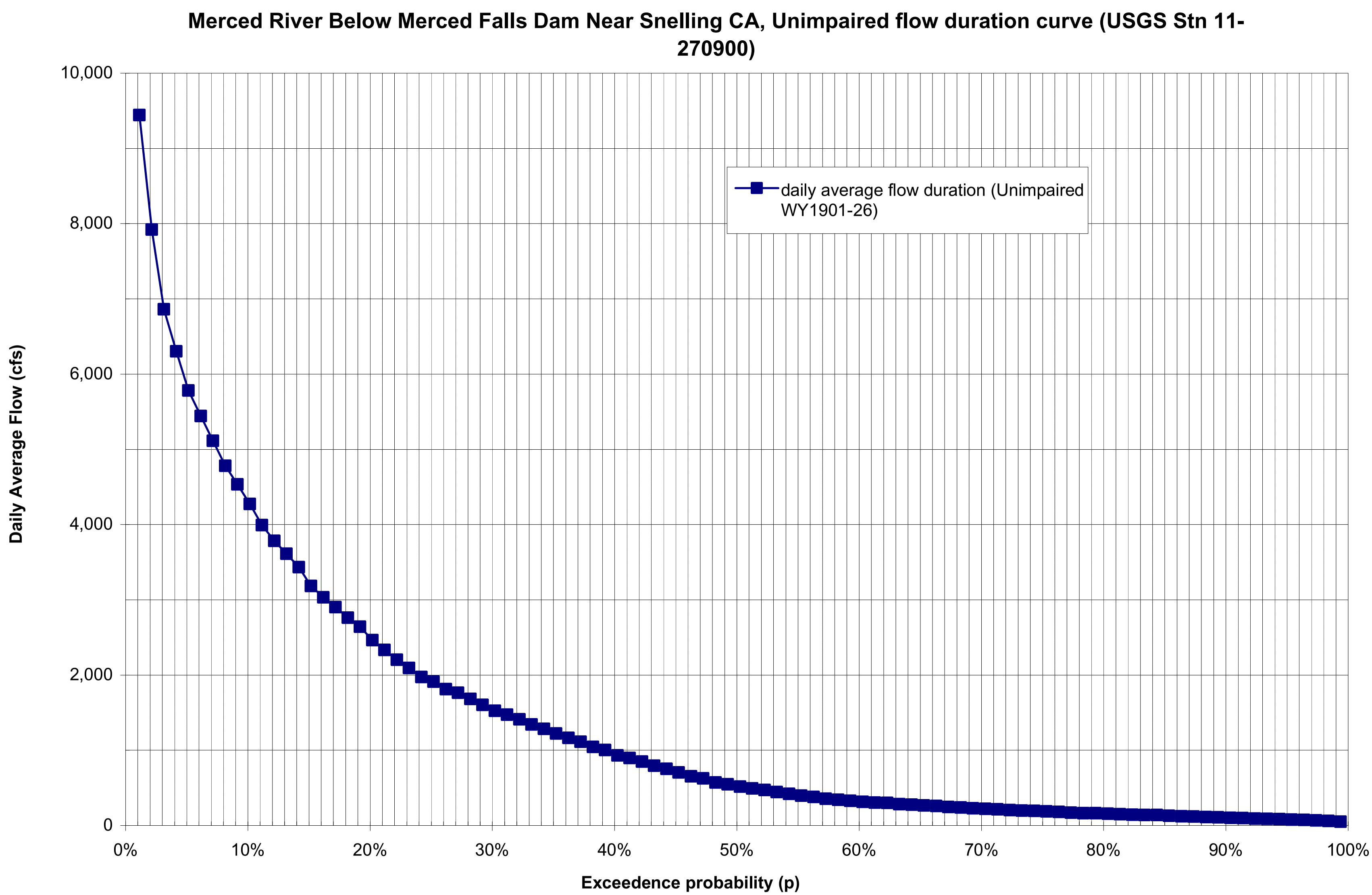
Merced River Below Merced Falls Dam Near Snelling CA, Unimpaired water yield 1901-1926 (USGS Stn 11-270900)

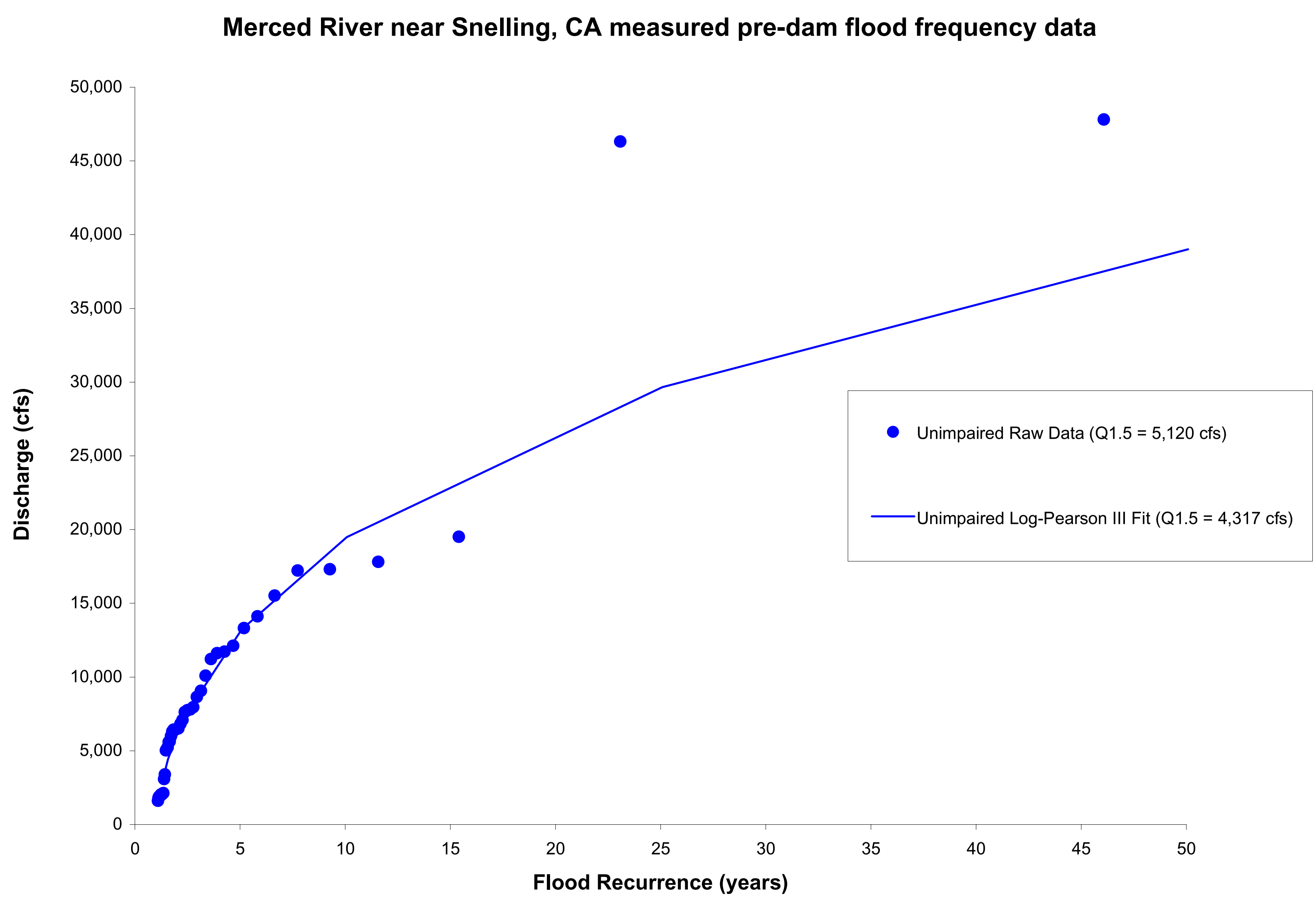
WATER YEAR	UNIMPAIRED ANNUAL WATER YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1901	931,388	NORMAL	52.0%	13
1902	750,726	DRY	68.0%	17
1903	947,302	NORMAL	44.0%	11
1904	1,144,463	WET	28.0%	7
1905	887,637	NORMAL	60.0%	15
1906	2,010,813	EXTREMELY WET	12.0%	3
1907	2,126,503	EXTREMELY WET	4.0%	1
1908	525,295	CRITICALLY DRY	84.0%	21
1909	1,484,138	EXTREMELY WET	16.0%	4
1910	1,067,859	WET	36.0%	9
1911	2,119,962	EXTREMELY WET	8.0%	2
1912	514,772	CRITICALLY DRY	88.0%	22
1913	440,395	CRITICALLY DRY	92.0%	23
1916	1,441,928	EXTREMELY WET	20.0%	5
1917	1,124,945	WET	32.0%	8
1918	843,755	DRY	64.0%	16
1919	708,670	DRY	72.0%	18
1920	708,540	DRY	76.0%	19
1921	1,011,156	WET	40.0%	10
1922	1,418,394	WET	24.0%	6
1923	942,016	NORMAL	48.0%	12
1924	251,814	CRITICALLY DRY	96.0%	24
1925	910,136	NORMAL	56.0%	14
1926	607,408	DRY	80.0%	20


Merced River Below Merced Falls Dam Near Snelling CA, unimpaired water yield (USGS Stn 11-270900)
Mean Annual Yield = 1,038,000 acre-ft
Annual Yield (acre-feet)
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1901
1902
1903
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
Water Year

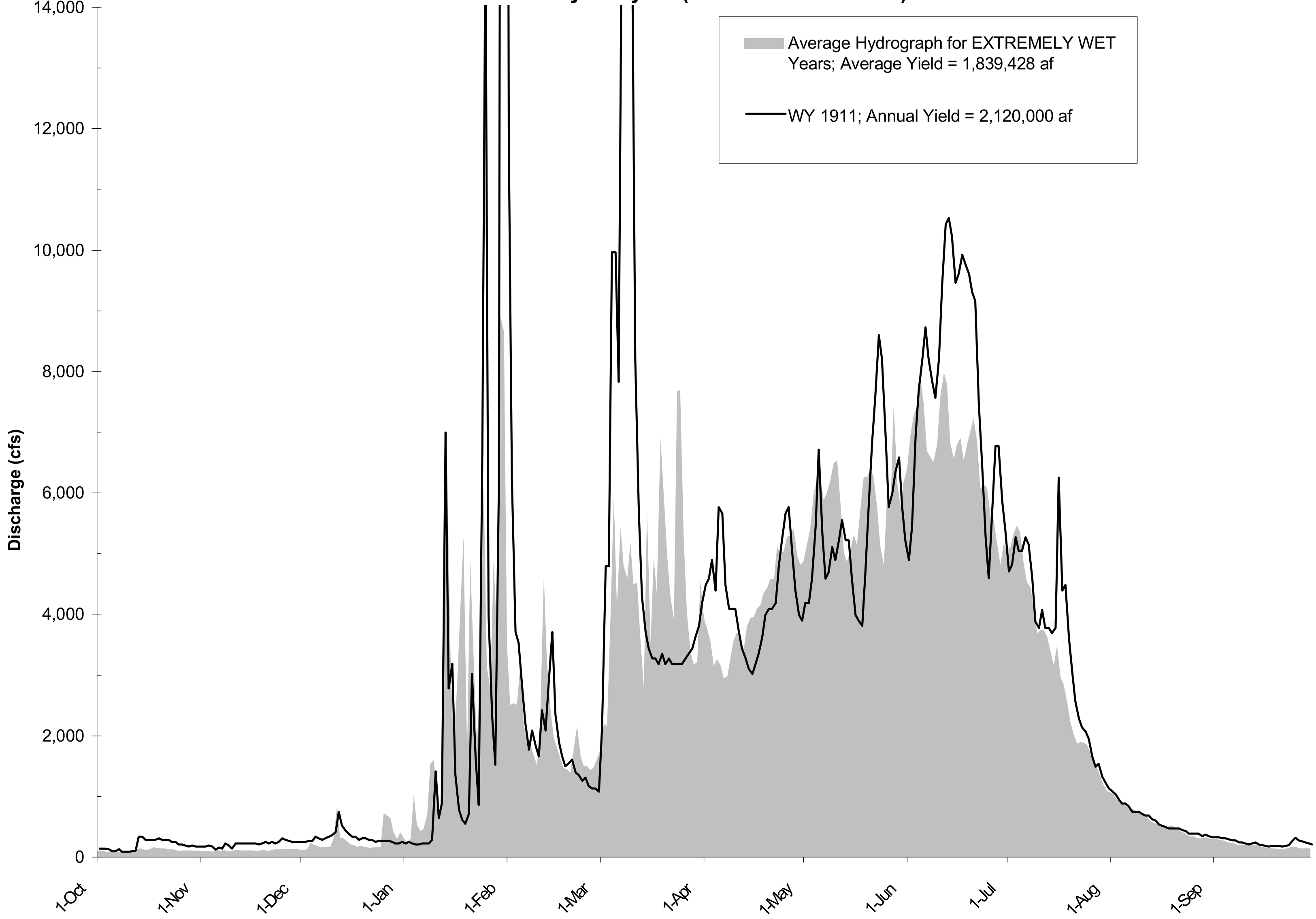
Merced River Below Merced Falls Dam Near Snelling CA, unimpaired water yield exceedance (USGS Stn 11-270900)



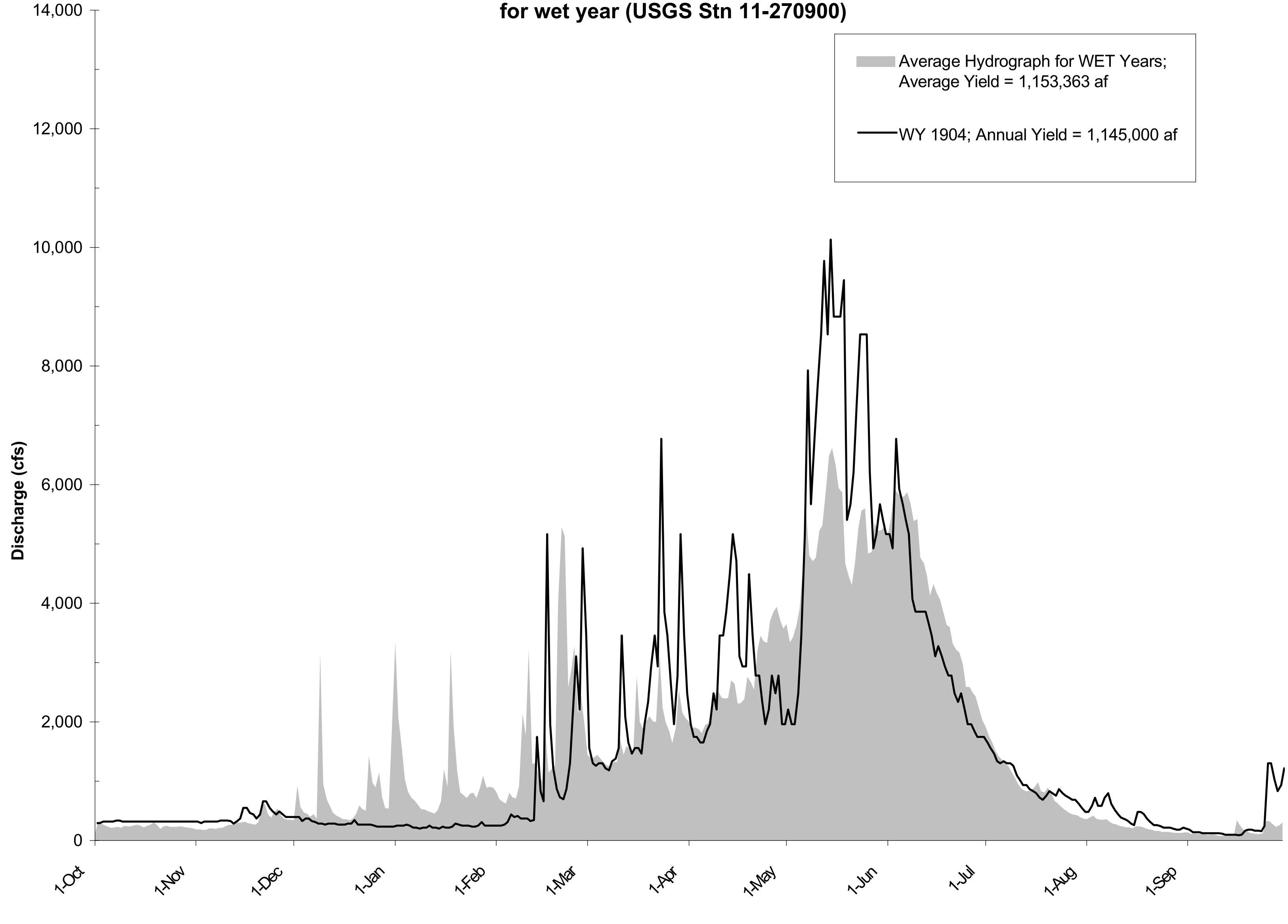

Merced River Below Merced Falls Dam Near Snelling CA, Unimpaired flow duration curve (USGS Stn 11-270900)
daily average flow duration (Unimpaired WY1901-26)
Daily Average Flow (cfs)
10,000
8,000
6,000
4,000
2,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Exceedence probability (p)


Merced River near Snelling, CA measured pre-dam flood frequency data
Discharge (cfs)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0
5
10
15
20
25
30
35
40
45
50
Flood Recurrence (years)
Unimpaired Raw Data (Q1.5 = 5,120 cfs)
Unimpaired Log-Pearson III Fit (Q1.5 = 4,317 cfs)

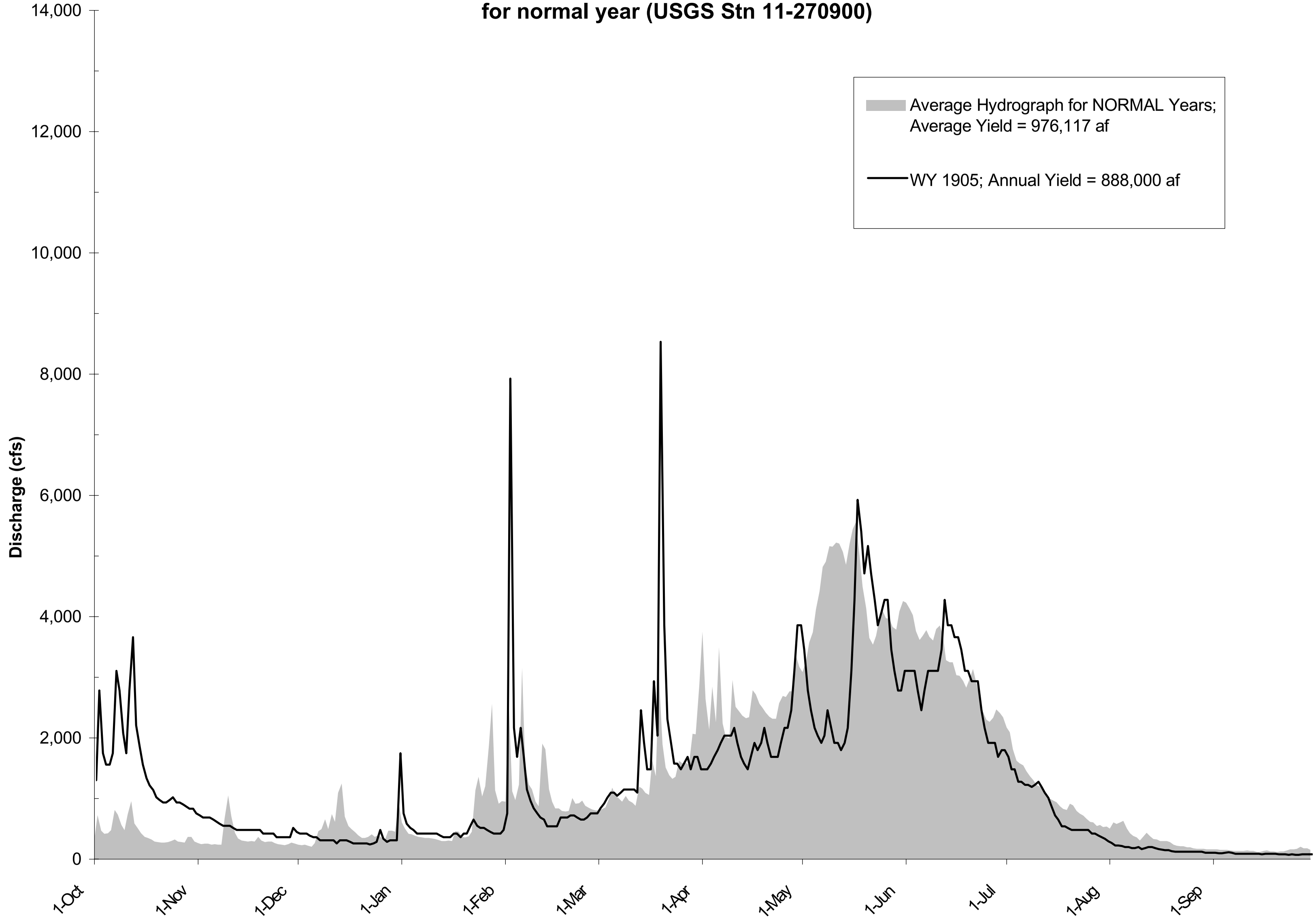
Merced River Below Merced Falls Dam Near Snelling CA, representative and average annual hydrograph for extremely wet year (USGS Stn 11-270900)



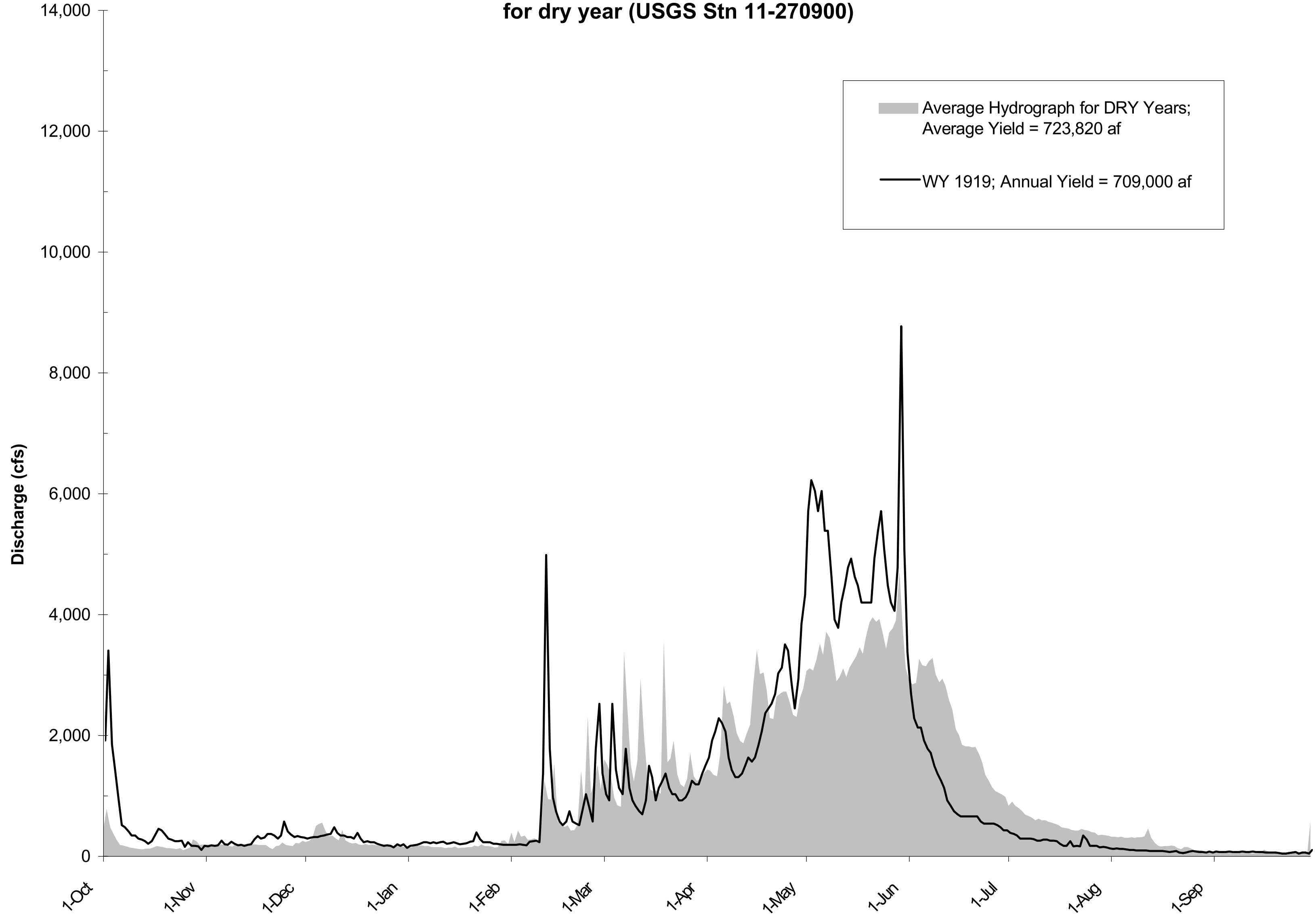
Merced River Below Merced Falls Dam Near Snelling CA, representative and average annual hydrograph for wet year (USGS Stn 11-270900)



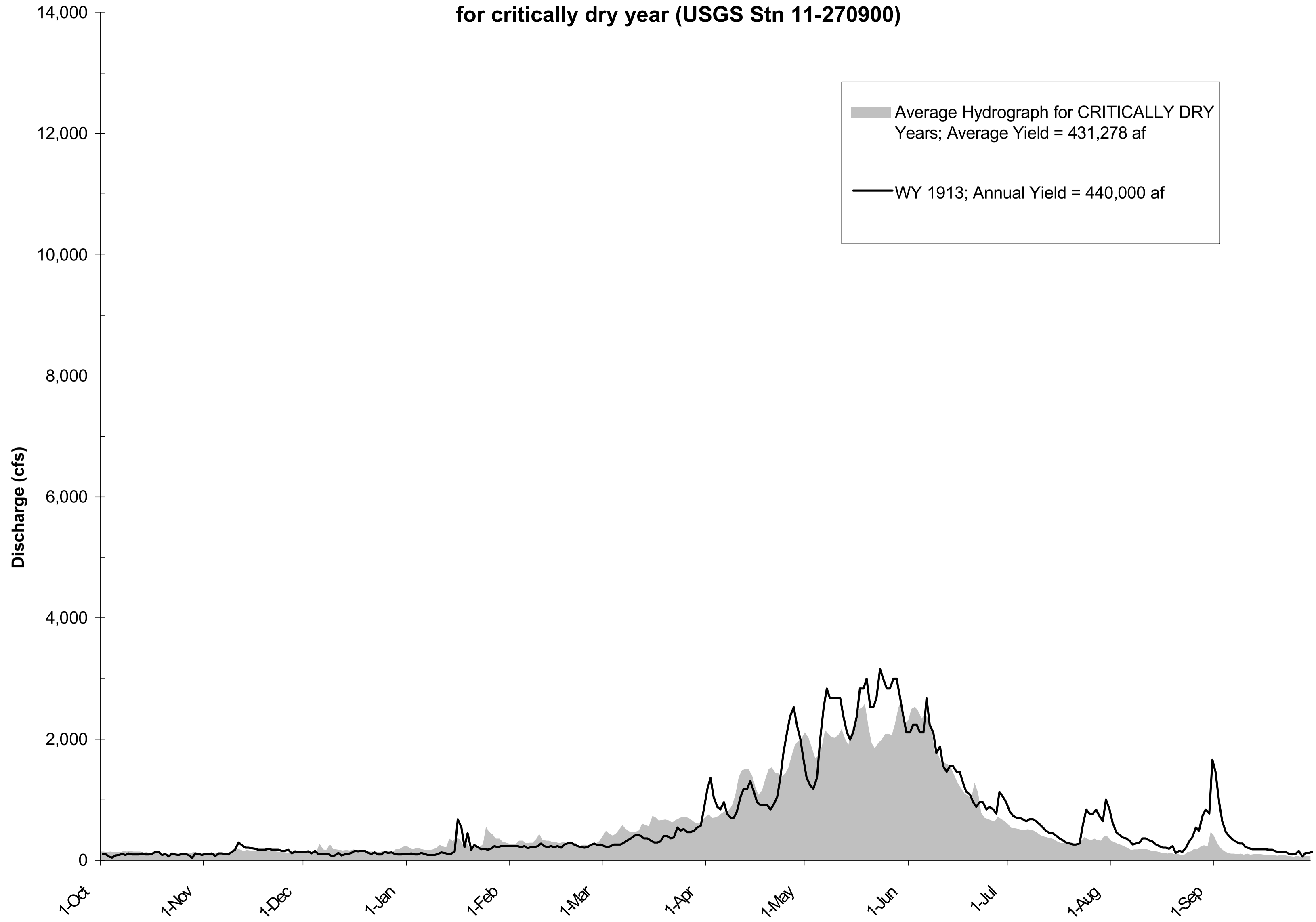
Merced River Below Merced Falls Dam Near Snelling CA, representative and average annual hydrograph for normal year (USGS Stn 11-270900)

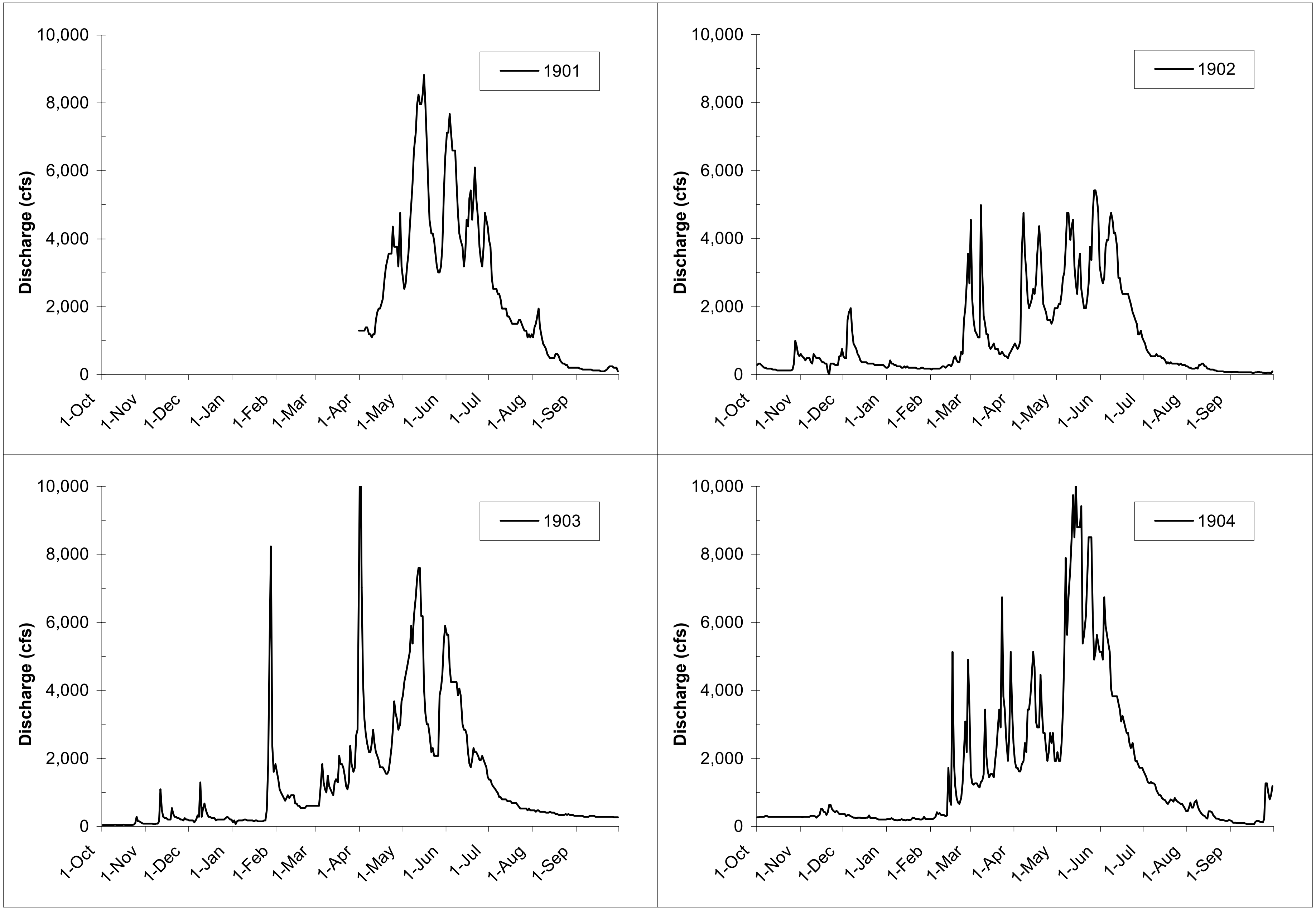


Merced River Below Merced Falls Dam Near Snelling CA, representative and average annual hydrograph for dry year (USGS Stn 11-270900)

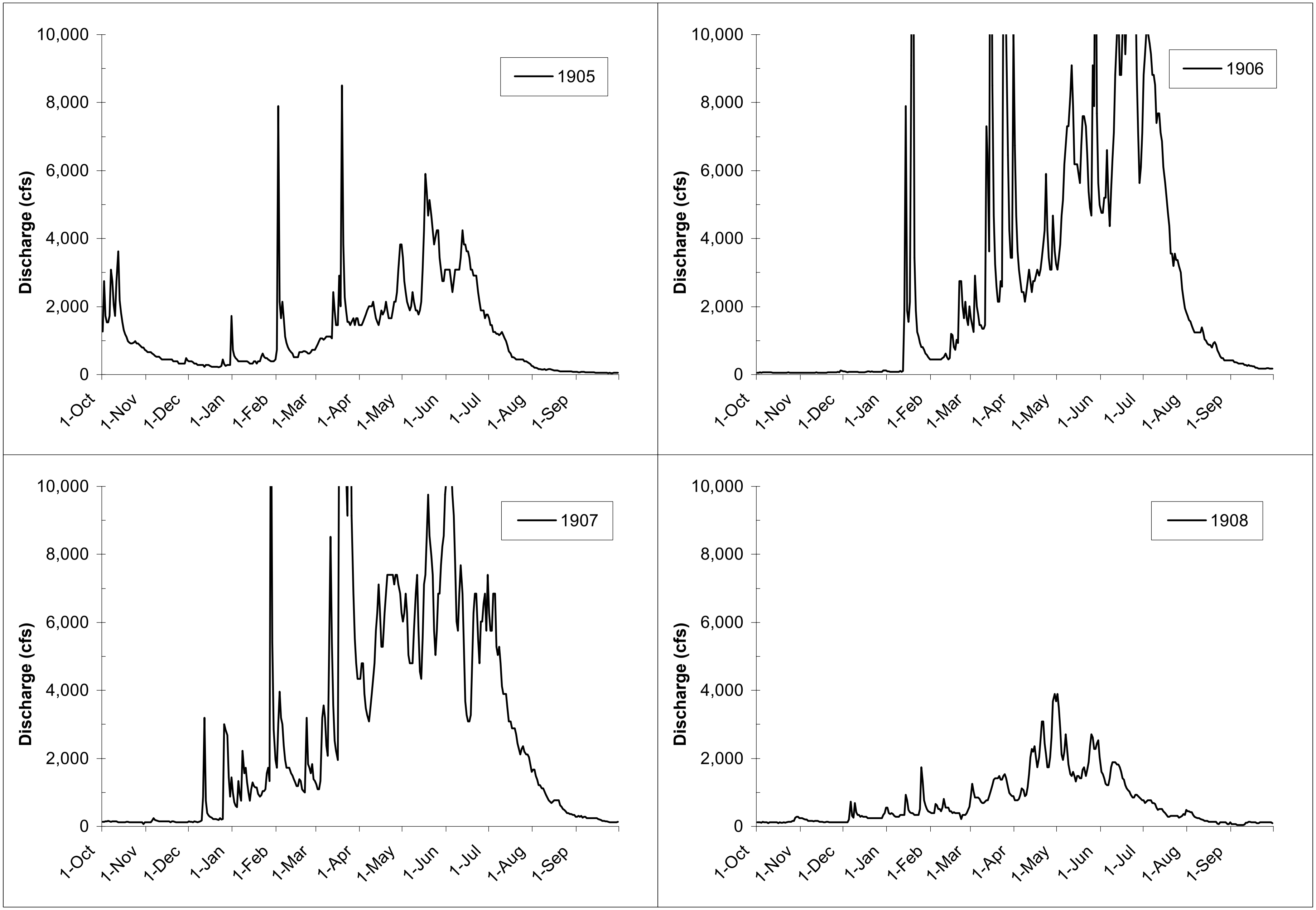


Merced River Below Merced Falls Dam Near Snelling CA, representative and average annual hydrograph for critically dry year (USGS Stn 11-270900)

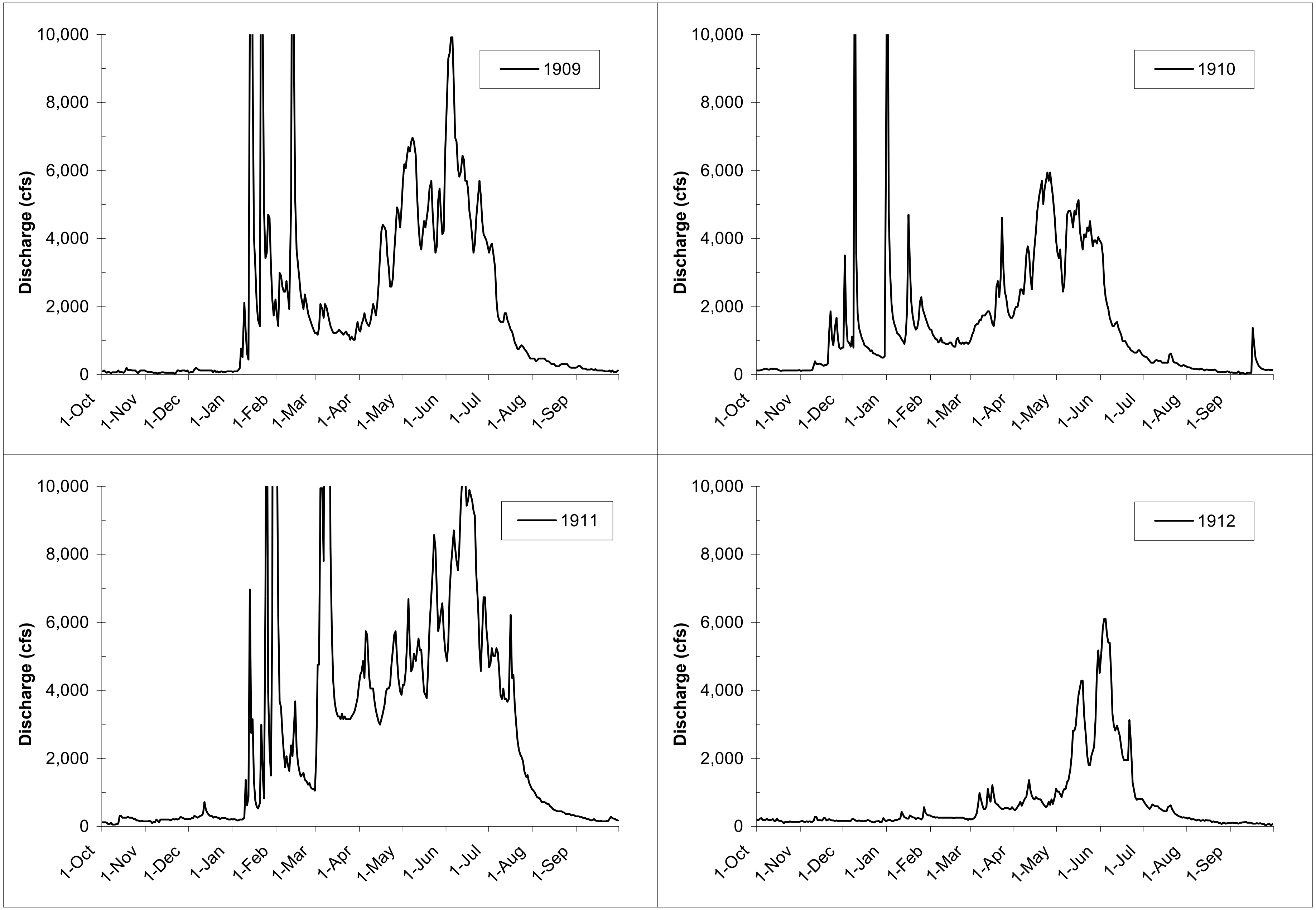




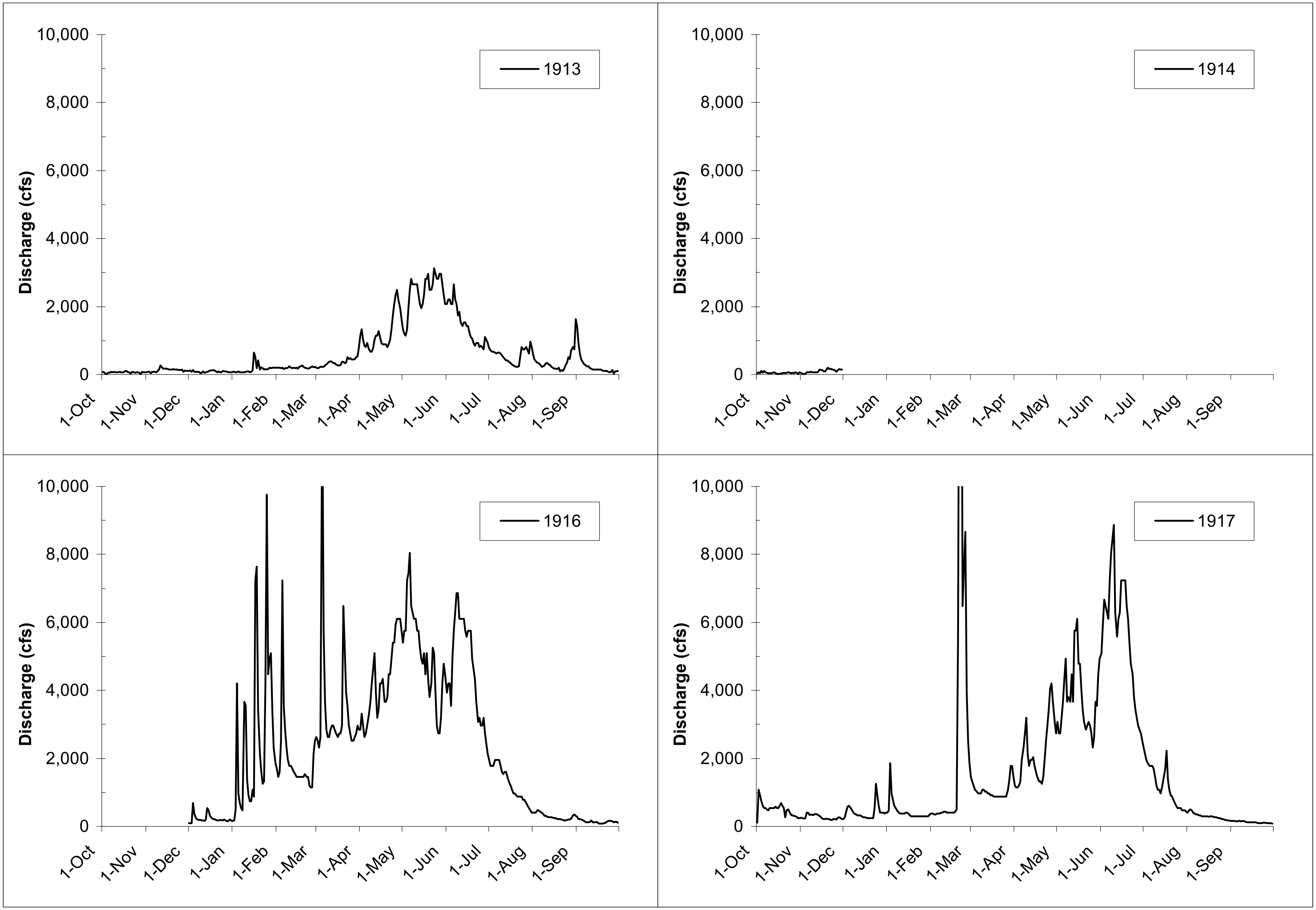
Merced River blw Merced Falls Dam Near Snelling CA, UNIMPAIRED hydrographs for WY1901-1926 (USGS Stn 11-270900)



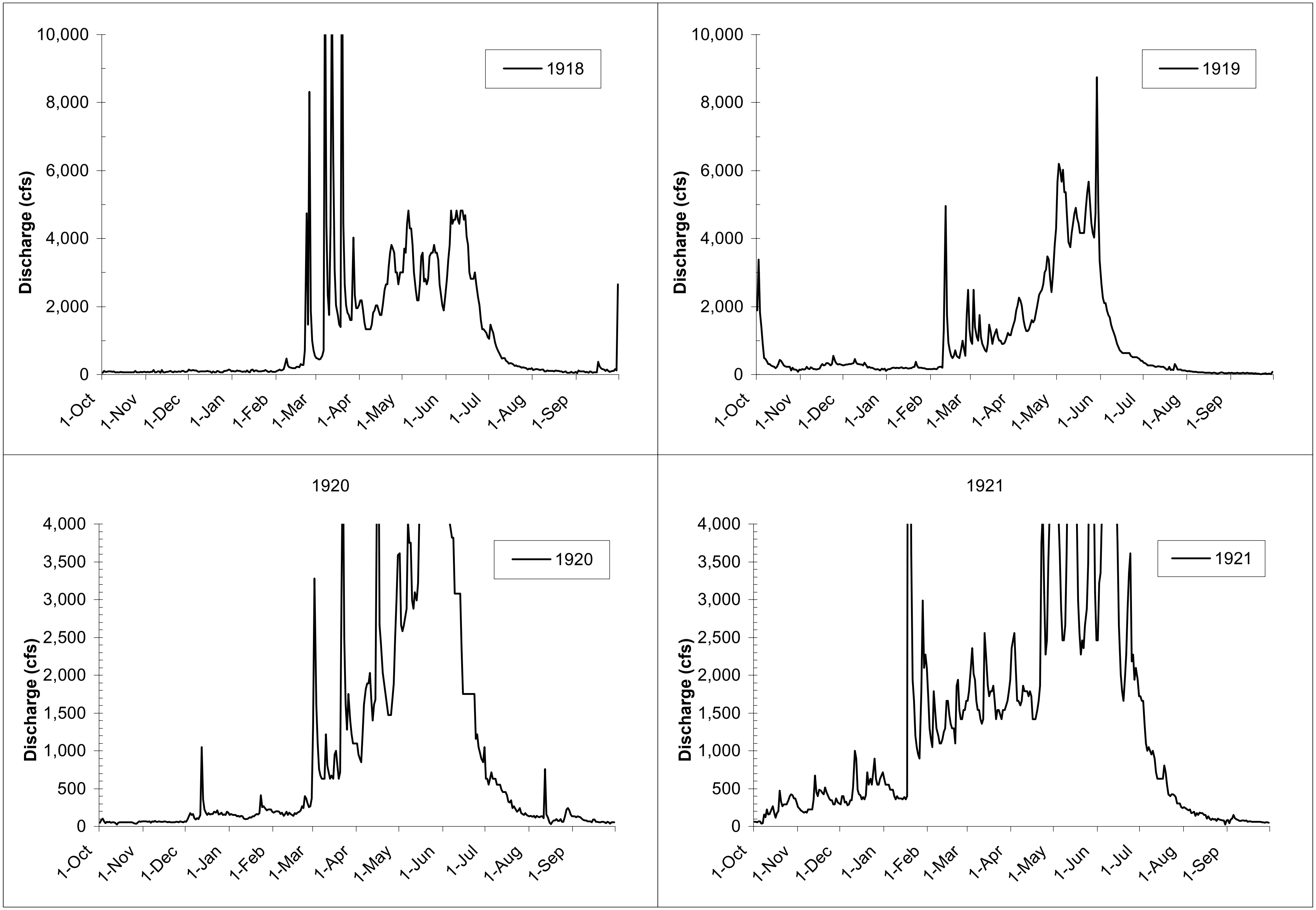
Merced River blw Merced Falls Dam Near Snelling CA, UNIMPAIRED hydrographs for WY1901-1926 (USGS Stn 11-270900)



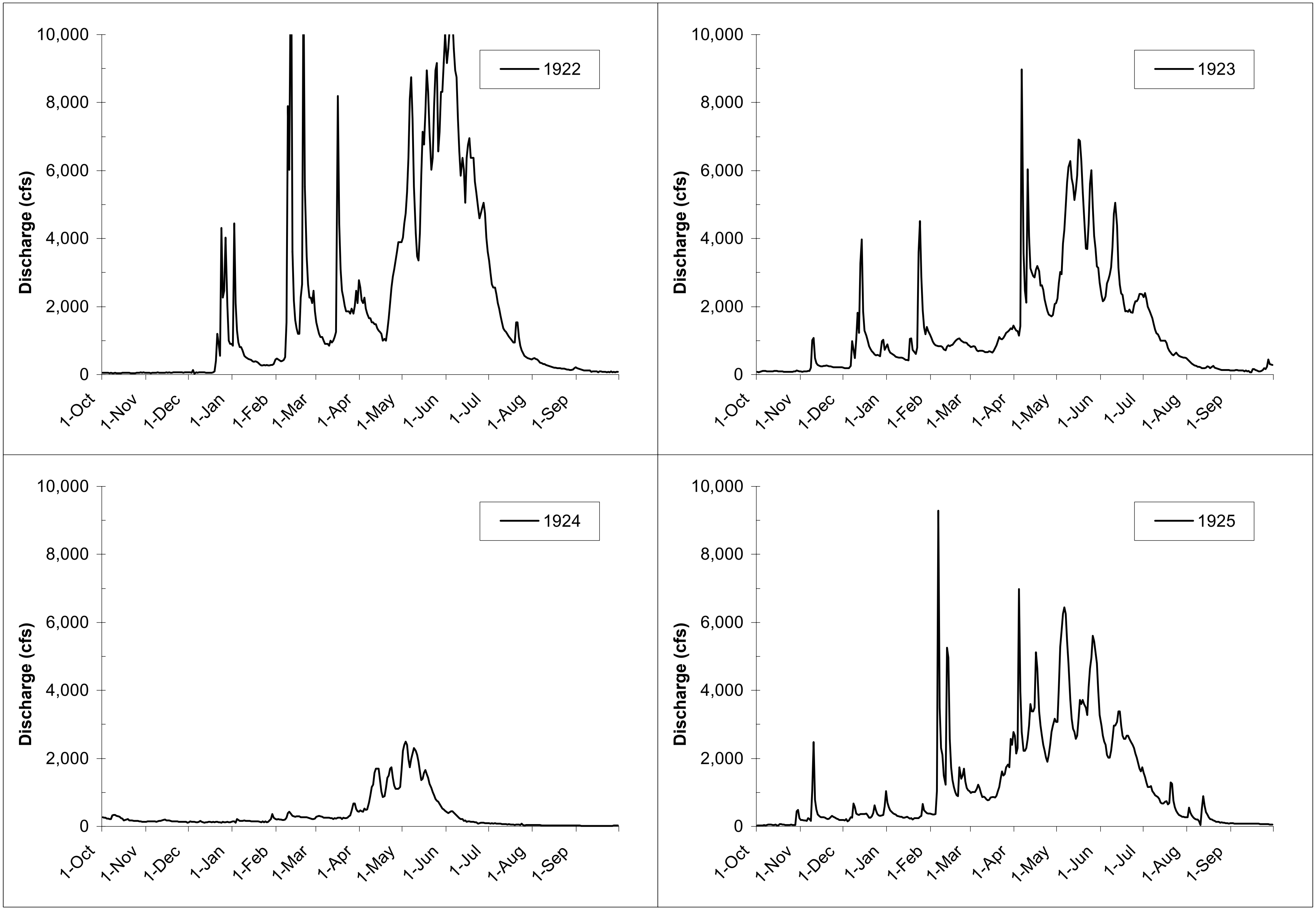
Merced River blw Merced Falls Dam Near Snelling CA, UNIMPAIRED hydrographs for WY1901-1926 (USGS Stn 11-270900)



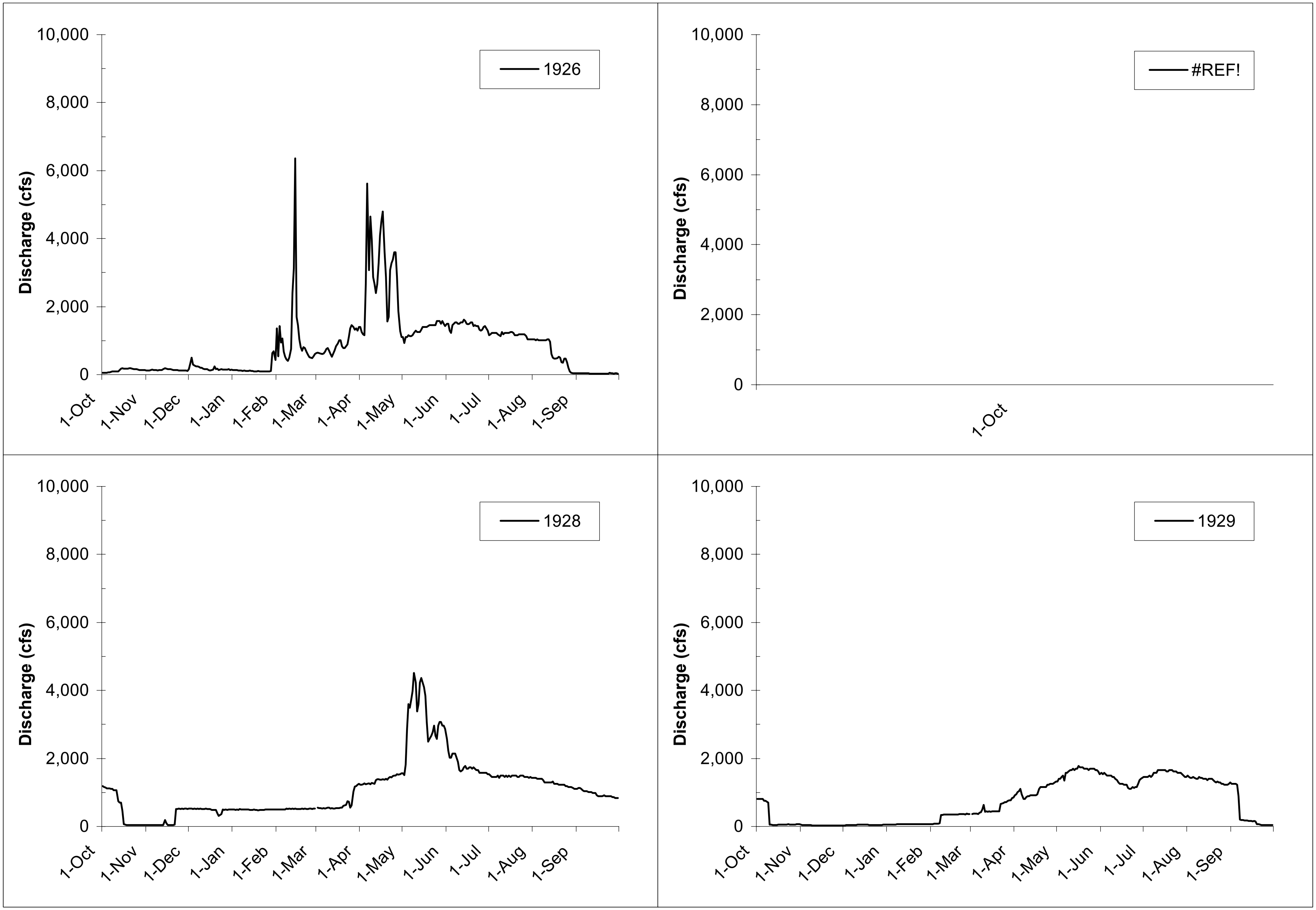
Merced River blw Merced Falls Dam Near Snelling CA, UNIMPAIRED hydrographs for WY1901-1926 (USGS Stn 11-270900)



Merced River blw Merced Falls Dam Near Snelling CA, UNIMPAIRED hydrographs for WY1901-1926 (USGS Stn 11-270900)



Merced River Below Merced Falls Dam Near Snelling CA, Unimpaired (USGS Stn 11-270900)



Merced River Below Merced Falls Dam Near Snelling CA, Unimpaired Through 1926 (USGS Stn 11-270900)

APPENDIX D.

