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Conjunctive Use for Flood Protection

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Providing leadership to this study were Chris Dunn, Chief of HEC's Water Resource Systems Division, Arlen Feldman Chief of the Hydrology and Hydraulics Technology Division, and Darryl Davis, Director of HEC.

Executive Summary

At the request of the Sacramento District and as part of the Sacramento and San Joaquin River Basins Comprehensive Study, the Hydrologic Engineering Center (HEC) conducted a "pre-reconnaissance" study to assess whether employing Conjunctive Use (CU) within the Sacramento and San Joaquin River Basins produces sufficient flood protection benefits to warrant further investigation. CU is the cooperative management of both surface water (reservoirs, rivers, canals) and groundwater (aquifer) resources to expand the utility of both systems. Within California, the conjunctive use of surface and groundwater resources is often discussed as the most promising nonstructural means to increase water yield while protecting and improving groundwater resources. CU for the purpose of flood protection is a relatively new idea that has received little attention in the literature yet seems highly promising.

While recognizing that flood protection is not in reality the first priority of conjunctive use operations in California, HEC pursued an investigation that evaluated CU reservoir operations focused on providing "guaranteed" flood protection. Resulting estimates can be viewed as an upper bound on flood protection for a given level of infrastructure, and also include the new water yield that would be provided as a secondary benefit. Actual implementation of conjunctive use would likely reside at a point on the yield/flood-protection tradeoff curve that was much closer to maximization of yield.

Reservoirs provide flood protection by lowering the reservoir storage level prior to the flood season to vacate a pool for anticipated floodwater storage. This pool intercepts and detains high flows to lower damage-causing releases from the reservoir during flood events. Water released to create this pool in time for the flood season is lost to the reservoir system. With CU operations aimed to increase flood protection, the reservoir storage level is lowered further, but displaced water is transferred to groundwater storage. This transfer not only vacates an additional flood pool (CU Pool) in the reservoir to intercept seasonal flood flows, but also conserves that water in another location. Thus, the CU Pool represents reservoir volume that serves the dual purpose of flood protection and conservation storage.

CU operations aimed at flood protection also generate new water yield in two ways. While space is available in accessible aquifers, wet-season flows released from the reservoir can be captured there and stored. After the flood season, the CU Pool may capture additional snowmelt runoff in a wet spring. Even those CU operations aimed at increasing "guaranteed" flood protection aim to maintain or increase existing water supply and minimize impact to recreation.

For this study, HEC developed a conceptual model to represent CU reservoir/aquifer operations focused on maximizing guaranteed flood protection to determine an upper bound on that objective. The conceptual model specifies transfers between reservoir, aquifers, agricultural demand, and additional end users within six sub-basins. Selected reservoir sub-basins included: Oroville Reservoir on the Feather River, New Bullards Bar Reservoir on the Yuba River, and Folsom Reservoir on the American River in the Sacramento Basin, and Millerton Lake (Friant Dam) on the San Joaquin River, Lake McClure (New Exchequer Dam) on the Merced River, and Don Pedro Reservoir on the Tuolumne River in the San Joaquin Basin.

For each sub-basin, calculations were made to quantify the factors limiting the creation of additional flood protection space. These initial estimates were verified using an interactive Water Transfer Model to simulate operations with a weekly time-step. HEC determined both the volume of a CU Pool created in each reservoir and amounts of new yield generated from CU operations considering four scenarios of CU infrastructure. Detailed computation was based upon a 14-year historical record of reservoir inflows in each sub-basin, synthesized agricultural demand data, and an assumption that 15% of the transfer to groundwater storage was lost. (15% is the loss value often used in Conjunctive Use studies)

For a "Maximum Infrastructure" scenario, CU operations focusing on flood protection created between 100 and 140 thousand acre-feet (KAF) of additional "guaranteed" flood protection space, representing 28% to 71% increases in flood storage over existing flood pools (Table ES-1). These CU operations also generated between 92 and 322 KAF of average annual new yield per reservoir. Cost estimates to implement these CU operations range from $69 million to $300 million per sub-basin when considering land purchase, conveyance structure construction, extraction facility construction, and well field operation and maintenance costs (Table ES-2). New Exchequer and Friant Dams appear to provide the largest amount of new yield for the least cost.

Table ES-1. Flood Storage Space and New Yield Generated from CU Operations

Reservoir	Existing Flood Pool (10^3 ac-ft)	Reservoir Storage Capacity (10^3 ac-ft)	CU with Maximum Infrastructure (Scenario 1)		
			Size of CU Pool (10^3 ac-ft)	Percent Increase in Flood Storage Space	New Yield Generated (10^3 ac-ft)
Sacramento Basin					
Oroville	480	3538	138	29%	148
New Bullards Bar	170	960	120	71%	120
Folsom	451	978	142	31%	211
San Joaquin Basin					
Don Pedro	340	2030	124	36%	160
McClure / New Exch	350	1025	98	28%	92
Millerton / Friant	171	521	121	71%	322

Table ES-2. CU Project Costs by Reservoir for Maximum Infrastructure Scenario

Reservoir	Land Purchase Price (10^6 $)	Low Conveyance Cost (10^6 $)	Extraction Facillity Construction (10^6 $)	Recharge Facility Construction (10^6 $)	Total Capital Cost (10^6 $)	Annual O&M (10^6 $/yr)
Sacramento Basin						
Oroville	330	680	1300	0	2300	26
New Bullards	210	130	450	0	780	10
Folsom	170	260	530	0	950	10
San Joaquin Basin						
Don Pedro	200	51	450	0	700	15
New Exchequer	130	150	300	0	590	5
Friant	140	280	750	0	1200	26
TOTAL	**1200**	**1500**	**3800**	**0**	**6500**	**93**

New Exchequer, New Bullards Bar, and Friant Dams appear to be the sub-basins in which CU can provide the largest percentage increase in flood storage space for the least cost. CU operations at Folsom Reservoir and the three San Joaquin Basin reservoirs provide the most *significant* flood protection as seen by the reduction in peak flows for CU regulated flood frequency curves compared to without-CU regulated frequency curves (Appendix B). Flood frequency curves were calculated by incorporating CU flood storage space into an HEC-5 reservoir simulation model and routing synthetic flood events through the Sacramento and San Joaquin basin reservoir networks.

For a more conservative modeling scenario (assuming a minimum level of infrastructure), CU operations secured between 60 and 120 KAF of additional guaranteed flood protection space representing 21% to 70% increases in flood storage over existing flood pools. These CU operations generated between 45 and 240 KAF of average annual new yield per reservoir. Cost estimates ranged from $37 million to $150 million per basin.

Aquifer storage loss assumptions used in the Water Transfer Modeling were validated by detailed groundwater modeling and simulation of CU recharge and retrieval operations for a "typical" San Joaquin basin aquifer. The groundwater model has broad potential for future use in the design of CU facilities, optimization of operations procedures, and evaluation of site- and project-specific scenarios. Site-specific modeling of prospective CU projects would benefit greatly from the ability to carefully represent the response of the groundwater table to storage and retrieval activities.

The "strict management" arrangement modeled in the study likely represents the most expensive type of CU management arrangement. This arrangement (where a CU management authority buys land and builds the infrastructure to control the land, surface, and groundwater rights associated with the reservoir, aquifers, and recharge/retrieval operations) was chosen for investigation to allow creation of guaranteed flood storage space from CU operations. Strict management also represents the most active type of involvement for the management authority. Based on a review of current CU practices within the study basins, pursuit of contractual arrangements instead could lower project costs and spur more enthusiastic involvement. These arrangements would require greater coordination and cooperation between a CU management authority and groundwater management authorities, reservoir operators, end users, local water districts, aquifer, and landowners within the basin. Available new water yield might be an incentive to participation.

Compared to structural methods for increasing flood protection such as raising levees or building new dams, CU may be a cheaper alternative for providing commensurate level(s) of additional flood protection. At the same time, CU operations can increase water yield, providing multi-objective benefits with a single infrastructure investment. Because of the significant volume of reservoir storage space that could be made available, HEC finds that CU for flood protection merits further study. Analysis suggests that study should focus on incorporating flood protection into planned and existing CU programs designed to maximize new yield. It will be important to decide whether to actively or passively pursue CU flood protection programs. For *active* involvement, the CU management authority role would need to be defined. Work could then

proceed to gather groundwater management plans drafted by local agencies located within the study basins, contact program managers to determine the feasibility of adding flood protection to their programs, and locate and approach property owners to assess their willingness to participate in a CU program or enter into contractual agreements.

Alternatively, the CU for flood protection could be promoted more passively. The primary need in that case would be to develop new methodology to quantify both the guaranteed and incidental flood protection benefits gained from CU management for other purposes. As follow-up, the Corps could assist the efforts of local agencies to compute these benefits and incorporate them into their groundwater management plans.

KEYWORDS

conjunctive use, flood protection, Sacramento basin, San Joaquin basin, California, USACE, new yield, recharge and retrieval operations simulation, water transfer model, cost estimate, reservoir flood storage space.

Conjunctive Use Pre-Reconnaissance Study

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1 Introduction

The Hydrologic Engineering Center (HEC) conducted a "pre-reconnaissance" study to assess whether employing Conjunctive Use for increased flood protection within the Sacramento and San Joaquin River Basins merits further study. The study was performed for the Sacramento District as part of the Sacramento and San Joaquin River Basins Comprehensive Study.

Conjunctive Use (CU) is the cooperative management of both surface water (reservoirs, rivers, canals, diversions) and groundwater (aquifer) resources to expand the utility of both systems. CU operations exploit storage space available in depleted groundwater aquifers and incorporate that space into the overall storage capacity of the integrated surface and groundwater system. This non-traditional water management arrangement has the potential to increase water storage capacity, restore groundwater aquifers, and increase flood protection.

CU for flood protection is a relatively new idea that has received little attention in the literature. Within California, the conjunctive use of surface- and ground-water resources is often discussed as the most promising nonstructural means to increase water yield [DWR, 1998; CALFED, 1999; Davis, 1998]. Nonstructural alternatives to increase water supply and mitigate flooding are increasingly being sought because they could have the potential to minimize capital outlays and environmental impacts compared to conventional "structural" solutions such as reservoir construction, levees, groundwater depletion, wastewater recycling, or desalinization.

The typical focus of CU for new yield directly addresses water scarcity, and provides incentive reservoir owners and water users (surface or groundwater) to participate in CU and groundwater banking projects. Flood protection, like other social use values, accrues to a group [Mitsch and Gooselink, 1992, p. 535] that may or may not include water providers and users. Cooperation can be more difficult to achieve.

Proponents of CU for flood protection suggest that additional flood protection can be achieved by "skimming the peak" of flood flows during a flood event and diverting that water into aquifer storage. Alternatively—or additionally—flood protection can be achieved by drawing down an additional portion of the reservoir conservation pool during the flood season and transferring the displaced water to aquifer storage. This transfer not only vacates a CU Pool in the reservoir that (in addition to the Flood Pool) can intercept and detain seasonal flood flows, but also conserves the transferred water in another location. Thus, the CU pool denotes reservoir volume that serves the dual purpose of flood protection and conservation storage. After the flood season, empty CU Pool space can also be used to capture additional late season runoff. Thus, CU operations have the potential to supplement flood protection and generate new water yield.

Flood protection and new yield benefits are de facto byproducts of CU operations, but the tradeoff between these benefits is not yet clear (Figure 1-1). To some extent, the benefits are complimentary. Operation schemes designed to secure maximum flood protection (Point B), can still increase yield by transferring high winter flows to an aquifer. Additionally, snowmelt runoff can be captured in the CU pool after the flood season. These transfers and captures amount to the minimum level of new yield associated with the increased flood protection.

Alternatively, CU operations with a priority for maximizing new yield can improve flood damage reduction by lowering reservoir pools. Operations would vacate the CU pool by the start of the flood season to create room to capture high winter flows and snowmelt runoff. This pool, present during some of the flood season, provides an incidental level of additional flood protection associated with maximum yield (Point A).

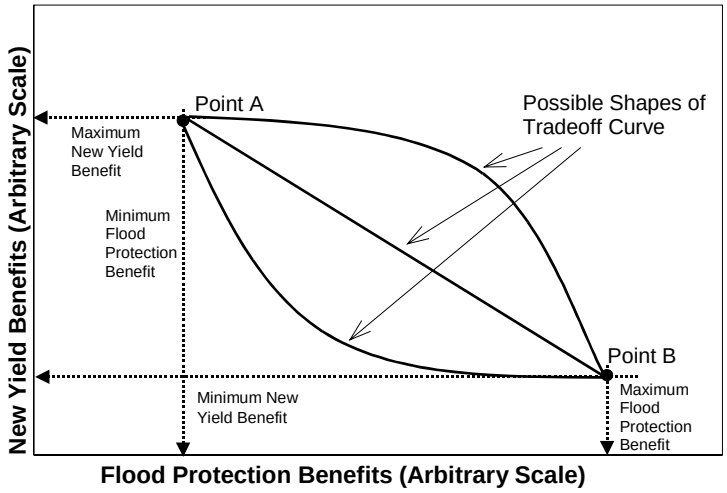


Figure 1-1 Possible Tradeoff Curves between Flood Protection and New Yield Benefits

Conflicts between the goals of flood protection and new yield arise during the flood season. After a flood event refills part or all of the CU pool, holding water in the CU Pool secures the water as new yield, but decreases the level of flood protection (point A). If the captured floodwater cannot be transferred to an aquifer, vacating the CU pool restores the additional flood protection but sacrifices yield (point B). This conflict translates to a downward sloping tradeoff curve between Points A and B.

The shape of the benefit tradeoff curve is uncertain because (i) the relative marginal benefit of flood protection to new yield is uncertain and (ii) Corps' policy only values flood protection benefits (quantified as reduction in expected flood damage) for reservoir storage space that is *guaranteed* to be available during the entire flood season. I*ncidental* reservoir storage space (not guaranteed) cannot be used to quantify flood protection benefits according to current policy.

Ordinarily, operating for flood protection is fairly straightforward. Flood protection reservoirs first lower the reservoir storage level at the start of the flood season to vacate a pool for floodwater storage, and then maintain the lowered level throughout the flood season (when the reservoir is not actively storing a flood). Water released to maintain the flood season storage level is lost to the reservoir. For example, *during* flood events, the Flood Pool intercepts and attenuates floodwaters to reduce peak flows and damage. *After* the flood event, the reservoir gradually releases the captured water to reestablish flood storage space in preparation for a future flood event.

The official quantification of reservoir damage reduction is based upon the *guaranteed* storage space remaining vacant during flood season. With existing methodology, incidental flood

storage space cannot be quantified. Therefore, depending on the CU operation priorities, either (or both) guaranteed and incidental flood storage space can be created, and so the actual and quantified flood protection benefits may differ.

Potential conflicts between flood protection and new yield benefits, and uncertainly in quantifying flood protection benefits resulting from CU operations, raises several issues that are ripe for investigation with a quantitative study.

- In areas surrounding the reservoirs, what aquifer storage space exists and how does it compare to existing flood storage space in the reservoirs?
- How much reservoir water can be transferred to the aquifers and retrieved when needed?
- How much flood protection will the CU Pool provide?
- How much spring runoff will be captured in the CU pool?
- If the CU Pool stores floodwater some of the time, what is the reduction in damage associated with the creation of this *incidental* flood storage space?

The last issue will serve as impetus for further study. The Corps should attempt to develop methodology to quantify expected flood damage reduction associated with incidental reservoir storage space. The other issues will be addressed in this "pre-reconnaissance" study. The focus will be determination of flood protection benefits and costs when flood protection is the principal priority of CU operations (Point B).

1.1 Problem Statement

It would be useful to determine if CU for flood protection is a valid concept, and whether the policy idea can be translated into an operational program that mitigates damage associated with floods while minimizing or avoiding impact on water supply. The problem can be separated into several issues: (i) is CU for flood protection technically feasible? (ii) where can the practice be implemented? and (iii) can flood protection be integrated with CU managed for other goals such as new water supply yield?

1.2 Study Goal

The goal of this study is to assess whether employing Conjunctive Use within the Sacramento and San Joaquin River Basins can produce flood protection benefits that warrant further study.

Study methods will focus on evaluating the CU operations, constraining factors, and benefits associated with Point B of Figure 1-1 (i.e., flood protection benefits are considered the first priority to be maximized, and development of new yield is secondary.)

1.3 Study Objectives

The study will address the goal by meeting the following objectives:

- Identify reservoir sites within the San Joaquin and Sacramento River basins that would most benefit from additional flood storage space.

- Use water transfer modeling to determine the volume of additional flood storage space created at reservoir sites from CU operations.
- Calculate the reduction in expected annual flood damages the additional flood storage space provides.
- Compare the benefits and costs for implementing CU at each site. The comparison will be used to evaluate if CU for flood protection "merits further investigation."
- Evaluate aquifer losses from recharge / extraction operations and optimize well-field configurations using detailed groundwater modeling.
- Review current studies and implementations of CU within California. Identify legal and institutional underpinnings as well as impediments for CU and groundwater management, and incentives needed to persuade water users to participate in CU programs. Analysis of these factors will help identify pathways to mesh current CU practices with the goal of flood protection.

1.4 Study Area

The study area encompassed the entire Sacramento and San Joaquin River basins. Locations of the six sub-basins (reservoir sites), 19 aquifer storage sites (compiled by Purkey, 2001), and downstream river monitoring points selected for detailed investigation are shown in Figure 1-2. Based on consultation with the Sacramento District, reservoirs were selected that could most benefit from additional reservoir flood storage space. Aquifer sites were spread over the sub-basins and selected based on their accessibility from the reservoirs. Reservoir sub-basins selected for detailed study included:

In the Sacramento basin:

- New Bullards Bar Reservoir on the **Yuba** River
- Oroville Reservoir on the **Feather** River
- Folsom Reservoir on the **American** River

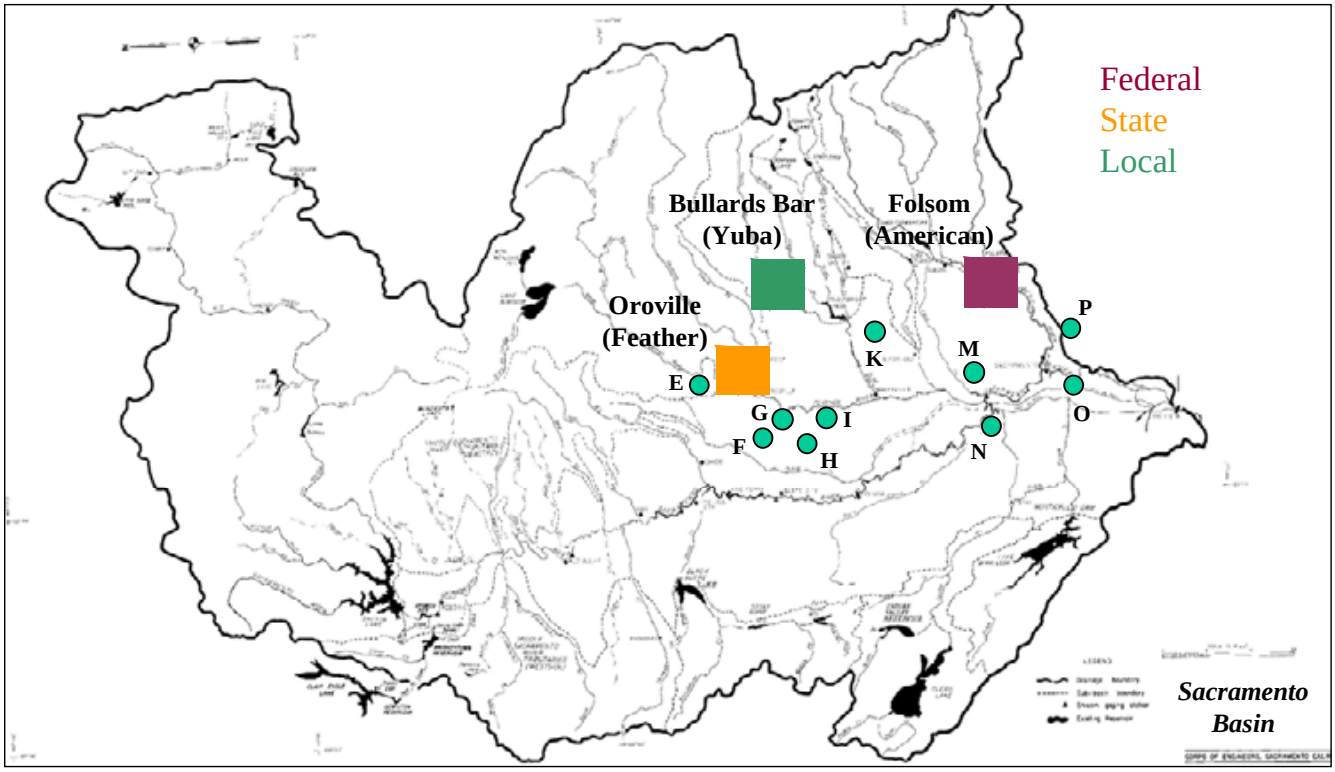
In the San Joaquin basin:

- Friant Dam (Millerton Lake) on the **San Joaquin** River
- Don Pedro Reservoir on the **Tuolumne** River
- New Exchequer Dam (Lake McClure) on the **Merced** River

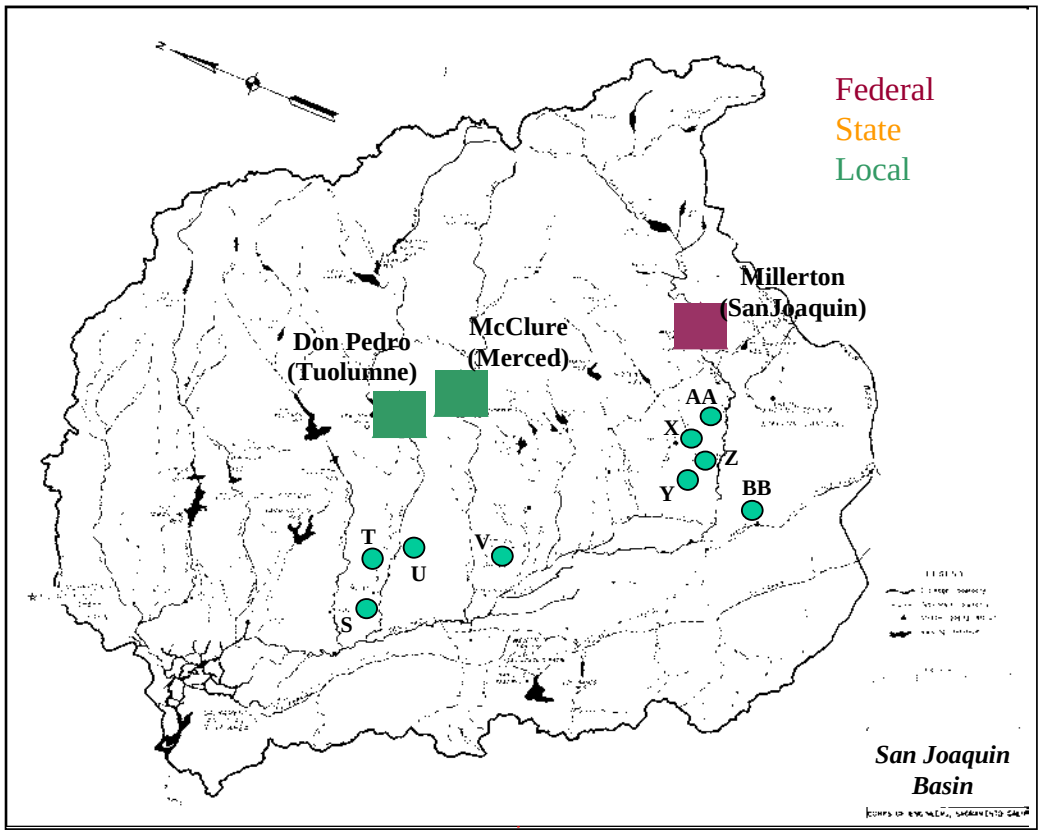
Procedures used to select reservoir and aquifer sites are further described in section 3.1.

1.5 Cost/Benefit Analysis

In this "pre-reconnaissance" study, a complete cost/benefit *analysis* was not computed due to time and budgetary constraints. Computation of dollar values of reduction in expected annual flood damages realized from increased reservoir flood storage space (using the 72 synthetic flood events routed through the 6 reservoir systems) would have required significant computation time in a dynamic flood routing model. While costs of various CU infrastructure were approximated, the benefits were stated in the volume of reservoir storage space made available for flood protection on a "guaranteed" basis, rather than dollars. This specification allows comparison to other flood protection alternatives as a cost per acre-foot of flood space.



A. Sacramento Basin



B. San Joaquin Basin

Figure 1-2. Reservoir and Aquifer Sites in Study Basins

1.6 *Report Format*

The remainder of this report is separated into sections for background information and concepts, methodologies, results, a summary of other CU activities within the Sacramento and San Joaquin basins, and conclusions & recommendations. Legal arrangements (including *strict management*, *contractual*, *direct recharge*, *in-lieu*, and *single-user* water transfers) and operational terminology (physical transfers, reservoir operations, and accounting terms) specific to CU management are introduced in Chapter 2. These explanations define the technical, working language used in the study.

Chapter 3 covers methodologies used to select reservoir sites and groundwater recharge areas, calculate the extra flood protection space created and new yield generated from CU operations, and enumerate the costs associated with these operations. Results, including additional flood storage space created in each reservoir, flood protection provided by that storage space, average annual new yield generated, costs, and how transfer volumes can vary seasonally and annually, are presented in Chapter 4. Detailed analysis of aquifer storage losses resulting from recharge / retrieval operations is made in Chapter 5.

By summarizing other CU activities within the study area in Chapter 6, role-players, legal, political, and institutional frameworks affecting groundwater management and conjunctive use, as well as impediments to CU management, are identified with the aim of highlighting pathways to mesh the goals of flood protection and new yield. Conclusions are made in Chapter 7, as well as recommendations for follow-up study.

2 Background Information

Before calculating the additional flood storage space and new yield generated from CU operations aimed at maximizing flood protection, types of arrangements that govern CU management are introduced. These arrangements define a conceptual model of CU-flood-protection operations in and transfers between river, reservoir, aquifer, agricultural demand, and end user elements within an integrated surface/groundwater network. Based on the layout of the conceptual model, five factors are discussed that constrain the size of CU transfers. Background discussion defines the technical language used throughout the remainder of the study.

2.1 Types of CU Arrangements and Modes of Operation

Strict management and *contractual* arrangements represent separate, unique assemblages of land, capital, surface-, and groundwater storage for implementing CU operations. CU operations involve acquiring water for recharge, performing recharge and recovery of water, and delivering "banked" water to its final destination. Modes for performing these types of operations are listed in Table 2-1 and can be combined to create CU programs serving diverse goals such as new yield, groundwater restoration, or flood protection [Thomas, 2001, pp.5-6]. Modes of operation denoted with an asterisk (*) are applicable to CU for flood protection. In the flood protection case, reservoir conservation pool water or runoff captured in the reservoir is the source of groundwater recharge. *Direct recharge, In-lieu exchange,* and *Single-user* modes of recharge and recovery and further explained in Section 2.1.3.

Table 2-1. Modes of Conjunctive Use Operations
[Adapted from Thomas, 2001, p. 6.]

Source of Groundwater Recharge
- Natural recharge via infiltration of runoff
- **Artificial recharge from a hydrologically disconnected source (*)**
- Recharge using recycled/reclaimed water

Recharge and Recovery
- Recovery before direct recharge
- **Direct recharge before recovery (*)**
- **In-Lieu exchange (*)**
- **Single-user exchange (*)**

Destination
- **Local basin (*)**
- **Export (*)**

* Denotes operations applicable to CU for Flood Protection

Strict management and contractual arrangements are made in response to the legal, political, and institutional factors within California that assign (or fail to assign) responsibility for groundwater management, and permit (or impede) Conjunctive Use operations. A full review of these factors and their implications for management of CU programs for flood protection is made in Chapter 5. Because of irregularities in the California water law, the CU management authority role—the organization or group that selects modes of CU operations and implements them—is open to many types of private, local, regional, state or Federal organizations or agencies.

2.1.1 Strict Management Arrangement

In a *strict management* arrangement, a CU management authority (e.g. an irrigation district) purchases land near the reservoir and directly controls the water extraction and recharge rights to the aquifer below that land. The authority builds and operates recharge and extraction infrastructure so that the authority first infiltrates water to recharge the aquifer underlying the land acquisition, and later pumps the aquifer to extract that water. When convenient, strict management arrangements can also use *in-lieu* or single-user exchanges (Section 2.1.3), and can generally be offset by new water yield.

2.1.2 Contractual Arrangement

Contractual arrangements are legal contracts between the CU management authority, reservoir operators, landowners, and end users to provide, store, retrieve, and deliver managed waters. Contracts result from interest-based negotiation between the parties.

An *easement* is a type of contractual arrangement wherein the landowner is compensated for the use of his or her land for a specific type of operation, e.g. recharge. This use is for a stipulated period of time and tends not to conflict with pre-existing patterns of land use. Compensation can be in new water yield or financial payment. In exchange for the compensation, the CU management agency acquires the right to recharge water on the privately held land at specific time(s) of the year. The easement property must be hydrologically connected to the groundwater aquifer.

2.1.3 Modes of Operation

Strict management or contractual arrangements can be established as *direct recharge*, *in-lieu* or *single user* exchanges. Direct recharge and *in-lieu* exchanges exist within Central Valley counties [Schlager and Blomquist, 1999; ARBCA and SNAGMA, 2000; Sharpe, 2001] and are alternatively referenced in the literature as *groundwater storage*, *banking*, or *recharge* [Purkey, *et. al*, 1998; DWR, 1998].

A *direct recharge* occurs when surface water is transferred to an aquifer with sufficient storage space, and stored there by recharge or injection. When needed at a future time, the surface water provider pumps the stored groundwater from the aquifer. Water losses during the recharge, aquifer storage, and pumping process will depend on surface/groundwater interactions, well yields, and other aquifer properties. Losses mean that the volume of recovered water will be somewhat less than the recharged water volume.

An *in-lieu* exchange is a water exchange in which surface water is delivered to a ground water user, the user stops pumping groundwater and uses the surface water as an alternative. Groundwater is conserved for future use. The conserved groundwater is credited to the surface water provider. The surface water provider collects the credit at a future time by pumping from the stored groundwater.

A *single-user* exchange is a special kind of *in-lieu* exchange wherein the landowner is a user of *both* surface and groundwater. In the wet season, surface water from a reservoir is "pre-delivered" to a landowner. The landowner recharges the water to store it as groundwater, then later in the dry season calls upon the stored groundwater in place of a surface water delivery. Alternatively, if the landowner is using groundwater at the time of the surface water transfer, the landowner can conserve his/her groundwater for future use by using the surface water instead of groundwater. In dry years or other times of need, the landowner pumps the groundwater to supplement supply. The latter type of single-user exchange works the same as an *in-lieu* exchange, except that the land owner rather than the surface water provider has right to the banked water.

2.1.4 Comparisons

Cost structuring for the types of CU arrangements are summarized in Table 2-2. Strict management arrangements require capital to purchase land and build water conveyance, injection, and pumping structures to hydraulically link the reservoir, aquifer, and end users. Contractual arrangements avoid capital costs because the structures already exist and are owned by the reservoir operators, landowners, and water users. Participation is voluntary and motivated by an expectation of financial benefit or compensation created from financial efficiency. Contracts can be crafted to patch the legal gaps in California groundwater law and cover contingencies such as drought, floods, or lower-than-expected new yield. Direct recharge and *in-lieu* contractual arrangements have the disadvantage of requiring administrative overhead to account for and enforce stored groundwater credits. Also, the management authority must take the role of water broker and find suitable contract partners. I*n-Lieu* exchange is the only arrangement that avoids water losses to aquifer storage because reservoir water is not actually recharged to the aquifer.

Table 2-2 Cost Requirements for Types of Conjunctive Use Arrangements

Cost Item		Strict Management Arrangement	Contractual Arrangements		
			Direct Recharge	In-Lieu Exchange	Single User
Conveyance (Reservoir to Aquifer)	Capital	✓			
	O&M	✓	✓	✓	
Infiltration & Recharge	Capital	✓			
	O&M	✓	✓		✓
Pumping & Extraction	Capital	✓			
	O&M	✓	✓	✓	✓
Conveyance (Aquifer to User)	Capital	✓	✓	✓	
	O&M	✓	✓	✓	
Water Lost to Storage in Aquifer		✓	✓		✓
Aquifer Land Purchase		✓			
Administration			✓	✓	

2.2 A Conceptual Model of CU Operations In a River Basin

The aim of Conjunctive Use flood operations is to generate additional reservoir flood protection while maintaining or increasing water yield and minimizing impact on recreation. For the purpose of simulating CU operations, HEC developed a conceptual model of how such operations might work. CU operations are the reservoir operations, physical water transfers, and accounting balances that govern how water resources are moved between reservoir(s), aquifer(s), agricultural demand, and additional end user elements in a river basin where surface and groundwater resources are co-managed. For a generic watershed, physical water movements required by CU operations are depicted in Figure 2-1a. Accounting balances and transfers used to track CU operations are depicted in Figure 2-1b. For comparison, only reservoir inflow, the reservoir guide curve, and agricultural demand govern normal basin operations without conjunctive use (Figure 2-1c).

Introduction of *CU transfers* (both physical and accounting) creates new types of reservoir operation and physical delivery pathways. CU reservoir operations—including changed storage levels, releases, and (additional) flood protection—are made possible by CU transfers. Direct recharge, extraction, and *in-lieu* exchange are physical transfers, and involve movement of water between elements in the integrated river basin. Accounting transfers, including aquifer debt, new yield, CU pool transfer, excess flow transfer, payback, sale of new yield, and spring capture of runoff, attach purpose to the physical movements. The conceptual model lays out the terminology, and the operational, physical, and accounting constructs for CU operations in an integrated river basin. These concepts and terms provide the framework in which conjunctive use operations will be discussed in the remainder of the study.

2.2.1 CU Reservoir Operations

Normal Guide Curve Operation
The reservoir Guide Curve is the time-dependent rule describing the maximum water storage level allowed in the reservoir. The Guide Curve represents the dividing line between the Conservation and Flood Pools and thus defines the amount of flood protection space and water supply storage space offered by operation of the reservoir.

USACE policy defines the Flood Pool as reservoir storage space that is "guaranteed" to be available (empty) to capture floodwaters during the flood season. Additional storage space that may or may not be available is termed *incidental* space. In current policy, incidental space cannot be considered part of the Flood Pool or used to calculate quantifiable flood protection benefits.

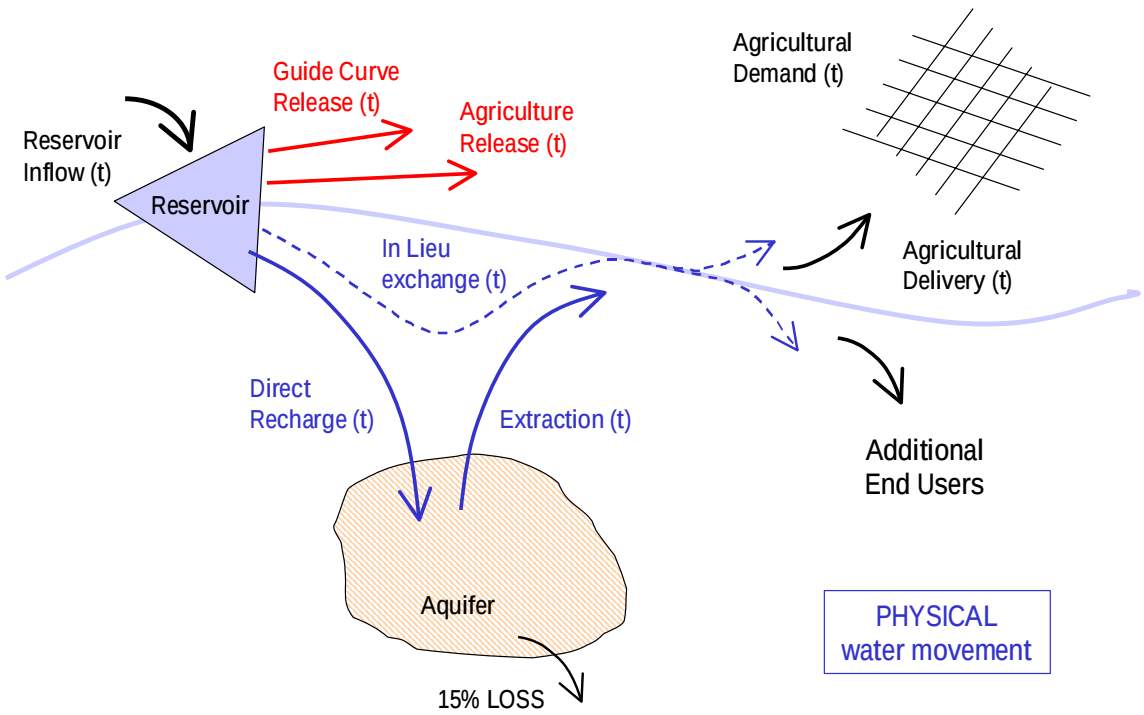
Figure 2-2's blue line depicts a generic Guide Curve of a reservoir operating for flood protection in California. The Guide Curve is low during the wet winter season, decreasing reservoir storage to create a Flood Pool that can capture high winter flows. The Curve is high during the dry summer season when the probability of high flows is less, reducing the size of the Flood Pool and increasing the size of the Conservation Pool. When the timing is right, the rise in the Curve permits capture of spring snowmelt runoff.

In normal operation, except during a flood event the reservoir storage must remain below the Guide Curve. This operation ensures that the Flood Pool will be available (empty) during the defined flood season. If a winter flood raises the reservoir storage level above the Guide Curve, reservoir operators must release the excess water as soon as possible. This water cannot be exploited for future supply purposes because there is no space to store it.

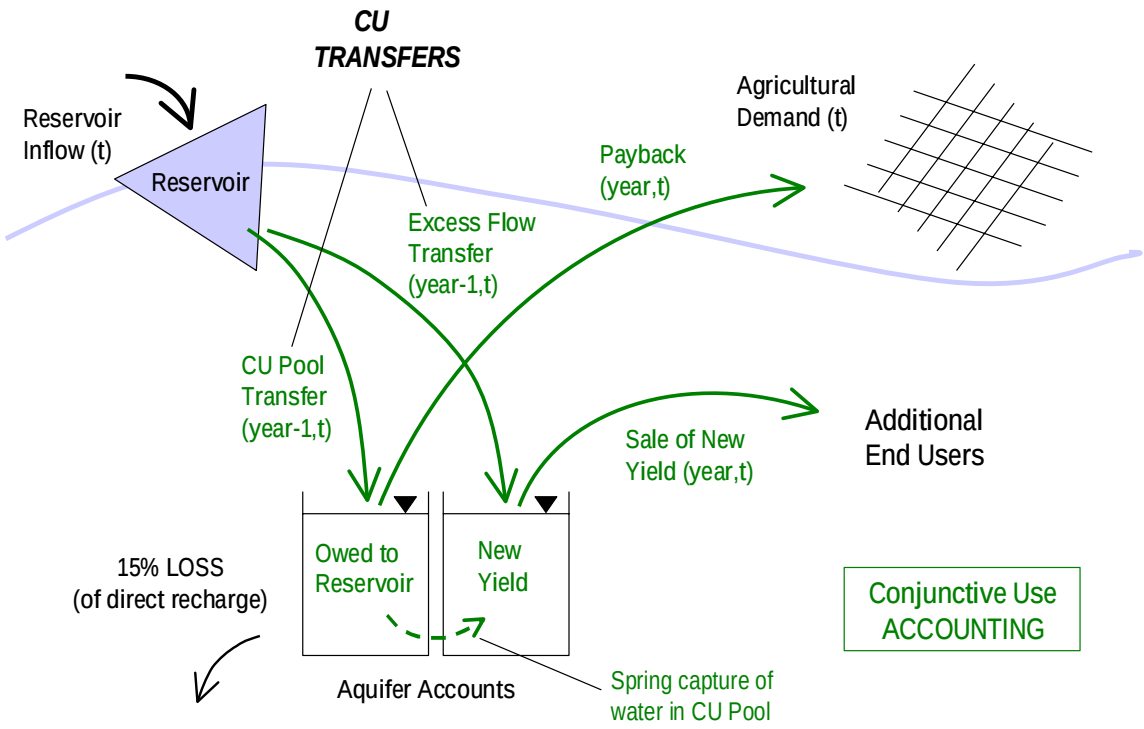
CU-modified Guide Curve and CU Pool
The orange line in Figure 2-2 depicts the modified Guide Curve describing CU operations. An additional portion of the winter Conservation Pool is drawn from the reservoir and transferred to an aquifer for storage. This transfer empties a Conjunctive Use Pool (CU Pool) that provides additional space to intercept winter floods and/or capture spring runoff without decreasing the total conservation storage in the system. The CU Pool supplements the reservoir's normal flood storage pool to provide additional flood protection to downstream areas.

Unlike the normal Guide Curve, the CU-modified guide curve only defines the amount of flood protection space and *not* conservation space. Even though the CU Pool is empty, that storage volume is also considered part of the Conservation Pool because an equivalent volume of water exists in aquifer storage. Thus, the CU pool denotes reservoir space that serves dual duty for flood protection and conservation storage.

When the CU Guide Curve rises in the spring, the normal Conservation Pool has first priority to capture spring snowmelt runoff. The CU Pool has a lower priority to store (represented by the dotted brown line in Figure 2-2, and the continuation of CU Pool space above that line) because the water already exists in aquifer storage. If spring runoff is high, water captured in the CU Pool allows an equal volume in aquifer storage to be considered new water yield.

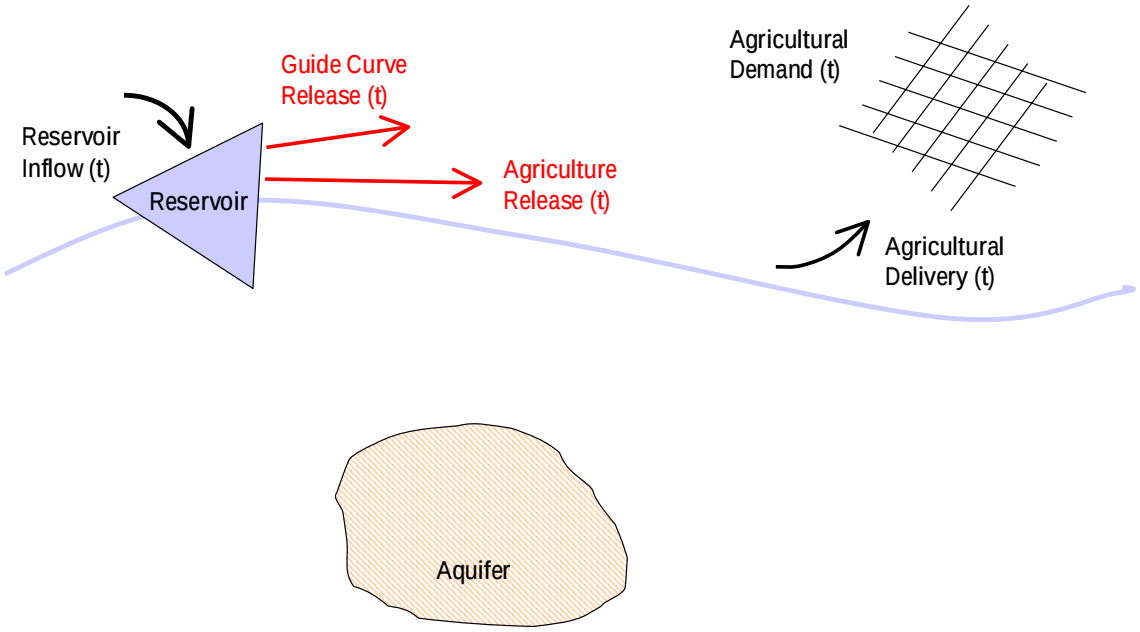


A. CU Physical Transfers



B. CU Accounting Transfers

Figure 2-1. Conceptual Models of Water Transfers



C. Without CU Operations

Figure 2-1 (Cont). Conceptual Models of Water Transfers

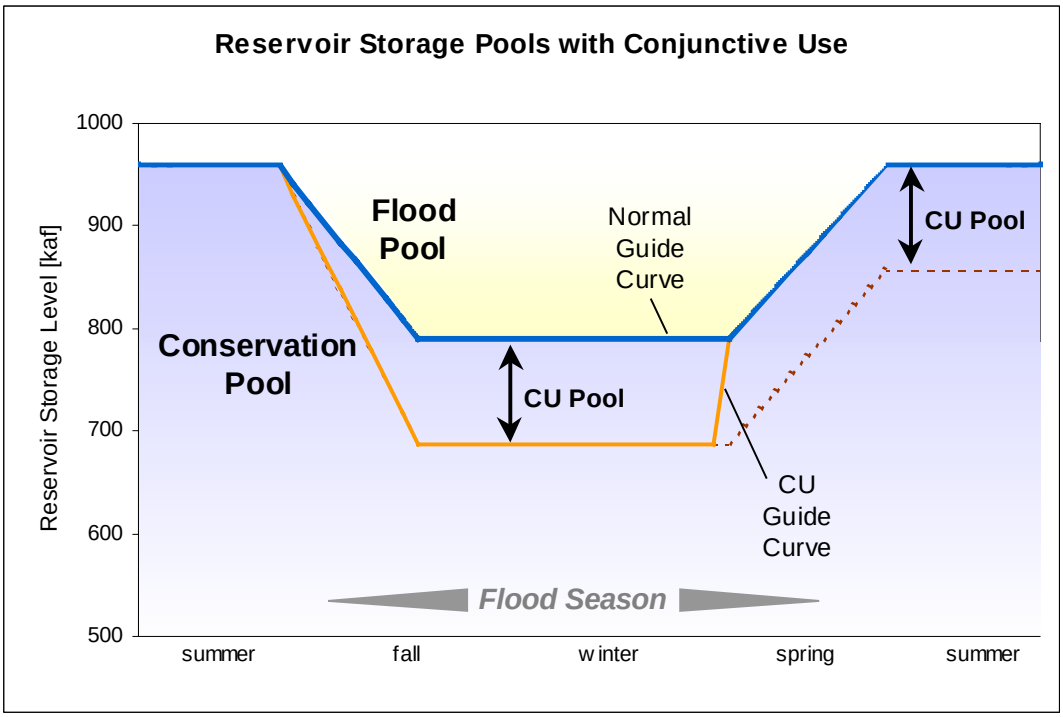


Figure 2-2. Guide Curves and Pools associated with Normal and CU Reservoir Operations

After establishing the CU pool, various reservoir operations are possible; two types were considered. Reservoir operators can either maintain maximum flood protection throughout the winter (Type 1) or sacrifice some flood protection to generate additional new yield (Type 2). Procedures for both types of reservoir operations are described below. Flood protection and new yield benefits are not exclusive to each type of CU reservoir operation; rather each type of operation provides some level of flood protection and some new yield. The operations differ in whether the CU Pool space is "guaranteed" (and quantifiable as a flood protection benefit) or incidental (and not quantifiable).

Type 1 CU Operation: Maximize Flood Protection. Type 1 CU reservoir operations maximize flood protection by strictly maintaining the reservoir storage level below the CU Guide Curve. CU Pool space is "guaranteed" with Type 1 operations and therefore quantifiable as a flood protection benefit. After the CU pool is vacated in Fall, winter flows or floods are managed as in normal guide curve operation: excess winter flows, and flood waters above the CU Guide Curve, are released to maintain the CU pool space as flood protection. When possible, the release is transferred to aquifer storage. Type 1 operation restricts the opportunity for capturing new yield to refilling the CU Pool with spring snowmelt runoff and transferring excess winter flows into aquifer storage.