REGULATED HYDROLOGIC DATA FOR THE

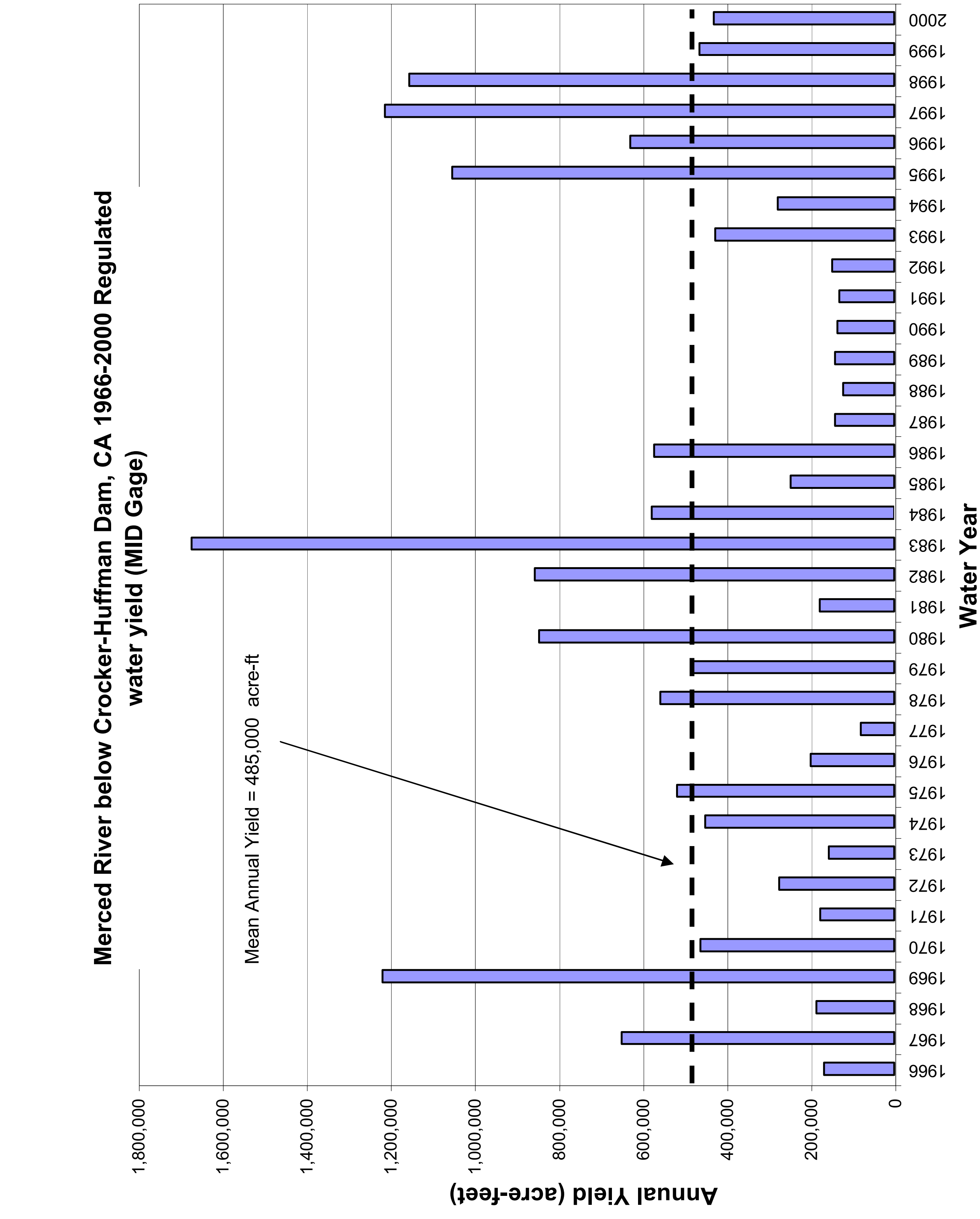
- MERCED RIVER

INCLUDING:

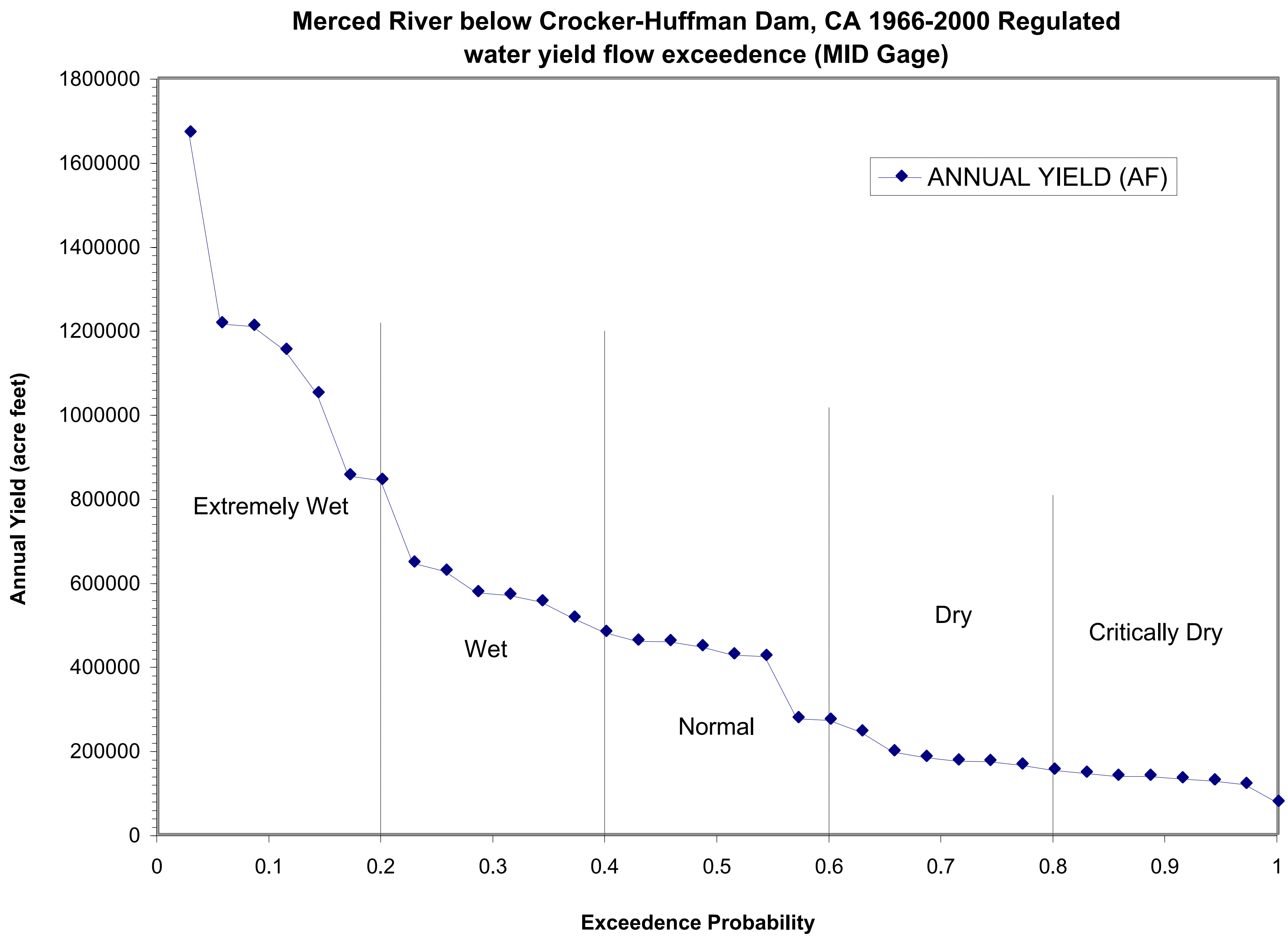
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

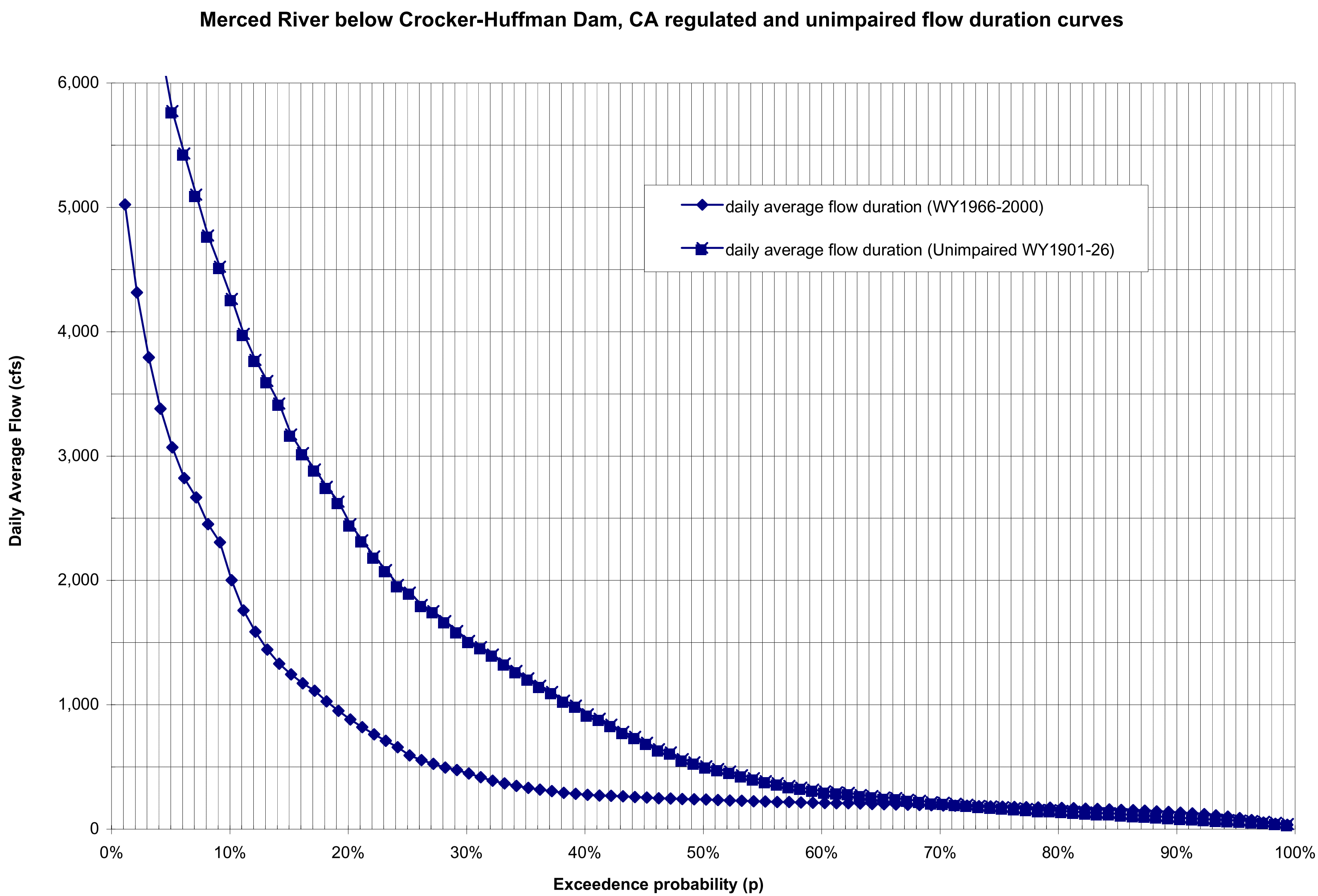
Merced River below Crocker-Huffman Dam, CA 1966-2000 (Regulated) (MID Gage)

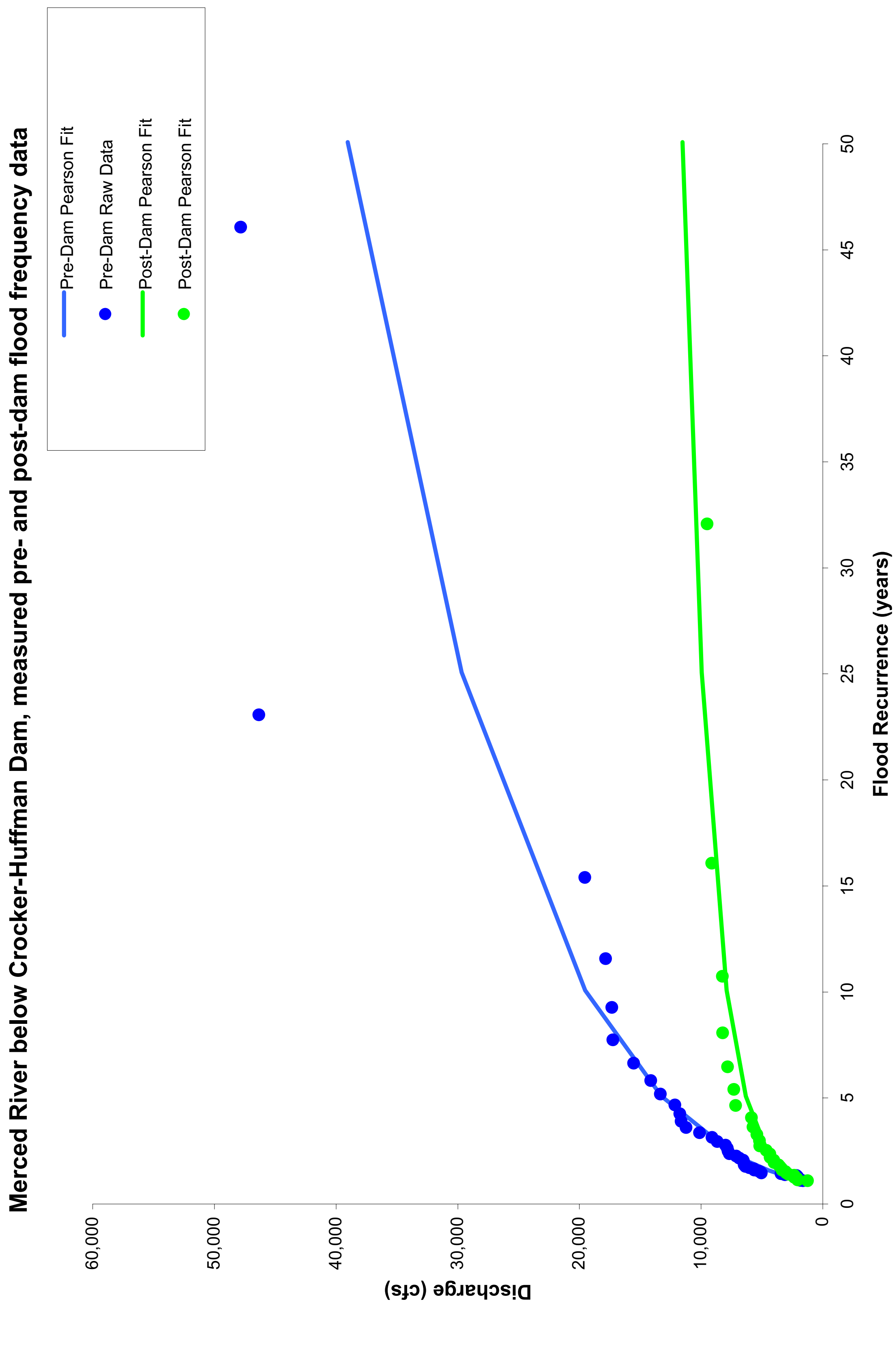
WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1966	166,909	DRY	77.1%	27
1967	648,014	WET	22.9%	8
1968	185,324	DRY	68.6%	24
1969	1,217,915	EXTREMELY WET	5.7%	2
1970	461,347	NORMAL	45.7%	16
1971	176,325	DRY	74.3%	26
1972	274,126	NORMAL	60.0%	21
1973	155,883	DRY	80.0%	28
1974	449,300	NORMAL	48.6%	17
1975	516,486	WET	37.1%	13
1976	198,895	DRY	65.7%	23
1977	78,932	CRITICALLY DRY	100.0%	35
1978	556,278	WET	34.3%	12
1979	483,570	WET	40.0%	14
1980	845,167	EXTREMELY WET	20.0%	7
1981	177,483	DRY	71.4%	25
1982	855,449	EXTREMELY WET	17.1%	6
1983	1,671,221	EXTREMELY WET	2.9%	1
1984	577,337	WET	28.6%	10
1985	246,222	DRY	62.9%	22
1986	571,575	WET	31.4%	11
1987	140,842	CRITICALLY DRY	85.7%	30
1988	121,263	CRITICALLY DRY	97.1%	34
1989	140,392	CRITICALLY DRY	88.6%	31
1990	134,705	CRITICALLY DRY	91.4%	32
1991	130,149	CRITICALLY DRY	94.3%	33
1992	147,901	CRITICALLY DRY	82.9%	29
1993	425,887	NORMAL	54.3%	19
1994	277,369	NORMAL	57.1%	20
1995	1,051,636	EXTREMELY WET	14.3%	5
1996	628,122	WET	25.7%	9
1997	1,211,786	EXTREMELY WET	8.6%	3
1998	1,154,225	EXTREMELY WET	11.4%	4
1999	463,018	NORMAL	42.9%	15
2000	429,425	NORMAL	51.4%	18

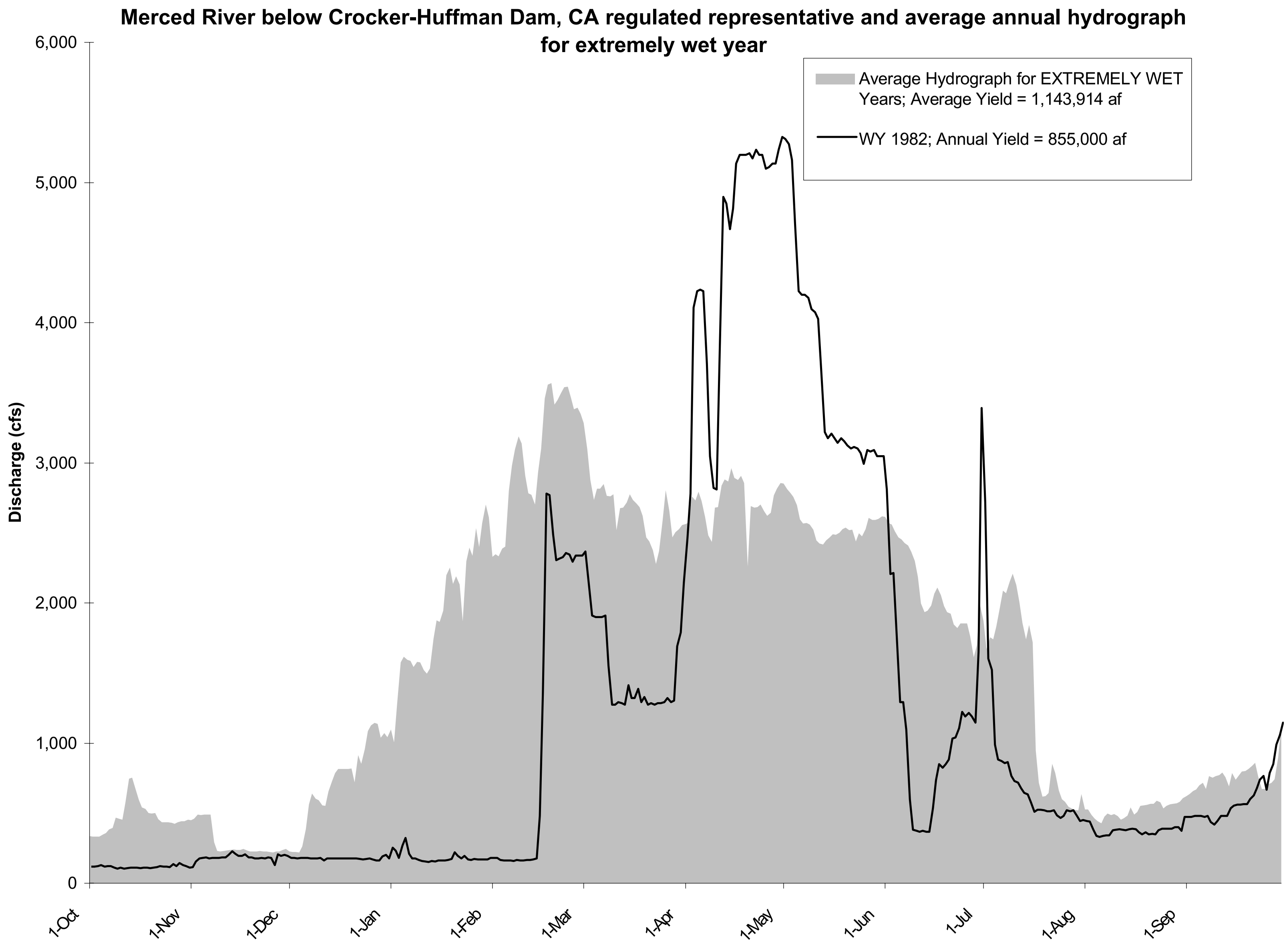


Merced River below Crocker-Huffman Dam, CA 1966-2000 Regulated water yield (MID Gage)
Mean Annual Yield = 485,000 acre-ft
Annual Yield (acre-feet)
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
1,400,000
1,600,000
1,800,000
Water Year
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000

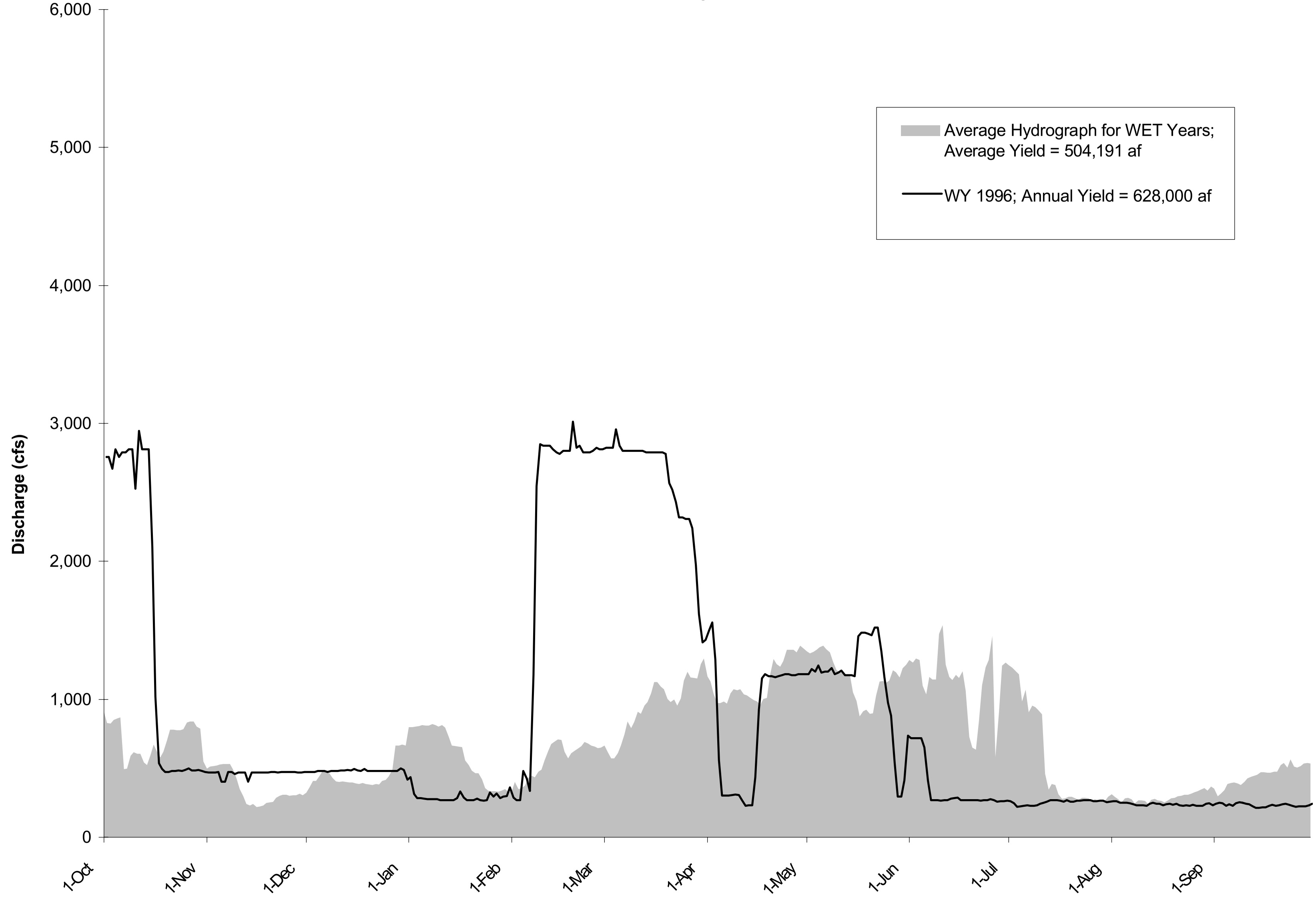

Merced River below Crocker-Huffman Dam, CA 1966-2000 Regulated water yield flow exceedence (MID Gage)
ANNUAL YIELD (AF)
Extremely Wet
Wet
Normal
Dry
Critically Dry
Annual Yield (acre feet)
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Exceedence Probability

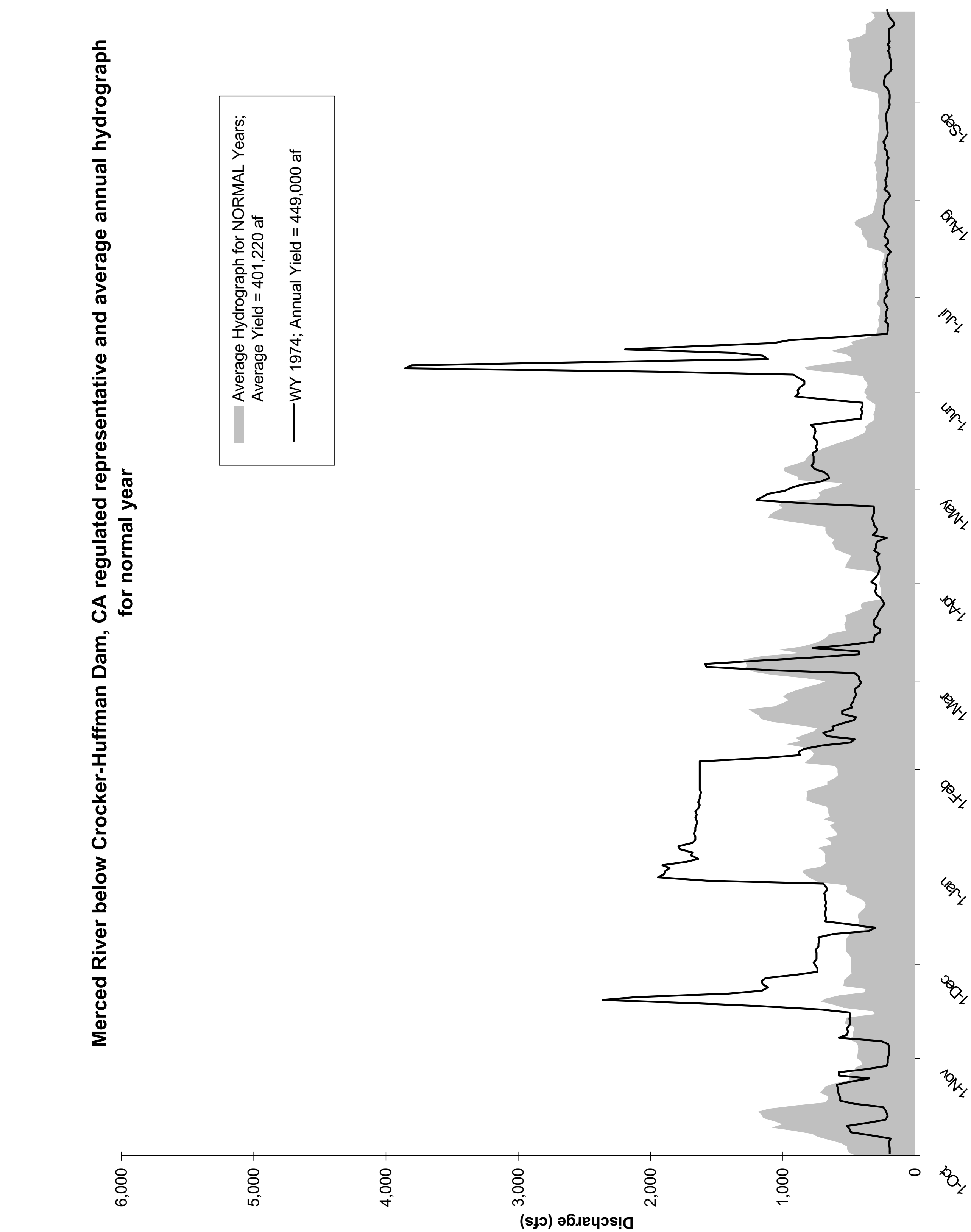

Merced River below Crocker-Huffman Dam, CA regulated and unimpaired flow duration curves
6,000
5,000
4,000
3,000
2,000
1,000
0
Daily Average Flow (cfs)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Exceedence probability (p)
daily average flow duration (WY1966-2000)
daily average flow duration (Unimpaired WY1901-26)


Merced River below Crocker-Huffman Dam, measured pre- and post-dam flood frequency data
Pre-Dam Pearson Fit
Pre-Dam Raw Data
Post-Dam Pearson Fit
Post-Dam Pearson Fit
Discharge (cfs)
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5
10
15
20
25
30
35
40
45
50
Flood Recurrence (years)

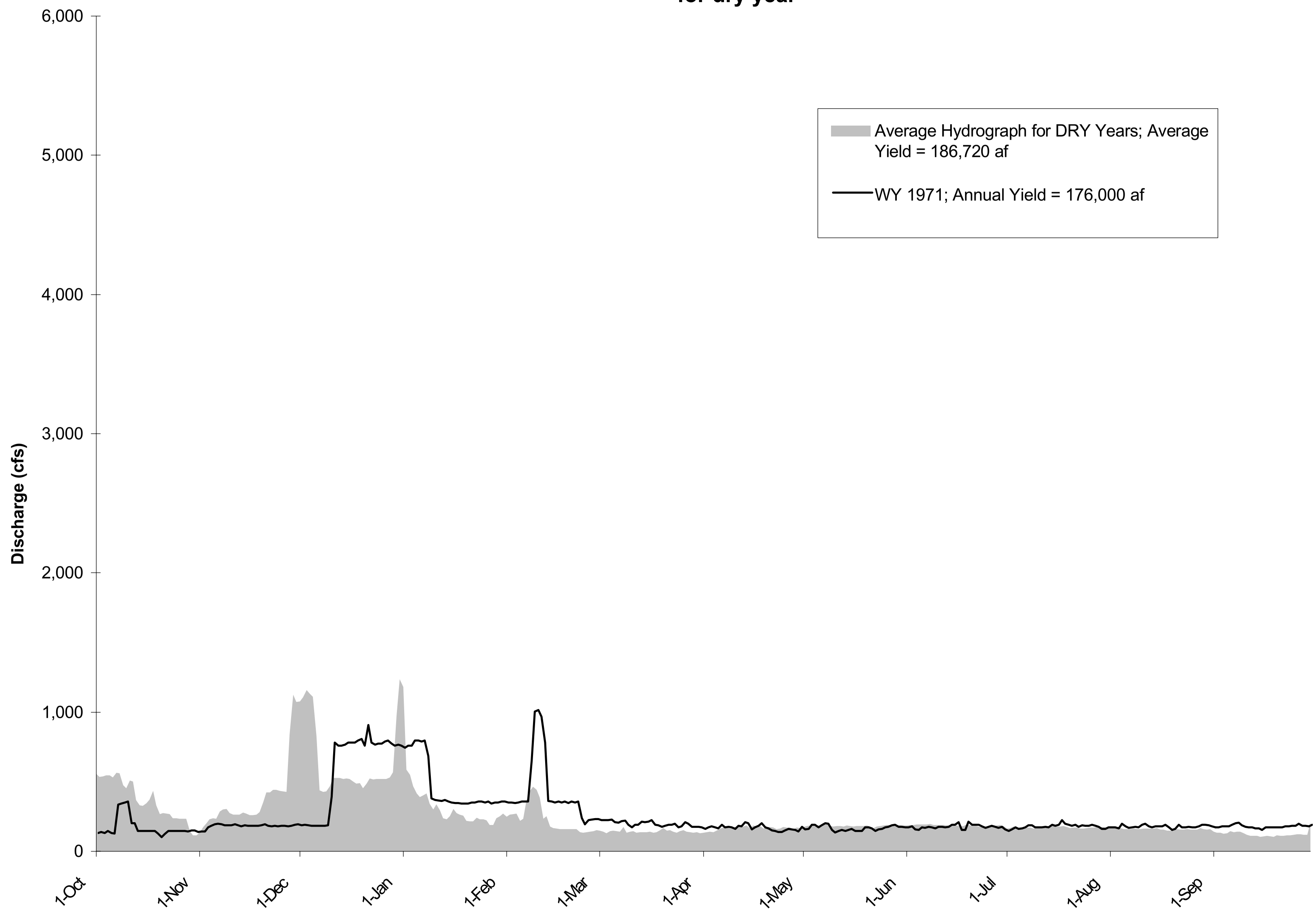

Merced River below Crocker-Huffman Dam, CA regulated representative and average annual hydrograph
for extremely wet year
Average Hydrograph for EXTREMELY WET Years; Average Yield = 1,143,914 af
WY 1982; Annual Yield = 855,000 af
Discharge (cfs)
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

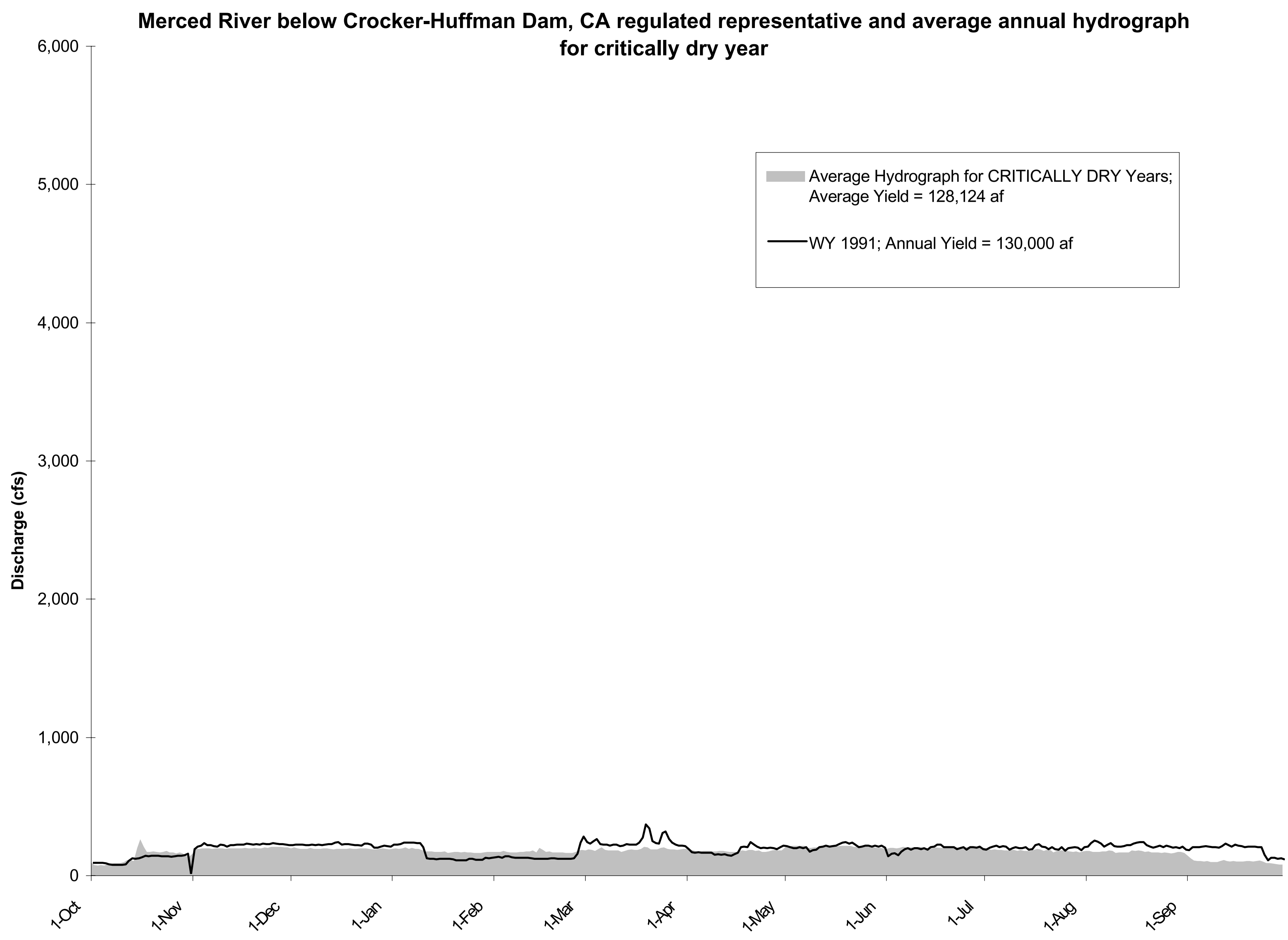
Merced River below Crocker-Huffman Dam, CA regulated representative and average annual hydrograph for wet year

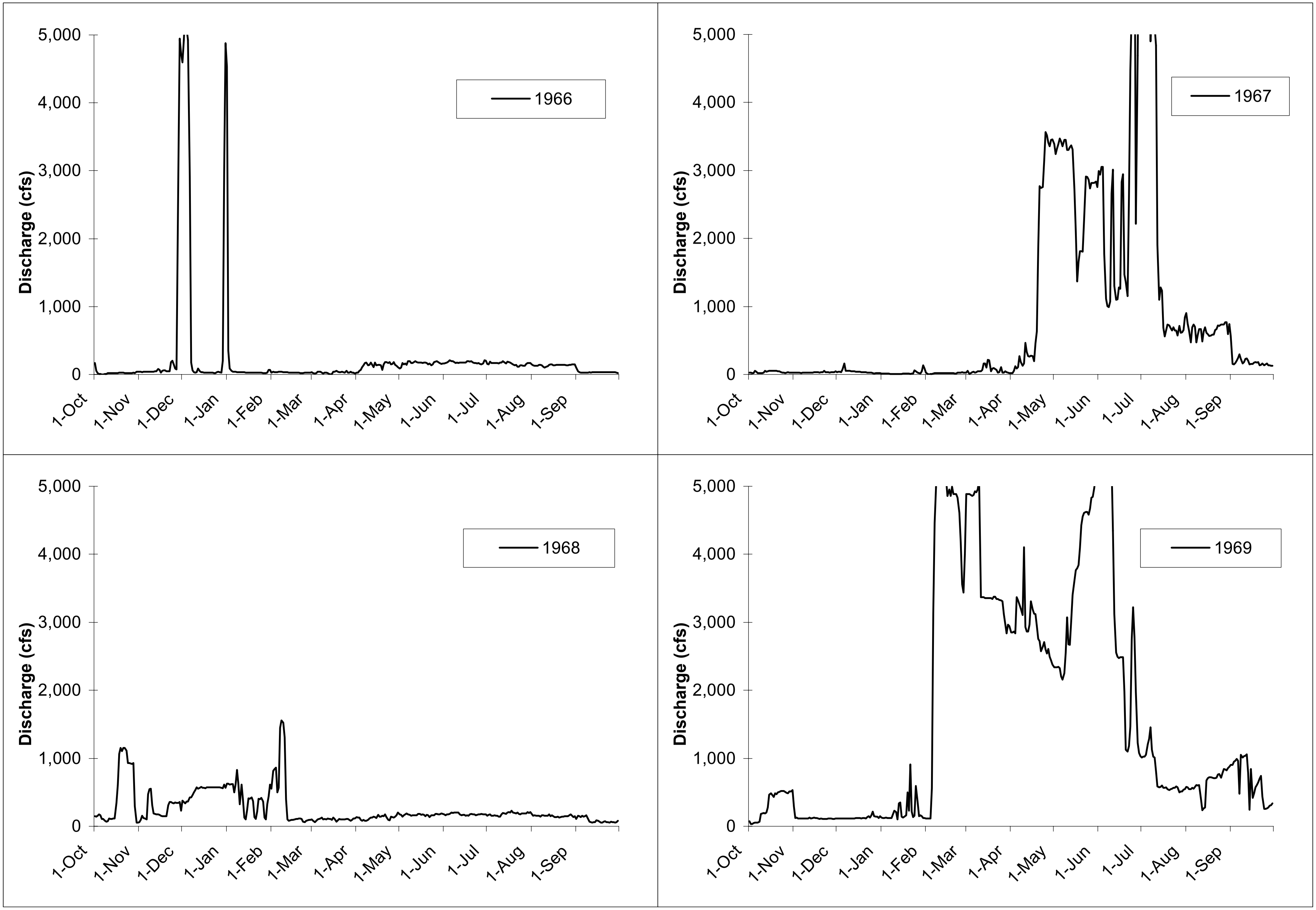



Merced River below Crocker-Huffman Dam, CA regulated representative and average annual hydrograph for normal year
Average Hydrograph for NORMAL Years; Average Yield = 401,220 af
WY 1974; Annual Yield = 449,000 af
Discharge (cfs)
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

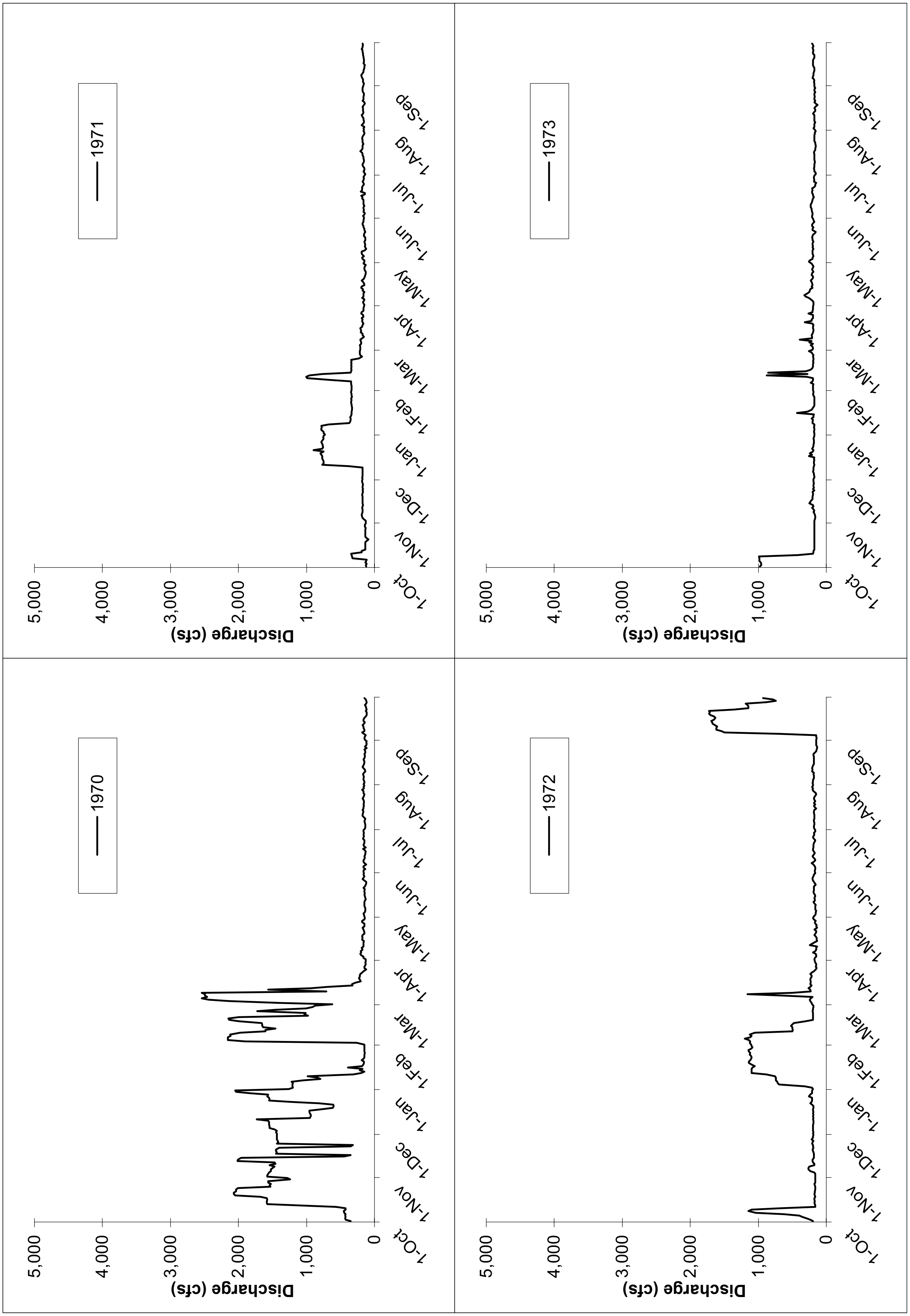
Merced River below Crocker-Huffman Dam, CA regulated representative and average annual hydrograph for dry year



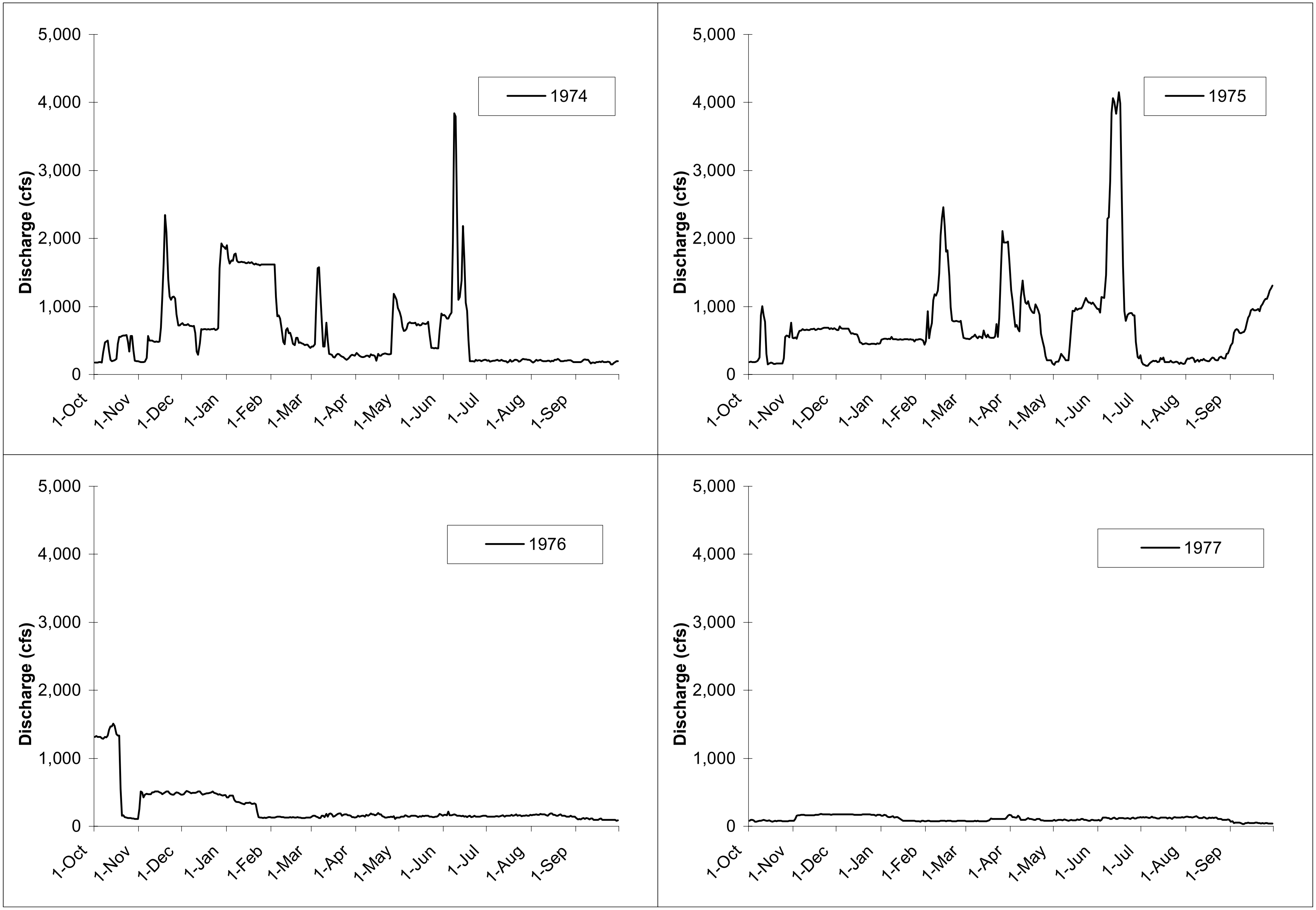

Merced River below Crocker-Huffman Dam, CA regulated representative and average annual hydrograph
for critically dry year
Discharge (cfs)
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Average Hydrograph for CRITICALLY DRY Years;
Average Yield = 128,124 af
WY 1991; Annual Yield = 130,000 af



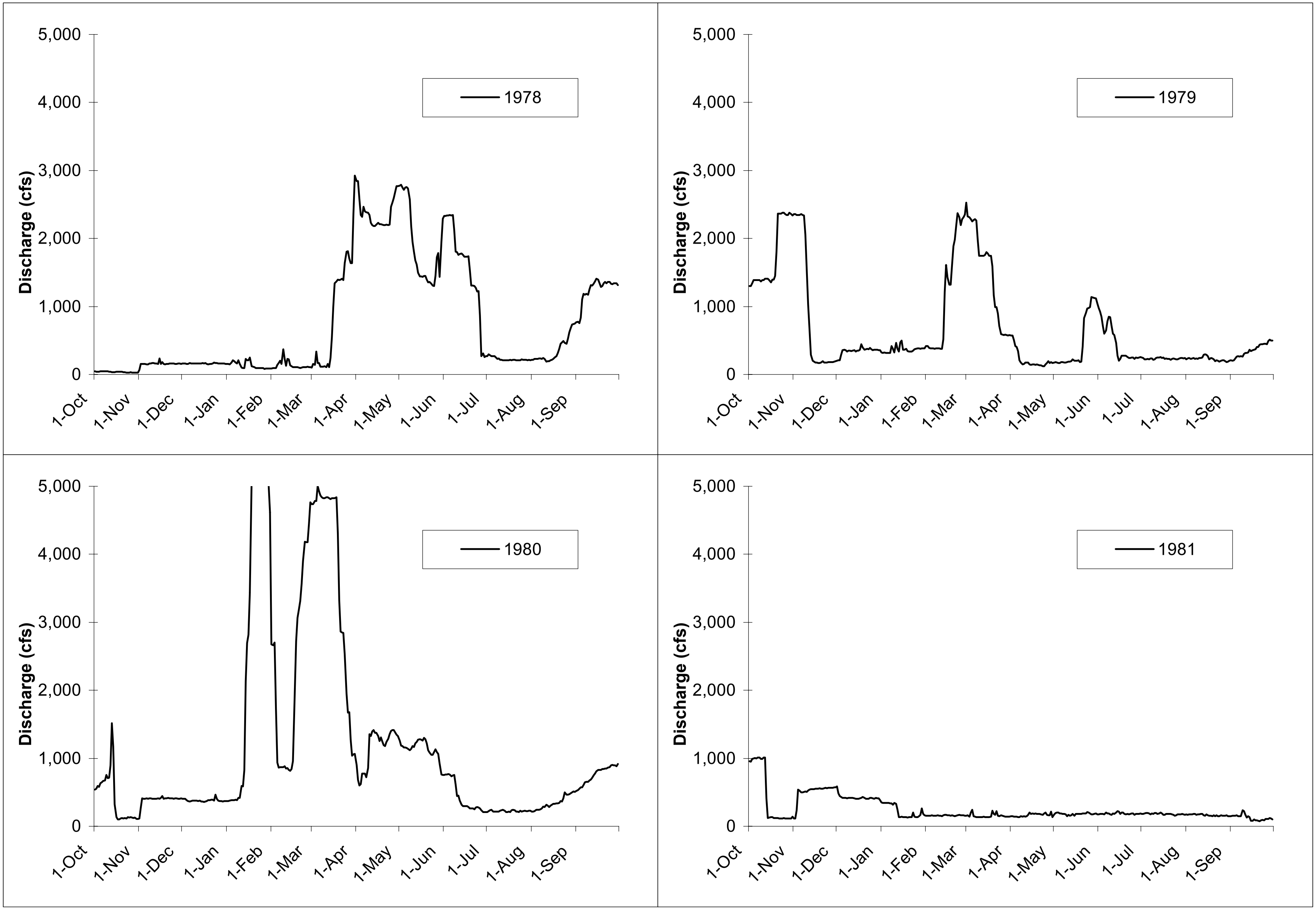
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



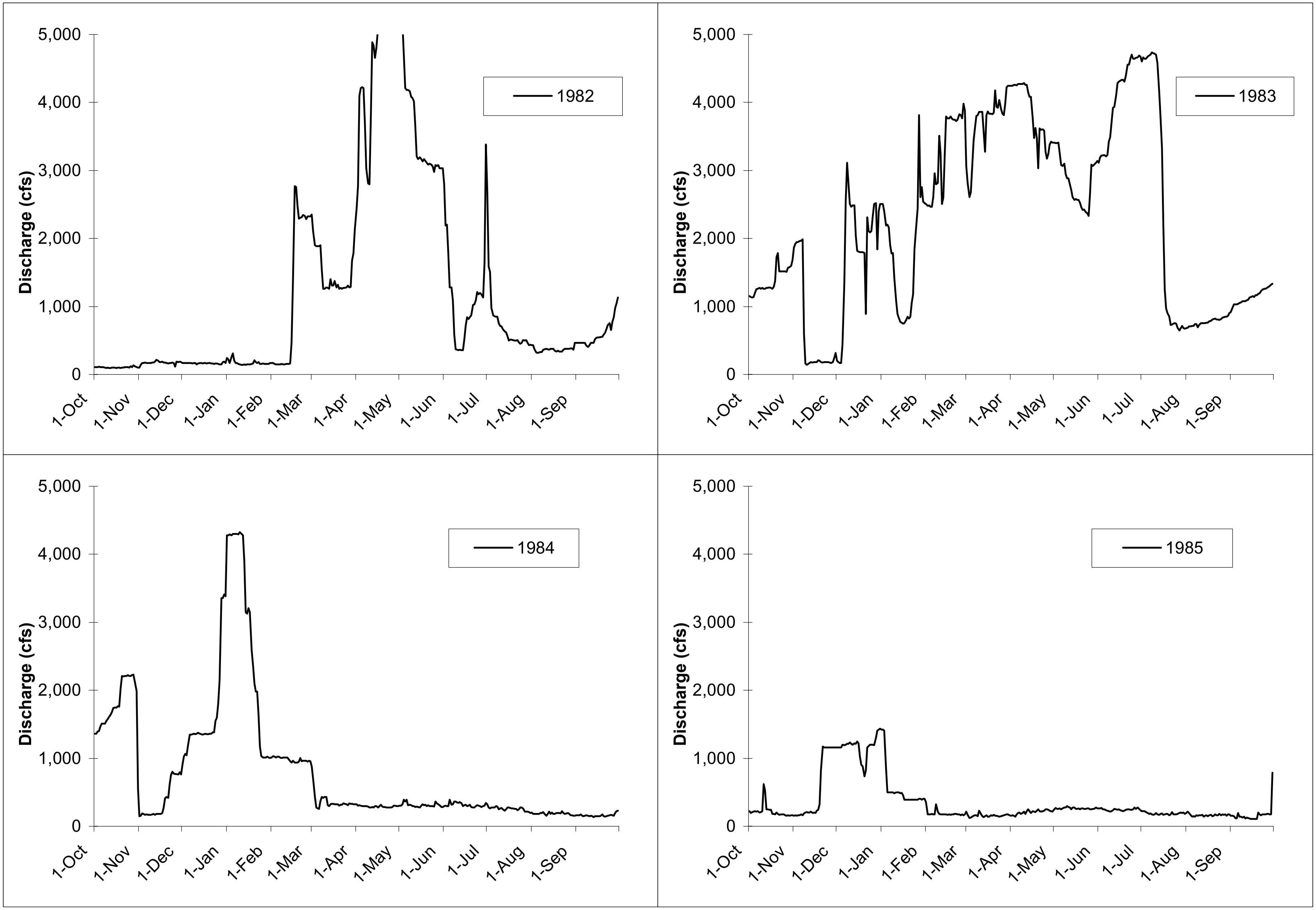
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



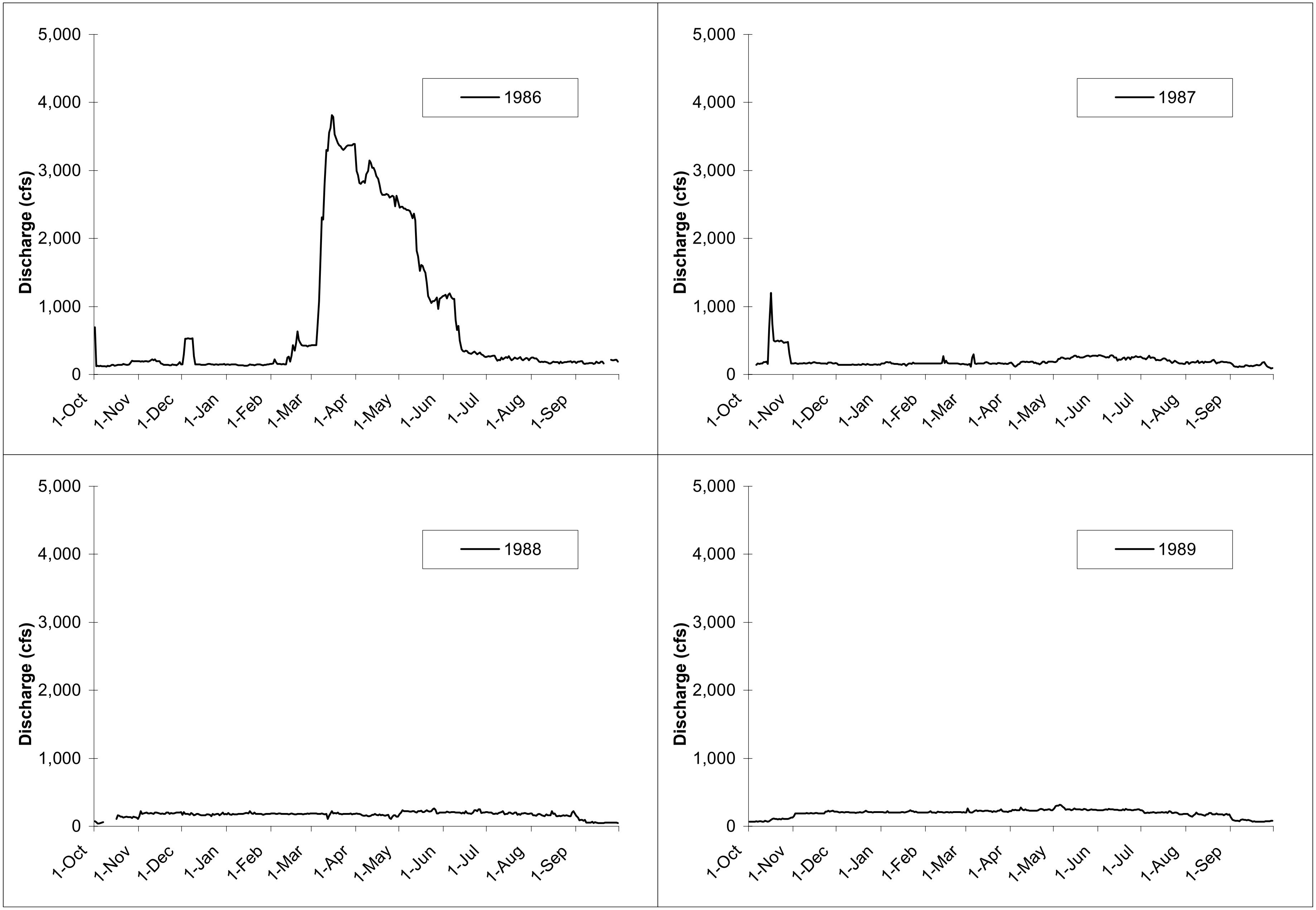
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



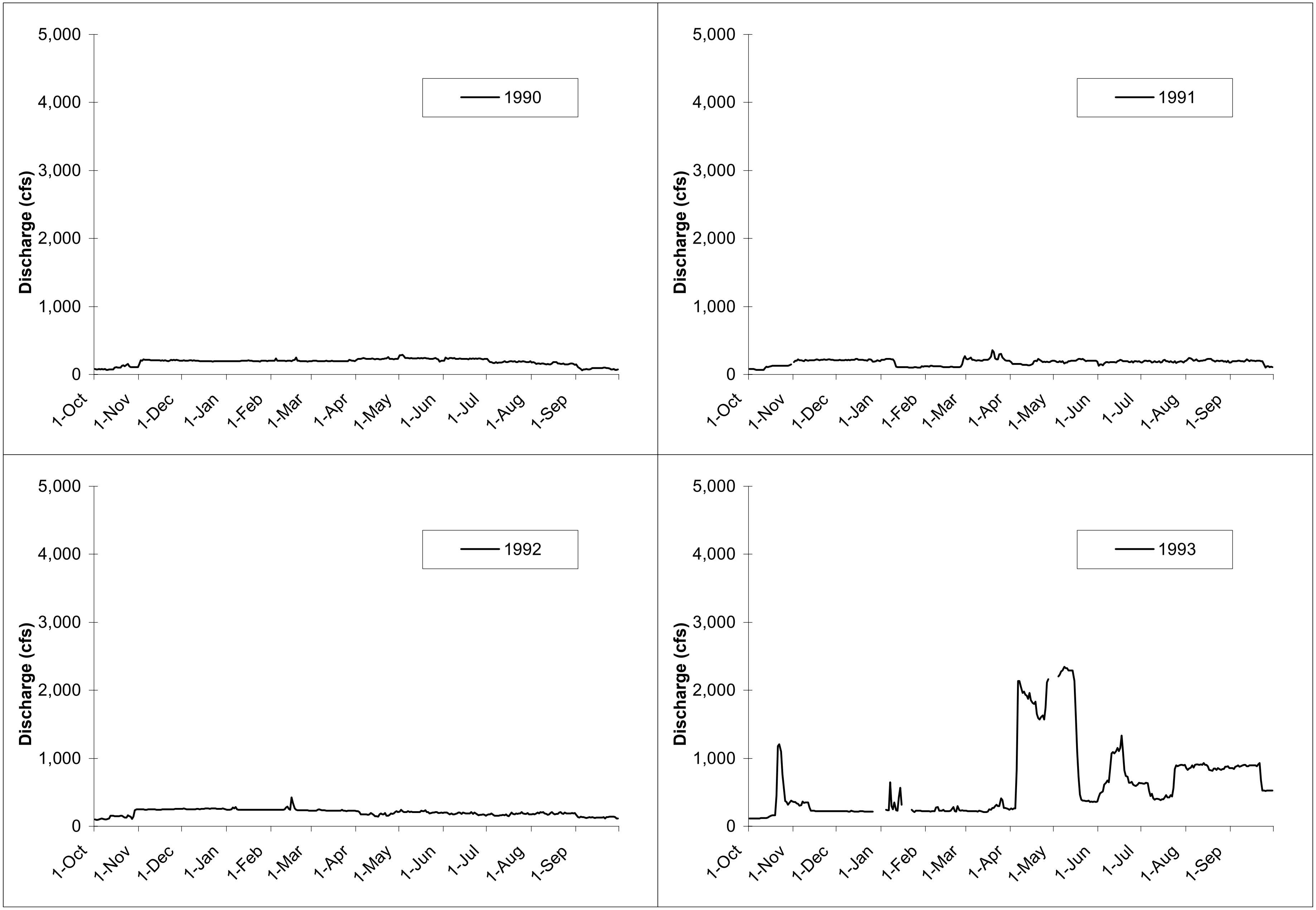
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



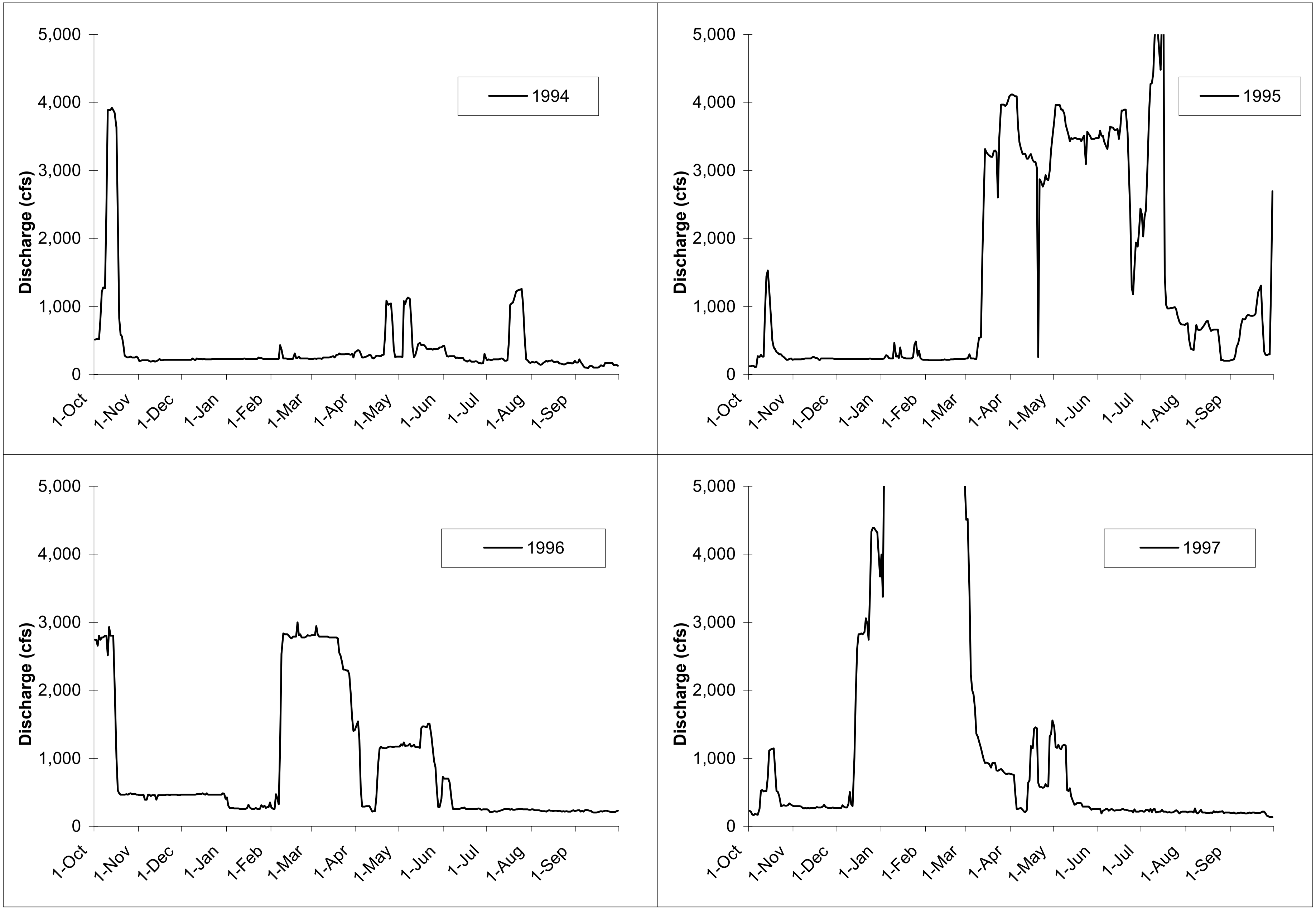
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



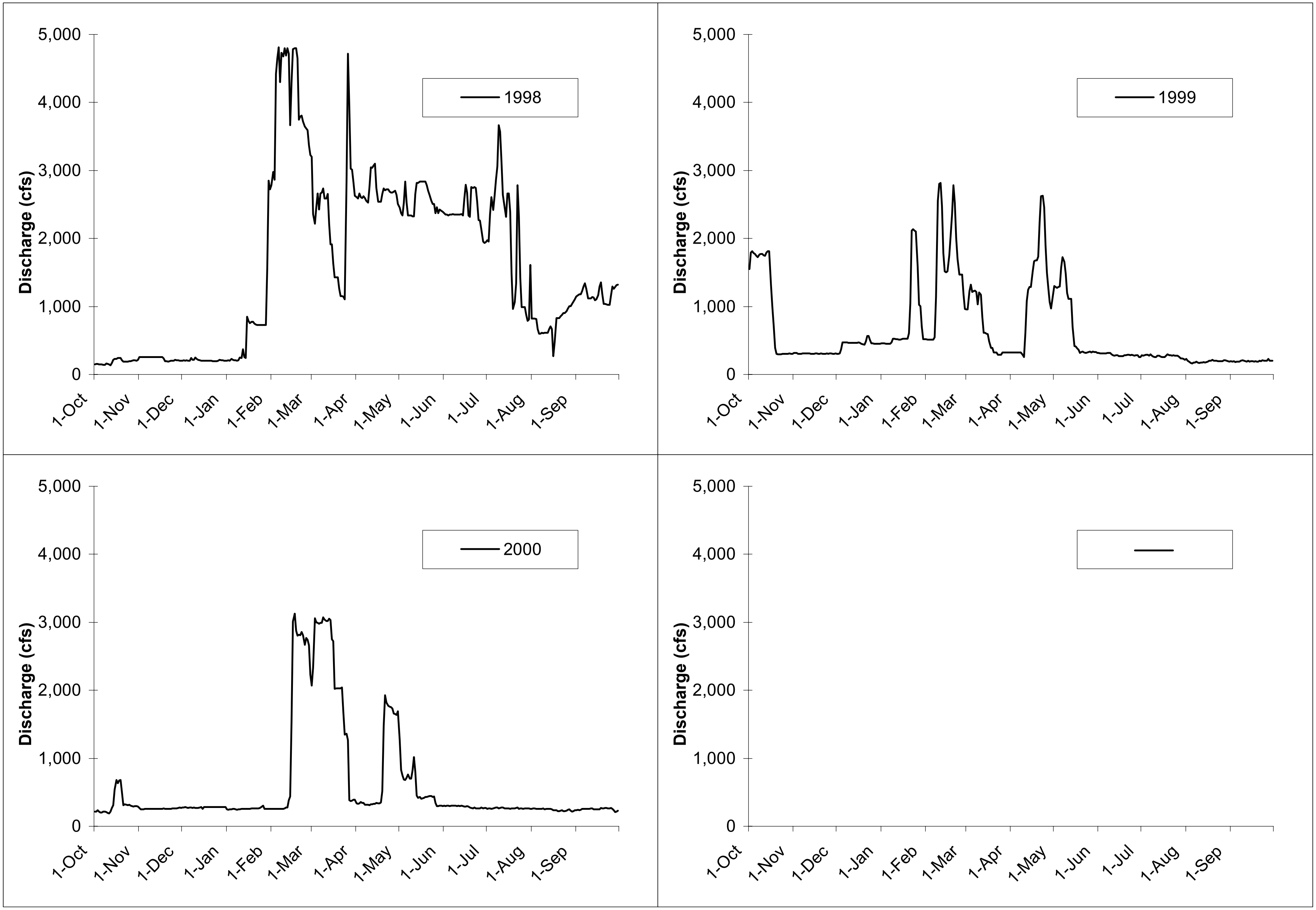
Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)



Merced River below Crocker-Huffman Dam, CA REGULATED hydrographs for WY1966-2000 (MID Gage)

APPENDIX E.

UNIMPAIRED HYDROLOGIC DATA FOR THE

- TUOLUMNE RIVER

INCLUDING:

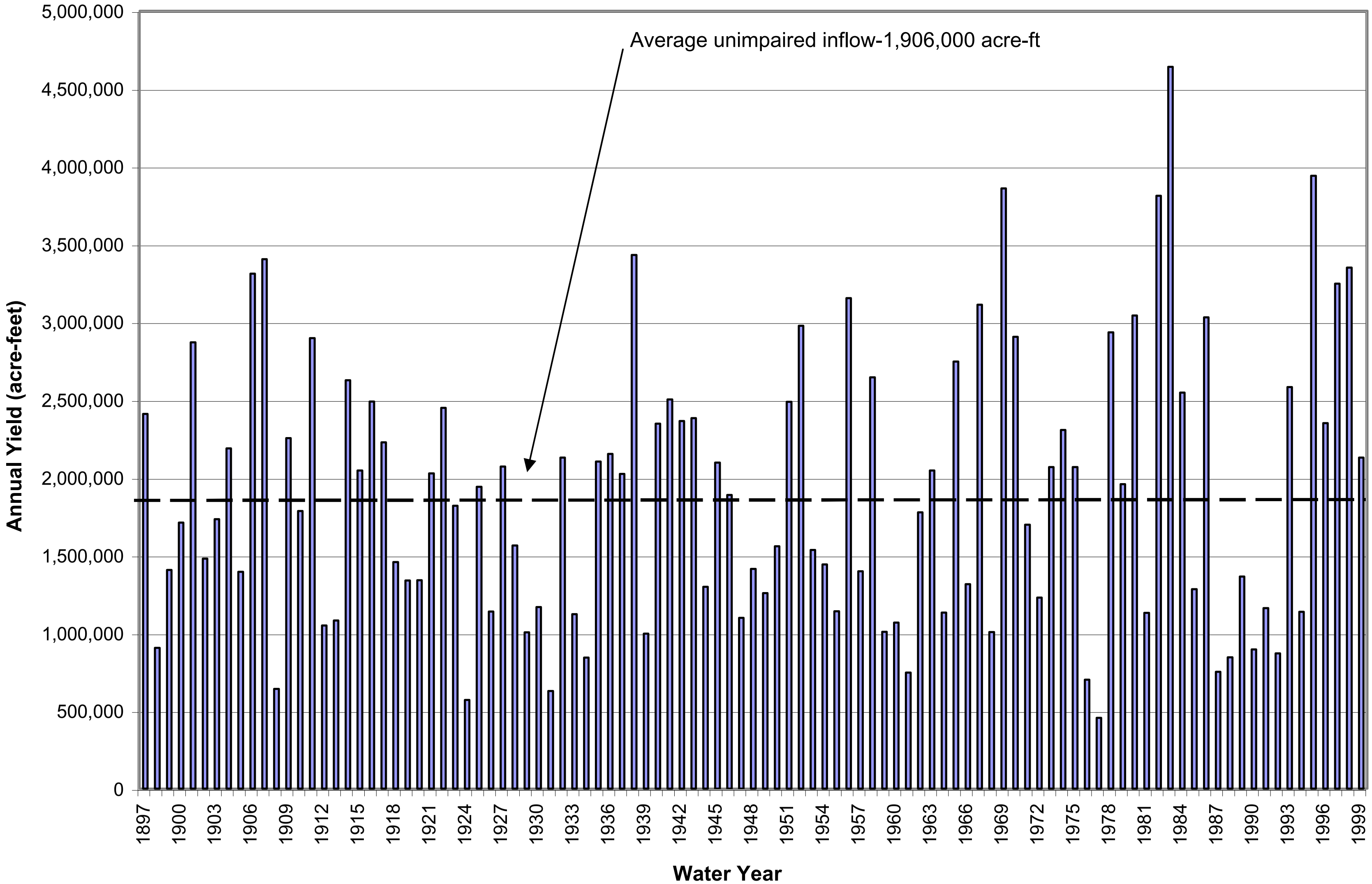
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

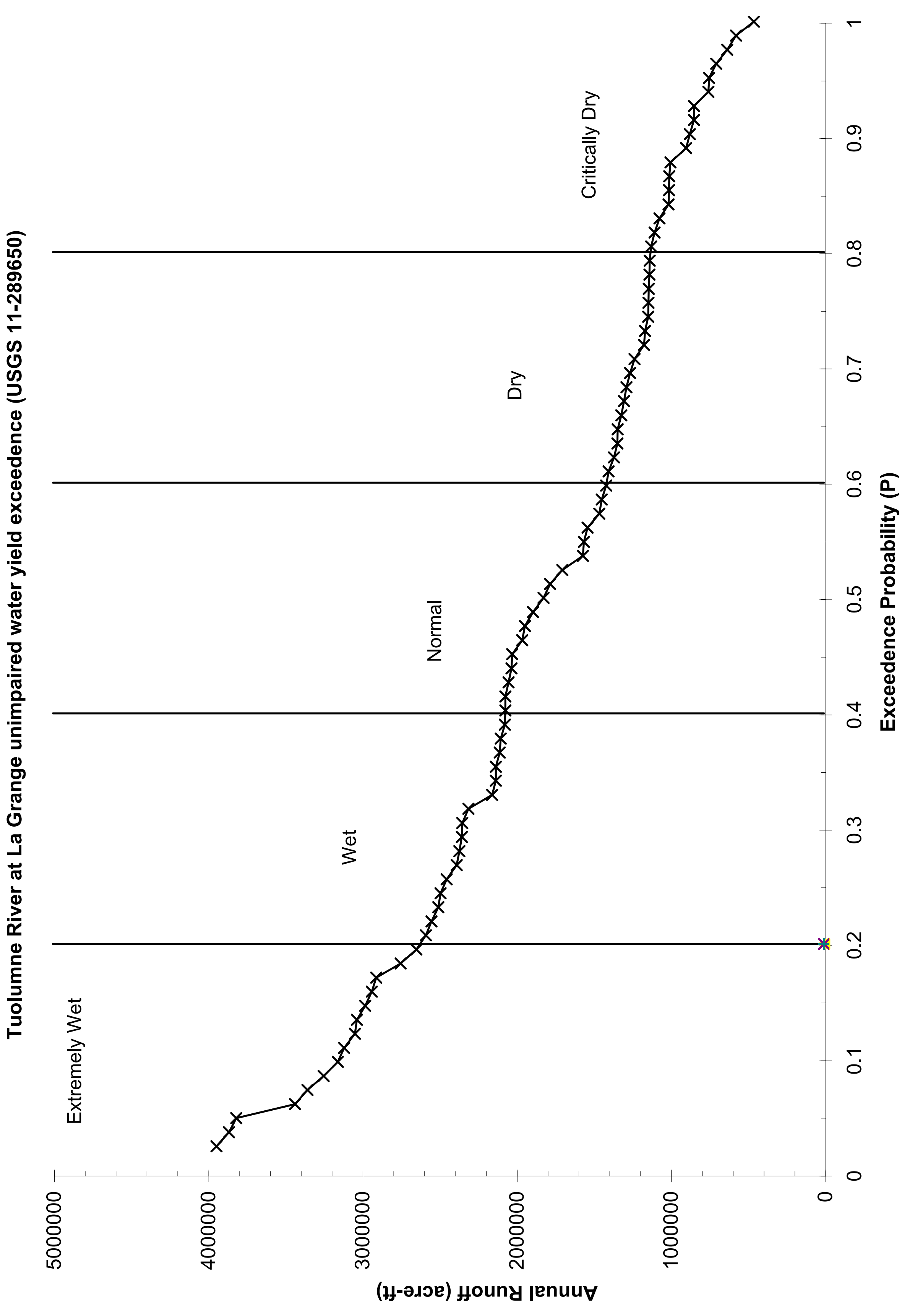
Tuolumne River at La Grange 1896-1999 (USGS11-289650) USGS data and modeled Unimpaired water yield data from TID

WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1897	2,408,626	NOT USED		
1898	904,929	NOT USED		
1899	1,405,080	NOT USED		
1900	1,709,988	NOT USED		
1901	2,868,440	NOT USED		
1902	1,478,285	NOT USED		
1903	1,732,731	NOT USED		
1904	2,186,807	NOT USED		
1905	1,394,306	NOT USED		
1906	3,309,416	NOT USED		
1907	3,402,943	NOT USED		
1908	641,423	NOT USED		
1909	2,253,531	NOT USED		
1910	1,784,531	NOT USED		
1911	2,895,247	NOT USED		
1912	1,049,518	NOT USED		
1913	1,081,250	NOT USED		
1914	2,624,557	NOT USED		
1915	2,044,411	NOT USED		
1916	2,488,186	NOT USED		
1917	2,226,657	NOT USED		
1918	1,456,903	NORMAL	57.3%	47
1919	1,337,742	DRY	64.6%	53
1920	1,340,043	DRY	63.4%	52
1921	2,026,884	NORMAL	43.9%	36
1922	2,447,486	WET	25.6%	21
1923	1,819,087	NORMAL	50.0%	41
1924	570,826	CRITICALLY DRY	98.8%	81
1925	1,940,010	NORMAL	47.6%	39
1926	1,138,400	DRY	75.6%	62
1927	2,069,819	WET	39.0%	32
1928	1,562,925	NORMAL	53.7%	44
1929	1,004,076	CRITICALLY DRY	86.6%	71
1930	1,166,851	DRY	72.0%	59
1931	627,292	CRITICALLY DRY	97.6%	80
1932	2,128,335	WET	34.1%	28
1933	1,120,610	CRITICALLY DRY	80.5%	66
1934	843,120	CRITICALLY DRY	92.7%	76
1935	2,102,592	WET	36.6%	30
1936	2,152,228	WET	32.9%	27
1937	2,022,282	NORMAL	45.1%	37
1938	3,429,698	EXTREMELY WET	6.1%	5
1939	995,539	CRITICALLY DRY	87.8%	72
1940	2,345,490	WET	30.5%	25
1941	2,501,575	WET	23.2%	19
1942	2,363,833	WET	28.0%	23
1943	2,381,340	WET	26.8%	22
1944	1,297,111	DRY	67.1%	55
1945	2,095,788	WET	37.8%	31
1946	1,887,704	NORMAL	48.8%	40
1947	1,098,414	CRITICALLY DRY	81.7%	67
1948	1,412,392	NORMAL	59.8%	49

WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1897	2,408,626	NOT USED		
1949	1,256,930	DRY	69.5%	57
1950	1,557,473	NORMAL	54.9%	45
1951	2,485,956	WET	24.4%	20
1952	2,975,644	EXTREMELY WET	14.6%	12
1953	1,533,804	NORMAL	56.1%	46
1954	1,441,268	NORMAL	58.5%	48
1955	1,139,613	DRY	74.4%	61
1956	3,152,732	EXTREMELY WET	9.8%	8
1957	1,397,742	DRY	61.0%	50
1958	2,643,558	EXTREMELY WET	19.5%	16
1959	1,008,562	CRITICALLY DRY	84.1%	69
1960	1,067,594	CRITICALLY DRY	82.9%	68
1961	745,506	CRITICALLY DRY	95.1%	78
1962	1,776,171	NORMAL	51.2%	42
1963	2,045,209	NORMAL	42.7%	35
1964	1,131,801	DRY	78.0%	64
1965	2,744,866	EXTREMELY WET	18.3%	15
1966	1,313,905	DRY	65.9%	54
1967	3,110,883	EXTREMELY WET	11.0%	9
1968	1,005,905	CRITICALLY DRY	85.4%	70
1969	3,858,598	EXTREMELY WET	3.7%	3
1970	2,903,749	EXTREMELY WET	17.1%	14
1971	1,696,685	NORMAL	52.4%	43
1972	1,228,740	DRY	70.7%	58
1973	2,066,837	NORMAL	40.2%	33
1974	2,306,285	WET	31.7%	26
1975	2,066,348	NORMAL	41.5%	34
1976	699,777	CRITICALLY DRY	96.3%	79
1977	454,334	CRITICALLY DRY	100.0%	82
1978	2,932,759	EXTREMELY WET	15.9%	13
1979	1,957,501	NORMAL	46.3%	38
1980	3,040,767	EXTREMELY WET	12.2%	10
1981	1,130,446	DRY	79.3%	65
1982	3,810,491	EXTREMELY WET	4.9%	4
1983	4,639,714	EXTREMELY WET	1.2%	1
1984	2,544,881	WET	22.0%	18
1985	1,281,836	DRY	68.3%	56
1986	3,028,685	EXTREMELY WET	13.4%	11
1987	750,286	CRITICALLY DRY	93.9%	77
1988	843,629	CRITICALLY DRY	91.5%	75
1989	1,362,947	DRY	62.2%	51
1990	894,134	CRITICALLY DRY	89.0%	73
1991	1,160,524	DRY	73.2%	60
1992	870,146	CRITICALLY DRY	90.2%	74
1993	2,581,784	WET	20.7%	17
1994	1,136,409	DRY	76.8%	63
1995	3,939,017	EXTREMELY WET	2.4%	2
1996	2,348,979	WET	29.3%	24
1997	3,245,211	EXTREMELY WET	8.5%	7
1998	3,348,765	EXTREMELY WET	7.3%	6
1999	2,127,404	WET	35.4%	29

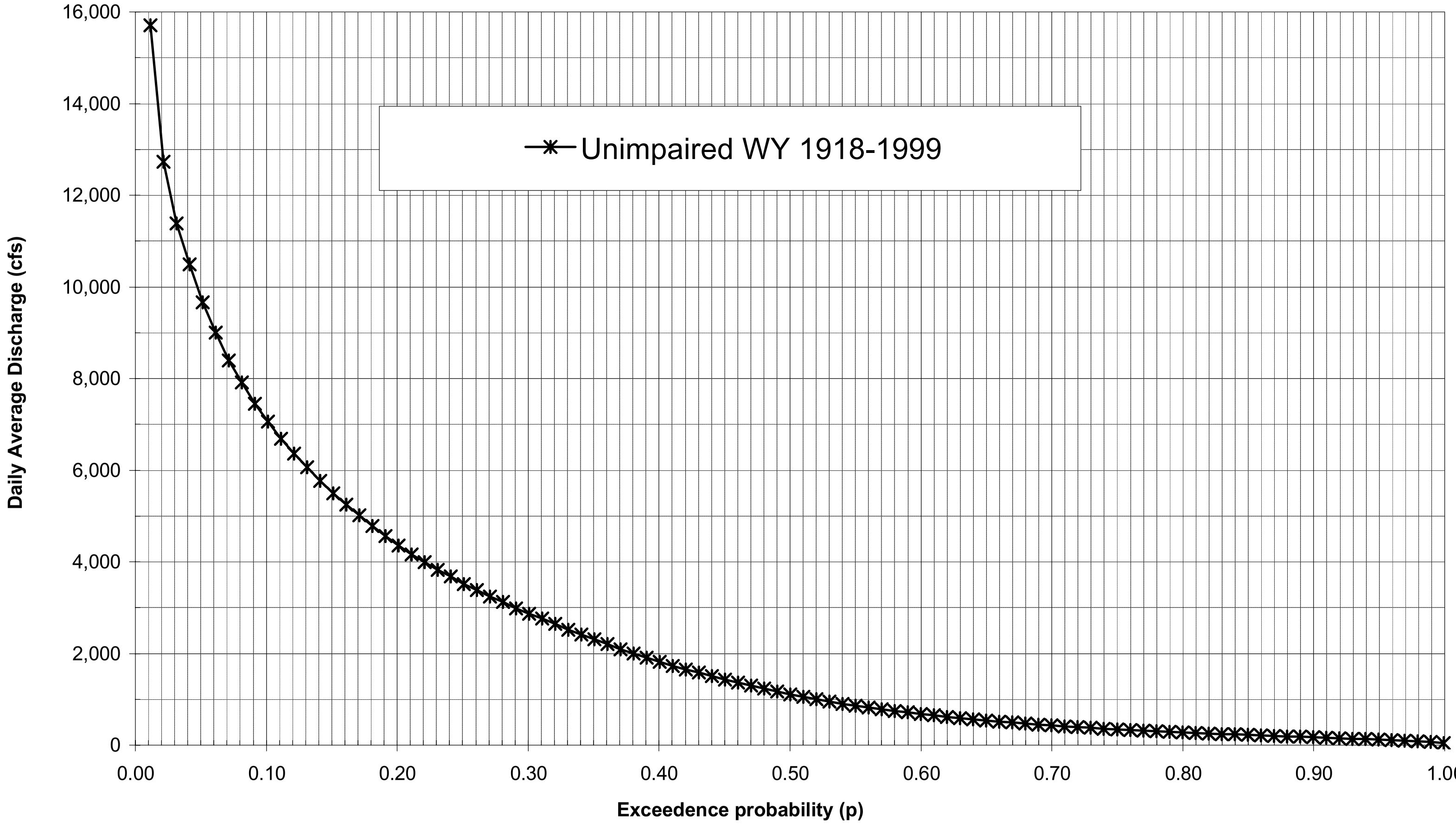
Tuolumne River at La Grange unimpaired water yield (USGS 11-289650)

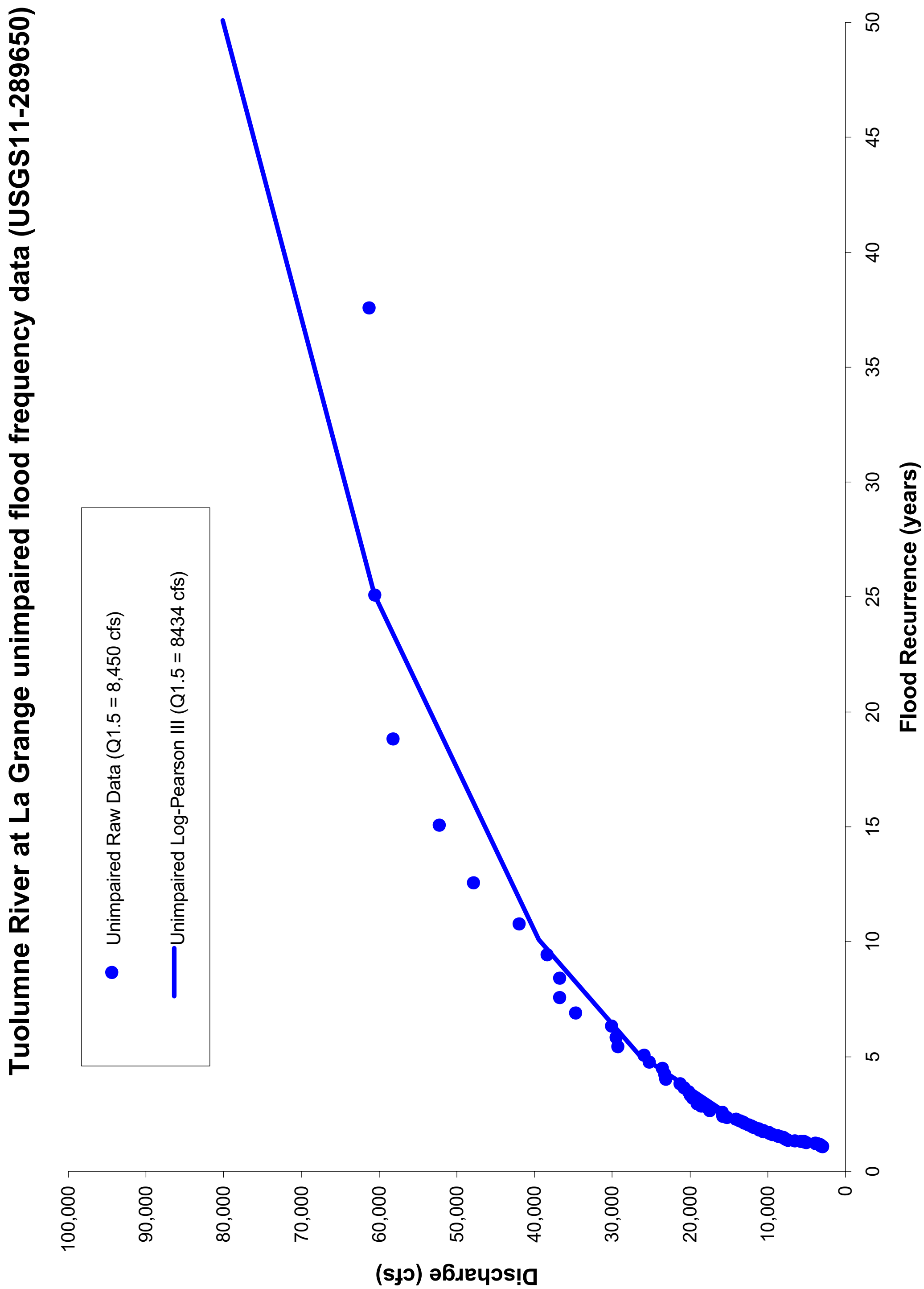


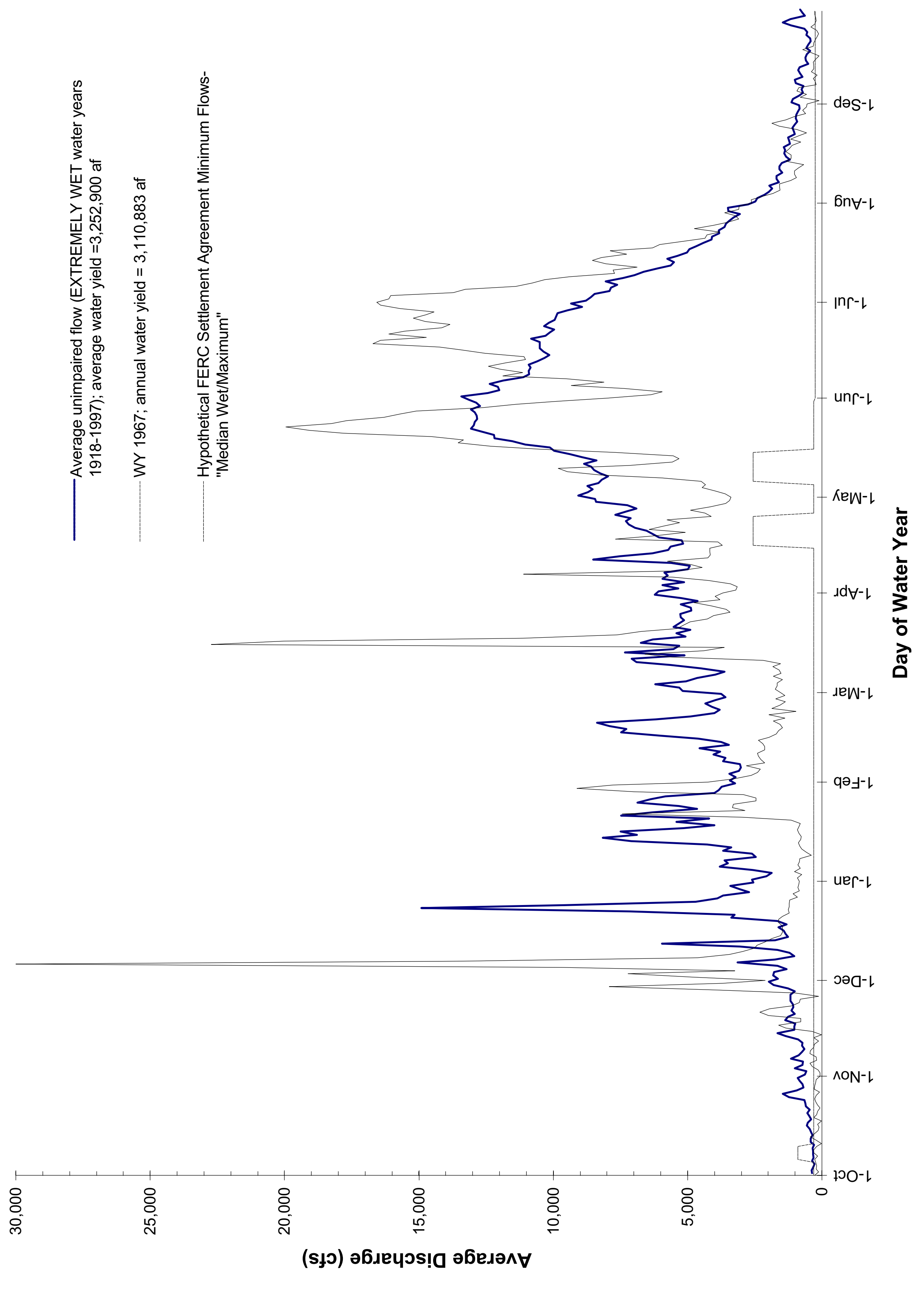


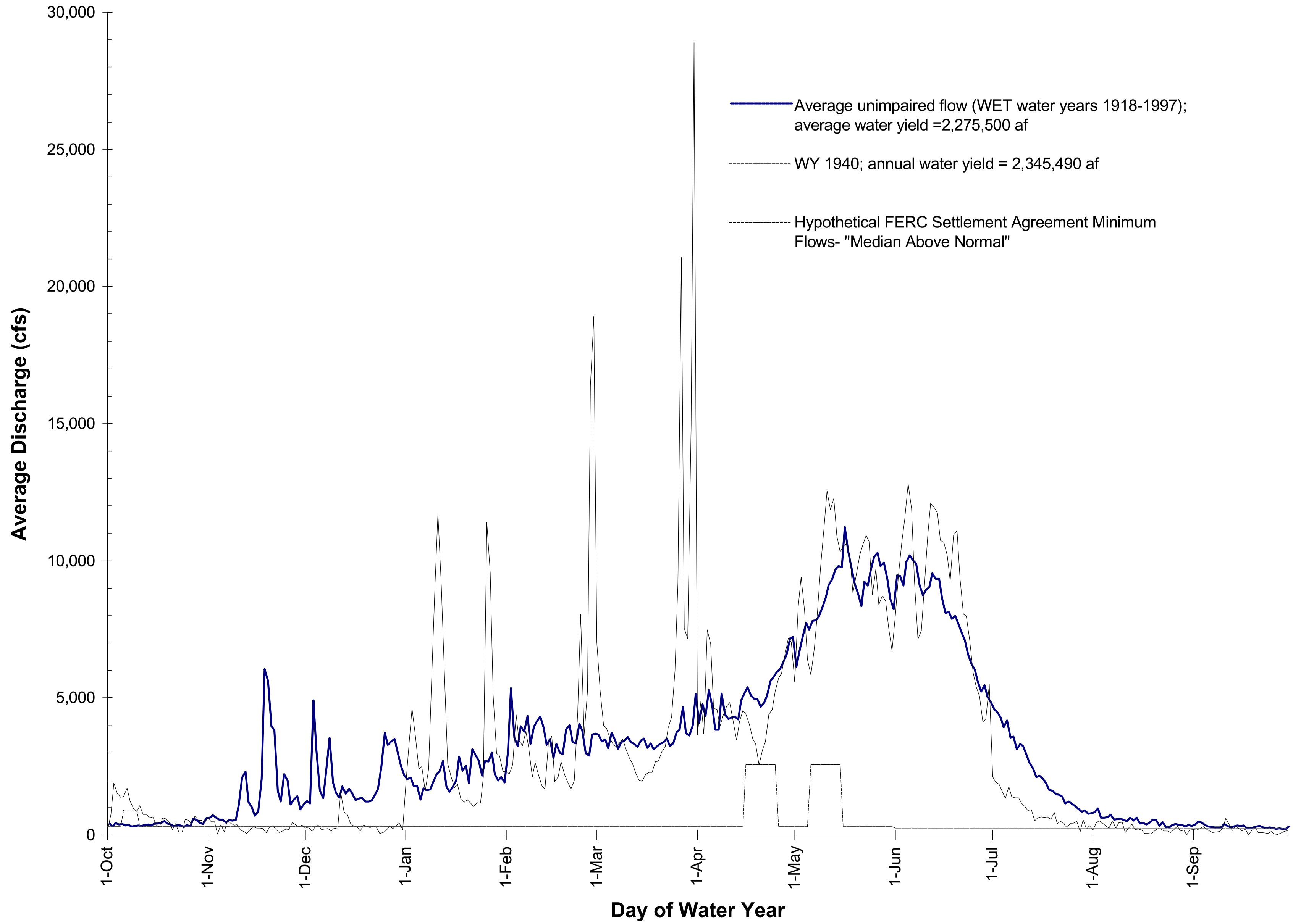
Tuolumne River at La Grange unimpaired water yield exceedence (USGS 11-289650)
Extremely Wet
Wet
Normal
Dry
Critically Dry
Annual Runoff (acre-ft)
5000000
4000000
3000000
2000000
1000000
0
Exceedence Probability (P)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

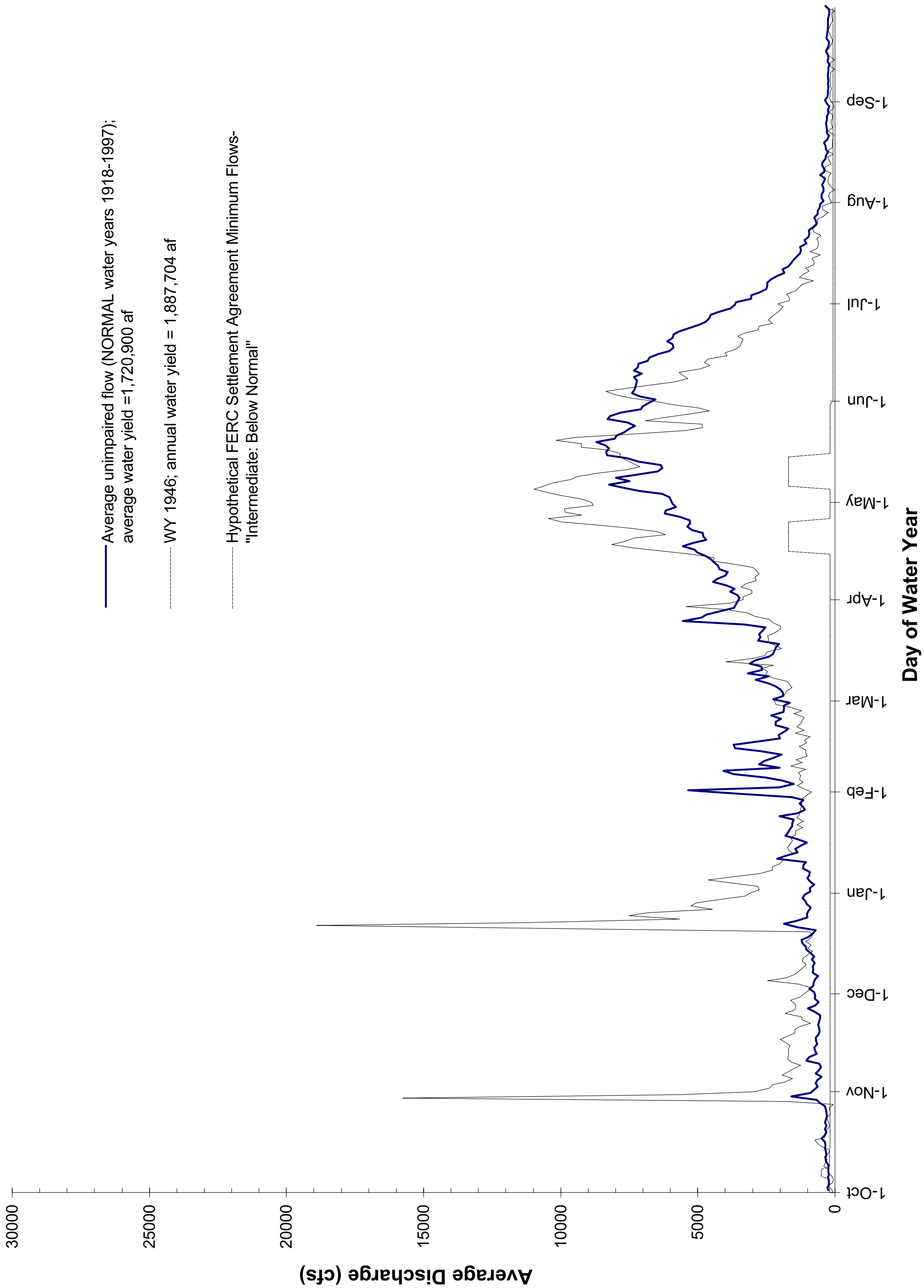
Tuolumne River at La Grange unimpaired flow duration curves (USGS11-289650)



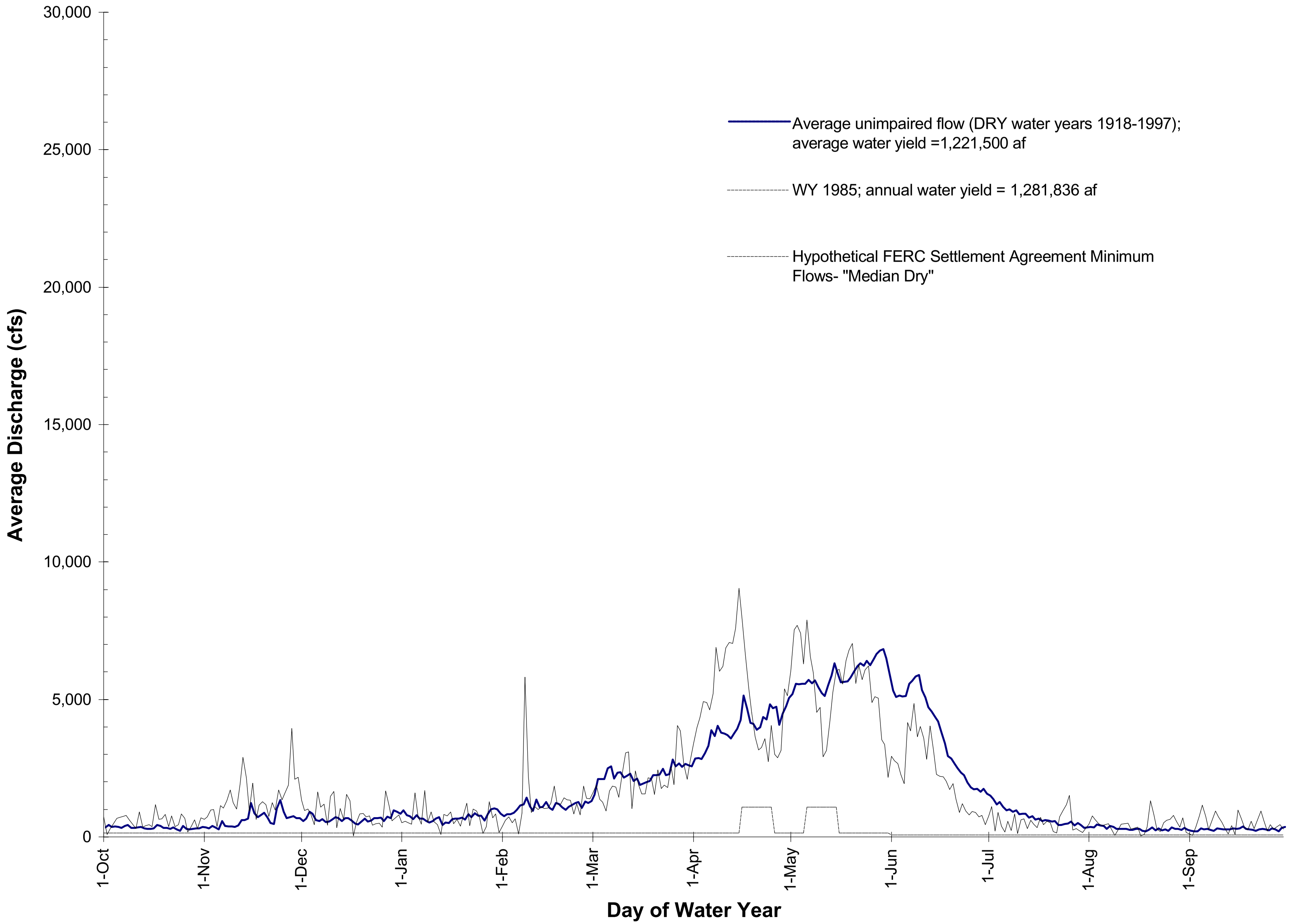

Tuolumne River at La Grange unimpaired flood frequency data (USGS11-289650)
Unimpaired Raw Data (Q1.5 = 8,450 cfs)
Unimpaired Log-Pearson III (Q1.5 = 8434 cfs)
Discharge (cfs)
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Flood Recurrence (years)
0
5
10
15
20
25
30
35
40
45
50

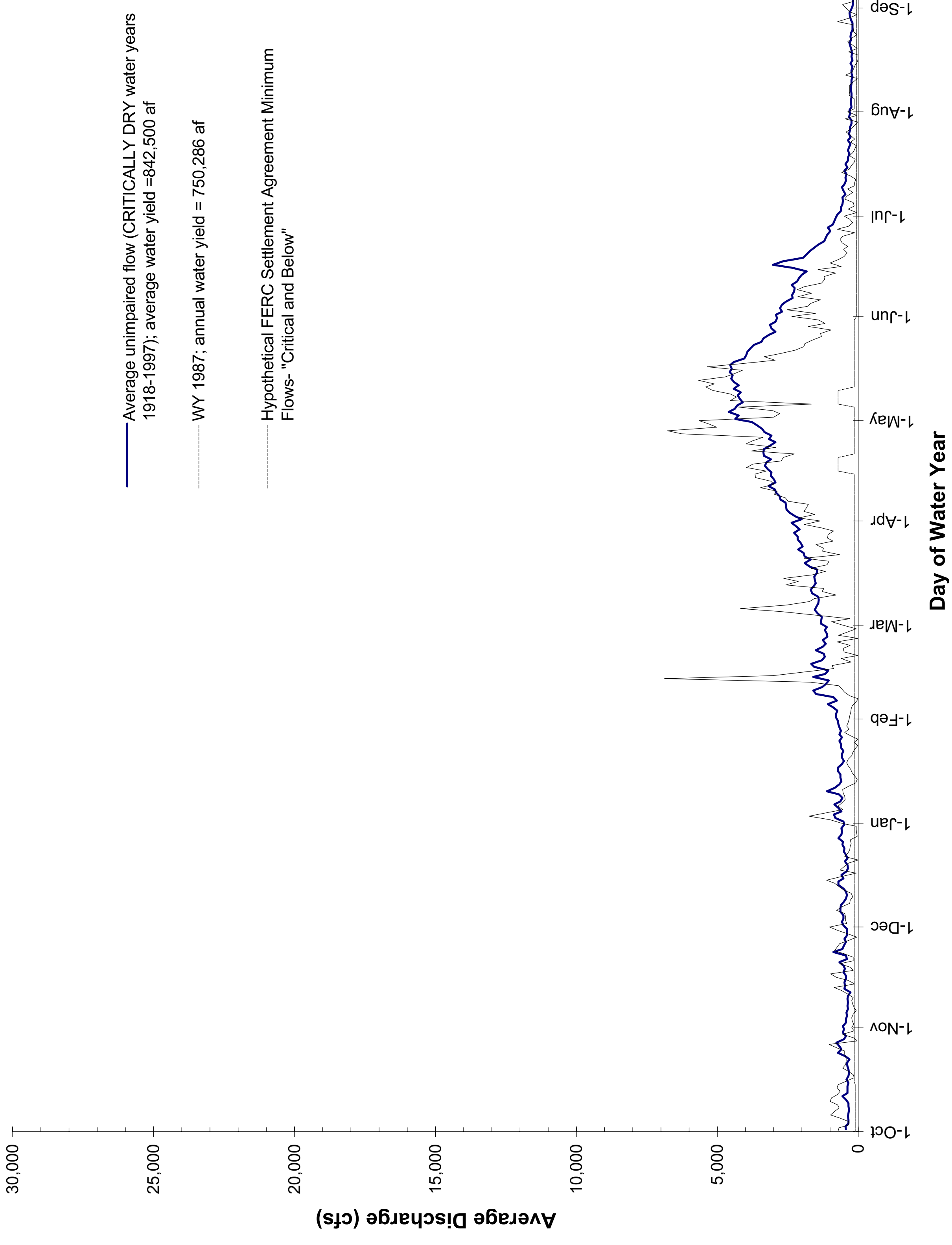

Average unimpaired flow (EXTREMELY WET water years 1918-1997); average water yield =3,252,900 af
WY 1967; annual water yield = 3,110,883 af
Hypothetical FERC Settlement Agreement Minimum Flows- "Median Wet/Maximum"
Average Discharge (cfs)
30,000
25,000
20,000
15,000
10,000
5,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Day of Water Year

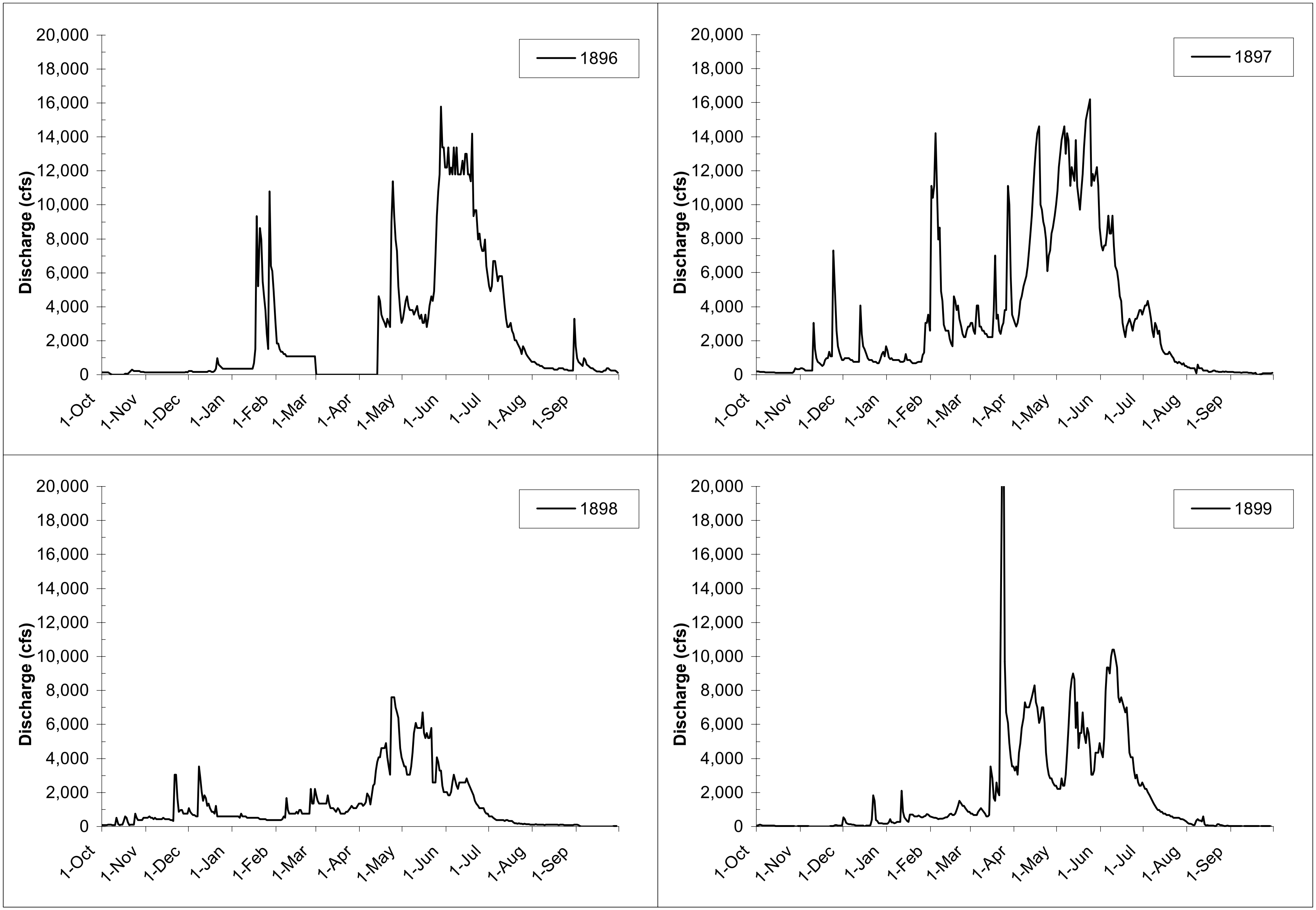

Average Discharge (cfs)
30,000
25,000
20,000
15,000
10,000
5,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Day of Water Year
Average unimpaired flow (WET water years 1918-1997); average water yield =2,275,500 af
WY 1940; annual water yield = 2,345,490 af
Hypothetical FERC Settlement Agreement Minimum Flows- "Median Above Normal"



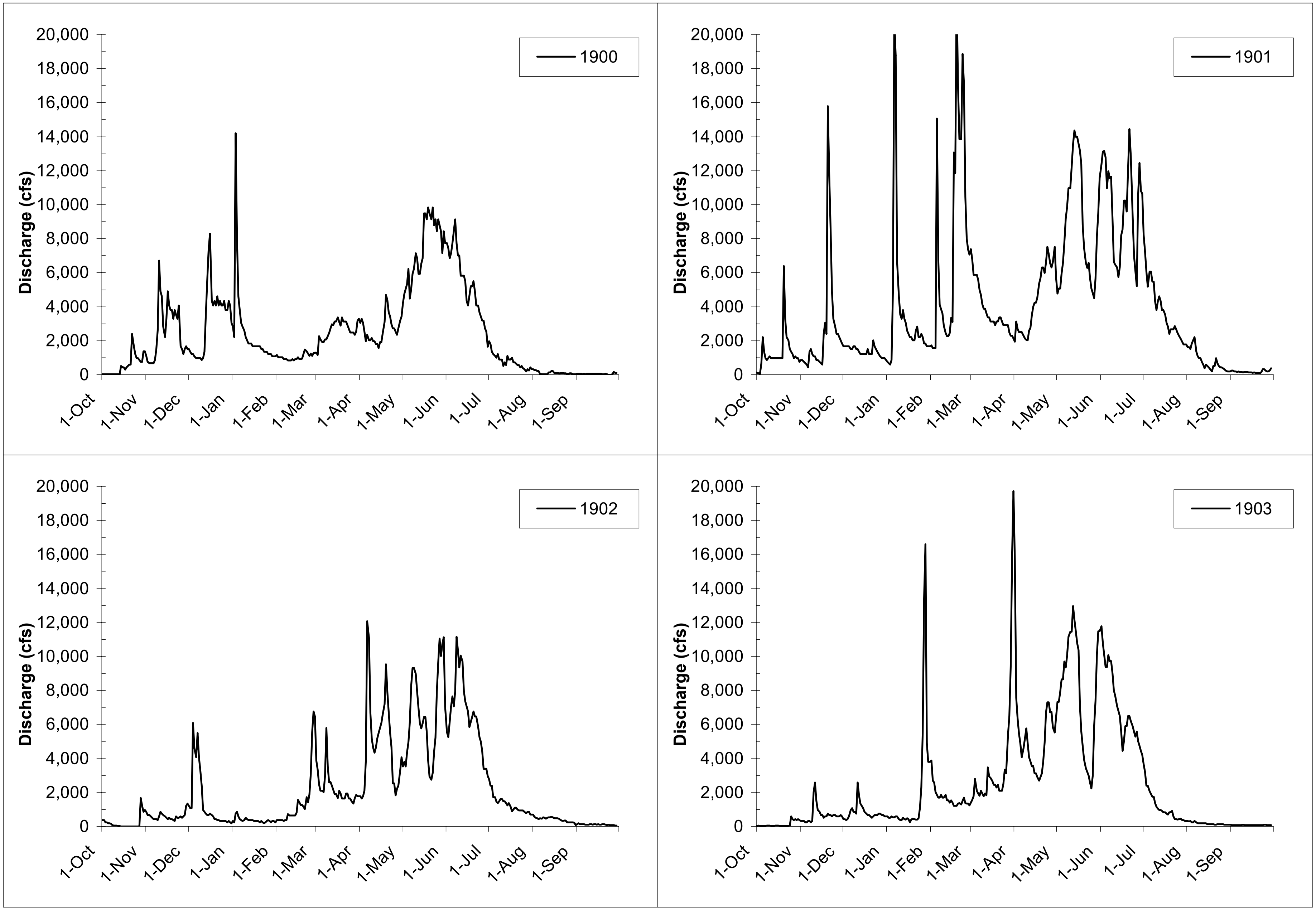
Average unimpaired flow (NORMAL water years 1918-1997); average water yield =1,720,900 af
WY 1946; annual water yield = 1,887,704 af
Hypothetical FERC Settlement Agreement Minimum Flows- "Intermediate: Below Normal"
Average Discharge (cfs)
Day of Water Year
0
5000
10000
15000
20000
25000
30000
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep


Average Discharge (cfs)
30,000
25,000
20,000
15,000
10,000
5,000
0
Average unimpaired flow (DRY water years 1918-1997); average water yield =1,221,500 af
WY 1985; annual water yield = 1,281,836 af
Hypothetical FERC Settlement Agreement Minimum Flows- "Median Dry"
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Day of Water Year

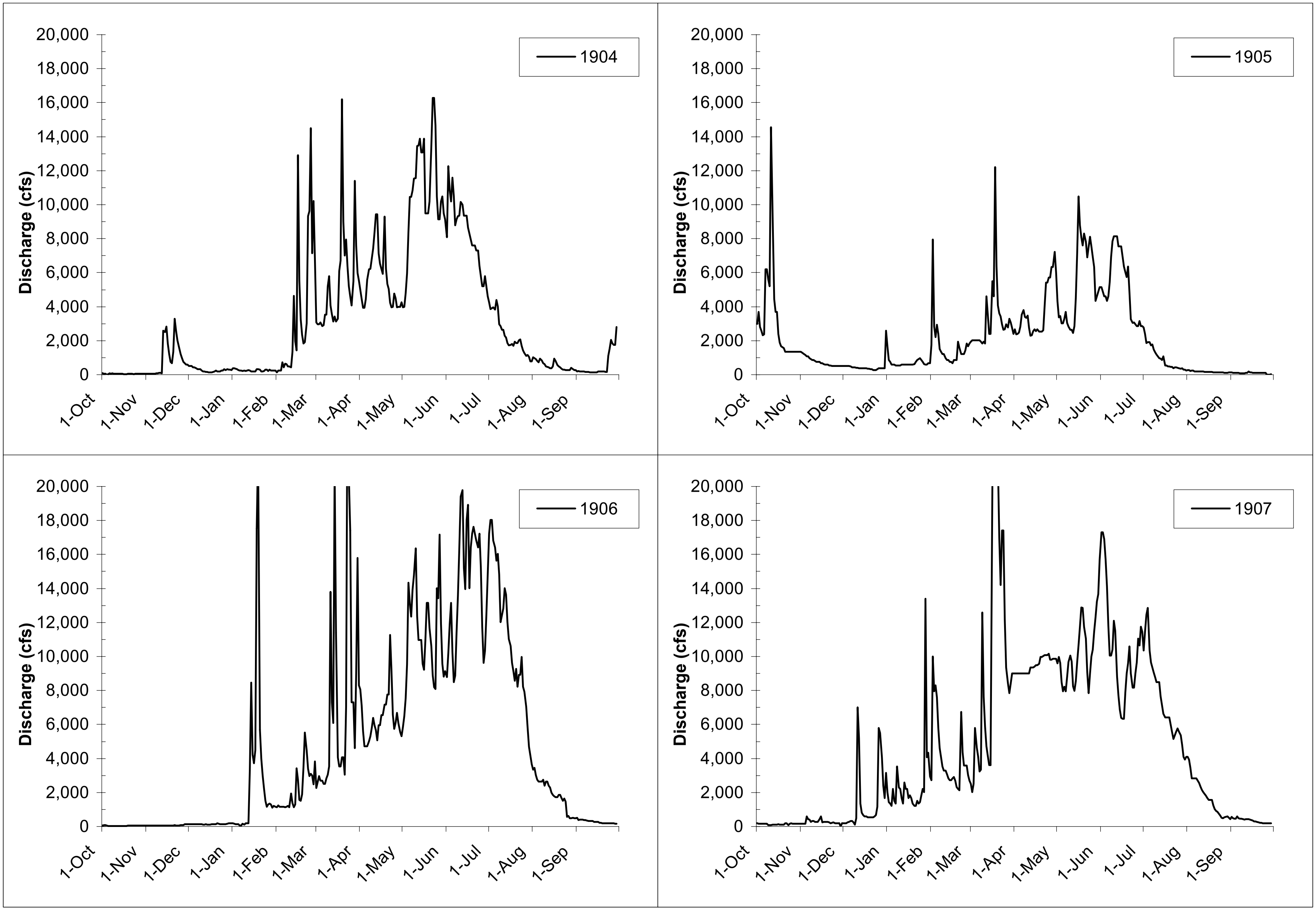

Average unimpaired flow (CRITICALLY DRY water years 1918-1997); average water yield =842,500 af
WY 1987; annual water yield = 750,286 af
Hypothetical FERC Settlement Agreement Minimum Flows- "Critical and Below"
Average Discharge (cfs)
30,000
25,000
20,000
15,000
10,000
5,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Day of Water Year



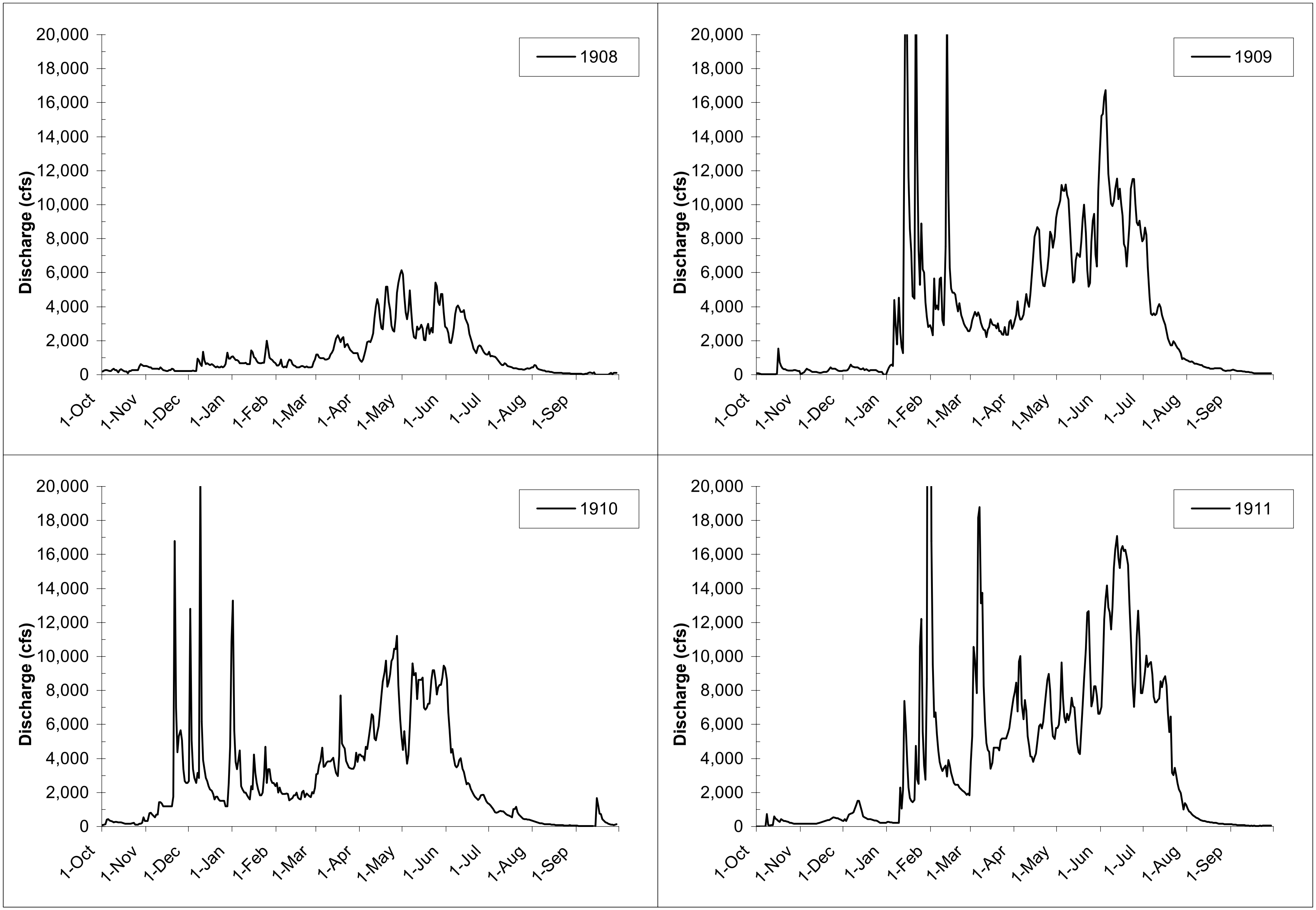
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