Type 2 CU Operation: Increase Yield. Like Type 1 operations, Type 2 operations vacate the CU Pool the CU pool before the beginning of the flood season. However, high winter flow or a flood event are permitted to partially or completely fill the CU Pool. This water is stored in the CU Pool until Excess Flow Transfers (section 2.2.2) can move it into aquifer storage. Type 2 CU reservoir operations therefore increase yield by using the CU Pool as temporary storage for high winter flows and captured flood volume, and represent a less strict adherence to the CU Guide Curve. CU Pool space is not guaranteed but instead "incidental," and not quantifiable as a flood protection benefit in current USACE policy. Compared to Type 1 operation, Type 2 captures more yield in the aquifers (by reducing wasted releases) but sacrifices some of the additional flood protection (by allowing water to be stored in the CU Pool).

2.2.2 Physical transfers

Physical water transfers (blue items in Figure 2-1a) describe the flows of water between elements in the river basin for the purpose of Conjunctive Use, and include Direct Recharge, Extraction, and *In-Lieu* Exchange. The transfer rates are constrained by basin, reservoir, and aquifer parameters such as reservoir inflow, reservoir capacity, agricultural demand, aquifer storage capacity, maximum aquifer recharge and extraction rates, and aquifer losses (black items in Figure 2-1a) and operator decisions. Agricultural Release and Guide Curve Release (red items in Figures 2-1a and 2-1c) are physical transfers that are not specific to CU operations.

- **CU Direct Recharge**
  CU Direct Recharge water is physically moved from the reservoir and stored (banked) in the aquifer. Water is spread in recharge basins to allow infiltration for aquifer recharge. A percentage of the water is lost to evaporation during recharge and to the groundwater aquifer (see "Water Loss" below).

- **Extraction**
  Extracted water is physically moved out of the aquifer via pumping wells. Extraction represents the removal of water stored (banked) in the aquifer by Direct Recharge. Only a percentage of the water stored is available for extraction because of loss incurred from aquifer recharge and storage (see "Water Loss" below). Extracted water is returned to the river or canal and moved to either agricultural demand or additional end users.

- ***In-Lieu* Exchange**
  In-Lieu Exchange bypasses the aquifer and moves water directly from the reservoir to either agricultural demand or additional end users. This exchange (of reservoir water for groundwater) is made if CU operations call for the coincident timing of direct recharge and extraction transfers. The *in-lieu* exchange is made to convey water directly to users along the river and avoid pumping costs and aquifer storage water loss.

- **Agricultural Release**
  Agricutural release is water released from the reservoir, conveyed along the river and canals, and delivered to meet agricultural demand not met by extraction or *in-lieu* exchanges.

- **Guide Curve Release**
  Guide Curve release is water released from the reservoir to keep the reservoir storage level at or below the Guide Curve. Direct recharge, *in-lieu* exchange, and agricultural releases are considered before the Guide Curve release is computed.

2.2.3 Accounting Balances and Transfer Terms

Accounting balances and transfers (green items in Figure 2-1b) are used to track CU operations and describe the purpose of CU transfers. New-Yield and Owed-to-Reservoir are the two accounts that track water stored in or credited to the aquifer. The CU Pool Transfer and Excess Flow Transfer are CU accounting transfers that track water transferred from the reservoir and credited to the aquifer; these transfers can be made as either Direct Recharge (to the aquifer) or *In-Lieu* Exchange (to agricultural demand or additional end users). Payback and Sale of New Yield are CU accounting transfers that track water deliveries from aquifer accounts to agricultural demand and additional end users; these transfers can be made as either extraction (from the aquifer) or *in-lieu* exchange (from the reservoir). Because of the flexibility of CU accounting, the purpose of a CU transfer need not correspond with the physical pathway of delivery. For example, a CU Pool Transfer can be implemented as an *in-lieu* exchange. Water is physically delivered from the reservoir to agricultural demand, but the purpose of the transfer is to credit the aquifer with both conservation water evacuated to create the CU Pool, and with a "payback" to demand.

- **CU Pool Transfer**
  The *CU-Pool transfer* vacates the CU Pool. The transfer represents the portion of the reservoir Conservation Pool that is temporarily stored in—or credited to—the aquifer. The transfer can be implemented as either a direct recharge (to the aquifer) or *in-lieu* exchange (to agricultural demand). The CU pool transfer normally occurs between June and October to reach the reservoir's low winter operation level. If the reservoir storage level is already at or below the winter CU guide curve level, the CU Pool transfer is reduced, eliminated, or

delayed until winter, when high flows or flood events allow the reservoir to recover storage. This delay is intended to reduce the risk of not recovering aquifer storage losses (see "Minimizing Loss" below). Since the CU Pool and its relocated volume of water are still considered part of the reservoir Conservation Pool, CU Pool transfer water is owed back to the reservoir in spring. CU Owed, CU payback, and Sale of New Yield are the accounting balance and transfer terms (see explanations below) that describe how debt incurred by the CU Pool transfer is repaid to the reservoir. Type 1 and Type 2 CU reservoir operations each use CU pool transfers.

- **Excess Flow Transfer**
  Excess Flow Transfers move surplus water to aquifers during fall drawdown and during winter. Because CU Pool Transfer operations established a hydrologic connection between the reservoir and aquifers, these transfer facilities can also be used beneficially to divert *excess* flow for storage in—or credit to—the aquifer. In normal reservoir operations, surplus supply that exists in the reservoir after the year's agricultural demand is met must be released during the fall drawdown to establish the winter Flood Pool. With CU operations, these releases may be captured in the aquifer to the extent possible. Additionally, during the winter, high flows must released from the reservoir (rather than stored) to maintain the winter Guide Curve storage level. This excess flow can also be transferred to aquifer storage. In Type 1 reservoir operations, this transfer is made at the maximum aquifer recharge rate. Excess flow above the maximum rate is lost downstream. Type 2 reservoir operations limit release to the maximum aquifer recharge rate and temporarily store water in the CU Pool until it can be transferred to the aquifer. Since Excess Flow Transfers (unlike the CU Pool Transfer) are *not* made from the reservoir conservation pool, these transfers represent immediate new yield that is not owed back to the reservoir

- **Owed to Reservoir**
  Owed to the Reservoir is the aquifer account representing the amount of Conservation Pool water stored in aquifer that must be returned to the reservoir at the end of the flood season. At the start of the flood season the amount owed equals the size of the CU Pool Transfer. However, the amount owed decreases by the equivalent amount of water captured in the CU Pool after the flood season (see "Spring Capture of Water in CU Pool" below). In summer, the remaining amount owed is extracted from the aquifer and delivered to demand. A complete payback resets the amount owed to zero for the next flood season. Water not paid back (due to extraction limits or inadequate demand) is carried to the following year.

- **CU Payback**
  The *CU payback* transfer represents the return of water owed to the reservoir. Payback can be made as either water extracted from the aquifer and sent to meet agricultural demand, or an *in-lieu* exchange from the reservoir credited as both transfer (for the current season) and payback (from the previous season). The required payback is the volume of water in aquifer storage "owed to the reservoir".

  After determination of the aquifer volume "owed to the reservoir," payback extraction pumping begins and continues until either the debt is repaid or agricultural demand ends (in which case the debt is carried over to the following year).

- **Spring Capture of Water in CU Pool**
  Spring capture of water in the CU pool is an accounting transfer that shifts water from the "owed to reservoir" aquifer account to the "new yield" account. The purpose of the transfer is to allow spring snowmelt runoff captured in the CU Pool (and so developed by the CU Pool) to reduce the amount to be repaid from aquifer storage. New water captured in the reservoir is used to offset water "owed" to the reservoir.

  The capture credit applies only to spring capture amounts that exceed the size of the non-CU drawdown. Because the Conservation Pool has higher priority for refilling than the CU Pool, the first portion of runoff captured (equal to the size of the non-CU drawdown) is *not* shifted between accounts. (The CU pool has lower priority because that water already exists as stored/credited water in the aquifer. The reservoir filling priority guarantees water supply, and is represented by the dotted brown line in Figure 2-2). Spring captures that do fill the CU Pool can be shifted and considered new yield.

  Spring capture amounts are determined using the reservoir storage level after the flood season, generally two to six weeks after the Guide Curve first permits storage at the summer operation level (i.e., permits the reservoir to fill). The two to six week delay period was chosen for each reservoir after studying the historical record to determine when that reservoir normally filled. To further explain how the accounting capture works, Figure 2-3 and Sidebar 2-1 illustrate hypothetical Guide Curves, reservoir storage levels, and the corresponding new yields and amounts owed for three different cases of spring runoff capture.

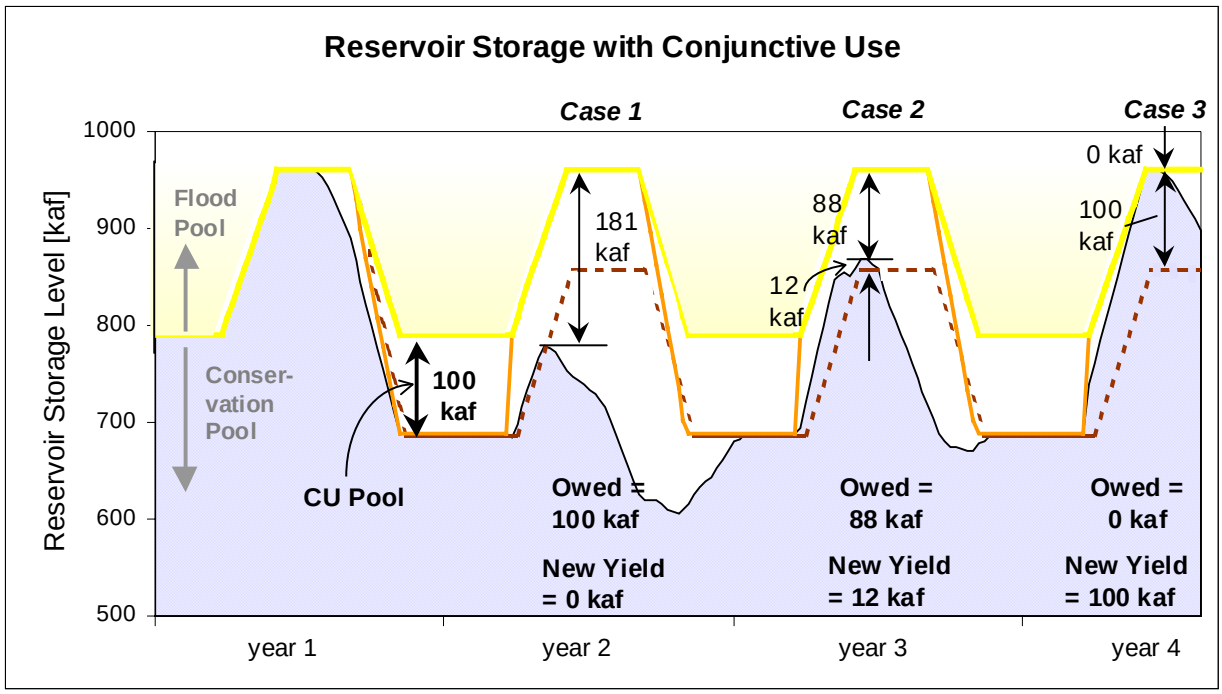


Figure 2-3. Storage, Yield, and Amounts Owed from CU Operations with Various Spring Runoff Capture Scenarios

Sidebar 2-1. Calculating Owed Amounts and New Yield for Different Cases of Spring Runoff Capture depicted in Figure 2-3.

Figure 2-3 illustrates Guide Curves and hypothetical reservoir storage levels for three different cases of spring snowmelt runoff capture. In the example, the CU Pool is 100 KAF after considering a 15% loss from recharge and aquifer storage. Spring runoff does not refill the CU pool in Case 1. In Cases 2 and 3, spring runoff partially and completely refills the CU pool, respectively. Case summaries describe how the new yield and amount owed are computed for each amount of spring runoff capture.

Case 1: Spring runoff does not fill the Normal Flood Pool or the CU Pool. No captured water becomes new yield.

Spring runoff capture is significantly less than the normal Flood Pool drawdown, and so the CU Pool is not refilled. Therefore, the entire CU pool transfer of 100 KAF is "owed" back to the reservoir Conservation Pool. (Owed = 100 KAF, New Yield = 0).

Case 2: Spring runoff completely refills the normal Flood Pool drawdown and partially fills the CU Pool. The portion of runoff captured in the CU Pool becomes new yield.

Spring runoff capture exceeds the normal drawdown by 12 KAF, caught by the CU Pool and credited as new yield in aquifer storage. Of the initial CU Pool transfer of 100 KAF, only (100 - 12) = 88 KAF is owed back to the reservoir. (Owed = 88 KAF, New Yield = 12 KAF)

Case 3: Spring runoff completely refills the CU Pool. All runoff captured in the CU Pool becomes new yield.

Spring runoff completely refills the reservoir leaving no unfilled volume. The entire 100 KAF of CU Pool transfer water now residing in aquifer is considered new yield in the aquifer, and no water is owed back to the reservoir. (Owed = 0, New Yield = 100 KAF)

Based on the historical timing of reservoir fill, the determination of captured volume is made 2 to 6 weeks after the fill date described by the reservoir Guide Curve.

- **New Yield**
  New Yield is the aquifer account representing water stored in reservoir or aquifer that would have been released downstream if CU operations were not in place. New Yield is developed by (i) capture of additional spring snowmelt runoff in the CU Pool and (ii) Excess Flow Transfers.

As described in Spring Capture of Water in the CU Pool above, the amount of new yield by spring capture depends on the amount of spring snowmelt runoff captured in the CU Pool after the Conservation Pool has refilled. Excess Flow transfers, however, are considered new yield in all cases. This yield is independent of the reservoir refill status because Excess Flow transfers are credited directly to the New Yield aquifer account rather than the Owed account.

New yield is "located" in the aquifer even though capture is made in the reservoir. This relocation is effected by a transfer between aquifer accounts, from "owed" to "new yield." The accounting shift is made because water captured in the reservoir is preferentially used to serve agricultural demand from the reservoir via cheaper, more efficient gravity flow. Water transferred to the aquifer then becomes surplus and is therefore considered new yield.

- **Sale of New Yield**
  In this study, new yield is immediately sold during the spring and summer after capture. Sale of new yield can be made as extraction from the aquifer or an *in-lieu* exchange from the reservoir. This transfer vacates the aquifer and makes space available for future CU transfers. (Sale is from the aquifer account because new yield is realized in the aquifer rather than in the reservoir). This sale assumes that a market exists for the yield in every year it is available, which is a simplification of the actual water market situation.

- **Water Loss to Aquifer Storage**
  Because of "mounding" (see Section 5.1) during recharge operations, groundwater flows away from the recharge site over time. Loss occurs when the water moves such a distance that it cannot be recovered with extraction wells on the site. Loss is represented as a percentage of the amount of groundwater recharge (i.e., 15% in many CU studies). Using this percentage means that for every 100 acre-feet of water recharged to aquifers, 85 acre-feet can be recovered. (Or, for every 100 acre-feet of underground storage required, 118 acre-feet must be recharged.) The assumed loss rate of 15% is an aggregate value for storage/retrieval operations that also includes the evaporative losses out of recharge basins during recharge operations.

- **Minimizing Loss to Aquifer Storage**
  Careful CU reservoir operation can ensure that aquifer storage loss is replaced or avoided in most years. Whenever possible, *in-lieu* exchanges can be used to avoid storage loss. As explained previously, *in-lieu* exchanges avoid water loss because additional water is not directly recharged to the aquifer. Instead, water is transferred directly to users. This transfer bypasses recharge and the loss associated with physical storage in the aquifer. (The assumption that *in-lieu* exchange avoids loss is a simplification sufficient for the current level of analysis. In reality, leaving water in aquifer storage by halting extraction pumping might incur further loss of previously banked water, because regular pumping is a factor that counteracts or reduces groundwater flow.)

  When *in-lieu* exchange is not possible (because a concurrent agricultural demand does not exist or aquifer payback is not necessary), aquifer storage losses may be offset with the first portion of the Excess Flow transfer. The Excess Flow transfer may consist of either water

from the reservoir drawdown or surplus winter flows. Since all Excess Flow Transfers are considered new yield (see "Excess Flow Transfer" above), the net effect is that the first [CU Pool Transfer Amount)*(Loss Rate)] (i.e. 15 KAF for every 100 KAF transferred) of Excess Flow Transfer is used to offset aquifer storage loss. This first portion of the Excess Flow Transfer is therefore not available for extraction.

Aquifer storage loss can only be replaced with Excess Flow transfers when the reservoir is filled to the Guide Curve level. When the reservoir storage level is *below* the Guide Curve, all flow is stored to reach the Curve and there is no "excess" water available for transfer to the aquifer. The reservoir is only vulnerable to the 15% loss in a case where the CU Transfer is made and the year becomes dry, bringing the reservoir significantly below the Guide Curve. During successive dry years, the aquifer storage loss will be unrecoverable only in the first dry year. In subsequent dry years, the reservoir storage level will be below the CU Guide Curve at the beginning of the flood season, so a CU Pool transfer will not be made.

Risk of not recovering the aquifer loss can be reduced by delaying the CU Pool transfer until winter. If at that time climate indicators suggest a wet enough season to refill the reservoir past the winter CU Guide Curve, the transfer can proceed.

2.3 Factors Constraining Creation of CU Flood Pool space

As outlined in the conceptual model, CU operations include water transfers between reservoirs, aquifers, agricultural demand, and other end users with the aim of increasing both flood storage space in the reservoir (CU Pool) and new yield. Understanding the upper bounds on CU transfers (and the associated CU flood storage space) is important and provides insight into the utility of CU operations for flood protection. Major factors constraining the creation of CU flood storage space are:

- proximity of aquifer storage to the reservoir,
- available storage space in the aquifers,
- aquifer recharge rate, and
- aquifer extraction rate.

Minor factors are:

- timing of water deliveries and end uses, and
- reservoir size.

Background discussion of these factors describes how each factor constrains the CU pool storage volume. Constraints posed by the factors depend on the hydrological and hydro-geological conditions at the aquifer sites. The available storage space, aquifer recharge rate, and the aquifer extraction rate are also dependent upon the recharge basin area, and in a small range are linearly dependent. The recharge area at each aquifer site was considered a design variable in the study, and is one of the most influential elements in evaluating Conjunctive Use for flood protection.

2.3.1 Proximity of aquifer storage

The topographical and spatial proximity of potential storage aquifers to the reservoir and end users determines who has access to the surface and banked waters, or what conveyance structures are needed to create access. In the best (least cost) case, the aquifer is located downstream of the reservoir and upstream of the end users so that all transfers between the reservoir, aquifer, and end users can be made by gravity flow along the river. Otherwise, pumping and conveyance structures are required to transfer water. Aquifers that are further from the reservoir (or river turnout point) require additional conveyance structures and increased costs.

A *single-user* transfer is the most proximate type of CU arrangement because the aquifer storage site and end user are coincident. The arrangement assumes that the single-user already has a hydrologic connection to the river (by diversion, canal, etc.) to receive reservoir deliveries and access to the aquifer through an existing well. Costs for these existing facilities would not be part of the single-user CU project.

2.3.2 Available aquifer storage space

Aquifer storage capacity is a primary constraint on the amount of water that can be temporarily relocated into an aquifer for storage. Aquifer storage capacity is a function of the depth to groundwater, area of the recharge basin and soil porosity. Groundwater pumping in amounts above the natural recharge rate (perennial yield) creates a deficit that lowers water table levels. This drawdown represents space in the aquifer that can be refilled with transferred water. In "healthy" aquifers, the rate of natural recharge approximates the rate of extraction. The water table does not decrease over time and additional space is not available for artificial recharge. Thus, situations where aquifer depletion and overdraft occur can result in increased storage opportunities.

Storage space within an aquifer can also change through time as water table elevations fluctuate. Fluctuations can be expected from Conjunctive Use operations. CU Direct Recharges (to the aquifer) may add quantities of water greater than the volume of extraction. The artificial recharge raises water table levels, counteracts depletion, and reduces storage space. Additionally, while "healthy" aquifers are a positive result as far as yield and environmental interests are concerned, they also represent decreased groundwater storage space available for CU and flood protection.

Because the aquifer storage capacity is directly dependent on the size of the recharge basin, increasing or decreasing the basin size (i.e., buying more land or acquiring additional rights to recharge at an aquifer site) can significantly alter the recognized storage capacity of an aquifer. Thus, recharge basin size was considered a design variable in the study.

2.3.3 Recharge to the Aquifer

The aquifer recharge rate describes the volume of water per unit time that can be transferred to the subsurface. Recharge can be achieved through recharge basins, pools, or injection wells. In the case of recharge basins or pools, the recharge rate depends on soil properties of the aquifer

such as vertical hydraulic conductivity (as described by Darcy's Flow Equation), initial soil moisture, moisture potential, and recharge area. Similar to the constraint for available aquifer storage, the size of the recharge basin is a design factor that also defines the recharge volume to the aquifer. Larger basin areas will allow for a greater recharge rate to the aquifer.

In the case of injection wells, the potential recharge rate is a function of the saturated hydraulic conductivity and the effective porosity (specific yield) of the aquifer. Injection may achieve faster recharge rates than basins or pools on a per-acre basis, but injected water must be treated to limit groundwater contamination (while water infiltrated through the soil underlying a recharge basin is "naturally" treated). This increased recharge rate is therefore accompanied by increased costs for water treatment and well construction.

2.3.4 Retrieval from the Aquifer

In a manner similar to the aquifer recharge charge rate, the aquifer extraction rate describes the volume of water per unit time that can be retrieved from the aquifer through pumping wells. This retrieval rate is a function of the number and capacity of extraction wells penetrating the aquifer. Well-spacing and well field configuration determine extraction efficiency and the effects from overlapping cones-of-depression. Investigations into the effects of extraction well field configurations are further detailed in the groundwater modeling section (Chapter 5). Each configuration will produce a maximum retrieval rate that governs the amount of water per unit time that can be delivered to agricultural demand or other end users.

Overall retrieval is also affected by how stored water behaves underground. Recharged water will "mound" on the water table beneath the recharge site. But aquifers are not sealed and stationary storage vessels. Rather, they are slow-moving underground "flows." Over time, mounded water will spread away from the recharge point and escape recapture. The rate and direction of spread are dependent upon aquifer parameters such as specific yield, horizontal hydraulic conductivity, the regional flow gradient, and the hydrologic connection between the aquifer and nearby surface waters. The flows represent loss, meaning that the volume of water available for extraction is always less than the volume recharged. Expected loss can be calculated using simplified analytical methods or more detailed groundwater computer models.

Similar to the constraints for available aquifer storage and recharge rate, the size of the recharge basin is a design factor that also determines extraction volume from the aquifer. Larger project areas will allow more wells and increased extraction from the aquifer and vice versa.

2.3.5 Timing of Uses

When *in-lieu* exchange in used as the water transfer mechanism, coincident timing of uses is a crucial factor limiting the CU transfer. An end-user must need water that would otherwise be pumped from an aquifer at the same time surface water is delivered from the reservoir (for example, before the start of the flood season). Otherwise, the *in-lieu* exchange will breakdown because either (i) the end-user does not have a source other than groundwater, or (ii) the reservoir does not have a user to accept the surface water release. *In-lieu* exchange is limited to the pre-existing demand for extracted groundwater.

2.3.6 Reservoir Size

Theoretically, the size of the reservoir Conservation Pool is the upper bound on the amount of additional flood storage space that can be created by CU operations. To access this flood storage space, the entire Conservation Pool would need to be transferred to groundwater storage, which would be an extreme proposal. In practice, extra flood storage space is limited by the factors previously discussed and the amount of Conservation Pool water that reservoir operators and CU managers can mutually agree to transfer to groundwater storage. The transfer amount is a decision variable within the conceptual model.

3 Methodology

The question posed in this study was whether Conjunctive Use for the purpose of flood protection within the Sacramento and San Joaquin basins is reasonable and worth pursuing. To answer this question, the costs and benefits related to CU flood protection operations were evaluated.

CU operations were evaluated for only a strict management arrangement. This arrangement could guarantee creation of flood storage space and be structured to preference creation of such space over new yield. Of all the CU arrangements, strict management costs were also easiest to value and least dependent on the market behaviors of landowners and end-users.

Analysis of benefits resulting from strict management CU operations was the main focus of the study. Ultimately, the goal was to value the additional flood storage space created in reservoirs by CU operations. Quantification of this benefit would require several intermediate steps, the most important of which was determining the additional flood storage space created from CU operations. Further steps in the valuation process are described here, but were not pursued in the study due to complexity and budget limitations.

As a first step, several reservoirs and sub-basins within the Sacramento / San Joaquin basins were selected for in-depth analysis (Section 3.1). Second, initial calculations were made considering a variety of reservoir and aquifer factors to determine the upper bounds on the size of the CU Pool (Section 3.2). In Section 3.3, actual values for CU Pool transfers were determined using more detailed Water Transfer Modeling (Section 3.4). This interactive modeling accepted user decisions for CU transfers and water sales and made simplifying assumptions about groundwater hydrogeology and groundwater parameter values. Using 14 years of historical reservoir inflow and approximated agricultural demands, the model used mass balance to calculate the direct recharge, extraction, and *in-lieu* exchanges resulting from CU operations. Water balance calculations also determined the additional reservoir storage space created by CU transfers and the amount of new yield generated for sale.

Next, project costs and benefits were evaluated (Section 3.5). Methodology for valuing guaranteed reservoir storage space created from CU operations (using an algorithm that determined the net reduction in expected annual damages compared to a control case of normal reservoir (without CU) operations) was described, but not implemented (Section 3.5.1.1). New yield was totaled but not valued (Section 3.5.1.2). Finally, project cost estimates were developed considering the land purchase, conveyance facility, extraction facility, and recharge facility construction, and operations and maintenance costs required to implement and sustain CU operations (Section 3.5.2).

Section 3.6 describes Sensitivity Analysis to determine the sensitivity of results—including CU Pool sizes, new yield, and project costs—to 4 configurations (scenarios) of CU project infrastructure. Recharge basin size and conveyance capacity from the river turnout to the aquifer site were two design variables that were simultaneously varied between low and high values (Table 3-9).

Detailed groundwater modeling was performed to determine the amount of water lost from CU aquifer recharge and retrieval operations (Chapter 5). Results collaborated assumptions made about aquifer storage losses in the Water Transfer Model. Groundwater modeling was also used to represent several extraction well field configurations and evaluate water losses for those configurations.

Methods used to perform each of these steps are described in the remainder of this chapter.

3.1 Selecting Sub-basins for detailed study

The first step in the study was to identify sub-basins, including reservoir and aquifer sites, where the feasibility of using CU for flood protection is promising. The areal scope of the study covered the Sacramento-San Joaquin river basins, but this area was much larger than could be evaluated with detailed analysis. Therefore, six reservoir sites within the study basin area were selected and potential aquifer storage sites fore each were identified.

3.1.1 Selecting Reservoir Sites

The need for additional reservoir flood storage space in a sub-basin was used as the criteria to select sub-basins/reservoirs for study. Reservoirs were chosen that: (i) had a current level of protection lower than the desired level of protection, or (ii) were extremely stressed by large floods of record. These criteria identified sub-basins that would most-likely benefit from increased flood protection.

The January 1997 flood event was near the 1%-exceedance probability for many sub-basins within the Sacramento and San Joaquin basins. Based on discussions with the Sacramento District's Water Management Section, Oroville, New Bullards Bar, and Folsom Reservoirs in the Sacramento basin and Don Pedro Reservoir, New Exchequer Dam (Lake McClure), and Friant Dam (Millerton Lake) in the San Joaquin basin were identified as reservoirs that would have operated more successfully with extra flood storage space during the January 1997 flood event.

3.1.2 Selecting Aquifer Sites

Potential aquifer storage sites were identified from an index compiled by Dr. David Purkey of 33 aquifer sites (labeled A through GG) located in the Sacramento and San Joaquin river basins [NHI, 2000]. The index lists aquifer parameters such as porosity, conductivity, current depth-to-water, and quality. Aquifer location was specified by the township and range coordinate system.

For each sub-basin, the list of accessible aquifer sites was narrowed to include only aquifers that were located within the sub-basin watershed and downstream of the reservoir (with one exception in the Oroville Reservoir sub-basin) so that the aquifer could receive gravity-fed water diversions. Aquifers accessible from each reservoir are listed in Table 3-1. In addition to those sites accessible to only one reservoir, within the Sacramento basin, aquifer's "M" and "N" are accessible to both Oroville *and* New Bullards Bar reservoirs. Aquifer "O" is accessible to all three Sacramento Basin reservoirs (Figure 3-1a). No aquifers are shared in the San Joaquin basin; although site "U" is accessible from both Don Pedro and New Exchequer dams, the site is partitioned into storage space reserved exclusively for Don Pedro Reservoir (U) and New

Exchequer Dam (U') (Figure 3-1b). Sharing conflicts between reservoirs are resolved by assigning reservoirs priority to use aquifers. Priorities are further explained in the water transfer modeling section 3.3.5 and Table 3-4.

It is important to note that these aquifer sites were chosen for this analysis strictly to determine when Conjunctive Use is feasible for flood protection. These choices are not a recommendation, and no effort was made to determine if these sites were in fact available or the owners amenable.

Table 3-1. Aquifers Accessible to Each Reservoir

Reservoir	Accessible Aquifers	
	Non-shared	**Shared***
Oroville	E, F, G, H, I	*M, N, O*
New Bullards Bar	K	*M, N, O*
Folsom	P	*O*
New Don Pedro	S, T, U	
McClure/New Exchequer	U'	
Millerton/Friant	X, Y, Z, AA, BB	

*****Shared aquifers are accessible from more than one reservoir

3.2 An Initial Estimate of Reservoir Flood Storage Space Created by CU

As discussed in the background section, aquifer storage space, maximum aquifer recharge rate, maximum extraction rate, and reservoir size are four factors that constrain the potential volume of additional flood storage space that can be created in reservoirs from CU operations. Since the three aquifer-related factors are directly dependent on the project area of each recharge basin, estimates for each factor were made for each aquifer considering two options: (1) full-sized (original assumption) and (2) half-sized recharge basin project areas. The following sections address how a volume equivalent was calculated for each factor at each aquifer. Maximum values served as user inputs to the Water Transfer Model (Section 3.3) and identified the factor(s) that constrained CU Pool Transfers in each reservoir basin (Section 4.1).

3.2.1 Aquifer Storage Constraint

The limit on CU Pool transfer caused by aquifer volume is exactly equal to the available aquifer storage space accessible to reservoir. Aquifer storage space is a function of aquifer porosity, depth to groundwater, and the aquifer project area (a design variable in this study). Based on aquifer index data provided by Purkey et al [2000], aquifer storage space was estimated to range from 0 to 607 KAF (Table 3-2) for the option of considering full-sized recharge basin project areas (see section 3.4 for more details).

Aquifer storage values in Table 3-2 are from 1997 water depth data because these values demonstrated the "wettest case" scenario that likely represents the most elevated water table

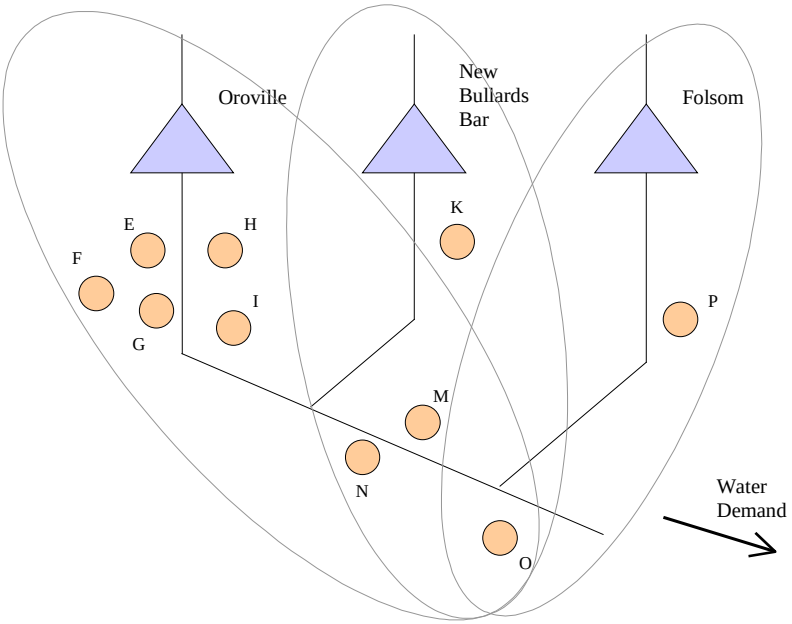
levels and hence the most conservative estimate of available aquifer storage space. Total aquifer storage space available to each reservoir is the sum of aquifer storage spaces to which the reservoir has first priority to access.

Table 3-2 Maximum Storage, Extraction, and Recharge Rates for Aquifer Sites

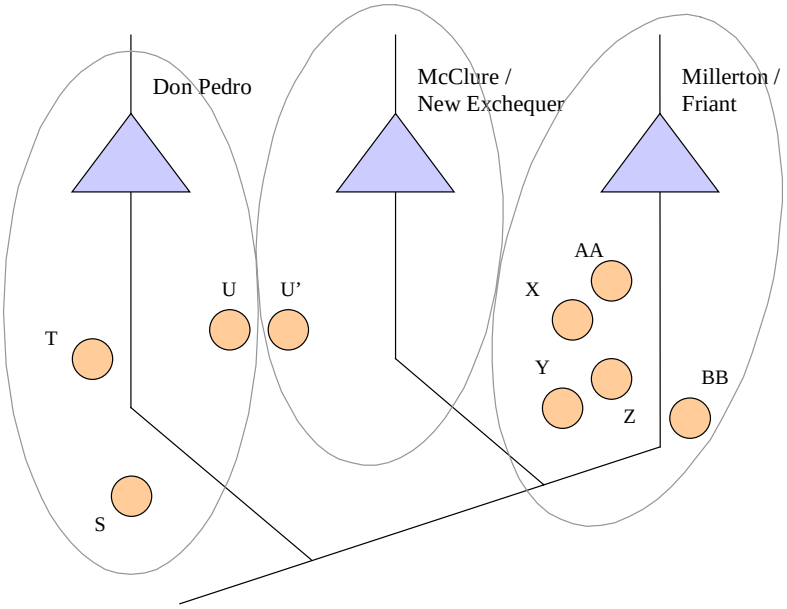
Aquifer	Area (mi^2)	Maximum Recharge (cfs)	(KAF/week)	Maximum Extraction (cfs)	(KAF/week)	Max Storage (KAF)
E	8	1850	25.7	335	4.6	172.3
F	8	1850	25.7	335	4.6	25.4
G	2	370	5.1	83.7	1.2	2.2
H	8	278	3.9	335	4.6	0
I	8	370	5.1	335	4.6	30
K	4	370	5.1	167	2.3	52.6
M	8	740	10.3	335	4.6	105.3
N	8	1850	25.7	335	4.6	32.9
O	8	370	5.1	335	4.6	115.4
P	6	556	7.7	251	3.5	214.8
S	4	741	10.3	167	2.3	11.3
T	4	926	12.9	167	2.3	144.5
U	4	926	12.9	167	2.3	378
U’	8	370	5.1	335	4.6	67.2
X	4	833	11.6	167	2.3	358.4
Y	4	650	9	167	2.3	143
Z	4	926	12.9	167	2.3	261.1
AA	4	926	12.9	167	2.3	606.4
BB	4	926	12.9	167	2.3	412.7

3.2.2 Aquifer Recharge Rate Constraint

For each reservoir, the recharge rate constraint on the CU pool transfer was the sum of all aquifer recharge rates for aquifers accessible from the reservoir. Recharge rates were calculated for each aquifer site (Table 3-2) for “full-sized” recharge basin project areas using procedures further explained in Section. 3.4. Recharge rates were converted to a volume equivalent at each recharge site by considering recharge over a 22-week period during the summer. Determination of recharge rates was made considering only recharge basins and not injection well technology.



A. Sacramento Basin



B. San Joaquin Basin

Figure 3-1. Aquifer Accessibility From and Sharing Among Reservoirs

3.2.3 Aquifer Extraction Rate Constraint

The extraction rate constraint on the CU pool transfer volume was calculated in a manner analogous to the recharge rate constraint. Aquifer-specific extraction rates were calculated (Table 3-2) using procedures further explained in Section 3.4. Aquifer extraction rates were converted to volume equivalents by considering extraction over the entire time period agricultural demand existed within the basin (see Section 3.3.2).

As seen in Table 3-2, extraction is significantly slower than recharge in the Sacramento and San Joaquin Basin aquifers. Conjunctive Use operations are therefore limited by the ability to extract previously stored water during the irrigation season.

3.2.4 Reservoir Size

Total reservoir storage, existing flood control pool, and conservation pool volumes were provided by the Sacramento District, USACE. The winter Conservation Pool volume served as the reservoir size constraint on the CU pool transfer. This constraint was unaffected by change recharge basin project area.

3.3 Water Transfer Modeling

3.3.1 Overview

Conjunctive Use operations were modeled using an interactive, mass-balance simulation of the water transfers between surface and groundwater systems, including reservoirs, aquifers, agricultural demands, and additional end users in the Sacramento and in the San Joaquin Basins. Simulation modeling was based on the conceptual model introduced in Section 2.2. This simulation model makes simplifying assumptions about groundwater hydrogeology, losses, and aquifer storage space to represent aquifer(s) as “leaky tank(s)” with a maximum storage size and rate of “inflow” and “outflow.” Groundwater parameter estimation (Section 3.4) provided the values used for these assumptions.

The operations goal represented in the transfer modeling was to maximize flood protection from CU water transfers. Based on current USACE and FEMA policy, this goal requires ensuring that, except *during* floods, additional flood storage space is available every year for the entire flood season. Simulation modeling assumed a “strict management” type of operation (Section 2.1.1) that had the best chance of being successfully implemented every year.

The CU reservoir operations and accounting modeling included:

- Reservoir releases for agriculture and Guide Curve
- CU transfers by direct recharge and *in-lieu* exchange
- CU payback by extraction and exchange
- Accounting of the aquifer “owed to reservoir” and “new yield” volumes
- Aquifer delivery to agriculture

- Sale of new yield, and
- Aquifer loss

These transfers are based on inputs of reservoir inflow, agricultural demand, aquifer capacity, maximum aquifer recharge and extraction rates.

Interactive models were created in Microsoft Excel. The model used a one-week time step and covered a fourteen-year time period (through analysis of two, non-contiguous seven-year data periods.)

Development of model input data, decision variables, groundwater parameters, transfer elements, rules governing transfers and implicit assumptions of the water transfer model follow. Mathematical relationships between model transfer flows are presented in Sidebar 3-1 (Section 3.3.6).

3.3.2 Model Input

Inflow to each of the six reservoirs and agricultural demand served by each of the six reservoirs are model inputs and specified by weekly time series data. Reservoir inflow data from two seven-year periods of the historical record covering 1973 through 1979, and 1983 through 1989 was used. These years were chosen to span a range of wet and dry years.

Time series values for agricultural demand are presented in Table 3-3. These values were approximated from reservoir release patterns observed during drier years of a 30-year historical period since actual demand data was not available for any of the study basins. In drier years of the historical record, it was assumed that reservoir releases would be minimal and used exclusively to meet the minimal level of agricultural demand.

The reservoir release pattern shaped agricultural demand for each year simulated by the Water Transfer Model. An exception was made for driest year simulations, in which case the agricultural demand was reduced to half the value of the reservoir release pattern. This exception assumed that the balance of (simulated) dry year agricultural demand would be met with additional groundwater pumping that was outside the scope of the CU project. .

3.3.3 Decision Variables

Model decision variables allow the user to make weekly decisions about Conjunctive Use transfers. These decisions include:

- Attempted CU Transfers (CU Pool and Excess Flow) in each week, from each reservoir (to produce the same *total* CU Pool transfer each year)
- Attempted extraction and sale of New Yield in each week, from each aquifer group

For each series of weekly decisions made, the model computed other system state variables to demonstrate to the user how successful the decisions were. The user could then adjust decisions to produce a more favorable result. This interactive approach allows the user to optimize CU operations by trial and error. As adjustments proceed, the user develops insights about the

sensitivity of CU operations to various system constraints such as extraction rate from aquifers and capacity of conveyance facilities.

To use the seven-year weekly model to produce the most realistic results, decisions concerning CU transfers in summer and fall were made without consideration of future hydrology (to simulate lack of knowledge) beyond what can be foretold by seasonal forecasting. Other user decisions, such as sale of new yield, are made after the hydrology has been realized. Therefore, prior knowledge is not an issue.

Table 3-3. Assumed Agricultural Demands for Each Reservoir

Month	Reservoir					
	Oroville (cfs)	Bullards Bar (cfs)	Folsom (cfs)	Don Pedro (cfs)	McClure (Exchequer) (cfs)	Millerton (Friant) (cfs)
April	0	0	0	1500	0	0
May	5000	1000	2000	2000	1000	1500
June	5000	1000	2000	2000	1000	3000
July	5000	1000	2000	2000	1000	3600
August	5000	1000	2000	2000	1000	2000
September	5000	1000	2000	750	1000	1000
October	0	1000	0	0	1000	0

3.3.4 Groundwater Parameters

Groundwater aquifers were represented as “tanks” within the water transfer model, subject to inflow, outflow, and a storage volume. Groundwater parameters (maximum aquifer storage capacities, maximum aquifer recharge rates, and maximum aquifer extraction rates) completely describe water storage and transfer into and out of groundwater aquifers. Groundwater parameter values (Table 3-2) were identical to values used to estimate the aquifer-factor constraints on CU Pool Transfers in Section 3.2. Groundwater parameter values were developed using methods discussed in Section 3.4.

3.3.5 Implicit Model Assumptions

Based on the conceptual layout of the Water Transfer Model, several implicit assumptions were made about the physical locations of the modeling elements. Assumptions include losses incurred from groundwater storage, the location of agricultural demand, and prioritization of aquifer storage to individual reservoir transfers.

- Fifteen-percent (15%) of all CU direct recharges are assumed to be lost from evaporation out of recharge basins and/or storage in the aquifer (Section 2.2.3, Water Loss). Therefore, only 85% of CU direct recharges are available for later extraction. This initially assumed aquifer loss rate is significantly above aquifer losses later predicted by groundwater modeling of CU recharge and extraction operations (Section 5).

- Agricultural demand that is served by extraction from an aquifer is assumed to be located *downstream* of the aquifer. This physical arrangement enables payback to be delivered by gravity flow. Demand met from aquifer storage measures less than half of total demand, making this assumption reasonable. Aquifers M, N, and O are located along the mainstem of the Sacramento River, so extractions from these aquifers are used to satisfy demands south of the Delta.
- For aquifers accessible to more than one reservoir, storage space and retrieval capacity was allocated according to a reservoir priority chosen for this study (Table 3-4). Aquifer accessibility is outlined in Table 3-1. A reservoir with higher priority (lower number) has, at all times, first right to maximize its CU water transfers using all existing recharge and extraction capacity in the aquifer ahead of reservoirs with lower priority. For example, Aquifer M is accessible to both Oroville and New Bullards Bar Reservoirs, and New Bullards Bar reservoir has the higher priority. At any time, New Bullards Bar reservoir uses as much recharge and retrieval capacity in Aquifer M as it needs to implement its direct recharges or extractions. Oroville reservoir can allocate its CU operations using the capacity in aquifer M that is not used by New Bullards Bar.

Table 3-4. Reservoir Priorities for Accessing Aquifers

Aquifer	Priority	Reservoir
M	1	New Bullards Bar
	2	Oroville
N	1	Oroville
	2	New Bullards Bar
O	1	Folsom
	2	New Bullards Bar
	3	Oroville

Rules governing transfers

Rules for Conjunctive Use (CU) transfers in the Water Transfer Model were developed without in-depth knowledge of water supply operations at these reservoirs. The rules can easily be adjusted and the simulations repeated. Rules used were:

- The CU transfer occurs between June and October, when the reservoir reaches its low winter level. If the reservoir is already lower than the CU winter level, the CU transfer is reduced, eliminated or delayed until winter when flood events raise the storage level above the winter CU level.
- Type 1 CU reservoir operations were used to establish development of CU flood pool space as the explicit first priority.
- Water is recovered from the aquifer during the following agricultural season (year $t+1$) to payback water owed to the reservoir (temporarily stored in year t).
- Recovered water is delivered directly to the reservoir's normal agricultural demand.

- Each year, the water owed to the reservoir is computed at the end of the flood season, two to six weeks after the spring date when the guide curve allows the reservoir to refill towards the summer operation level.
- *In-Lieu* exchanges are made instead of direct recharge and extraction if aquifer recharge and extraction would occur simultaneously.
- *In-Lieu* exchanged water (year *t*) is simultaneously (i) credited to aquifer accounts as either a CU Pool Transfer (year *t*) or Excess Flow Transfer (year *t*) and (ii) debited from aquifer accounts as Payback (year *t-1*) and/or Sale of New Yield (year *t-1*).
- After water owed to the reservoir is paid back, all new yield water is sold in the year the yield is realized.

3.3.6 Mass Balance Computation of Model Variables

Using reservoir Guide Curves, time-series input data, agricultural demand, groundwater parameters, and user suggestions for water transfers, the model applies mass balance principles to compute weekly values for each model flow and storage state variable. These variables include:

Physical:
- Reservoir storage volume
- Reservoir release for agricultural demand
- Additional reservoir release to maintain Guide Curve
- Water volume stored in each aquifer site
- Available storage space in each aquifer site
- Distribution of attempted CU transfer and recharge among aquifers
- Distribution of extraction requirement among aquifers
- *In-Lieu* exchanges for agricultural delivery and sale of New Yield

Accounting:
- Credited CU transfers (CU Pool and Excess Flow)
- Current aquifer storage volume credited to each reservoir
- CU “Owed to reservoir” account after Spring refill (to be recovered from aquifers)
- Payback to reservoir of “Owed” water via agricultural demand
- Volume of “New Yield” realized after Spring refill
- New yield account within aquifers

Mathematical descriptions of parameters, time-series data, user decision and state variables used in the Water Transfer Model appear in Sidebar 3-1, and directly reference Figure 2-1 a and b.

Sidebar 3-1. Descriptions of Parameters, Time-Series Data, User Decision and State Variables Used in the Water Transfer Model, see Figure 2-1

Parameters:

Reservoir: Capacity
Guide Curves
Aquifer: Capacity
Maximum Recharge
Maximum Extraction
15% Storage Loss

Time-Series Data:

Reservoir Inflow for each of the 6 study reservoirs
Agricultural Demand from each of the 6 study reservoirs

User Decisions:

***Attempted* CU Pool Transfer and Excess Flow Transfer (year 1, week t)** from Reservoir
User specifies "Attempted" CU Pool Transfer and the Excess Flow transfer, dependent on the state of the reservoir and inflow.

***Attempted* Sale of New Yield (year 2, week t)**
User decides the amount of new yield to sell each week. However, should attempt to sell all new yield each year it exists.

Computed Values:

Without Conjunctive Use:

Guide Curve Release from Reservoir:
The release aimed at remaining on the guide curve while maintaining a minimum release. In summer, filling the reservoir and releasing excess to avoid allowing storage above the curve. In winter, releasing excess.

GuideCurve Release (t) = [Storage(t-1) – GuideCurve(t)] + *Inflow(t)* – All Releases(t)

Agriculture Release from Reservoir:
Reservoir supplies the complete agricultural demand normally met by the reservoir.