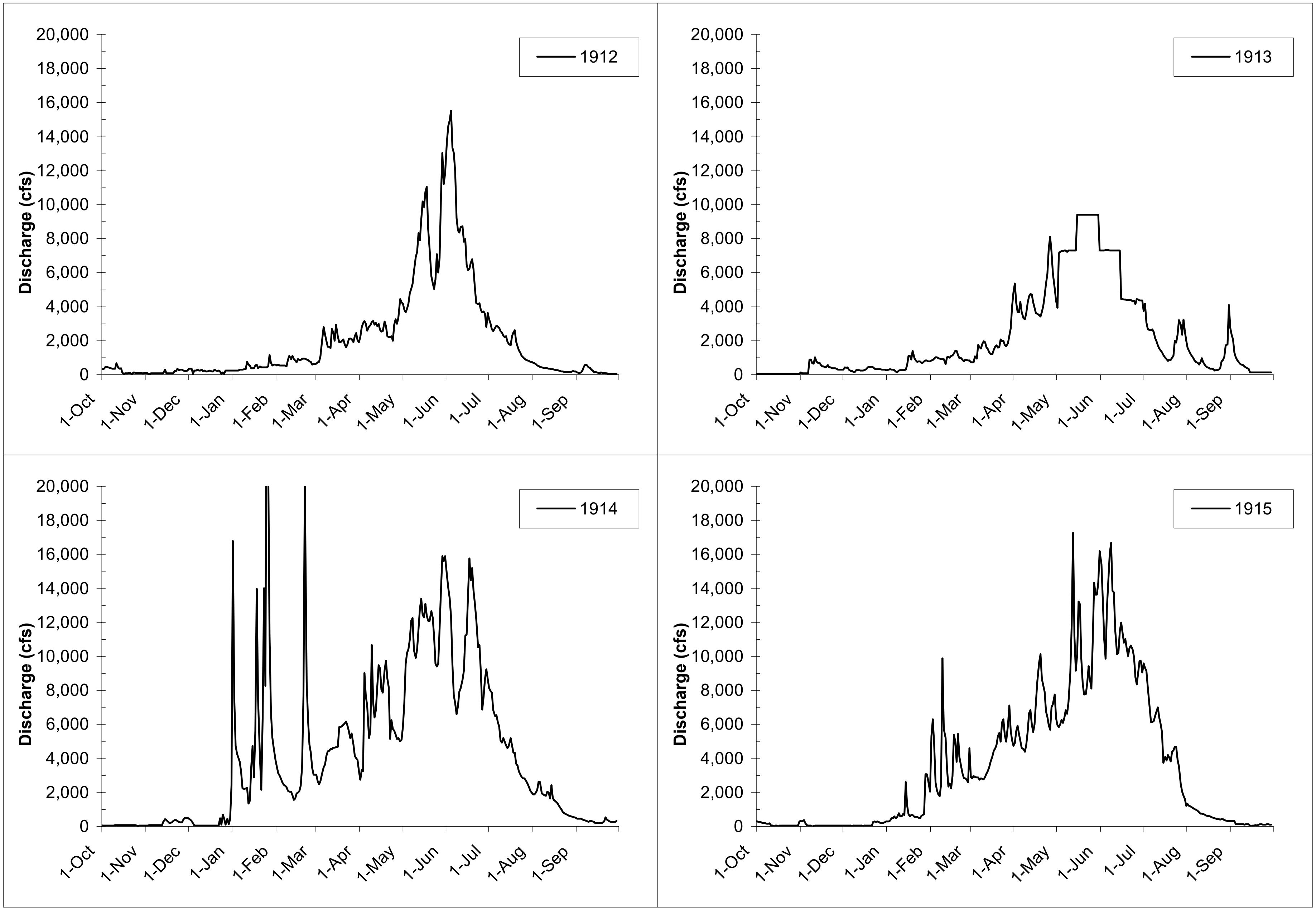
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



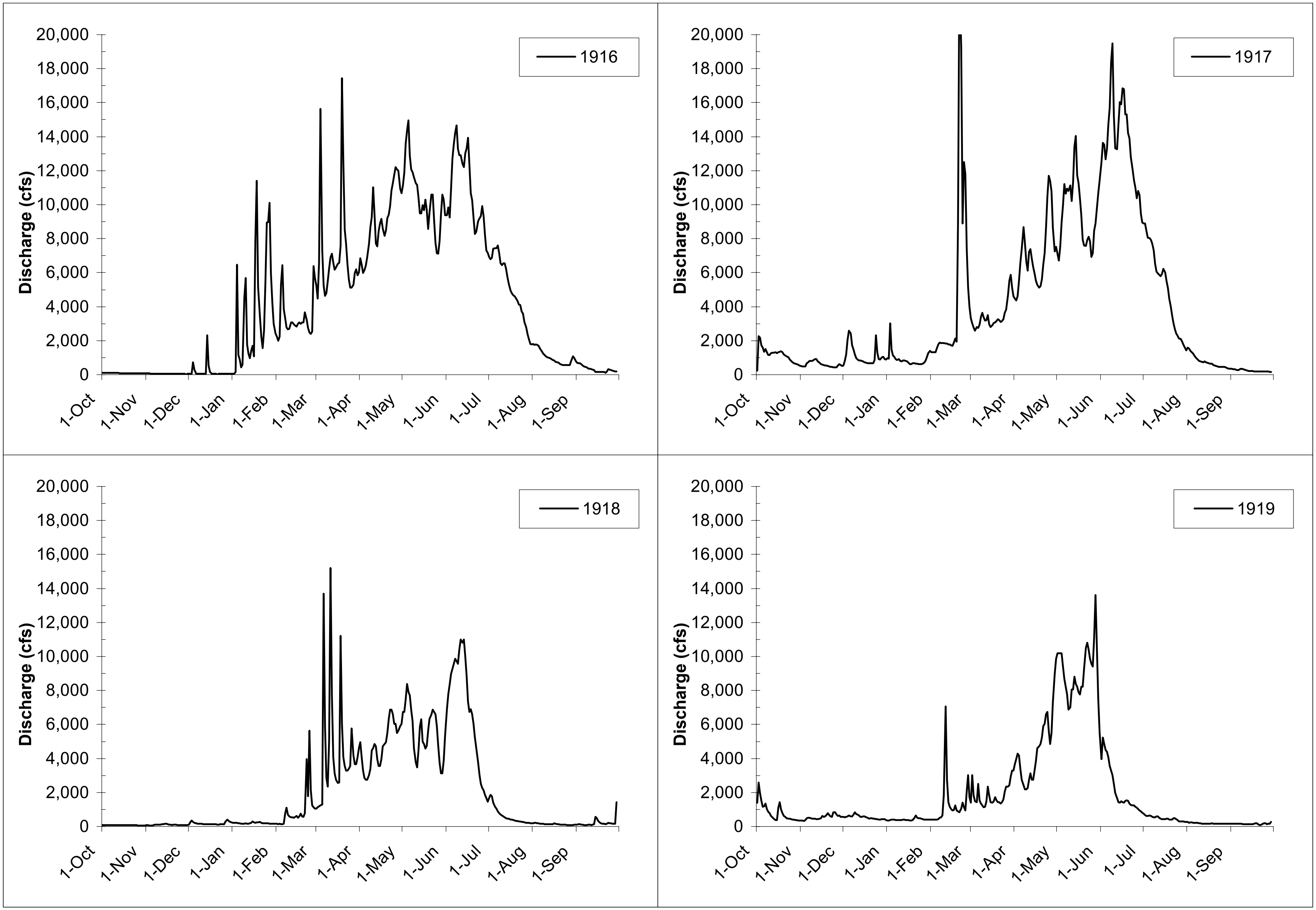
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



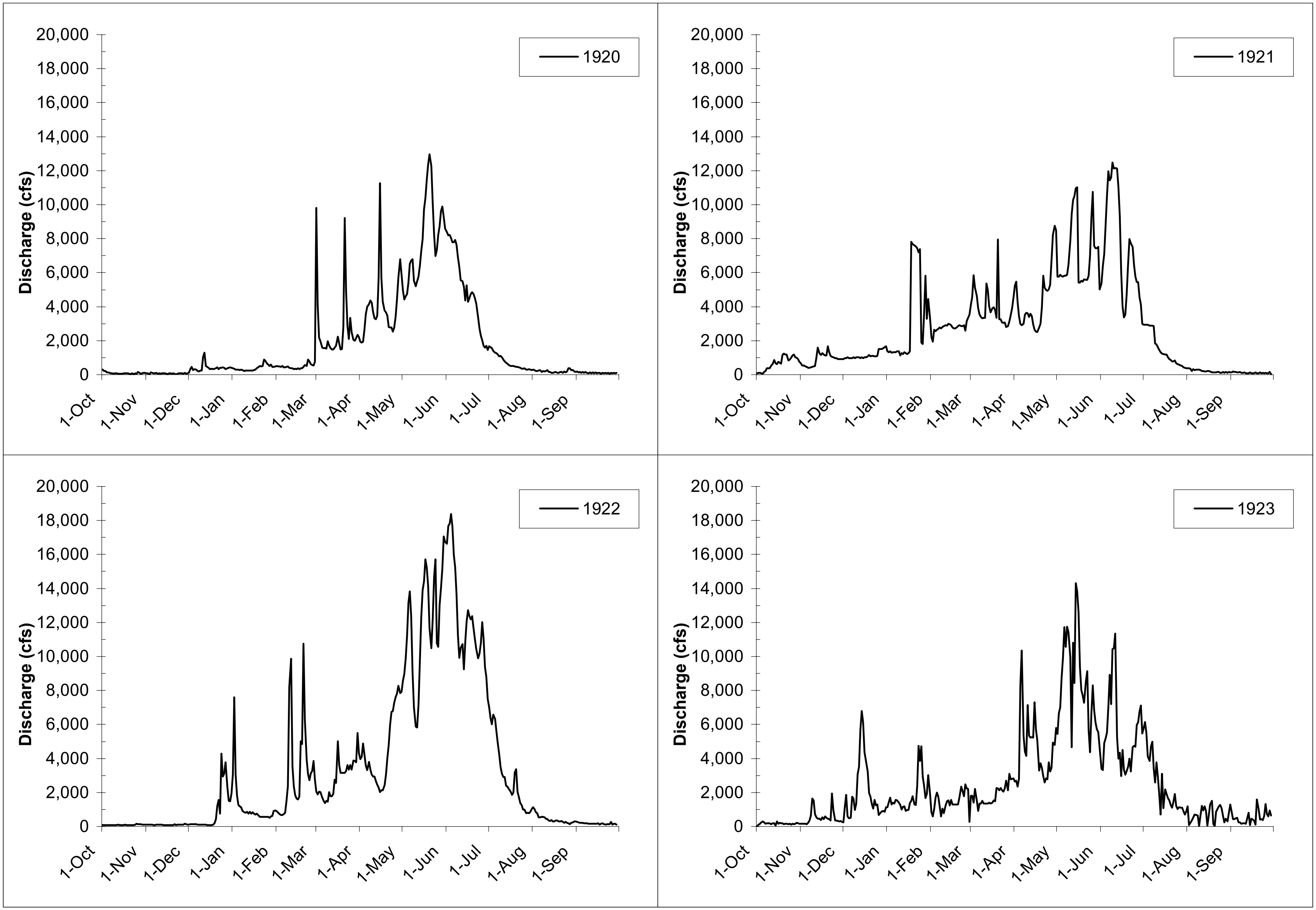
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



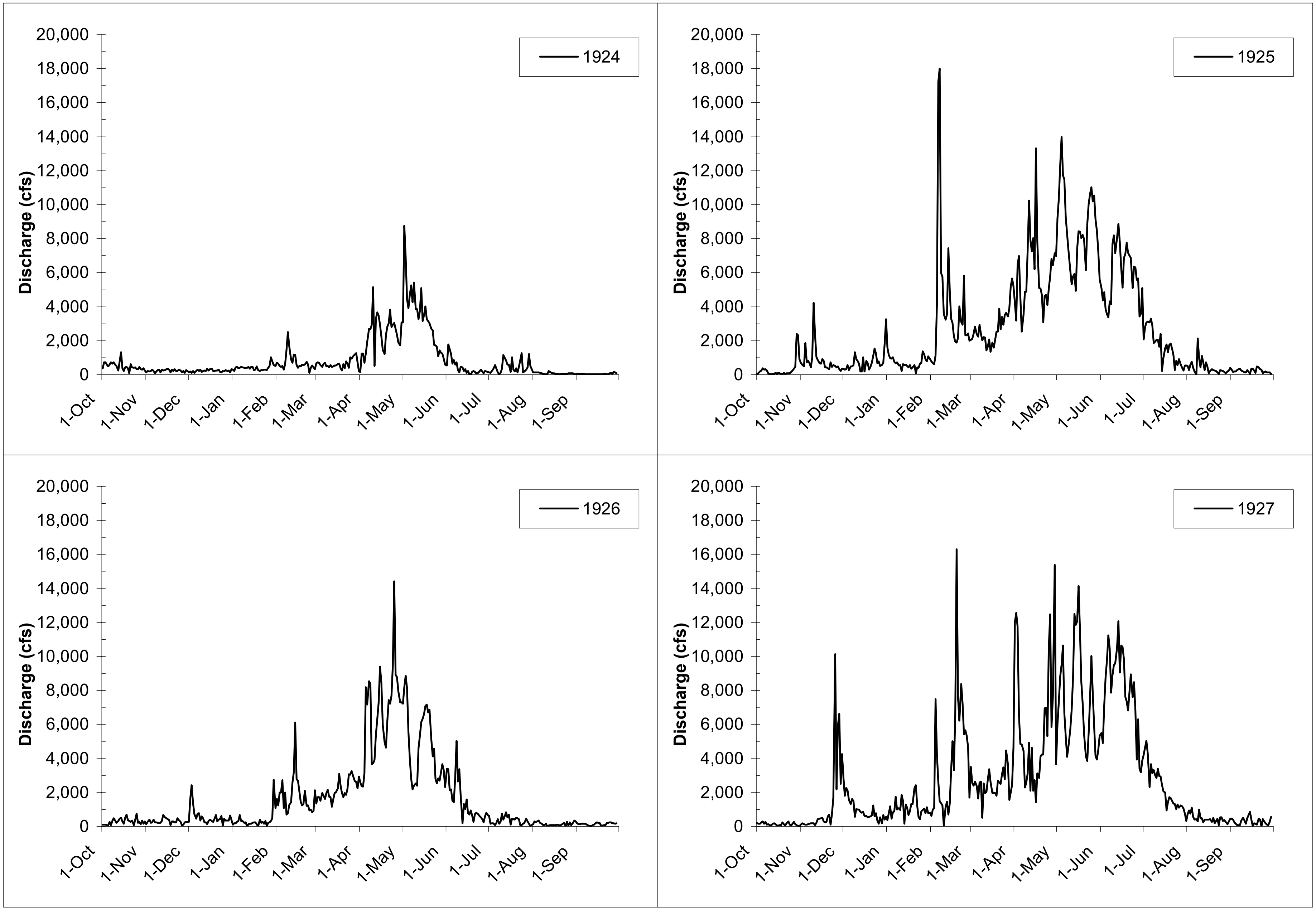
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



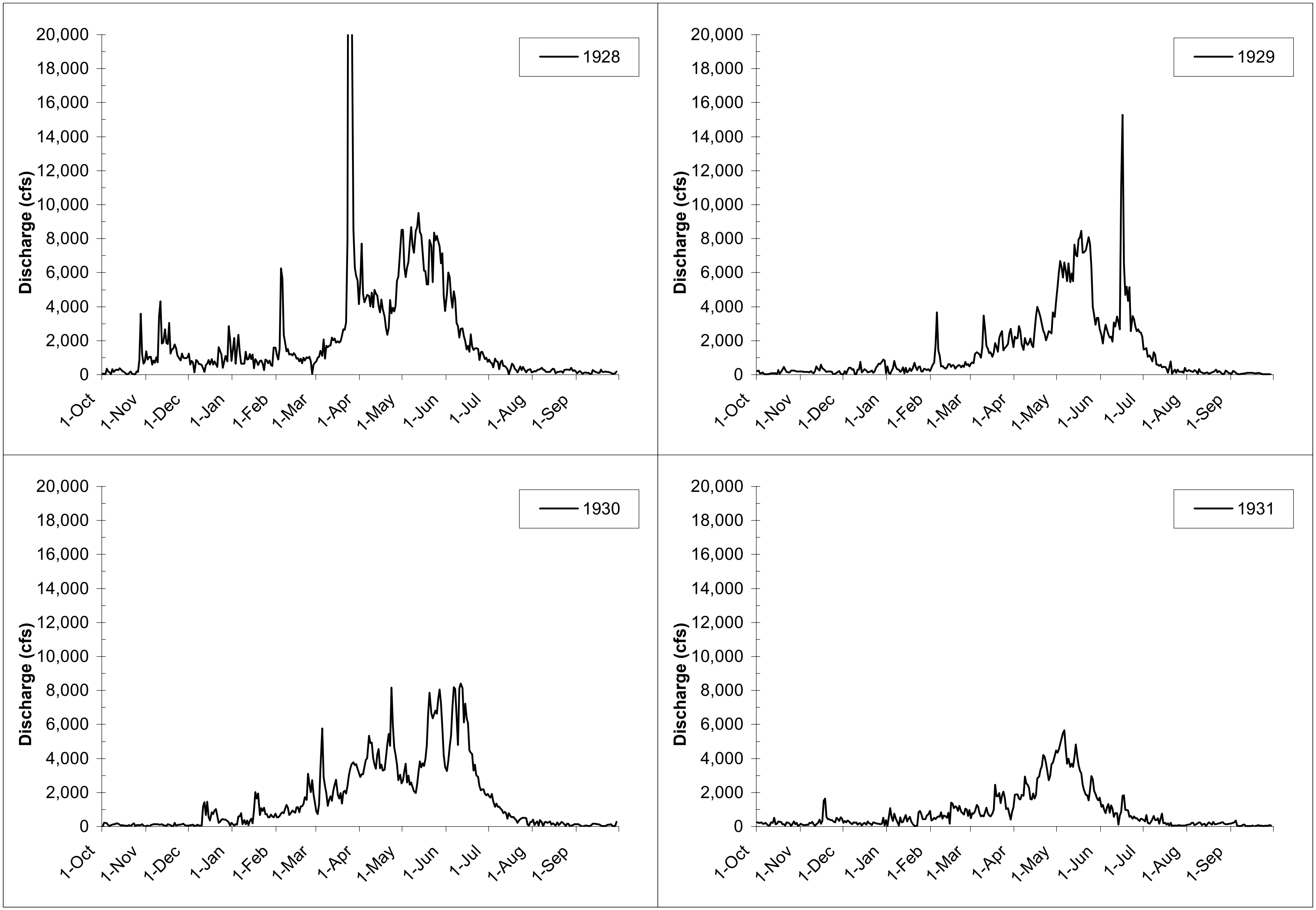
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



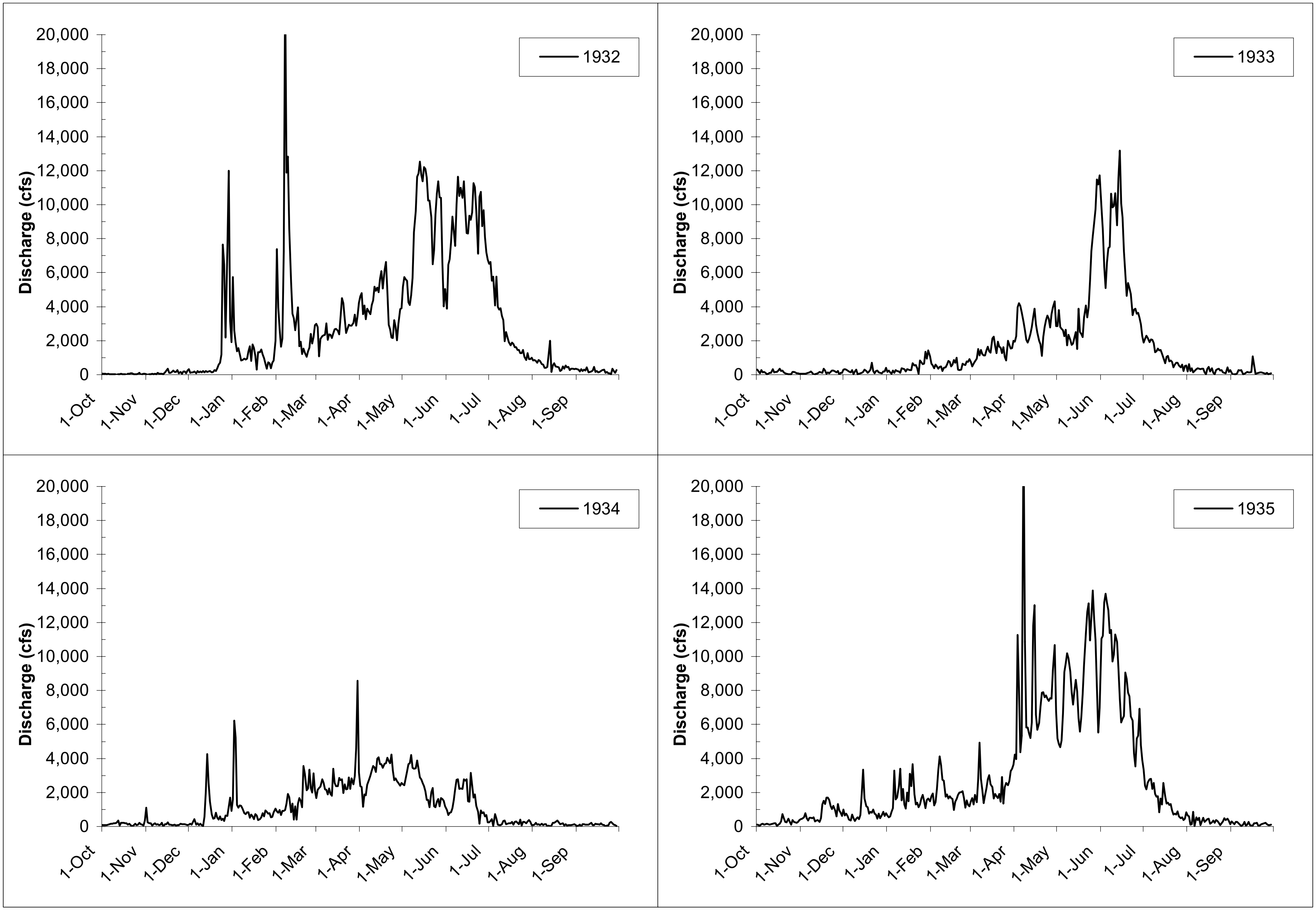
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



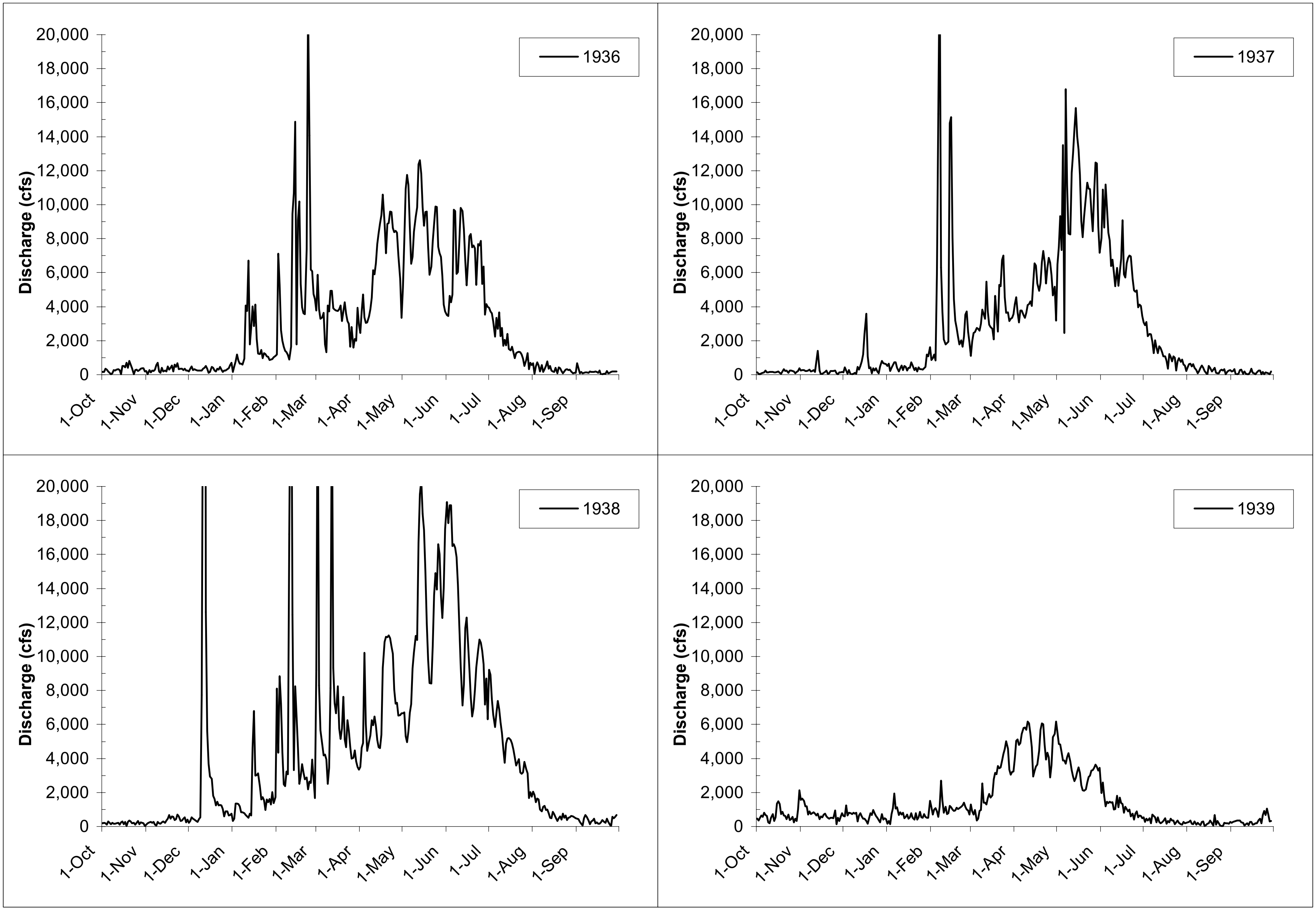
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



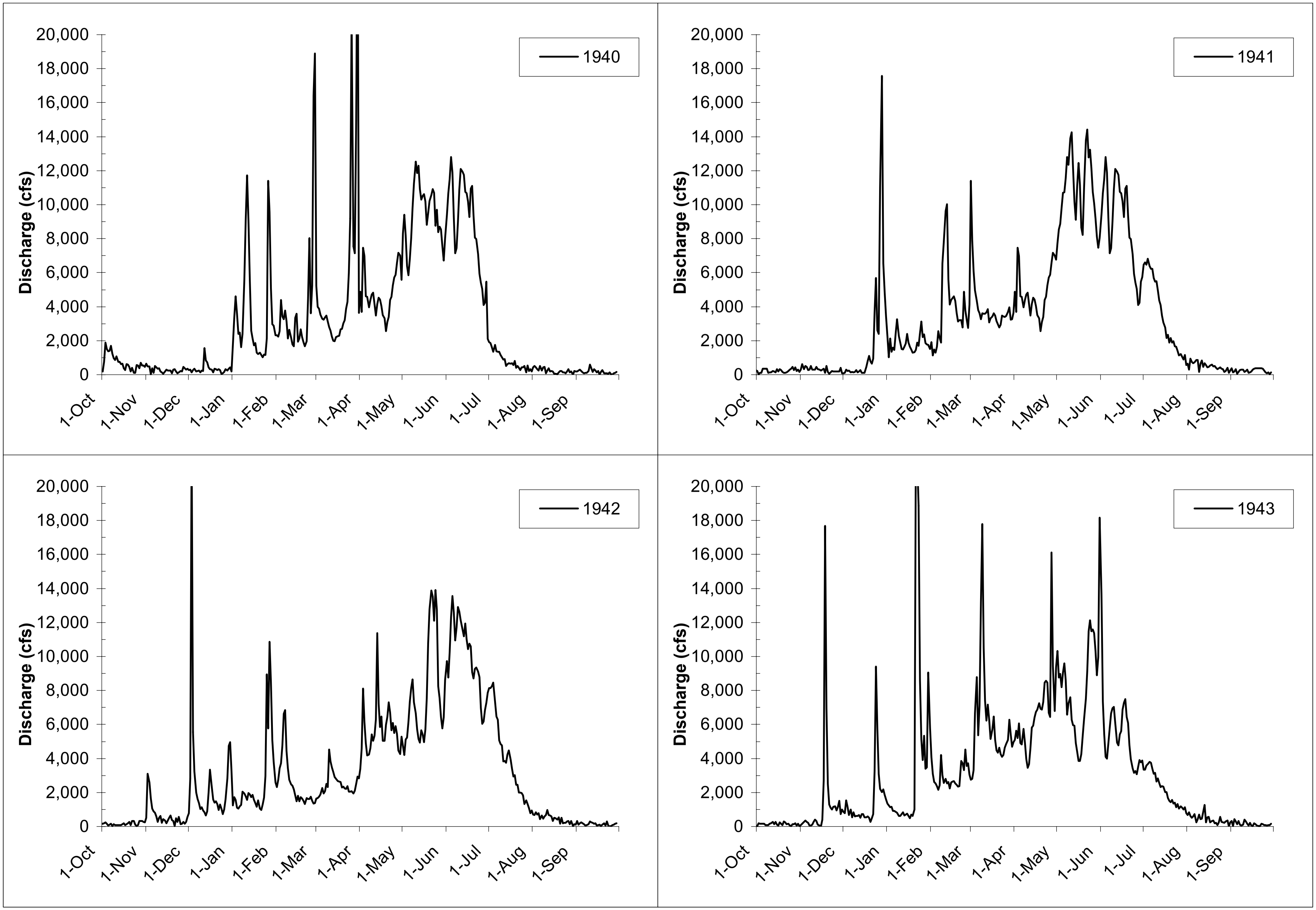
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



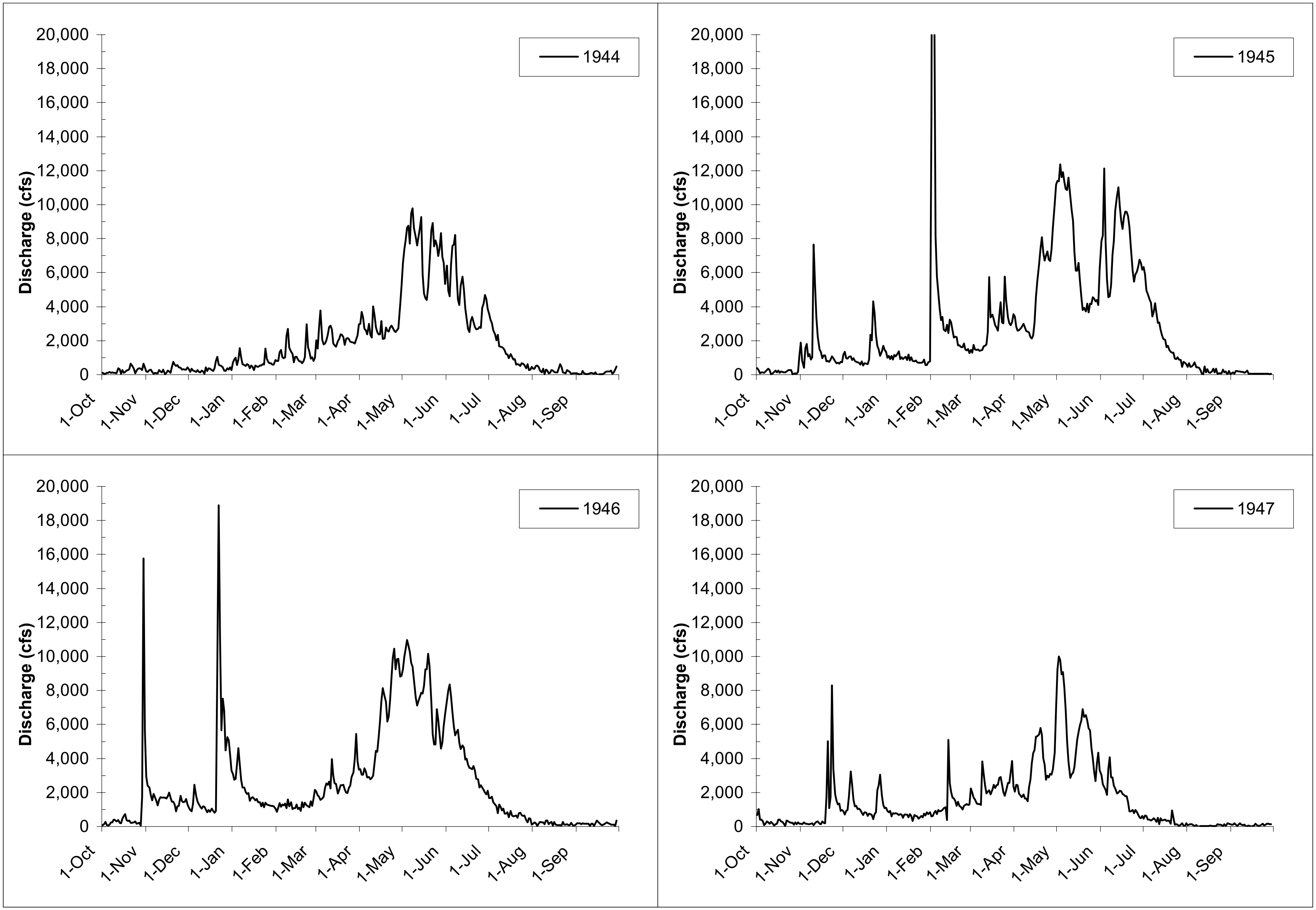
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



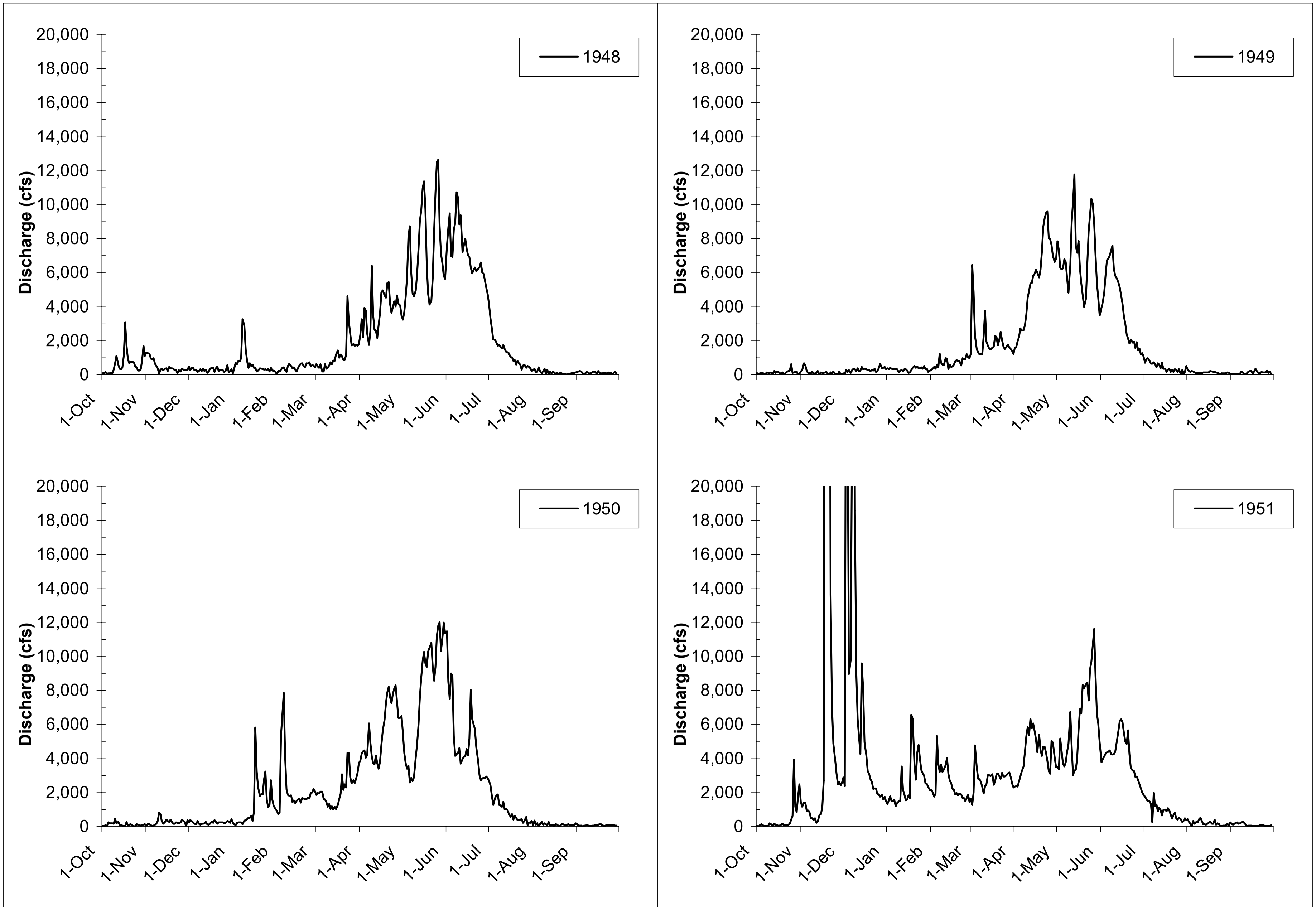
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



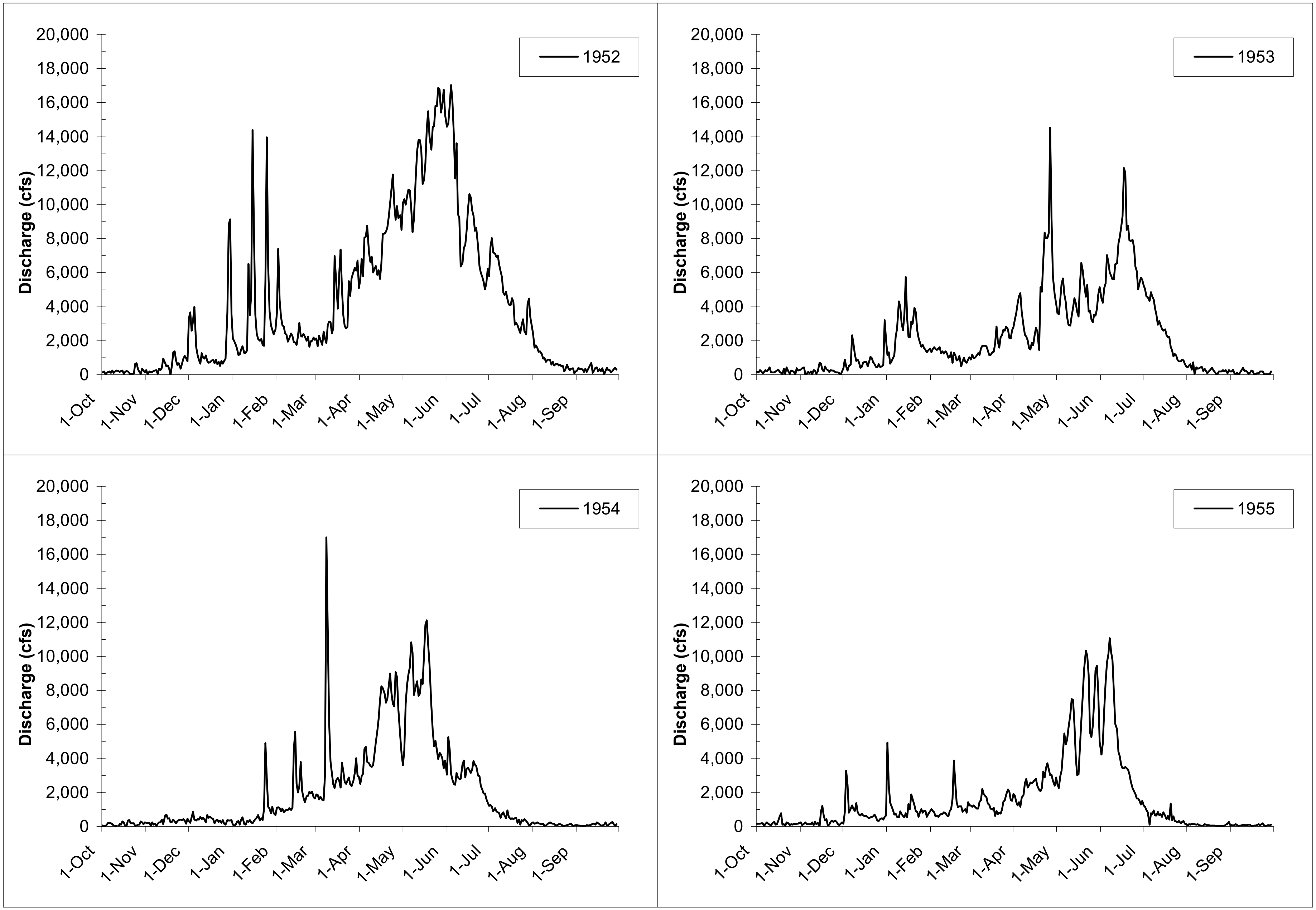
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



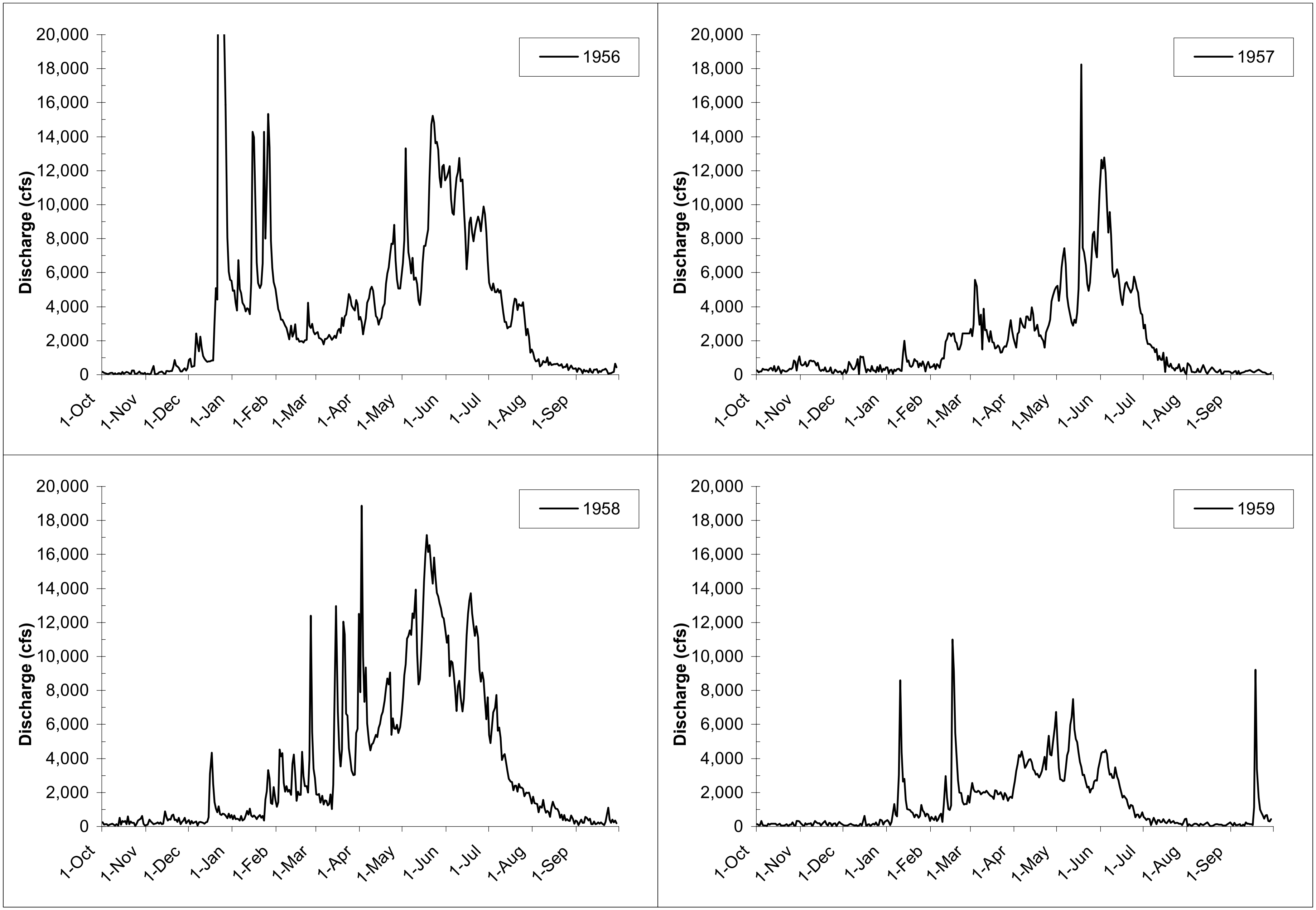
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



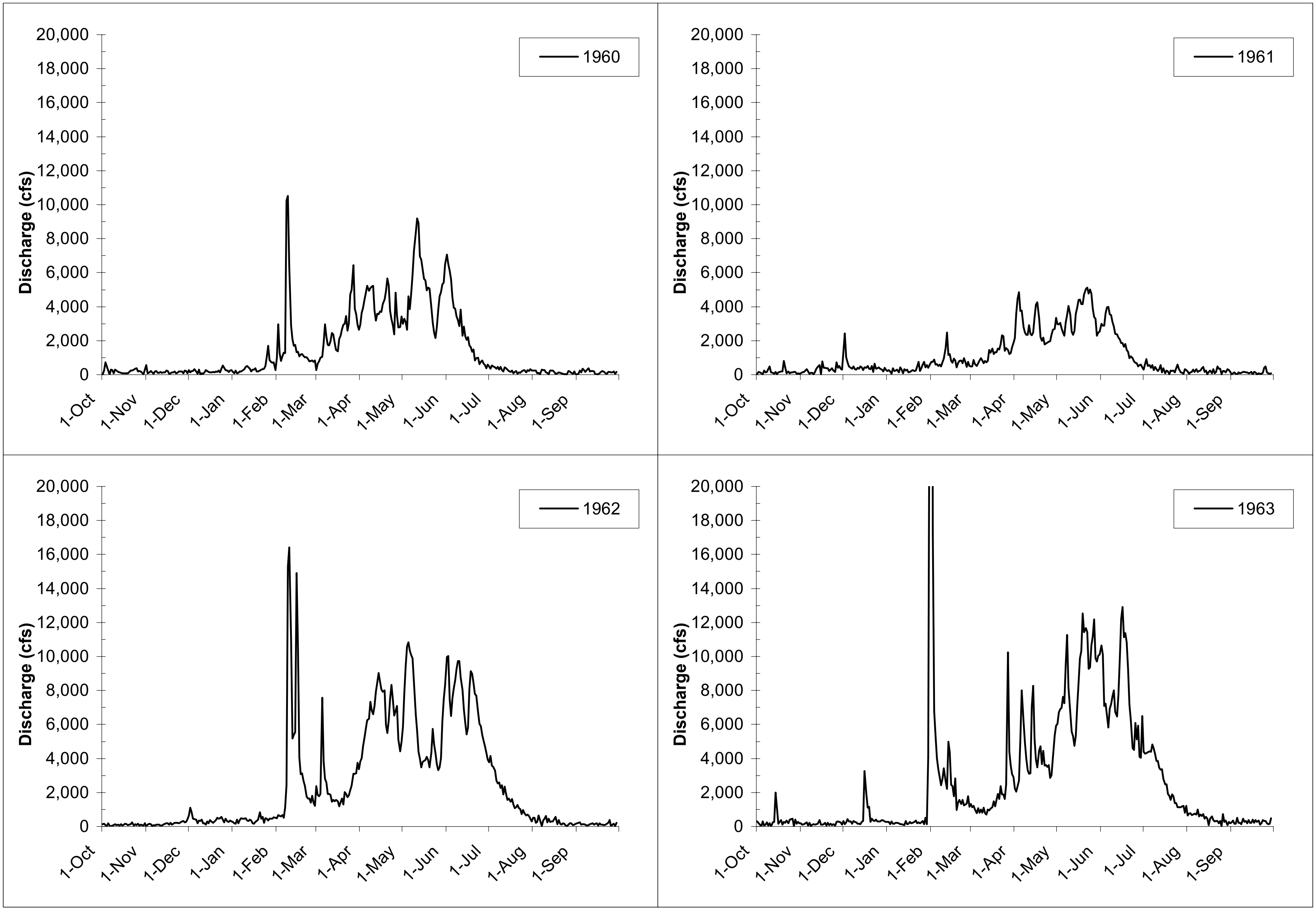
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



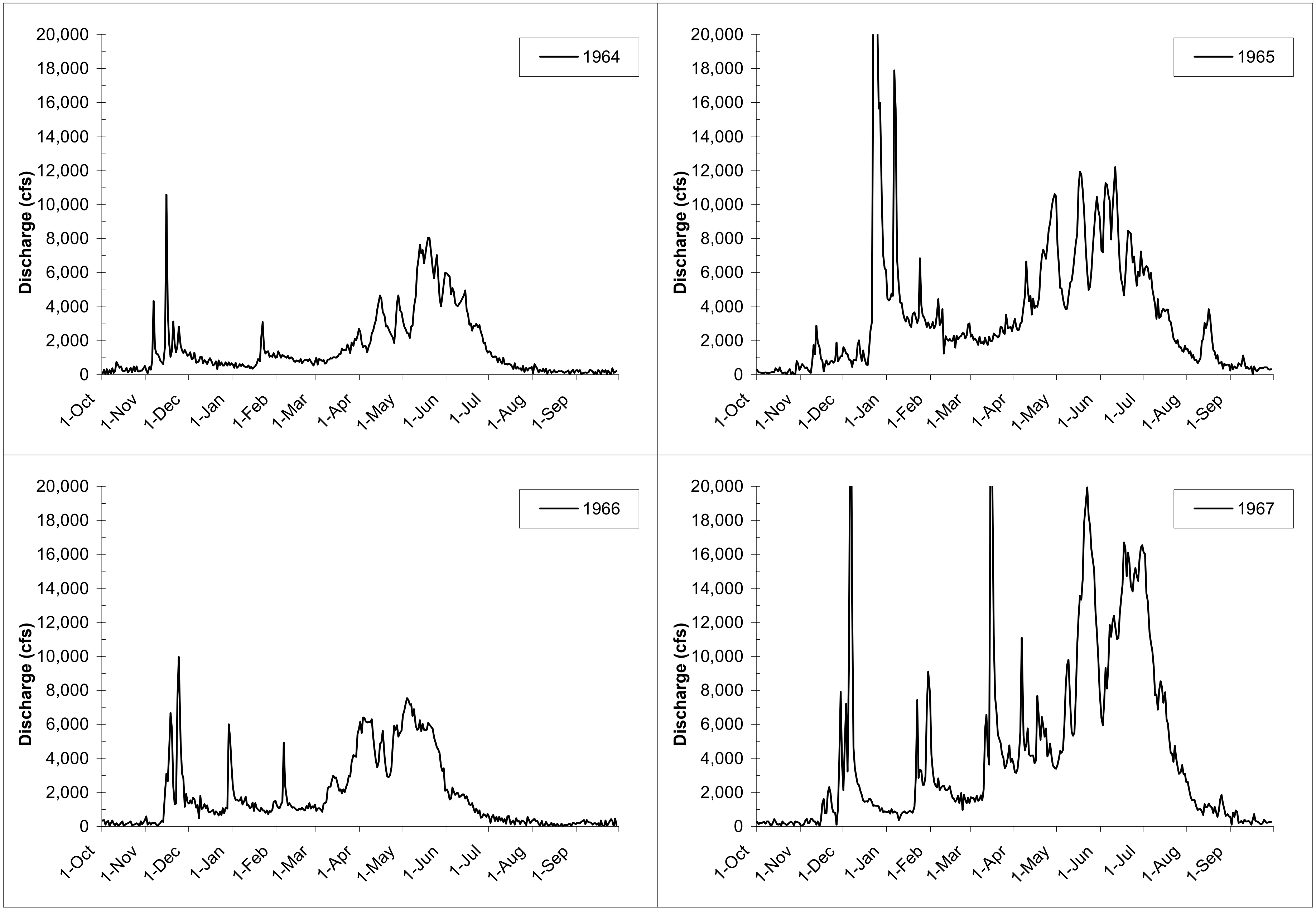
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



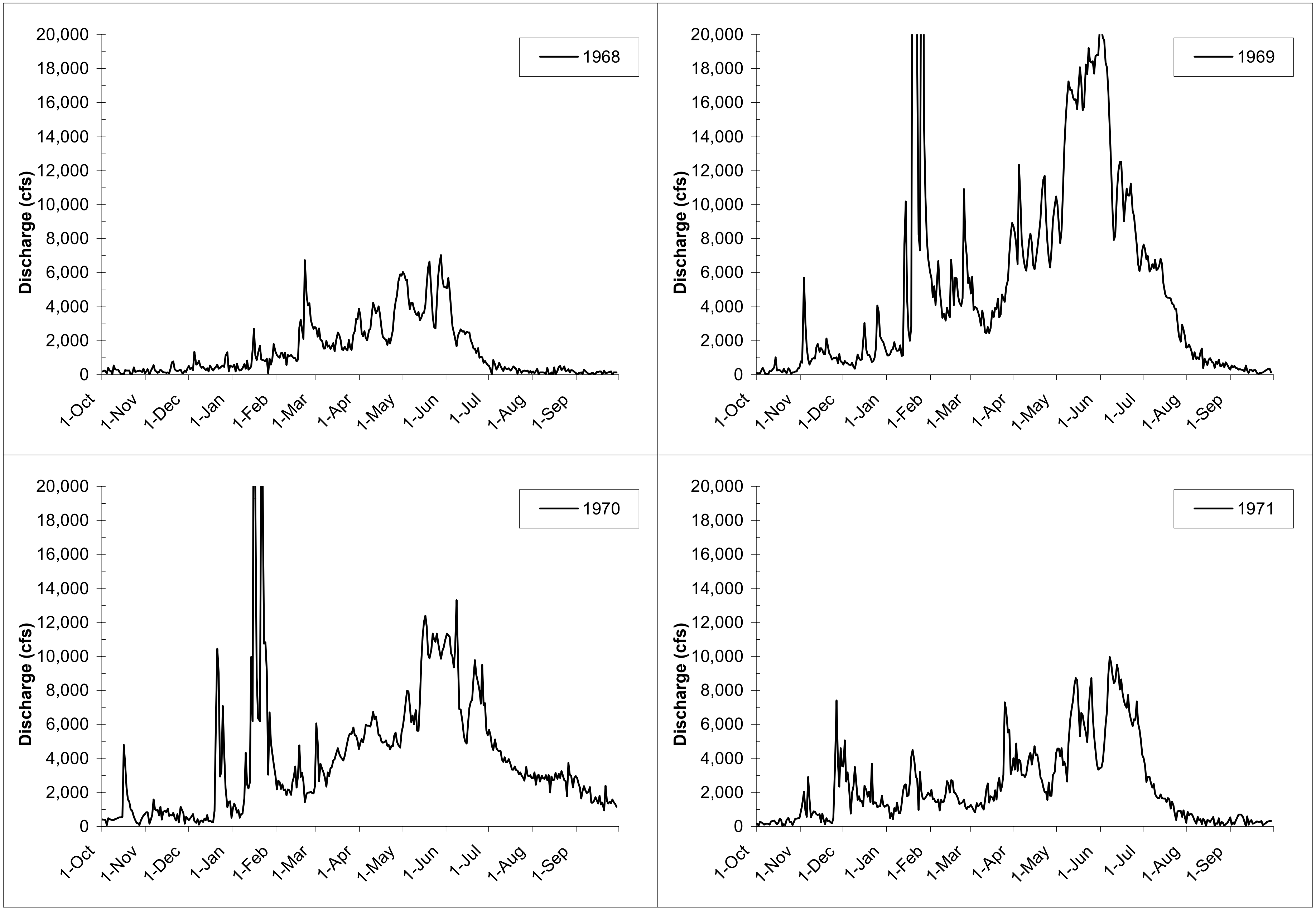
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



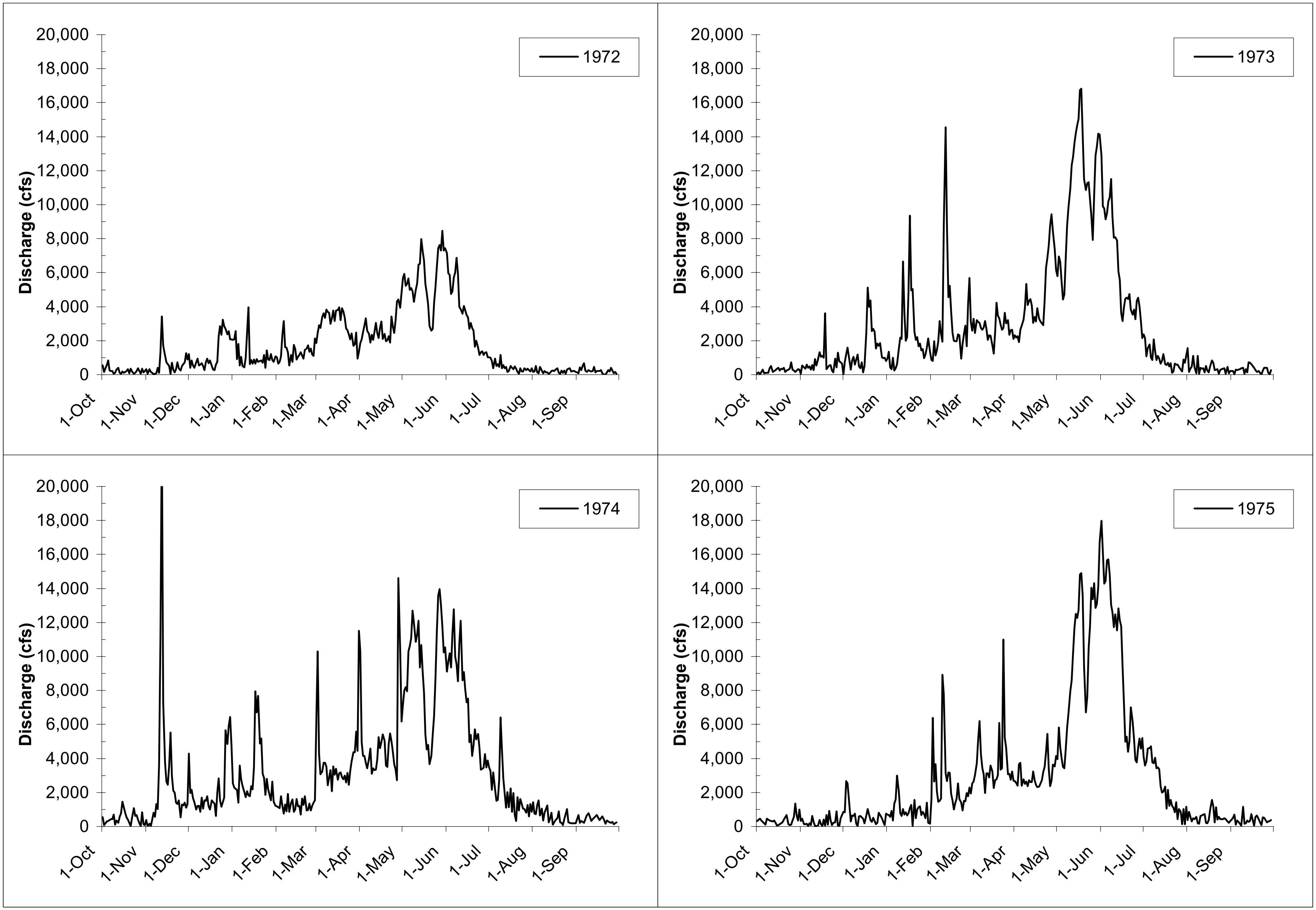
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



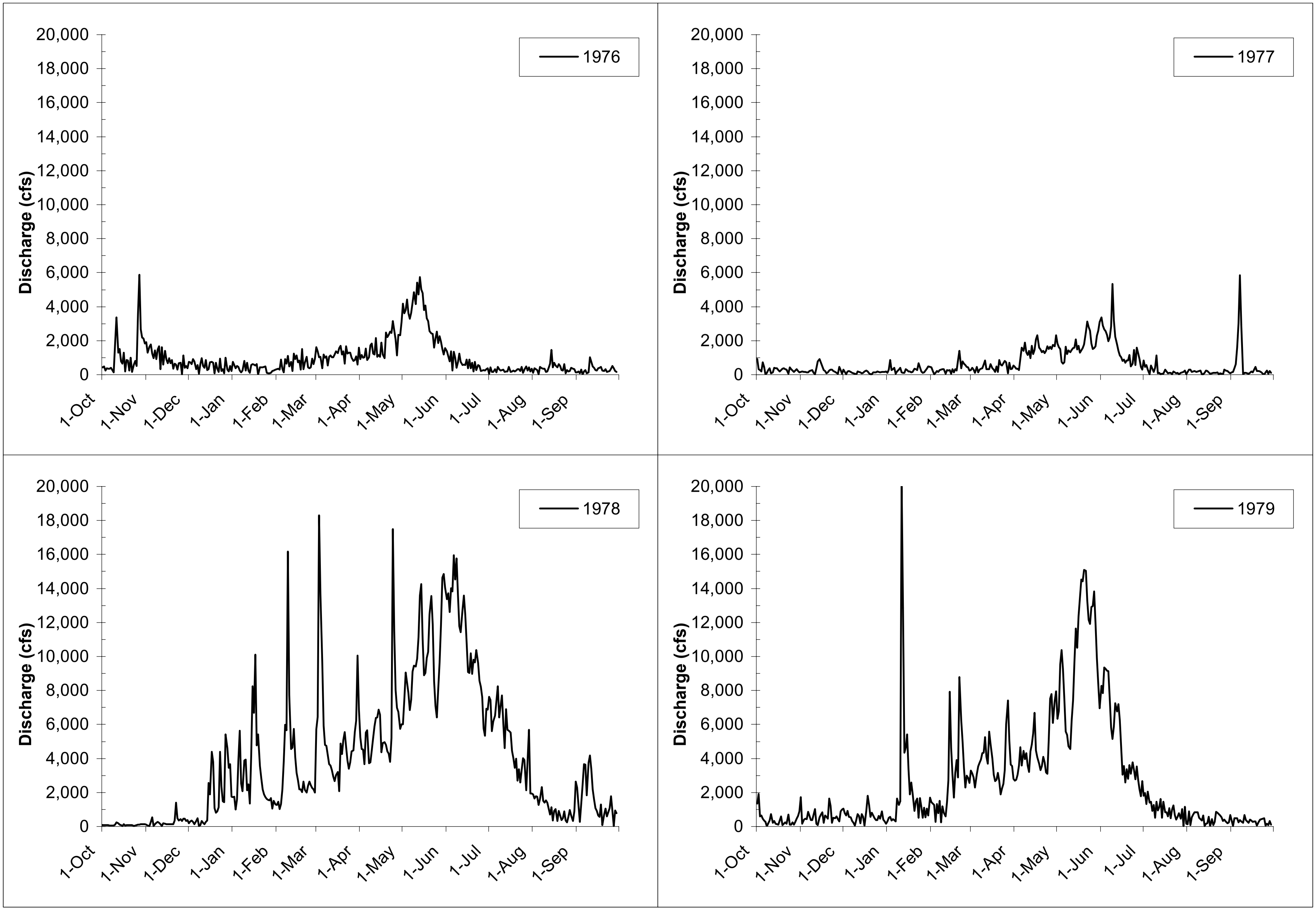
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



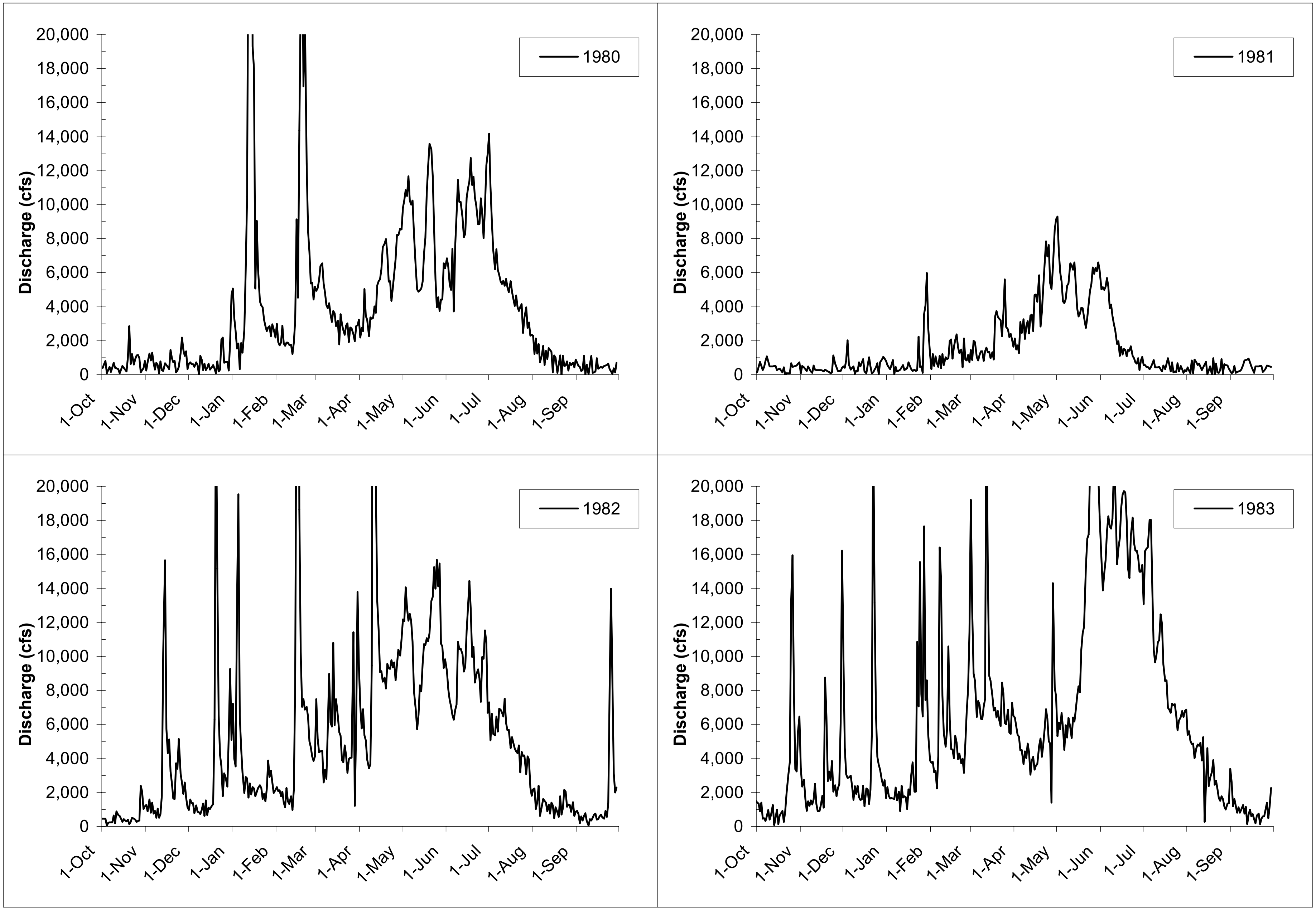
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



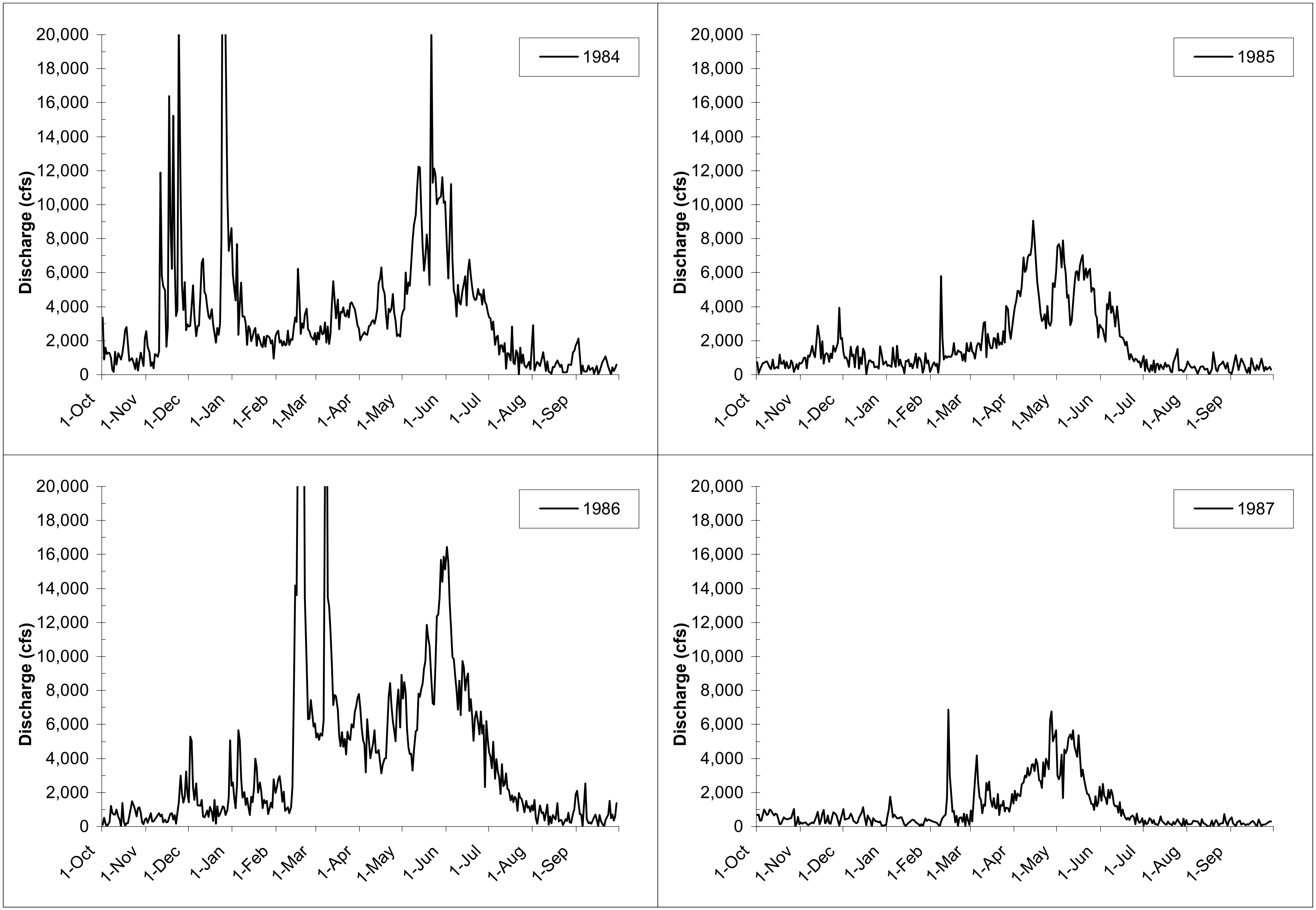
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



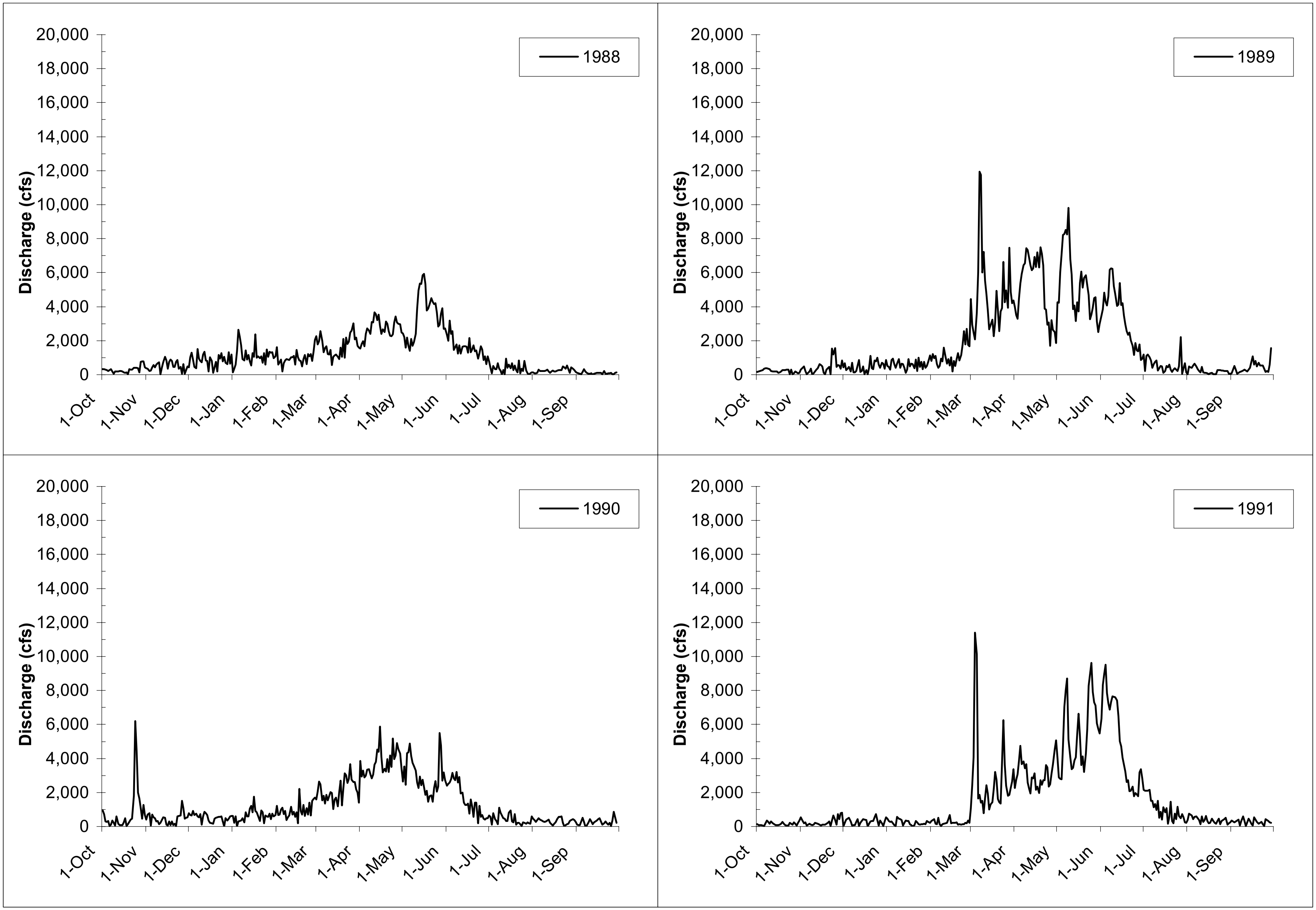
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



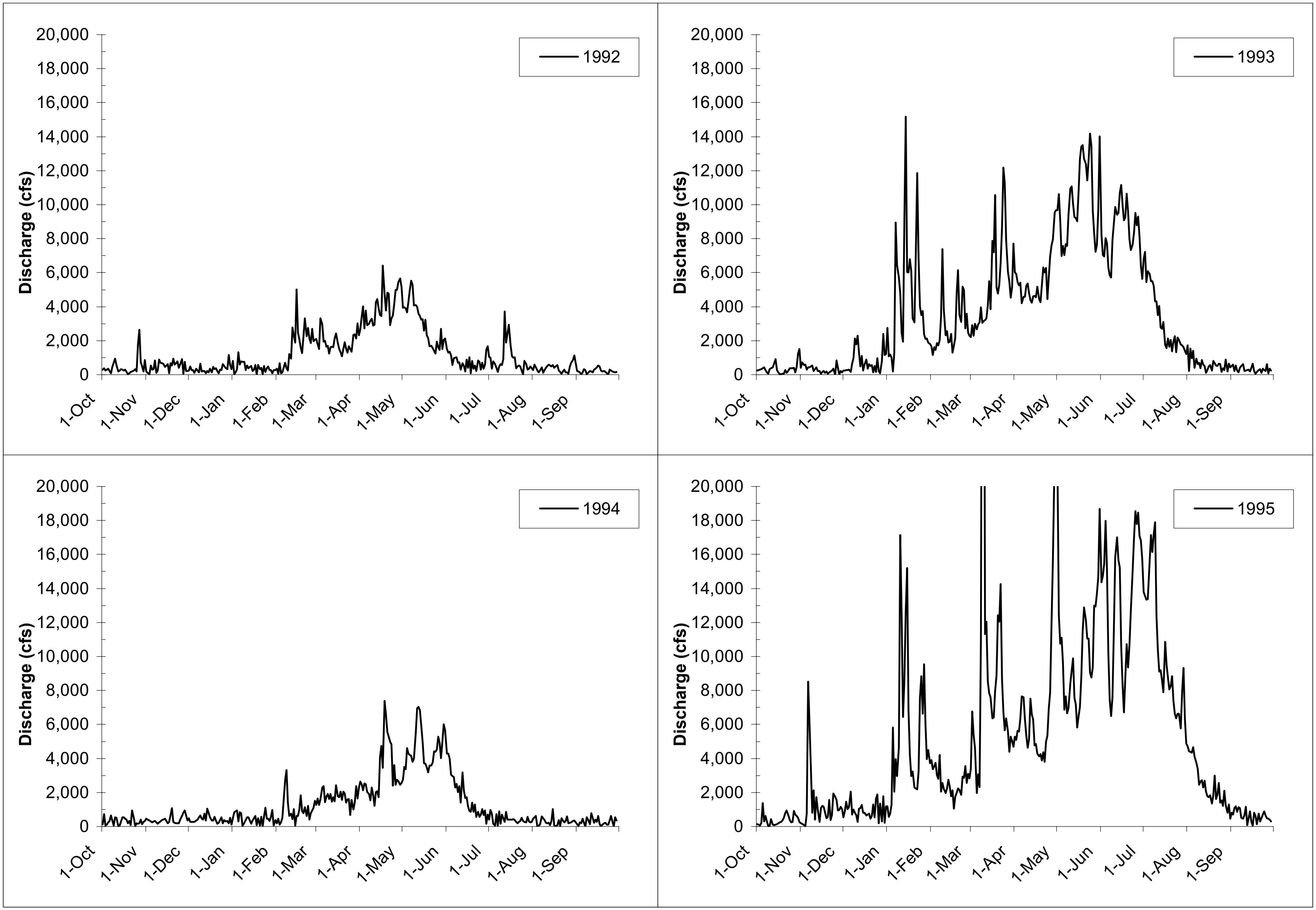
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



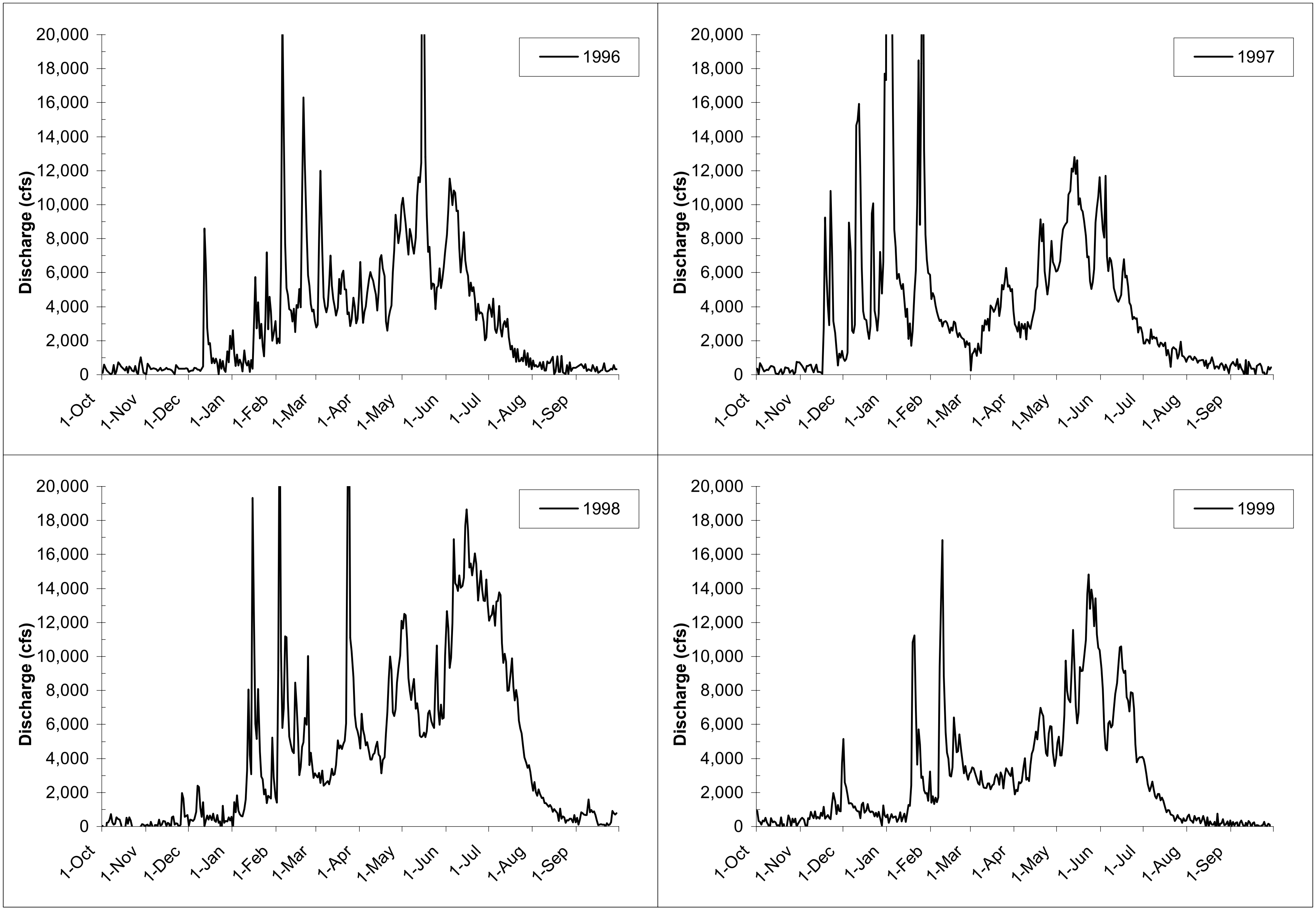
Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)



Tuolumne River at La Grange UNIMPAIRED hydrographs for WY1896-1999 (USGS11-289650)

APPENDIX F.

REGULATED HYDROLOGIC DATA FOR THE

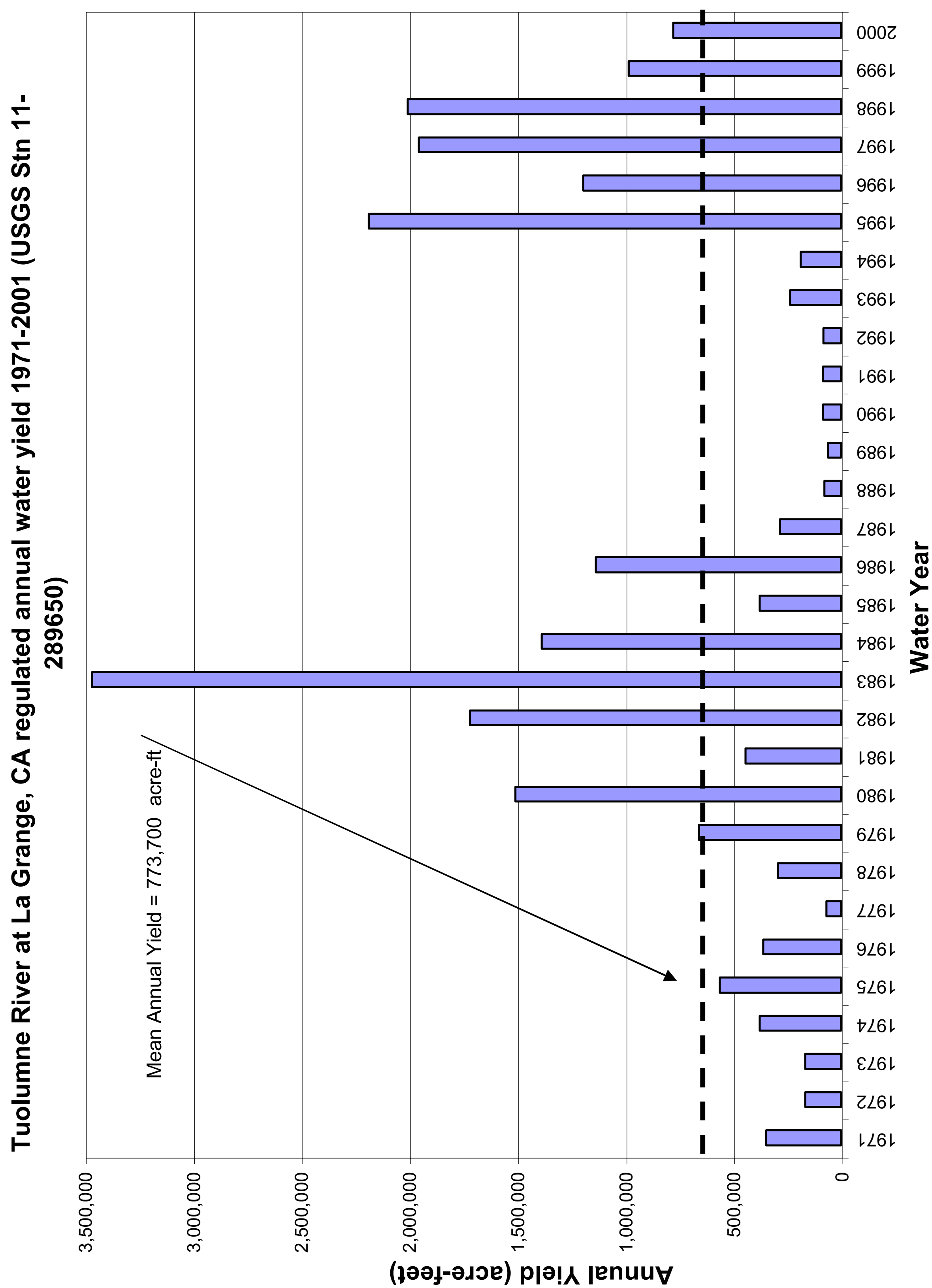
- TUOLUMNE RIVER

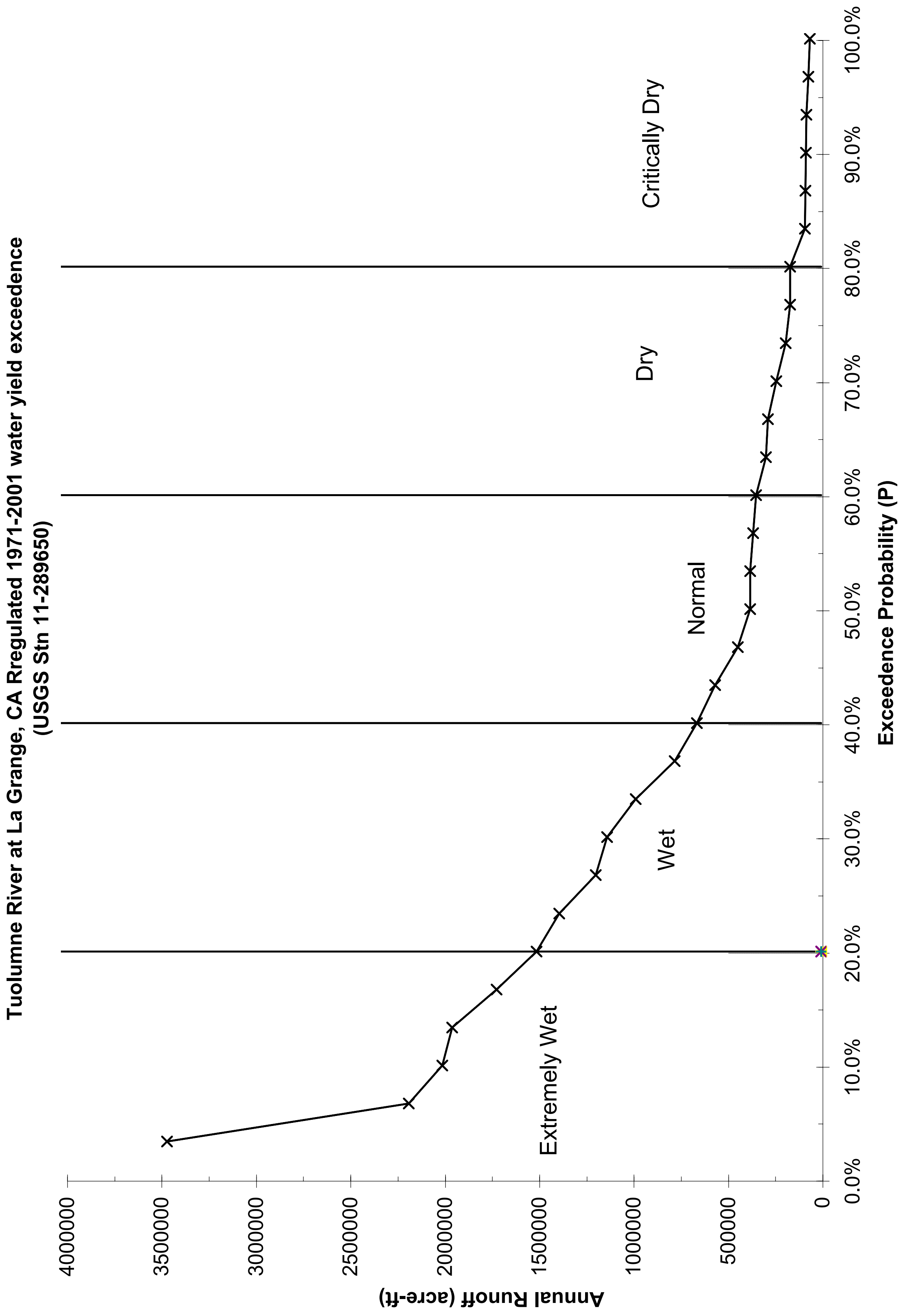
INCLUDING:

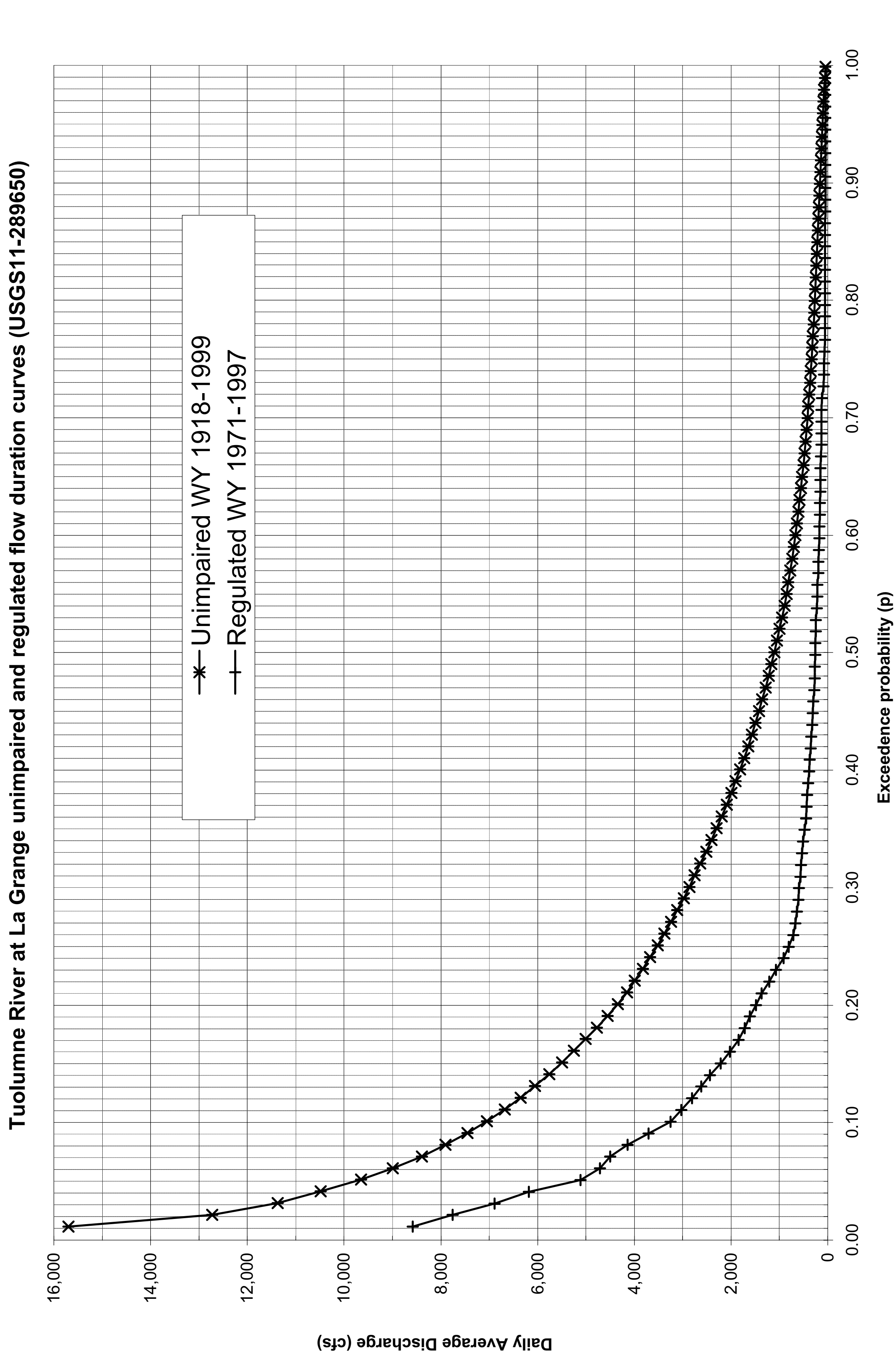
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

Tuolumne River at La Grange, CA regulated water yield 1971-2001 (USGS Stn 11-289650)

WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1971	345,889	NORMAL	60.0%	18
1972	165,266	DRY	76.7%	23
1973	165,014	DRY	80.0%	24
1974	375,652	NORMAL	53.3%	16
1975	561,473	NORMAL	43.3%	13
1976	361,002	NORMAL	56.7%	17
1977	67,115	CRITICALLY DRY	96.7%	29
1978	292,052	DRY	63.3%	19
1979	657,186	WET	40.0%	12
1980	1,507,251	EXTREMELY WET	20.0%	6
1981	441,488	NORMAL	46.7%	14
1982	1,718,285	EXTREMELY WET	16.7%	5
1983	3,464,878	EXTREMELY WET	3.3%	1
1984	1,386,117	WET	23.3%	7
1985	376,094	NORMAL	50.0%	15
1986	1,133,989	WET	30.0%	9
1987	283,365	DRY	66.7%	20
1988	77,853	CRITICALLY DRY	93.3%	28
1989	61,029	CRITICALLY DRY	100.0%	30
1990	84,964	CRITICALLY DRY	83.3%	25
1991	83,115	CRITICALLY DRY	86.7%	26
1992	80,791	CRITICALLY DRY	90.0%	27
1993	236,660	DRY	70.0%	21
1994	187,313	DRY	73.3%	22
1995	2,184,597	EXTREMELY WET	6.7%	2
1996	1,193,843	WET	26.7%	8
1997	1,954,320	EXTREMELY WET	13.3%	4
1998	2,006,106	EXTREMELY WET	10.0%	3
1999	982,980	WET	33.3%	10
2000	776,087	WET	36.7%	11

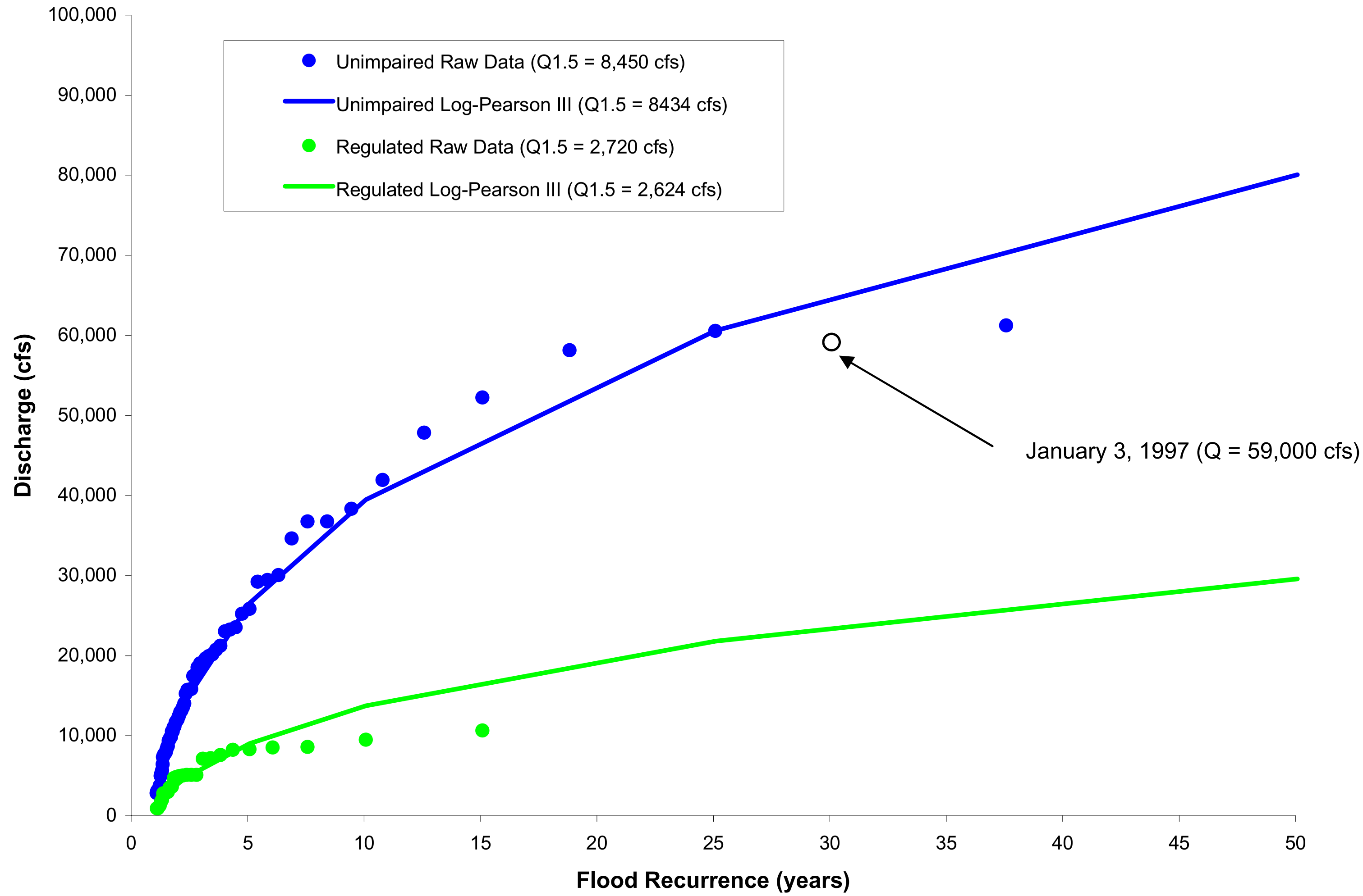

Tuolumne River at La Grange, CA regulated annual water yield 1971-2001 (USGS Stn 11-289650)
Mean Annual Yield = 773,700 acre-ft
Annual Yield (acre-feet)
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Water Year
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000

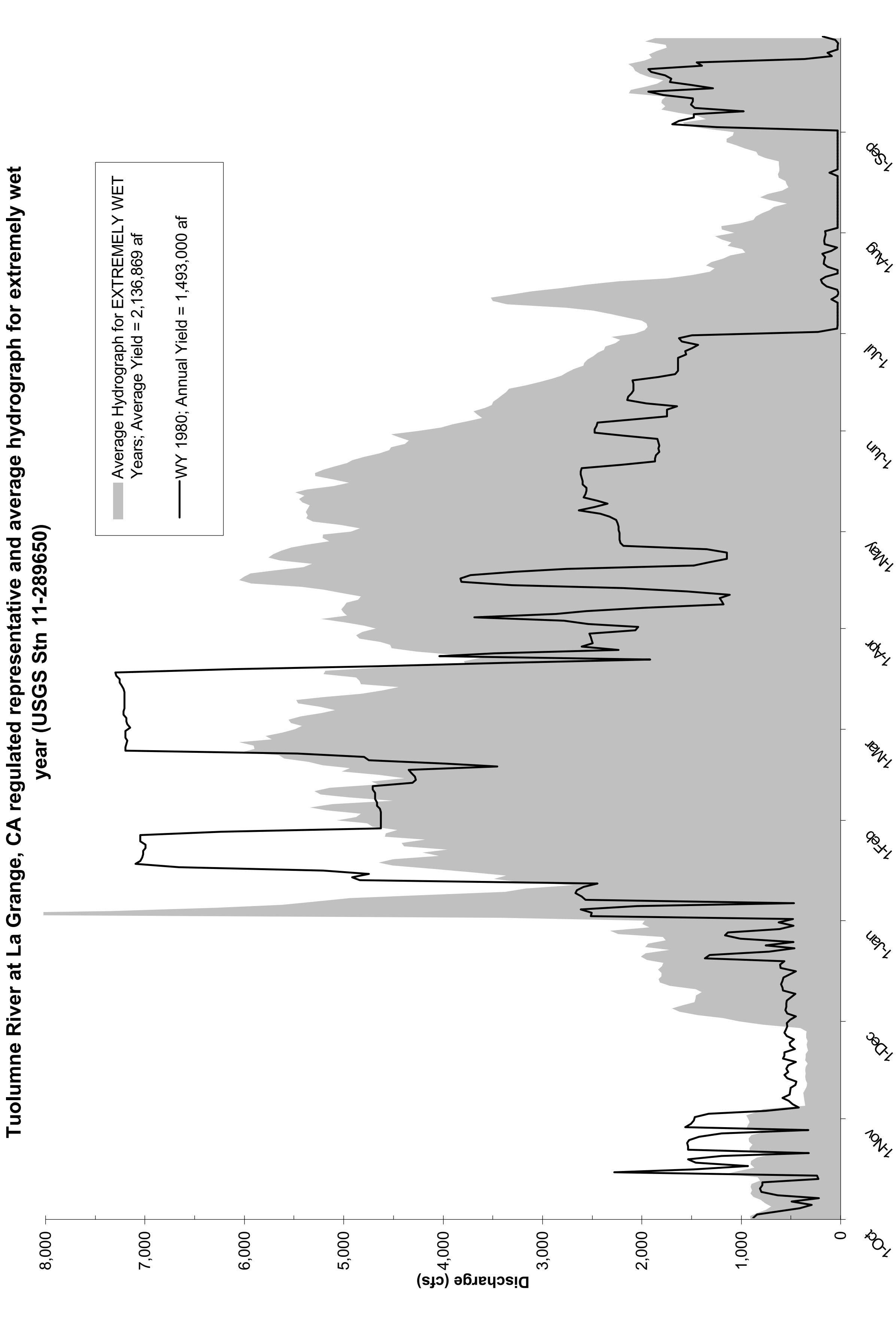

Tuolumne River at La Grange, CA Rregulated 1971-2001 water yield exceedence
(USGS Stn 11-289650)
Annual Runoff (acre-ft)
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
Exceedence Probability (P)
0.0%
10.0%
20.0%
30.0%
40.0%
50.0%
60.0%
70.0%
80.0%
90.0%
100.0%
Extremely Wet
Wet
Normal
Dry
Critically Dry

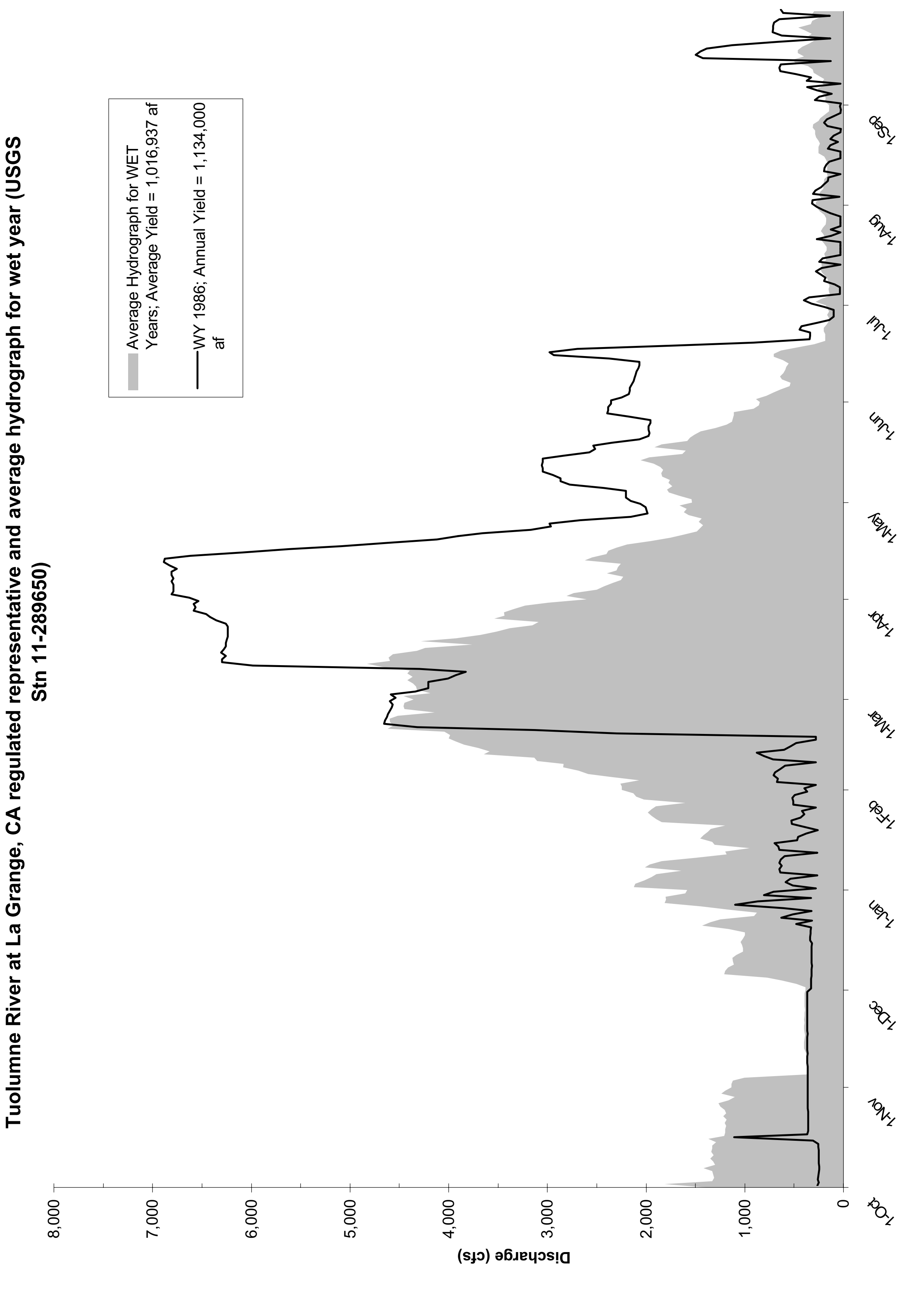


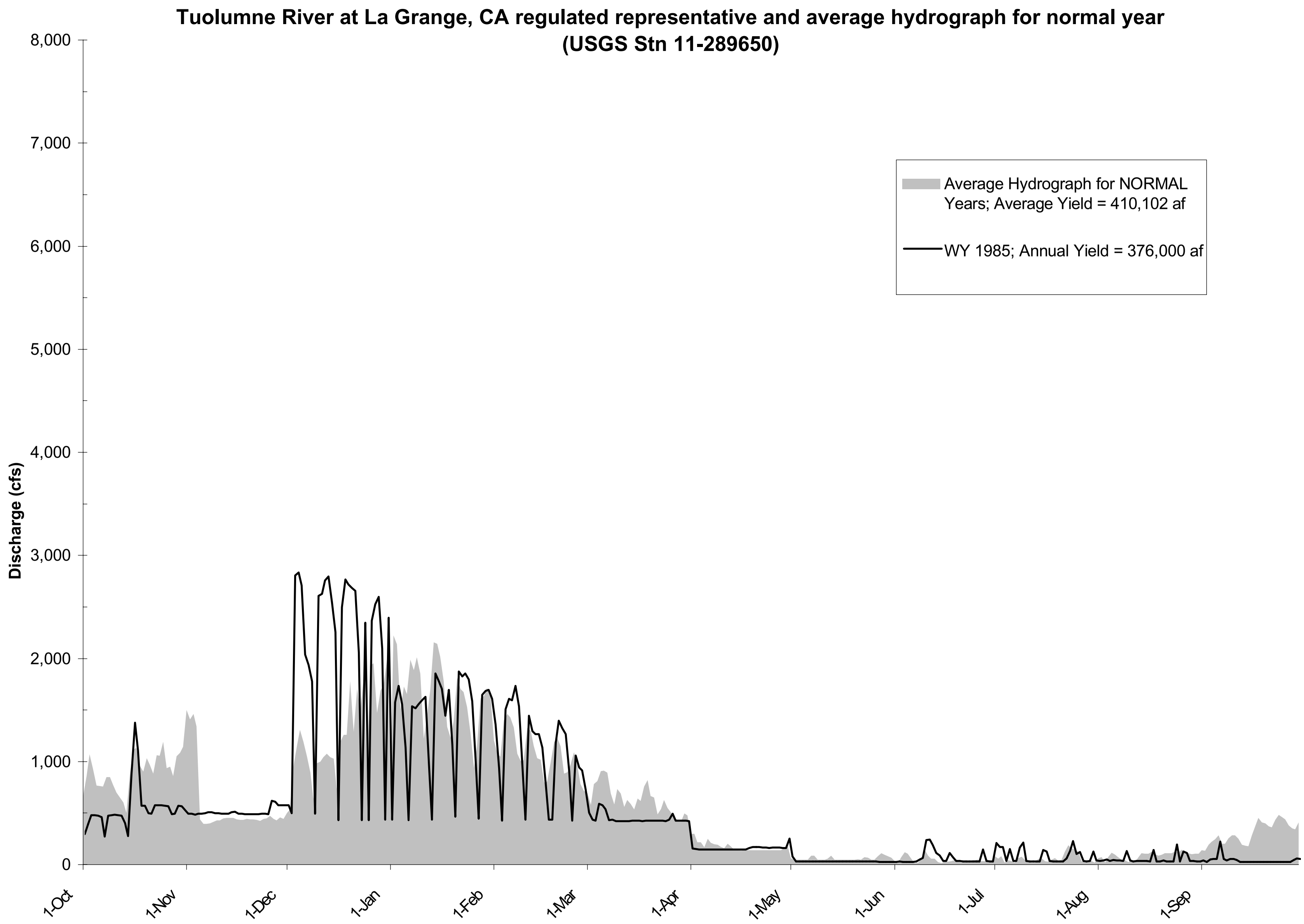
Tuolumne River at La Grange unimpaired and regulated flow duration curves (USGS11-289650)
Unimpaired WY 1918-1999
Regulated WY 1971-1997
Daily Average Discharge (cfs)
Exceedence probability (p)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

Tuolumne River at La Grange regulated and unimpaired flood frequency data (USGS11-289650)

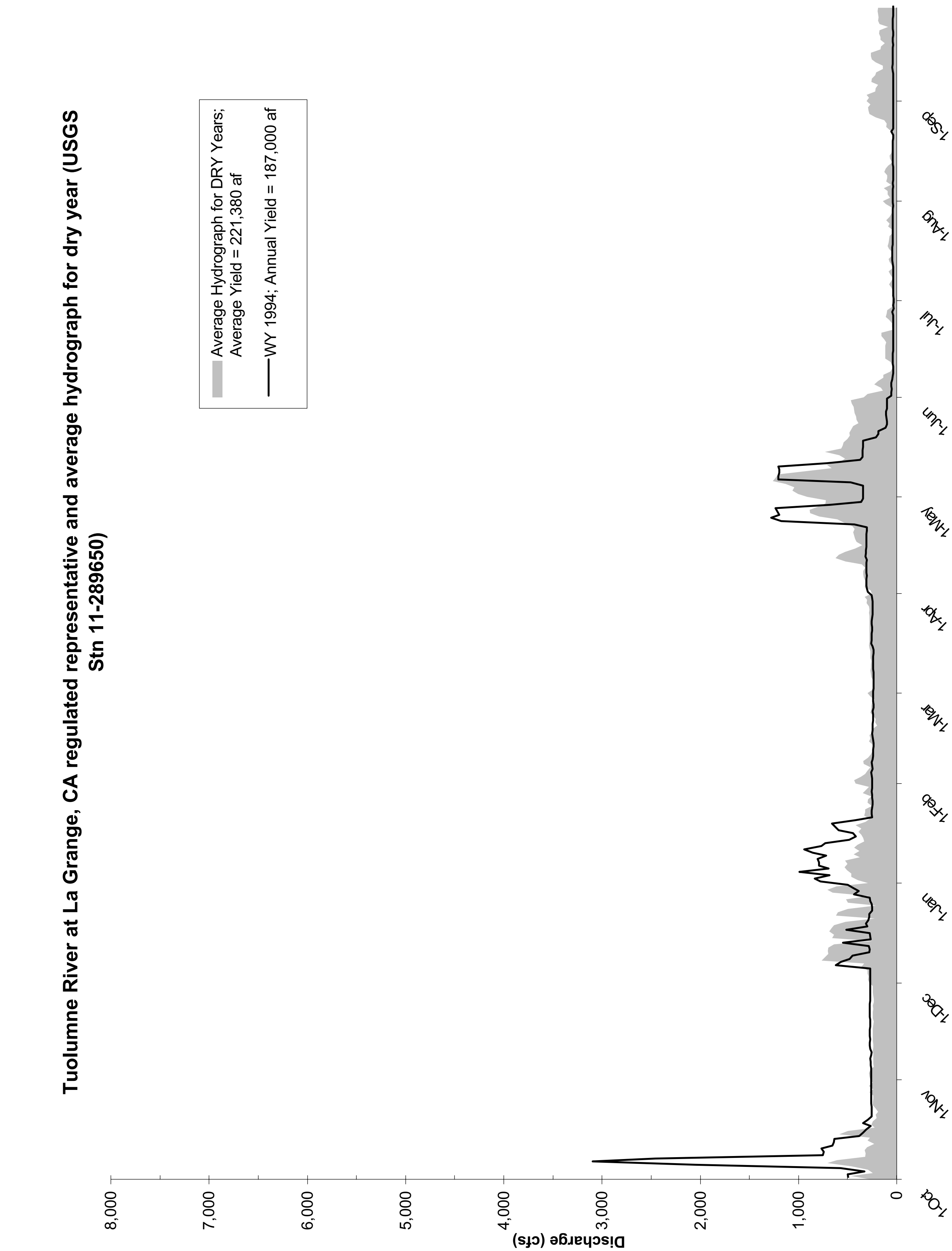



Tuolumne River at La Grange, CA regulated representative and average hydrograph for extremely wet year (USGS Stn 11-289650)
Average Hydrograph for EXTREMELY WET Years; Average Yield = 2,136,869 af
WY 1980; Annual Yield = 1,493,000 af
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

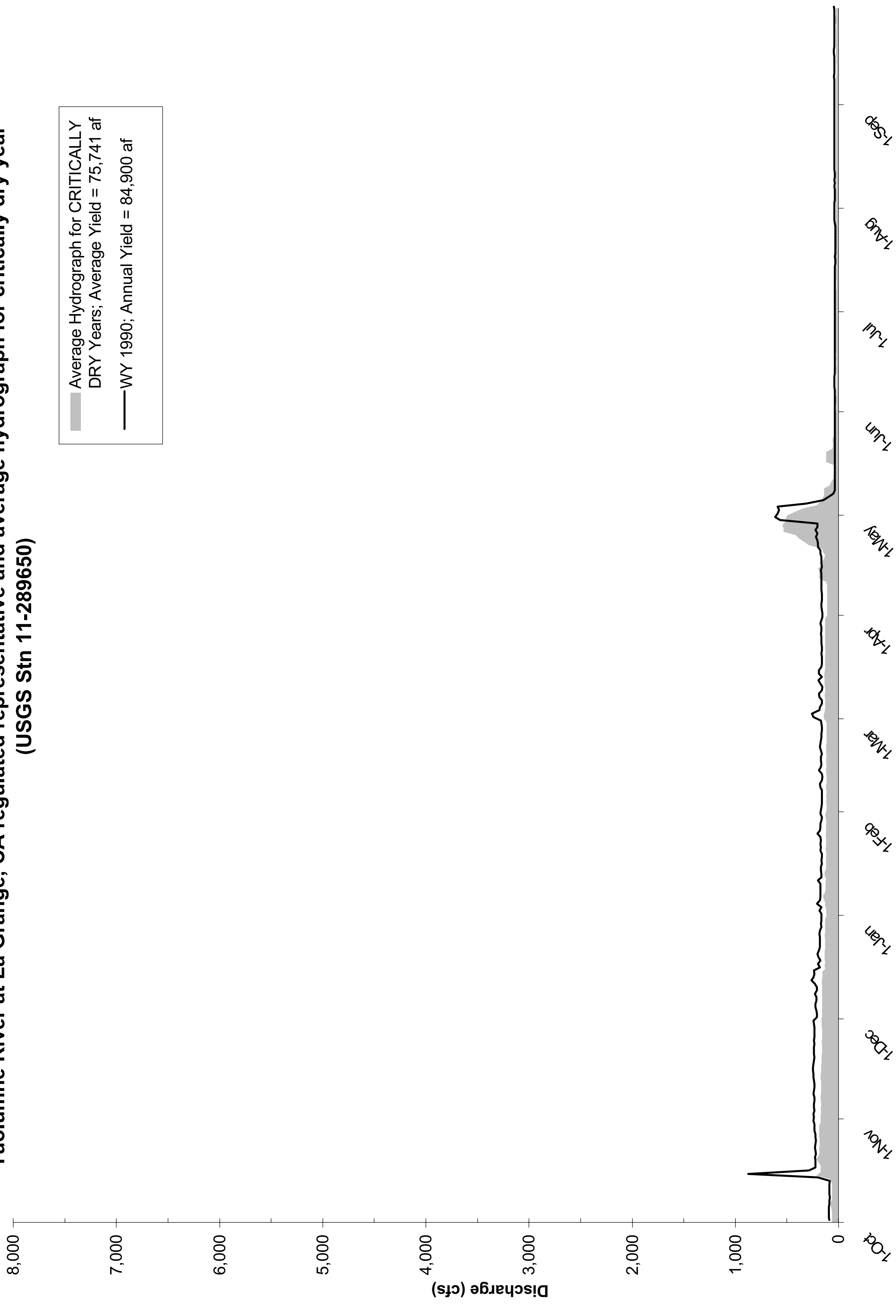

Tuolumne River at La Grange, CA regulated representative and average hydrograph for wet year (USGS Stn 11-289650)
Average Hydrograph for WET Years; Average Yield = 1,016,937 af
WY 1986; Annual Yield = 1,134,000 af
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

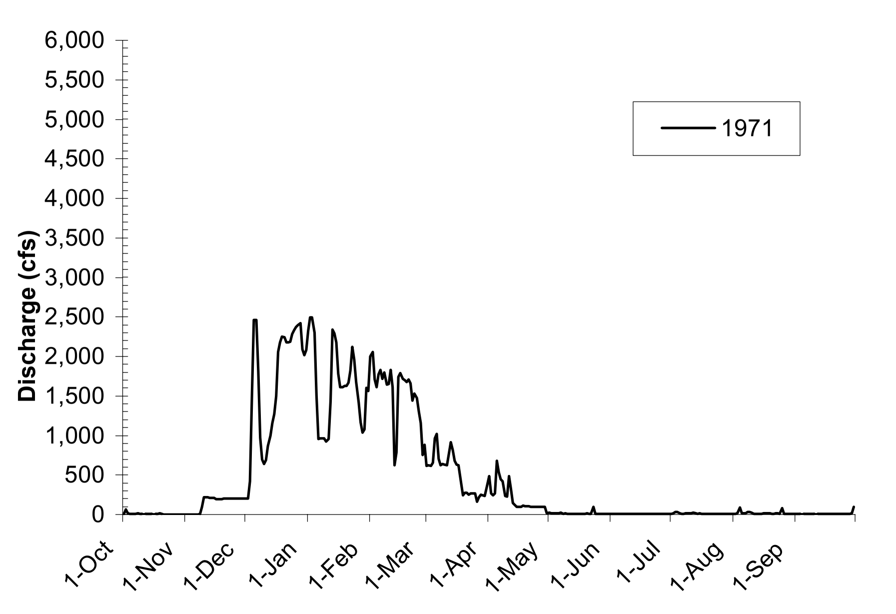

Tuolumne River at La Grange, CA regulated representative and average hydrograph for normal year
(USGS Stn 11-289650)
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Average Hydrograph for NORMAL Years; Average Yield = 410,102 af
WY 1985; Annual Yield = 376,000 af

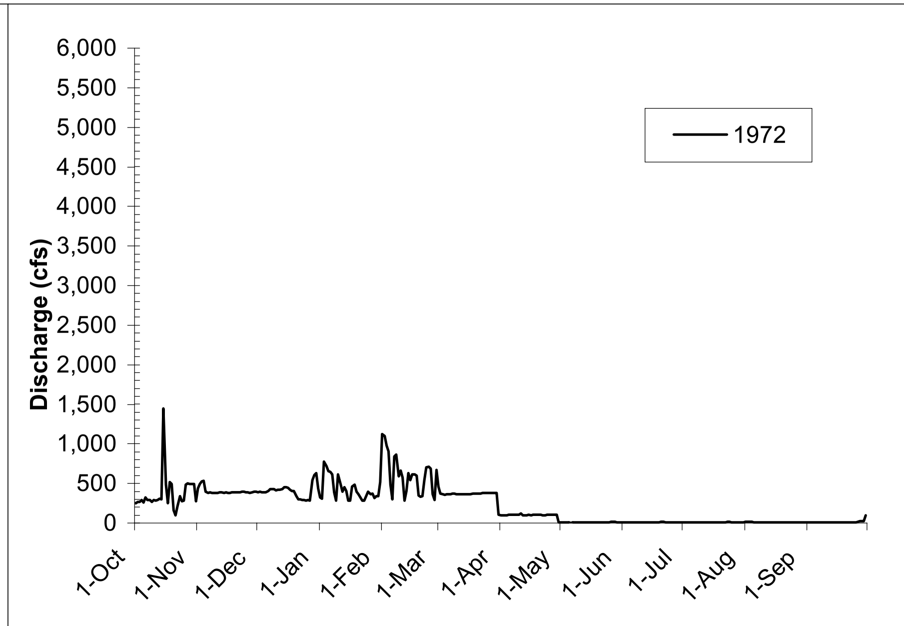
Tuolumne River at La Grange, CA regulated representative and average hydrograph for dry year (USGS Stn 11-289650)