Agriculture Release (t) = *Agricultural Demand (t)*

Physical Flows:

Agriculture Release (t) (after CU) from Reservoir:
After water owed back from the aquifer is delivered to agriculture, the difference is delivered from the reservoir as usual.

Agriculture Release (t) = *Agricultural Demand (t)* – Payback (1,2,t)

Direct Recharge (t) to aquifer
The "attempted" CU Transfer not met by In Lieu exchange, limited to the recharge capacity at each aquifer site. Losses of 15% are subtracted immediately.

Direct Recharge (t) = 85% * MIN (Recharge needed, Recharge capacity) in week t
Recharge needed = *Attempted* CU transfers (t) – In Lieu (t)
Recharge capacity = MIN(max recharge, [max aquifer storage - AquiferStorage(t)])

Extraction (t) from aquifer
Retrieval needed for payment of water "owed" to the reservoir and sale of new yield that is not me by In Lieu exchange, limited to the extraction capacity at each aquifer site.

Extraction (t) = MIN (Retrieval needed, max extraction)
Retrieval needed = CU payment (t) + Sale of new yield (t) – In Lieu (t)

***In Lieu* Exchange (t)** from Reservoir:
When Direct Recharge and Extraction coincide, transfer bypasses the aquifer and supplies the agriculture payback directly from the reservoir.

In Lieu (t) = MIN (*Attempted* CU Transfers, CU payment + "attempted" Sale)
In Lieu to Agri (t) = MIN (In Lieu (t), Payback (t))
In Lieu to Sale (t) = (In Lieu (t), In Lieu to Agri (t))

Accounting Flows:

***Credited* CU Transfers (year 1, week t)**
Credited CU Transfers are the attempted CU Transfers subject to limitation of maximum recharge at each aquifer, current storage capacity of each aquifer, and In Lieu exchange. (15% loss removed immediately)

***Credited* CU Pool Transfer (1,t) = MIN ("Attempted" CU Pool, Direct Recharge (t) + In Lieu (t))**
***Credited* Excess Flow Transfer (1,t) = Direct Recharge (t) + In Lieu (t) – *Credited* CU Pool Transfer**

Reservoir CU Pool (year 1) = Σ_t *Credited* CU Pool Transfer (1,t) * 85%

Payback (year 1 water, in year 2, week t) from Aquifer:
When it is determined that CU water delivered the previous year is *owed* back (ie, the "debt" isn't erased by new yield), water is delivered from the aquifer at maximum extraction toward the agricultural demand until deficit goes to zero. If possible, In Lieu deliveries are pursued before pumping.

Payback (1,2,t) = MIN (*Water Owed*, max extraction, *Agricultural Demand(t)* – In Lieu to Agri) + In Lieu to Agri

(*Water Owed* is an account described and defined in Figure 2.3 and Sidebar 1)

Sale of New Yield (year 2, week t)
When new yield exists, after agriculture payback, the capacity for *In Lieu* and extraction is used to remove new yield from the aquifer for sale. If possible, In Lieu deliveries are pursued before pumping (extraction).

Sale of New Yield (2,t) = MIN (*New Yield*, max extraction, [*attempted* Sale(t) – In Lieu to Sale(t)]) + In Lieu to Sale(t)
(*New Yield* is an account described and defined in Figure 2.3 and Sidebar 1)

Aquifer Loss (t)

Aquifer loss is assumed to equal 15% of water recharged. Loss is the result of evaporation from recharge basins and flow within the aquifer. Loss is subtracted directly from the direct recharge computation.

3.4 Estimating Groundwater Parameters

This section explains how values for aquifer storage capacity, and aquifer recharge and extraction rates were developed for each potential aquifer storage site. These groundwater parameter values were estimated for the simplified "tank" representation of groundwater used in the Water Transfer Model (Section 3.3).

3.4.1 Overview

The recharge of surface water to the water table creates an artificial stress on the groundwater flow regime. Initially a groundwater mound is created at the water table. Over time, this mound flattens as water flows away from the recharge area. The efficiency of storage and retrieval of water recharged to an aquifer is dependent upon groundwater parameters such as specific yield and hydraulic conductivity, and is governed by conservation of mass and Darcy's Law ($Q = -KA\ dh/dl$).

Four general parameters should be considered to better understand the processes involved in storing water in the subsurface: the rate of recharge of surface water to groundwater; the available storage capacity of an aquifer; the retrieval of stored water by pumping wells; and the loss of stored water over time. This section addresses the first three parameters. The fourth parameter, water loss, occurs because groundwater migrates outside the hydrologic boundaries associated with the project area. Loss rates of stored water were estimated using numerical methods and are discussed in Chapter 5.

3.4.2 Recharge to Groundwater

There are two mechanisms through which water can be transferred into the subsurface: injection wells and recharge basins. Injection wells allow for the direct simulation of a specified flux placed on the water table. Recharge basins require the percolation of water through the

subsurface to the water table. In this analysis, it is assumed that saturated flow occurs from the surface recharge basin to the water table. This assumption can be used in areas with shallow water tables and/or situations where recharge occurs over long time intervals. Additionally it is assumed that the moisture content of the soil remains constant before and after a recharge event. In other words, all water that percolates into the subsurface is eventually stored in the phreatic aquifer.

There are two general parameters that control the rate of recharge into the subsurface: recharge area and soil permeability. The recharge rate is the product of the two parameters.

3.4.2.1 Recharge Area

In this section, unit recharge rates are based upon a project area of 1 square mile. (These values may later be linearly-scaled to a 4 square mile site.) An assumed 70% of project area (20,000,000 ft^2) is devoted to the percolation pond through which recharge will percolate. The amount of recharge will vary linearly with the project area.

3.4.2.2 Infiltration Rate

The infiltration rate is dependent upon initial soil moisture, saturated hydraulic conductivity, moisture potential (wetting front suction), and the surface area of the recharge basin. In cases where water is recharged to the subsurface using injection wells, the rate of recharge depends upon aquifer parameters such as hydraulic conductivity and effective porosity (specific yield). Purkey et al. (2001) estimated values of percent hardpan and percent sand for several potential groundwater banking sites in the Central Valley of California. Values of saturated vertical hydraulic conductivity were estimated as a function of these parameters. Infiltration rate and recharge area values were multiplied to estimate the recharge rate (Table 3-5).

3.4.3 Estimating Storage Capacity

The Central Valley groundwater system can be portrayed as a single homogeneous aquifer. The region is characterized by water-bearing sediments interspersed with clay lenses (Purkey et al., 2001). The subsurface storage capacity of a specific site is the product of the volume of available unsaturated soil and the effective porosity of the soil. The volume of unsaturated soil is a function of the depth to water table and surface area. For this analysis, the groundwater storage region is assumed to begin 10 ft below ground surface.

This section discusses the estimated storage capacity values (SCVs) for the previously selected potential groundwater banking sites. The suitability of potential sites was determined based on multiple considerations: soil characteristics, geologic settings, water quality and degree of hydrologic connections. Detailed discussion on the selection of the sites is given by Purkey et al. (2001). While the first three factors are significant in determining groundwater banking sites, many sites are selected due to their location in a depression where water can be stored.

Table 3-5. Recharge Rates for Aquifer Sites (per 1 square mile Area)

Index	Site	Basin	Kv (ft/day)	Recharge Rate (ft^3 /day)
E	Chico Fan	Butte	1	20,000,000
F	Butte Creek	Butte	1	20,000,000
G	Feather River	Butte	0.8	16,000,000
H	Sutter Buttes	Sutter	0.6	12,000,000
I	Yuba City	Sutter	0.2	4,000,000
M	American Basin	Sutter	0.4	8,000,000
N	Cache-Putah Plain	Solano-Yolo	1	20,000,000
O	South Fork Putah Creek	Solano-Yolo	0.2	4,000,000
P	Elk Grove	Sacramento	0.4	8,000,000
S	Hetch Hetchy Aqueduct	Modesto	0.8	16,000,000
T	Dry Creek	Modesto	1	20,000,000
U	Montpellier	Turlock	1	20,000,000
V	Owens Creek	Merced	0.2	4,000,000
W	Dutchman Creek	Merced	0.7	14,000,000
X	Beranda Creek	Madera	0.9	18,000,000
Y	Chowchilla Bypass	Chowchilla	0.5	10,000,000
Z	Gravelly Ford	Madera	1	20,000,000
AA	Little Dry Creek	Madera	1	20,000,000
BB	James Bypass	Kings	1	20,000,000

Table 3-6 contains aquifer site information, including site name, the groundwater basin where the site is located, Township and Range locations (from the California State Land Survey System. Figure 3-1 shows aquifer locations within the Sacramento and San Joaquin Valleys.

3.4.3.1 Methodology

Groundwater and ground surface elevation data were retrieved from the web site maintained by the California Department of Water Resources, Division of Planning and Local Assistance (http://well.water.ca.gov). Information collected for each aquifer site included: UTM (the Universal Transverse Mercator Coordinate System) location, water table elevations with respect to sea level (WTE), the difference between the ground surface elevations and water table elevations (GSWS), the state well number for the well where WTE measurements were taken, and the date when measurements were recorded. Measurements for WTE and GSWS are given in feet. Data was collected for spring and fall of 1992 and 1997.

Ground surface elevations (GSE) were obtained by adding GSWS to WTE. For each aquifer site, GSEs and WTEs were imported into the 3-D mapping program Surfer (Golden Software), to create contour maps of GSE and WTE. Values for the volume of storage capacity at each site were determined as follows:

- The first 10 feet of ground depth was assumed to be unavailable for groundwater storage. Thus, a value of 10 ft was subtracted from the GSE to create a new grid of adjusted GSE.
- Adjusted GSE and WTE data were converted to meters and stored as grid files using Surfer.

- Blanking files were prepared. The files contained the x-y grid coordinates of the boundaries for each 4 mi^2 project area.
- Surfer calculated the volume of space between adjusted GSE and WTE surfaces over the project area. Adjusted GSE was specified as the upper surface and WTE was specified as the lower surface. For each site, the calculated volume was multiplied by the average porosity to give the estimated value of storage capacity (SCV).

Using the procedure described above, SCVs for fall and spring of 1992 and 1997 were calculated at each site using date specific water table elevation (WTE) data. To consider the effects of water spreading outside the depression zone, the project area was expanded to 16 mi^2 at each aquifer site and the SCV was recalculated. This expansion assumed a spreading of one-mile outward from each original 4 mi^2 project area.

3.4.3.2 Results

Table 3-8 shows estimated storage capacity values (SCVs) at each aquifer site for both 4 mi^2 and 16 mi^2 project areas for years 1992 and 1997. Calculations show that San Joaquin Valley sites provide more water storage capacity than Sacramento Valley aquifer sites. This difference is explained by the fact that Sacramento Valley groundwater supplies are healthier than San Joaquin Valley supplies. San Joaquin Valley aquifers are over-drafted and further depleted. The depletion represents greater capacity for groundwater storage.

Depth to water table (DWT) contour plots from fall 1992 graphically show the difference in storage capacity between Sacramento and San Joaquin Valley aquifer sites (Figures 3-3 and 3-4). DWT is the difference between the adjusted ground surface elevation and the water surface elevation (i.e., GSWS - 10). San Joaquin Valley sites are mostly located in the vicinity of depression zones, whereas Sacramento Valley sites are not. Several SCVs were negative in value, meaning that subtracting the 10-ft ceiling depressed the adjusted GSE below the WSE. In these instances, we concluded that no storage capacity exists.

Overall, fall SCVs were higher than spring SCVs for both 1997 (Figure 3-5) and 1992 (Figure 3-6). SCVs for 1997 fall were lower than SCVs for 1992 fall (Figure 3-7), since 1997 was a very wet year. However, 1992 spring SCVs are lower than expected compared to 1997 Spring SCVs (Figure 3-8), especially for San Joaquin Valley aquifer sites (see total values in Table 3-7). This shortfall is due to increased WSEs throughout the San Joaquin Valley in spring 1992. San Joaquin Valley sites—more so than Sacramento Valley sites—contribute a much larger portion of SCV to the total project SCV.

Sutter Buttes was the aquifer site with the smallest storage capacity. SCVs were zero except for the 1992 fall season. The Little Dry Creek is the aquifer site with the highest potential for groundwater storage. SCVs at Little Dry Creek were largest in all time shots. A detailed contour plot of depth to water table (DWT) in fall of 1992 shows that the Little Dry Creek aquifer site (AA) resides in the largest zone of groundwater depression (Figure 3-9). Boundaries for the 4 mi^2 and 16 mi^2 project areas are depicted in Figure 3-9b.

DWTs did not fluctuate significantly when the project areas were expanded. Unit area SCVs (taf/mi^2) for each aquifer site at each time shot were calculated for the smaller (4 mi^2) and larger

(16 mi^2) project areas by dividing the SCV with the size of the project area (Table 3-8). A paired *t-test* (paired by aquifer site and time shot) showed that variations in unit-area SCVs between the small and expanded project areas were not statistically significant [$P = 0.219 < 0.05$]. This result means that for each aquifer site, GWEs inside the 4 mi^2 boundary do not differ significantly from GWEs immediately outside the boundary. SCV is linearly related to the project area for areas up to 16 mi^2.

3.4.4 Estimating the Rate of Retrieval

Groundwater extraction is a function of pumping rate, well efficiency, aquifer transmissivity, and specific yield (effective porosity). For simple (single) well systems, analytical methods can be used to estimate extraction rates. However, in the case of multiple well systems, groundwater models must be used to estimate the effect of pumping on groundwater flows and elevations.

In the Central Valley aquifer, typical values of hydraulic conductivity range from 40-200 ft day in production zones. Values of effective porosity range in the Central Valley typically range from 0.20-0.30 for sand aquifers. For a 12-inch well with a screened interval of 50-100 ft, a reasonable assumption for yield is 1,000 gpm (or 192,500 ft^3/day). For the initial project area of 1 mi^2, it is not uncommon that 15-20 extraction wells can be used for the seasonal groundwater retrieval system (Purkey, August 2001). Thus, for a 1 mi^2 square mile project area, retrieval can be estimated at 20,000 gpm (or 3,850,000 ft^3/day). For a 4mi^2 project area, the retrieval rate is linearly expanded to 80,000 gpm (or 15,400,000 ft^3/day).

Table 3-6. Reference Information for Potential Aquifer Storage Sites.

Index	Site Name	Basin	Township and Range	Sections
E	Chico Fan	Butte	T21N, R1E	15,16,21,22
F	Butte Creek	Butte	T17N, R1E	27,28,33,34
G	Feather River	Butte	T17N, R2E	26,27,34,35
H	Sutter Butter	Sutter	T15N, R1E	1,2,11,12
I	Yuba City	Sutter	T15N, R3E	4,5,8,9
M	American Basin	Sutter	T11N, R4E	26,27,34,35
N	Cache-Putah Plain	Solano-Yolo	T10N, R2E T10N, R3E	24,25 19,30
O	South-Fork	Solano-Yolo	T7N, R2E	2,3,10,11
P	Elk Grove	Sacramento	T7N, R5E	27,28,33,34
S	Hetch Hetchy Aqueduct	Modesto	T3S, R8E	19,20,29,30
T	Dry Creek	Modesto	T3S, R9E	25,26,35,36
U	Montpellier	Turlock	T4S, R12E	19,20,29,30
V	Owens Creek	Merced	T8S, R11E	13,14,23,24
W	Dutchman Creek	Merced	T8S, R17E T9S, R17E	31,32 5,6
X	Berenda Creek	Madera	T10S, R16E	21,22,27,28
Y	Chowchilla By pass	Chowchilla	T11S, R14E	2,3,10,11
Z	Gravelly Ford	Madera	T12S, R16E	11,12,13,14
AA	Little Dry Creek	Madera	T11S, R19E	25,26, 35,36
BB	James Bypass	Kings	T15S, R17E	23,24,25,26

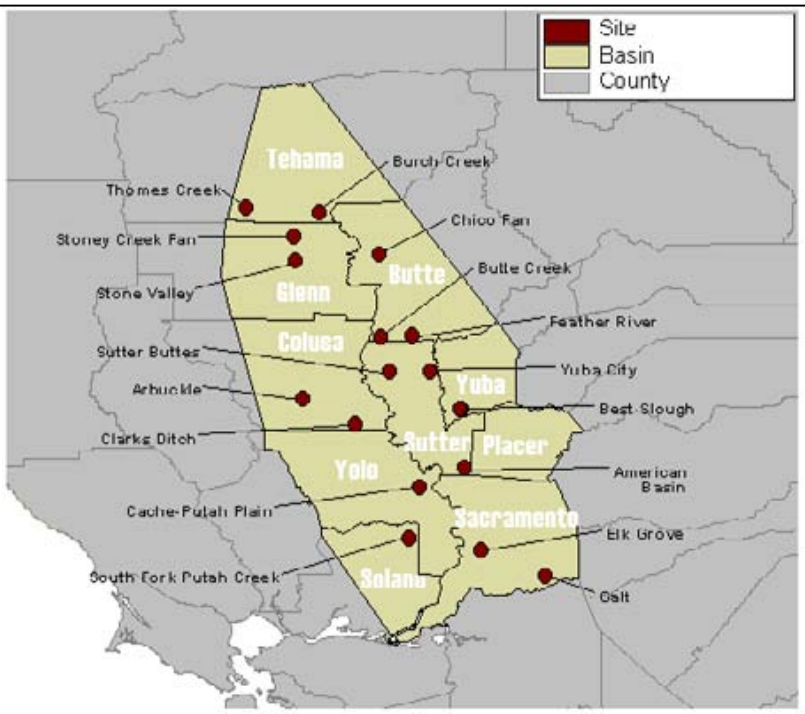
Table 3-7. Storage Capacity Volumes (SCVs) at Potential Aquifer Storage Sites

Aquifer Site	4 mi^2 Project Area				16 mi^2 Project Area			
	Fall 97 (TAF)	Spring 97 (TAF)	Fall 92 (TAF)	Spring 92 (TAF)	Fall 97 (TAF)	Spring 97 (TAF)	Fall 92 (TAF)	Spring 92 (TAF)
E Chico Fan	17.9	8.5	27.0	15.8	86.2	86.2	102.2	59.1
F Butte Creek	4.7	3.3	7.4	0.3	12.7	7.9	23.2	0.6
G Feather River	0.8	0.5	1.0	0.0	4.4	2.9	5.8	0.0
H Sutter Buttes	0.0	0.0	0.4	0.0	0.0	0.0	2.2	0.0
I Yuba City	3.6	1.1	4.2	3.9	15.0	5.0	14.8	16.1
M American Basin	12.9	11.0	14.3	10.2	52.6	42.6	53.9	39.8
N Cache-Putah Plain	3.5	0.0	15.1	5.1	16.4	0.0	61.6	23.1
O South Fork Putah Creek	14.4	10.8	22.4	14.3	57.7	44.6	103.3	66.0
P Elk Grove	35.2	29.8	35.3	32.8	143.2	116.8	132.5	123.9
S Hetch Hetchy Aqueduct	2.9	1.3	6.2	3.7	11.3	7.3	20.3	14.5
T Dry Creek	37.4	26.4	50.7	42.2	144.5	135.5	178.7	170.6
U Montpellier	103.3	76.3	105.6	99.3	378.1	392.1	379.9	344.0
V Owens Creek	9.5	9.9	18.1	5.2	33.6	43.8	61.9	20.1
W Duchman Creek	30.8	68.4	53.8	40.9	143.1	206.1	245.0	196.7
X Berenda Creek	75.9	71.5	77.6	81.9	358.4	338.0	325.4	304.7
Y Chowchilla Bypass	26.5	26.8	50.2	46.0	127.0	117.0	245.0	174.1
Z Gravelly Ford	64.1	61.6	67.0	58.6	261.1	247.5	290.5	254.5
AA Little Dry Creek	190.5	161.4	149.9	128.6	606.4	512.0	523.7	468.1
BB James Bypass	106.9	151.4	97.5	95.8	412.7	328.4	400.9	351.5
MEDIAN	**17.9**	**11.0**	**27.0**	**15.8**	**86.2**	**86.2**	**103.3**	**66.0**
TOTAL	**740.7**	**719.9**	**803.6**	**684.6**	**2864.4**	**2633.5**	**3170.7**	**2627.3**

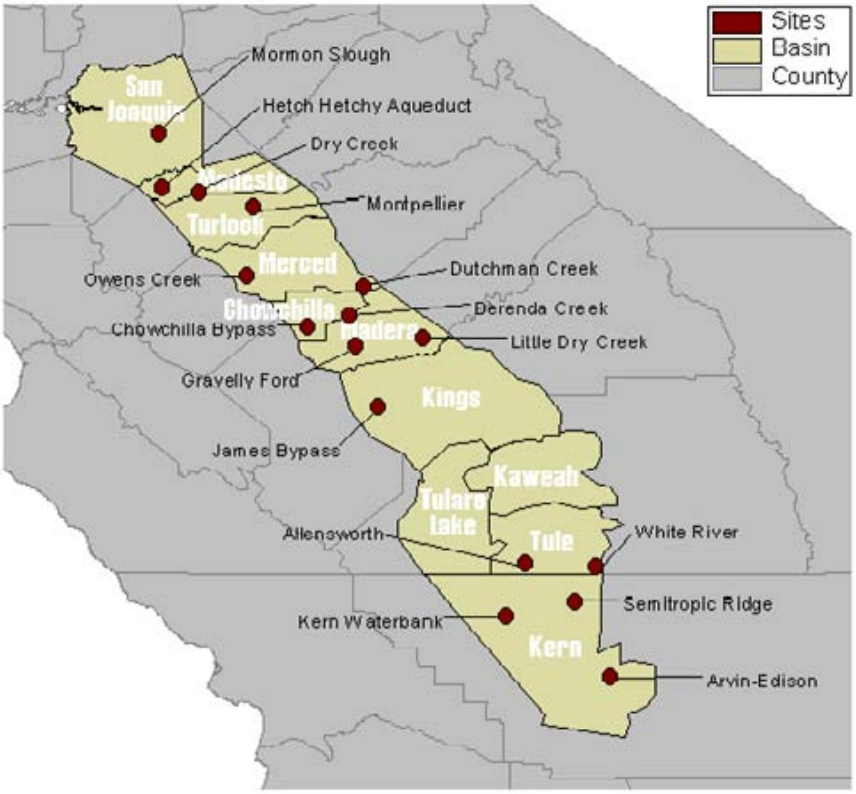
Table 3-8. Unit-Area Storage Capacity Volumes (SCVs) at Potential Aquifer Storage Sites

Aquifer Site	4 mi^2 Project Area				16 mi^2 Project Area			
	Fall 97 (TAF/mi^2) = SCV / 4	Spring 97 (TAF/mi^2) = SCV / 4	Fall 92 (TAF/mi^2) = SCV / 4	Spring 92 (TAF/mi^2) = SCV / 4	Fall 97 (TAF/mi^2) = SCV / 16	Spring 97 (TAF/mi^2) = SCV / 16	Fall 92 (TAF/mi^2) = SCV / 16	Spring 92 (TAF/mi^2) = SCV / 16
E Chico Fan	4.5	2.1	6.8	3.9	5.4	5.4	6.4	3.7
F Butte Creek	1.2	0.8	1.9	0.1	0.8	0.5	1.4	0.0
G Feather River	0.2	0.1	0.3	0.0	0.3	0.2	0.4	0.0
H Sutter Buttes	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
I Yuba City	0.9	0.3	1.1	1.0	0.9	0.3	0.9	1.0
M American Basin	3.2	2.7	3.6	2.5	3.3	2.7	3.4	2.5
N Cache-Putah Plain	0.9	0.0	3.8	1.3	1.0	0.0	3.9	1.4
O South Fork Putah Creek	3.6	2.7	5.6	3.6	3.6	2.8	6.5	4.1
P Elk Grove	8.8	7.5	8.8	8.2	8.9	7.3	8.3	7.7
S Hetch Hetchy Aqueduct	0.7	0.3	1.6	0.9	0.7	0.5	1.3	0.9
T Dry Creek	9.4	6.6	12.7	10.5	9.0	8.5	11.2	10.7
U Montpellier	25.8	19.1	26.4	24.8	23.6	24.5	23.7	21.5
V Owens Creek	2.4	2.5	4.5	1.3	2.1	2.7	3.9	1.3
W Duchman Creek	7.7	17.1	13.4	10.2	8.9	12.9	15.3	12.3
X Berenda Creek	19.0	17.9	19.4	20.5	22.4	21.1	20.3	19.0
Y Chowchilla Bypass	6.6	6.7	12.5	11.5	7.9	7.3	15.3	10.9
Z Gravelly Ford	16.0	15.4	16.7	14.7	16.3	15.5	18.2	15.9
AA Little Dry Creek	47.6	40.3	37.5	32.1	37.9	32.0	32.7	29.3
BB James Bypass	26.7	37.8	24.4	24.0	25.8	20.5	25.1	22.0
MEDIAN	**4.5**	**2.7**	**6.8**	**3.9**	**5.4**	**5.4**	**6.5**	**4.1**
TOTAL	**185.2**	**180.0**	**200.9**	**171.2**	**179.0**	**164.6**	**198.2**	**164.2**

Paired T-test (4 mi2 Unit SCVs, 16 mi2 Unit-area SCVs): P < 0.219



A. Sacramento Valley



B. San Joaquin Valley

Figure 3-1 Location of Potential Aquifer Storage Sites

Figure 3-3. Depth to water table at potential GW banking sites in the Sacramento Basin

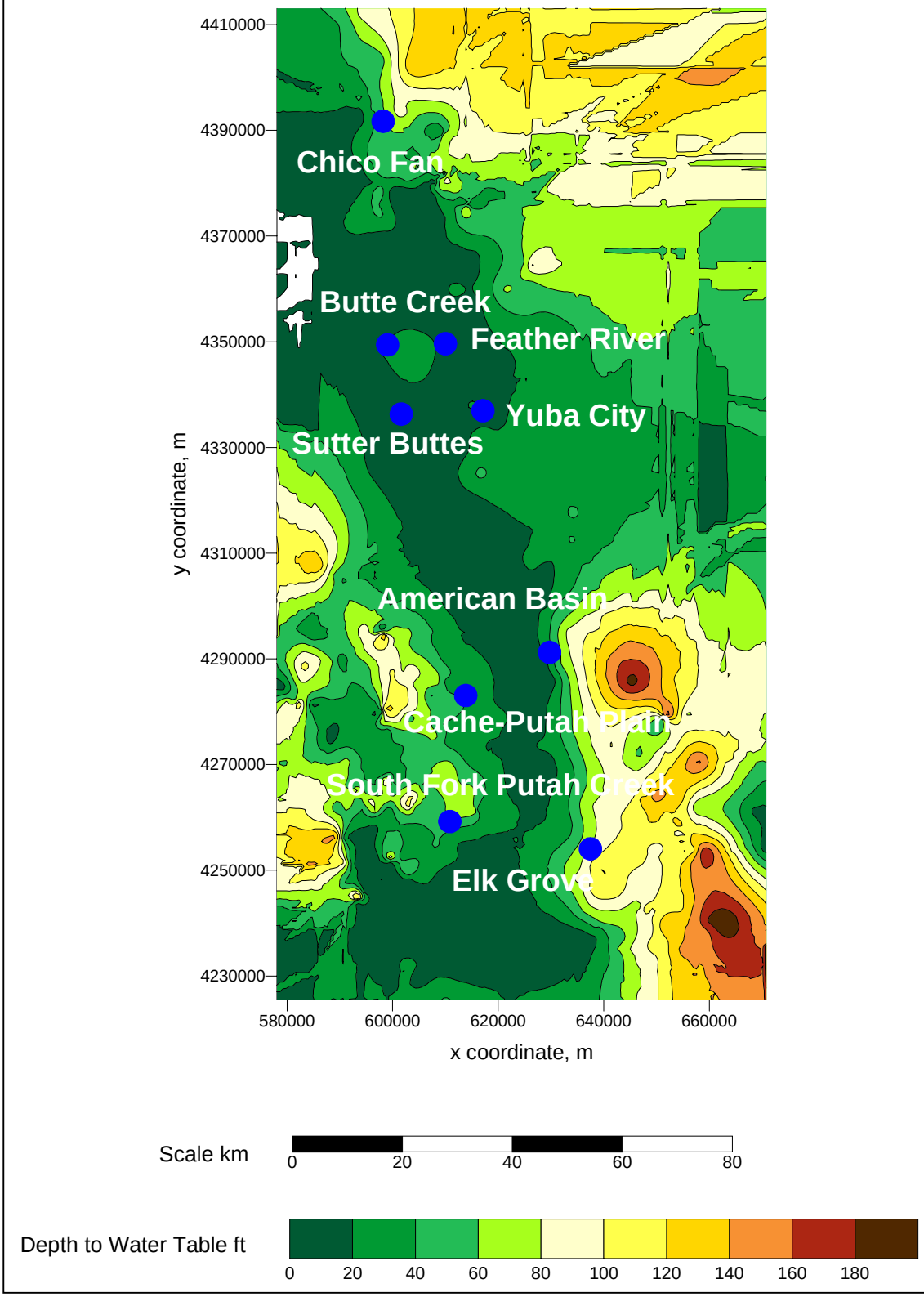
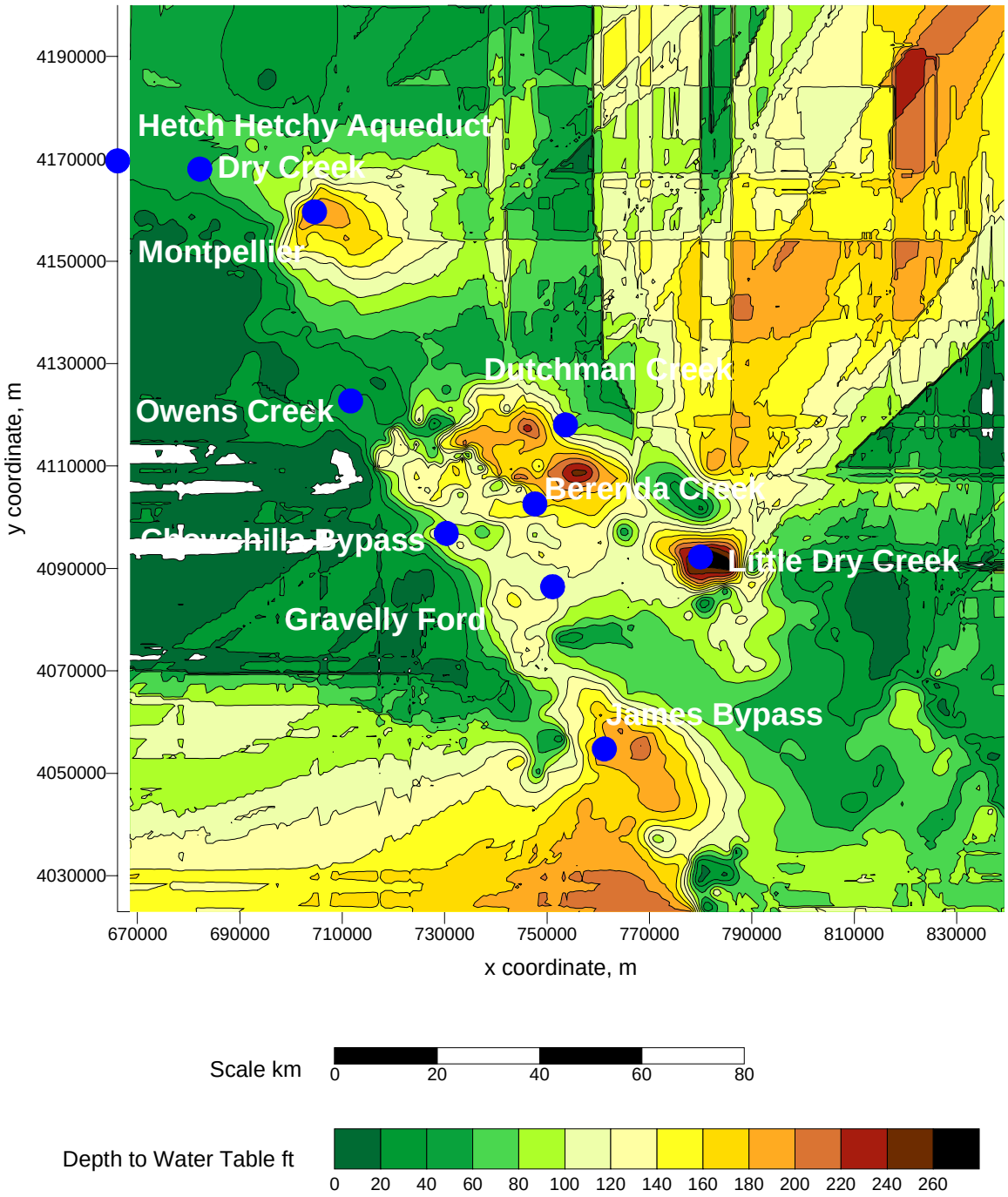
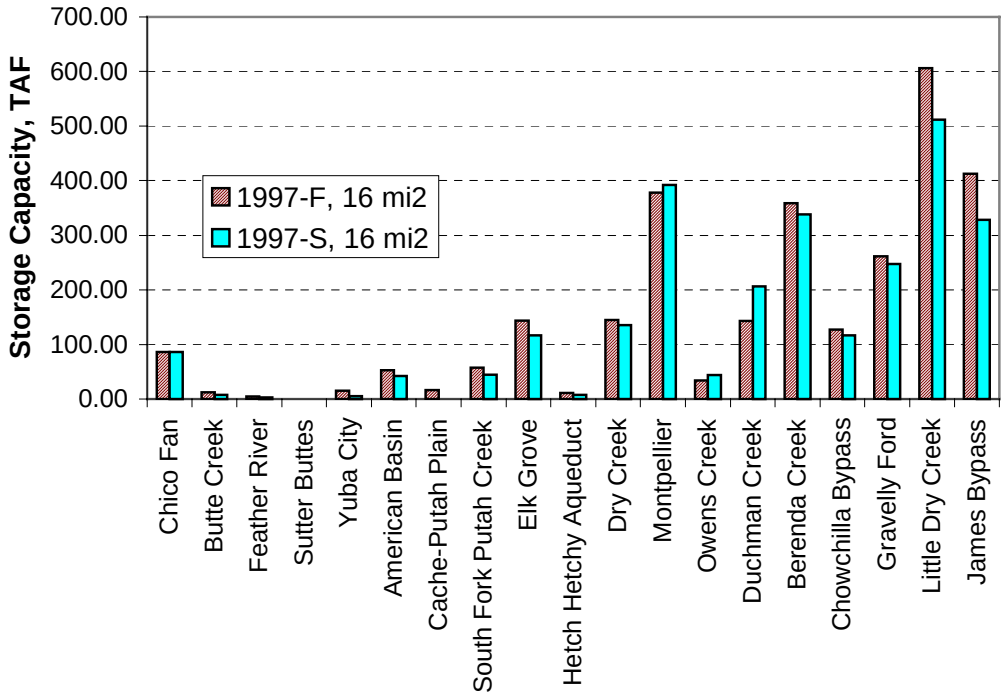


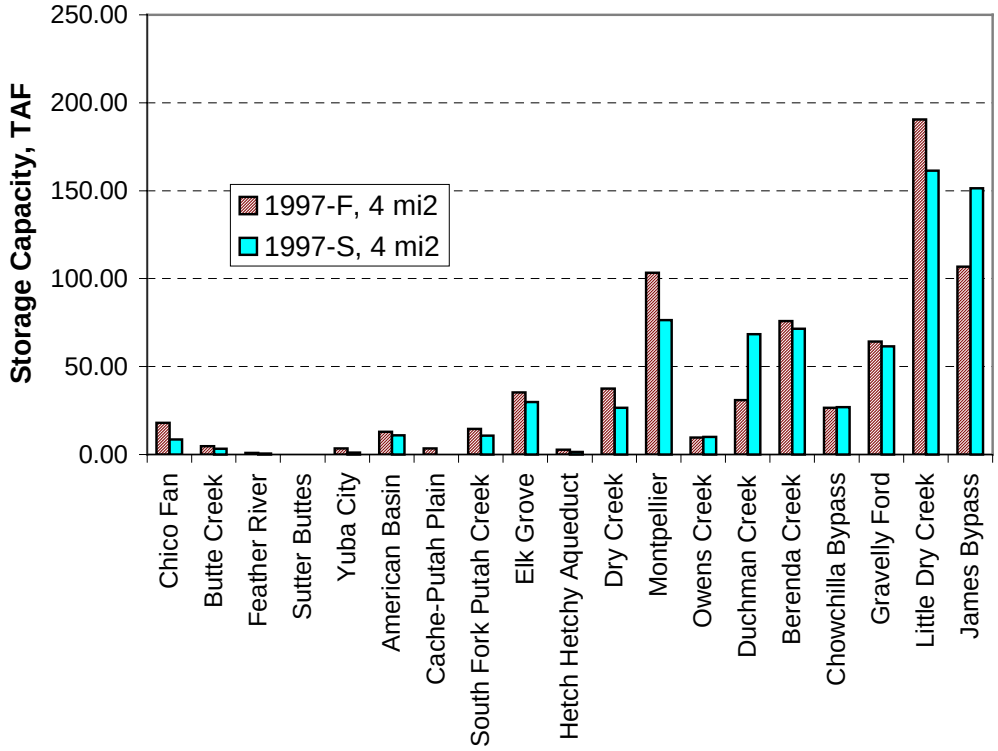
Figure 3-4. Depth to water table at potential GW banking sites in the San Joaquin Basin