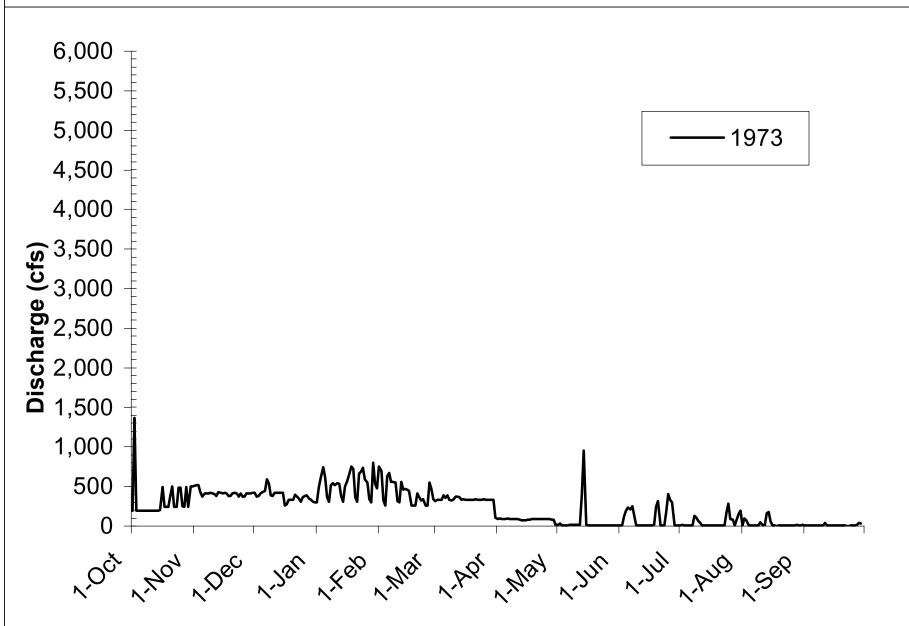


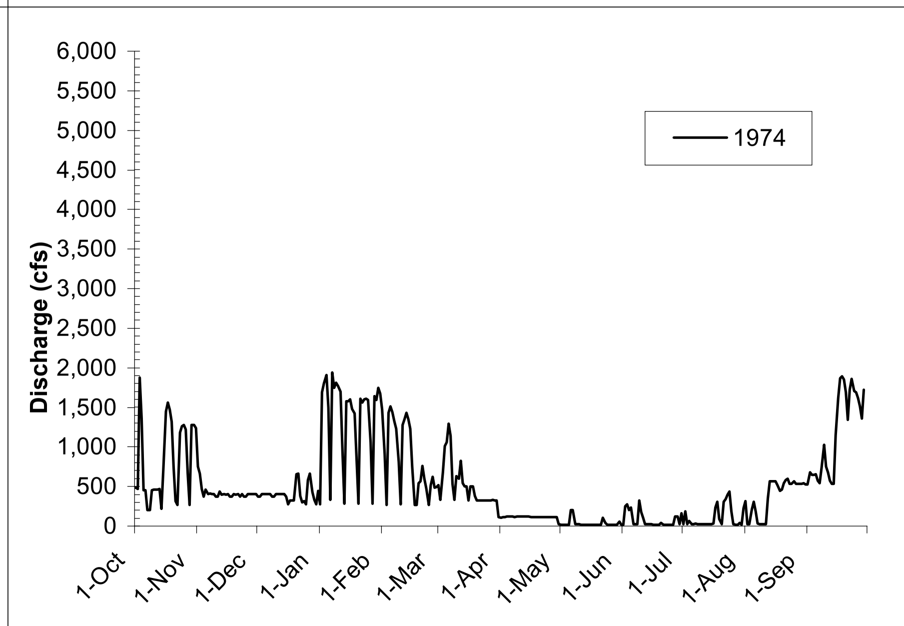
Tuolumne River at La Grange, CA regulated representative and average hydrograph for critically dry year (USGS Stn 11-289650)



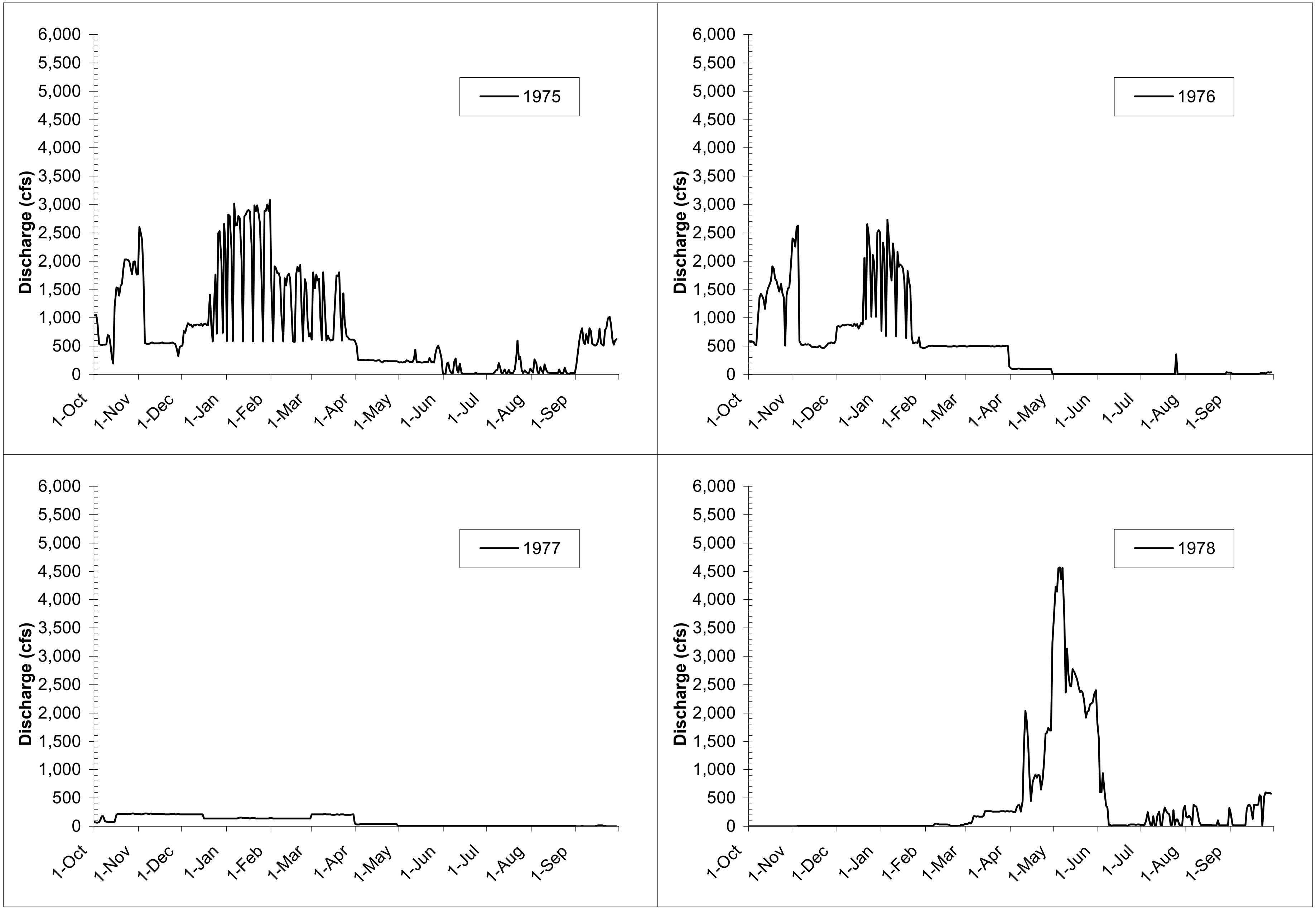




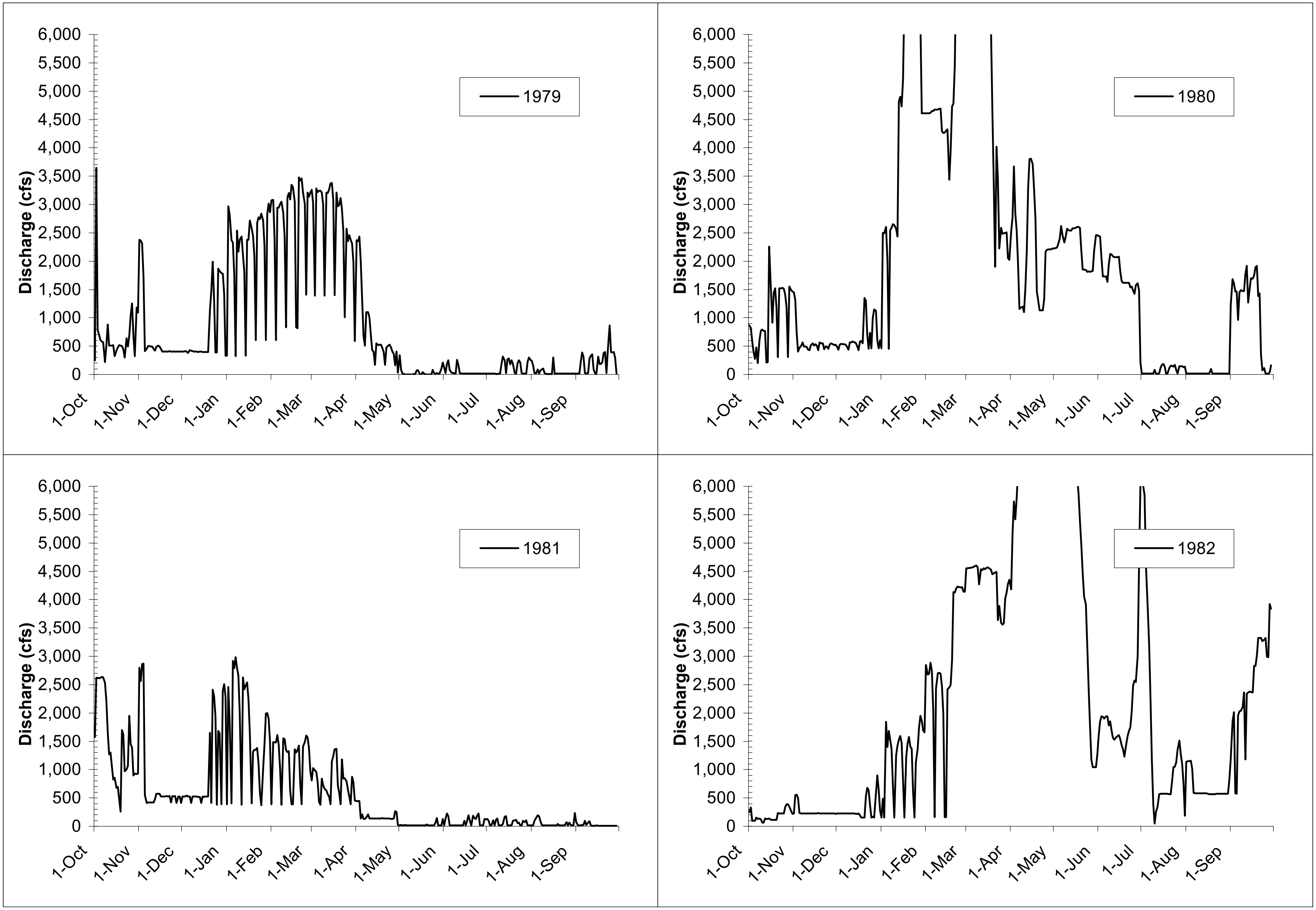




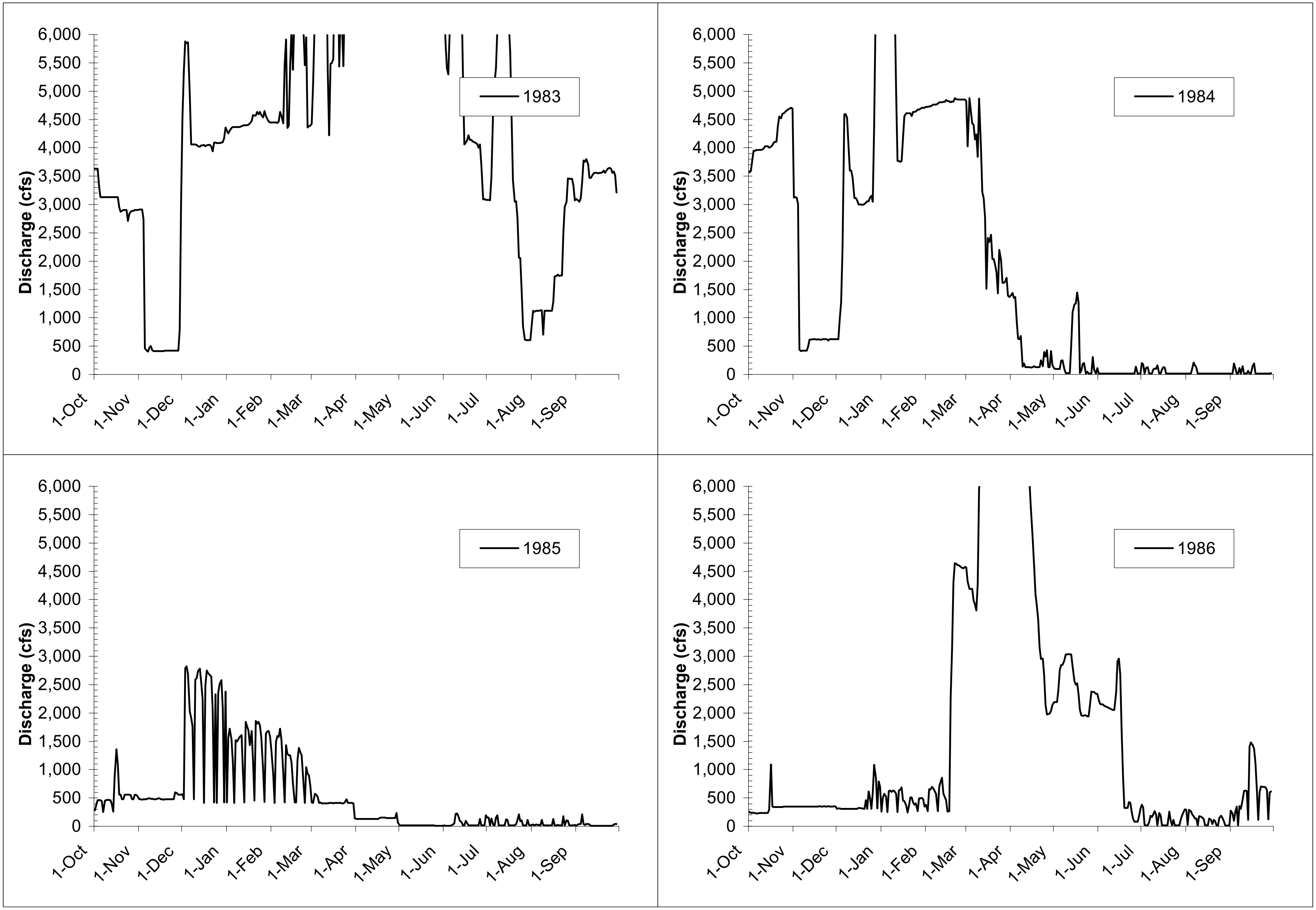
Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



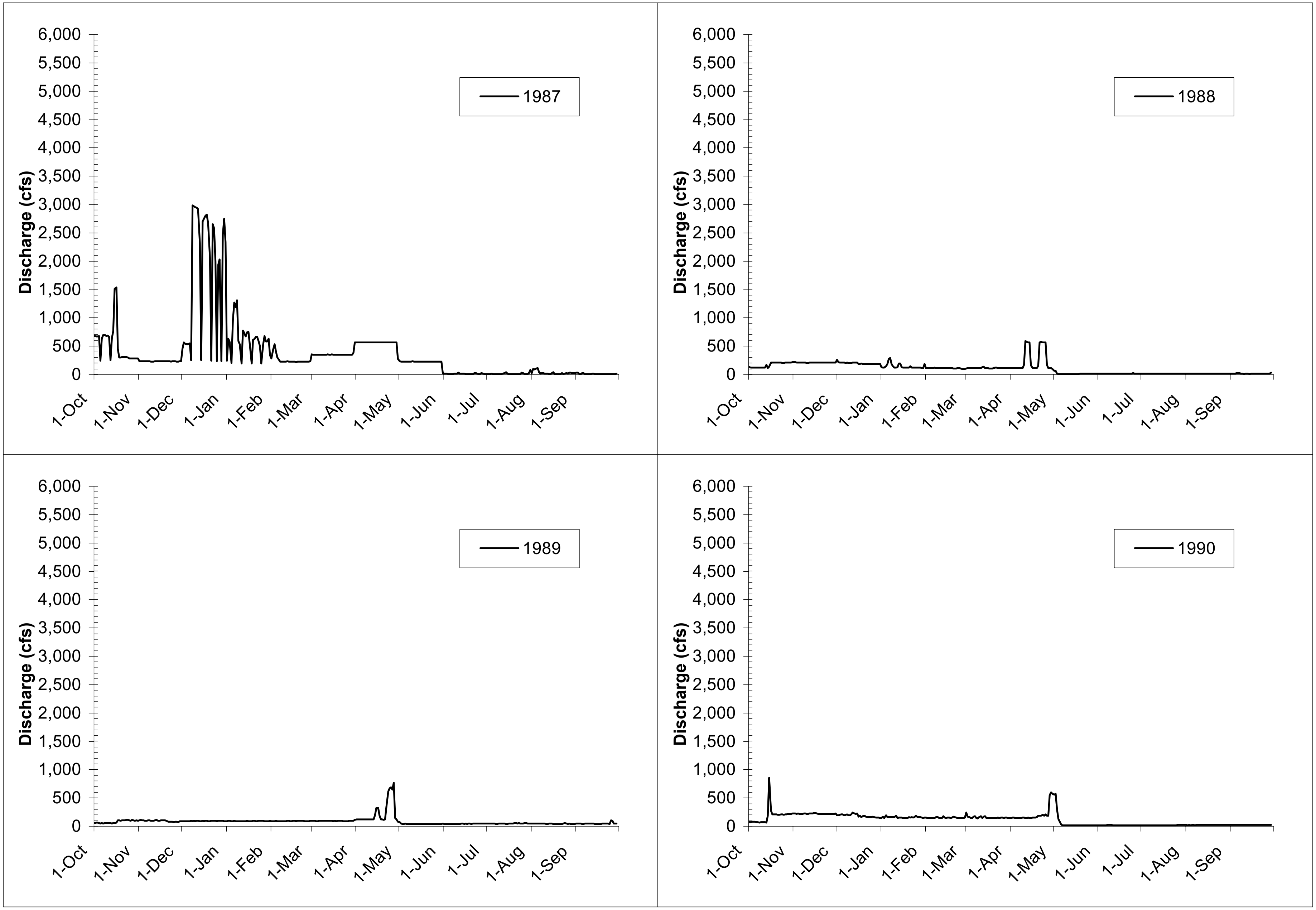
Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



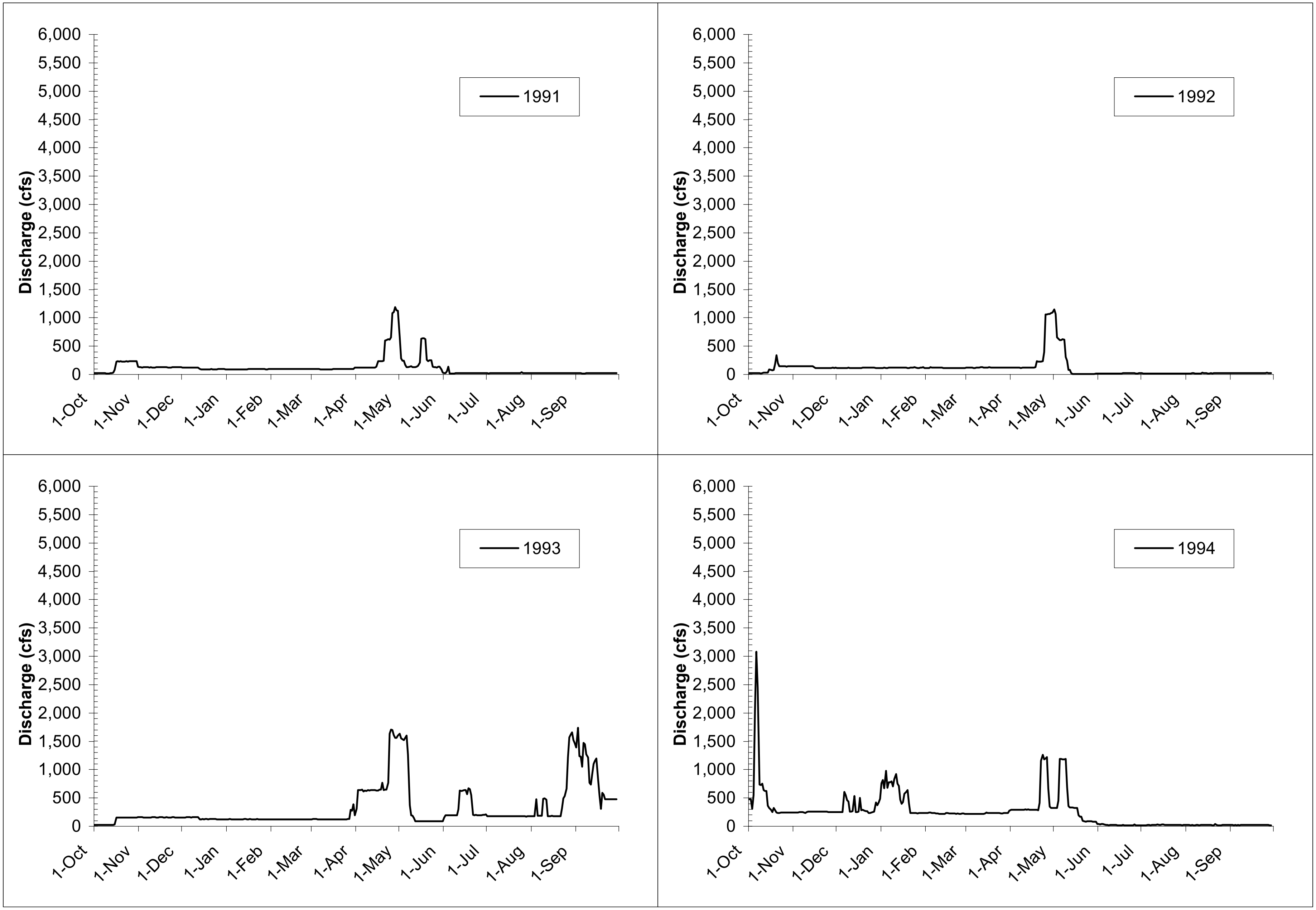
Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



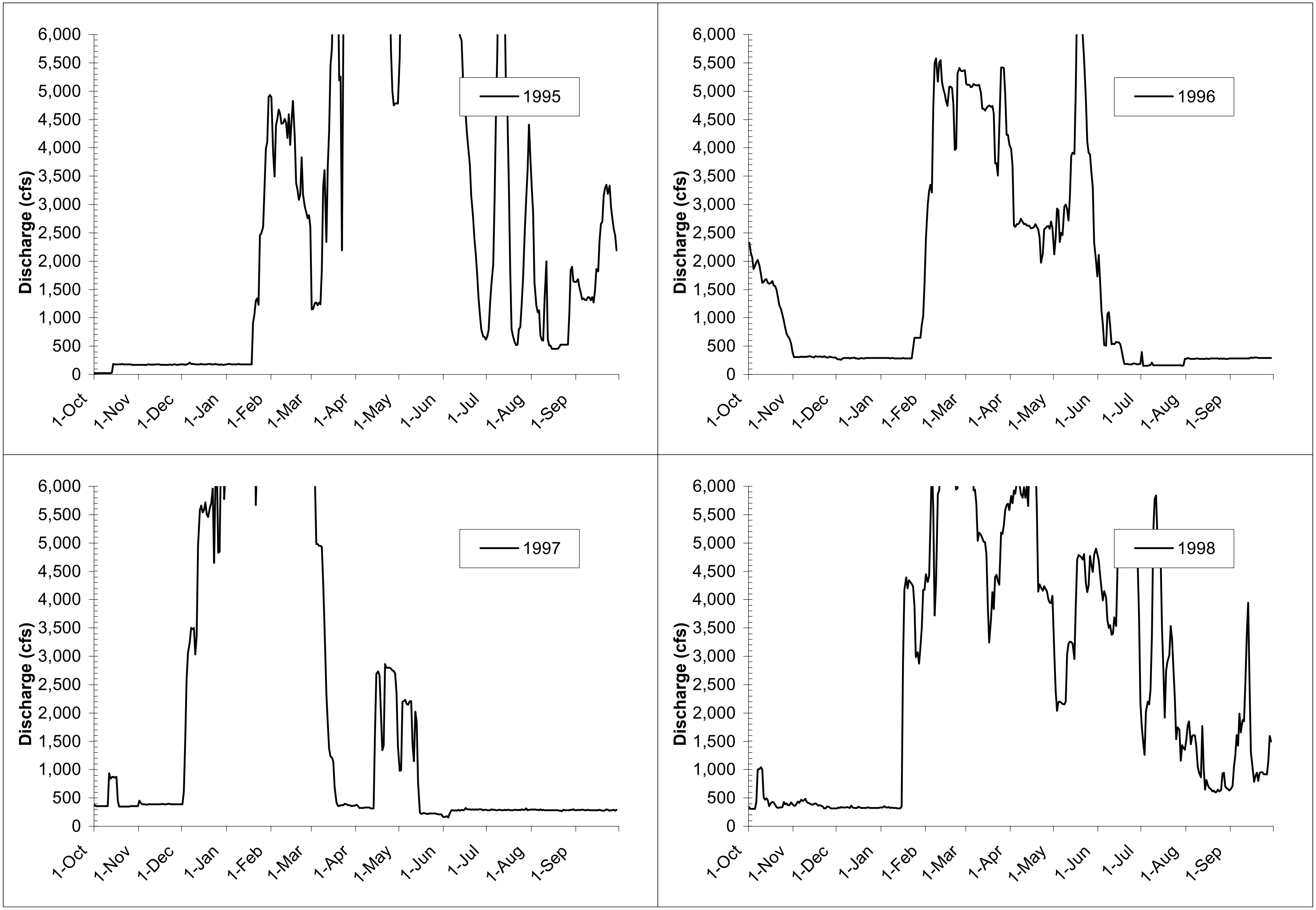
Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



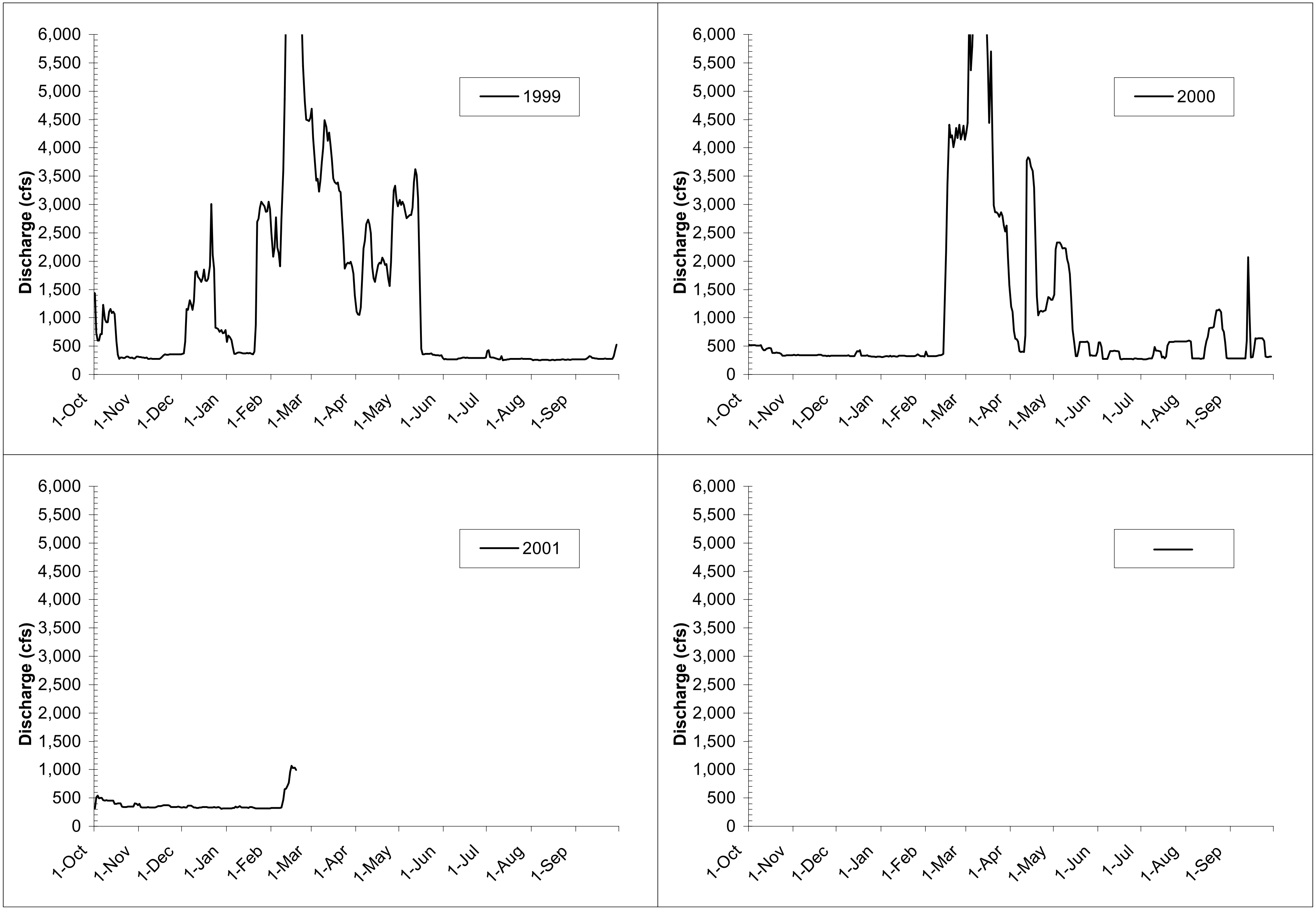
Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)



Tuolumne River at La Grange, CA REGULATED hydrographs for WY1971- 2001 (USGS Stn 11-289650)

APPENDIX G.

UNIMPAIRED HYDROLOGIC DATA FOR THE

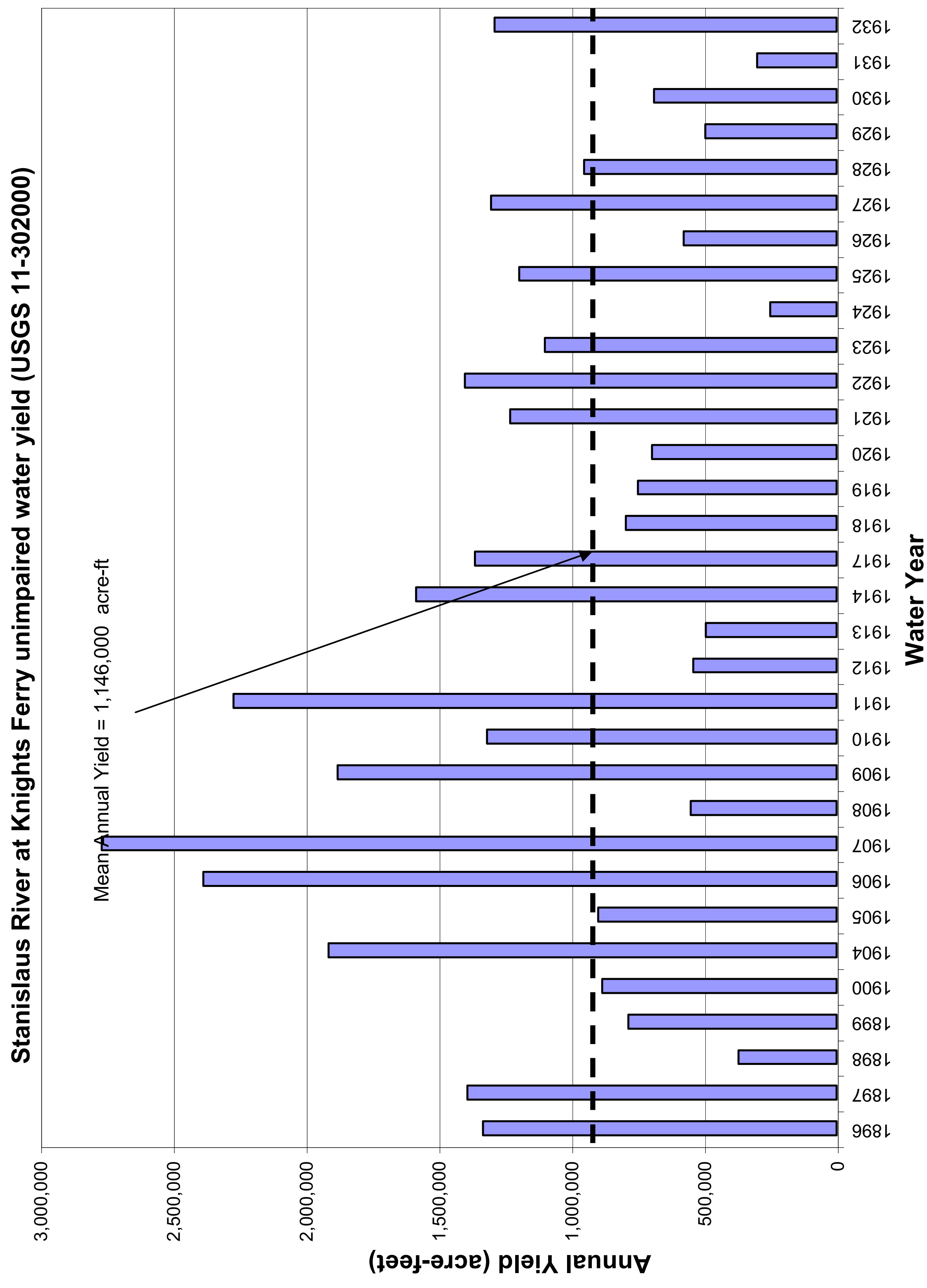
- STANISLAUS RIVER

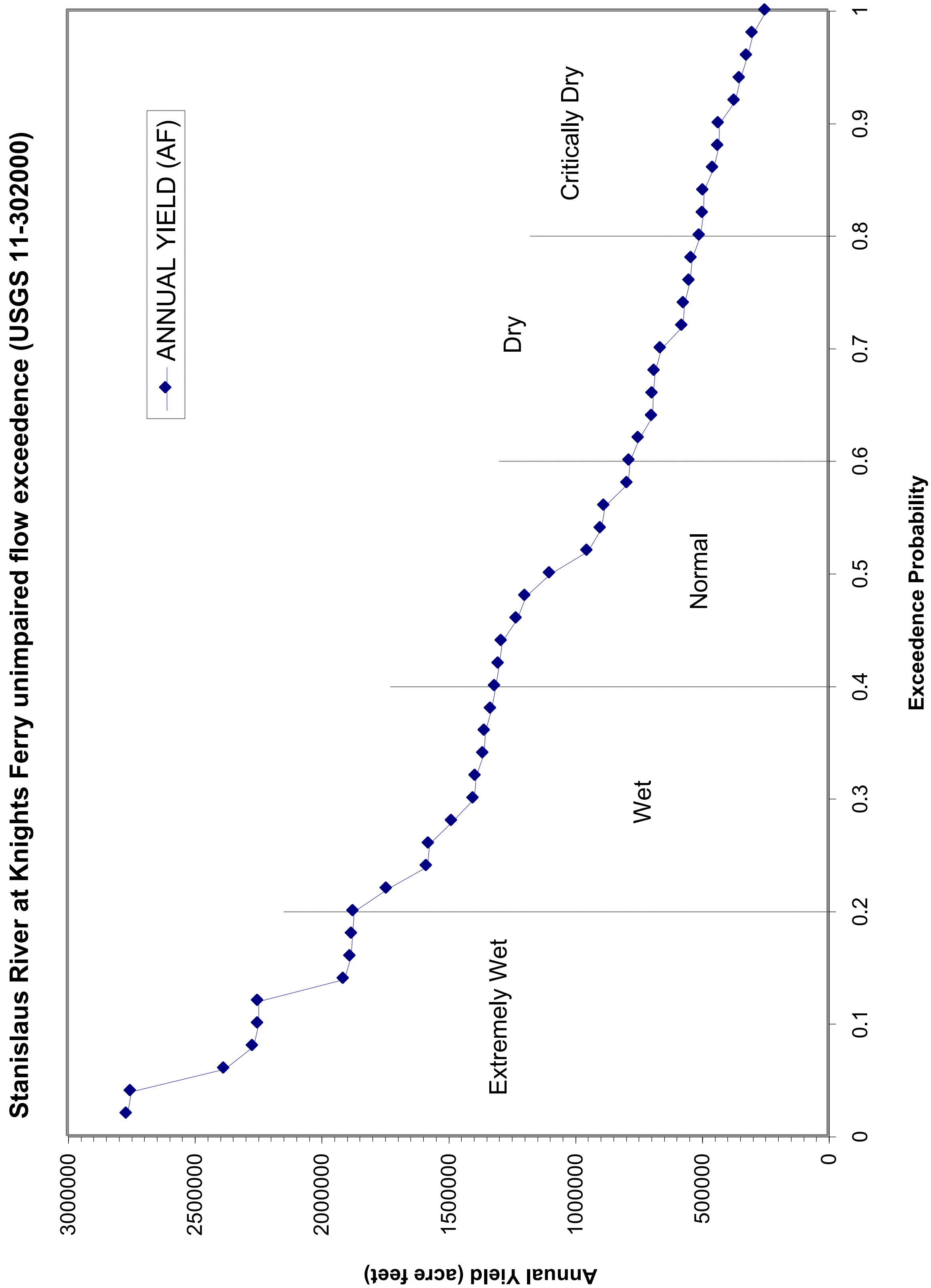
INCLUDING:

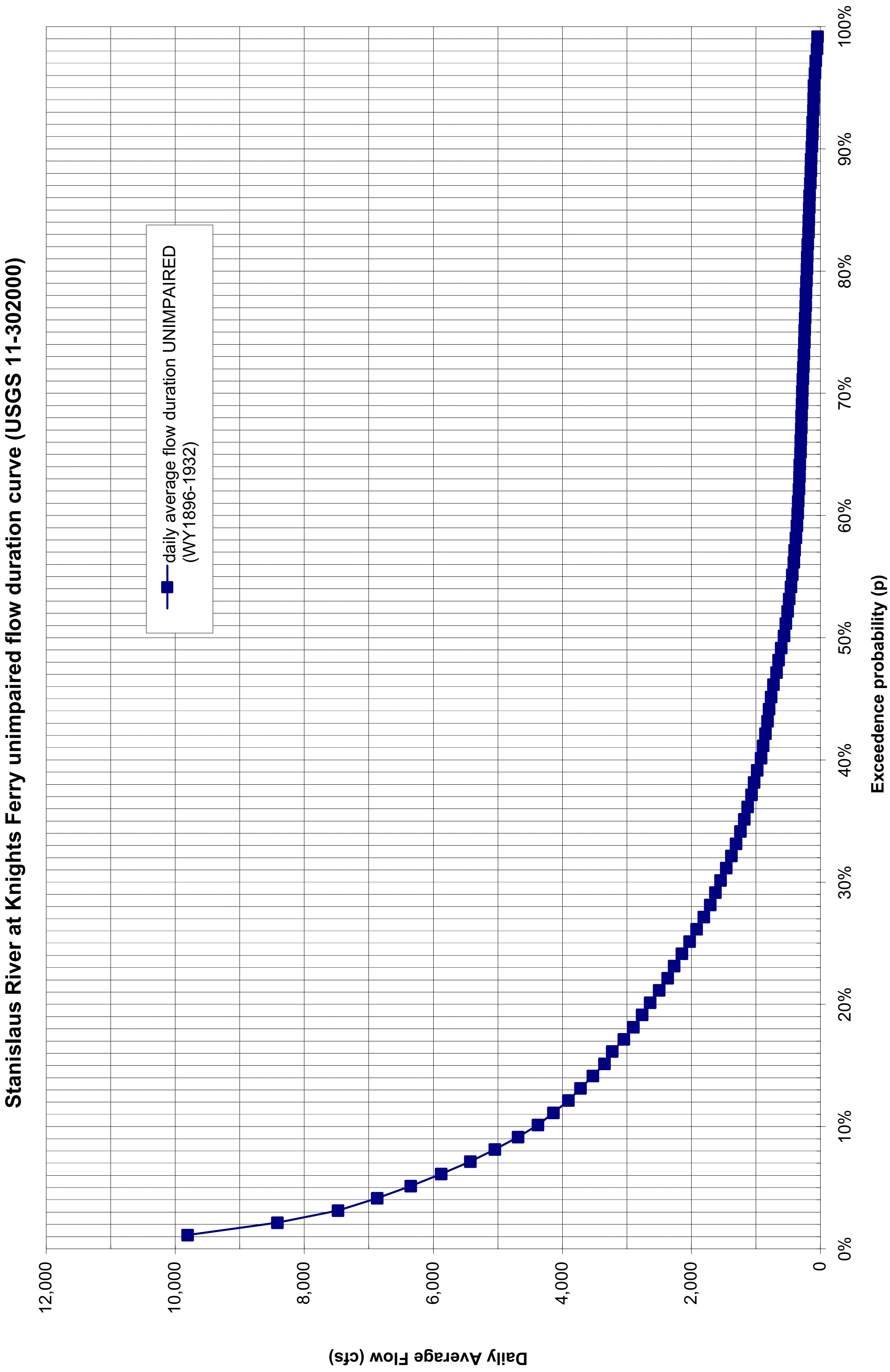
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

Stanislaus River at Knights Ferry unimpaired water yield (USGS 11-302000)

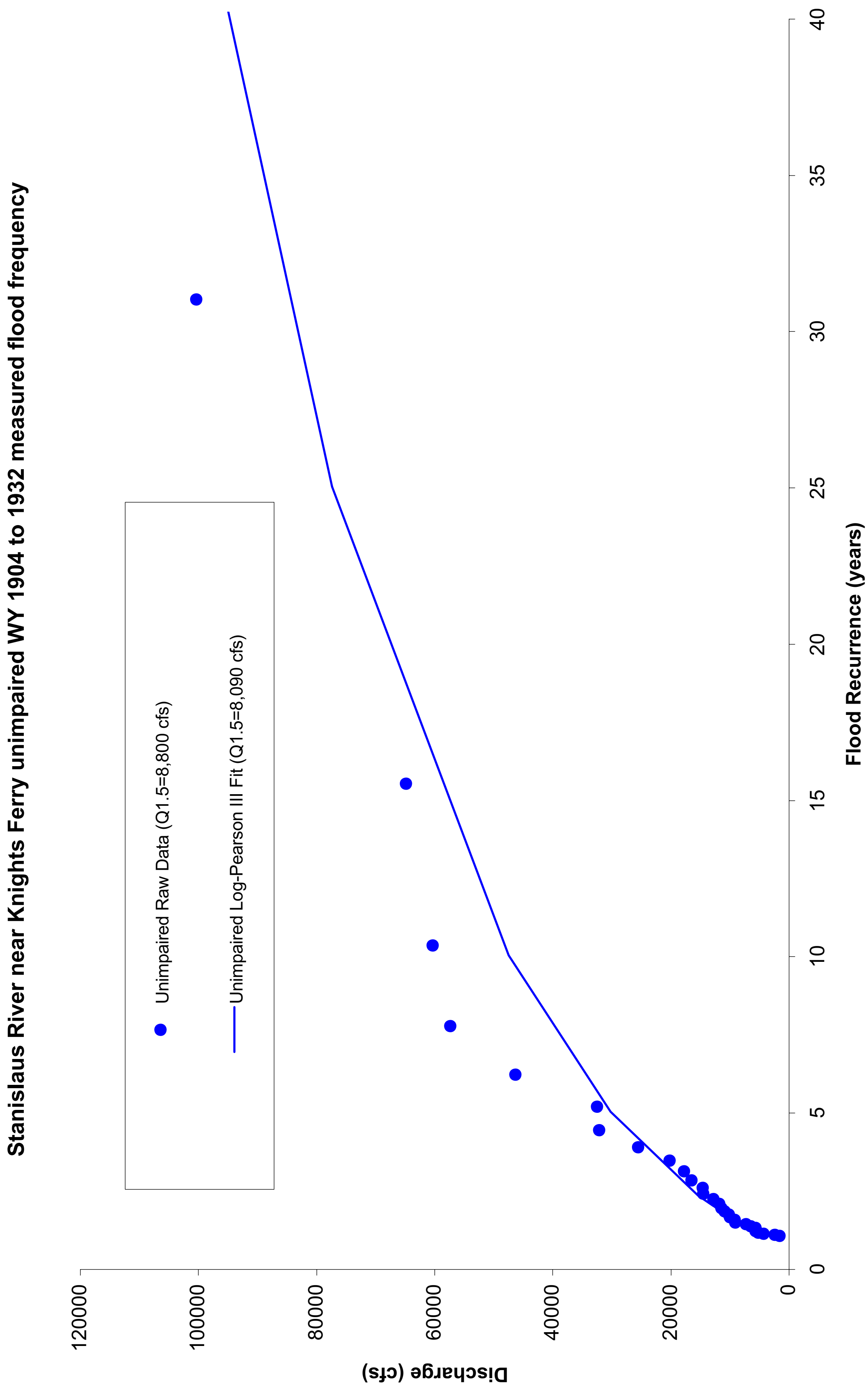
WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1896	1,332,036	WET	38.0%	19
1897	1,390,834	WET	32.0%	16
1898	369,832	CRITICALLY DRY	92.0%	46
1899	784,858	NORMAL	60.0%	30
1900	883,021	NORMAL	56.0%	28
1904	1,912,656	EXTREMELY WET	14.0%	7
1905	898,250	NORMAL	54.0%	27
1906	2,383,696	EXTREMELY WET	6.0%	3
1907	2,767,666	EXTREMELY WET	2.0%	1
1908	548,897	DRY	76.0%	38
1909	1,879,681	EXTREMELY WET	18.0%	9
1910	1,315,626	WET	40.0%	20
1911	2,269,894	EXTREMELY WET	8.0%	4
1912	539,643	DRY	78.0%	39
1913	492,752	CRITICALLY DRY	84.0%	42
1914	1,583,572	WET	24.0%	12
1917	1,361,494	WET	34.0%	17
1918	793,938	NORMAL	58.0%	29
1919	748,764	DRY	62.0%	31
1920	694,336	DRY	66.0%	33
1921	1,229,506	NORMAL	46.0%	23
1922	1,398,908	WET	30.0%	15
1923	1,098,109	NORMAL	50.0%	25
1924	249,197	CRITICALLY DRY	100.0%	50
1925	1,195,569	NORMAL	48.0%	24
1926	576,026	DRY	72.0%	36
1927	1,300,637	NORMAL	42.0%	21
1928	950,817	NORMAL	52.0%	26
1929	494,618	CRITICALLY DRY	82.0%	41
1930	686,710	DRY	68.0%	34
1931	300,137	CRITICALLY DRY	98.0%	49
1932	1,287,742	NORMAL	44.0%	22
1980	1,742,069	WET	22.0%	11
1981	570,233	DRY	74.0%	37
1982	2,249,176	EXTREMELY WET	12.0%	6
1983	2,750,926	EXTREMELY WET	4.0%	2
1984	1,575,028	WET	26.0%	13
1985	695,723	DRY	64.0%	32
1986	1,873,117	EXTREMELY WET	20.0%	10
1987	349,352	CRITICALLY DRY	94.0%	47
1988	322,541	CRITICALLY DRY	96.0%	48
1989	660,827	DRY	70.0%	35
1990	454,472	CRITICALLY DRY	86.0%	43
1991	507,401	DRY	80.0%	40
1992	432,533	CRITICALLY DRY	90.0%	45
1993	1,355,998	WET	36.0%	18
1994	435,602	CRITICALLY DRY	88.0%	44
1995	2,250,064	EXTREMELY WET	10.0%	5
1996	1,483,927	WET	28.0%	14
1997	1,885,768	EXTREMELY WET	16.0%	8
Average =	**1,146,284**			


Stanislaus River at Knights Ferry unimpaired water yield (USGS 11-302000)
Mean Annual Yield = 1,146,000 acre-ft
Annual Yield (acre-feet)
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Water Year
1896
1897
1898
1899
1900
1904
1905
1906
1907
1908
1909
1910
1911
1912
1913
1914
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932


Stanislaus River at Knights Ferry unimpaired flow exceedence (USGS 11-302000)
ANNUAL YIELD (AF)
Extremely Wet
Wet
Normal
Dry
Critically Dry
Annual Yield (acre feet)
Exceedence Probability
0
500000
1000000
1500000
2000000
2500000
3000000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

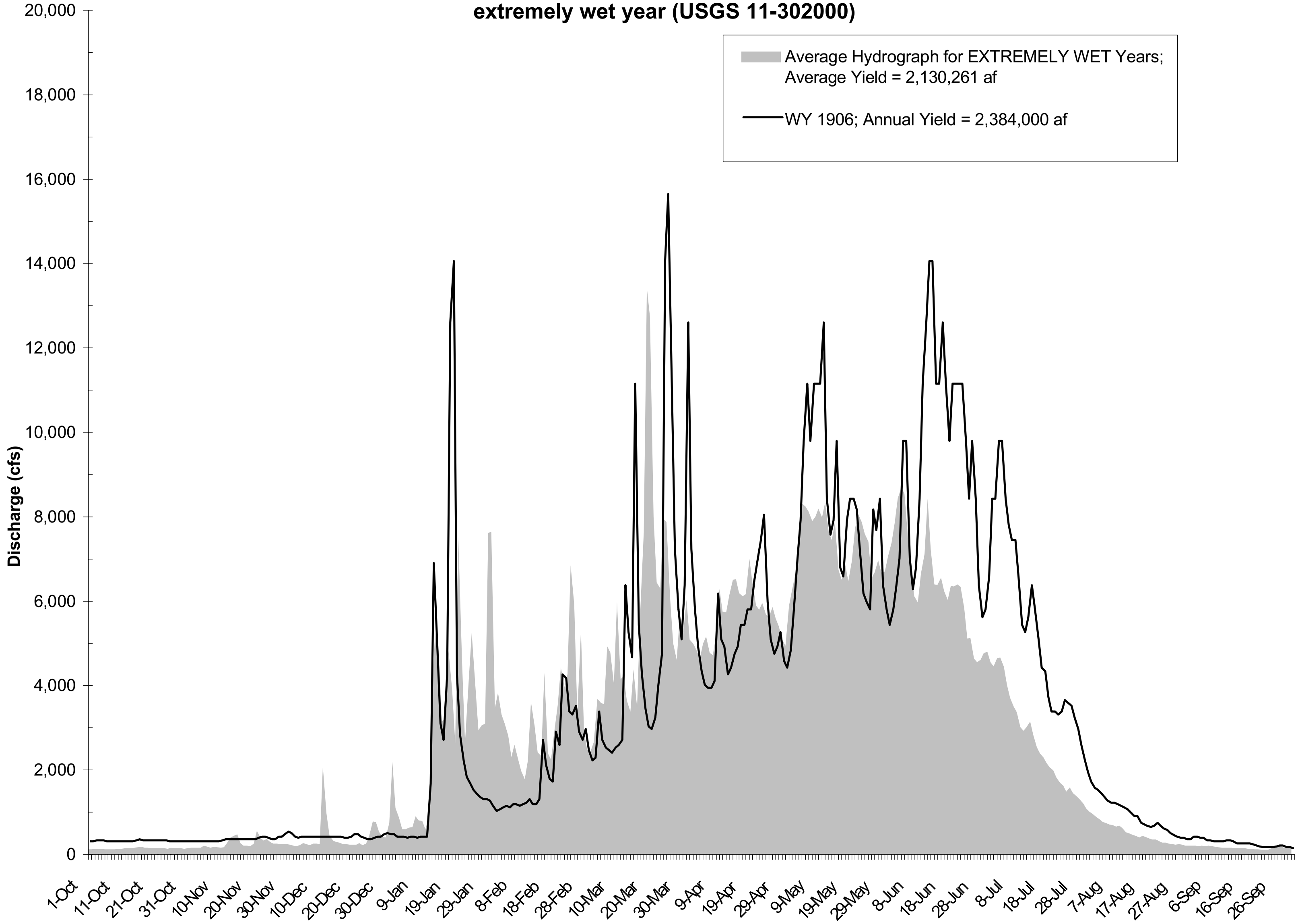


Stanislaus River at Knights Ferry unimpaired flow duration curve (USGS 11-302000)
daily average flow duration UNIMPAIRED (WY1896-1932)
Daily Average Flow (cfs)
Exceedence probability (p)
12,000
10,000
8,000
6,000
4,000
2,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

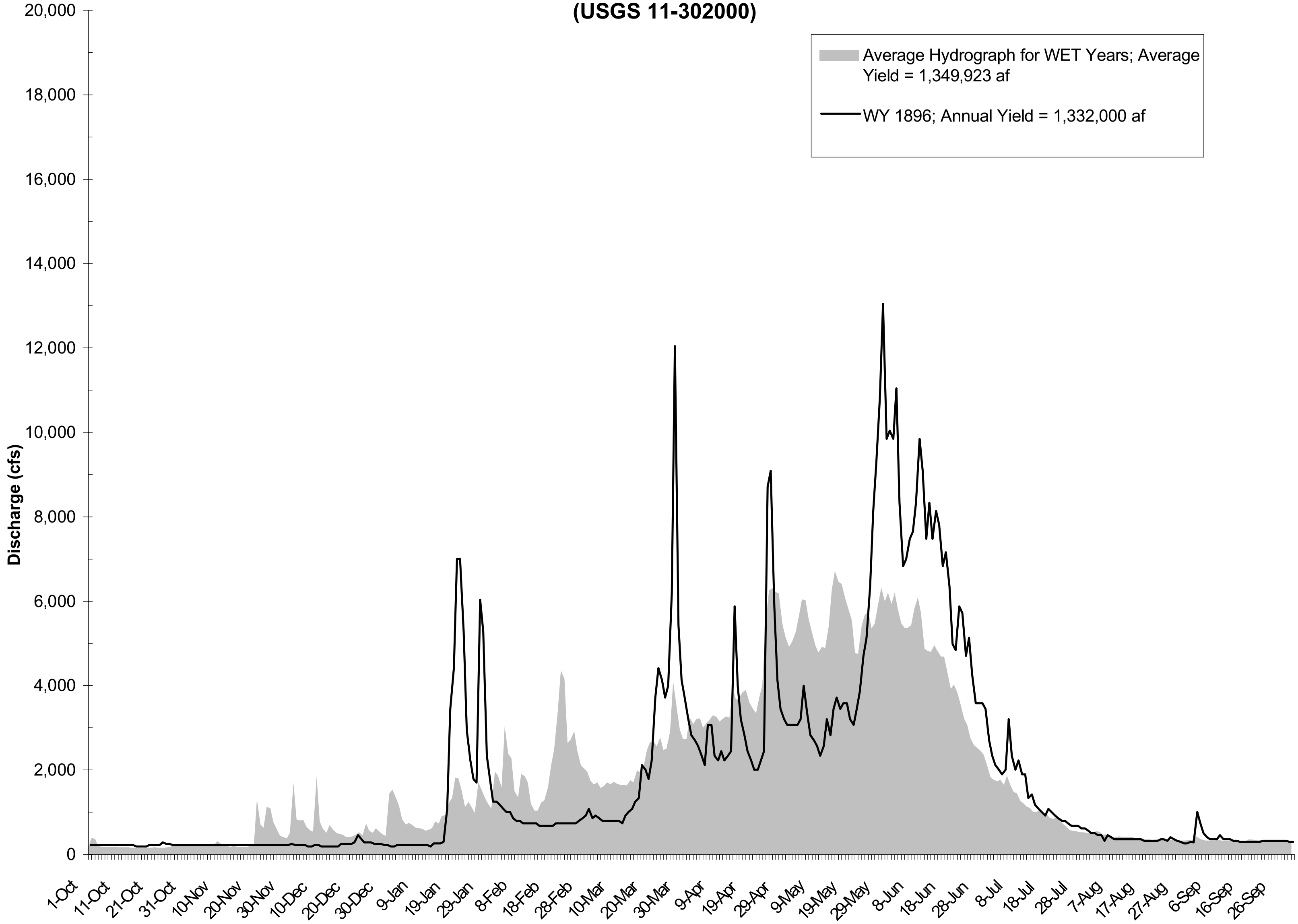


Stanislaus River near Knights Ferry unimpaired WY 1904 to 1932 measured flood frequency
Unimpaired Raw Data (Q1.5=8,800 cfs)
Unimpaired Log-Pearson III Fit (Q1.5=8,090 cfs)
Discharge (cfs)
Flood Recurrence (years)
0
20000
40000
60000
80000
100000
120000
0
5
10
15
20
25
30
35
40

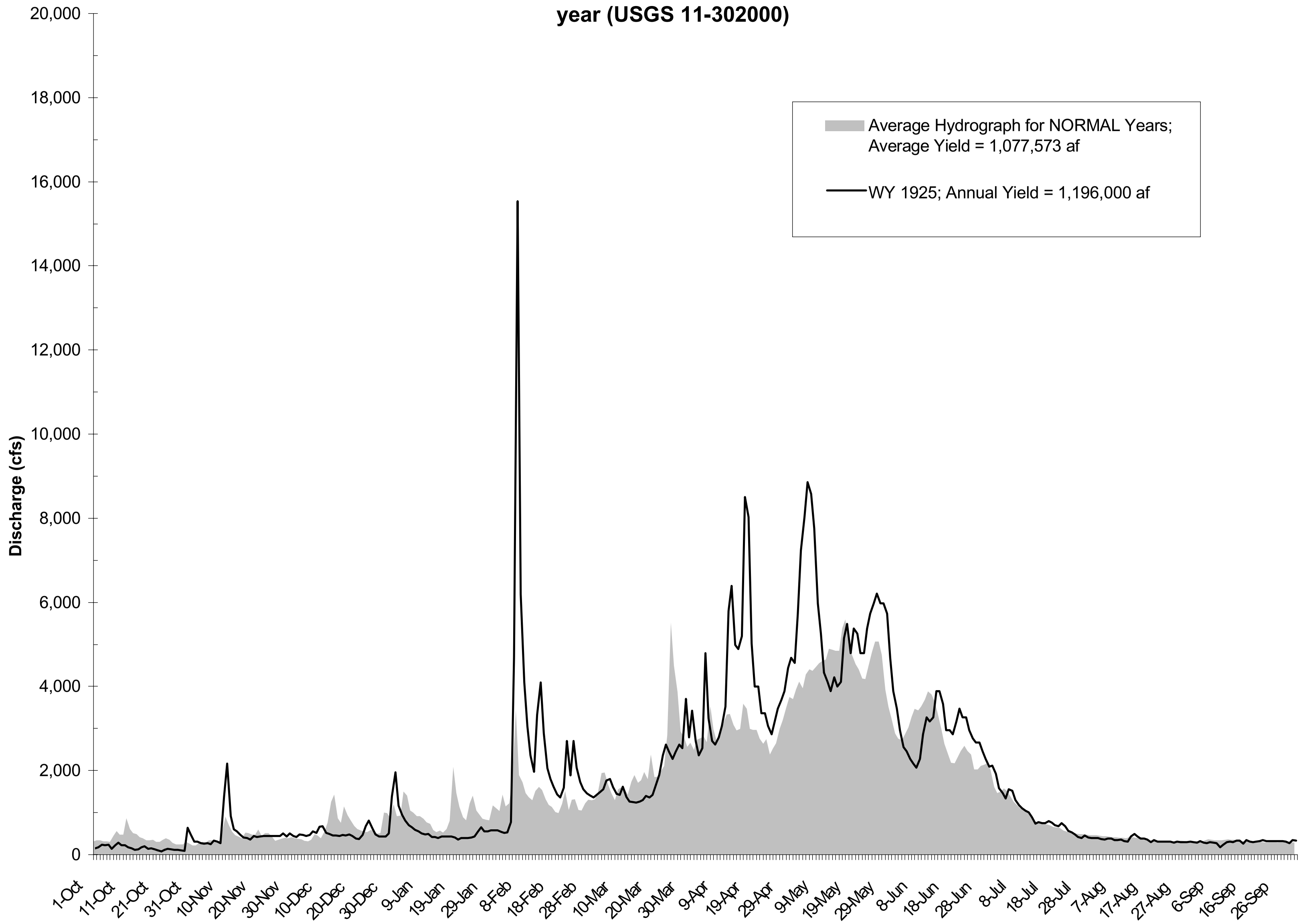
Stanislaus River at Knights Ferry unimpaired representative and average annual hydrograph for extremely wet year (USGS 11-302000)



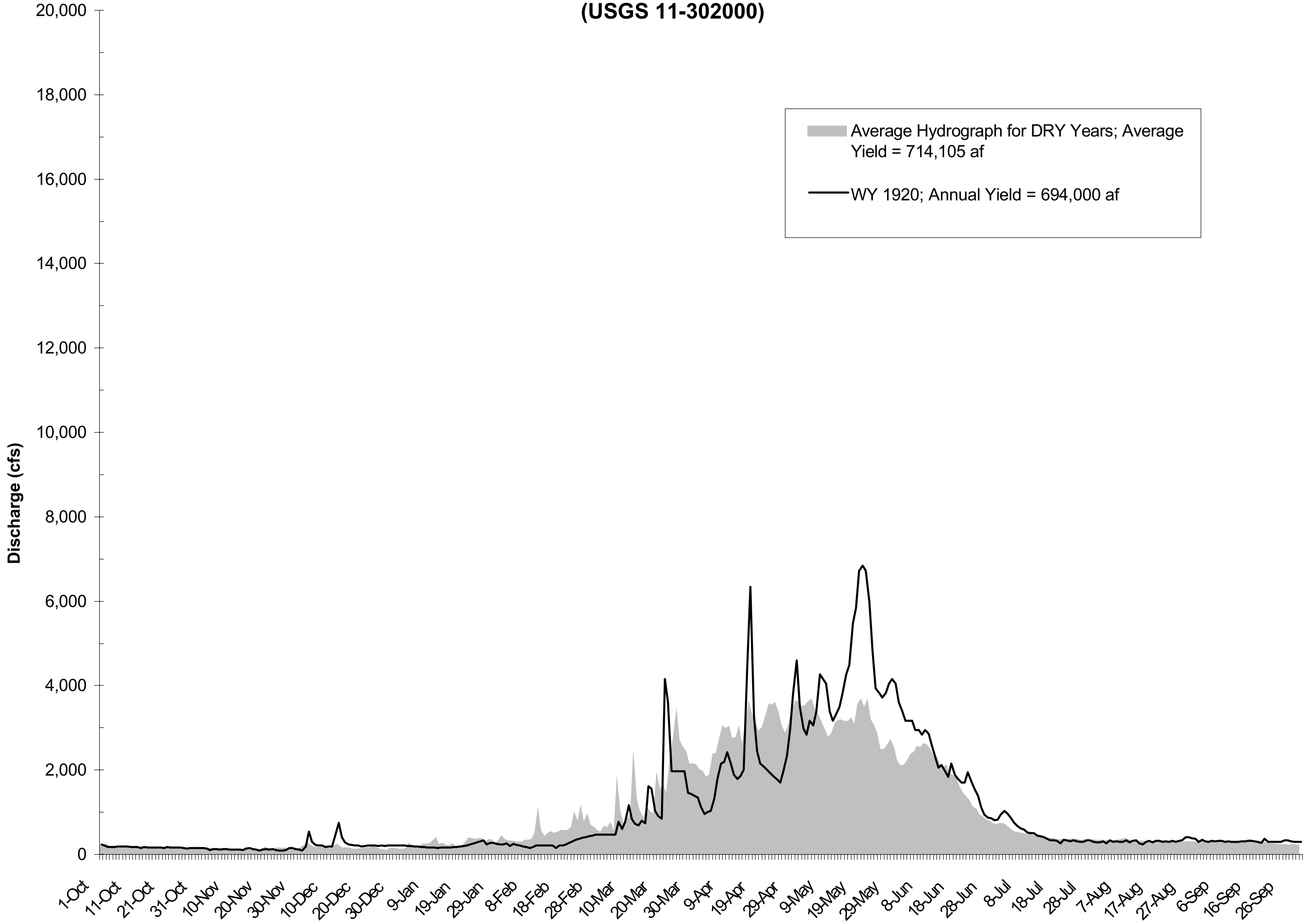
Stanislaus River at Knights Ferry unimpaired representative and average annual hydrograph for wet year (USGS 11-302000)