USA

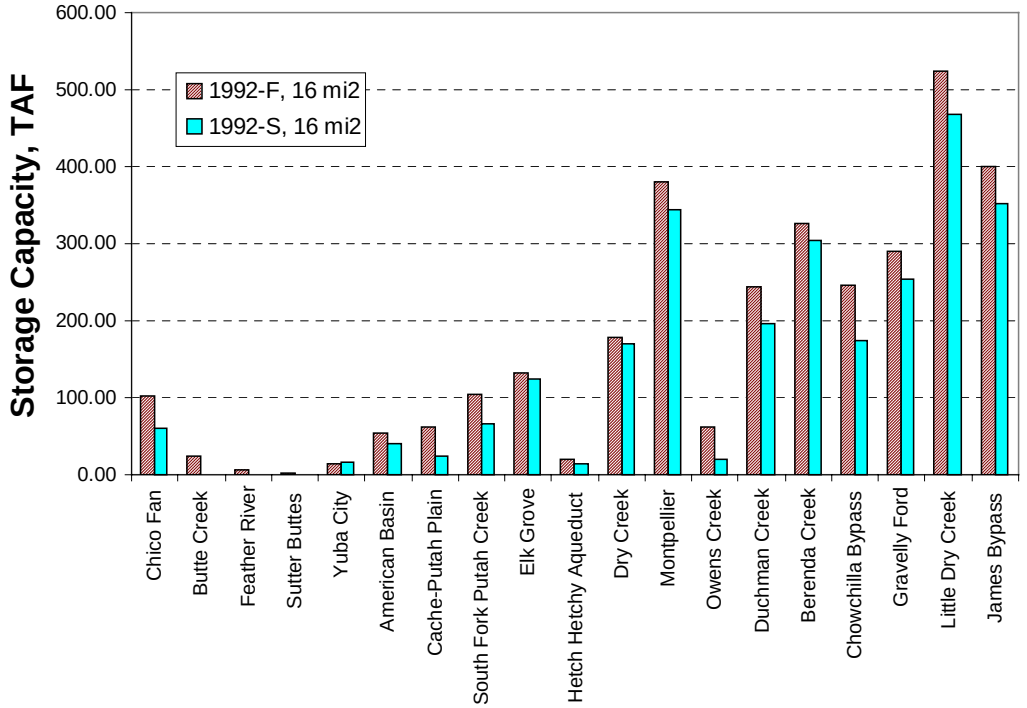


A. 16 mi^2 Project Area

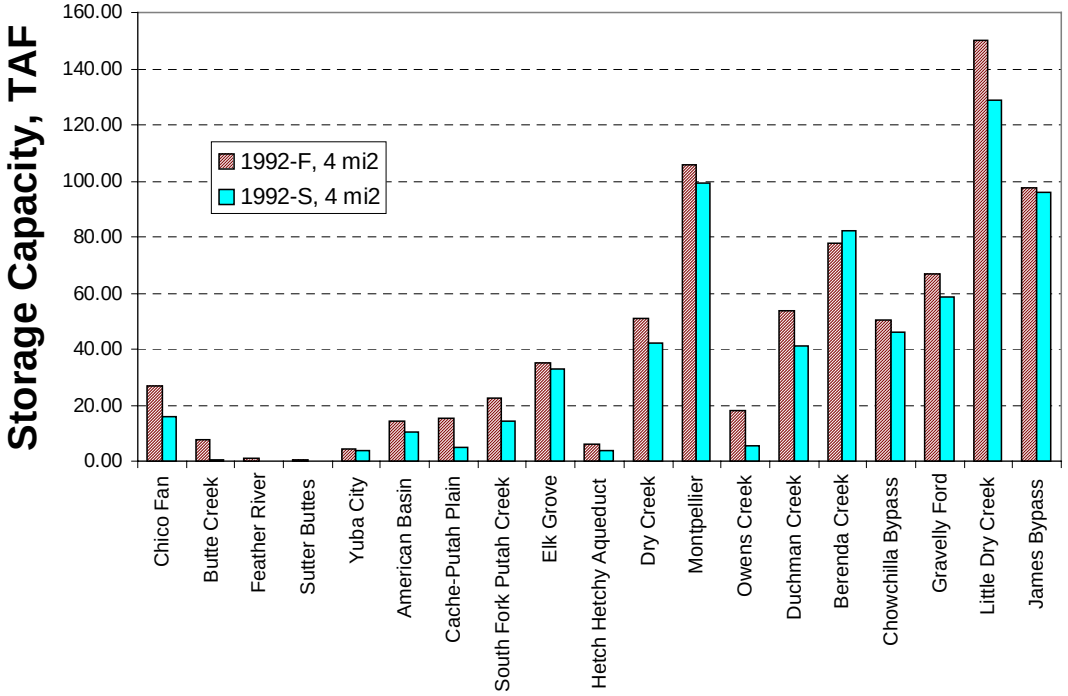


B. 4 mi^2 Project Area

Figure 3-5. Comparison of Fall and Spring SCVs for 1997

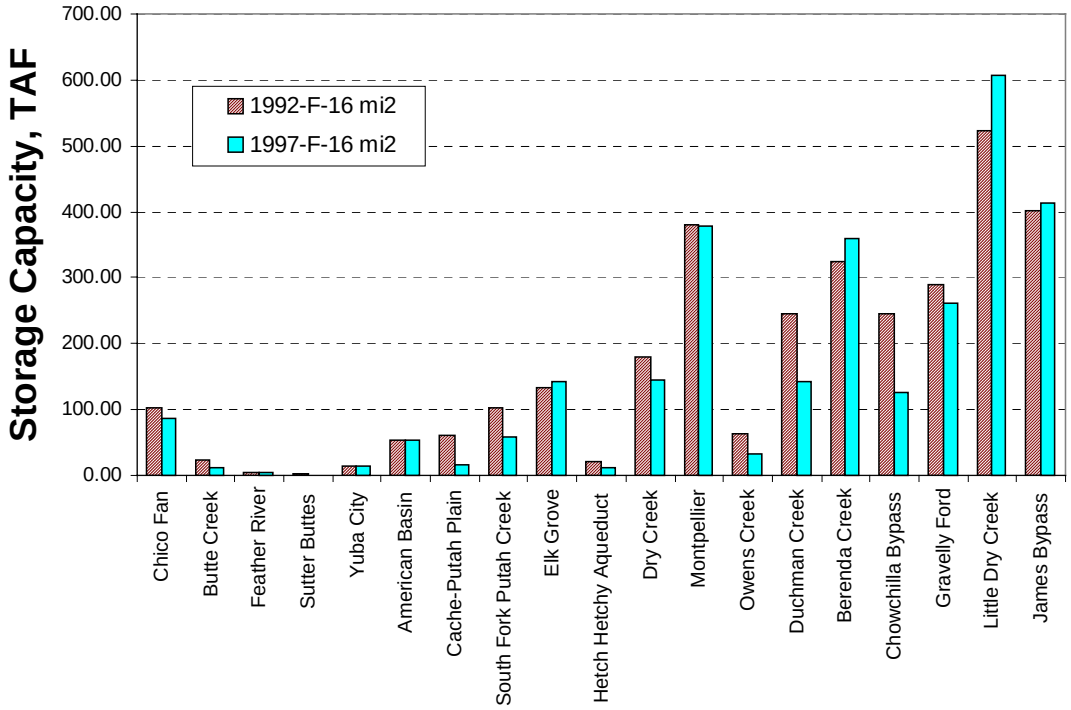


A. 16 mi^2 Project Area

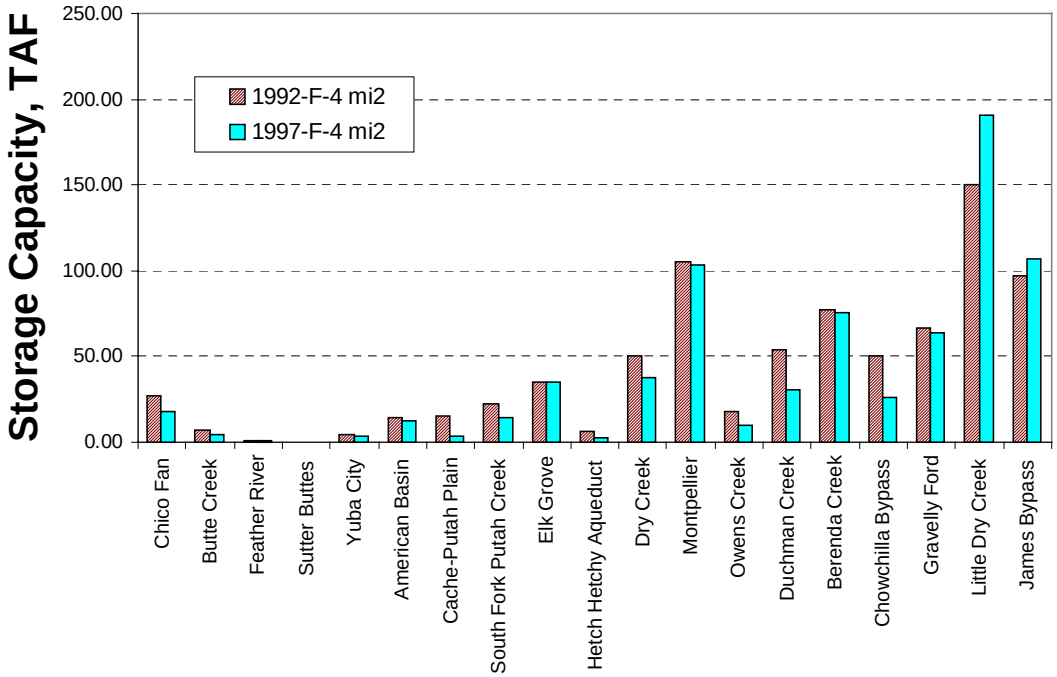


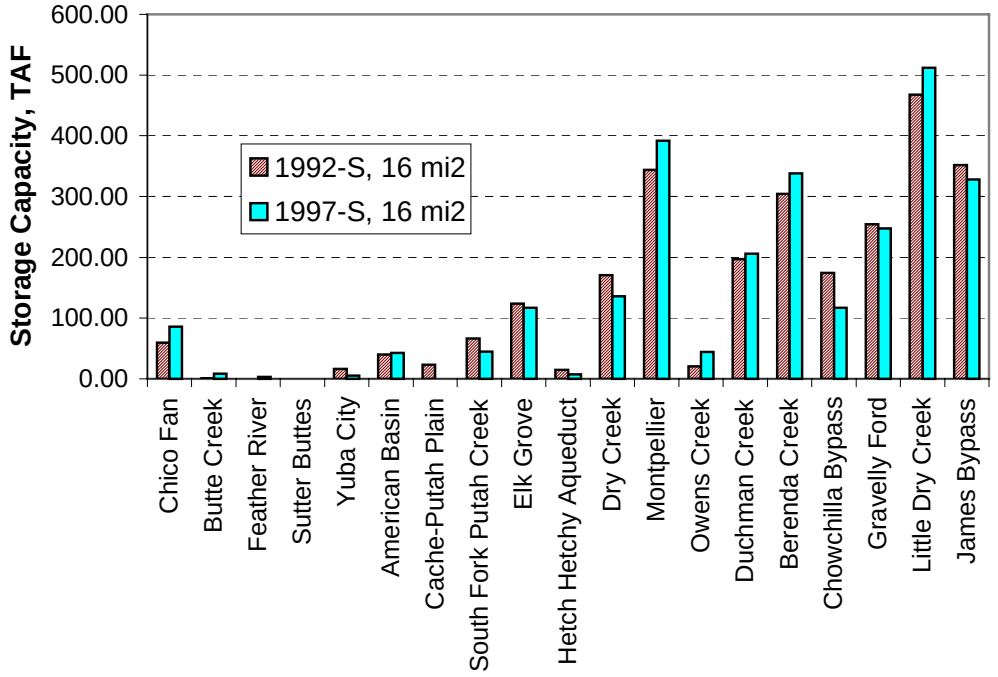
B. 4 mi^2 Project Area

Figure 3-6. Comparison of Fall and Spring SCVs for 1992

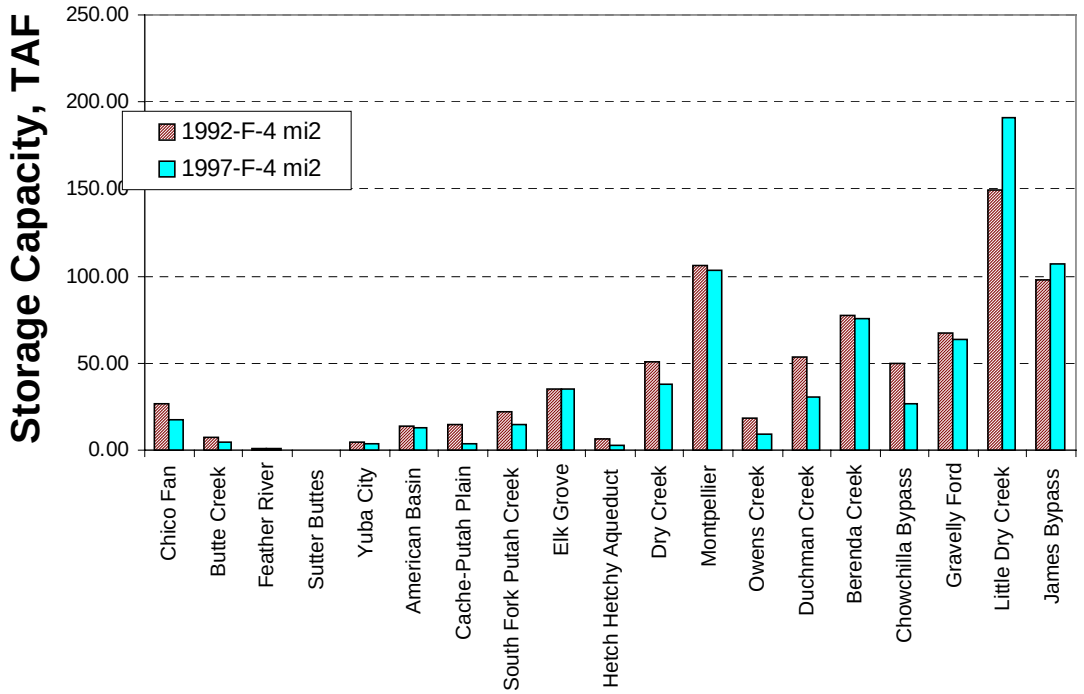


A. 16 mi^2 Project Area



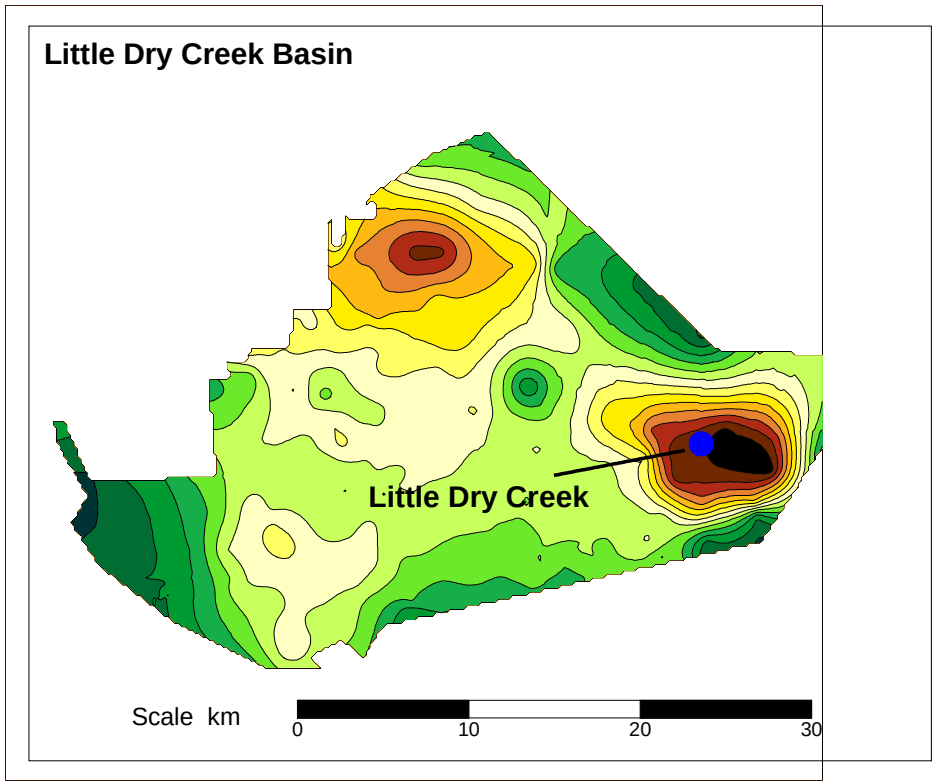


A. 16 mi^2 Project Area



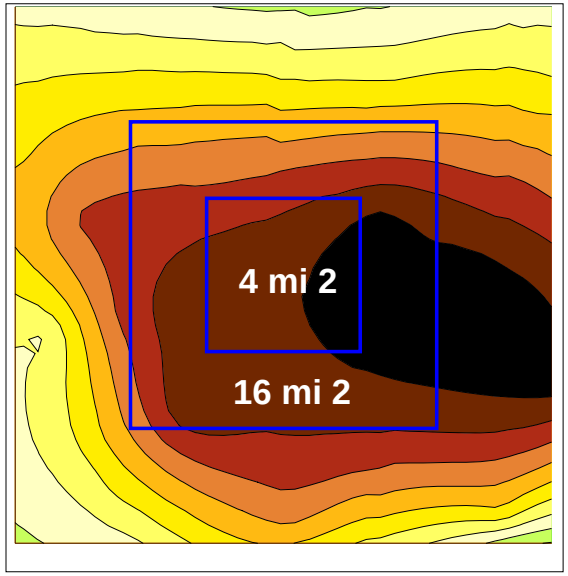
B. 4 mi^2 Project Area

Figure 3-9. Depths of water table at Little Dry Creek aquifer site AA.

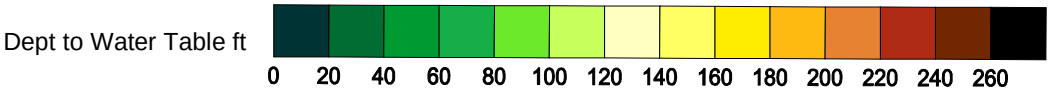


A. Little Dry Creek, located in Madera County, is one of the potential sites for groundwater banking. Contours of depth to water table for fall 1992 is shown on the left.

Recharge Area



B. Alternative recharge areas of 4 and 16 sq. mi at the site. In general, the estimated storage capacity values tend to increase linearly with increase in area. The value of volume storage capacity for 4 sq. mi is estimated as 149.89 TAF, while 16 sq. mi results in volume storage value of 606.43 TAF, about four times greater than the value for 4 sq. mi.



3.5 Methodology of Cost and Benefit Comparison

Costs and benefits were enumerated to study the net benefits of the CU flood control scenarios (Section 3.6) modeled for the six reservoir sites under a "strict management" arrangement. Benefits include reduction in expected annual flood damage and sale of new yield. Costs are associated with land acquisition, infrastructure construction for water conveyance, recharge, and extraction facilities, and operation and maintenance of those facilities. Procedures for valuing the costs and benefits are described below.

3.5.1 Methods to Compute Benefits

3.5.1.1 Flood Protection

In this study, reduction in expected annual flood damage was the primary benefit pursued from CU operations. The hypothesis is that CU operations create additional flood storage space in a reservoir, and this storage space can be used to mitigate downstream peak flows from extreme flood events. For each reservoir, the flood protection benefit can be computed as the difference in expected annual flood damage (EAD) resulting from the reservoir operating with (i) existing flood storage space (control case), and (ii) the existing plus the extra flood storage space created from CU operations (CU case). This computation was not done due to budget and time constraints, and the need for extensive dynamic routing of multiple flood events. However, the procedure is described here for future study. The difference in EAD is computed in five steps, which are:

1) *Determine the volume of additional reservoir flood storage space that is made available each year by CU operations.* Interactive water transfer modeling described in Section 3.3 is used to determine a feasible size of the CU pool at each reservoir.

2) *Derive the CU flood frequency curve (FFC) for points downstream of the reservoir using the volume of additional reservoir storage space created by CU operations.* A flood frequency curve is a representation of the probability distribution of flood peaks for a river location, plotted as peak flow vs probability of exceedance. Using the existing unregulated FFC for the reservoir inflow, seven synthetic flood events ranging in annual exceedance probability from 0.5 (50%) through 0.002 (0.2%) are routed through the reservoir operating with both Flood and CU pools. Flood routing uses the HEC-5 reservoir simulation model developed by the Sacramento District and follows the District's methods. HEC-5 runs return a time-series of CU reservoir releases for each synthetic flood event using the additional protection provided by the CU pool. Post-processing of the release hydrographs identifies the peak value of CU releases. Maximum CU releases are plotted versus their respective probability of exceedance to produce the CU regulated FFC.

3) *Derive the control FFC.* Step #2 is repeated routing storms through the reservoir operating with just the normal Flood Pool (i.e., without the CU pool).

4) *Determine water stage levels for all points within the watershed downstream of the reservoir based on event flood release hydrographs*. UNET models developed by the Sacramento

District are used to dynamically route the HEC-5 reservoir outflow hydrograph resulting from each synthetic flood event through all points in the watershed downstream of the reservoir. Dynamic routing is used because the reservoir outflows change through time as a flood event transpires. UNET output is a stage hydrograph for each downstream location of interest. The peak stage associated with each of the seven synthetic flood events becomes a point on the stage frequency curve. A separate UNET model run is made for each synthetic flood event and reservoir, operating in first the control and second the CU flood-storage mode.

5) *Compute the difference in expected annual flood damage (EAD) between the CU and control cases.* EAD is the dollar value of expected (average) annual damages. Flood damage computations are made with Sacramento District FDA models using exceedance probability versus stage and stage versus damage relationships. The stage-damage curve is a representation of the structures in the floodplain, specific to the watershed and independent of the storage space existing in the reservoir. EAD is calculated by combining the probability-stage and stage-damage curves into a composite likelihood versus damage curve and integrating damages over all probabilities to obtain the expected annual flood damage. The CU EAD is based on the CU stage frequency curve constructed from UNET output using HEC5 reservoir release hydrographs. The control EAD is based on control stage frequency curve constructed from UNET output using control reservoir release hydrographs. The difference between the control and CU EADs is the dollar value of the reduction in annual expected flood damage resulting from CU operations.

Steps #4 and 5 were not completed in this study. There was not sufficient time or budget to perform 168 UNET model runs spanning two operating strategies, seven flood events, and 6 storm-centerings and 2 basins (7*2*6 runs for each basin). Instead, feasible CU Pool volume was determined for each reservoir, and FFCs from altered and control cases were computed and then compared.

3.5.1.2 New Yield

New yield is water captured in the CU pool or aquifer that the reservoir would otherwise lose if CU management was not in place. In this study, new yield was considered a secondary benefit and could be sold on the spot market during the year following its capture.

New yield is generated in years with enough spring runoff to refill the Conservation Pool *and* some of the CU pool after the flood season, and in years that high winter flows can be transferred to aquifers. New yield captured in the CU pool (i.e., after the normal Conservation Pool has filled) serves to reduce the “debt” the aquifer owes to the reservoir. In the water transfer model, the volume of yield captured each year is calculated through interactive simulation of reservoir operations and CU transfers given agricultural demands, reservoir inflows, and available storage space in aquifer(s). The first portion of the yield captured (up to 15% of the volume of the CU Pool Transfer) is neither valued nor available for sale as it is used to offset loss from storage of water in the aquifer [NHI, 1998].

3.5.2 Methods to Compute Costs

3.5.2.1 Land Acquisition

CU capacities and flows can be guaranteed only when the CU management authority owns the land. Because of this need, CU operations modeled in this study assume a "strict management" arrangement, requiring land to situate percolation basins that recharge water to groundwater aquifers. Land purchase price and transaction fees are the significant costs associated with land acquisition. However, land rental price would be a more appropriate estimate of cost if contractual or easement arrangements were used to acquire water recharge rights (i.e., for flooding fallow fields or rangelands).

Agricultural land prices ($/acre) for each county in the Central Valley were researched by the Sacramento District's Real Estate division. The division developed low and high purchase price values for all types of agricultural land. Only Rangeland and Irrigated Field Crops type land were considered for purchase in the study.

3.5.2.2 Conveyance

Infrastructure costs include all costs associated with building conveyance structures, recharge and extraction facilities (wells), excluding land acquisition costs (see section 3.5.2.1 above). Conveyance costs are for gravity-flow canal diversions that transfer CU pool and winter flow water from the river turnout to the aquifer site, and extracted groundwater from the aquifer site back to the river. In some cases, conveyance structures might include equipment to pump transferred water uphill toward the aquifer site. Conveyance costs include canal construction (excavation) and property purchases to secure right-of-way.

For each aquifer site, elevation and UTM coordinates were located on a 7.5-minute USGS map using a web-based topographic map search engine (www.topozone.com). The nearest, up-gradient river turnout, canal, or lateral structure was identified by visual inspection of the topographic map. Elevation and UTM coordinates for the turnout were also identified; the distance and elevation differential between the turnout and aquifer site, and the longitudinal slope between them, were calculated. A canal capacity for each section of conveyance was selected using procedures described below. The required width and depth of a rectangular canal were estimated using that capacity and the computed longitudinal slope. The canal construction cost was estimated by multiplying the canal length and the unit cost of canal excavation ($\$24/yd^3$).

Anticipated flows (canal capacity) for conveyance from the aquifer site to the river return were based on the maximum aquifer extraction rate. Because extraction is the limiting factor in artificial recharge and recovery, aquifer extraction is often at the maximum rate.

Anticipated flows (canal capacity) for conveyance from the river turnout to the aquifer site are less certain. This capacity could equal the maximum aquifer recharge rate, or might be limited to a lower value to reduce the cost of canal construction. Lower canal capacity would be sufficient to perform the normal CU Pool transfer. However, higher canal capacity might be desired to more quickly transfer CU pool water (in dry years when the CU pool transfer is delayed until the

winter), excess flows, or winter floods captured in the CU pool. Amounts depend on the extent that CU operations are expanded from a focus on flood control towards gaining new yield.

To evaluate sensitivity to the varied canal capacities required for conveyance from the river turnout to aquifer site, two canal capacity values were considered. The lower capacity value was the flow required for normal Fall-season drawdown of the CU pool. The higher capacity value was the maximum recharge rate of the aquifer recharge basin.

Right-of-way land purchase costs were figured using the canal width, average land cost for the aquifer site (section 3.5.2.1), and the length of the conveyance structure. In figuring the right of way land purchase, canal widths were doubled to provide adequate buffering on each side of the canal.

3.5.2.3 Recharge Facilities

Recharge facilities are the percolation basins built at the aquifer sites to allow water storage. Acquisition of the required land was discussed previously (Section 3.5.2.1). The costs associated with building the recharge and extraction facilities themselves were not approximated.

3.5.2.4 Extraction Facilities

Extraction facilities are the wells installed in the recharge basins to allow retrieval of stored water. Extraction facility construction costs are assumed to be $3,000,000 per 15 wells [Fenske, HEC]. Extraction facilities require a well density of no more than 75 wells per 4 mi^2 to maintain extraction rates of approximately 1,000 gpm per well. Therefore, the unit-area extraction facility construction cost is $3.75 million/$mi^2$ and final cost of extraction facility construction will depend on the extraction well field size inside each aquifer site.

3.5.2.5 Operation and Maintenance

Operation and Maintenance cost estimates are for the extraction system and include electrical operational and mechanical maintenance costs. Cost estimates were developed using the following assumptions:

1. Pumping well has a screened depth approx. 50 ft below ground surface
2. Wells pump at a constant rate of 1,000 gpm for 3 months out of the year.
3. Electrical costs - $15,000 per year (3 month pumping period), or approx. $150/day
4. For a well field consisting of 75 wells pumping at 1,000 gpm, the total electrical cost would be $11,250/day. Or $1 in electrical cost would pump about 10,000 gallons.
5. Mechanical maintenance O&M will run $500,000/yr.

3.6 Sensitivity Analysis

Sensitivity analysis was made to determine the sensitivity of Water Transfer Model outputs and results—such as CU Pool Sizes, New Yields, and Project Costs—to variations in CU project infrastructure. Recharge basin size and conveyance capacity from the river turnout to the aquifer site were two design variables that were varied between low and high values to represent 4 configurations (scenarios) of infrastructure development (see Table 3-9). Conveyance capacity

from the aquifer site to the river return was *not* a parameter varied in the sensitivity analysis; river return conveyance capacity was set equal to maximum aquifer extraction rate in each scenario.

Table 3-9. Water Transfer Model Scenarios

Scenario	Recharge Basin Size	Conveyance Facility Flow Capacity
1. Maximum Infrastructure	Full	Maximum Aquifer Recharge Rate
2. Reduced Recharge Basin Area	Half	Maximum Aquifer Recharge Rate
3. Reduced Canal Capacity	Full	CU Pool Transfer Rate (smaller)
4. Minimum Infrastructure	Half	CU Pool Transfer Rate (smaller)

Scenario 1 represented the maximum level of infrastructure at all aquifer sites. "Full-sized" recharge basins were used and river to-aquifer conveyance capacity was set equal to the maximum rates of aquifer recharge (see values in Table 3-3). This maximum level of infrastructure represents the most expensive project alternative considered in the study and is the scenario expected to produce the largest possible flood protection benefits.

In Scenario 2, recharge basin areas were reduced to half the basin area used in Scenario 1. River-to-aquifer conveyance capacity was left unchanged from the values used in Scenario 1. By varying just the recharge basin size, the Reduced Recharge Basin scenario indicated the sensitivity of results to aggregate changes in the effective aquifer storage, recharge, and extraction capacities, which will affect the CU Pool volume that can be transferred to aquifer storage.

In Scenario 3, river-to-aquifer conveyance capacity was reduced to $^{1}/_{3}$ greater than the transfer rate required to move CU Pool volumes from the reservoir into the aquifer over a circa 18 week period. Recharge basin areas were the basin areas used in the maximum infrastructure scenario. By design, values of reduced conveyance capacity were selected so that they did *not* further constrain the size of CU Pool transfers computed in the maximum infrastructure scenario. Only Excess Flow transfers were limited. Based on these choices, Scenario 3 afforded the opportunity to independently investigate the sensitivity of New Yield to the level of infrastructure without impacting the level of additional guaranteed flood protection.

Scenario 4 represented the minimum level of CU infrastructure investigated in the sensitivity analysis. Half-sized recharge basins were used (as in Scenario 2) coupled with reduced conveyance capacity (as in Scenario 3). The Minimal Infrastructure scenario represented the least-expensive project alternative investigated in the study and is expected to generate the smallest amount of additional flood protection and new yield.

4 Results

Additional flood storage space (CU Pool sizes) and the new yield generated from modeling 4 scenarios of CU infrastructure are summarized for each reservoir sub-basin in Table 4-1. These values will be addressed in detail in this chapter.

As a first step in the modeling analysis, limits on CU Pool Transfer were calculated using groundwater aquifer parameter values. These limits are presented in Section 4-1. Raw outputs from the transfer model are described in Section 4.2 and include explanations for how the sizes of CU Pool Transfers were determined. CU Pool Transfers correspond to the CU Pool volume and represent the additional storage space created in each reservoir from CU operations (Section 4.3). Flood frequency curves and the flood protection provided by CU Pool storage space are contained in Section 4.4. Section 4.5 presents new yield generated under each of the 4 CU infrastructure scenarios.

Land purchase, conveyance structure, extraction and recharge facility, and operation and maintenance costs for the Maximum and Minimum Infrastructure scenarios are discussed in Section 4.6. Results from detailed groundwater modeling can be found in Chapter 5.

Table 4-1. Additional Flood Storage and Yield Created from Conjunctive Use

Reservoir	Normal Flood Pool (10^3 ac-ft)	Additional CU Pool		Volume of New Yield			
		Scenario 1,3 (10^3 ac-ft)	Scenario 2,4 (10^3 ac-ft)	Scenario 1 (10^3 ac-ft)	Scenario 2 (10^3 ac-ft)	Scenario 3 (10^3 ac-ft)	Scenario 4 (10^3 ac-ft)
Sacramento Basin							
Oroville	480	138	100	148	74	148	58
New Bullards Bar	170	120	73	120	59	131	55
Folsom	451	142	85	211	133	178	127
San Joaquin Basin							
Don Pedro	340	124	61	160	109	124	100
McClure / New Exch	350	98	64	92	60	49	45
Millerton / Friant	171	121	120	322	247	250	240

4.1 Limits to Conjunctive Use Transfer

Limits on the CU transfers were investigated to generate a basis for user-decisions used in the water transfer modeling. As discussed in Section 3.2, conservation pool size, aquifer storage capacity, maximum aquifer recharge rate, and maximum aquifer extraction rate are four factors that constrain the volume of the CU pool transfer. Aquifer storage capacity, maximum aquifer recharge rate, and maximum aquifer extraction rate factors are aquifer-specific. For each reservoir, the reservoir size constraint was compared against the sum of the constraining values for aquifer-related factors considering only the aquifers accessible from the reservoir.

Analysis of the constraint values at each aquifer site shows that the CU pool transfer from New Bullards Bar reservoir is constrained by just the storage capacities of all aquifers accessible from the reservoir. Transfers from Friant Dam are constrained by just the extraction rates of all

aquifers accessible from the reservoir (Table 4-2a). Transfers from Oroville, Folsom, Don Pedro, and New Exchequer Dams are constrained by a combination of storage capacities and extraction rates for the aquifers accessible from each reservoir. When half-sized recharge basins are considered at each aquifer site (Scenario 2), the same factors constrain CU Pool transfers into the aquifer site (Table 4-2b). Overall, CU Transfers are limited to between 116 KAF (New Exchequer Dam) and 255 KAF (Friant Dam) when considering full-sized recharge basins, and from 58 to 128 KAF when considering half-sized recharge basins.

4.2 Transfer Simulation Results

The interactive water transfer simulation described in Section 3.3 was used to model Conjunctive Use operations at Oroville, New Bullards Bar, Folsom, Don Pedro, New Exchequer, and Friant dams. The model was used to determine the storage space that could be created every year in each reservoir and the new yield developed over two 7-year simulation periods. Time-series results for Don Pedro Reservoir for the simulation period 1973 – 1979 (an illustrative example) are shown in Figure 4-1. Part A displays reservoir inflows and outflows (left axis), and reservoir Guide Curve and storage level (right axis.) Part B shows the storage volume in the three aquifer sites that are accessible from Don Pedro Reservoir. Part C displays flow rates for all CU transfers and *in-lieu* exchanges between the reservoir, aquifers, agricultural demand, and additional end users. Appendix A contains time-series results for Don Pedro Reservoir during the 2nd simulation period (1983 – 1989) and the remaining 5 reservoirs for both simulation periods.

Referring to Part A of Figure 4-1 representing reservoir operations, the CU storage pool is visible each winter as the space between the reservoir storage level and the low winter Guide Curve. Both types of CU transfer are visible in the graphic, the CU Pool transfer represented by the light blue line, and the winter flow transfer by the dark blue line. A CU Pool transfer was made in summer and fall of years 1, 2, 3, 6 and 7 to create the additional space but was not necessary in years 4 and 5 because the reservoir was already below the winter guide curve. However, the wet winter of year 5/6 made a delayed CU Pool transfer necessary.

The green line represents the agricultural delivery from the reservoir. (Total agricultural delivery can be seen in Part C for comparison.) Delivery in year 1 is made without the influence of conjunctive use, as no transfer was made in year 0. The reduced agricultural deliveries in other years display the aquifers' "payback" of CU deliveries by meeting some of the demand. Agricultural deliveries are uninterrupted in year 5 because no CU Pool transfer was made in year 4. Deliveries are uninterrupted in year 6 because the reservoir refilled completely, making payback of the relocated water unnecessary (i.e., changing that water from "owed" to new yield).

Part B of the graphic displays the storage level at each aquifer site accessible from the reservoir. For aquifers T and U, the pattern of fall and winter recharge (upward slope) coupled with summer extraction (downward slope) is visible in years 2, 3, 4, and 7. Extraction is less than recharge in years that temporal *In-Lieu* exchanges were used (Years 2, 3, 4, 7 for Aquifer U; Years 2 and 7 for aquifer T). In these cases *in-lieu* exchanges bypass the aquifers and deliver water directly to agriculture and sale, allowing water stored the previous year to remain in aquifer storage.

Table 4-2. Volume Constraints on CU Pool Transfers by Constraint Factor

Reservoir	Aquifer Site	A. Scenario 1: Full-Sized Recharge Basins — Constraint Factor: Conservation Pool Size (kaf)	Aquifer Storage (kaf)	Max Recharge *June-Oct* (kaf)	Max Extraction *Ag. Season* (kaf)	Limiting Aq. Constraint (kaf)	B. Scenario 2: Half-Sized Recharge Basins — Constraint Factor: Conservation Pool Size (kaf)	Aquifer Storage (kaf)	Max Recharge *June-Oct* (kaf)	Max Extraction *Ag. Season* (kaf)	Limiting Aq. Constraint (kaf)
Oroville	E		172	463	111	111		86	231	56	56
	G		2	93	28	2		2	46	14	2
	I		30	93	111	30		15	93	56	15
	F		25	463	111	25		13	231	111	13
	N		33	463	111	33		16	231	56	16
	Reservoir Total:	***3058***	***263***	***1574***	***473***	***202***	***3058***	***132***	***833***	***292***	***102***
New Bullards Bar	K		53	93	58	53		26	46	29	26
	M		105	185	116	105		53	93	58	53
	Reservoir Total:	***790***	***158***	***278***	***174***	***158***	***790***	***79***	***139***	***87***	***79***
Folsom	P		215	139	77	77		107	69	38	38
	O		115	93	102	93		58	46	51	46
	Reservoir Total:	***500***	***330***	***231***	***179***	***169***	***500***	***165***	***116***	***89***	***85***
Don Pedro	S		11	185	60	11		6	93	30	6
	T		145	231	60	60		72	116	30	30
	U		378	231	60	60		189	116	30	30
	Reservoir Total:	***1690***	***534***	***648***	***181***	***132***	***1690***	***267***	***324***	***90***	***66***
McClure	U'		756	463	125	125		378	231	63	63
	Reservoir Total:	***675***	***756***	***463***	***125***	***125***	***675***	***378***	***231***	***63***	***63***
Friant Dam	X		358	208	51	51		179	104	26	26
	Y		143	162	51	51		72	81	26	26
	Z		261	231	51	51		131	116	26	26
	AA		606	231	51	51		303	116	26	26
	BB		413	231	51	51		206	116	26	26
	Reservoir Total:	***350***	***1782***	***1064***	***255***	***255***	***350***	***891***	***532***	***128***	***128***

Part C of the graphic displays water transfers to agriculture and aquifer storage, and sale of new yield. Often, the CU transfer is made as an *In-lieu* exchange (yellow line, hidden by blue or green lines). In these cases, water is delivered directly to agriculture or sale and bypasses the aquifer. Results of CU operations at Don Pedro Reservoir also show that the "aquifer to agricultural demand" transfer (orange line) is less than half the total agricultural demand (dark blue line). A similar result is likewise seen for all the other reservoirs/aquifer systems (Appendix A), and is consistent with the assumption of demand distribution within the river basin—at least half of the agricultural demand is located downstream of aquifer sites.

4.3 Additional flood storage space created in each reservoir

Interactive water transfer modeling was performed with the goal of determining how large a CU Pool (for additional flood storage) could be created every year in each reservoir by relocating water to aquifer storage. For full-sized recharge basins (Scenarios 1 & 3), CU operations that focused on flood protection were able to secure between 98 KAF (New Exchequer) and 142 KAF (Folsom) of additional *guaranteed* flood protection space, representing 28% (New Exchquer) to 71% (Friant Dam) increases in flood storage over existing flood pools (Table 4-3).

Table 4-3. Additional Flood Storage Space from CU Operations

Reservoir	Flood Pool Size (10^3 ac-ft)	Size of CU Pool		% Increase in Flood Storage		Reservoir Storage Capacity (10^3 ac-ft)
		Scenario 1, 3 Full Recharge (10^3 ac-ft)	Scenario 2, 4 1/2 Recharge (10^3 ac-ft)	Scenario 1, 3 Full Recharge (10^3 ac-ft)	Scenario 2, 4 1/2 Recharge (10^3 ac-ft)	
Sacramento Basin						
Oroville	480	138	100	29%	21%	3538
New Bullards Bar	170	120	73	71%	43%	960
Folsom	451	142	85	31%	19%	978
San Joaquin Basin						
Don Pedro	340	124	61	36%	18%	2030
McClure / New Exch	350	98	64	28%	18%	1025
Millerton / Friant	171	121	120	71%	70%	521

These volumes were within the constraints on CU Pool transfer volume discussed in Section 4.1, and guaranteed that all CU Pool transfer water stored in aquifers could be retrieved the following year for delivery to agricultural demand or sale as new yield.

When recharge basin sizes were reduced by half (Scenarios 2 & 4), CU Pool sizes decreased up to 50% compared to the Full-Basin scenario. This decrease was due to decreased storage capacity and ability to extract stored water represented by the smaller project area. Notably at Friant Dam, CU Pool sizes were insensitive to the reduced recharge basin size, and indicate that aquifer recharge capacity is not a limiting constraint.

Flood storage space results for scenarios 1 & 3 and scenarios 2 & 4 were identical because the reduced conveyance capacity values for scenarios 3 & 4 were chosen so that flood storage space created in the full recharge basin scenarios could be maintained.

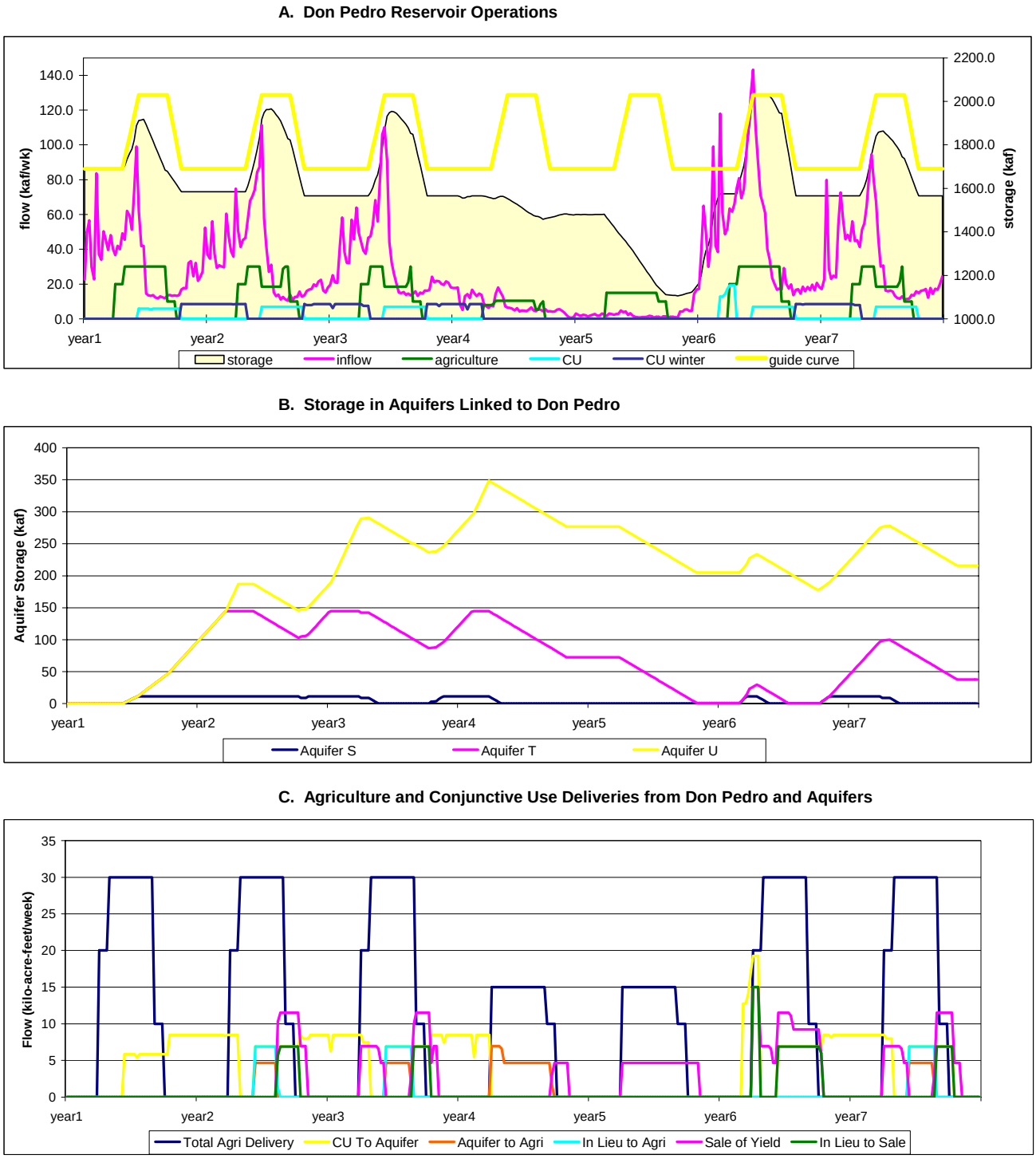


Figure 4-1. Transfer Model Simulation Results for Don Pedro Reservoir, 1973-1979

4.4 Flood protection

Methodology for determining the flood protection benefits provided by Conjunctive Use operations is described in section 3.6.1.1. Using the Sacramento District Water Control Section's HEC-5 reservoir routing models, reservoir releases at the 6 reservoirs being studied and river flows at 7 downstream points within the Sacramento and San Joaquin River basins were simulated for synthetic flood events corresponding to 0.5, 0.1, 0.04, 0.02, 0.01, 0.005, 0.002 (50%, 10%, 4%, 2%, 1%, 0.5% and 0.2%) exceedance probability. Peak releases and flows were calculated for normal reservoir operations (without CU), and Type 1 and Type 2 CU reservoir operations.

Figure 4-2 contains flood frequency curves (FFC) that compare peak values of inflow (unregulated FFC, black line), normal reservoir release without CU (regulated FFC, blue line), and total reservoir release with CU Type 1 operations (solid red line) at Don Pedro Reservoir. Total reservoir releases include water released as part of the CU Excess Flow Transfer since the river immediately downstream of the reservoir is also used to convey CU transfers. River flow following diversion of the CU Transfer to the aquifer (dotted red line) is less than the total release.

From the arrangement of FFCs in Figure 4-2, CU operations reduce peak values of streamflow downstream of Don Pedro Reservoir after diversion of Excess Flow Transfers to the aquifer for the complete range of flood events. For example with the 1% chance exceedance flood event, peak flow is reduced from 80,000 cfs to 42,000 cfs. The CU FFC and normal operations FFC coincide at 9,000 cfs for flood events with exceedance probability between 4 and 10%; for these smaller magnitude flood events, CU operations have minimal additional benefit because normal reservoir operations can safely manage them.

Figure 4-3 compares Don Pedro Reservoir FFCs for Type 1 (red line), Type 2 (green line) operations, and normal reservoir release without CU (blue line). The Type 2 operations FFC is above the Type 1 FFC and demonstrates that Type 2 operations are less suited to handle larger (lower exceedance probability) flood events than Type 1 operations. This disadvantage occurs because Type 2 operation allows the CU Pool to fill in the weeks prior to a flood event. Filling preserves the captured water as new yield but decreases guaranteed flood protection space and so decreases the flood protection provided. However, the Type 2 FFC is below the normal reservoir release FFC, indicating that type 2 operations do provide additional flood protection.

FFCs for other reservoirs and downstream river basin observation sites are included in Appendix B.

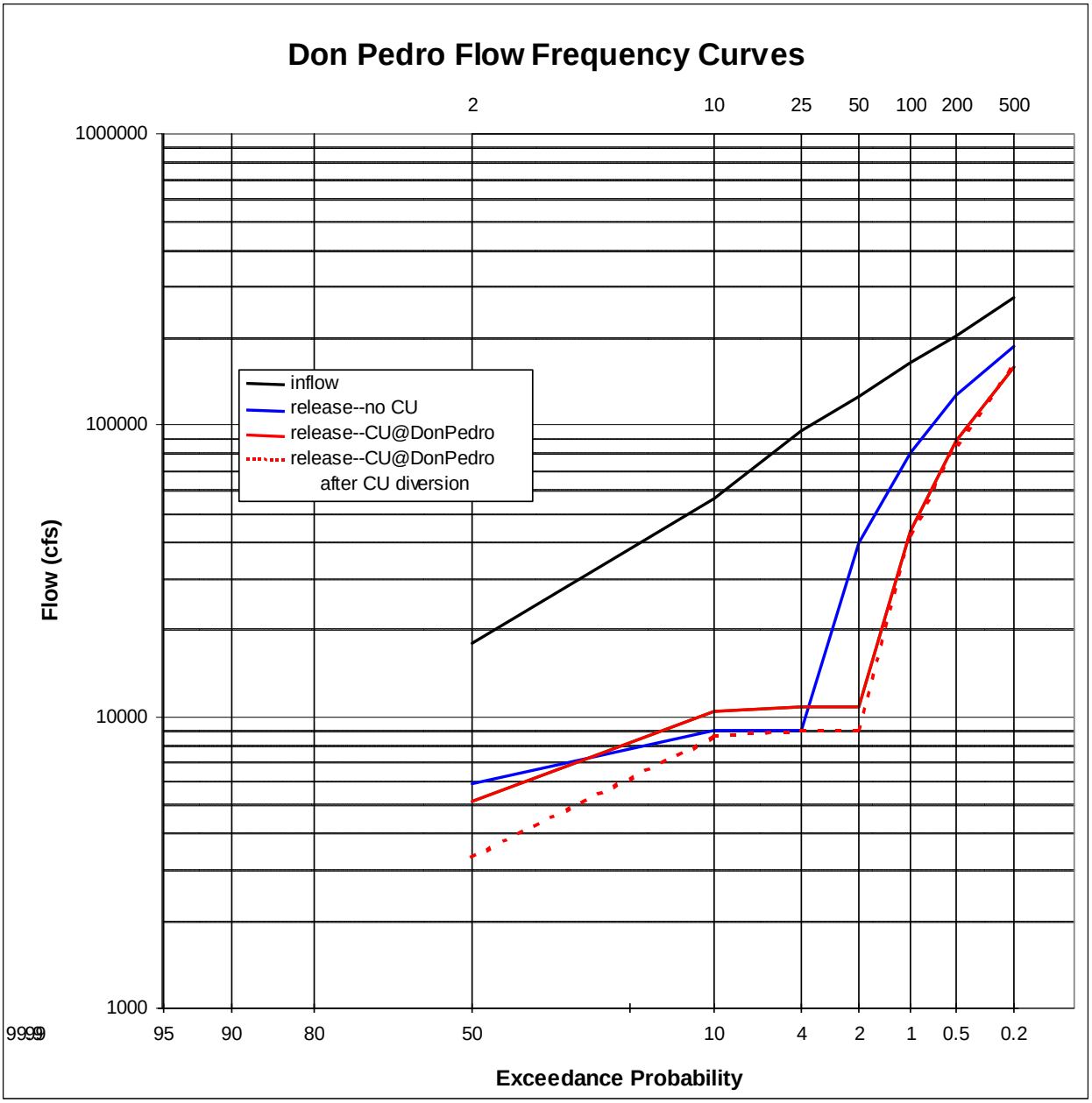


Figure 4-2. Don Pedro Frequency Curves, Unregulated, Regulated, Regulated w/CU

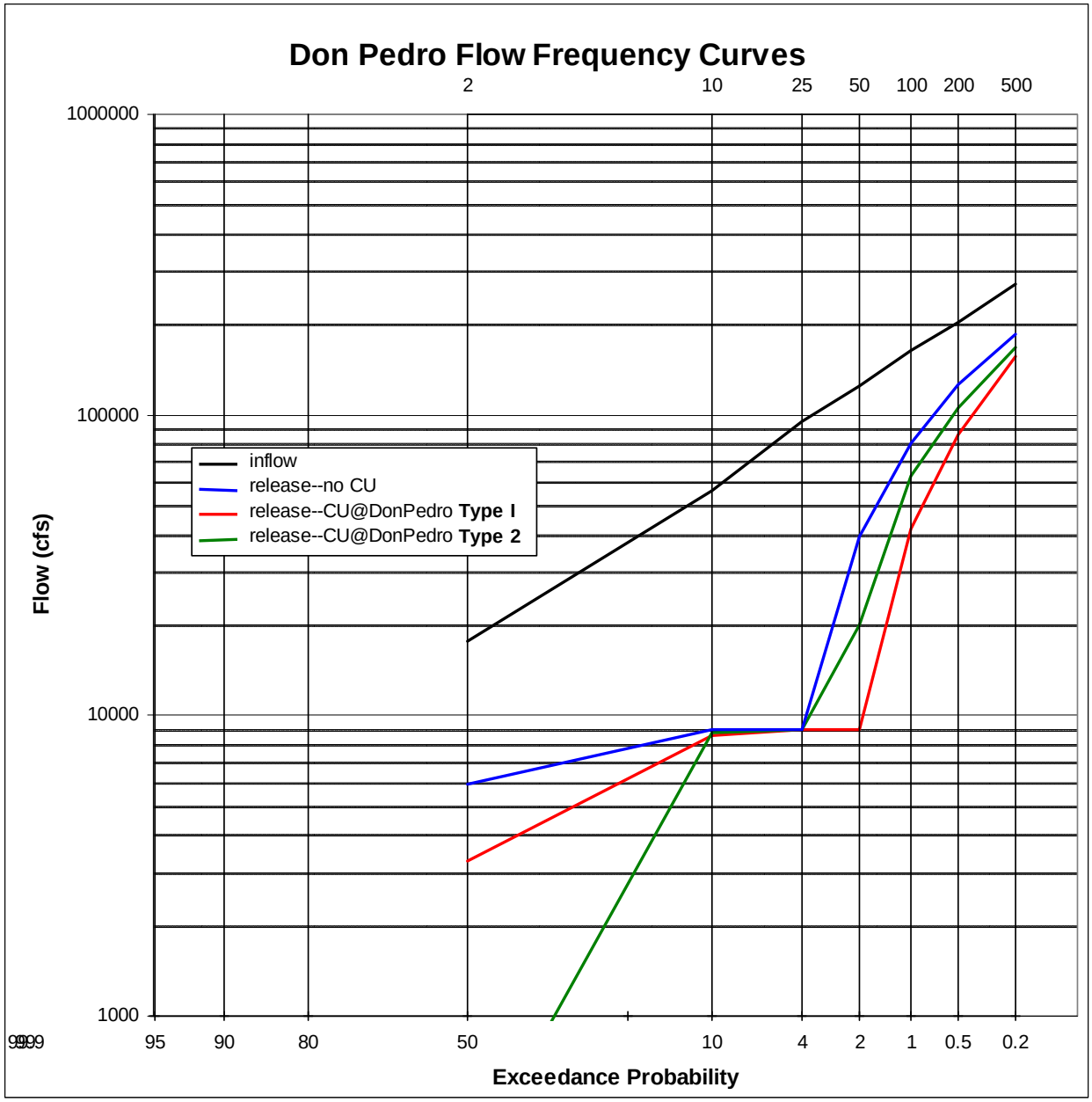


Figure 4-3. Don Pedro Flow Frequency Curves, Type 1 vs Type 2 Conjunctive Use Operations

4.5 Average annual new yield

New Yields were generated for each of the four Conjunctive Use infrastructure scenarios and are summarized in Table 4-4. Even with flood protection as the primary operations priority (Type 1 operations), some level of new yield was always achieved with Conjunctive Use operations. Yield was attained by (1) transferring excess winter flow to aquifer storage and (2) refilling the CU Pool after the flood season with spring runoff.

The water transfer modeling attempted to maximize new yield while maintaining flood protection as the first priority. New yield was calculated for each year in the two 7-year simulation periods and averaged. In modeling the water transfers, new yield was extracted each year and sold to maintain storage volume in the aquifer sites.

As expected, the maximum infrastructure scenario (Scenario 1) generated the largest amount of yield in both the Sacramento and San Joaquin Basins. Scenario 2 generated smaller amounts of yield because halving the size of the recharge basins reduced both the aquifer storage capacity and recharge and extraction rates. These reductions limited both the rate and total volume of Excess Flow transfers from each reservoir. With reduced conveyance capacity (Scenario 3), yields in the San Joaquin Basin were also reduced because Excess Flow transfers to the aquifer sites were constrained. Surprisingly, yields in the Sacramento basin were not significantly altered by the reduction in conveyance capacity. This result suggests that aquifer storage capacity—rather than the aquifer recharge rate—limits aquifer storage in the Sacramento basin and is confirmed by decreased incidence of overdraft in Sacramento Basin aquifers. Inspection of time-series results from Scenario 3 showed that the reduction in conveyance capacity (and corresponding Excess Flow transfers) delayed filling of Sacramento Basin aquifers until later in the winter. Of all the scenarios, Scenario 4 generated the smallest amounts of yields. Yield is more sensitive to recharge basin size than conveyance capacity.

Table 4-4. Average New Yield Resulting from Conjunctive Use Operations

Reservoir	Reservoir Storage Capacity (10^3 ac-ft)	Volume of New Yield			
		Scenario 1 Max. Infrastruct. (10^3 ac-ft)	Scenario 2 Red. Recharge (10^3 ac-ft)	Scenario 3 Red. Conveyance (10^3 ac-ft)	Scenario 4 Min. Infrastruct. (10^3 ac-ft)
Sacramento Basin					
Oroville	3538	148	74	148	58
New Bullards Bar	960	120	59	131	55
Folsom	978	211	133	178	127
Basin Total		***478***	***266***	***457***	***239***
San Joaquin Basin					
Don Pedro	2030	160	109	124	100
McClure / New Exch	1025	92	60	49	45
Millerton / Friant	521	322	247	250	240
Basin Total		***573***	***415***	***422***	***384***

4.6 Costs

Costs for land acquisition, construction of conveyance structures, recharge basins, and extraction facilities, and operation and maintenance at each aquifer site are grouped by aquifer site for the Maximum Infrastructure scenario (Table 4-5a) and Minimal Infrastructure scenario (Table 4-5b). Aquifers are grouped by reservoir subbasin and costs associated with aquifers shared between reservoirs were assigned to the reservoir with first priority for use of the aquifer storage site. Aquifer site U' is used to denote a separate recharge basin placed at aquifer site U. Aquifer U' has groundwater parameter values identical to aquifer U, but its groundwater storage space is

reserved exclusively for water transfers from New Exchequer Dam / Merced River. Explanations for each of the cost calculations follow.

4.6.1 Land Acquisition

The estimated cost of land purchases for all aquifer sites is $120 million for Scenario 1 and $60 million for Scenario 2. As described in section 3.5.2.1, land acquisition costs at each aquifer site were computed by multiplying the average land price by the required project area. Real estate prices for several types of agricultural lands were collected by the Sacramento District's Real Estate division (Tables C-1a through C-1g in Appendix C). Only the lowest-valued "Rangeland" and "Irrigated Field Crops" types of agricultural land were considered for purchase in this study. The average land purchase price ($/acre) for each aquifer site was computed by (i) averaging the high and low values for the each type of agricultural land, and (ii) assuming that $^2/_3$ of land acquisitions would come from agricultural "Rangeland" and $^1/_3$ from "Irrigated Field Crops" (Table C-2 in Appendix C).

4.6.2 Conveyance Structures

As described in section 3.5.2.2, conveyance costs were computed for the excavation and right-of-way acquisition associated with diverting water from the river turnout to the aquifer site and returning water from the aquifer site to the river using gravity flow canals. Costs were computed for two levels of flow capacity from the river turnout to the aquifer site: (i) $150 million for a low capacity where flow capacity was limited to $^1/_3$ more than the rate needed to make the CU Pool transfer (Table C-3a in Appendix C), and (ii) $270 million for a high capacity where flow capacity was set equal to the maximum aquifer recharge rate (Table C-3b). Securing right of way access through land purchases amounted to between 0.5 and 0.8% of the total conveyance construction cost.

4.6.3 Extraction Facilities

Based on a unit area cost of $3.75 million per mi^2 of the extraction area (section 3.5.2.4), extraction facility construction costs at each aquifer site range from $7.5 million to $30 million. For the Maximum Infrastructure Scenario, total extraction facility construction costs at all aquifer sites is estimated to be $380 million. This cost is reduced to $190 million for the Minimal Infrastructure Scenario.

4.6.4 Recharge Facilities

Costs for recharge facilities were not estimated for the present study.

4.6.5 Operation and Maintenance

Operation and maintenance costs are constant across aquifer sites. Based on the assumptions outlined in section 3.5.2.5, costs at each site are $15,000/year for 3 months of electricity to run extraction pumping and $500,000/year for mechanical maintenance on the well field. These amount to a total O&M cost of $9.3 million/year for the 18 aquifer sites.

Table 4-5. CU Project Cost for Aquifer Sites by Cost Category

A. Scenario 1: Maximum Infrastructure (Full Recharge Basin, High Conveyance Capacity)

Reservoir	Priority	Index	Aquife Site Name	Project Size (mi^2)	Land Purchase Price ($)	High Conveyance Cost ($)	Extraction Facillity Construction ($)	Recharge Facility Construction ($)	Total Capital Cost ($)	Annual O&M Cost ($/yr)
Oroville	1	E	chico fan	8	5,600,000	86,000,000	30,000,000		120,000,000	520,000
	1	F	Butte Creek	8	5,600,000	30,000,000	30,000,000		66,000,000	520,000
	1	G	Feather River	2	1,400,000	7,400,000	7,500,000		16,000,000	520,000
	1	I	Yuba City	8	14,000,000	3,800,000	30,000,000		48,000,000	520,000
	2	M	American Basin	8	0	0	0		0	0
	1	N	Cache Creek Drainage	8	6,800,000	14,000,000	30,000,000		51,000,000	520,000
	3	O	South-Fork	8	0	0	0		0	0
				Reservoir Subtotal	*33,000,000*	*140,000,000*	*130,000,000*	*0*	*300,000,000*	*2,600,000*
New Bullards Bar	1	K	Best Slough	4	6,900,000	110,000	15,000,000		22,000,000	520,000
	1	M	American Basin	8	14,000,000	3,600,000	30,000,000		47,000,000	520,000
	2	N	Cache Creek Drainage	8	0	0	0		0	0
	2	O	South-Fork	8	0	0	0		0	0
				Reservoir Subtotal	*21,000,000*	*3,700,000*	*45,000,000*	*0*	*69,000,000*	*1,000,000*
Folsom	1	O	South-Fork	8	6,800,000	15,000,000	30,000,000		52,000,000	520,000
	1	P	Elk Grove	6	10,000,000	11,000,000	23,000,000		43,000,000	520,000
				Reservoir Subtotal	*17,000,000*	*26,000,000*	*53,000,000*	*0*	*95,000,000*	*1,000,000*
Don Pedro	1	S	H&H Aqueduct	4	6,700,000	1,200,000	15,000,000		23,000,000	520,000
	1	T	Dry Creek	4	6,700,000	1,600,000	15,000,000		23,000,000	520,000
	1	U	Montpellier	4	6,700,000	5,300,000	15,000,000		27,000,000	520,000
				Reservoir Subtotal	*20,000,000*	*8,100,000*	*45,000,000*	*0*	*73,000,000*	*1,500,000*
New Exchequer	1	U'	Montpellier	8	13,000,000	26,000,000	30,000,000		69,000,000	520,000
				Reservoir Subtotal	*13,000,000*	*26,000,000*	*30,000,000*	*0*	*69,000,000*	*520,000*
Friant	1	X	Berenda Creek	4	3,100,000	13,000,000	15,000,000		31,000,000	520,000
	1	Y	Chowchilla By pass	4	3,100,000	790,000	15,000,000		19,000,000	520,000
	1	Z	Gravelly Ford	4	3,100,000	19,000,000	15,000,000		37,000,000	520,000
	1	AA	Little Dry Creek	4	3,100,000	790,000	15,000,000		19,000,000	520,000
	1	BB	James Bypass	4	1,800,000	37,000,000	15,000,000		53,000,000	520,000
				Reservoir Subtotal	*14,000,000*	*70,000,000*	*75,000,000*	*0*	*160,000,000*	*2,600,000*
GRAND TOTAL for all Reservoirs					120,000,000	280,000,000	380,000,000	0	770,000,000	9,300,000

Table 4-4 (Cont). CU Project Cost for Aquifer Sites by Cost Category

B. Scenario 4: Minimum Infrastructure Scenario (Reduced Recharge Basin Size, Reduced Conveyance Capacity)

Reservoir	Priority	Index	Aquife Site Name	Project Size (mi^2)	Land Purchase Price ($)	Low Conveyance Cost ($)	Extraction Facillity Construction ($)	Recharge Facility Construction ($)	Total Capital Cost ($)	Annual O&M Cost ($/yr)
Oroville	1	E	chico fan	4	2,800,000	42,000,000	15,000,000		60,000,000	520,000
	1	F	Butte Creek	4	2,800,000	11,000,000	15,000,000		29,000,000	520,000
	1	G	Feather River	2	1,400,000	5,300,000	7,500,000		14,000,000	520,000
	1	I	Yuba City	4	6,900,000	3,800,000	15,000,000		26,000,000	520,000
	2	M	American Basin	4	0	0	0		0	0
	1	N	Cache Creek Drainage	4	3,400,000	5,700,000	15,000,000		24,000,000	520,000
	3	O	South-Fork	4	0	0	0		0	0
				Reservoir Subtotal	*17,000,000*	*68,000,000*	*68,000,000*	*0*	*150,000,000*	*2,600,000*
New Bullards Bar	1	K	Best Slough	2	3,500,000	9,600,000	7,500,000		21,000,000	520,000
	1	M	American Basin	4	6,900,000	3,000,000	15,000,000		25,000,000	520,000
	2	N	Cache Creek Drainage	4	0	0	0		0	0
	2	O	South-Fork	4	0	0	0		0	0
				Reservoir Subtotal	*10,000,000*	*13,000,000*	*23,000,000*	*0*	*45,000,000*	*1,000,000*
Folsom	1	O	South-Fork	4	3,400,000	15,000,000	15,000,000		34,000,000	520,000
	1	P	Elk Grove	3	5,100,000	11,000,000	11,000,000		27,000,000	520,000
				Reservoir Subtotal	*8,500,000*	*26,000,000*	*26,000,000*	*0*	*61,000,000*	*1,000,000*
Don Pedro	1	S	H&H Aqueduct	2	3,400,000	1,100,000	7,500,000		12,000,000	520,000
	1	T	Dry Creek	2	3,400,000	1,000,000	7,500,000		12,000,000	520,000
	1	U	Montpellier	2	3,400,000	3,000,000	7,500,000		14,000,000	520,000
				Reservoir Subtotal	*10,000,000*	*5,100,000*	*23,000,000*	*0*	*38,000,000*	*1,500,000*
New Exchequer	1	U'	Montpellier	4	6,700,000	15,000,000	15,000,000		37,000,000	520,000
				Reservoir Subtotal	*6,700,000*	*15,000,000*	*15,000,000*	*0*	*37,000,000*	*520,000*
Friant	1	X	Berenda Creek	2	1,500,000	5,300,000	7,500,000		14,000,000	520,000
	1	Y	Chowchilla By pass	2	1,500,000	320,000	7,500,000		9,400,000	520,000
	1	Z	Gravelly Ford	2	1,500,000	8,000,000	7,500,000		17,000,000	520,000
	1	AA	Little Dry Creek	2	1,500,000	320,000	7,500,000		9,400,000	520,000
	1	BB	James Bypass	2	910,000	14,000,000	7,500,000		23,000,000	520,000
				Reservoir Subtotal	*7,100,000*	*28,000,000*	*38,000,000*	*0*	*73,000,000*	*2,600,000*
GRAND TOTAL for all Reservoirs					60,000,000	150,000,000	190,000,000	0	410,000,000	9,300,000

5 Groundwater Modeling

While a great deal of this study employed a simplified representation of groundwater physics in the simulation modeling, it was important to both verify some of the assumptions with more detailed groundwater modeling, and explore the value of groundwater simulation tools for further studies. This chapter describes groundwater simulation methods and the role they can play in planning Conjunctive Use activities.

5.1 Overview

The transient rise and fall of water levels resulting from a recharge event may result in a loss of water over time as recharged water flows away from the project area. The estimation of this loss of water can be quite complex, especially when multiple pumping wells are used in the recovery system and/or recharge rates vary with time. Computer models provide a tool for simulating the subsurface response to recharge and pumping events. For this study, a groundwater model was developed to simulate the operation of a CU recharge-recovery system and estimate the loss of recharged water. Parameters used in this groundwater model were representative of hydrogeologic conditions in the Central Valley.

5.2 Definition of "Lost" Water

For the purpose of this groundwater model, groundwater is "lost" from the recharge-recovery system when water flows outside the capture zone of the extraction (retrieval) pumping system and cannot be recovered under normal operation. Because subsurface hydrogeology is not always associated with surface features, the capture zone is not necessarily contiguous with (and in most cases is larger than) the physical, project property boundary. In other words, groundwater can flow outside the physical, project property boundary and still be recovered. This water should *not* be considered "lost" because it is still within the capture zone of the extraction system.

For the purpose of this model, normal pumping operations occur from June to September. Recharge occurs during a 6-month period from September to March.

5.3 Groundwater Model Construction

A simple groundwater model was constructed to simulate the stresses and responses that would occur in the operation of a CU floodwater storage and retrieval system. The parameters used in this model were consistent with parameter values in the Central Valley aquifer. The U.S. Geological Survey three-dimensional, finite-difference groundwater flow model MODFLOW was used for all analysis. The development of a groundwater model requires several steps that include grid construction, specification of aquifer parameters, and specification of boundary conditions.

<u>Grid Dimensions</u>
As depicted in Figure 1, a 40,000 ft x 40,000 ft grid was constructed from 160 rows and 160 columns. Cell sizes were specified to be 250 ft square. The size of the grid was based upon a

project area of approximately 4 mi^2 (10,000 ft by 10,000 ft). The model grid size was varied through an initial sensitivity analysis. The grid boundary was located far enough from the project area boundaries so that groundwater elevation changes at the boundary resulting from normal operations were insignificant. Cell size was varied from 1,000 ft square to 100 ft square. The 250 ft square cell was judged to best represent the stresses on the aquifer resulting from pumping. When smaller cell sizes were used, drawdown exceeded the layer thickness for cell containing a well.

Cell thickness was specified as 100 ft. This specification permitted simulating the drawdowns from pumping wells without any model cells going dry (i.e. drawdown exceeding the layer thickness) during model runs. The bottom of layer 1 was specified to be horizontal with an elevation of 0 ft. The starting water levels of layer 1 were specified to be horizontal (no flow gradient across the site) at an elevation of 100 ft.

Aquifer Parameters

The placement of a large volume of water on the water table (recharge) will result in an artificial mound. As time passes, the mound on the water table will subside as water flows down gradient. The specific yield (effective porosity) of the aquifer determines the rise in the water table resulting from a recharge event. The lower the specific yield, the greater this rise, and the greater the hydraulic flow gradient of the artificially created mound. The hydraulic conductivity of the aquifer governs how readily water will flow away from the recharge zone. In the simplified model, the hydraulic conductivity of the simulated aquifer was specified to be 60 ft/day. This is typical of sand aquifers found in the Central Valley. The effective porosity of the aquifer was specified to be 0.20.

Boundary Conditions

The project area was specified to be 10,000 ft by 10,000 ft. A total of 69 wells were distributed across the project area in a symmetrical manner (Figure 3-xx). Each well was specified to pump at a rate of approximately 1,150 gpm for a 90 day interval during each annual cycle. The total volume of water pumped was calculated to precisely equal the total volume of water recharged during the 180-day recharge period of each annual cycle. As depicted in Figure 2, recharge was distributed over approximately 70 % of the project area (8,759 ft by 8,759 ft). The recharge rate specified at .0972 ft/day for a 180-day interval. Head-dependent flux boundaries were located at edge of model grid to allow for flow across the model boundary. The boundary condition conductance value was calculated assuming a hydraulic conductivity of 60 ft/day. The value of specified head was 100 ft at a distance of 100,000 ft.

5.4 Determination of "Lost" Water

Loss was computed as the net volume of water that flows outside the pumping system capture zone (Figure 5-3). This zone was defined as the area outside the groundwater divide boundary. Inside the divide, groundwater flow direction is oriented towards the project area. Outside the boundary, groundwater flow is oriented away from the project area. For the water table elevation cross sections shown in Figure 5-3 (last stress period) and Figure 5-4, the divide boundary (lost water) is represented by the local maxi situated closest to the grid boundary.

Empirically, the groundwater divide was located on the model grid using water levels that were calculated following a specified number of annual cycles of recharge and withdrawals (operation period). Once the location of the groundwater divide was determined following a specified number of years of operation, the net flux was estimated by assigning a representative head-dependent flux boundary along the groundwater divide, and rerunning the model. The total flow across this boundary was then printed in the MODFLOW output file. The "total per cent loss" was calculated as "total loss" divided by "total recharge volume".

5.5 Groundwater Model Scenarios and Results

The model was run in the transient mode. Stress periods (SP) were specified to be 90 days in length. A total of 10 time steps were specified for each stress period. All simulations contained consistent stresses applied over an annual cycle beginning with Recharge:

- Recharge 180 days (2 SP)
- no stress 90 days (1 SP)
- Pumping 90 days (1 SP)

This annual cycle was repeated for periods of 1, 5, 10, and 50 years using the model with a symmetric pumping field (Figure 5-1). The total volume pumped was specified to be equal to the total volume recharged. Figure 5-3 presents the changes in water table elevations at 90-day intervals over a 1 year (360 day) period. Initially the water table is horizontal. It then rises as much as 70 ft as a result of recharge over a period of 180 days. During the 90 days of no stress, the peak water table falls to about 50 feet above initial conditions as water flows away from the project area. Water is then pumped for a period of 90 days. As depicted in Figure 5-3, a small amount of water remains outside the capture zone of the pumping system and is thus considered "lost". Water table elevations following 1, 3, 5, and 10 year operation periods are shown in Figure 5-4 (with the elevation scale exaggerated compared to the X-coordinate axis).

The total volume of lost water was calculated for each model run and divided into to the total volume recharged to the aquifer over the corresponding time period (Table 5-1).

Table 5-1. Volumes and Percentages of Lost Water for Operation Periods

Operation Period	Total Volume Recharged	Volume of "Lost" Water	% "Lost"
1 year	1.34×10^{9} ft^3	3.19×10^{7} ft^3	2.38
5 years	6.70×10^{9} ft^3	1.12×10^{8} ft^3	1.67
10 years	1.34×10^{10} ft^3	1.99×10^{8} ft^3	1.48

Volume and percentage of water loss after 10 years was also calculated for an additional scenario where the total volume of pumping was set to be 90% of the total volume recharged (Table 5-2). The well field distribution for this scenario was identical to the previous scenarios (Figure 5-1).

Table 5-2. Volume and Percentage Lost Water for 90% Extraction

Operation Period	Total Volume Recharged	Volume of "Lost" Water	% "Lost"
10 years	1.34×10^{10} ft^3	4.02×10^{8} ft^3	3.0

Losses were below 3% for both scenarios. To ensure a low loss rate, the system's extraction pumping capacity does not have to equal the recharge rate. In the 90% extraction case, hydrodynamical pumping (rather than quasi-mass balance) effectively contains the recharged water.

In a third scenario, a new well field distribution was simulated (Figure 5-5). The total volume pumped was specified to be equal to the total volume recharged. Percentage lost water for the reconfigured well field was comparable to previous scenarios (Table 5-3).

Table 5-3. Volume and Percentage Lost Water for Scenario 3 with New Well Field

Operation Period	Total Volume Recharged	Volume of "Lost" Water	% "Lost"
1 year	1.34×10^{9} ft^3	3.35×10^{7} ft^3	2.50
10 years	1.34×10^{10} ft^3	2.51×10^{8} ft^3	1.87

5.6 Conclusions and Future Applications

The Water Transfer Model portion of this study assumed losses were 15% when water was recharged to the aquifer and then later extracted. The results from the detailed groundwater model are much lower (< 3%) due to many assumptions that might not occur in real-field conditions. Most notably, the construction of a pumping system that has the capacity to hydrodynmaically contain a large percentage of water stored in the subsurface, and the assumption of a homogeneous aquifer.

The groundwater model demonstrated how to estimate the volume of water lost from CU recharge-recovery system operations. This simplified model can also be configured to represent much more complex situations, including:

- heterogeneous aquifers
- varying pumping and recharge rates,
- varying or non-contiguous placement of pumping and recharge, and
- separate, localized recharge basins.

Additionally, the groundwater model has broad potential for use in the design of CU facilities and development of operations procedures. Potential applications include:

- optimizing the configuration of the extraction well field to minimize lost water or maximize well yield efficiency

- optimizing pumping and recharge schedules to minimize construction costs, lost water or maximize well yield efficiency

The groundwater model serves as a model template with potential application for many future site- and project-specific situations. Pumping wells are depicted in red and are located to the extent of the project area border.

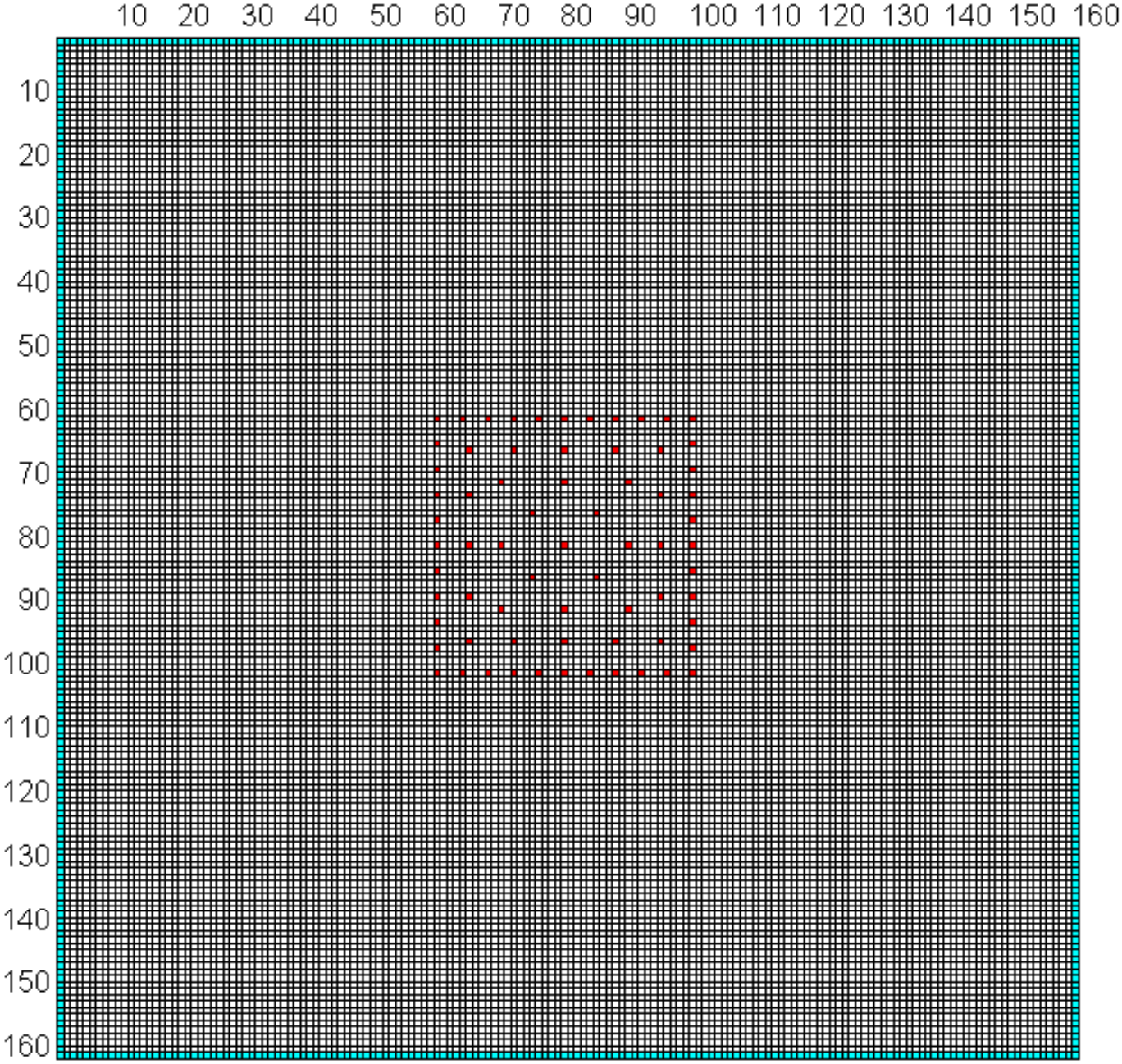


Figure 5-1 Initial model grid and Pumping Area

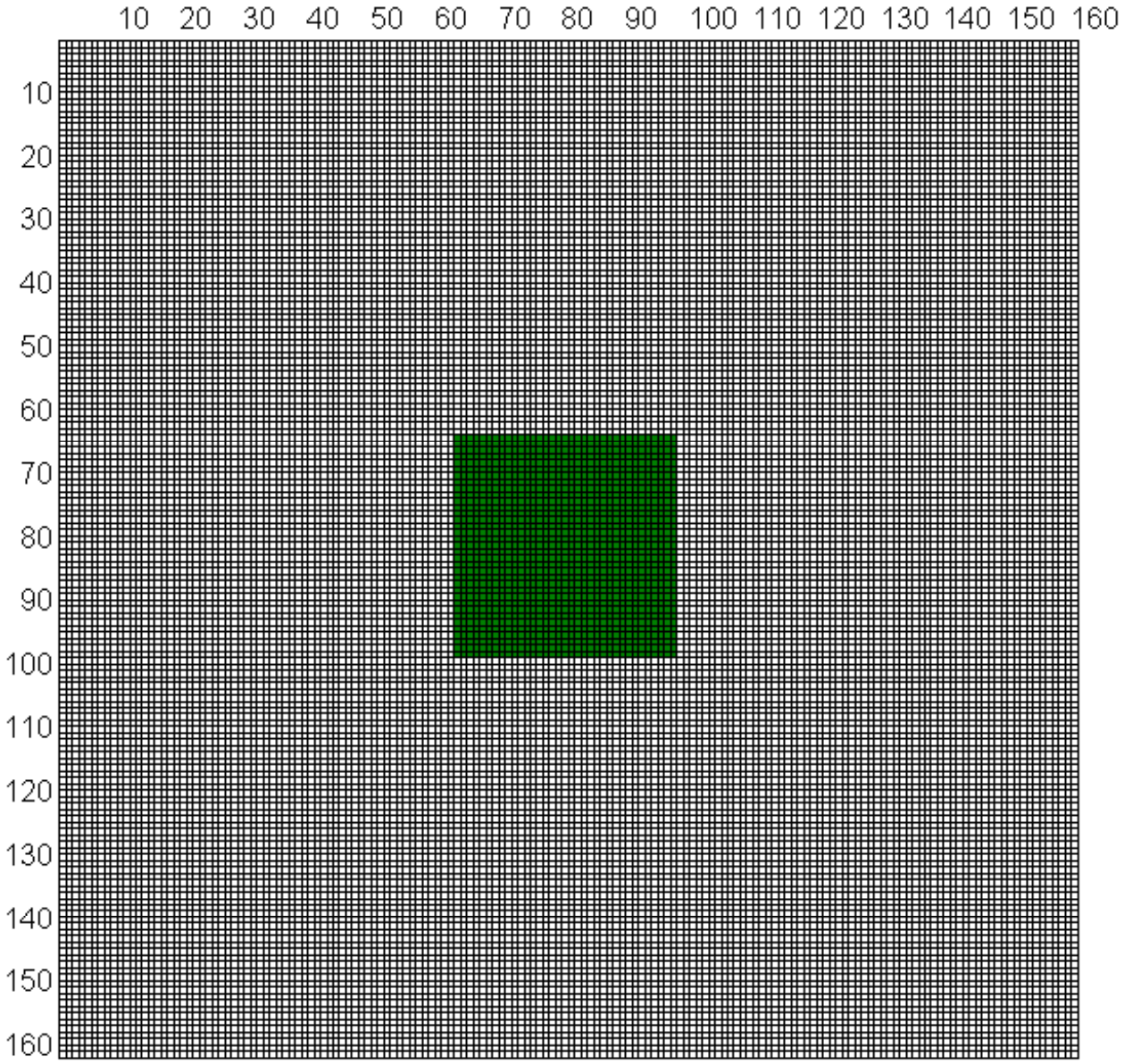


Figure 5-2. Initial Model Grid and Recharge Area

Area in green represents recharge area. Recharge is distributed homogeneously across this area at a constant rate.

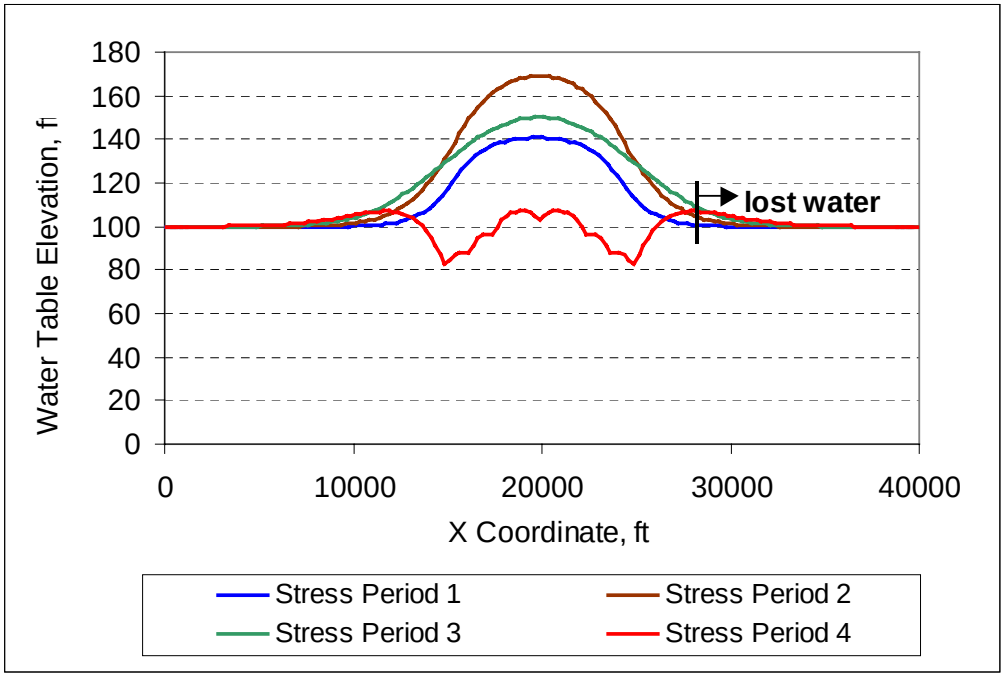


Figure 5-3. Changes in water table elevation during the first cycle (year).

Initially, the water table is horizontal. Recharge occurs during periods 1 and 2, pumping occurs during periods 3 and 4.

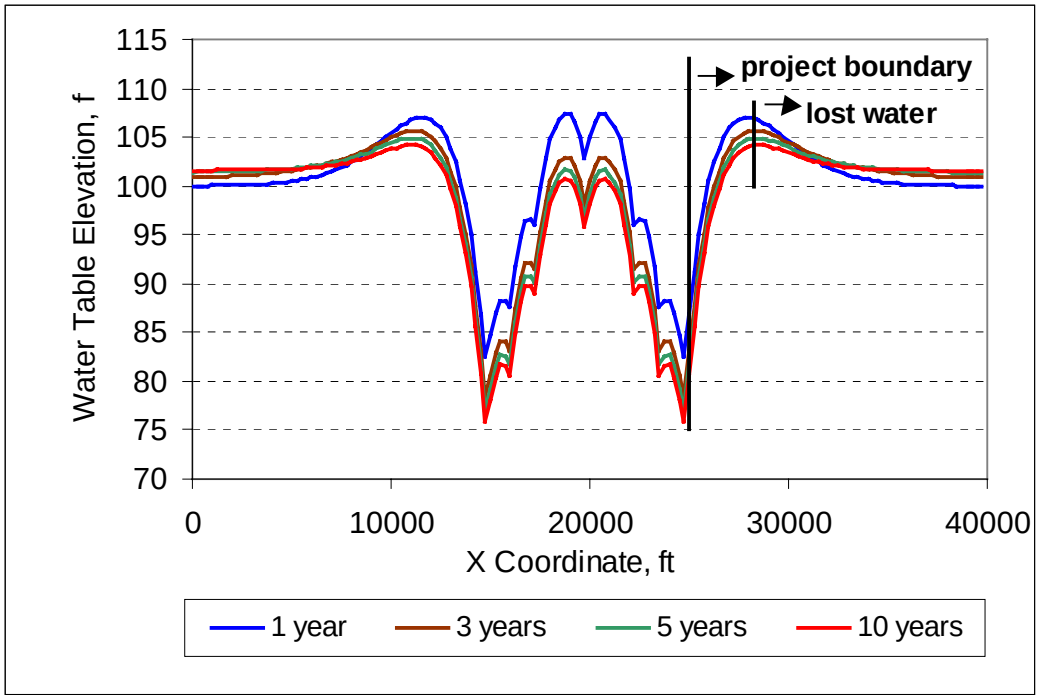


Figure 5-4. Cross section representing final water table elevations following 1, 3, 5, and 10 cycles (years) of recharge-extraction operation.

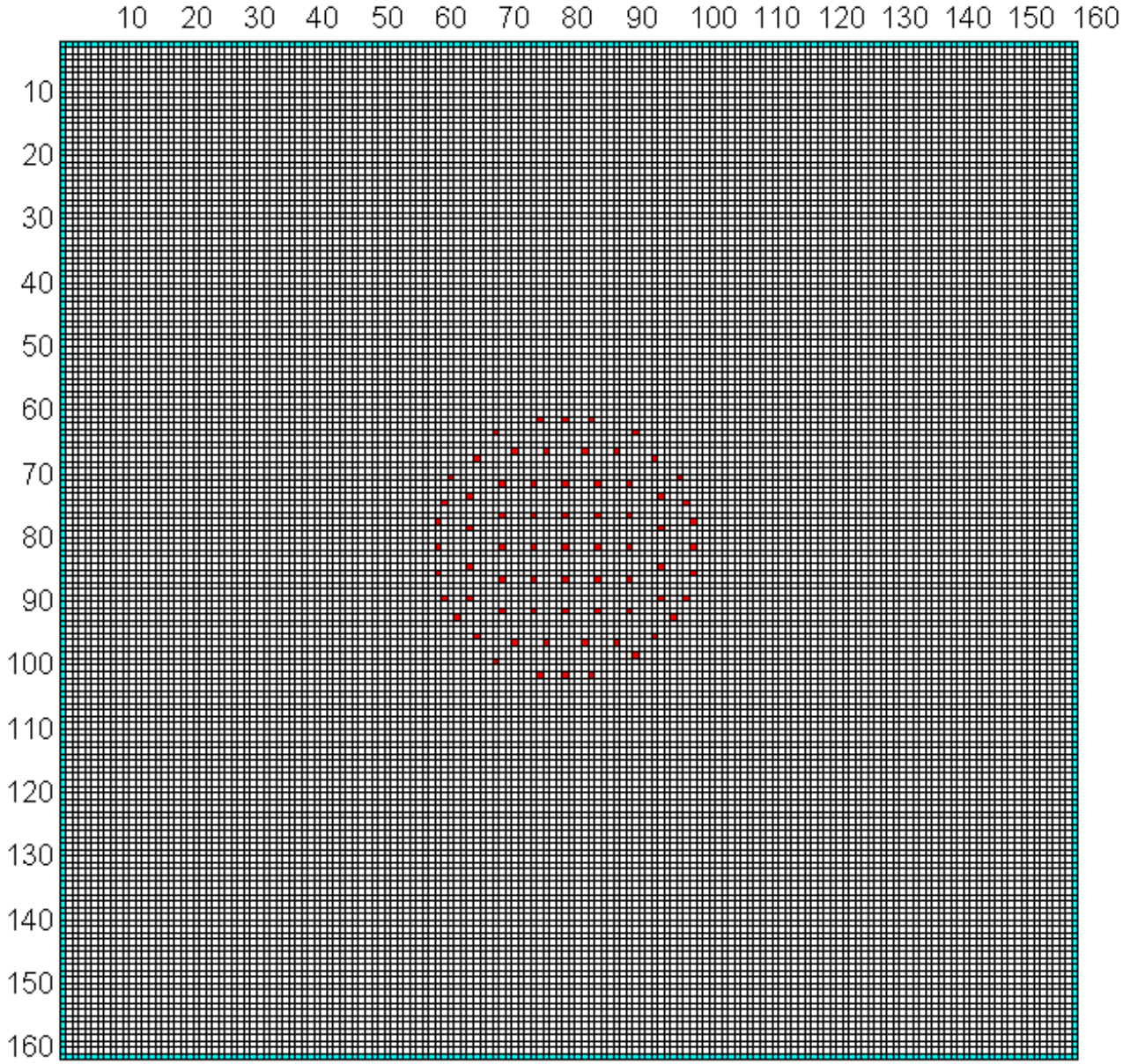


Figure 5-5. New pumping well locations for an alternative simulation.

6 Review of Ongoing and Planned CU Activities

6.1 Preface

Legal, political, and institutional factors to operate a conjunctive use (CU) program within the Sacramento and San Joaquin river basins of California are presented as a literature review of California-based, increased-yield CU programs. Roleplayers are first identified, relevant legal frameworks for groundwater management are discussed, and ongoing and proposed CU projects are summarized. Impediments to CU management are introduced. Types of CU arrangements are assessed, and pathways to coordinate CU with flood control are highlighted. The review is followed with recommendations for more detailed study.

6.2 Roleplayers

6.2.1 Federal

United States Army Corps of Engineers (USACE) – Agency of the Department of Defense whose mission is to develop, control, maintain and conserve the nation's navigable waters under the Rivers and Harbors Act and adjacent wetlands under the Clean Water Act.

United States Bureau of Reclamation (USBR) – Agency of the Department of Interior that constructs and maintains federal reclamation projects, including the Central Valley Project (CVP). [McClerg, 1997, p. 13]

6.2.2 State

Department of Water Resources (DWR) – California agency under the direction of the State Resources Agency that has overall responsibility for managing the state's water resources. DWR's mission is to evaluate current and projected needs for water and development programs, direct resource use, protect the public through water quality improvement, flood control and dam safety programs, and assist local water agencies with funds, expertise and technical support. [McClerg, 1997, p. 14]

California Water Resources Control Board (CWRCB) – Agency with its nine Regional Boards that regulate water quality in all of the state's waters. SWRCB also administers the state's permit system to appropriate and divert surface water. [McClerg, 1997, p. 15]

CALFED – Joint California state-federal planning organization created in June 1994 to provide more coordinated action in the Bay-Delta. Its three broad goals are: adopt mutually acceptable state water quality standards (accomplished in May 1995); coordinate CVP/SWP operation to meet water quality standards and protect endangered species; and develop a long-term Delta solution to resolve water quality, water use efficiency and levee stability problems, and restore the ecosystem. [McClerg, 1997, p. 15]

6.2.3 Local

Association of Groundwater Authorities (AGWA) – A nonprofit Public Benefit Corporation formed in 1994 by a group of eight Southern California groundwater basin management agencies and incorporated in 1995. Its mission is to promote interagency solutions that enhance the effective management of groundwater resources.

Association of California Water Agencies (ACWA) – Membership organization that represents 400 urban and agricultural water agencies on legislative matters. Member agencies manage 90 percent of the water delivered in the state.

Sacramento North Area Groundwater Management Authority (SNAGMA) –

American River Basin Cooperating Agencies – Water Districts of Arcade, Carmichael, Citrus Heights, Fair Oaks, North Ridge, Rio Linda/Elverta, and San Juan; Cities of Folsom, Roseville, and Sacramento; Counties of Placer and Sacramento; and Citizen's Water Resources organized in 1997 to develop equitable, cost-effective water resource management strategies of water users of Folsom Lake, the lower American River, and the connected groundwater basin [ARBCA and SNAGMA, 2000]

Metropolitan Water District of Southern California (MWD) –Agency responsible for bringing water to Los Angles. Operates Colorado River,

Local Water Districts

Third Parties – Landowners, holders of water rights, or others in the community whose water rights or economic livelihoods become affected by groundwater management plans, water transfers, or policy decisions to which they are not a participating party [DWR, Bulletin 160-98, p. 6-26; Nunn and Ingram, 1988, pp. 474-5].

6.3 Legal Frameworks for Groundwater Management

Excellent summaries and analysis of the California bodies of law governing surface water rights—including riparian use, appropriative use, exclusions, and pueblo rights—and groundwater rights are found in Purkey et al. [1998] and Schlager and Blomquist [1999]. In the California Water Code, groundwater is treated as a property right of the overlying landowner(s) [DWR, Bulletin 160-98] so that anyone can install a well and extract their correlative share of groundwater [DWR, 1999]. Correlative share is a portion of the available supply. Each landowner has the right to the use of groundwater to the full extent of their reasonable need if the supply is sufficient; when supply is short, landowners share the shortages of the limited resource [Jager, 1997]. Correlative, appropriative, prescriptive, or return-flow rights for "yield" and/or "flow" are determined on a basin-by-basin basis only if the basin is adjudicated. There is *no* system in California water law for determining rights to the storage capacity of a groundwater basin. Thus, the benefit of water stored in or recharged to an aquifer is the sole possession of the overlying landowner(s) [Purkey, et al., 1998].

California faces a huge political hurdle because conjunctive use requires groundwater management and California is one of only two states in the West without a comprehensive, statewide groundwater management code [McClurg, 1997, p. 38]. According to the DWR, frameworks for groundwater management permitted by the California Water Code are:

- *Local Agency*. Twenty-three types of districts, local agencies, or entities have the authority under the Code to implement groundwater basin management plans for the purposes of limiting overdraft, controlling land subsidence, managing contaminant migration, and/or conjunctive use.
- *Adjudicated Basins*. A court determines the groundwater rights of overlying property owners and appropriators. Court adjudication is a multi-year to decade-long process that results when stakeholders cannot reach consensus.
- *Special Legislation Districts*. Districts or agencies created by legislation or amendments to the Code with power to enact ordinances or regulate extraction.
- *AB 3030*. The systematic approach outlined in sections 10750--10756, 1992 of the Code for agencies to develop plans, raise revenue, and manage extraction, recharge, conveyance, and quality.
- *Ordinances.* Cities and counties retain the right to adopt local ordinances concerning groundwater. Most ordinances prohibit the transport of extracted groundwater outside the boundary of the county. [DWR, 1999]

6.4 Implications for Groundwater Management in Sacramento and San Joaquin Basins

Overlapping and/or conflicting mandates for groundwater management among districts, agencies, courts, and counties are common and also uncertain. Although 16 adjudicated basins and 12 legislated districts exist in California, none are located within the Sacramento and San Joaquin river basins. Ten counties in California have developed local groundwater ordinances [DWR, 1999]; of which Butte and San Joaquin counties are the only ordinance counties located in the study basins. San Joaquin county ordinance No. 4064 “encourages development of conjunctive use projects that would positively impact the critically overdrafted groundwater basin” with the caveat that exports outside the county require a permit such that “the project will result in a net addition to usable groundwater underlying the project.” [Board of Supervisors, San Joaquin, 2000]. Butte County’s groundwater conservation ordinance was established to prevent groundwater extraction for water export outside the county and substitution with surface water use “to protect against groundwater overdraft and insure the safe yield of” county aquifers. A permit is required for such practices. [Butte County, 1996] Toulumne County had a temporary groundwater ordinance on the books until December 21, 1997. The ordinance prohibited the export of groundwater outside the county [Tuolumne County Well Ordinance, Section 13.16.125, 1986]. The county is drafting a permanent ordinance to reinstate the prohibition with exclusions “permitted by the Board of Supervisors that do not frustrate” the beneficial use and health, safety and welfare of the people of the county [Leasure, 2001].

The bulk of groundwater management is handled by local agencies that are forming AB 3030 plans. Approximately 163 plans are on file with the DWR; 20 to 30 of these are for sites in the Yuba, Feather, American, San Joaquin, Tuolumne or Merced watersheds**.** But counts are

uncertain because no requirement exists for local agencies to file their AB 3030 plan with DWR or CWRCB. [DWR, Bulletin 160-98, p. 2-20; CALFED, 2000, Appendix H; DWR, 1999]. In 2000, the California State Legislature also passed the Local Groundwater Assistance Fund (California Water Code Section 10795) to award grants to assist local public agencies conduct groundwater studies, carry out groundwater monitoring and management activities, and draft plans [CALFED, 2000; DWR, 1999].

6.5 CU programs

6.5.1 Statewide

Within California, 267 local agencies are developing or operating a groundwater management plan [DWR, 2000]. These plans likely cover about 164 of the 400 hydrological basins within the State catalogued by the DWR. Based on 12 CU programs identified from a random stratified sample of 70 basins [Schlager and Blomquist, 1999], 68 conjunctive programs are estimated to exist within California. Despite 8 years since the adoption of AB 3030 enabling legislation, many programs are still in the planning or development stages [e.g. project summaries described by DWR, 1998, pp. 8-19 and 8-38].

Median storage volume for 12 CU programs identified by Schlager and Blomquist was 25 TAF per year with capacity ranging from 10.5 to 200 TAF per year. Projects were noteworthy for their long-term stability (up to 60 years), low operating costs, high economic efficiency, and large number of involved parties. The participant size meant that programs were implemented using a project-by-project, deal-by-deal approach that accommodated every participant. [1999]

CALFED is seeking to develop locally managed and controlled groundwater and conjunctive use projects with a total of 500 TAF to 1 MAF of additional storage capacity by 2007. The projects will be locally managed through partnerships with local and regional interests, and will include a combination of purchase, lease or shared storage space. CALFED has identified projects in the Sacramento Valley, near the Delta, the San Joaquin Valley and Southern California, and has negotiated three memoranda of understanding with local agencies as of June 2000. Projects will proceed in three stages: first, finalize agreements with new local project proponents for joint planning and development by February 2001. Second, conduct feasibility studies beginning in March 2001 with funding from CALFED and Proposition 13. $2,150,000 in funding for conjunctive use grant programs was authorized for fiscal year 2000 through the Bay-Delta Authorization Act [CALFED, 2000; Proposition 13, 2000]. CALFED money is complimented by $90 million in grant funds for Fall 2001 and $90 million in grant funds for Fall 2002 offered by DWR for local agencies to pursue groundwater management objectives [Davert, 2001b].

6.5.2 Tulare Region

The Semitropic Water Storage District operates a groundwater banking program in Wasco, California north of Bakersfield. The program is part of the Kern Water bank which has a storage capacity circa 1 MAF [CALFED, 1999] and recharge basins spread over 3000 acres [DWR, 1998, p. 8-51]. The program is fully subscribed and built upon *in-lieu* exchanges [Sharpe, 2001].

Program participants are the Vidler Water Company, Inc (185 TAF), the sole private holder of recharge facility and banking rights in the Southwestern United States [Reisner, 1997]; and 5 public entities including the MWD, the Santa Clara Valley Water District, Alameda County Water District, the Alameda County Flood Control, and Water Conservation District, Zone 7 [Vidler, 1998]. Although Vidler has recovered 100% of stored water and has excellent cooperation with its banking partners, sales have totaled less than 1 TAF for unit prices circa $120/AF. The shortcoming is caused by (i) poor overlap in timing between deliveries of surface water to Semitropic farmers and peak irrigation demand periods; (ii) variable down-stream users wanting to buy banked, credited water; and (iii) an inconsistent set of MWD wheeling fees to move water from the bank, through the L.A. aqueduct to end users such as the City of San Diego. [Sharpe, 2001]

6.5.3 Sacramento River Basin

The goal of CU programs within the Sacramento River Basin is to encourage existing surface water users to make greater use of groundwater resources, especially during dry years [DWR, 1998, p. 6-22]. SNAGMA and its American River Basin Cooperating Agencies have submitted 3 grants to fund a project on the American River in the Sacramento River [Davert, 2001b]. The agencies hope to transition from a 60/40 ratio of surface to groundwater use in “dry” years to 80/20 ratio in “wet” years. Total aquifer storage space is estimated at 1.5 MAF, of which 400 to 600 TAF is usable. The agencies are implementing a pilot program to investigate a large-scale banking and exchange program. [ARBCA and SNAGMA, 2000]

CALFED [1999] used technical and political feasibility criteria to identify 5 potential CU sites from a screening list of 19 sites developed by Purkey et al [1998]. A site was rated politically feasible if local agencies in the basin had begun formulating their own plans for CU. Technical feasibility was defined in terms of available aquifer storage capacity. South Sacramento County, San Joaquin County, Madera Ranch, Kings River Fan, and the Kern Water Bank were identified as sites worthy of further study, while Stony Creek, Butte Basin, and Cache-Putah Basins were excluded because the aquifers were generally full. CU is possible in filled aquifers, but first requires extraction, followed by active recharge or *in-lieu* exchanges. This arrangement may not be politically attractive until third-party impacts are addressed. CALFED completed the site assessments by determining the financial costs, recharge, and recovery rates for each project.