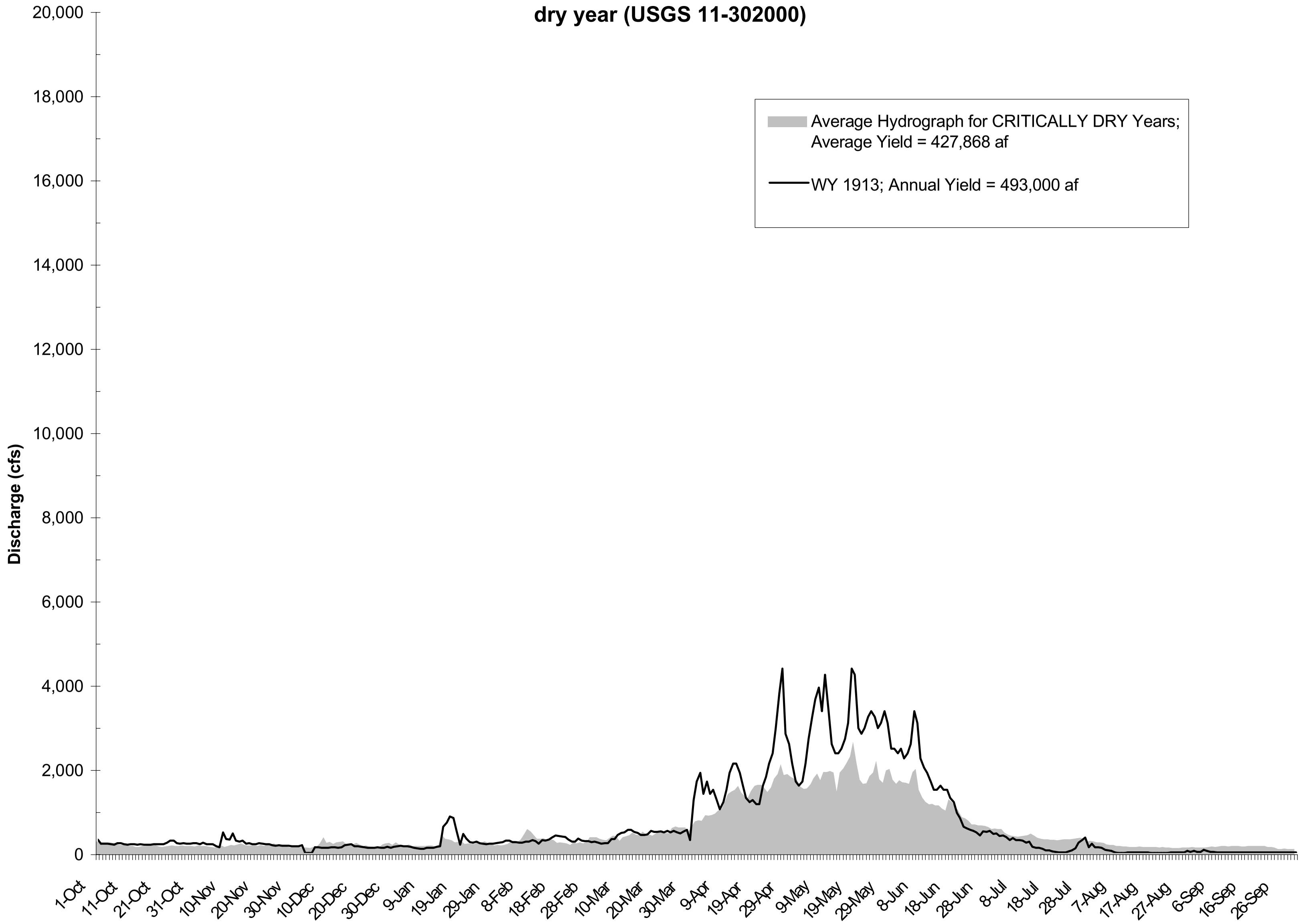
Stanislaus River at Knights Ferry unimpaired representative and average annual hydrograph for normal year (USGS 11-302000)

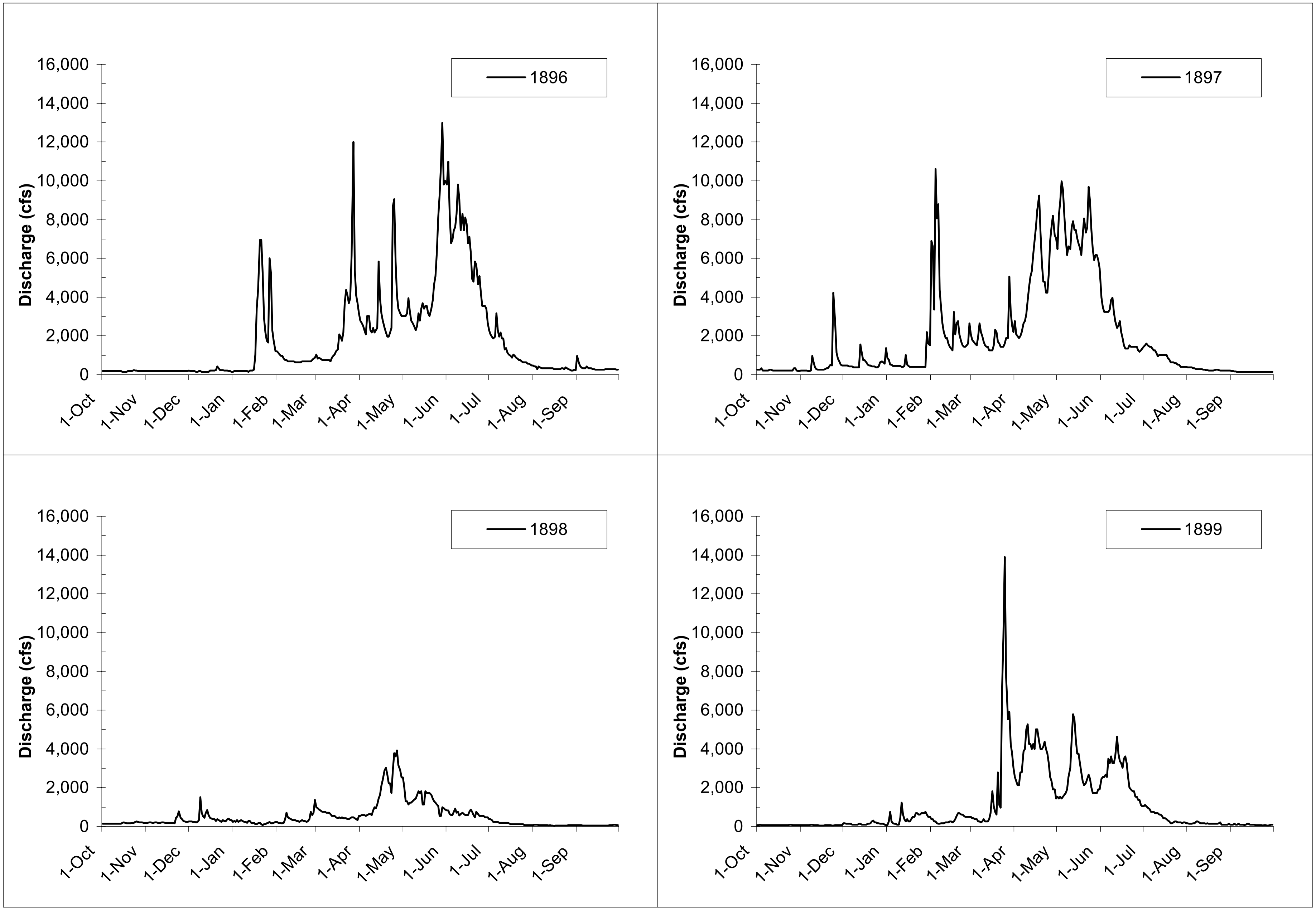


Stanislaus River at Knights Ferry unimpaired representative and average annual hydrograph for dry year (USGS 11-302000)

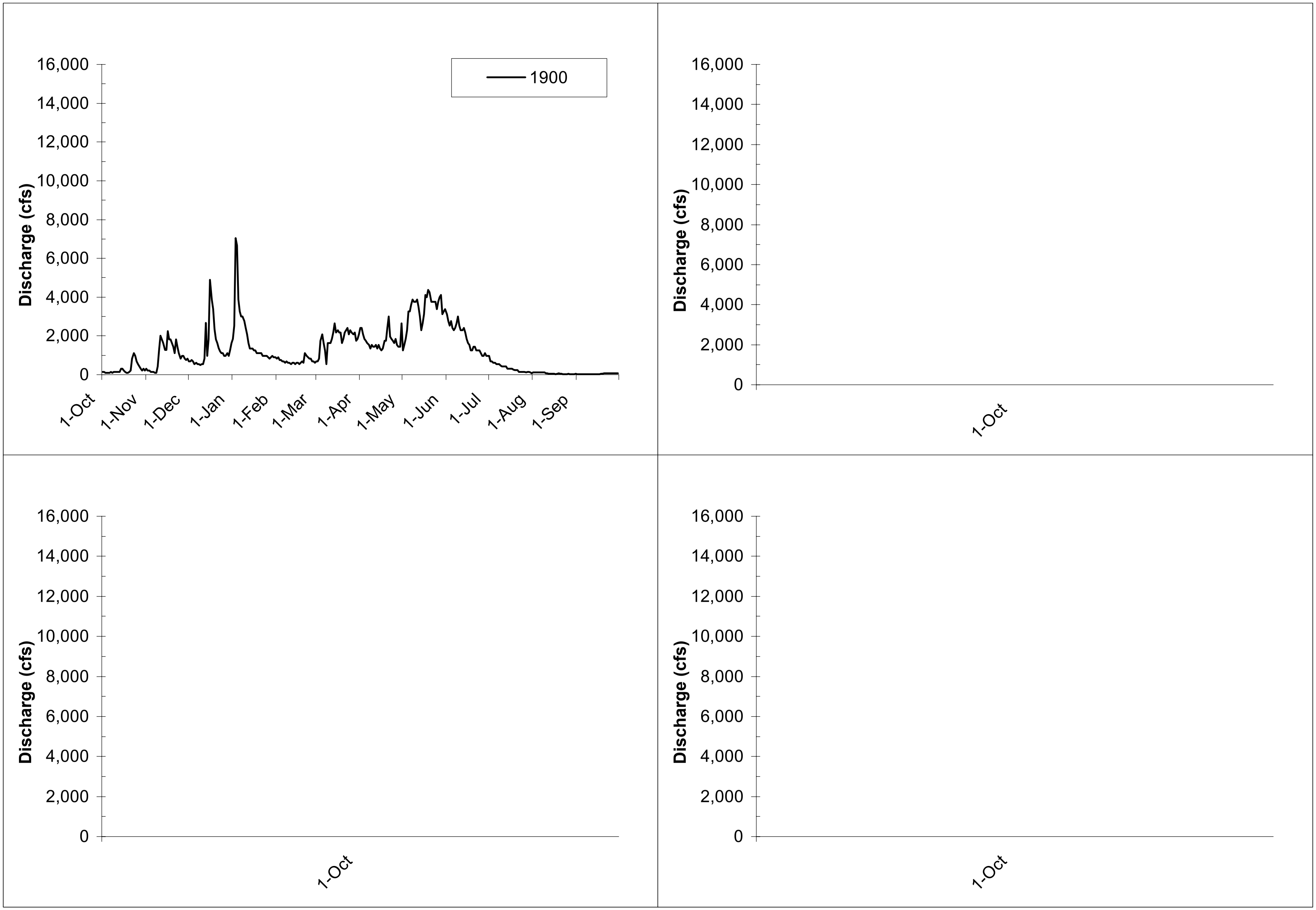


Stanislaus River at Knights Ferry unimpaired representative and average annual hydrograph for critically dry year (USGS 11-302000)

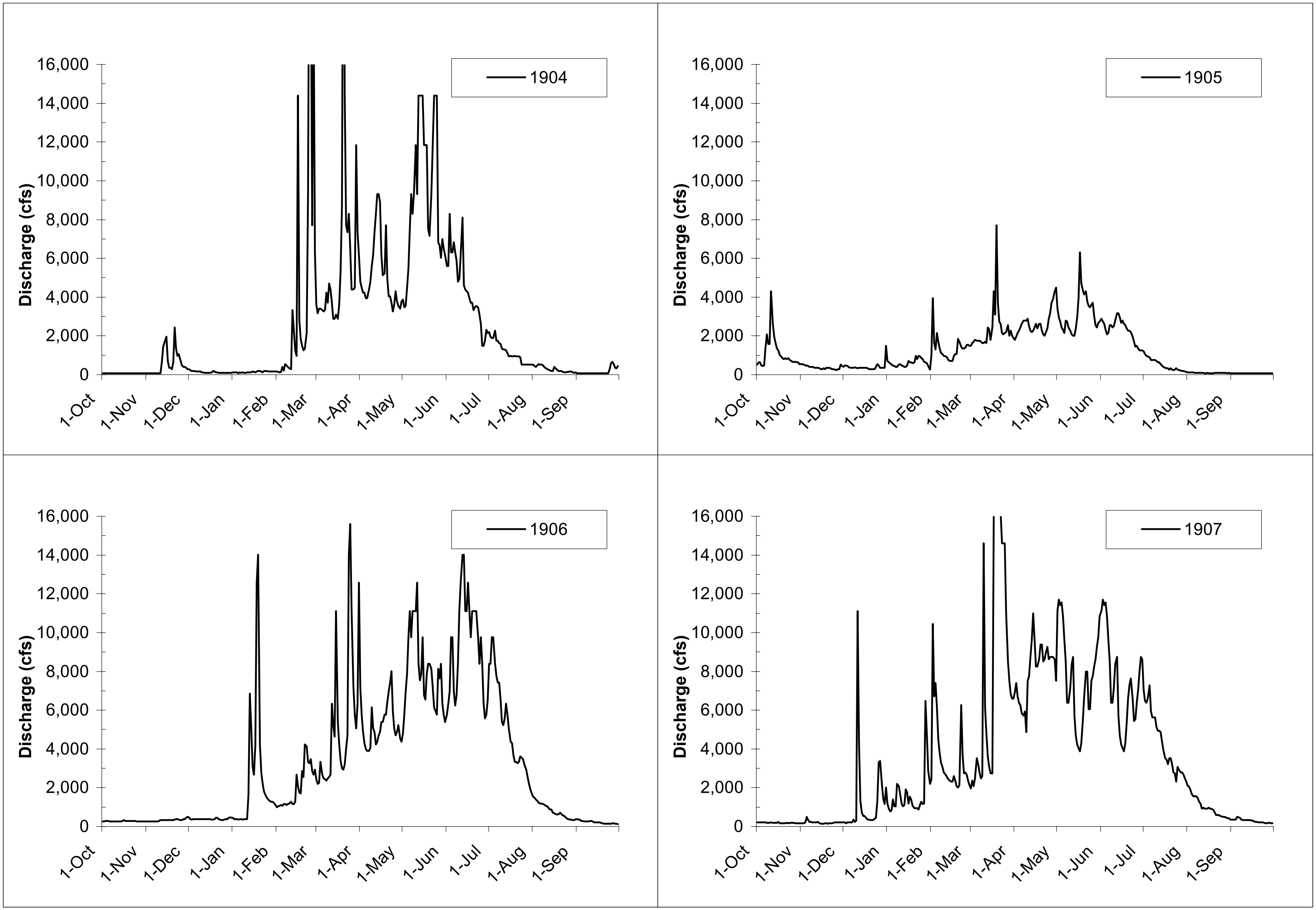




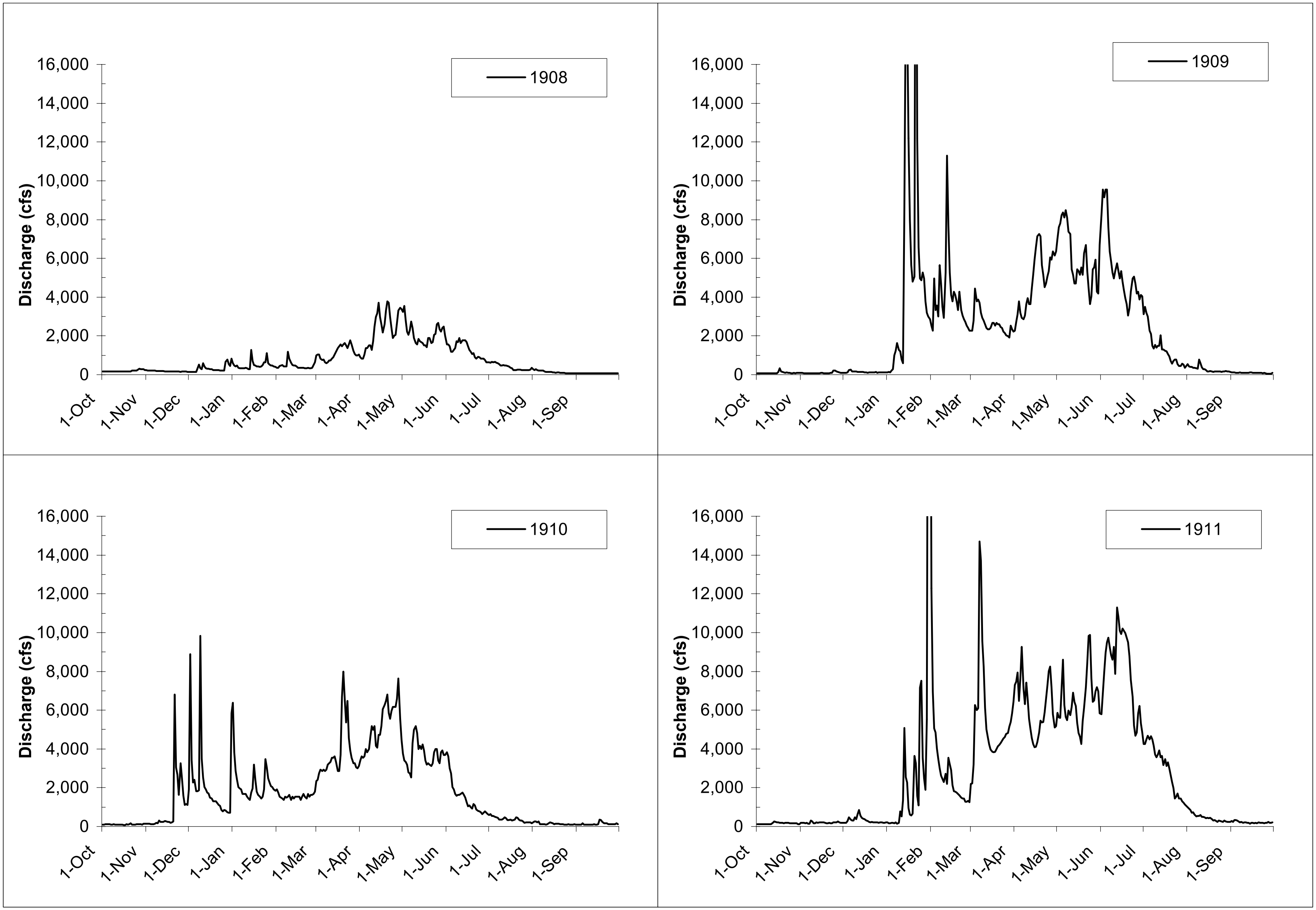
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



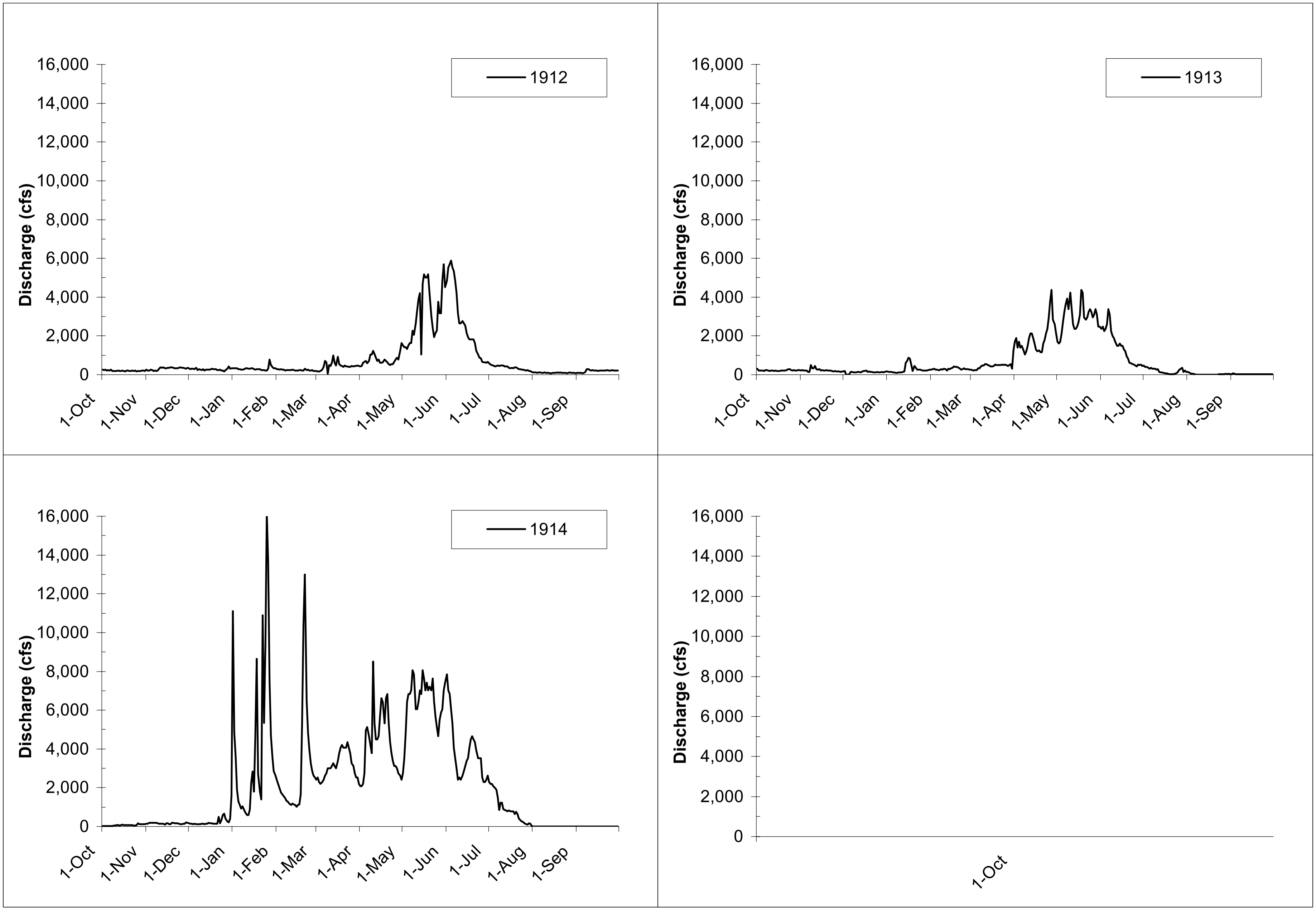
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



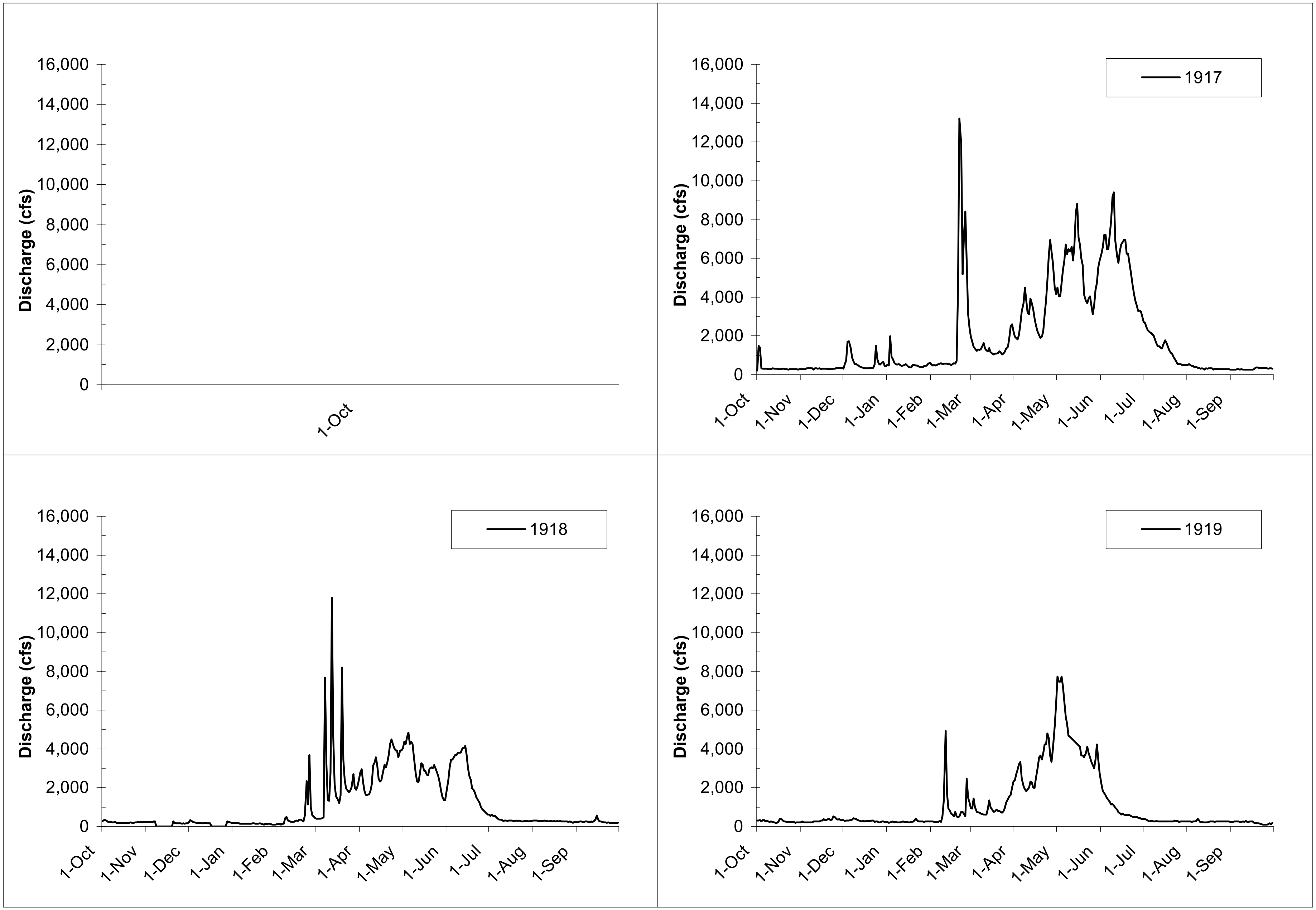
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



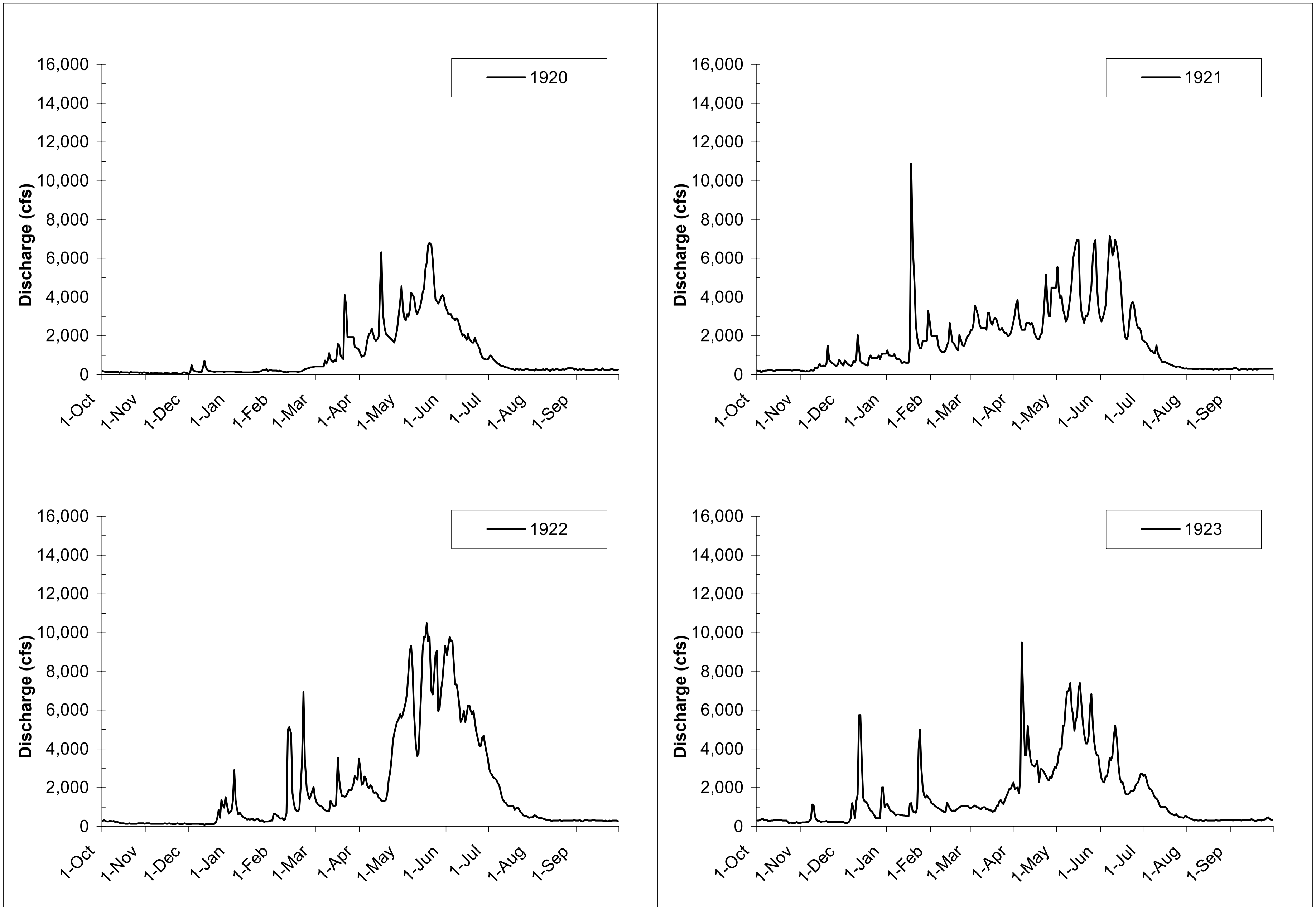
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



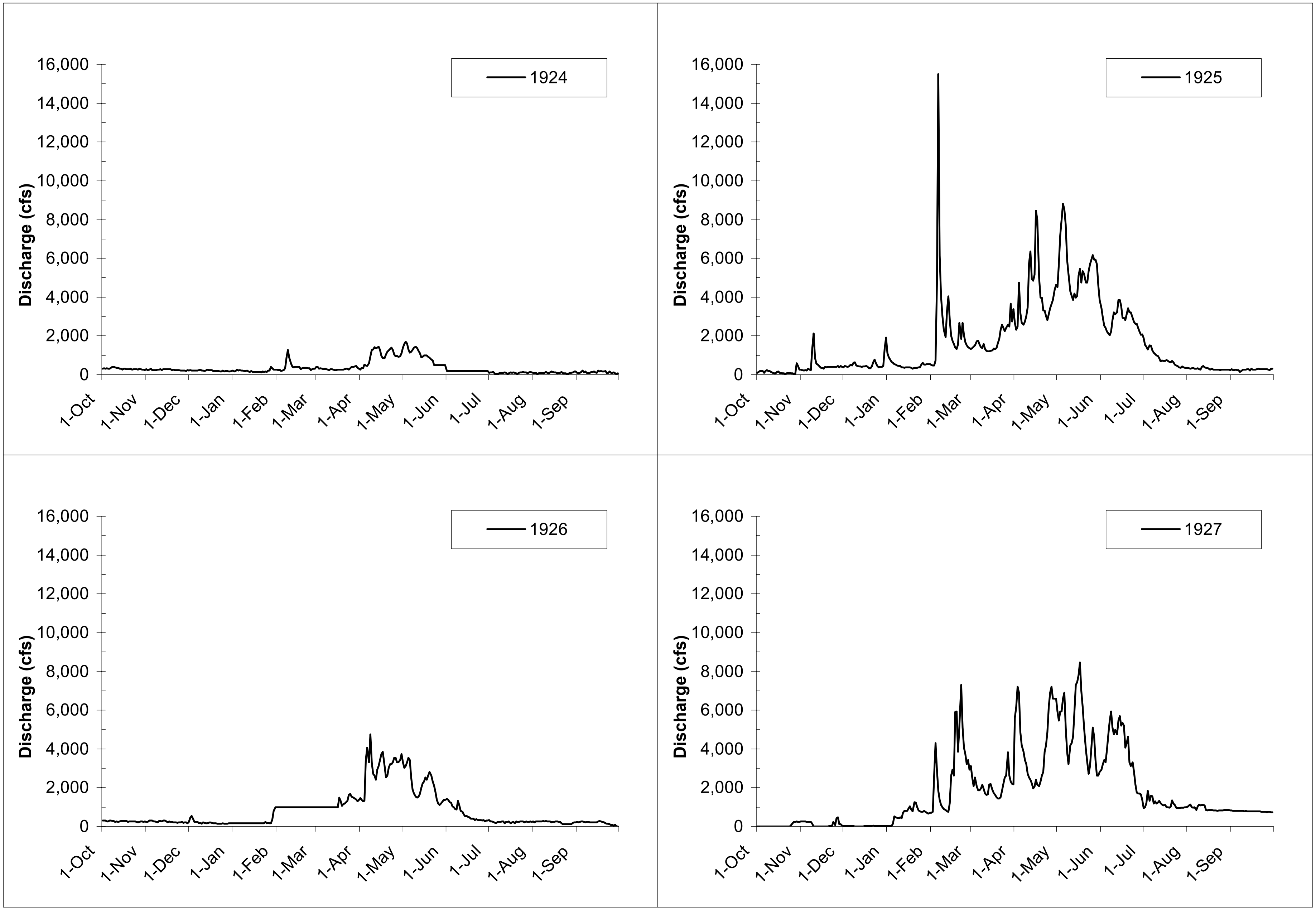
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



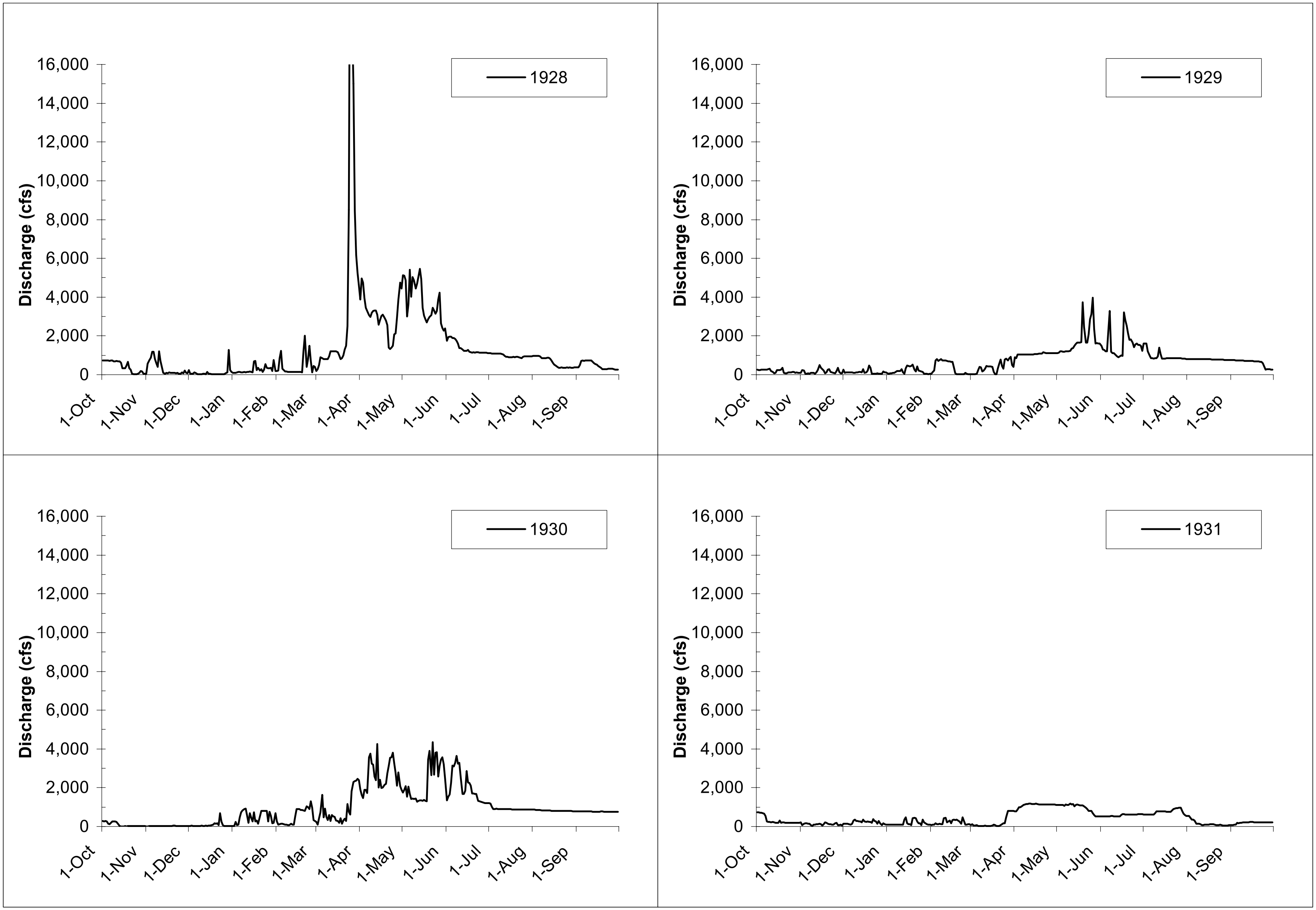
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



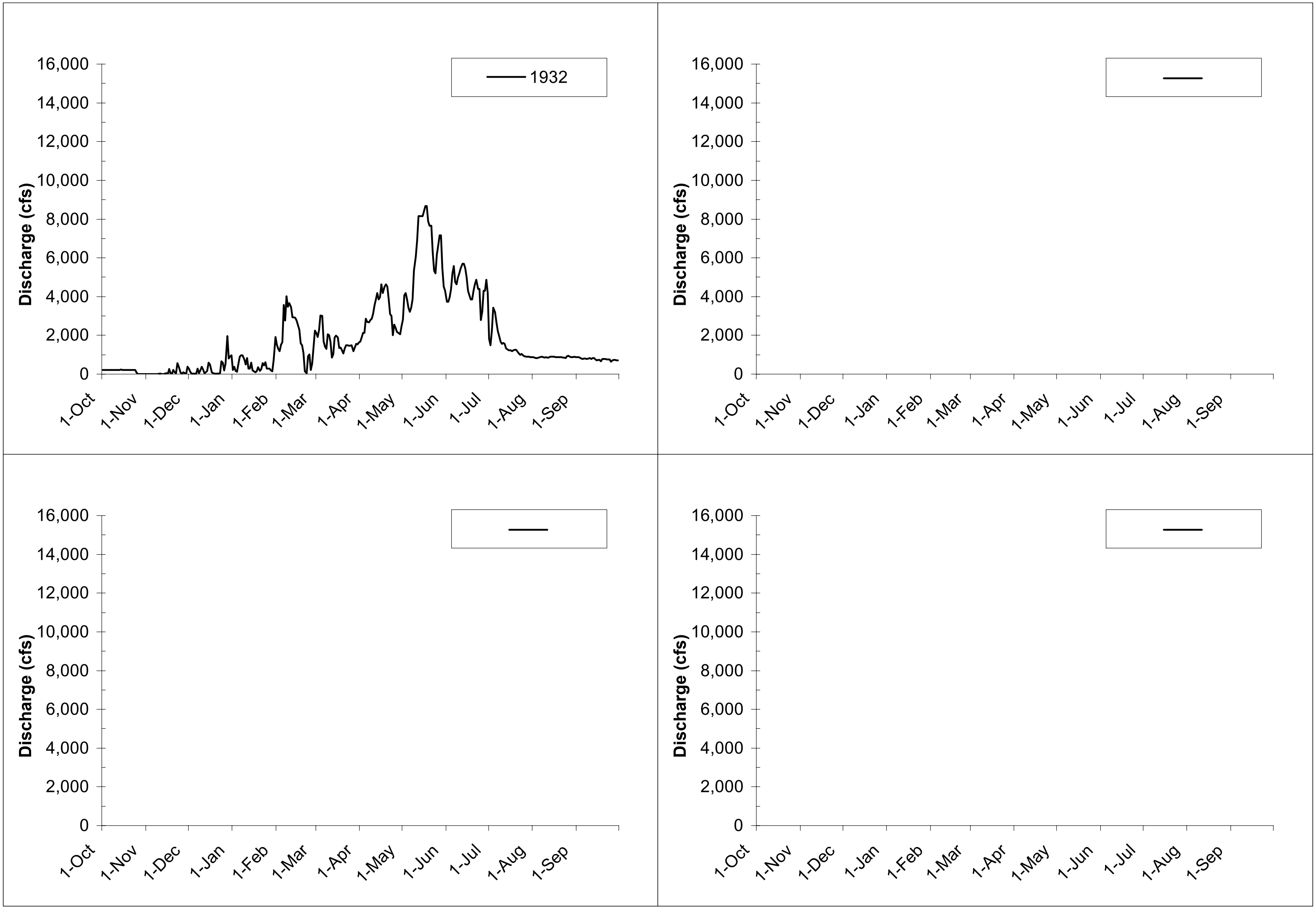
Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)



Stanislaus River at Knights Ferry UNIMPAIRED hydrographs for WY1896-1932 (USGS 11-302000)

APPENDIX H.

REGULATED HYDROLOGIC DATA FOR THE

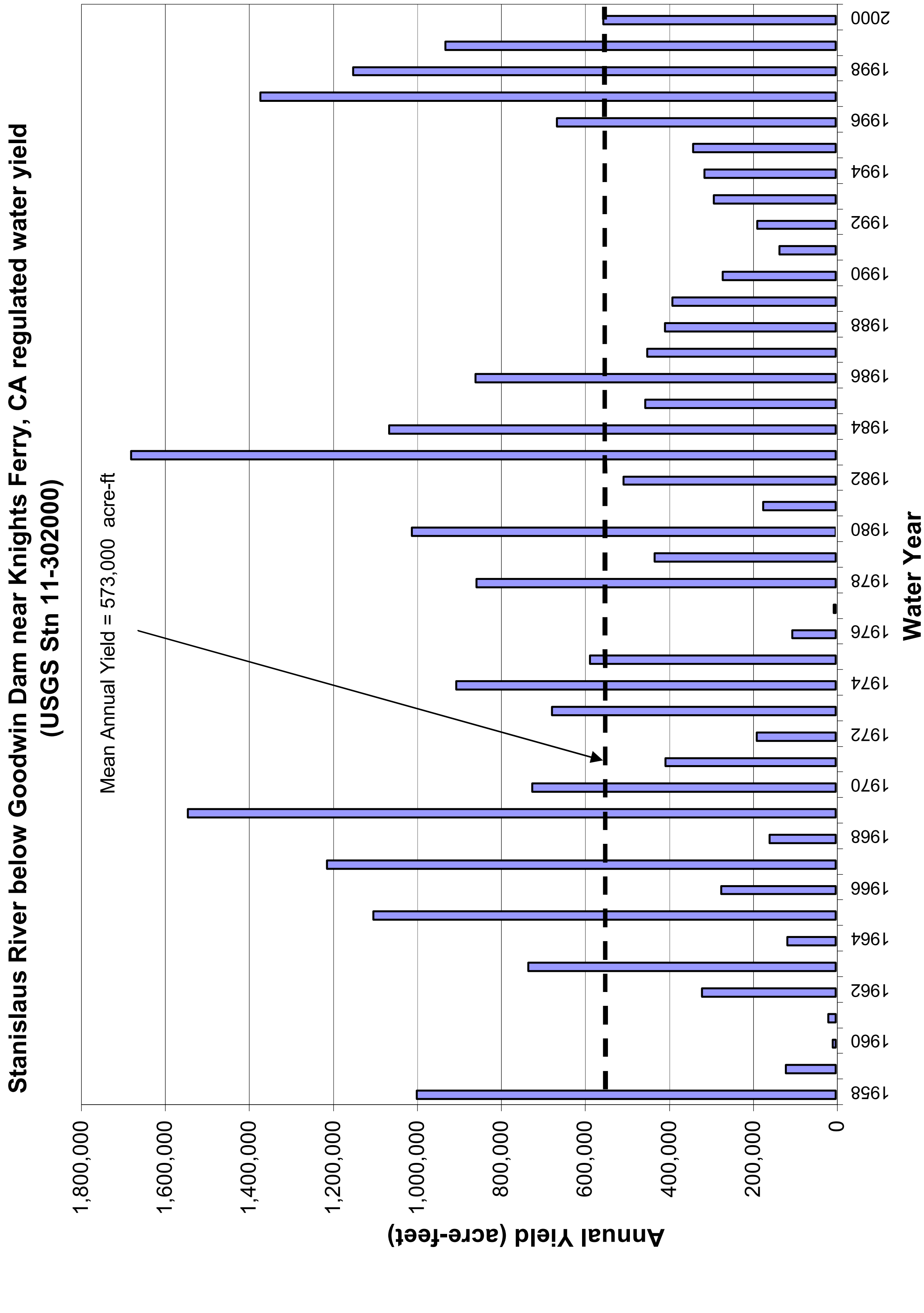
- STANISLAUS RIVER

INCLUDING:

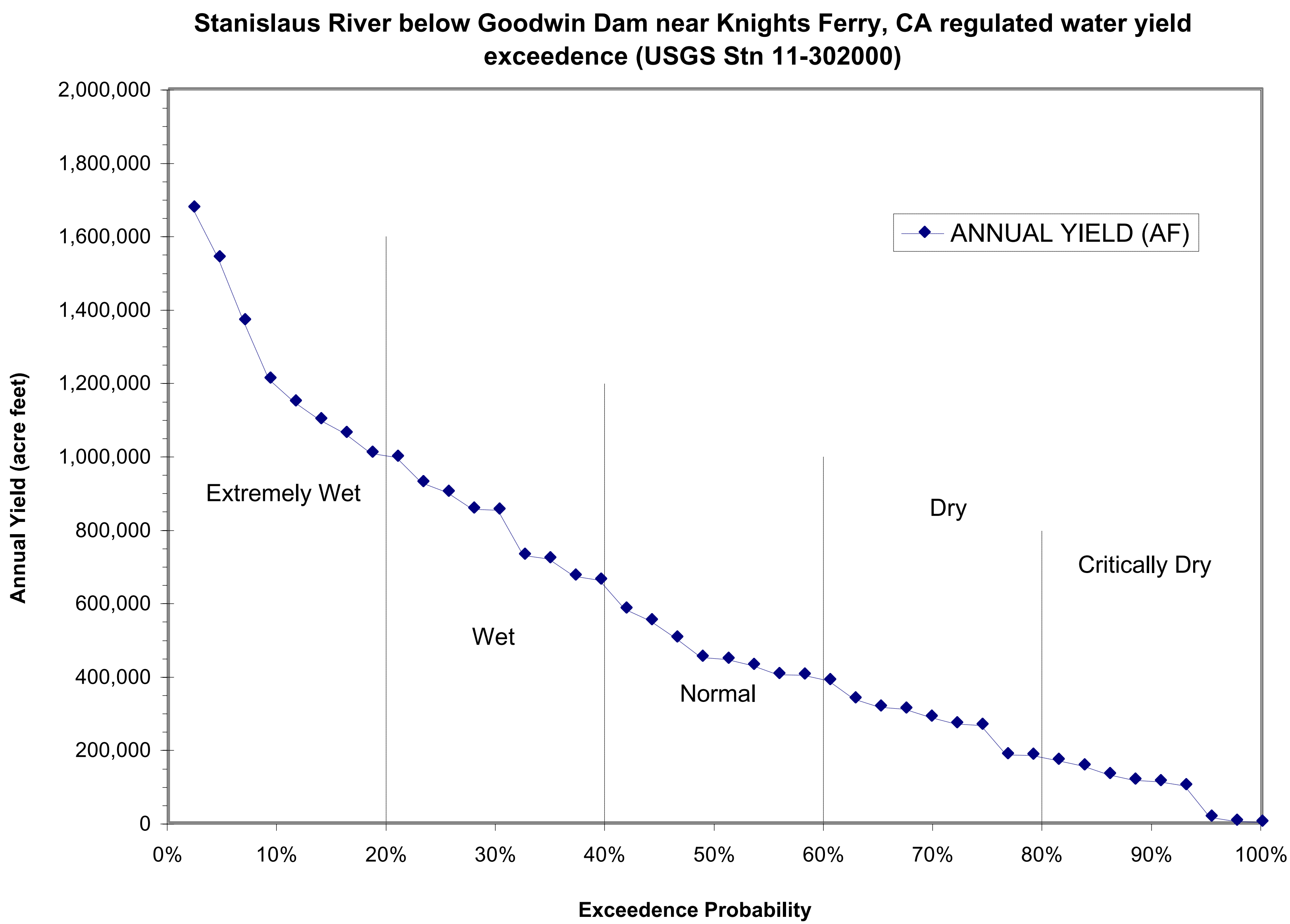
- ANNUAL WATER YIELD TABLE
- ANNUAL WATER YIELD BAR CHART
- ANNUAL WATER YIELD FREQUENCY DISTRIBUTION
- FLOW DURATION CURVE
- FLOOD FREQUENCY ANALYSIS
- AVERAGE AND REPRESENTATIVE ANNUAL HYDROGRAPHS FOR EACH WATER YEAR CLASSIFICATION
- ANNUAL HYDROGRAPHS FOR EACH WATER YEAR OF RECORD

Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED (USGS Stn 11-302000)

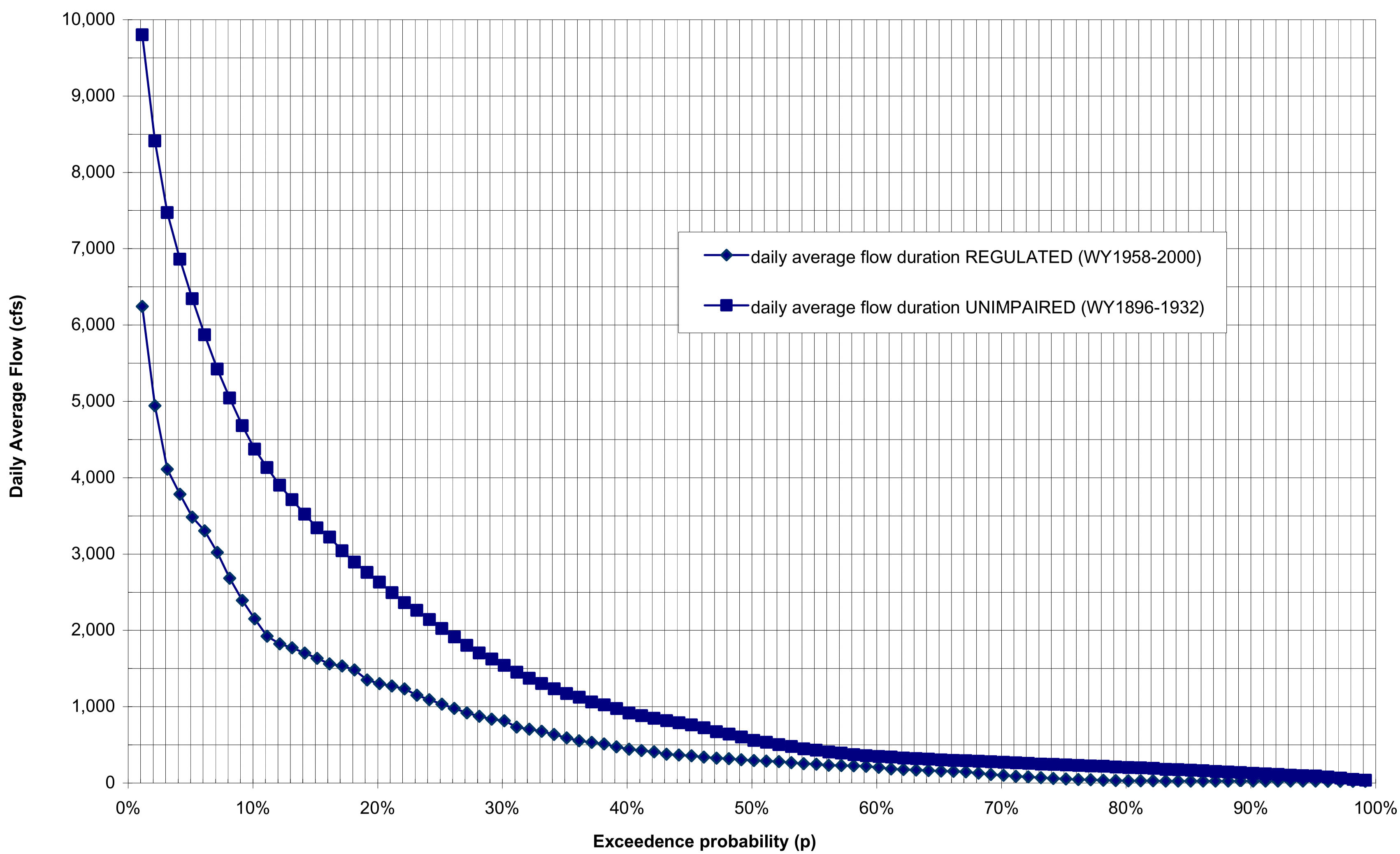
WATER YEAR	ANNUAL YIELD (AF)	WATER YEAR CLASSIFICATION	EXCEEDENCE PROBABILITY	RANK
1958	997,973	WET	20.9%	9
1959	118,862	CRITICALLY DRY	88.4%	38
1960	7,328	CRITICALLY DRY	97.7%	42
1961	17,319	CRITICALLY DRY	95.3%	41
1962	318,505	DRY	65.1%	28
1963	731,463	WET	32.6%	14
1964	115,358	CRITICALLY DRY	90.7%	39
1965	1,101,090	EXTREMELY WET	14.0%	6
1966	272,422	DRY	72.1%	31
1967	1,211,902	EXTREMELY WET	9.3%	4
1968	158,008	CRITICALLY DRY	83.7%	36
1969	1,542,692	EXTREMELY WET	4.7%	2
1970	722,402	WET	34.9%	15
1971	405,198	NORMAL	58.1%	25
1972	187,904	DRY	76.7%	33
1973	675,588	WET	37.2%	16
1974	903,075	WET	25.6%	11
1975	585,089	NORMAL	41.9%	18
1976	103,240	CRITICALLY DRY	93.0%	40
1977	4,685	CRITICALLY DRY	100.0%	43
1978	854,810	WET	30.2%	13
1979	431,319	NORMAL	53.5%	23
1980	1,009,201	EXTREMELY WET	18.6%	8
1981	173,150	CRITICALLY DRY	81.4%	35
1982	505,595	NORMAL	46.5%	20
1983	1,677,531	EXTREMELY WET	2.3%	1
1984	1,063,632	EXTREMELY WET	16.3%	7
1985	453,727	NORMAL	48.8%	21
1986	857,185	WET	27.9%	12
1987	448,421	NORMAL	51.2%	22
1988	406,467	NORMAL	55.8%	24
1989	389,397	DRY	60.5%	26
1990	268,677	DRY	74.4%	32
1991	133,706	CRITICALLY DRY	86.0%	37
1992	187,035	DRY	79.1%	34
1993	290,348	DRY	69.8%	30
1994	312,984	DRY	67.4%	29
1995	339,909	DRY	62.8%	27
1996	663,493	WET	39.5%	17
1997	1,370,517	EXTREMELY WET	7.0%	3
1998	1,148,805	EXTREMELY WET	11.6%	5
1999	929,423	WET	23.3%	10
2000	552,847	NORMAL	44.2%	19



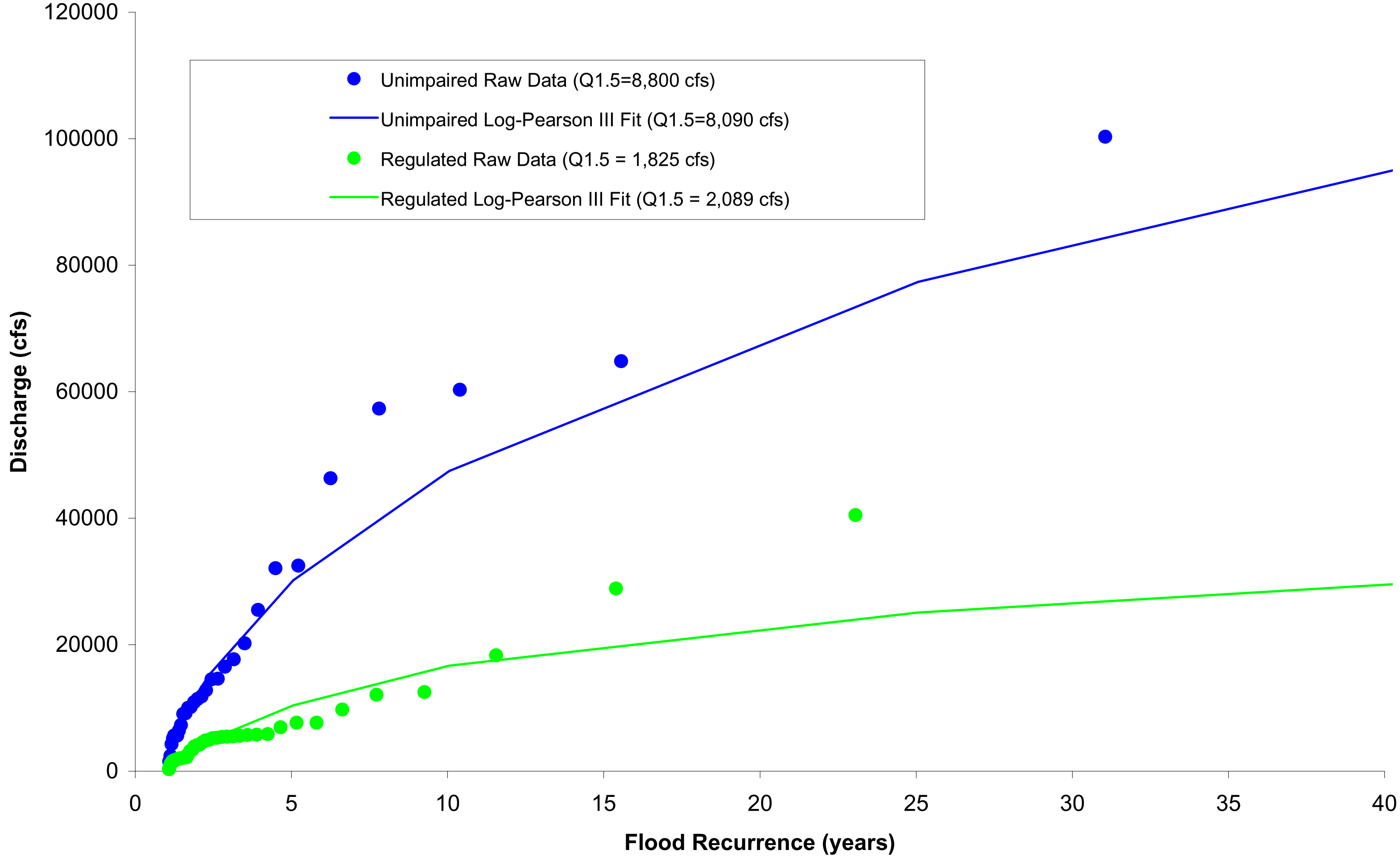
Stanislaus River below Goodwin Dam near Knights Ferry, CA regulated water yield
(USGS Stn 11-302000)
Mean Annual Yield = 573,000 acre-ft
Annual Yield (acre-feet)
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
Water Year
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000


Stanislaus River below Goodwin Dam near Knights Ferry, CA regulated water yield exceedence (USGS Stn 11-302000)
ANNUAL YIELD (AF)
Annual Yield (acre feet)
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Exceedence Probability
Extremely Wet
Wet
Normal
Dry
Critically Dry