6.5.4 San Joaquin Basin

The DWR views CU projects in the San Joaquin valley as empty or depleted groundwater storage space that should be recharged for later withdrawal [1998, p. 6-22]. To address 50 years of ongoing groundwater overdraft in eastern San Joaquin country, the USACE studied conjunctive use for the Farmington Dam and Reservoir. Re-operation of the Farmington Flood control project combined with groundwater recharge and water acquisition was identified as the apparent best alternative from a set of 12 scenarios. The recharge and acquisition scenario increased yield by 22.7 TAF over the recharge scenario alone, with yields ultimately constrained by the carrying capacity of the upper Farmington Canal to divert acquisition waters into the Farmington reservoir. Benefits associated with the reduction of salinity intrusion and protection of the groundwater resource (i.e.: so that the aquifer would be available to future generations of

users) were excluded from the quantification analysis and only correlated qualitatively to the volume of water recharged to the aquifer per year. [USACE, 1997]

As follow-up, the USACE performed pilot tests to determine the most appropriate method of groundwater recharge. From test options such as Flooded Fields (80 acre site), Spreading Basins (80 acre site), Excavated Recharge Pits (40 acre site), Unlined Flat Canal, Dry Wells, Injection Wells (4 wells), Enhanced Recharge through Streams, Flood Detention Basins, and *In-Lieu* Delivery (agricultural delivery program), flooded fields provided the most cost-effective combination of groundwater recharge performance and opportunities for seasonal habitat restoration. Steady-state infiltration rates ranged from 0.25 to 0.50 feet per day. Based on the pilot test results, recharging the expected "new" water supply of 35,000 acre-feet per year requires 1,200 acres of land at a projected, total project cost ranging from $12.8 million to $25.5 million or $31-$51/acre-foot-year. Presently, the Stockton East Water District, San Joaquin County water agencies, and the State of California are overseeing demonstration-scale projects to investigate the optimal design and layout of a flooded field program and potential environmental impacts. This step represents an incremental approach towards development of full-scale groundwater recharge and CU capabilities. [USACE, 2001]

Southwest of the City of Madera, the USBR and a local water authority are investigating the Madera Ranch Banking Project. In wet years, surplus water from the delta would be recharged through 3,500 acre recharge pond. Potential storage capacity is circa 390 TAF. Delta diversion rate for recharge and extraction rates for withdrawal from the aquifer could be up to 400 and 200 cfs respectively. Annual yield could be 70 TAF at a cost of $226/af. [DWR, 1998, p. 8-38].

6.6 Impediments

Ranked in increasing order of importance, physical, financial, and institutional impediments have limited the broad-scale use of CU [Schalger and Blomquist, 1999]. A geographical location with physical properties suitable for surface and groundwater management is essential. The absence of water supply with proximity to aquifer storage capacity [for example, see CALFED, 1999], lack of high yield wells (to the extract the water), or existence of surface/groundwater interactions are potential physical impediments. Financial impediments can be posed by the costs needed to manage operations and construct water conveyance, infiltration, recharge, and pumping structures. The benefits to be derived from CU—increased flood-control, increased-yield, decreased pumping costs—must outweigh the costs within the time horizon considered by decision makers.

Schalger and Blomquist define institutional impediments as the organizational arrangements, laws, long-standing norms of the community and culture, and rules governing interactions that shape human decisions by "ruling in" some behaviors, "ruling out" others, facilitating joint effort or impeding it. For CU programs (that require coordinated action), these impediments are the "organizational arrangements [that],

(a) [limit]/prohibit coordination of actions necessary to divert, impound, recharge, store, protect, and extract water, or
(b) do not protect those who invest in facilities, or who store water now for recapture later, or

(c) do not provide or recognize workable and fair methods for distributing the costs of a conjunctive management program among those who benefit from it." [1999]

Engineers, hydrogeologists, and water agency managers from local, regional, and state agencies as well as the academic and consulting communities ranked the top "impediments to implementing a cost-effective conjunctive use water management program in California [as]

- inability of local and regional water management governance entities to build trust, resolve differences (internally and externally), and share control;
- inability to match benefits and funding burdens in ways that are acceptable to all parties, including third parties;
- lack of sufficient federal, state, and regional financial incentives to encourage groundwater conjunctive use to meet statewide water needs;"

in a 1998 Workshop on Conjunctive Use convened by the National Water Research Institute and sponsored by the AGWA and the MWDSC. All of the top 10 barriers involved the assignment of rights, risks, and responsibilities, the distribution of costs and benefits, and the opportunities and disincentives for inter-organizational cooperation and coordination of activities. [NWRI, 1998: 5-39 as reported in Schalger and Blomquist, 1999]

6.7 Coordinating CU with Flood Control

A successful CU program for flood control must also overcome the physical, financial, and institutional impediments posed to new-yield CU programs. To date, our review of the conjunctive use literature has only identified CU programs operated for the purposes of increased yield or aquifer restoration. The legal, economic, and political institutions that govern conjunctive use within the Central Valley basins do not fully impede and preclude operation of a CU program for flood control benefits; however, they tend to favor arrangements that generate new yield.

A strict management arrangement for CU could be supervised by an agency like the Corps expressively for the purpose of flood control and would represent the highest cost and most intrusive program alternative. More cost efficient, contractual arrangements oblige less intrusion, but require balancing the goal of flood control with new-yield and habitat management goals favored by other stakeholders. Contract agreements could produce incremental increases in both flood protection and new yield at benefit levels below the maximal levels attained if the programs were operated separately.

For both strict management and contractual arrangements, flood protection benefits can be maximized by (i) linking them to the water user participants and (ii) siting recharge areas as close as possible to both the surface water supply reservoir and end user(s) [Purkey, et al., 1998]. Linking flood protection benefits to users would mean limiting participation to surface and groundwater users who reside within the flood plain and stand to increase their flood protection (and decrease their flood insurance payment) by taking direct recharge or *in-lieu* transfers of water.

As with new-yield CU programs, success of flood protection contractual arrangements will rest on the ability of stakeholders and water agencies to collaborate [Nyquist and Casey, 2000]. Collaboration will occur when individual agencies decide that participation is beneficial and does not unfairly burden their ratepayers [Davert, 2001 (a)]. Landowner participation can be motivated by financial compensation or water allocation. These institutional arrangements will continue to promote CU programs on a project-by-project, deal-by-deal approach that is basin specific with few possibilities for cross-locality connections [Schlager and Blomquist, 1999]. Thus, numerous scenarios for CU and flood control exist. Specific cases and locations need to be investigated for technical feasibility. At the same time, many programs will also go unrealized in basins where CU is technically feasible, but coordinated management is unrealistic.

6.8 Recommendations for Further Study

Topics to further the active study of CU and flood protection include:

- Gather and review the AB 3030 groundwater management plans drafted by the 30 agencies located within the Sacramento and San Joaquin river basins.
- Identify CU programs supervised by these plans. Contact program managers. Determine the feasibility of adding flood protection to programs.
- Locate property owners situated within Sacramento and San Joaquin river basin floodplains that stand to receive increased flood protection from CU. Cross reference floodplain residents with groundwater users to identify matches.
- Approach candidates and assess their willingness to participate in CU program or enter into contractual agreements.
- Develop monitoring program components of CU project. Determine needed data and develop procedures to measure future effects on groundwater hydrogeology [DWR, 1998, p. 6-22].

Alternatively, the Corps could take a passive approach and adopt an advisory role similar to the role taken by CALFED. The Corps could:

- Develop and publish the methodology for quantifying flood protection benefits gained from CU management
- Encourage local agencies to adopt voluntary AB 3030 groundwater management plans and locally-controlled, conjunctive use programs [McClurg, p. 68] that incorporate flood protection benefits.

Both active and passive action-points would support local agencies wishing to start CU programs for flood protection.

6.9 Summary

Within California, conjunctive use (CU) co-management of surface and groundwater resources is readily discussed as a promising nonstructural means to increase water yield [DWR, 1998; CALFED, 1999; Davis, 1998]. The current system of surface water and groundwater laws establishes groundwater management and CU as highly decentralized and locality-specific, yet falling within the conflicting authorities of local agency AB 3030 plans, groundwater ordinances, legislative authority, court adjudication, and landowner appropriation and riparian rights. Federal agencies like the Corps, State and local agencies also have overlapping and potentially

conflicting mandates regarding CU. And since most CU programs are still in the planning stages, ongoing issues remain as to whether the water gains will be “real” or “paper”; organizational, institutional, and legal impediments will obstruct program effectiveness; or political will-power exists to manage programs for the additional benefit of improving flood control.

Despite the impediments, several types of CU arrangements are possible: strict management or contractual, using direct recharge, *in-lieu*, and single-user exchanges. All types of arrangements require basin-specific, collaborative approaches that link reservoir water providers, landowners, and end-users in a division of benefits. For the purpose of flood protection, CU arrangements can be strengthened by (i) siting recharge areas as close as possible to surface water reservoirs and end water users (ii) encouraging participation from surface- and groundwater users who reside within affected floodplains. Further work should focus on assessing the willingness of local agencies to enter into CU deals or promoting CU for flood control so that local agencies can strengthen the benefits derived from their groundwater management plans.

7 Conclusions and Recommendations

HEC's “pre-reconnaissance” study of the integrated management of surface and groundwater for flood protection suggests that further study of Conjunctive Use (CU) for this purpose is warranted. Compared to structural methods for increasing flood protection such as raising levees or building new dams, CU may be a cheaper alternative for providing commensurate level(s) of additional flood protection. Simulation of strict management CU operations at six reservoir sub-basins within the Sacramento and San Joaquin basins using 14 years of the historic record demonstrated that both flood protection and new yield benefits can be achieved from CU operations without negatively impacting water supply or recreation.

The volume of additional flood storage space created in reservoirs from CU operations focused on flood protection depended on: (i) the available groundwater storage space geographically accessible to the reservoir, (ii) the rate at which water can be recharged into the storage space, and (iii) the rate at which water can be extracted from the storage space. These values are tied to aquifer site characteristics such as current water table elevation, porosity of the substrate, vertical hydraulic conductivity, and the size (area) of the recharge basin site. Of these parameters, only recharge basin size is a design variable under the control of decision-makers. In the study, recharge basin sizes were between 2 and 8 square miles, and represented only a portion of the range of realistic choices. *Increases to flood storage volumes reported in Section 4.2 are not absolute, but rather commensurate with the level of infrastructure (recharge basin size) chosen for study.* Overall limits to the creation of flood storage space expressed per unit-area of recharge basin size are listed in Table 7-1 by constraint factor for each aquifer site. These normalized values can reasonably be scaled to compute constraints for basin size between 0 and 12 square miles.

Table 7-1. Unit-area Limits on Individual Recharge Basin Contribution to CU Flood Pool Storage by Constraint Factor

A. Sacramento Basin

Reservoir Aquifer	Constraint Factor: Aquifer storage (kaf/sq.mi)	Constraint Factor: Maximum recharge (kaf/sq.mi)	Constraint Factor: Maximum extraction (kaf/sq.mi)	Limiting Constraint (kaf/sq.mi)
Oroville				
E	22	58	**14**	**14**
G	**1**	46	14	**1**
I	**4**	12	14	**4**
F	**3**	58	14	**3**
N	**4**	58	14	**4**
Bullards Bar				
K	**13**	23	15	**13**
M	**13**	23	15	**13**
Folsom				
P	36	23	**13**	**13**
O	14	**12**	13	**12**

B. San Joaquin Basin

Reservoir Aquifer	Constraint Factor: Aquifer storage (kaf/sq.mi)	Constraint Factor: Maximum recharge (kaf/sq.mi)	Constraint Factor: Maximum extraction (kaf/sq.mi)	Limiting Constraint (kaf/sq.mi)
Don Pedro				
S	**3**	46	15	**3**
T	36	58	**15**	**15**
U	95	58	**15**	**15**
McClure				
U'	95	58	**16**	**16**
Millerton				
Z	90	52	**13**	**13**
AA	36	40	**13**	**13**
BB	65	58	**13**	**13**
X	152	58	**13**	**13**
Y	103	58	**13**	**13**

* Unit-area storage constraint values are valid for recharge basins sized between 0 and 12 sq. mi.

Creation of additional flood storage space is also dependent on CU reservoir operations. Reservoirs can either maintain additional flood protection throughout the winter (Type 1 operation, guaranteeing storage space) or sacrifice some additional flood protection to capture additional new yield (Type 2 operation, creating "incidental" storage space). While both types of operation were developed and considered in this study for completeness, simulation was constrained by the need to create *guaranteed* reservoir flood storage space from CU operations. This constraint is imposed by current Corps policy that allows quantification of flood protection benefits only from guaranteed reservoir flood storage space. That storage space must be available every year during the entire flood season to be "unquestionably" available when an extreme flood event occurs.

To develop an upper bound on flood protection benefits available with CU operations, Type 1 reservoir operations and a strict management CU arrangement were investigated to make creation of flood storage space the first priority. In strict management, the CU management authority purchases lands, secures the surface and groundwater rights, and builds infrastructure dedicated to conveyance, recharge, storage, and extraction of CU transfers. Despite the priority on flood protection, simulation showed that a significant amount of new water yield was also generated in the process, indicating that new yield and flood protection benefits are at least partially complementary.

The strict management arrangement represents the simplest—and, in all likelihood, the costliest—type of CU operations management scheme, and one that requires an active involvement by the Corps. Contrasted with contractual arrangements identified during a review of CU activities within the Sacramento and San Joaquin basins, strict management also represents a fairly unrealistic type of arrangement to implement because it requires the imposition of outside interests on local communities. While too complex to model in this preliminary study, contractual arrangements are likely to be more successful because they build self-arbitrating institutional arrangements among the program participants. These arrangements coordinate participation for conveyance, storage, extraction, and sale among local reservoir operators, water users, and land and aquifer owners using existing infrastructure or temporary easements. New yield generated as a byproduct of CU for flood protection can be used as an incentive to encourage participation and offset third party impacts.

For the greatest chance of success, further study of CU for flood protection should emphasize integrating the goal of flood protection with ongoing CU programs having other objectives such as generation of new water yield. Project success would require collaborative approaches that are locality- and project-specific. Integration would require the Corps to cooperate with other local surface and groundwater management agencies whose objectives are not necessarily flood protection. The greatest impediment to such cooperation might be the need for flood storage space to be *guaranteed* in order to be recognized as providing flood protection benefits.

To pursue cooperation most effectively, the Corps would benefit from developing a methodology to quantify the value of flood protection benefits gained from *incidental* flood storage space created by CU activities. Flood-benefit quantification methodology is based upon describing the likelihood of occurrence of extreme flood events. Valuation of non-guaranteed reservoir storage space requires also describing the likelihood of occurrence of that space. A CU program

designed to maximize new yield, like a program aimed at maximizing flood protection, will relocate water from a reservoir conservation pool in winter to create storage space (a CU Pool), providing additional flood protection. As the flood season progresses and accessible *aquifer* storage space decreases, the new-yield program would fill the CU Pool to conserve captured water, decreasing the flood storage space available at that time. This operation introduces variability in the available reservoir flood storage space and additional uncertainty into the overall flood protection provided.

One of two conditions should exist to enable estimation of the likely availability of this incidental flood storage space. One is that operations must be regular (planned) enough that this likelihood can be described analytically. If not, the likelihood can be estimated as the relative frequency inferred from operation during the historical period of record. While historical records are not available for reservoir operations that as yet are only *proposed*, if those operations can be simulated with historical or synthetic hydrology, a record of the available reservoir storage space from those operations could be produced and the frequency assessed. Such simulation requires that either reservoir operation be at least somewhat regular or patterned, or that all of the variables that influence CU reservoir operation be included within the simulation model.

The variables that influence reservoir operation for Conjunctive Use are extensive, and include surface water and groundwater hydrology, demand for water, market price of water and agricultural products, and other more complex factors. Simulation that includes all these variables would be difficult, and require an in-depth understanding of water resource economics in addition to reservoir operation. It is perhaps reasonable to assume that such a study would be better conducted by a Conjunctive Use management authority other than the Corps to determine consequent flood protection benefits from CU operations aimed at attaining new yield. In this situation, the Corps could review those computations and authorize the resulting flood benefits.

It is the recommendation of HEC, based on the results of this study, that the Corps continue to study flood benefits attainable by Conjunctive Use. The most efficient path to success might be cooperation with existing practitioners of Conjunctive Use aimed at water supply yield. This study described a CU infrastructure and operations targeted at guaranteed flood protection, using new water yield as an incentive for participation by local water agencies. Instead, perhaps local water agencies could pursue CU reservoir operations targeted at yield, and credit for incidental flood protection would serve as an incentive to target flood protection more strongly.

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Appendix A. Water Transfer Model Output

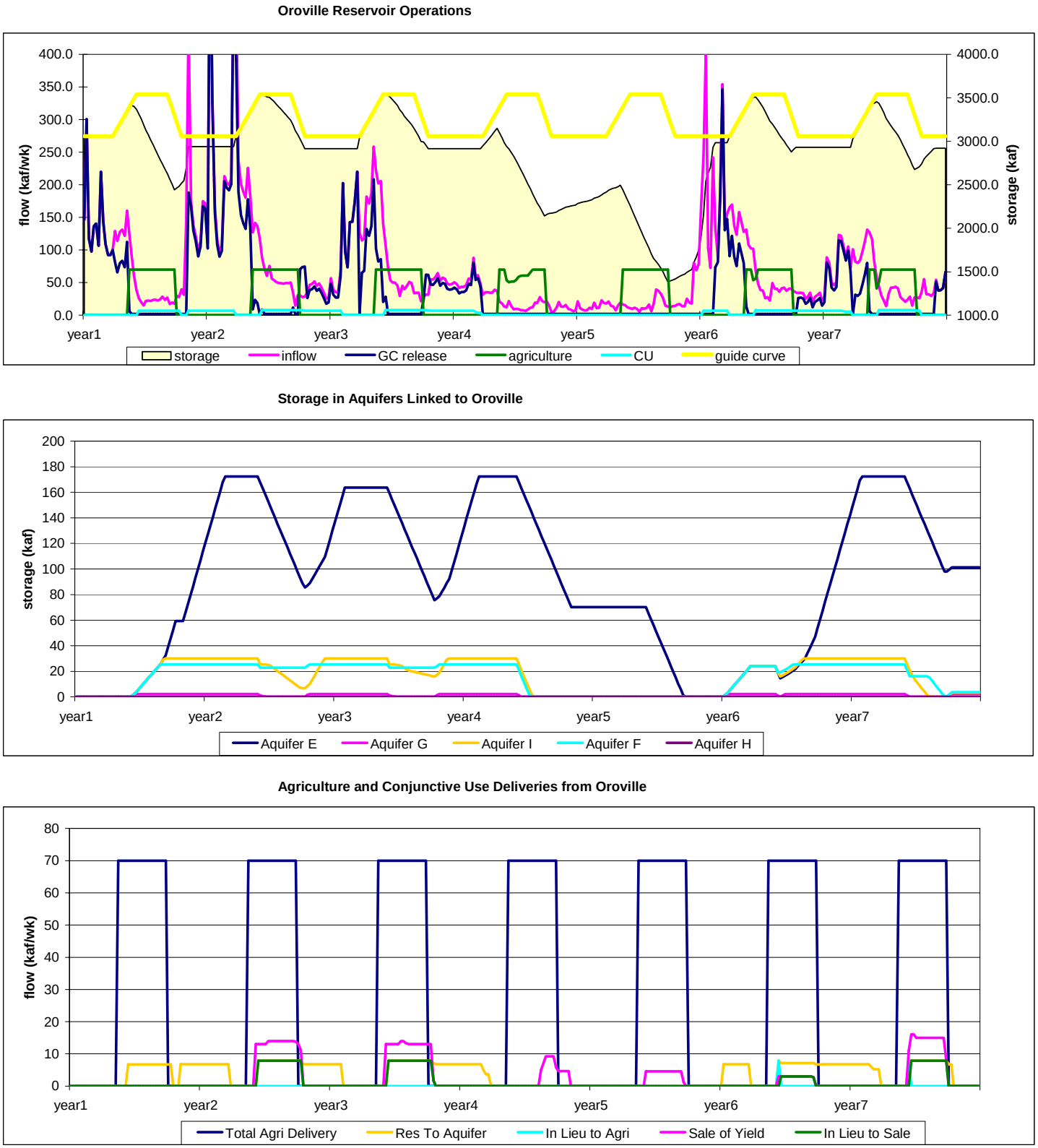


Figure A-1 Reservoir and Conjunctive Use Operations at Oroville Reservoir, 1973-1979

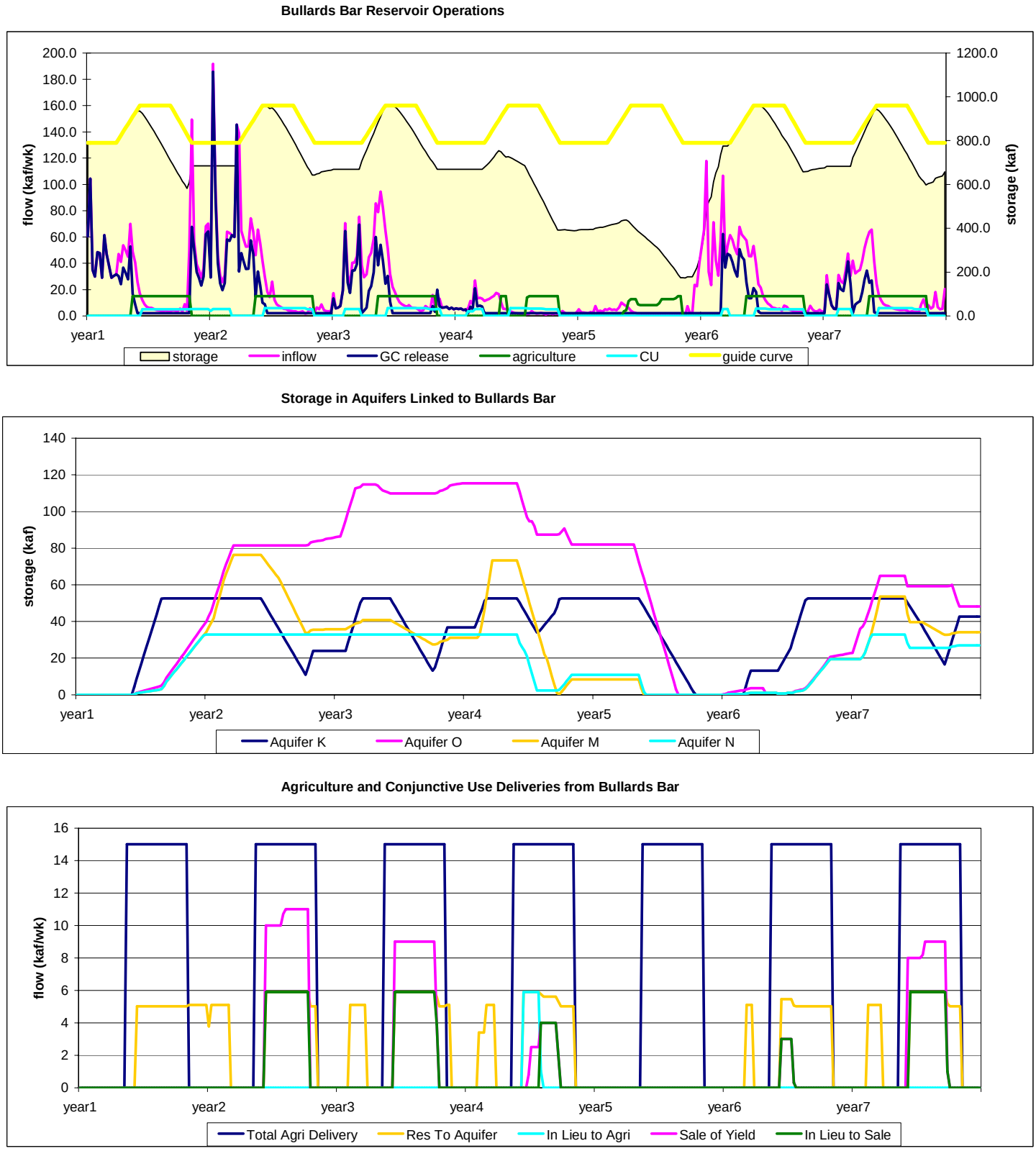


Figure A-2 Reservoir and Conjunctive Use Operations at Bullards Bar Reservoir, 1973-1979

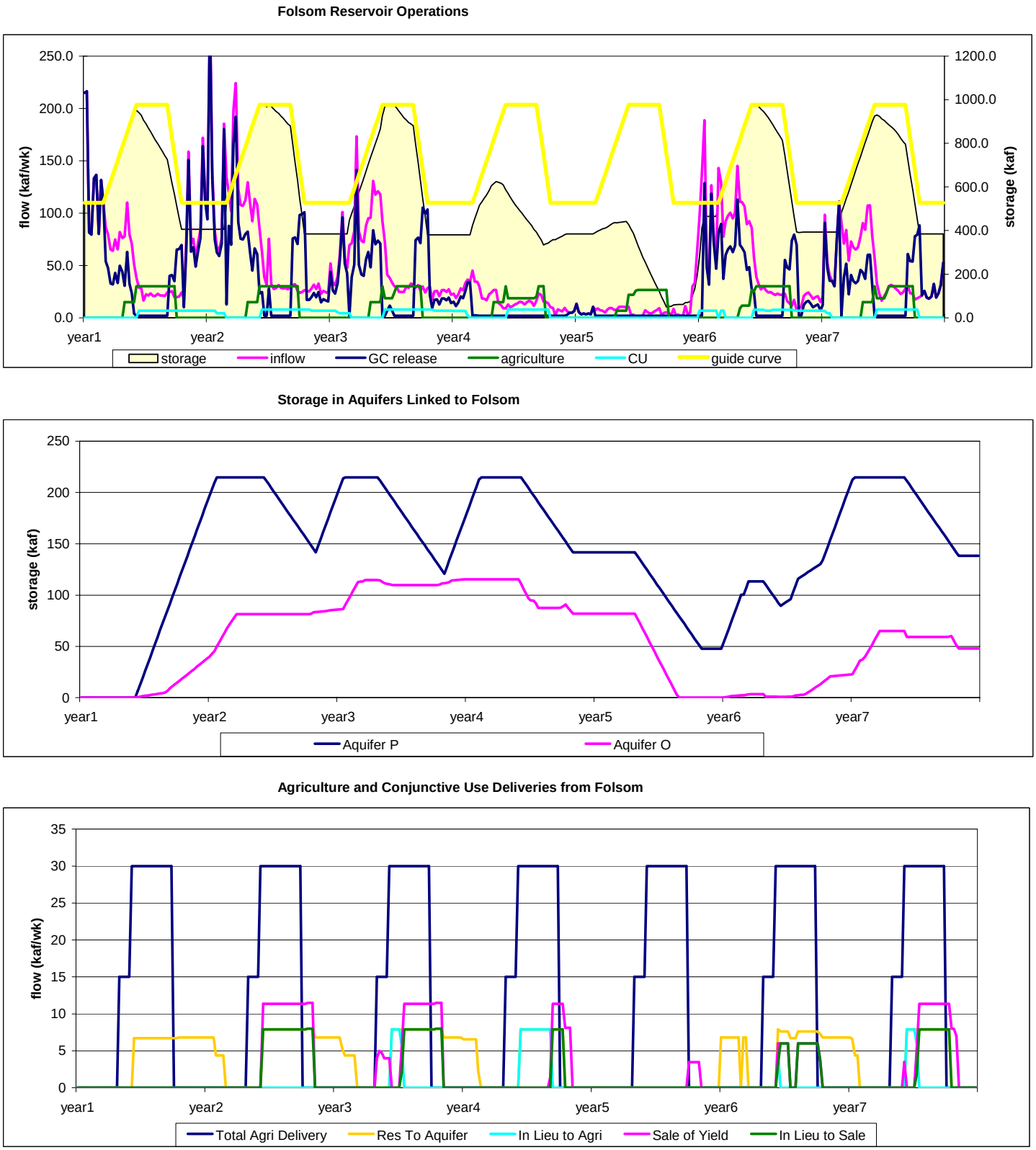


Figure A-3 Reservoir and Conjunctive Use Operations at Folsom Reservoir, 1973-1979

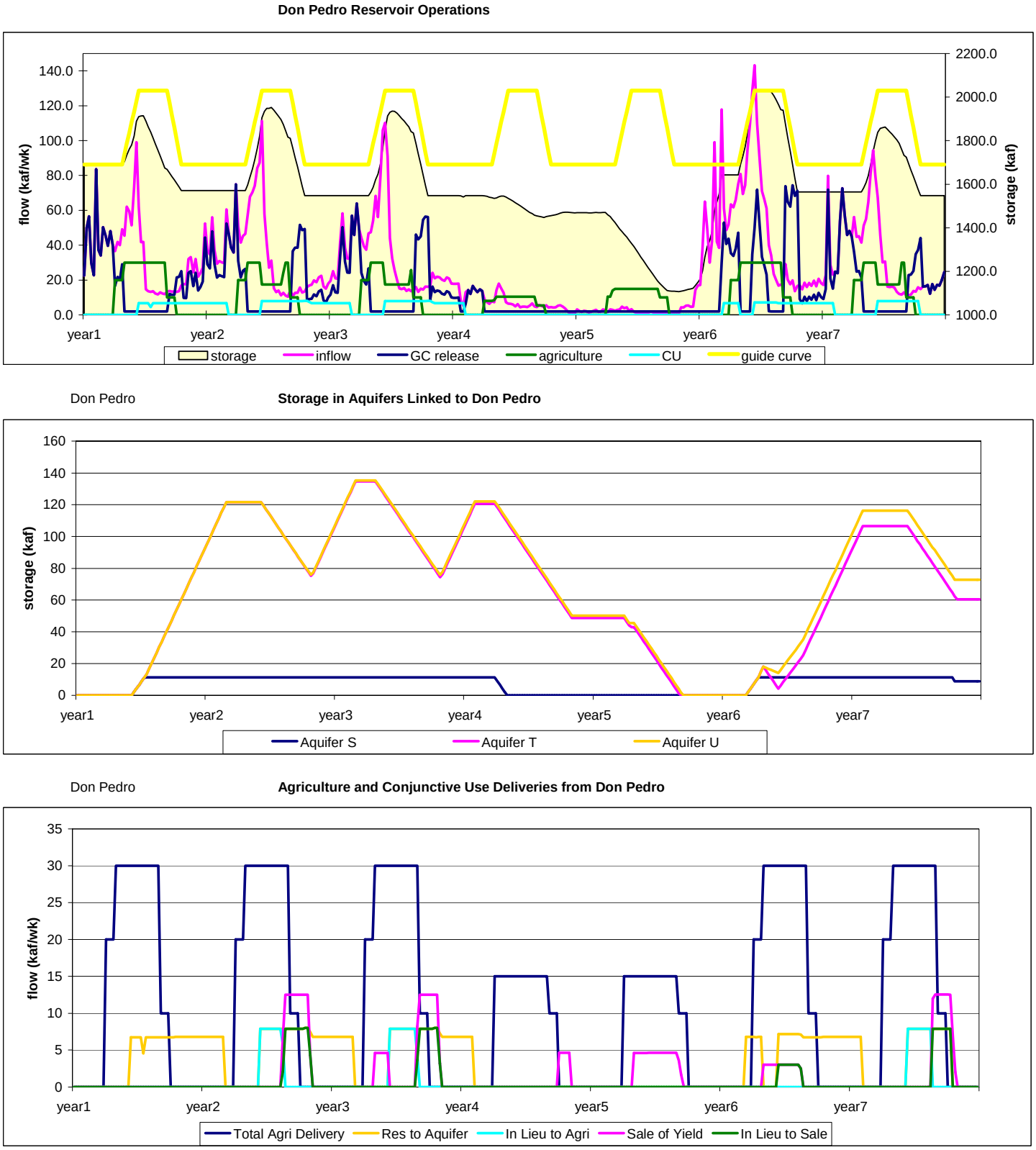


Figure A-4 Reservoir and Conjunctive Use Operations at Don Pedro Reservoir, 1973-1979

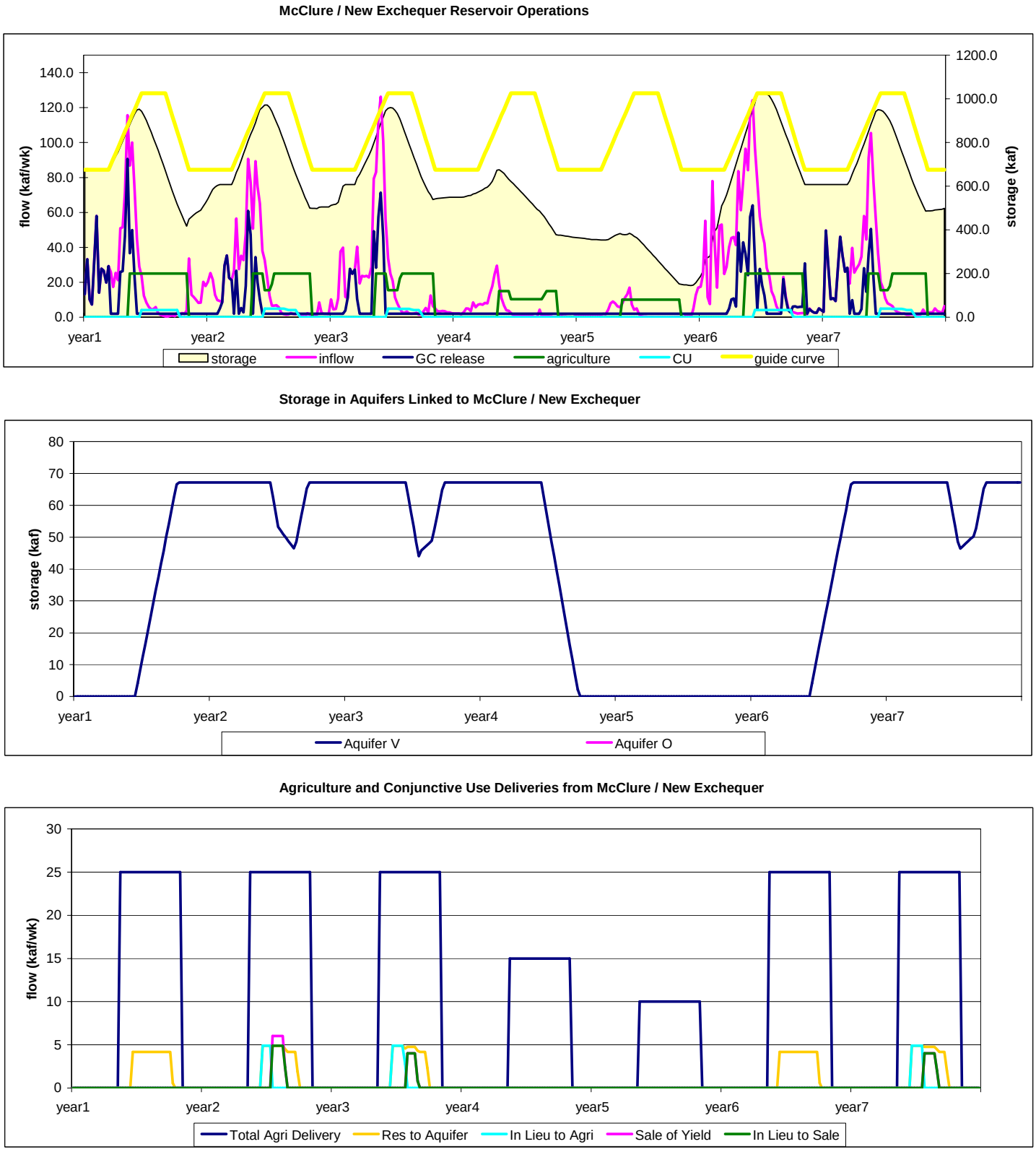


Figure A-5 Reservoir and Conjunctive Use Operations at McClure / New Exchequer, 1973-1979

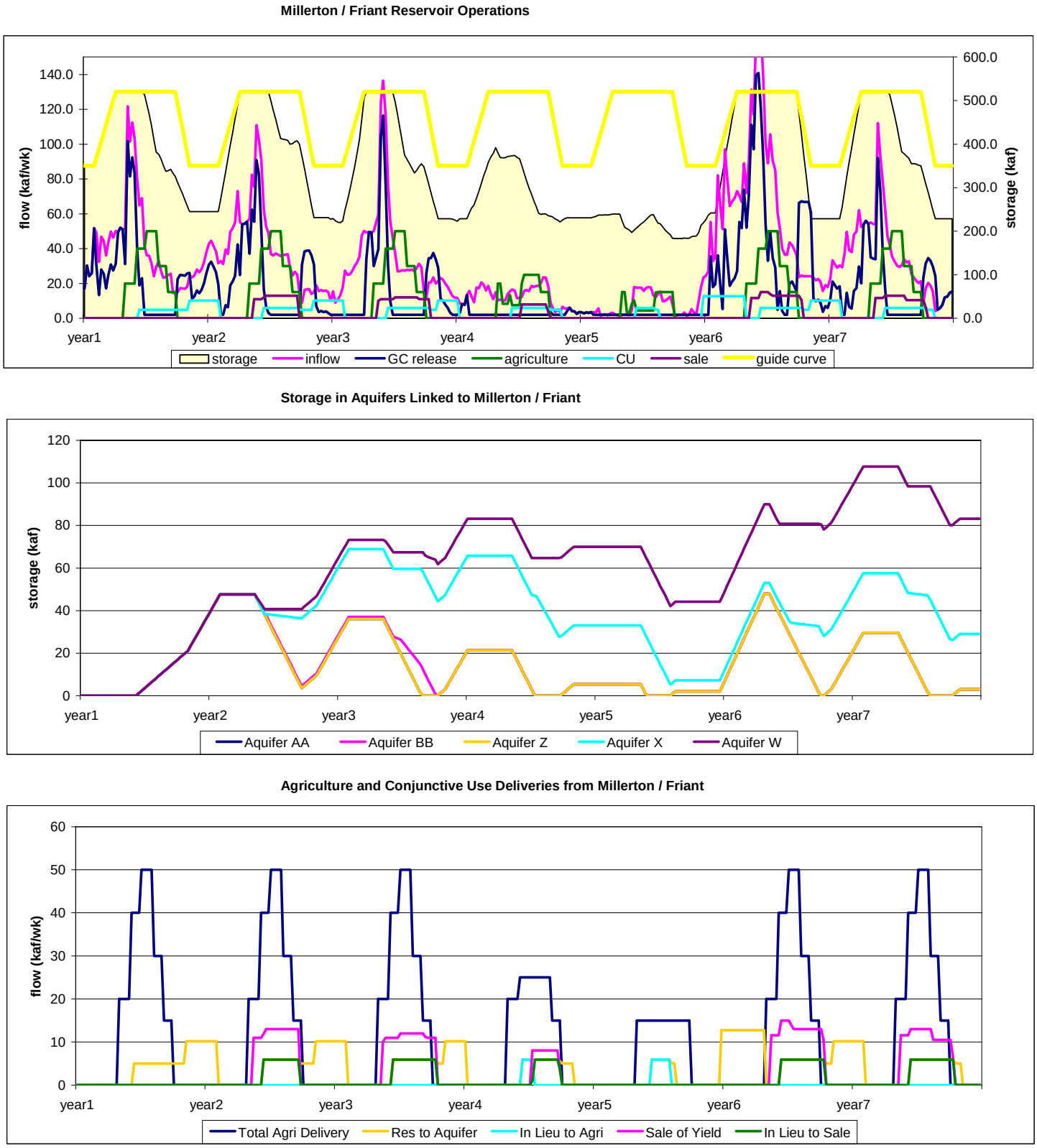


Figure A-6 Reservoir and Conjunctive Use Operations at Millerton / Friant, 1973-1979

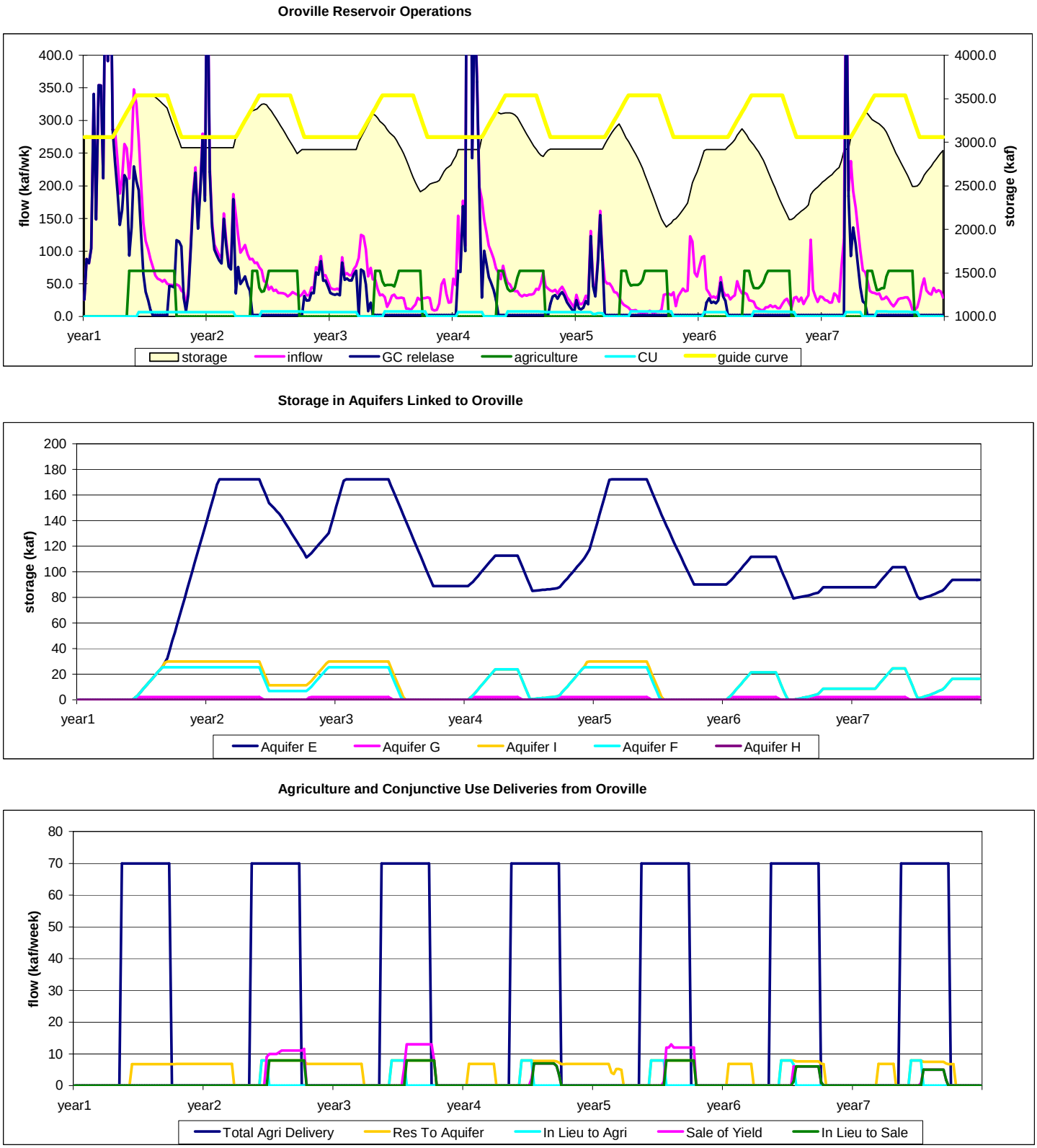


Figure A-7 Reservoir and Conjunctive Use Operations at Oroville Reservoir, 1983-1989

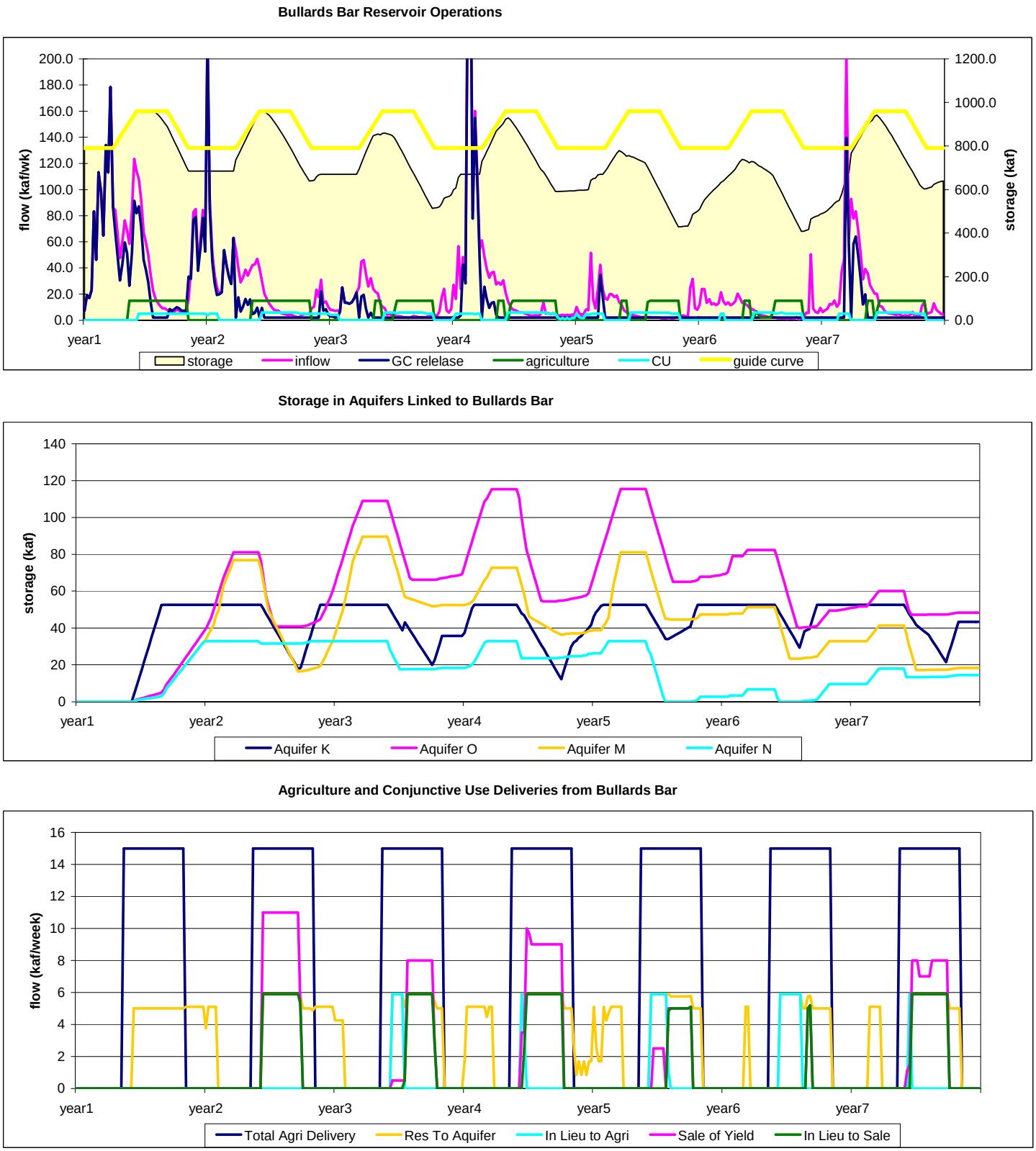


Figure A-8 Reservoir and Conjunctive Use Operations at Bullards Bar Reservoir, 1983-1989