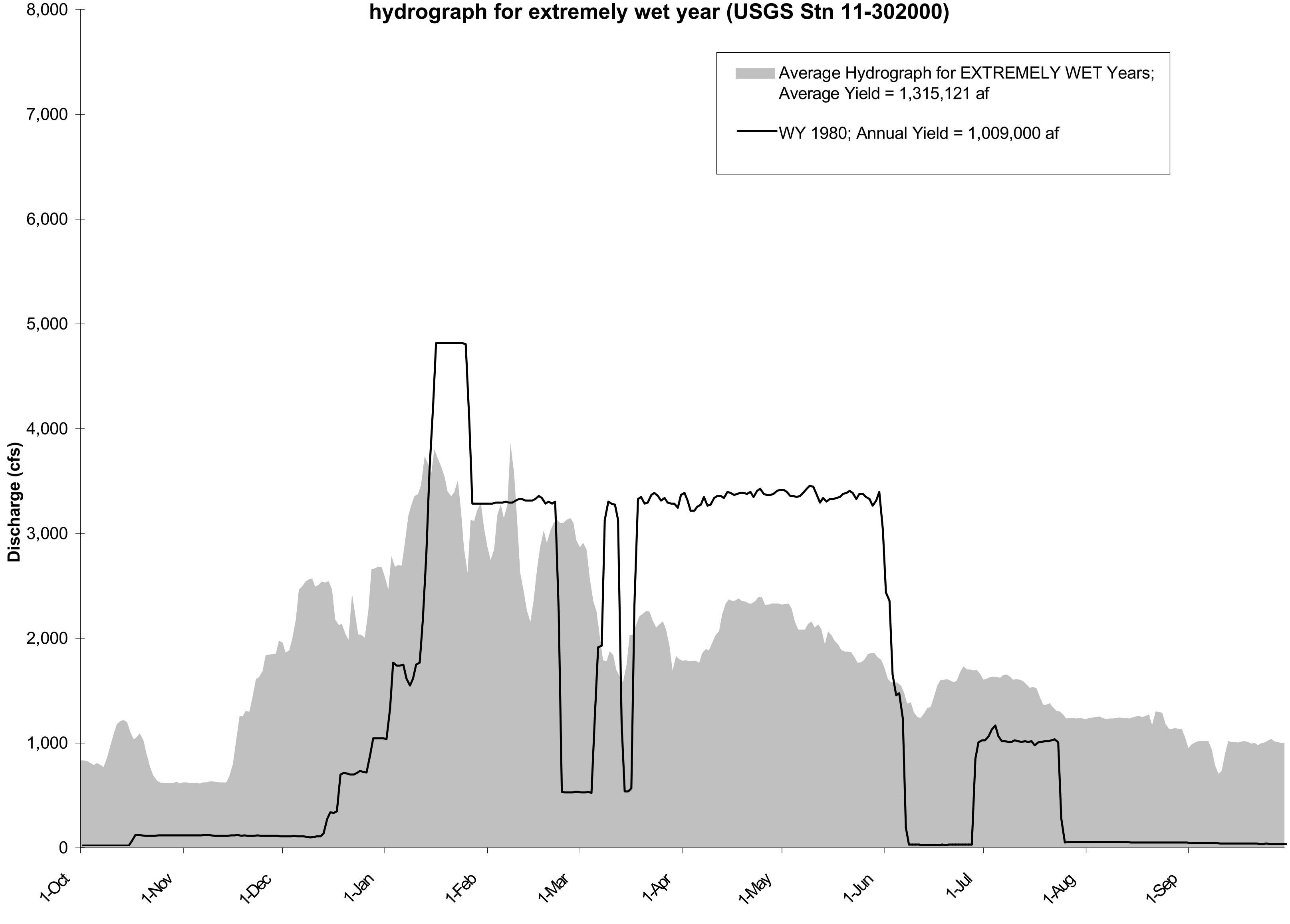
Stanislaus River below Goodwin Dam near Knights Ferry, CA measured unimpaired and regulated flow duration curves (USGS Stn 11-302000)

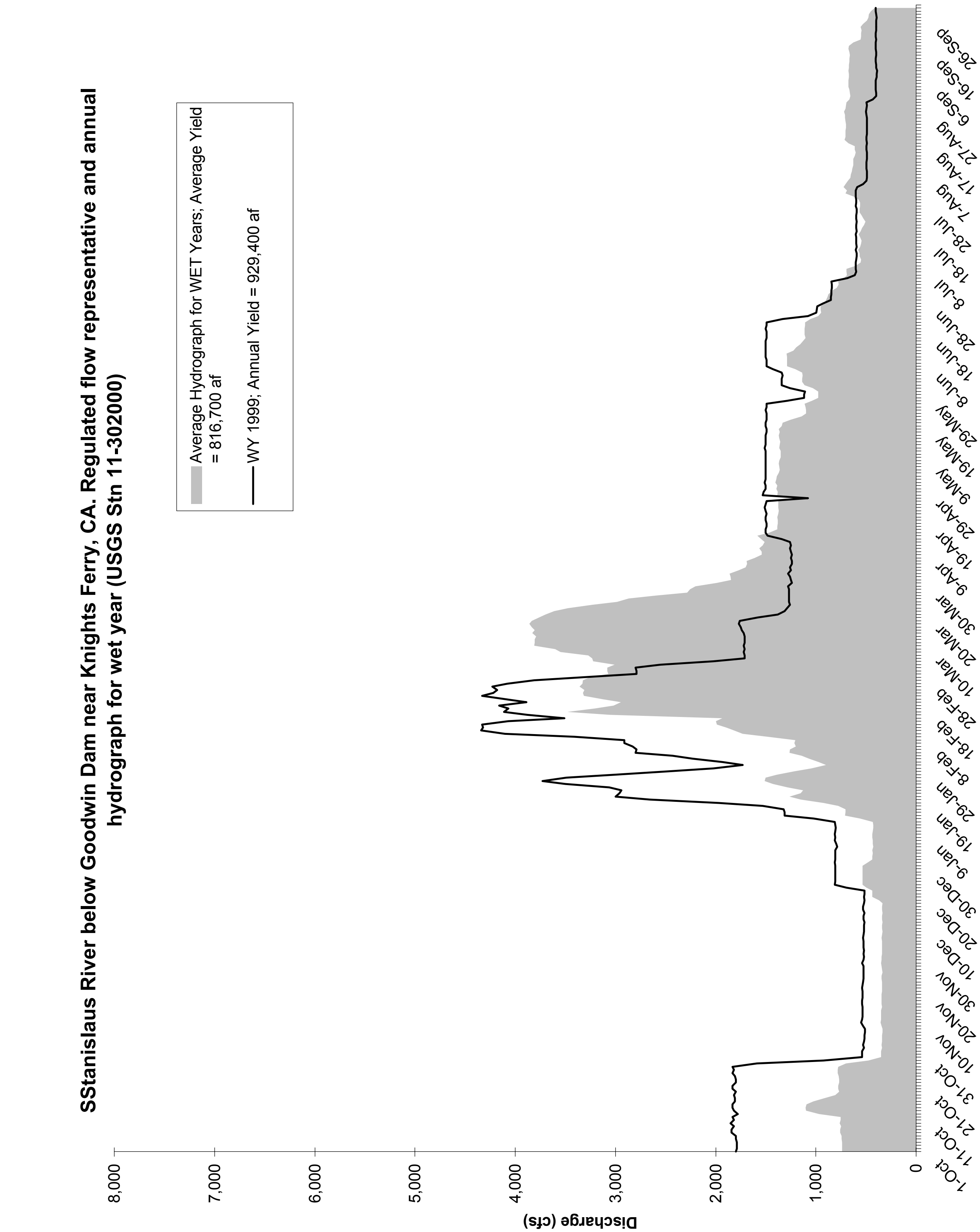


Stanislaus River near Knights Ferry unimpaired WY 1904 to 1932 Regulated WY 1956 to 2000 (Tullock 1957; New Melones 1983) measured pre- and post-dam Flood frequency

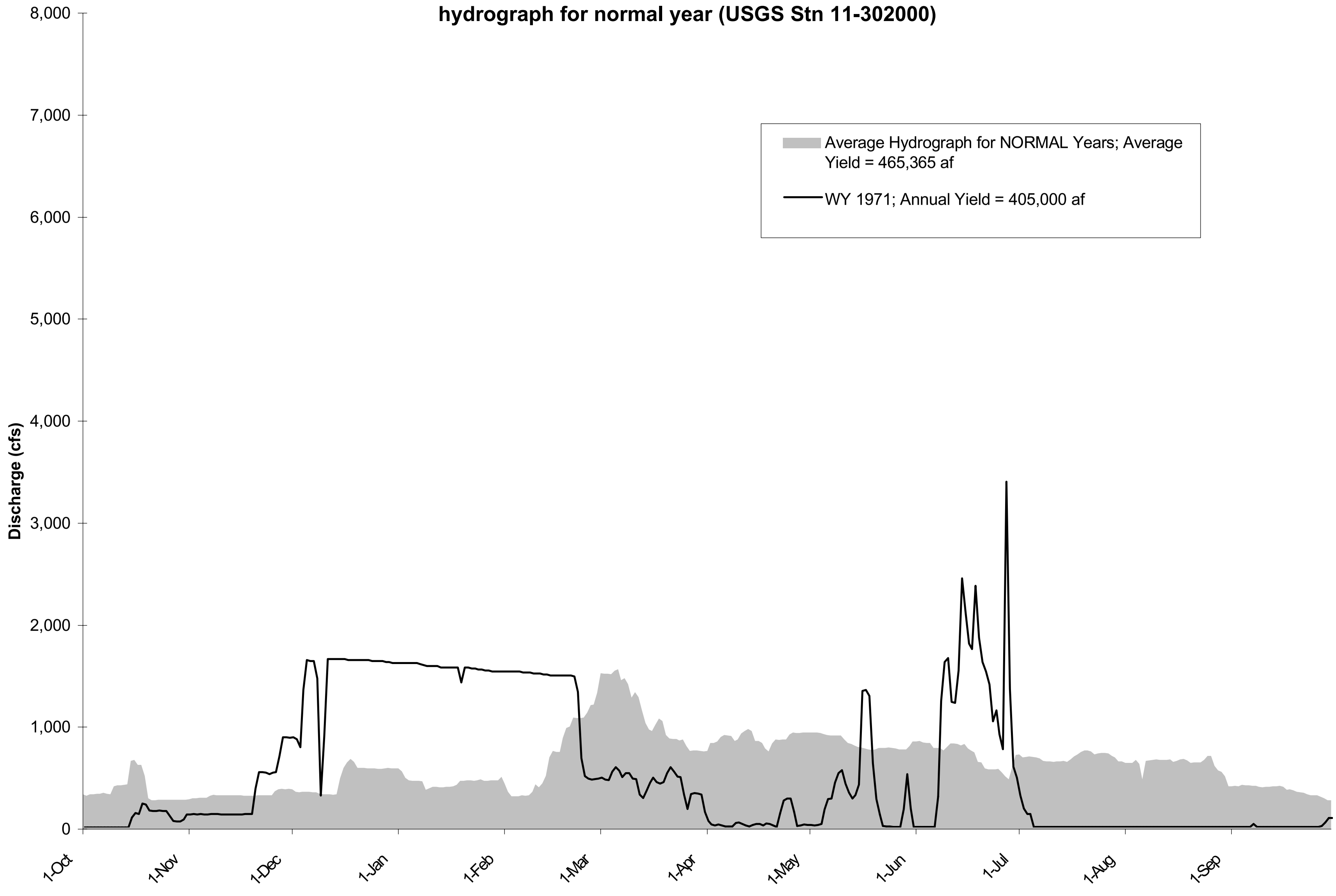


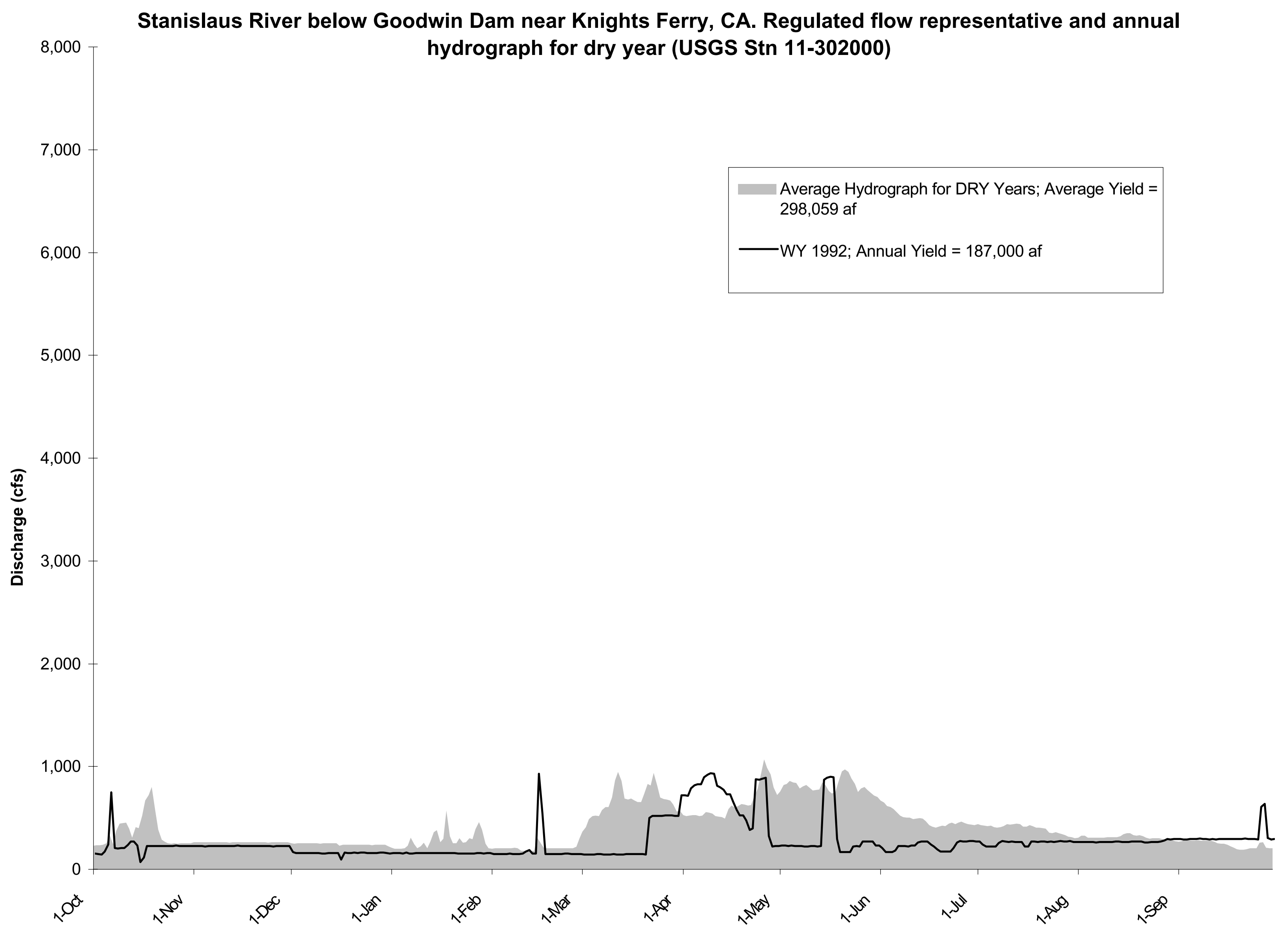
Stanislaus River below Goodwin Dam near Knights Ferry, CA. Regulated flow representative and annual hydrograph for extremely wet year (USGS Stn 11-302000)

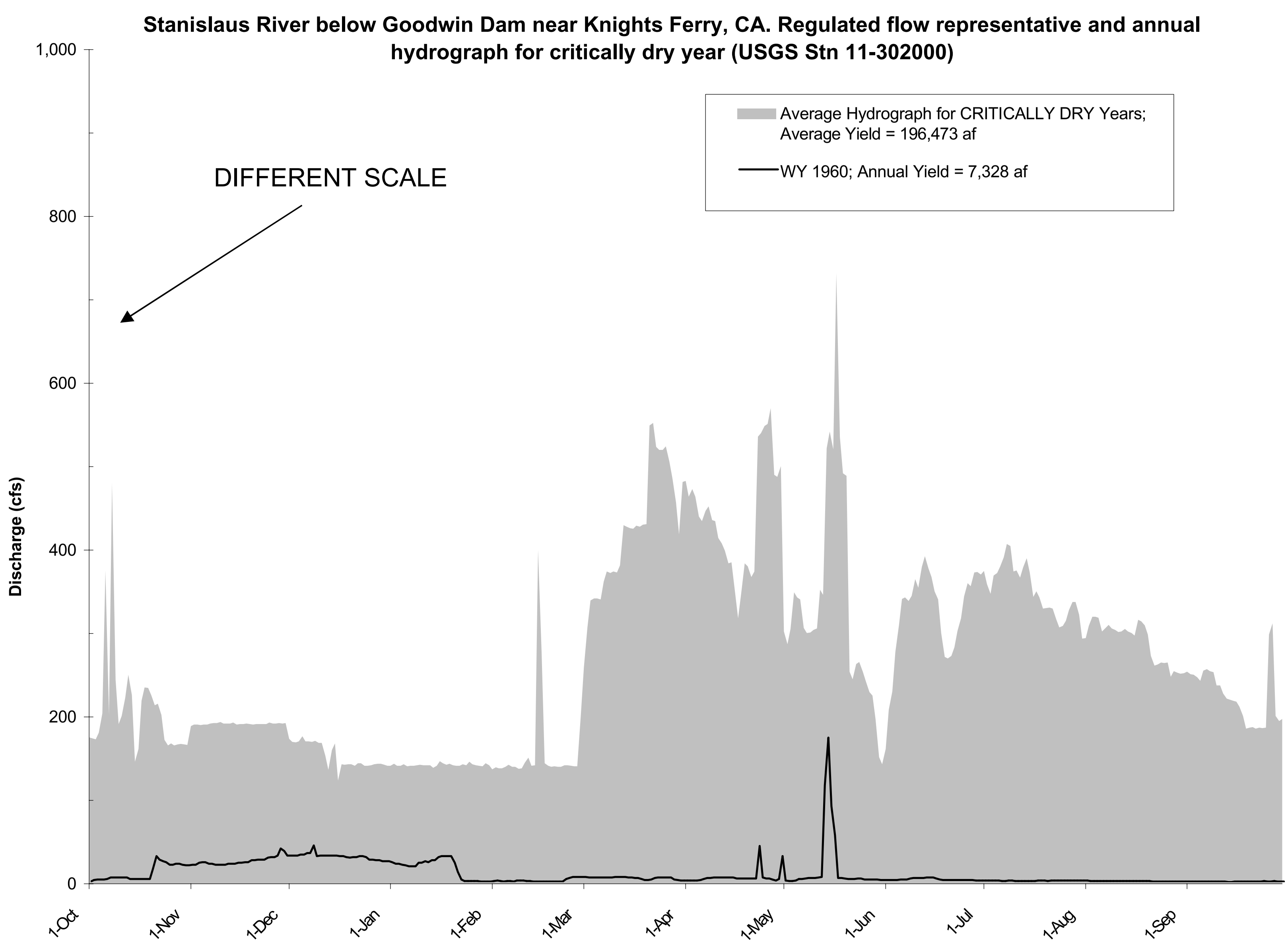


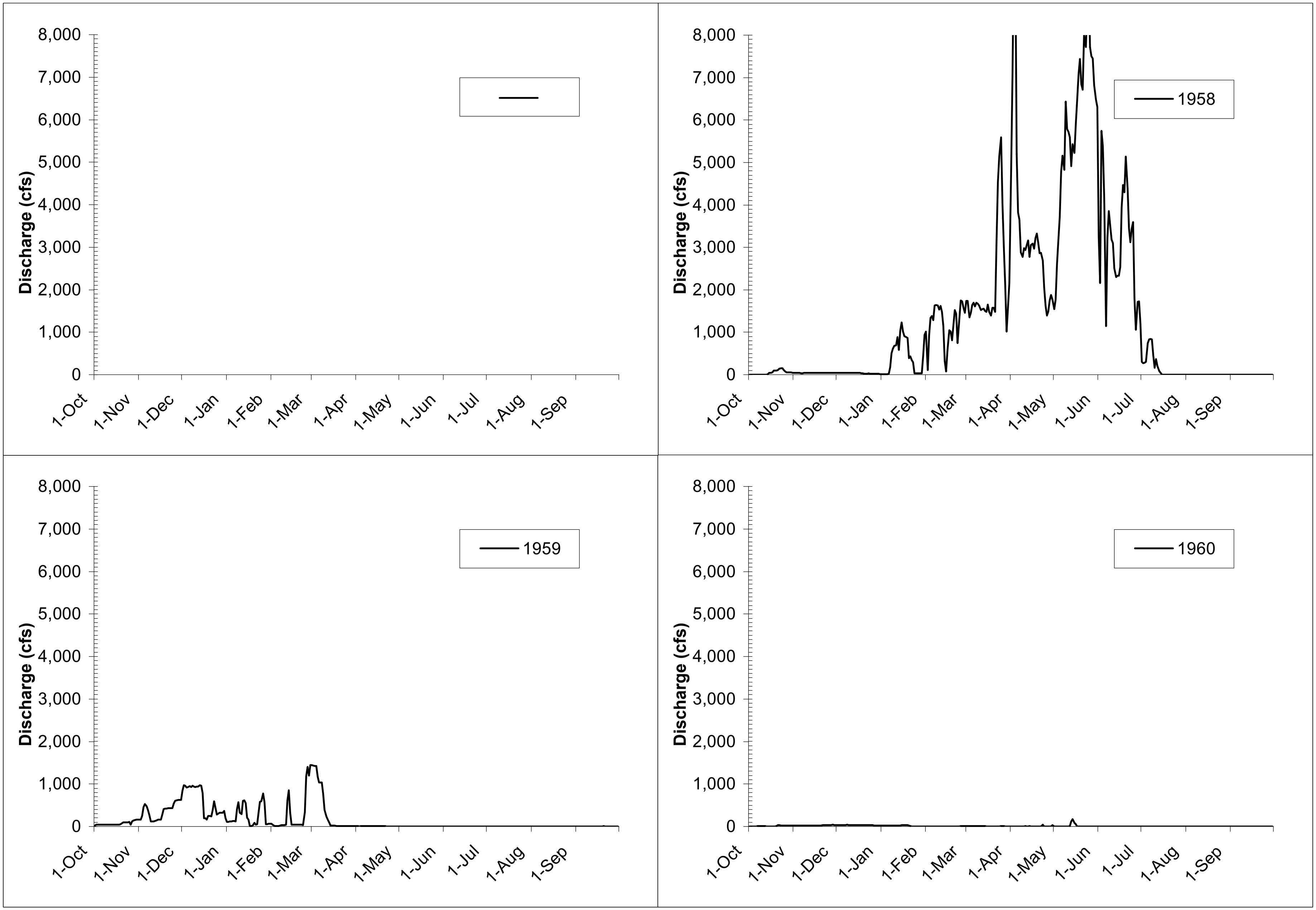

SStanislaus River below Goodwin Dam near Knights Ferry, CA. Regulated flow representative and annual hydrograph for wet year (USGS Stn 11-302000)
Average Hydrograph for WET Years; Average Yield = 816,700 af
WY 1999; Annual Yield = 929,400 af
Discharge (cfs)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec
9-Jan
19-Jan
29-Jan
8-Feb
18-Feb
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
8-Jul
18-Jul
28-Jul
7-Aug
17-Aug
27-Aug
6-Sep
16-Sep
26-Sep

Stanislaus River below Goodwin Dam near Knights Ferry, CA. Regulated flow representative and annual hydrograph for normal year (USGS Stn 11-302000)

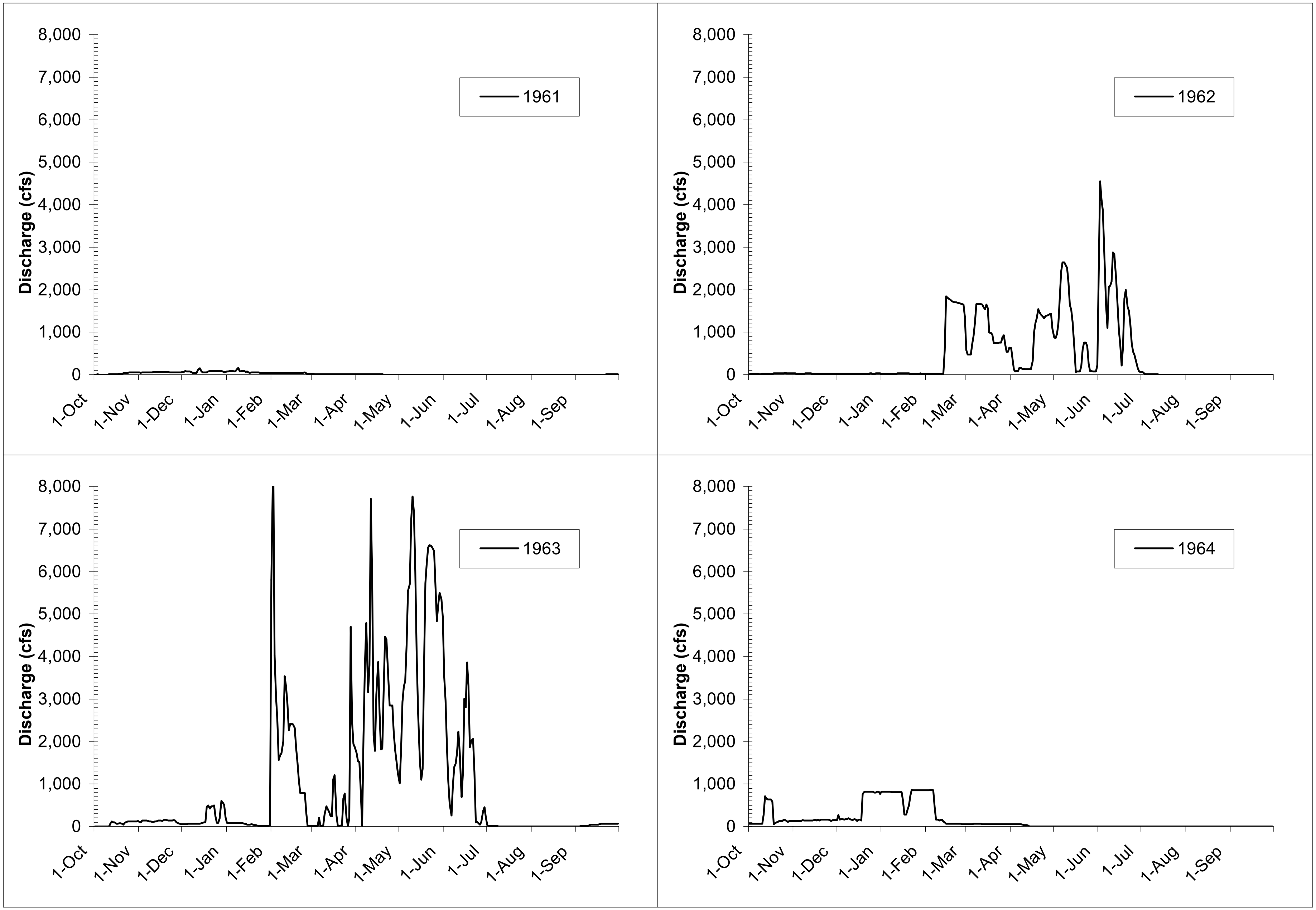



Stanislaus River below Goodwin Dam near Knights Ferry, CA. Regulated flow representative and annual hydrograph for dry year (USGS Stn 11-302000)
Discharge (cfs)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Average Hydrograph for DRY Years; Average Yield = 298,059 af
WY 1992; Annual Yield = 187,000 af

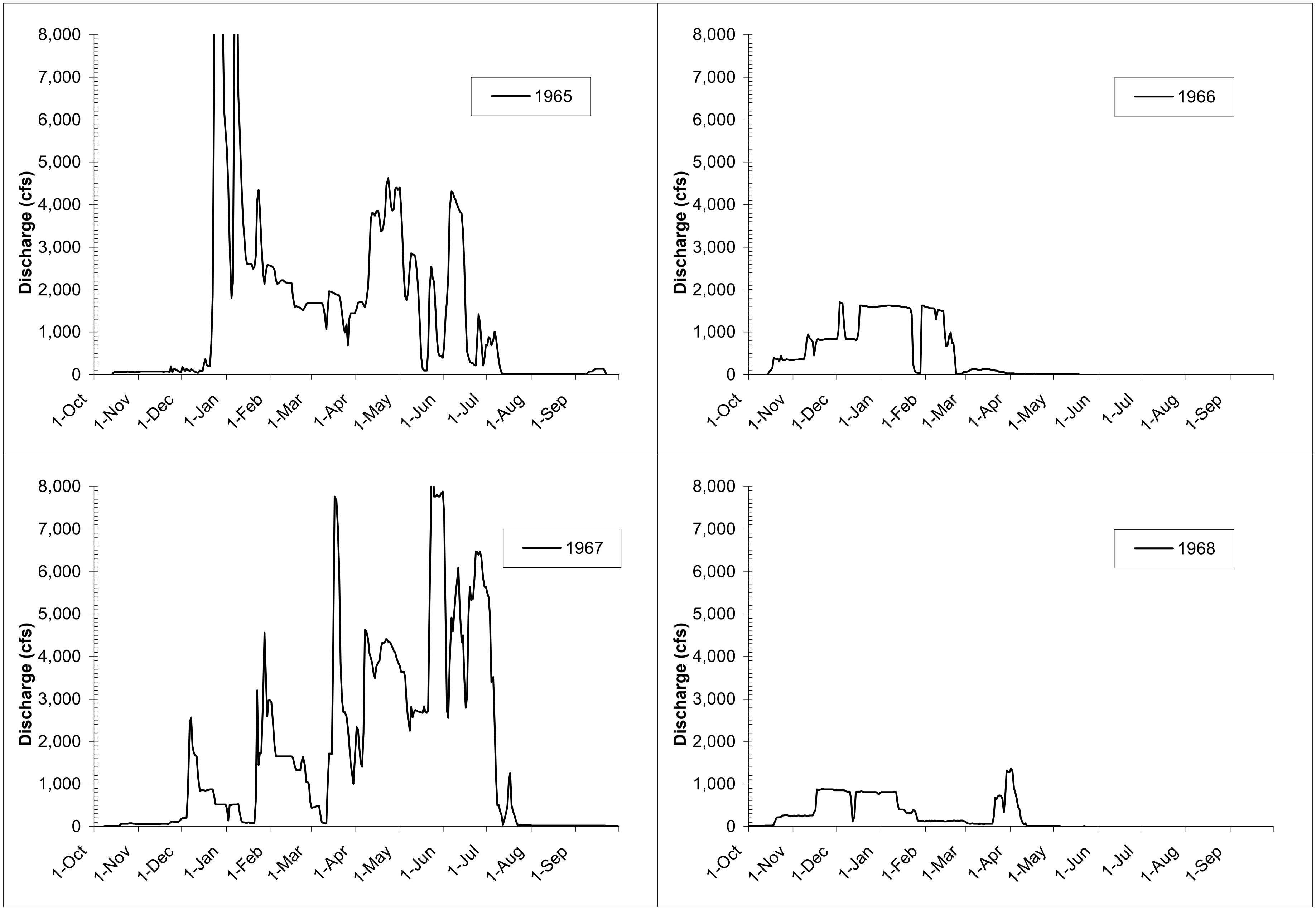

Stanislaus River below Goodwin Dam near Knights Ferry, CA. Regulated flow representative and annual hydrograph for critically dry year (USGS Stn 11-302000)
Average Hydrograph for CRITICALLY DRY Years; Average Yield = 196,473 af
WY 1960; Annual Yield = 7,328 af
DIFFERENT SCALE
Discharge (cfs)
1,000
800
600
400
200
0
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep



Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED hydrographs for WY1958-2000 (USGS Stn 11-302000)



Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED hydrographs for WY1958-2000 (USGS Stn 11-302000)



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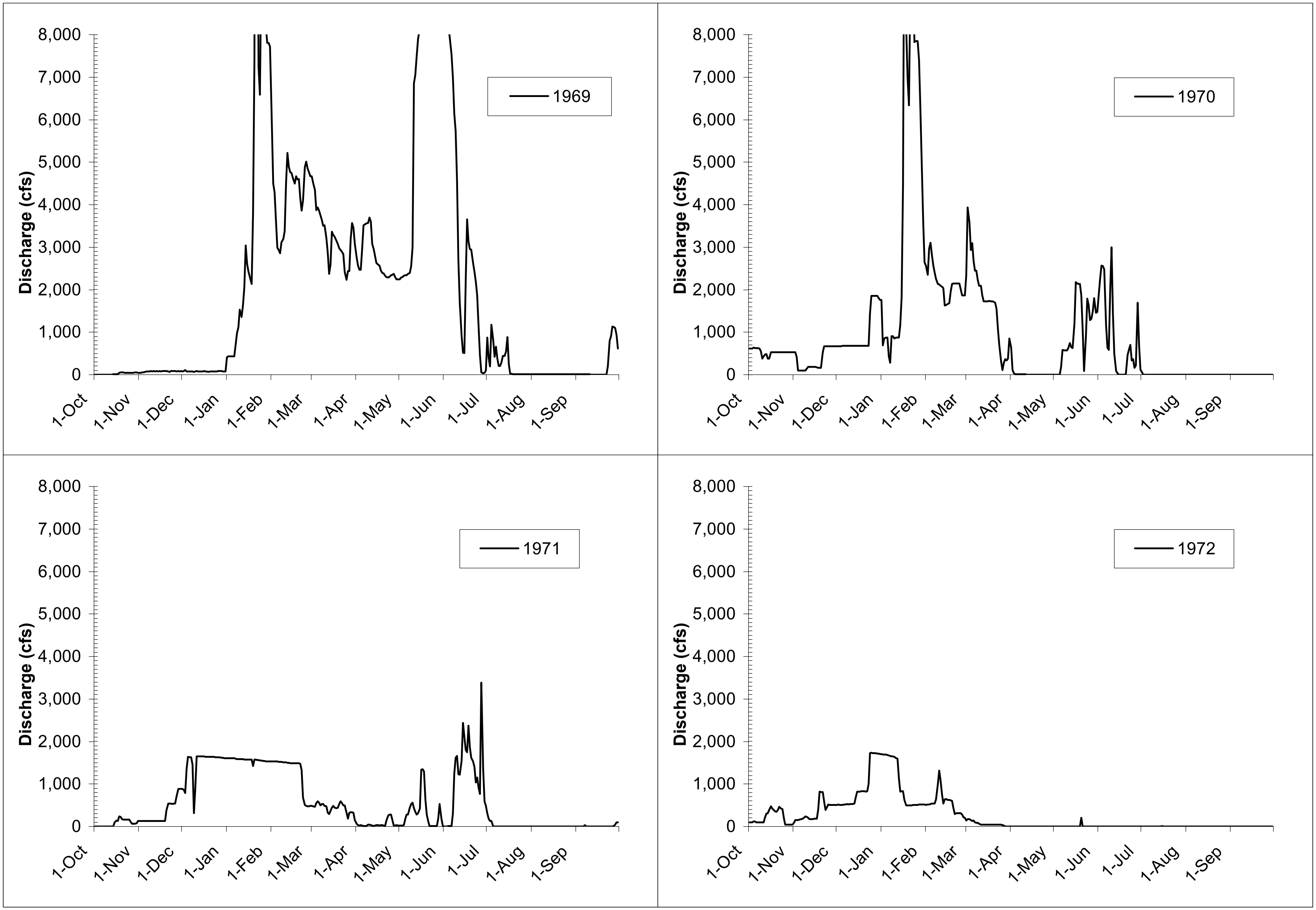

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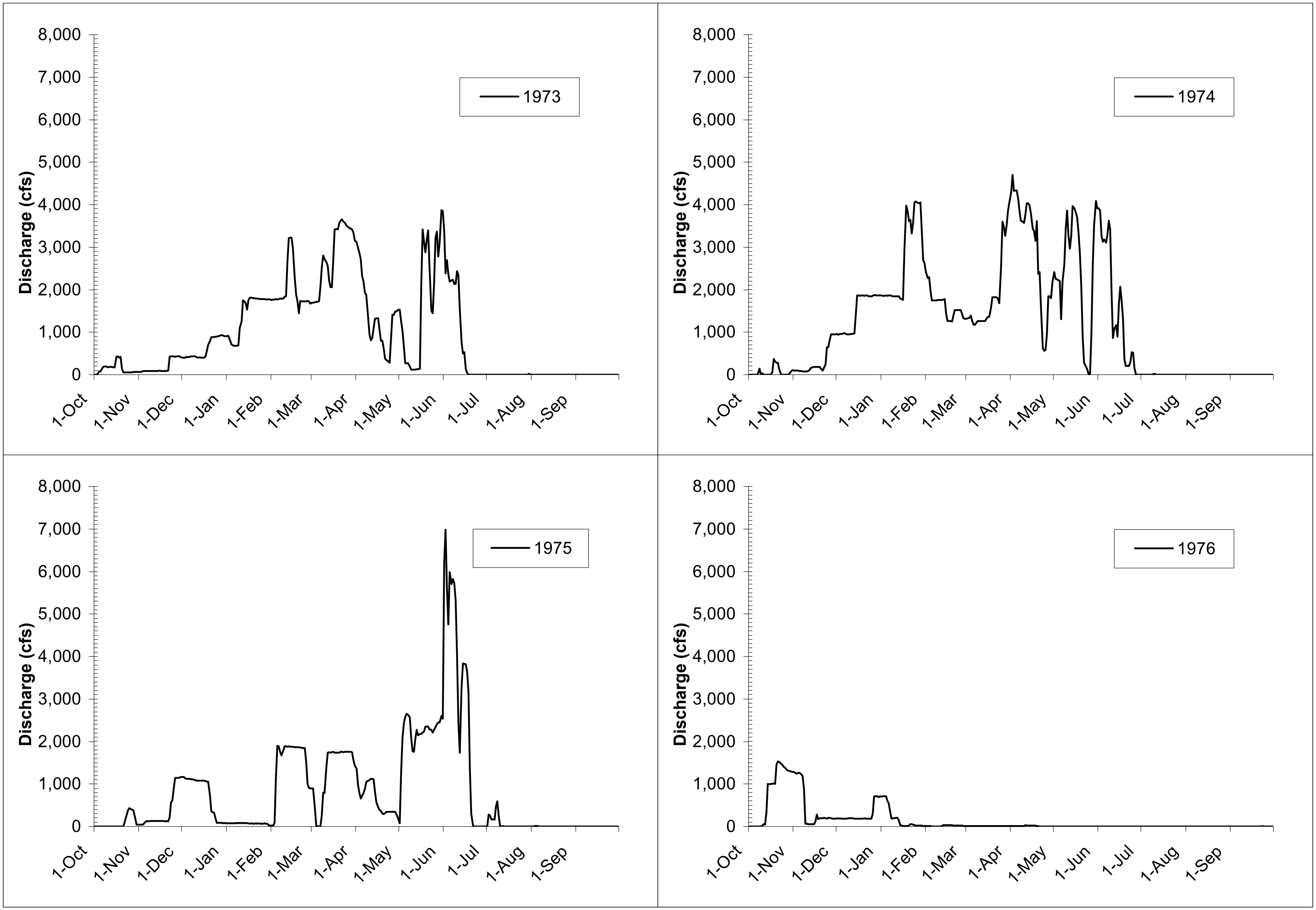

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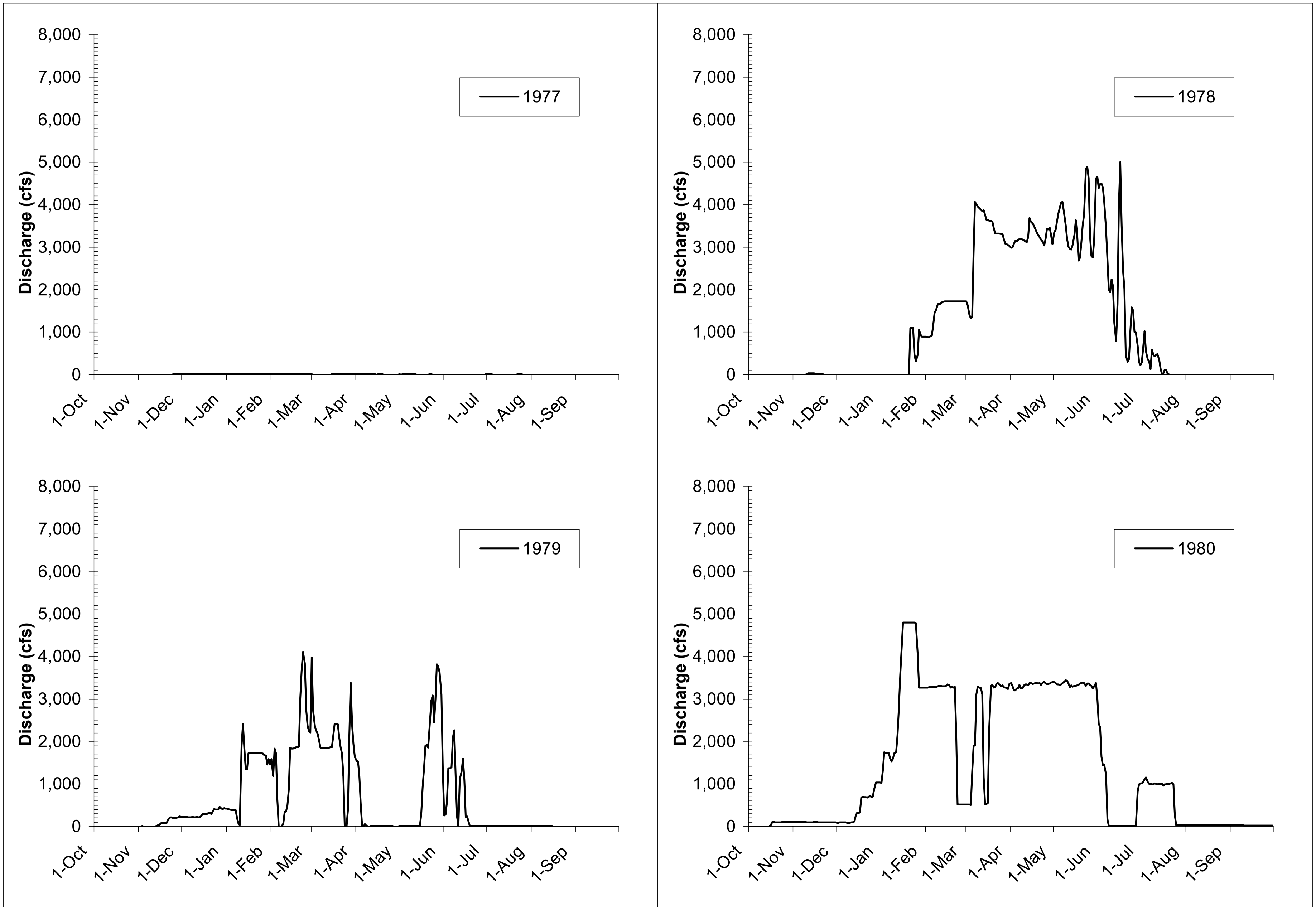

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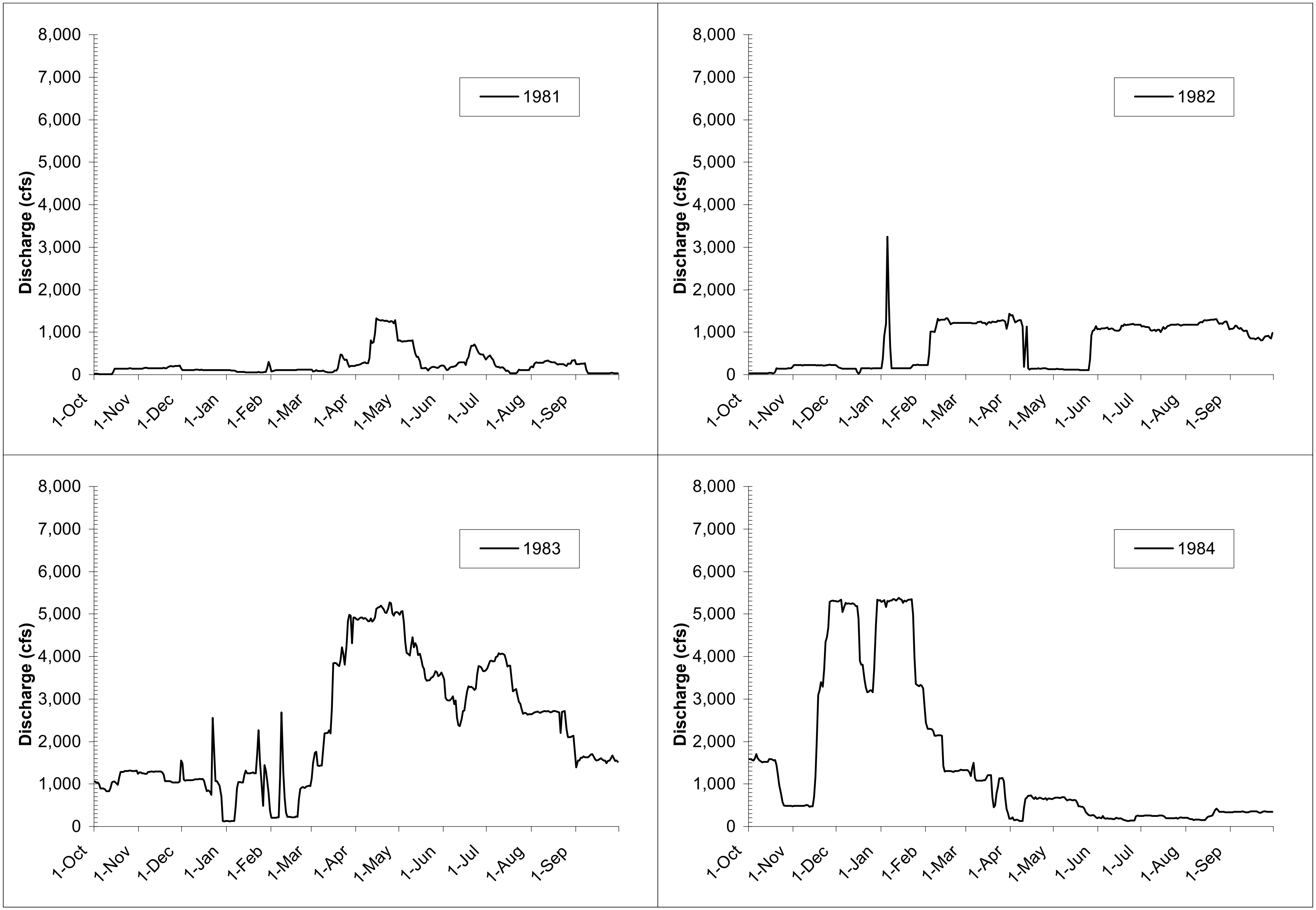
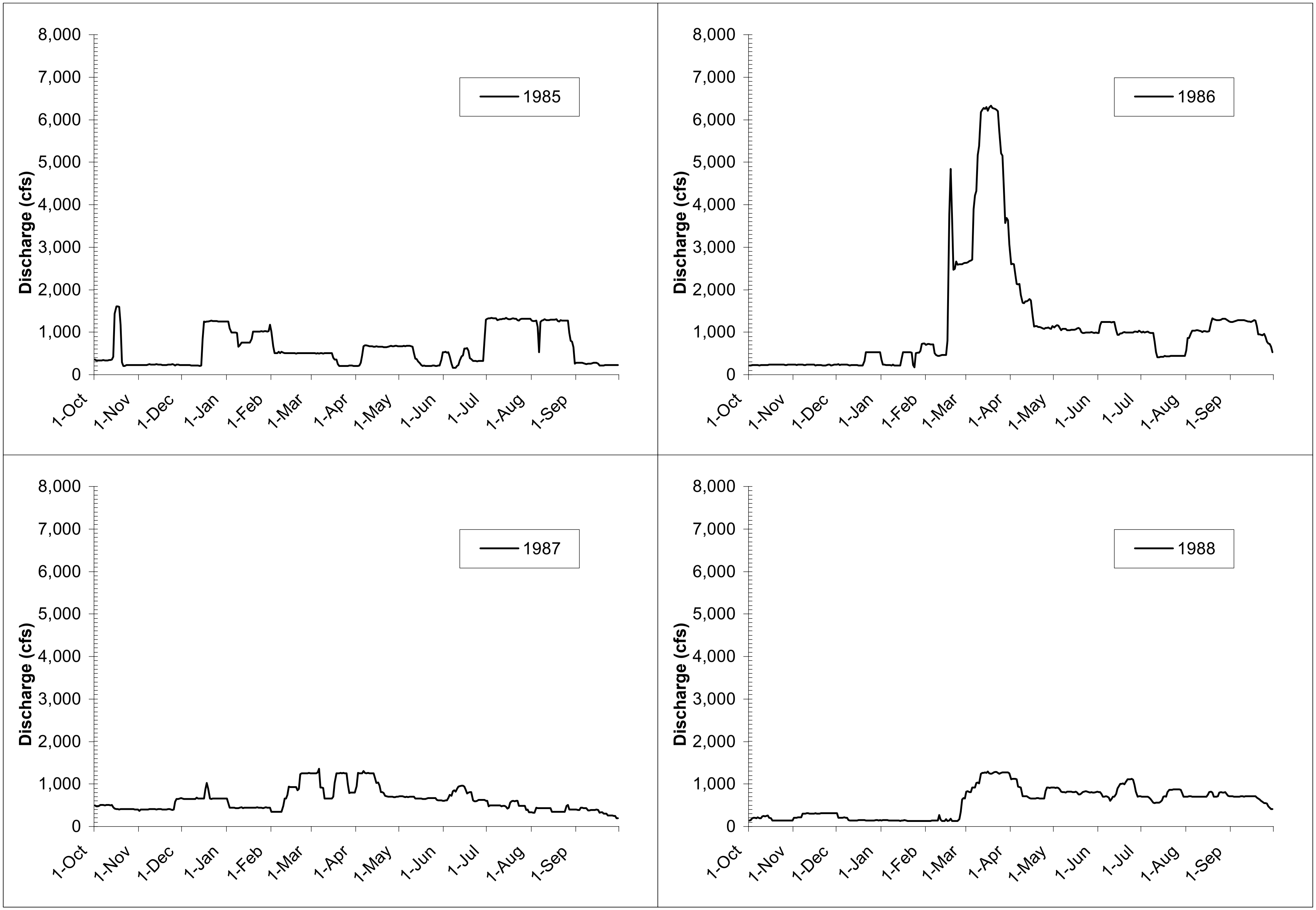


Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED hydrographs for WY1958-2000 (USGS Stn 11-302000)



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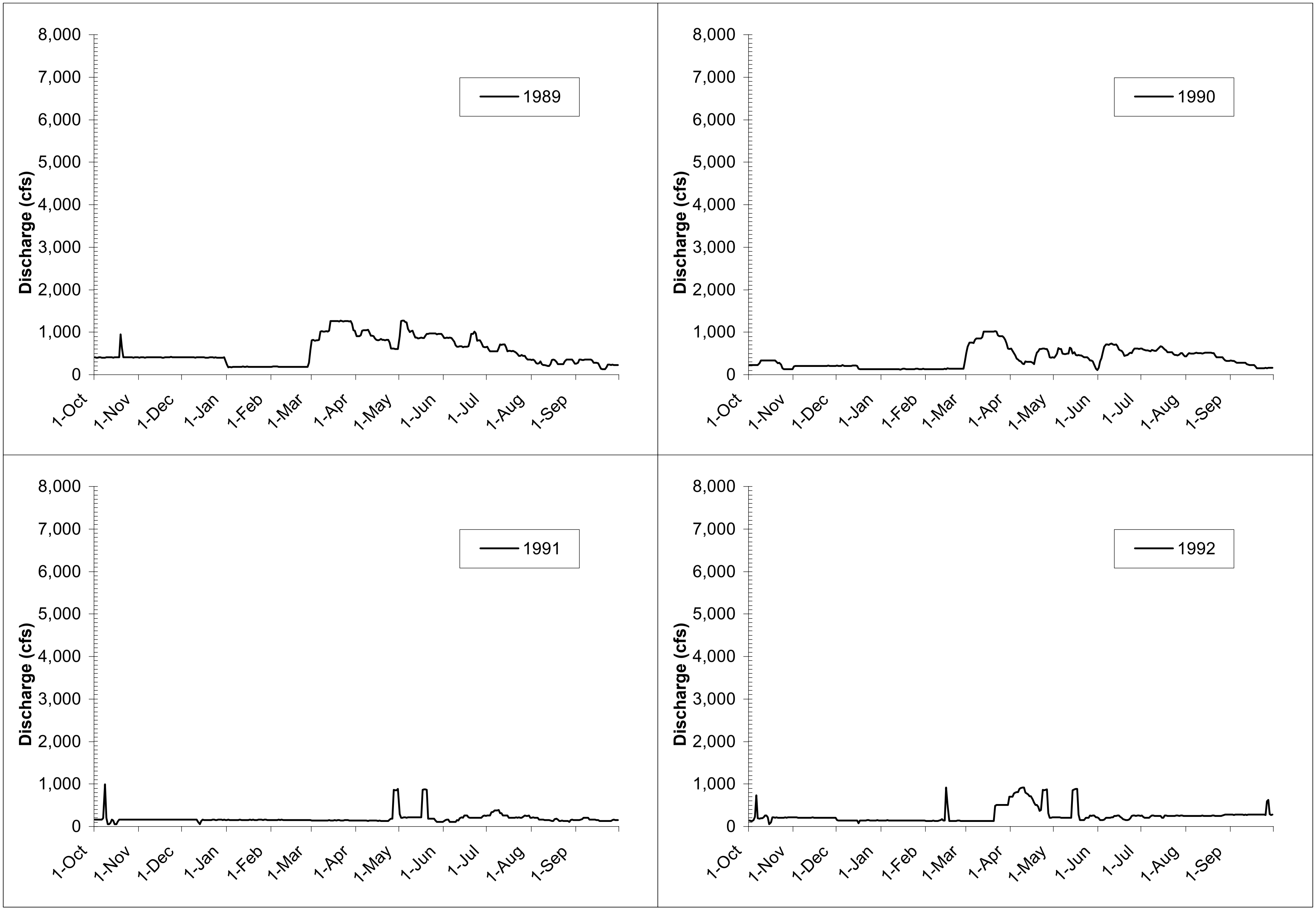

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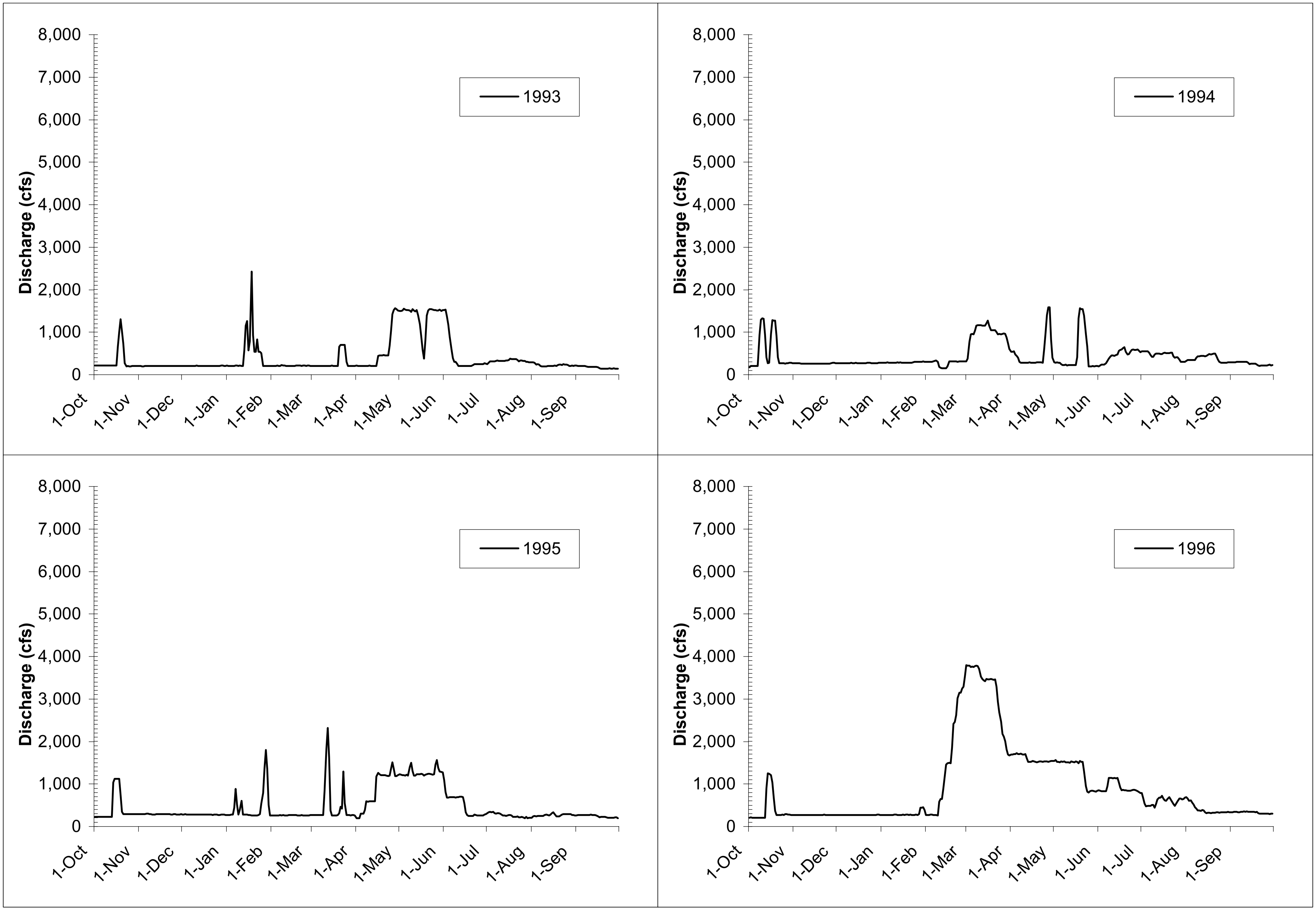

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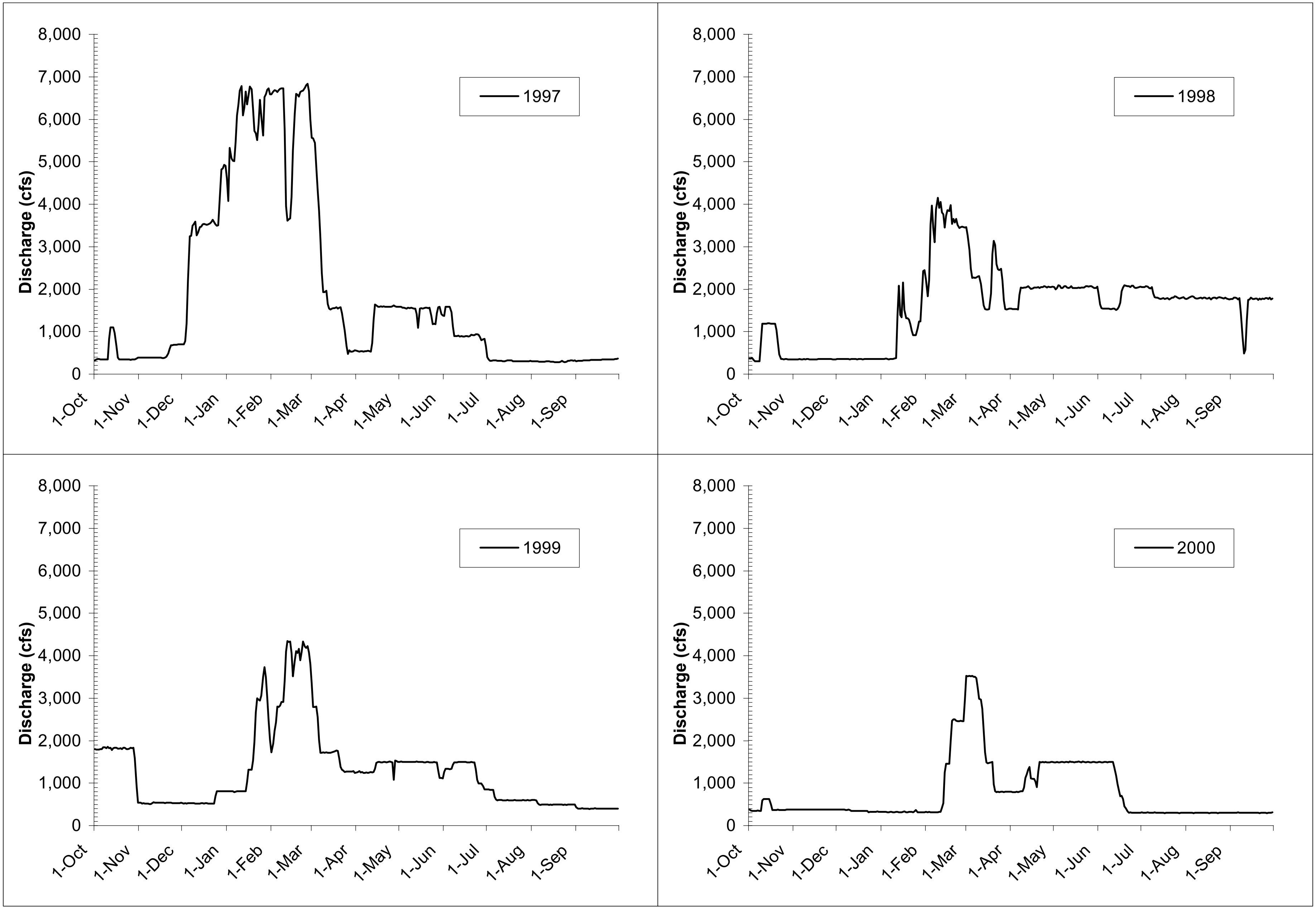

Stanislaus River below Goodwin Dam near Knights Ferry, CA REGULATED hydrographs for WY1958-2000 (USGS Stn 11-302000)