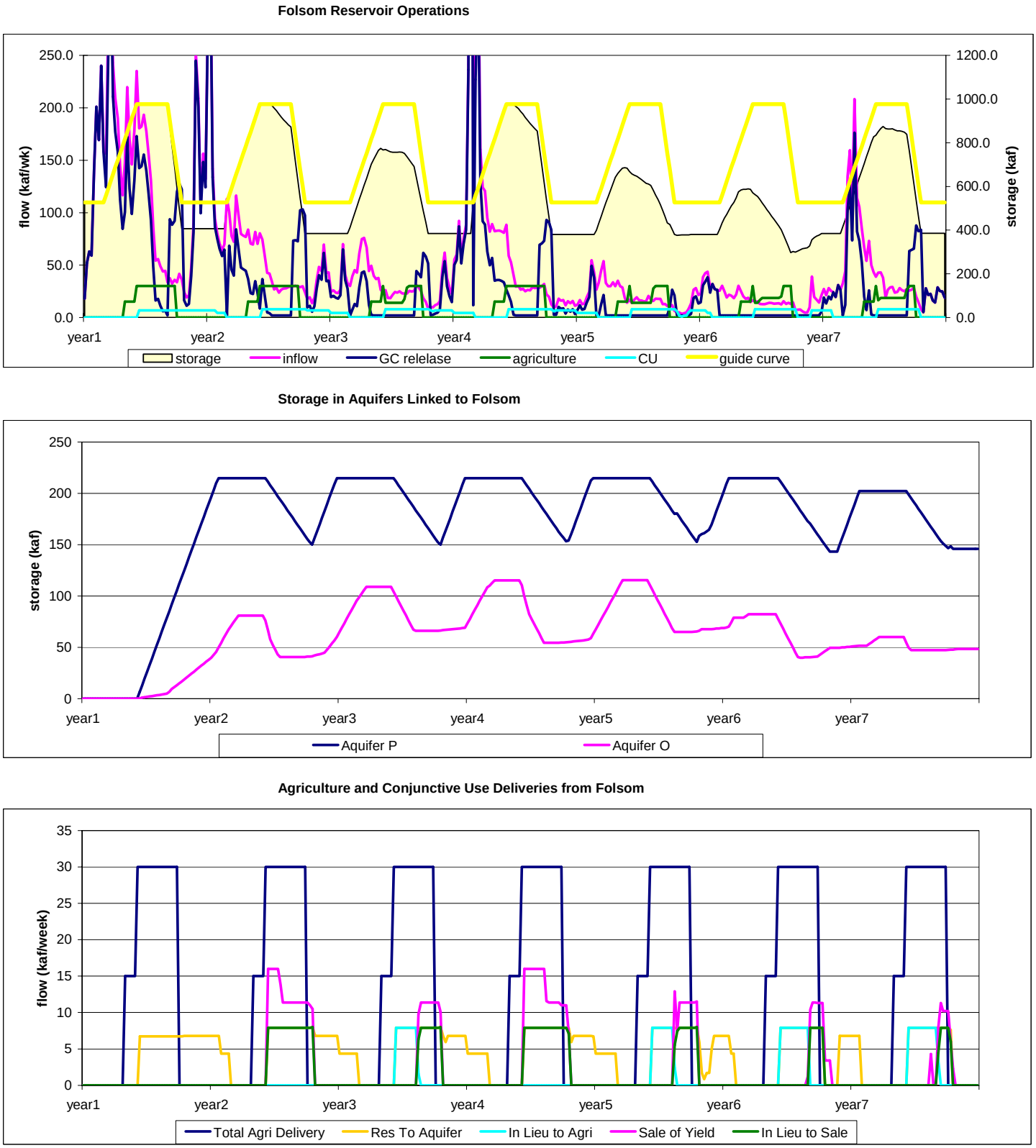


Figure A-9 Reservoir and Conjunctive Use Operations at Folsom Reservoir, 1983-1989

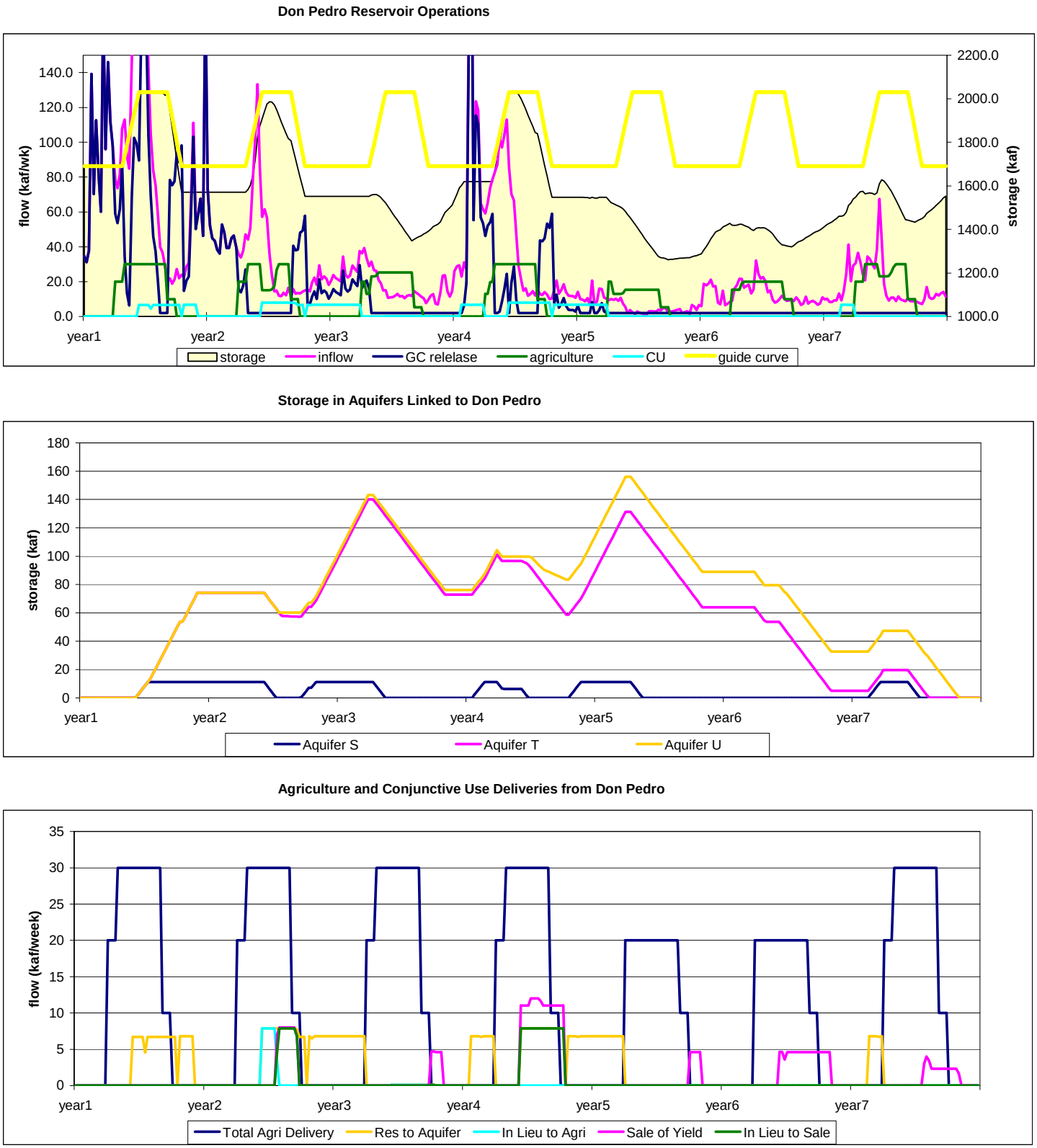


Figure A-10 Reservoir and Conjunctive Use Operations at Don Pedro Reservoir, 1983-1989

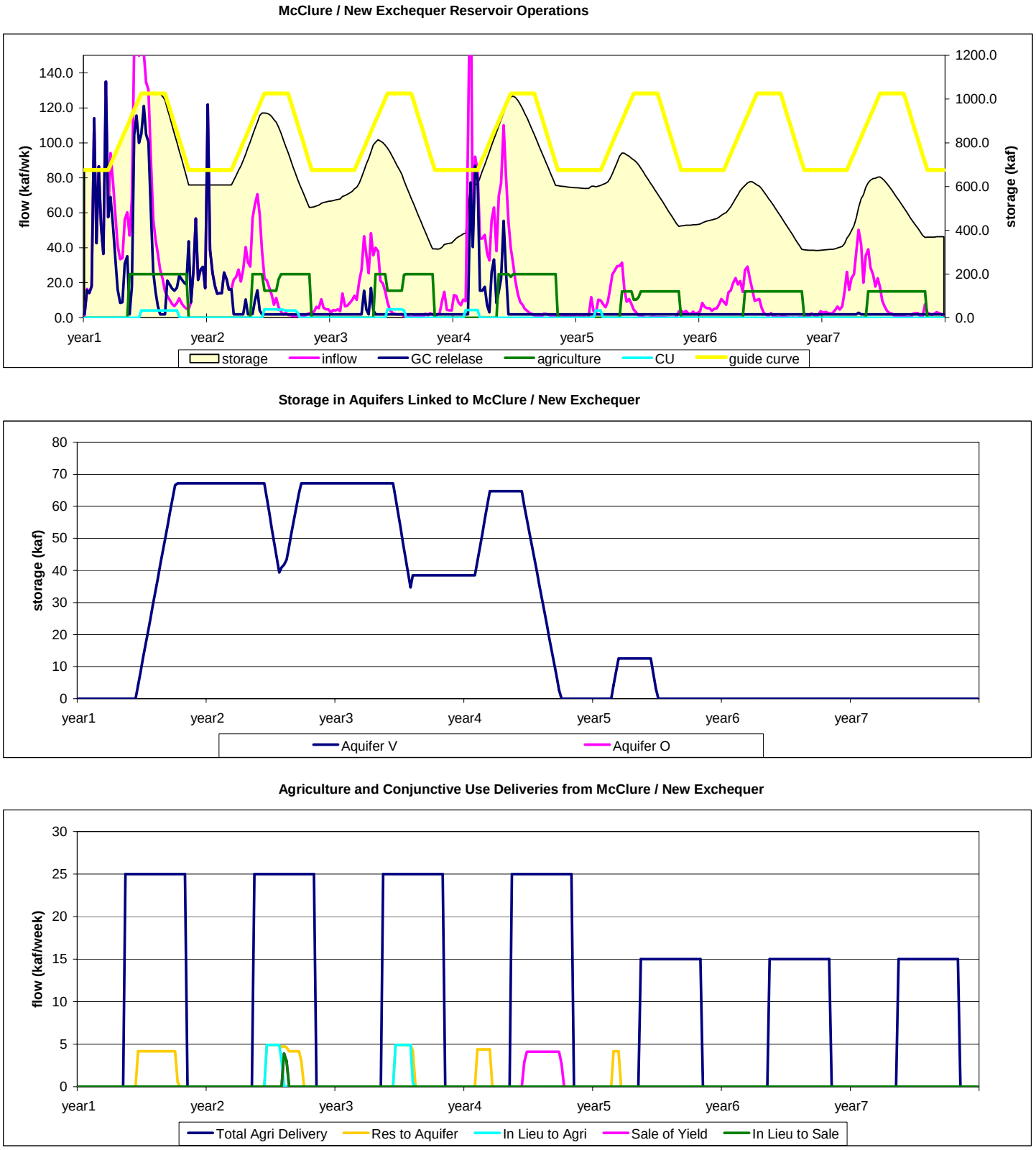


Figure A-11 Reservoir and Conjunctive Use Operations at McClure / New Exchequer, 1983-1989

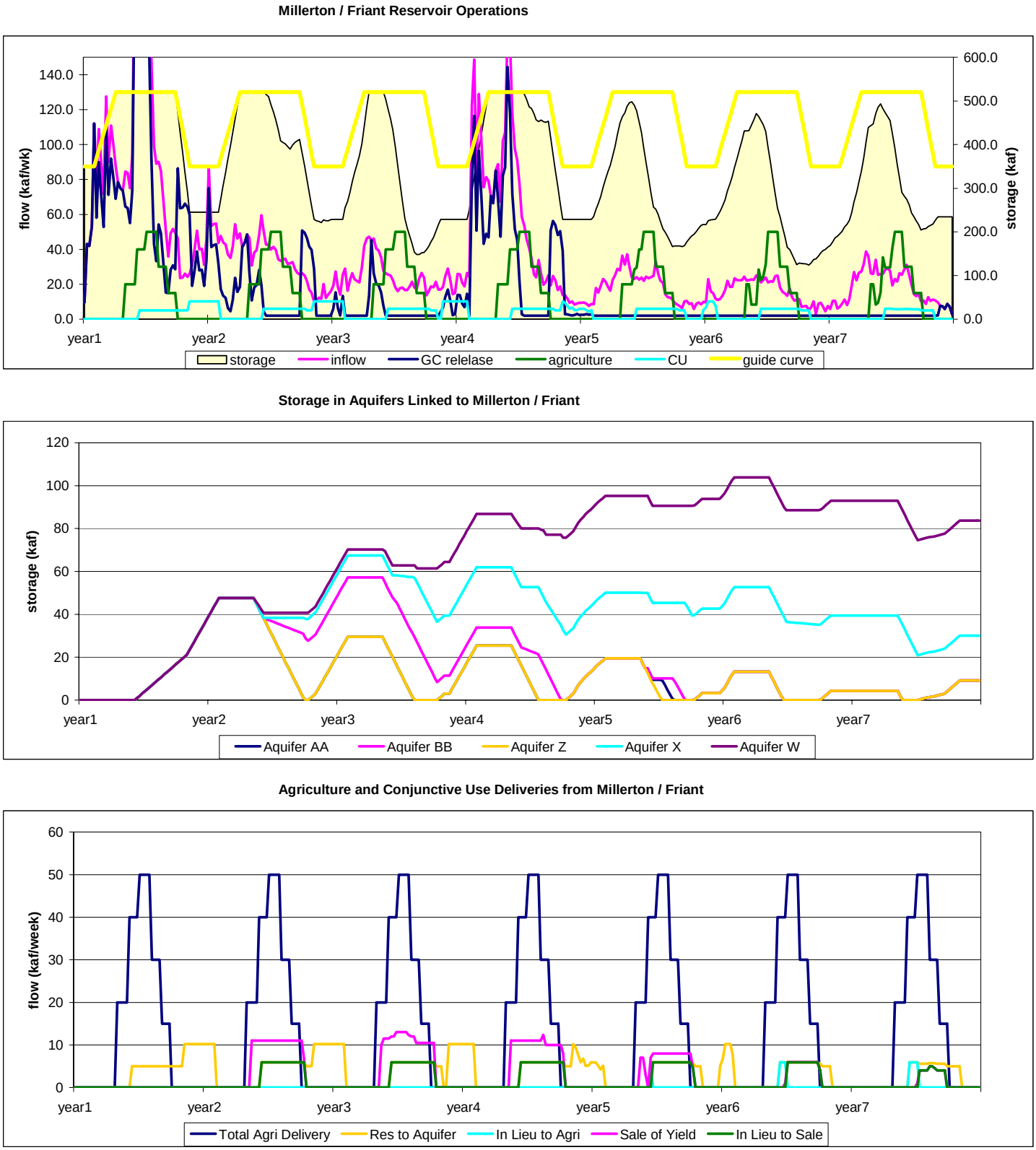
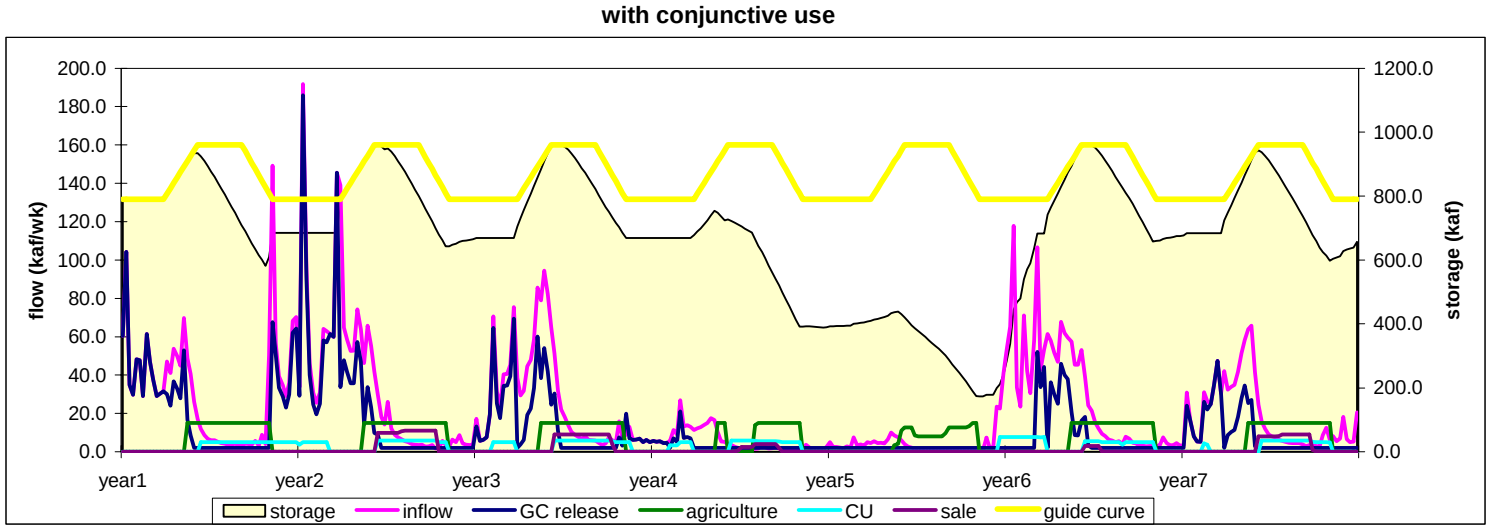


Figure A-12 Reservoir and Conjunctive Use Operations at Millerton / Friant, 1983-1989

Oroville Lake

Figure A-13 Oroville Reservoir Operations, with and without Conjunctive Use, 1973 - 1979

New Bullards Bar Reservoir



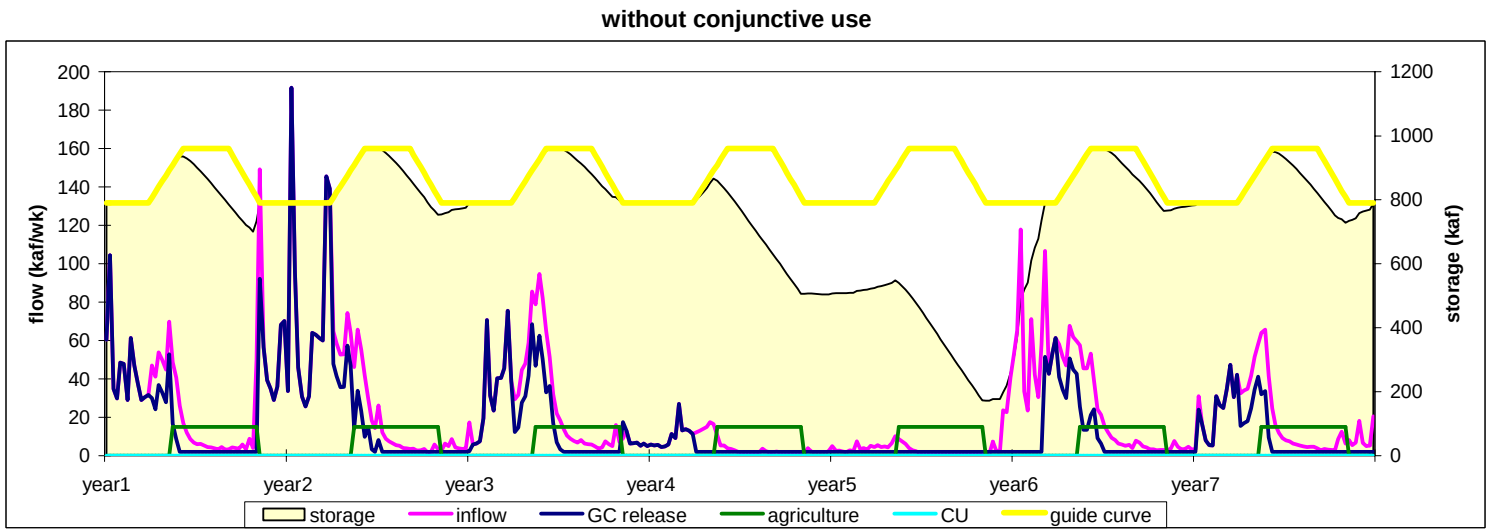


Figure A-14 New Bullards Bar Reservoir Operations, with and without Conjunctive Use, 1973 – 1979

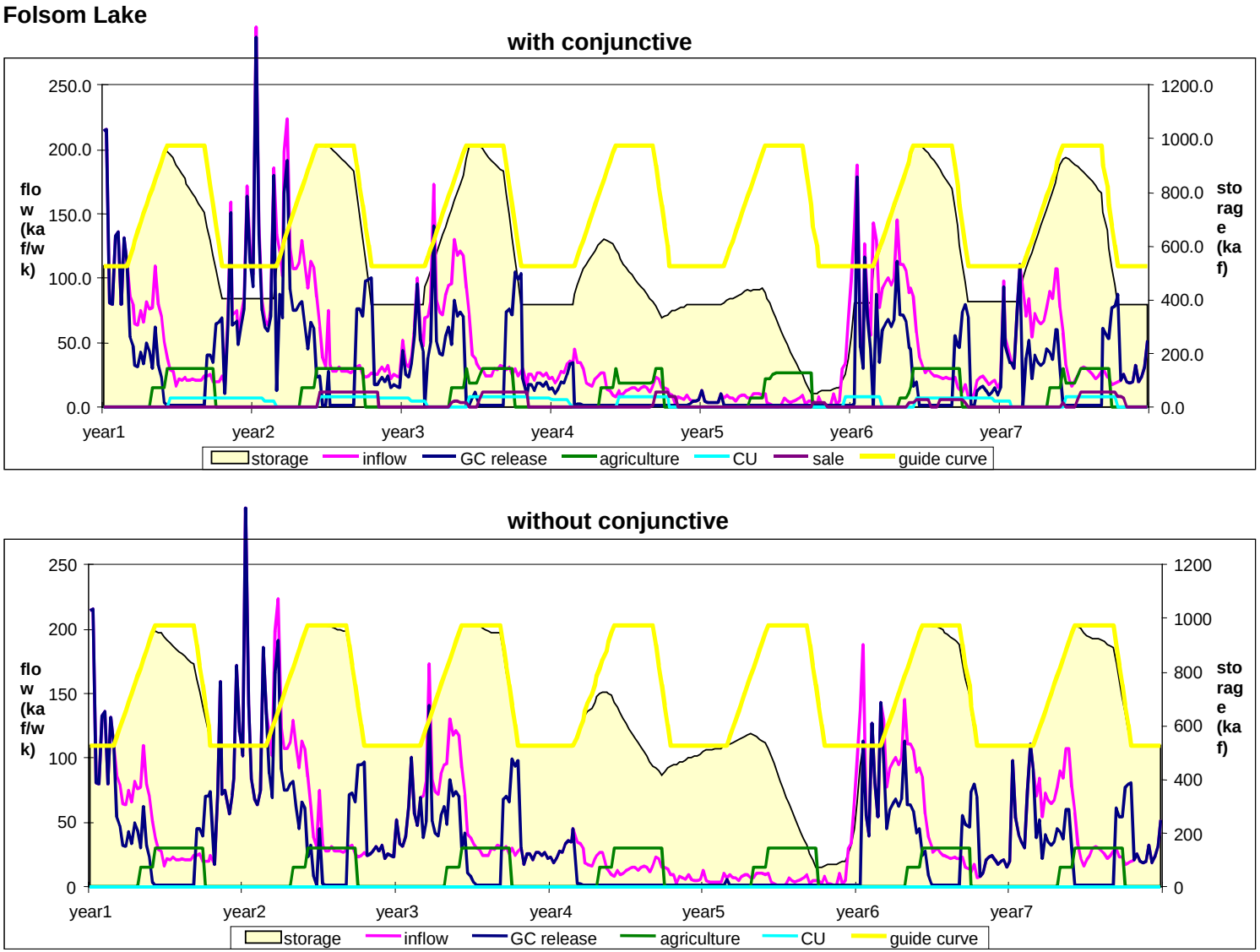
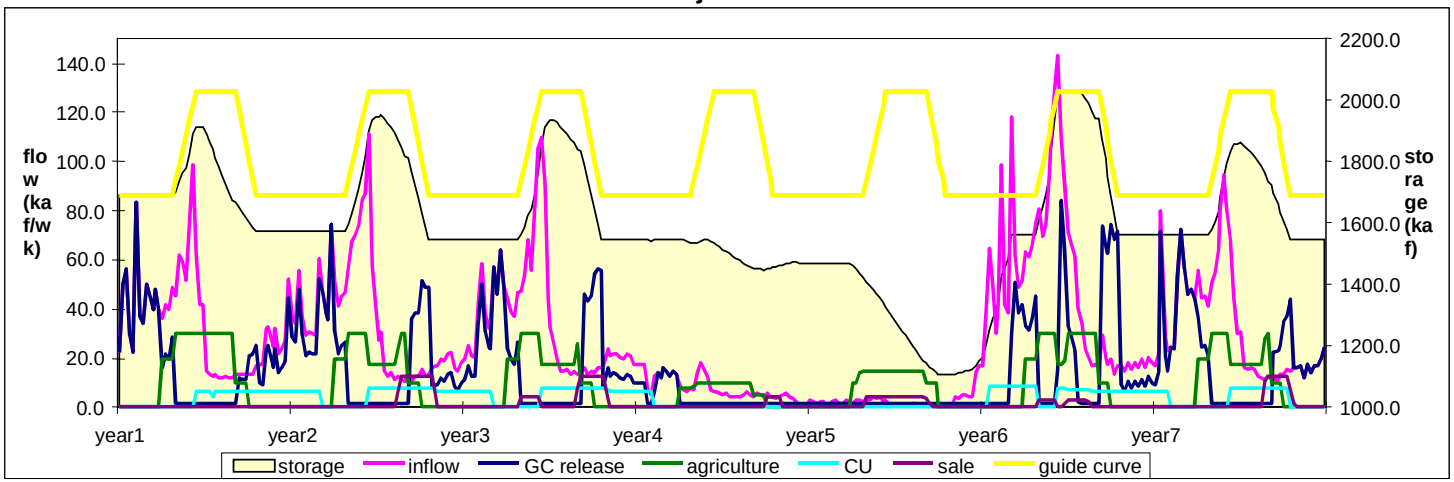


Figure A-15 Folsom Reservoir Operations, with and without Conjunctive Use, 1973 - 1979

New Don Pedro Reservoir

with conjunctive



without conjunctive

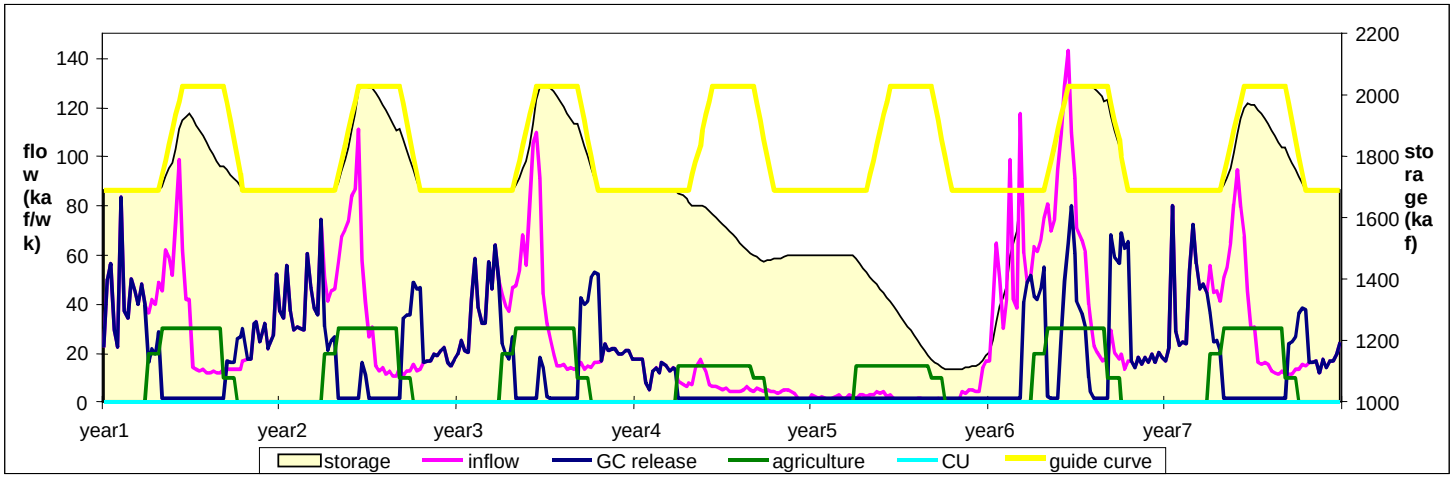


Figure A-16 Don Pedro Reservoir Operations, with and without Conjunctive Use, 1973 - 1979

Lake McClure / New Exchequer Dam

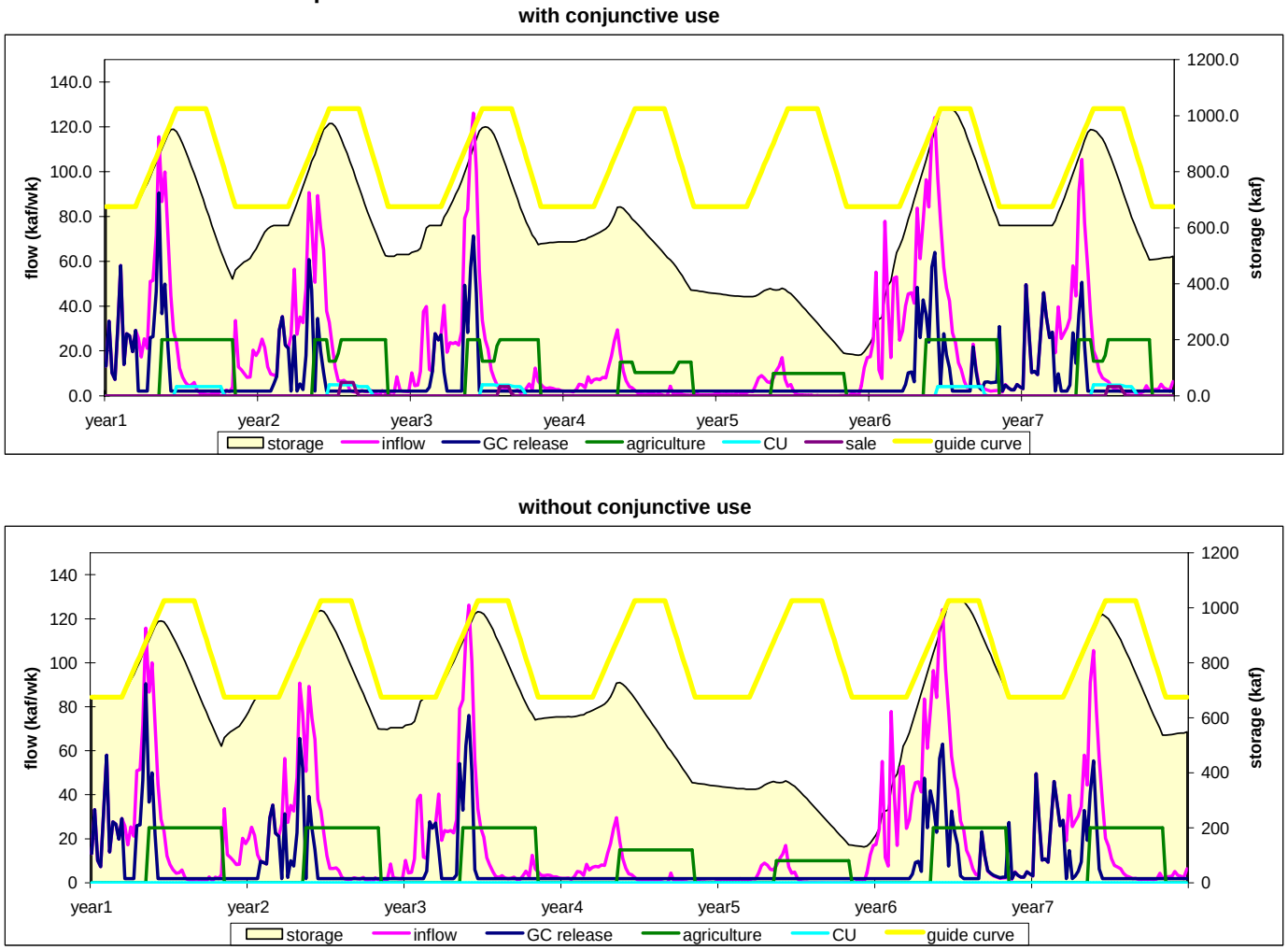


Figure A-17 McClure / New Exchequer Reservoir Operations, with and without Conjunctive Use, 1973 - 1979

Millerton Lake / Friant Dam

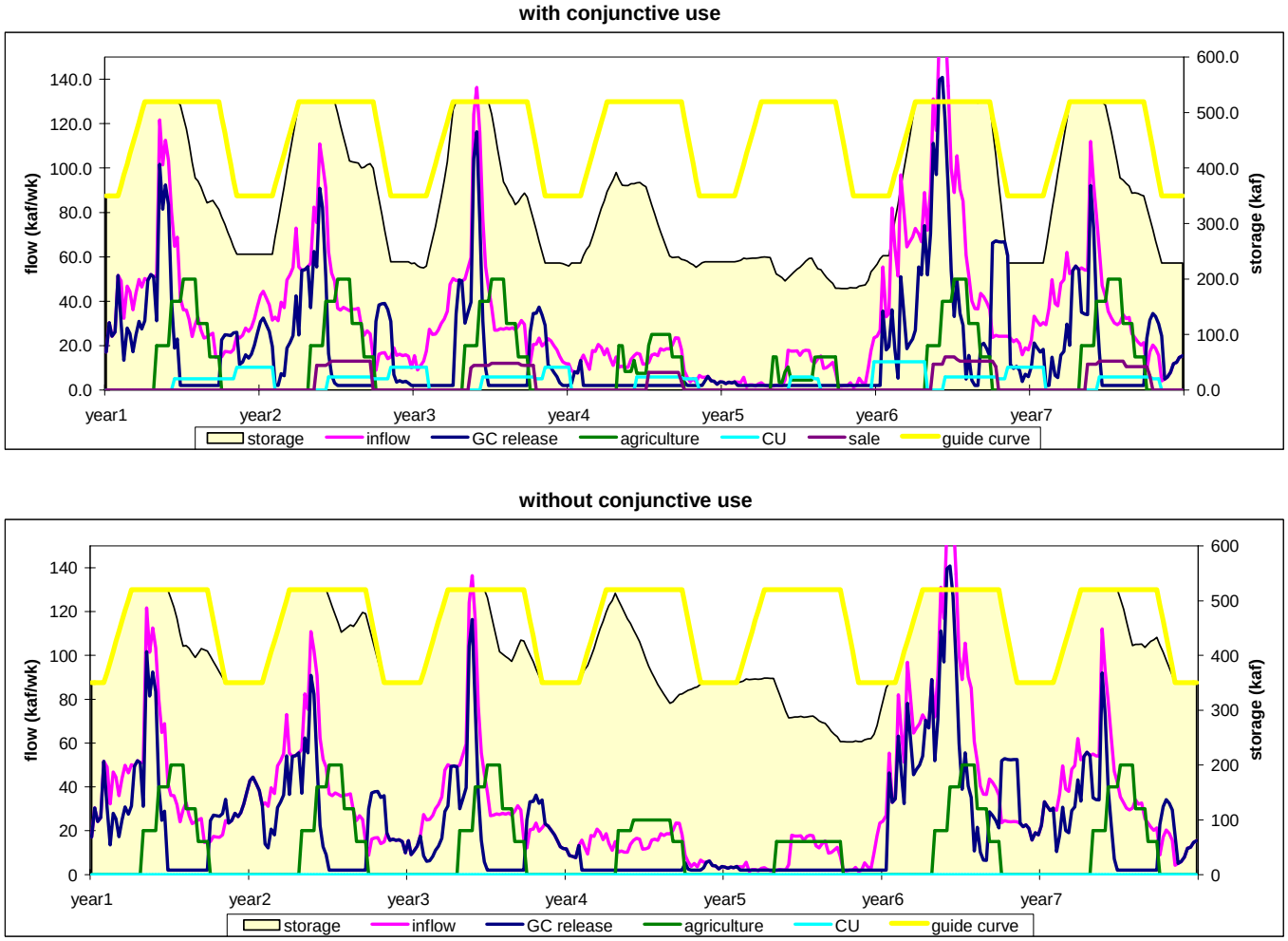


Figure A-18 Millerton / Friant Reservoir Operations, with and without Conjunctive Use, 1973 - 1979

Oroville Lake

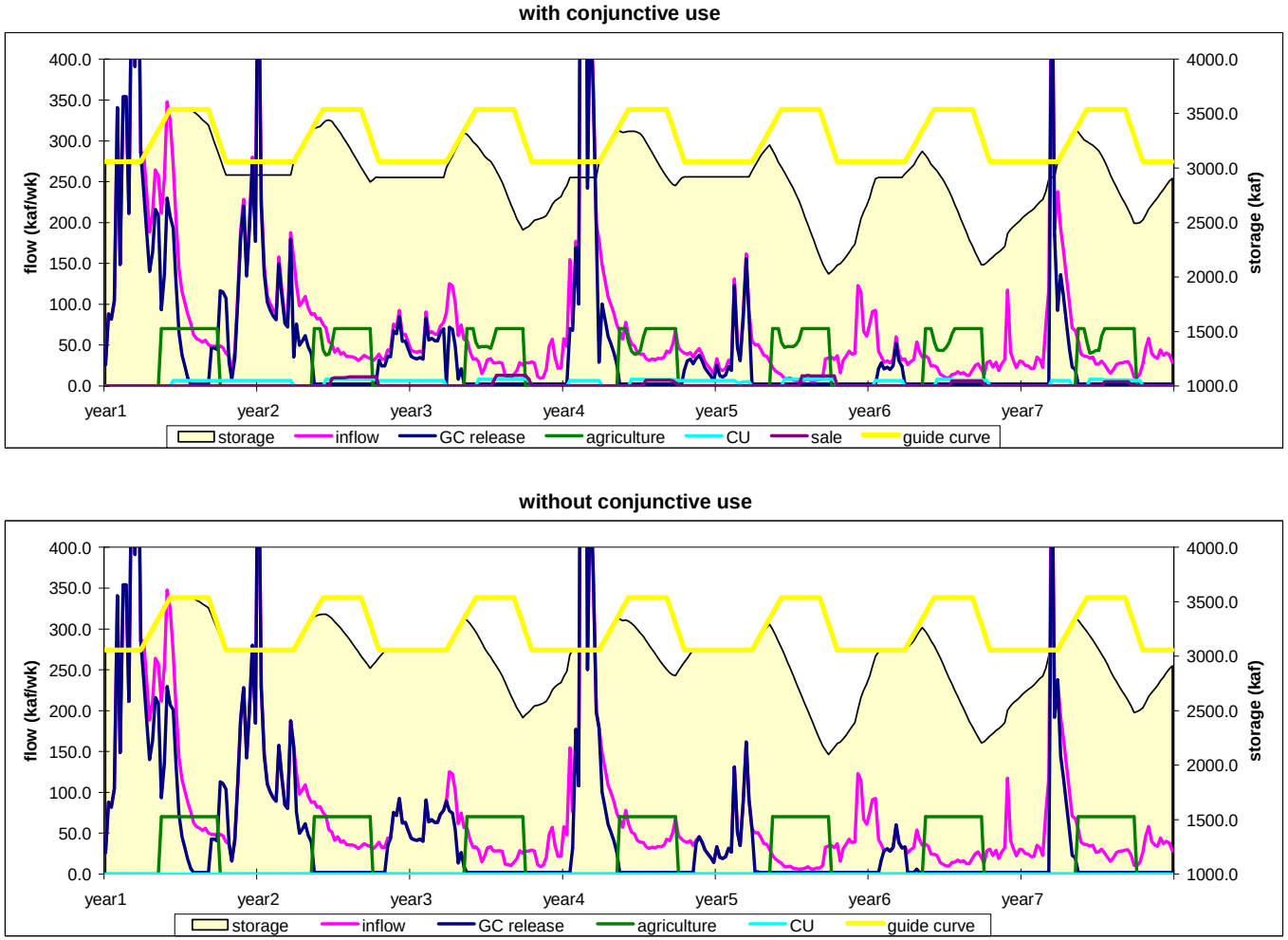


Figure A-19 Oroville Reservoir Operations, with and without Conjunctive Use, 1983 - 1989

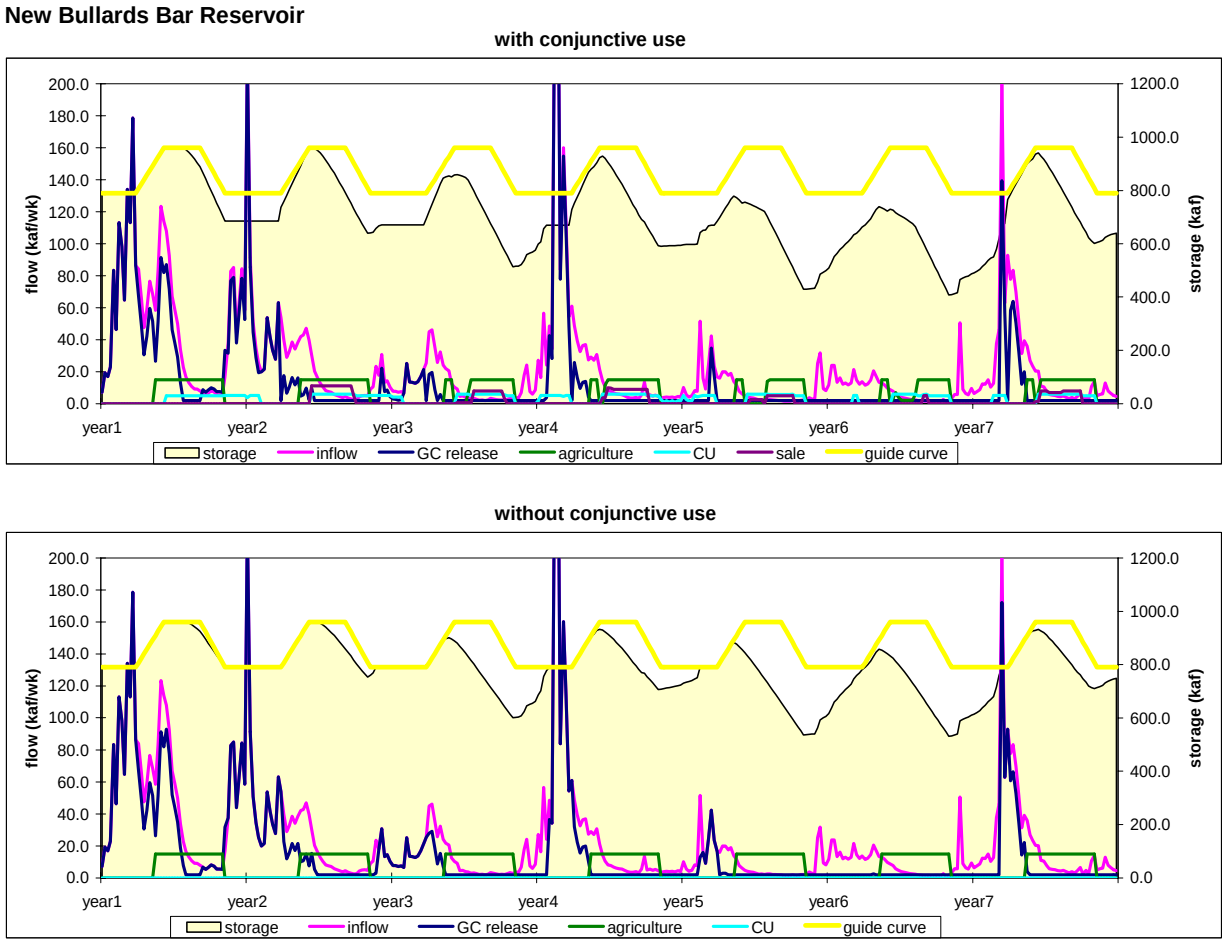


Figure A-20 New Bullards Bar Reservoir Operations, with and without Conjunctive Use, 1983 – 1989

Folsom Lake

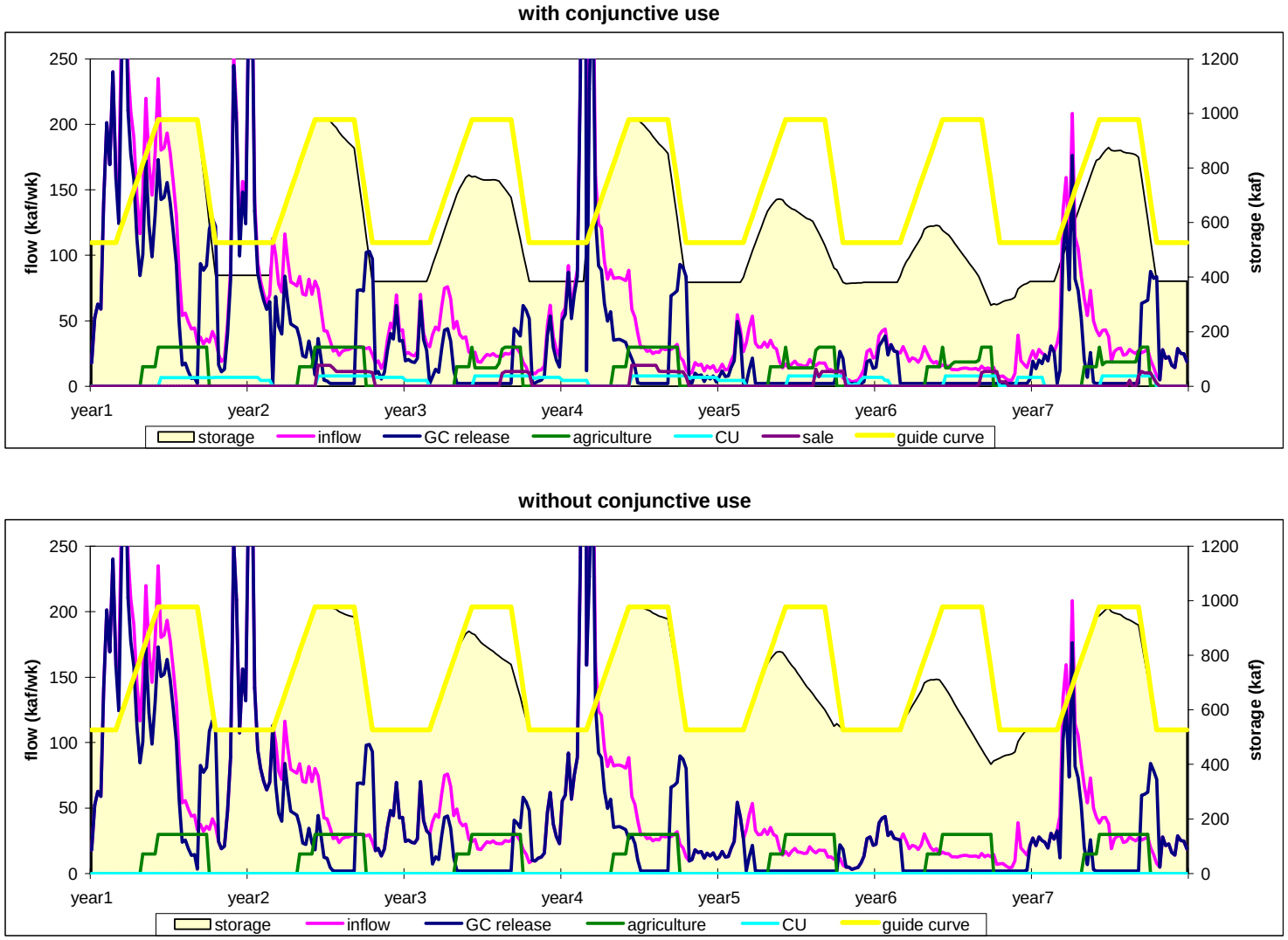


Figure A-21 Folsom Reservoir Operations, with and without Conjunctive Use, 1983 – 1989

New Don Pedro Reservoir

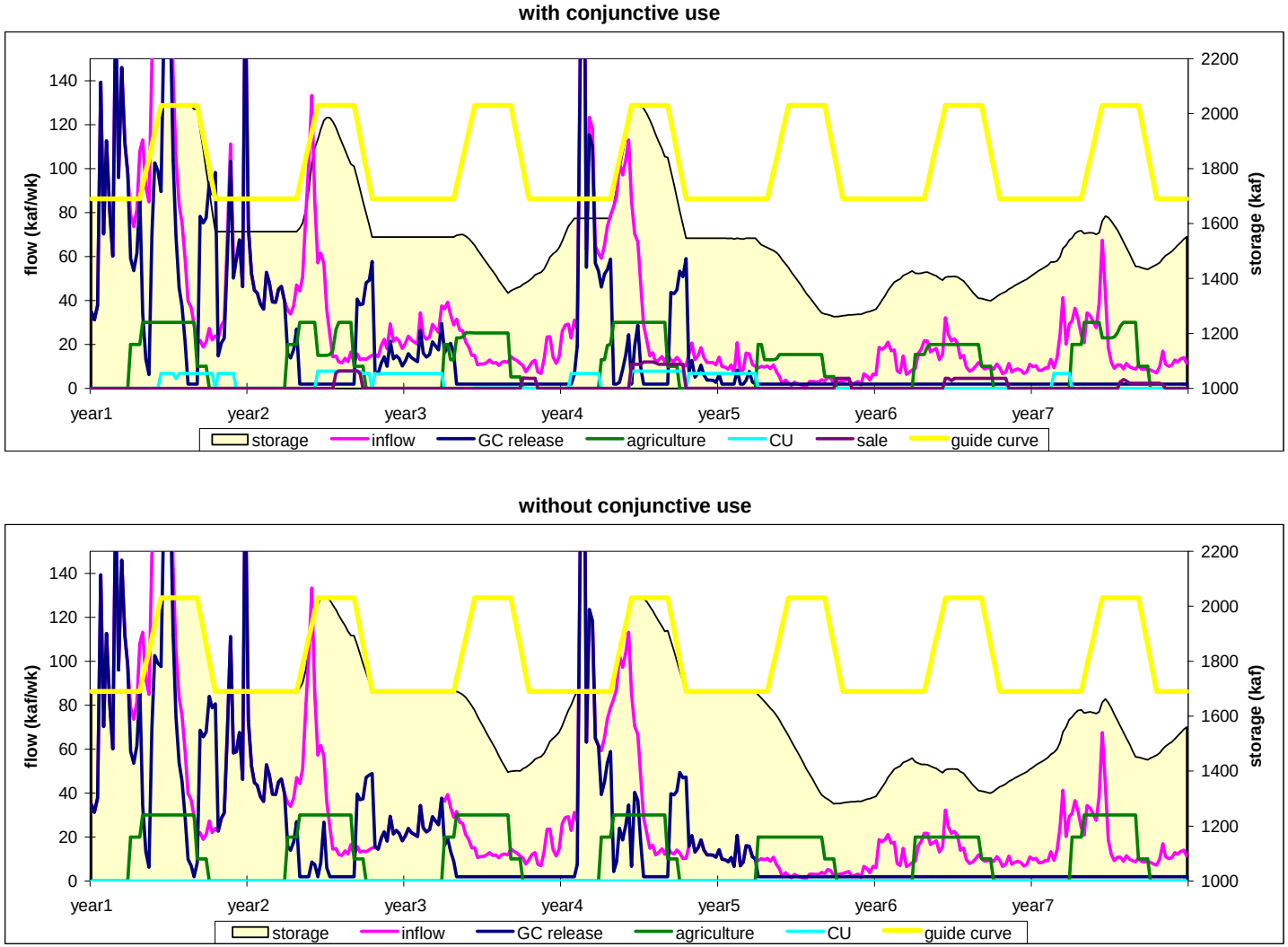


Figure A-22 Don Pedro Reservoir Operations, with and without Conjunctive Use, 1983 – 1989

Lake McClure / New Exchequer Dam

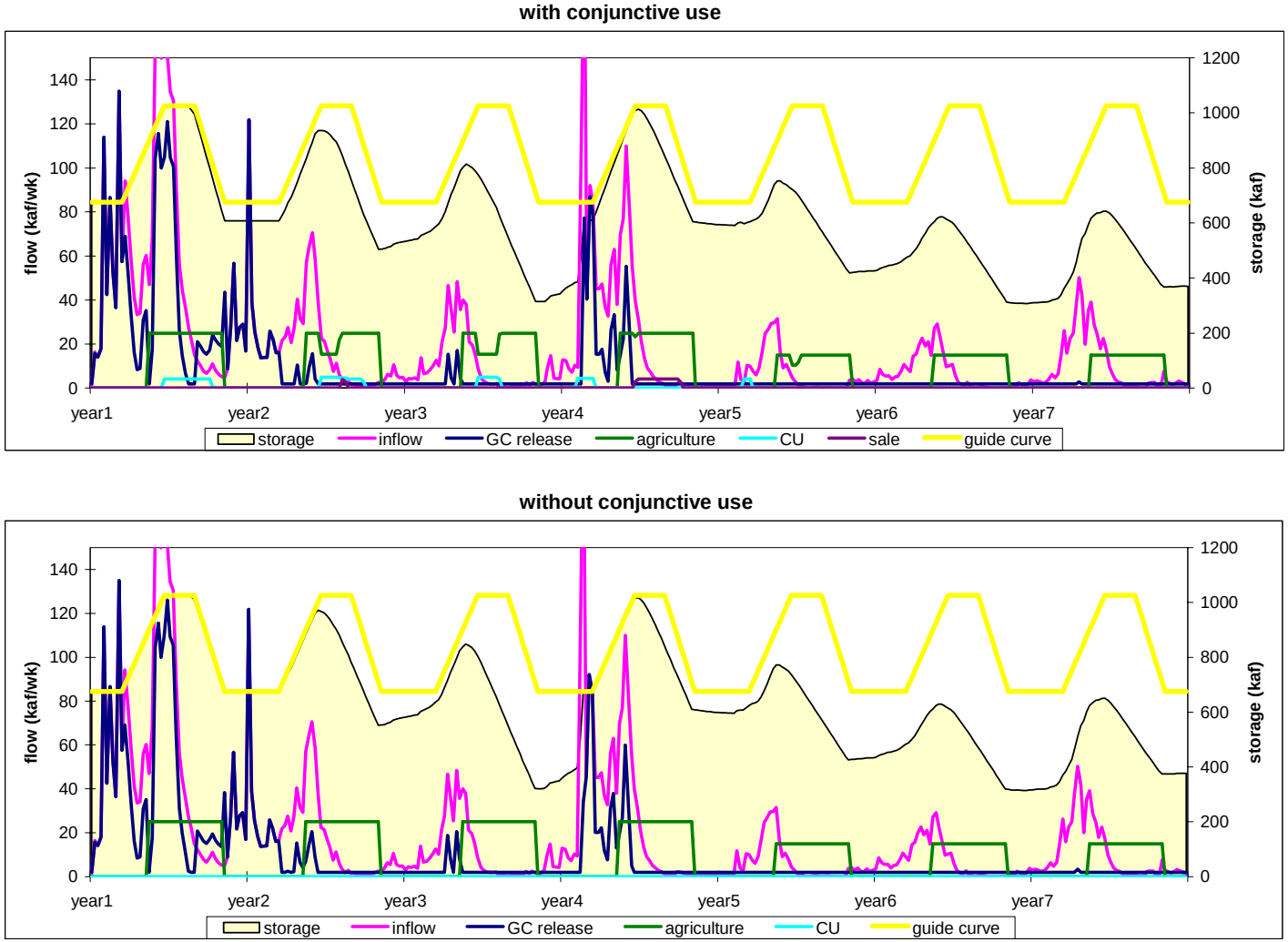


Figure A-23 McClure / New Exchequer Operations, with and without Conjunctive Use, 1983 – 1989

Millerton Lake / Friant Dam

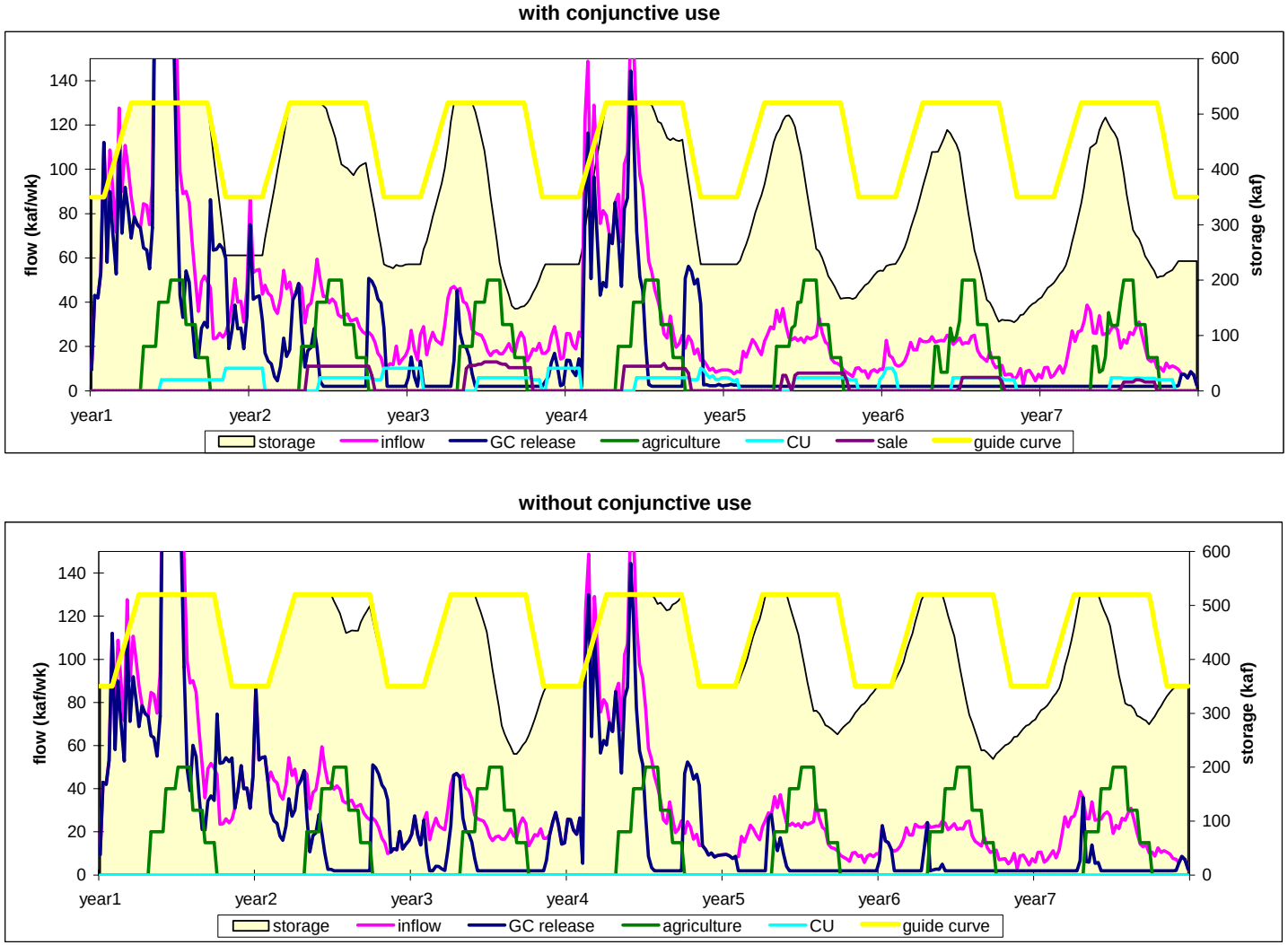


Figure A-24 Millerton / Friant Operations, with and without Conjunctive Use, 1983 – 1989

Appendix B. Flow Frequency Curves Resulting from Type 1 CU Operation

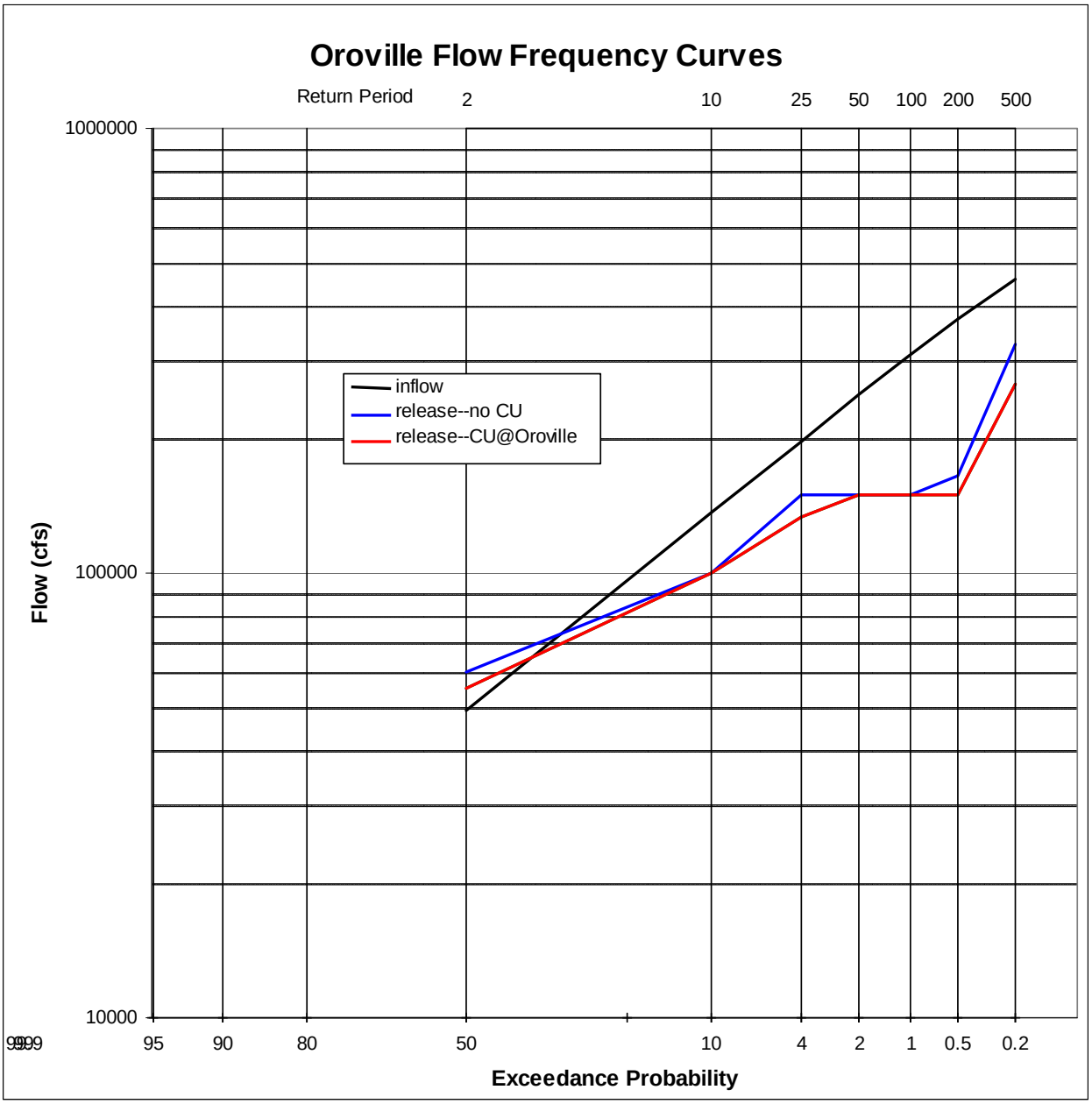


Figure B-1. Oroville Flow Frequency Curves, Unregulated, Regulated, Regulated w/CU

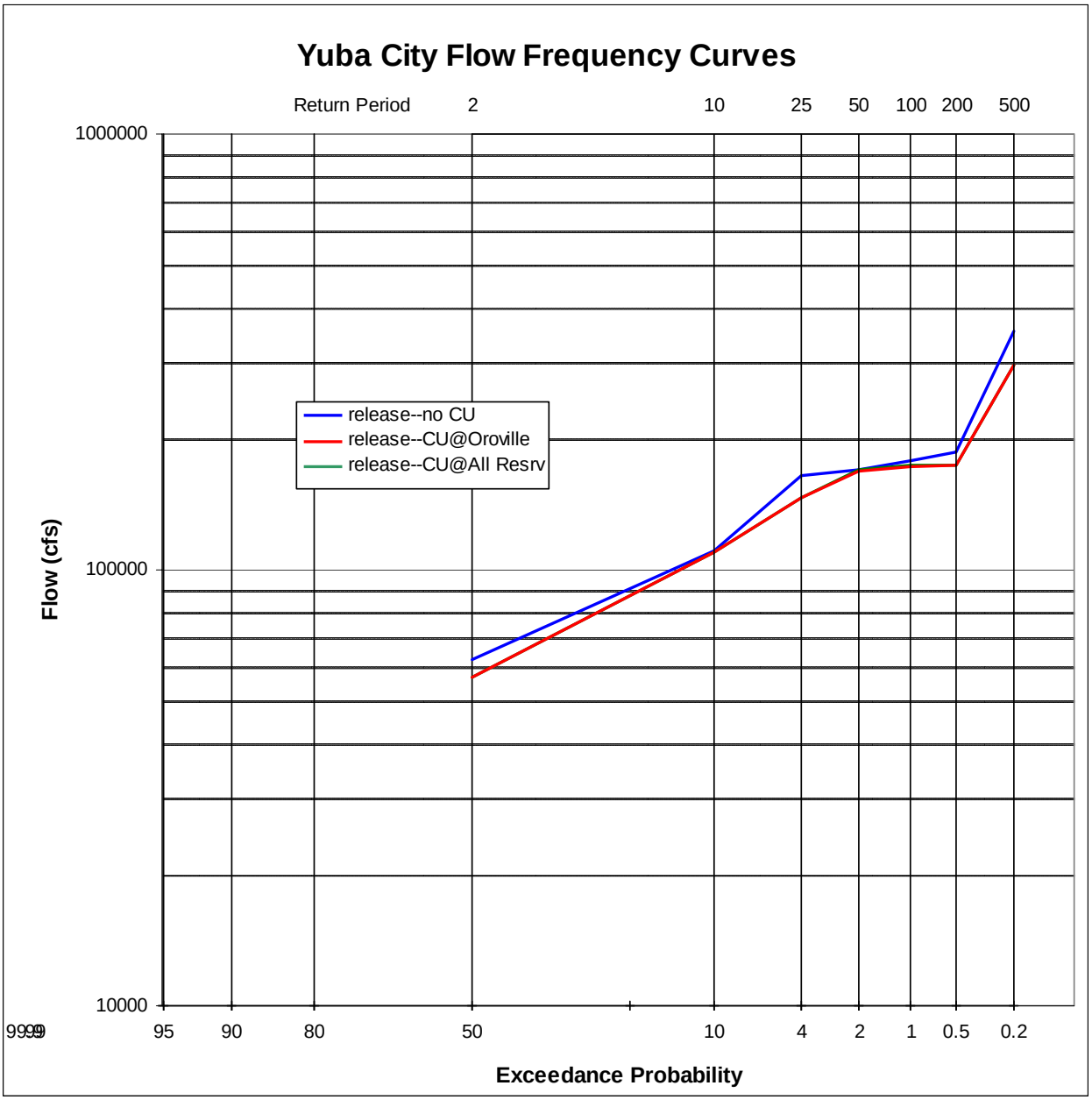


Figure B-2. Yuba City Flow Frequency Curves, Regulated, Regulated w/CU

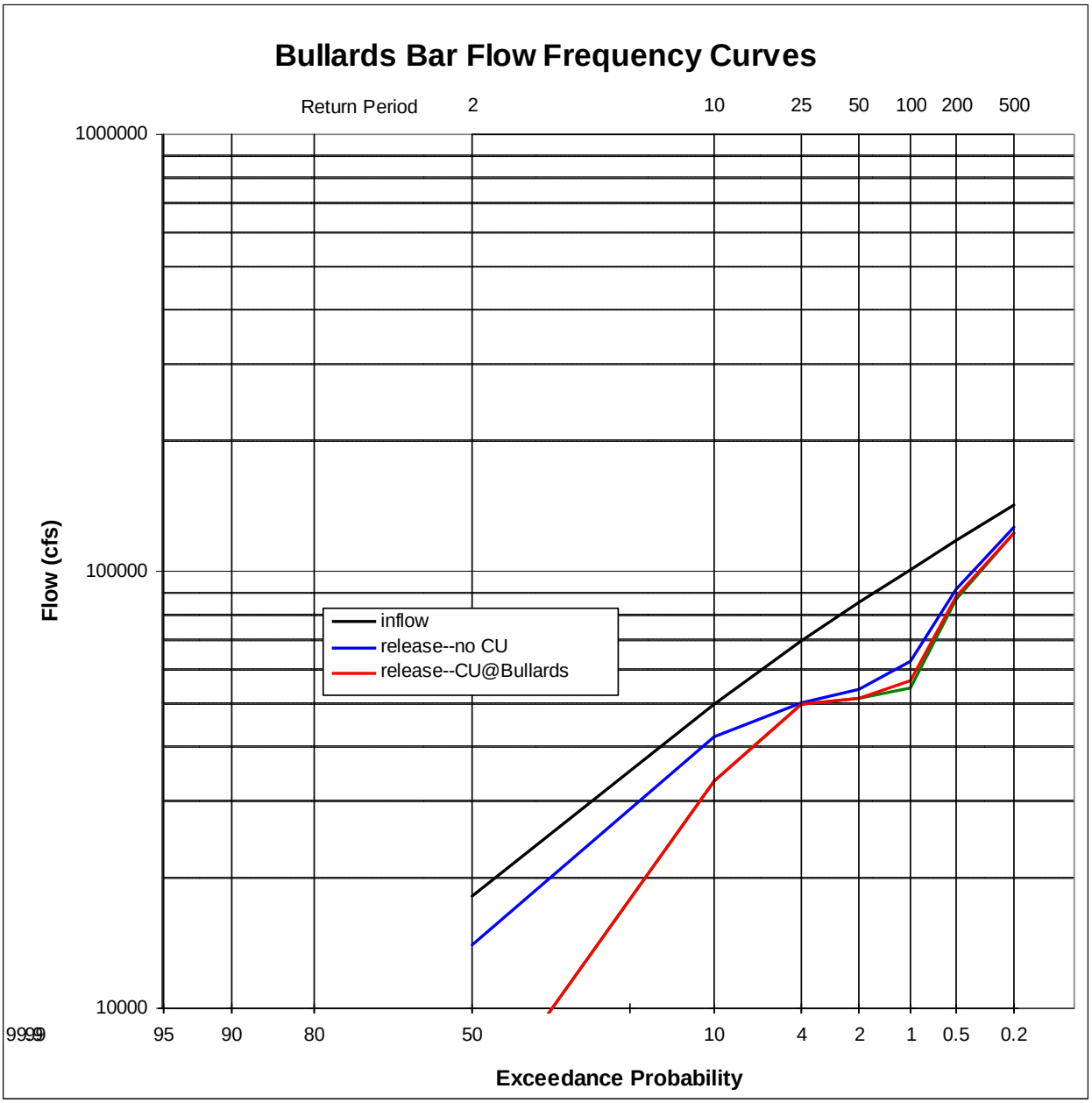


Figure B-3. New Bullards Bar Frequency Curves, Unregulated, Regulated, Regulated w/CU

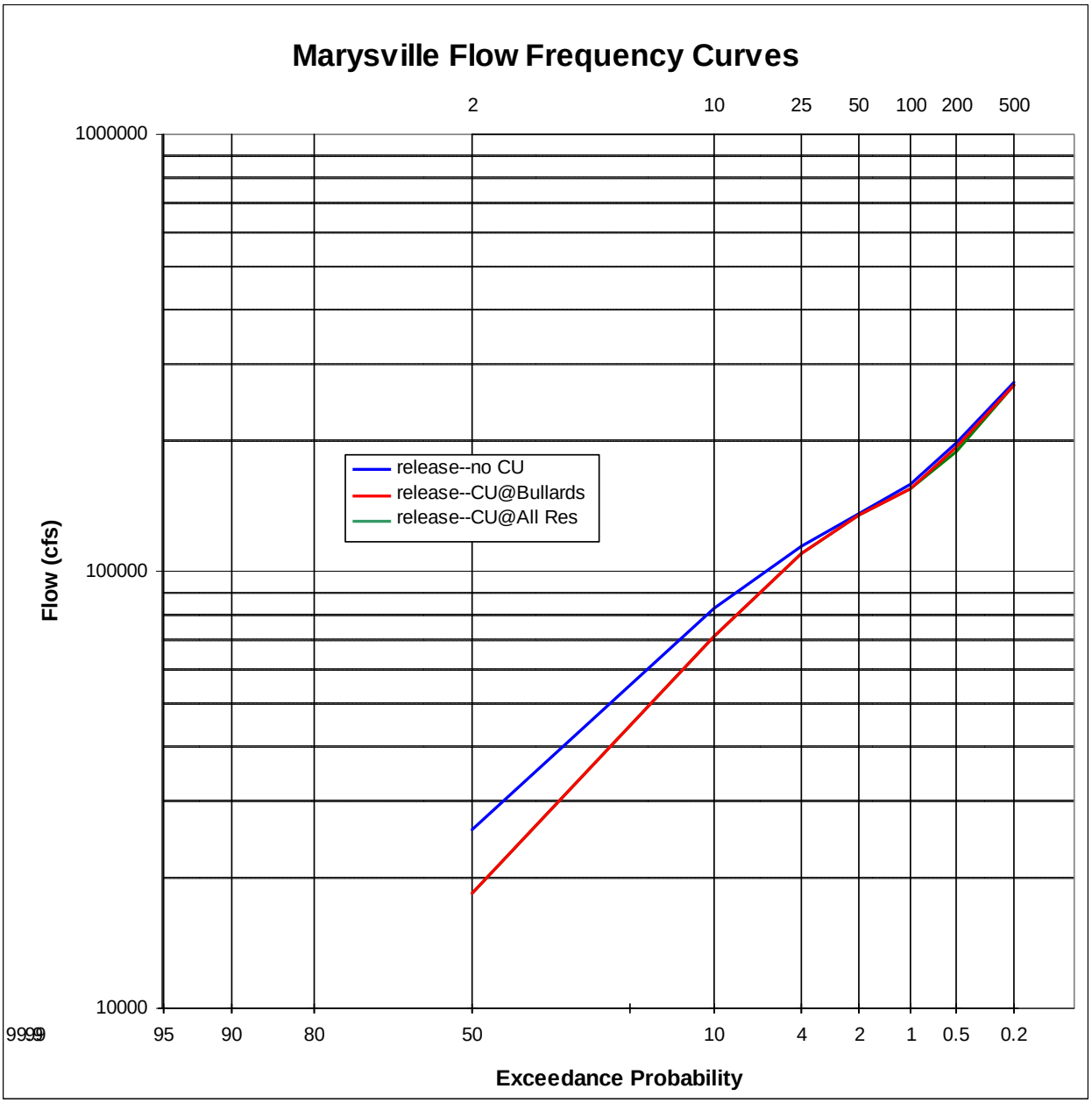


Figure B-4. Marysville Flow Frequency Curves, Regulated, Regulated w/CU

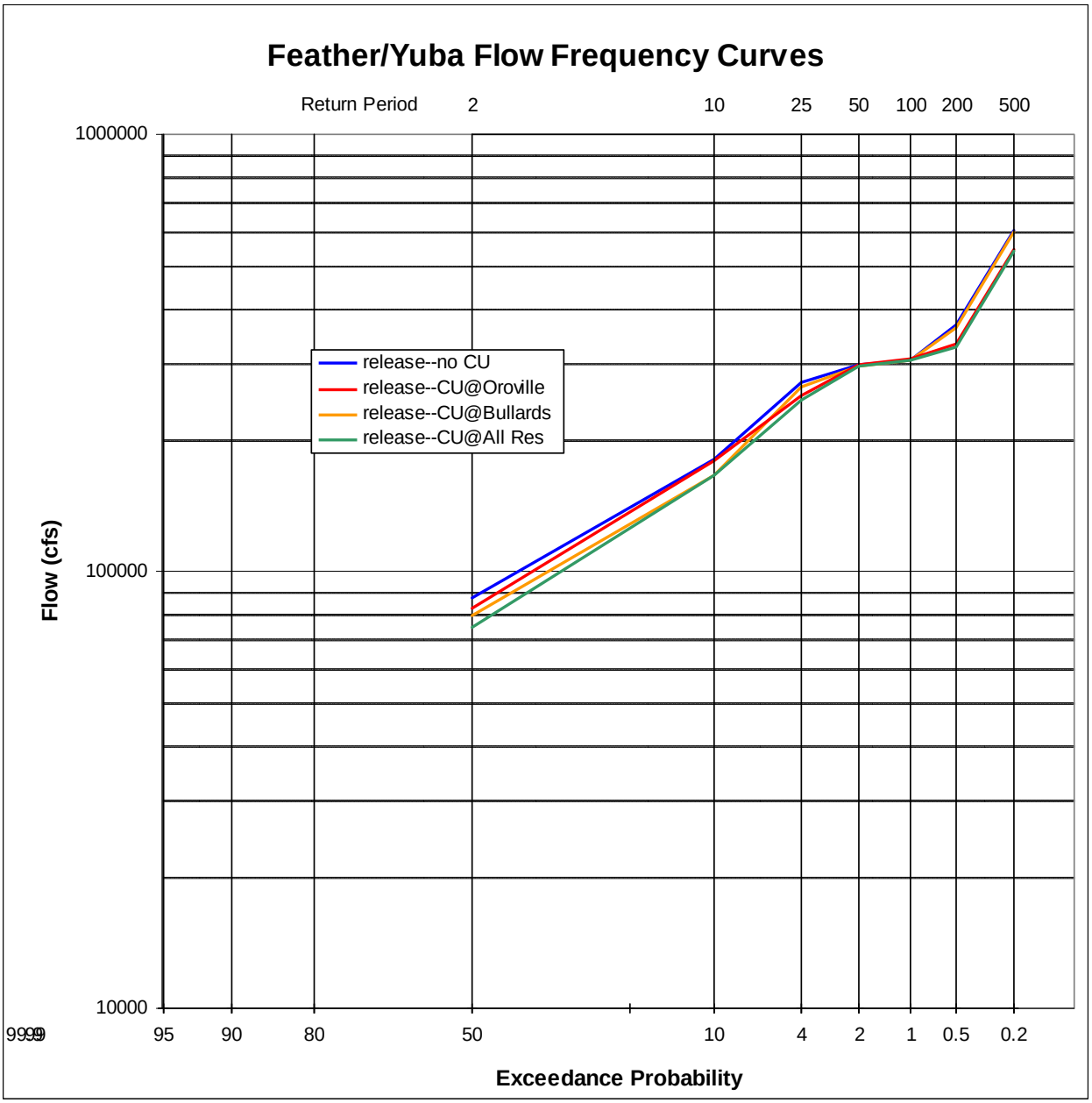


Figure B-5. Feather/Yuba Confluence Flow Frequency Curves, Regulated, Regulated w/CU

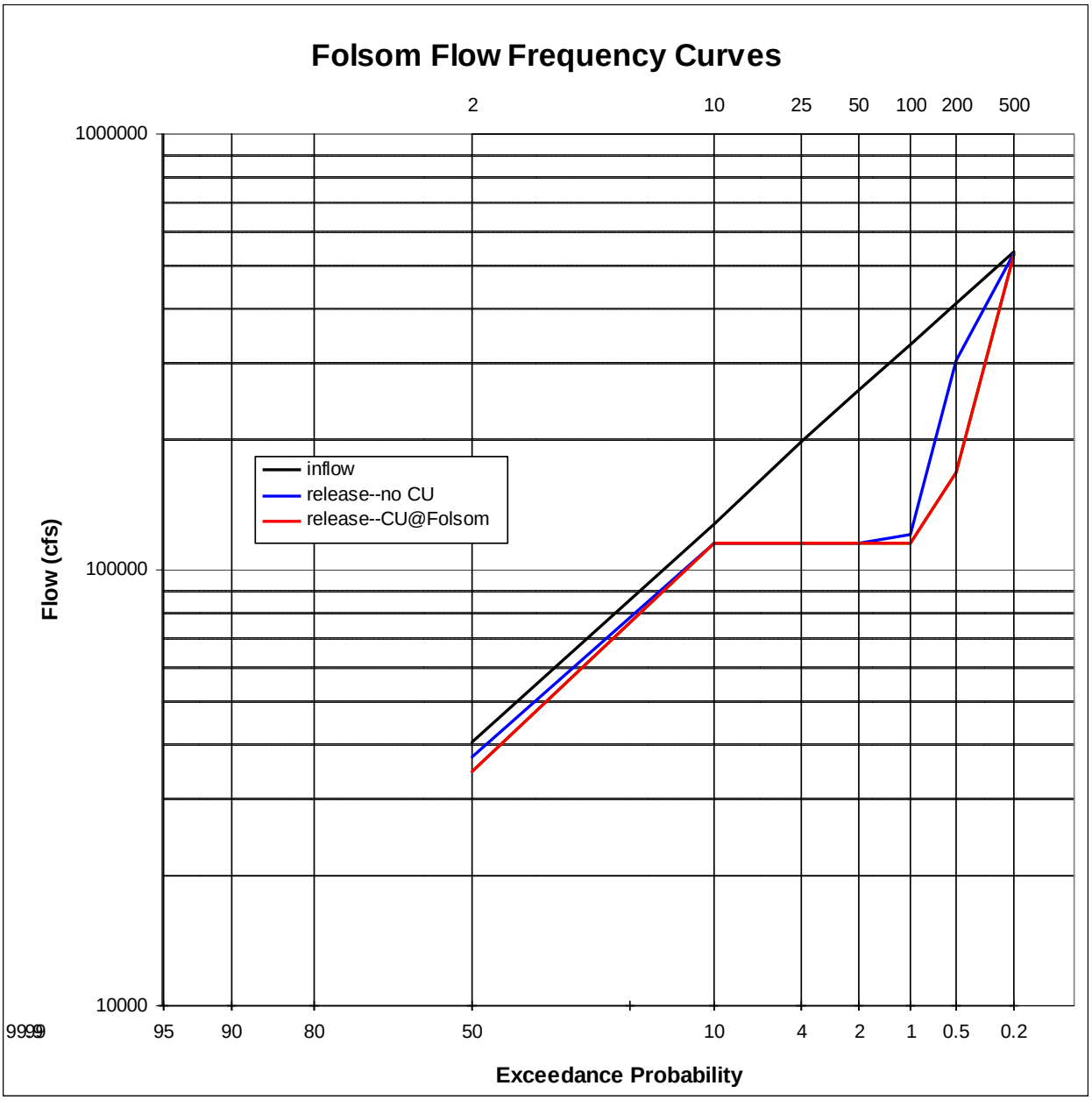


Figure B-6. Folsom Flow Frequency Curves, Unregulated, Regulated, Regulated w/CU

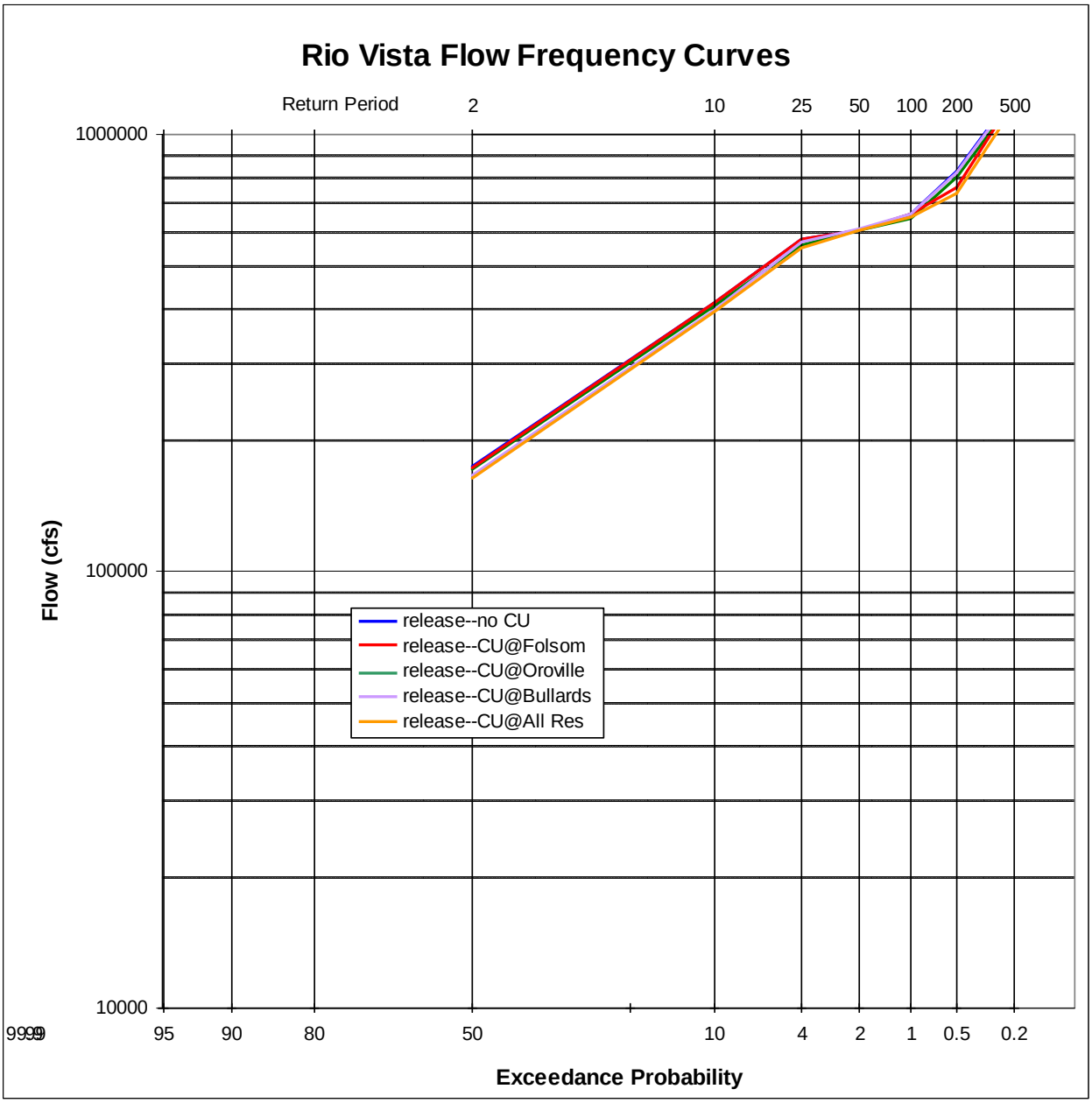


Figure B-7. Rio Vista Frequency Curves, Regulated, Regulated w/CU

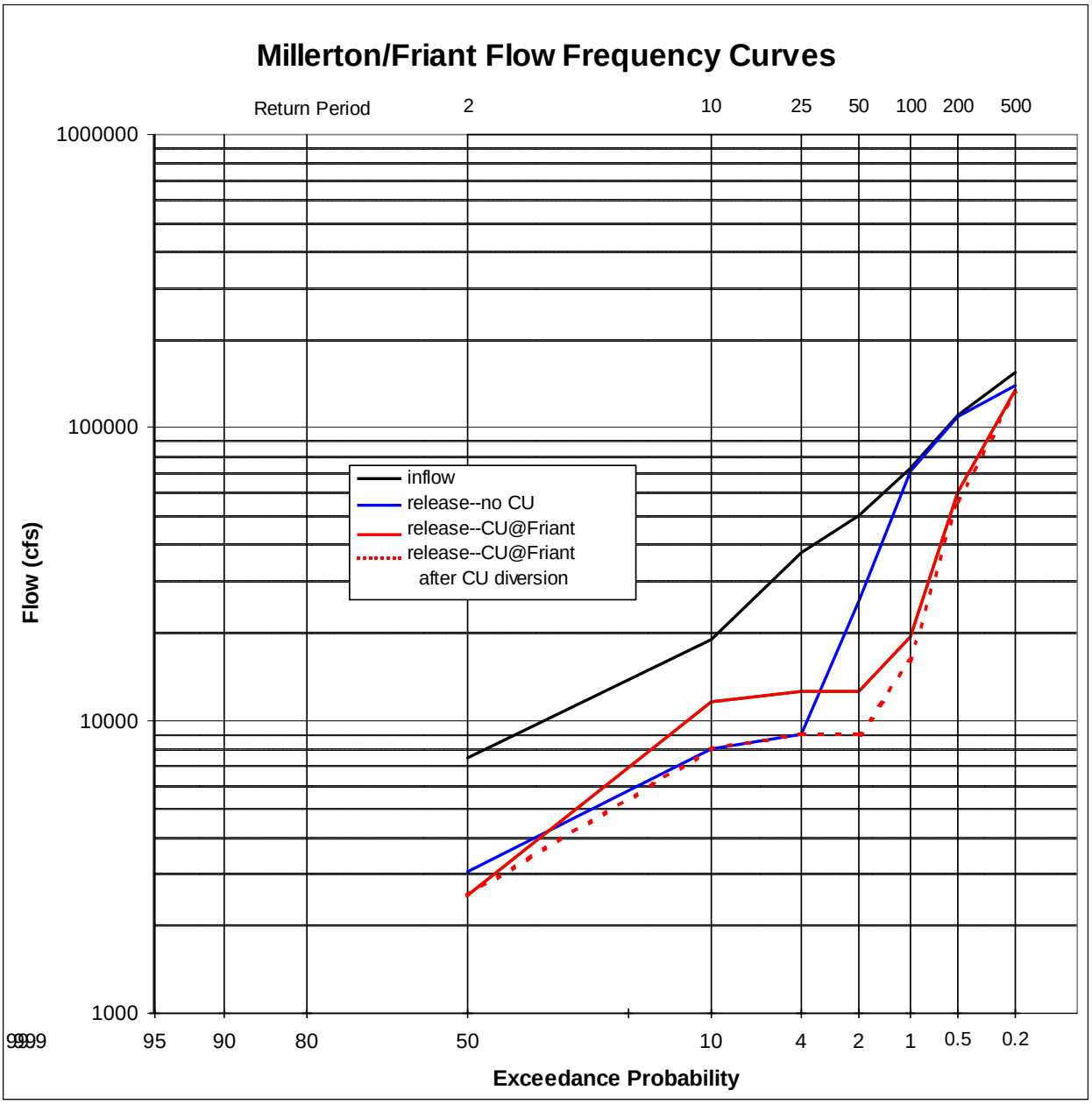


Figure B-8. Millerton/Friant Flow Frequency Curves, Unregulated, Regulated, Regulated w/CU

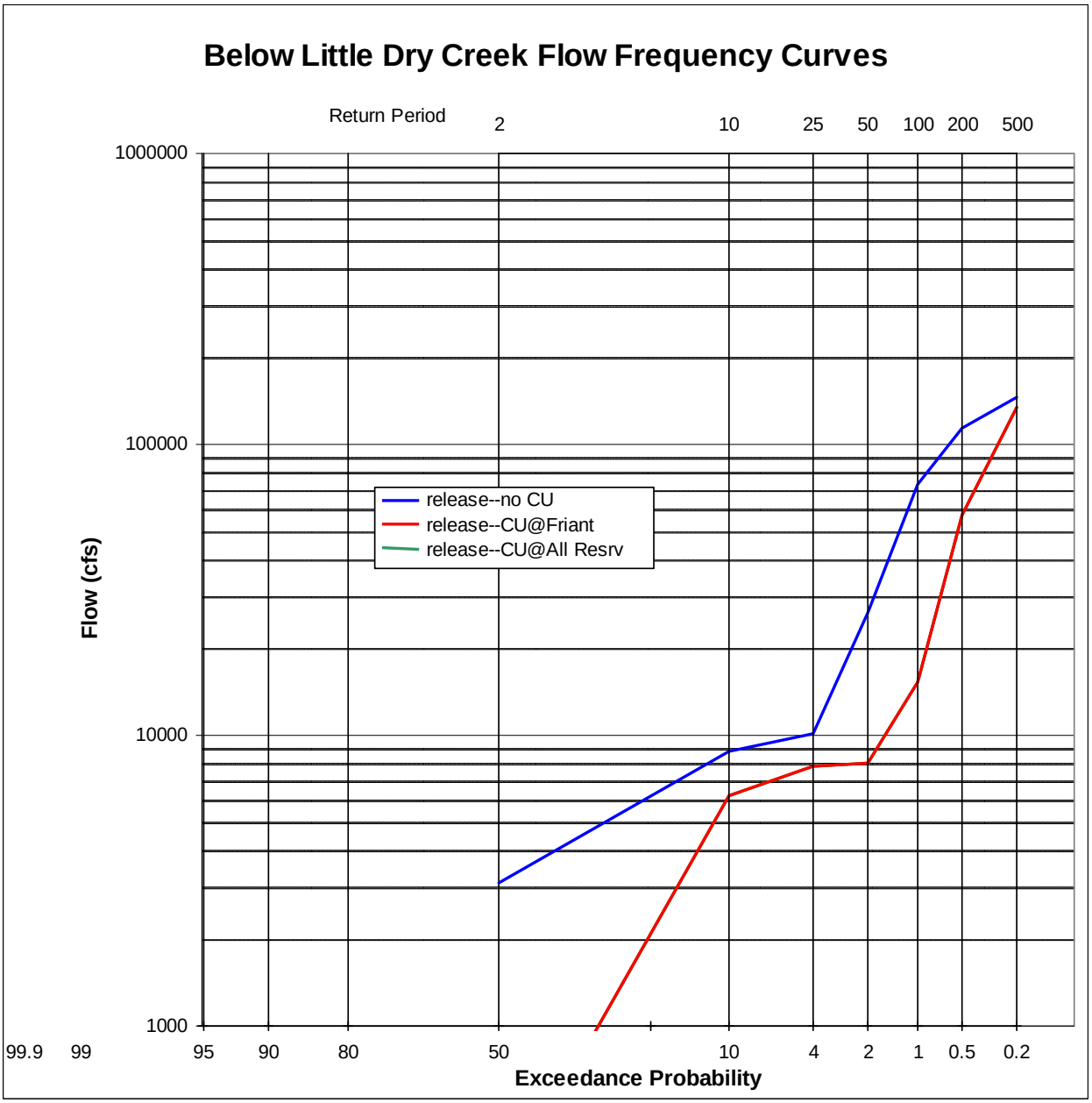


Figure B-9. Below Little Dry Creek Frequency Curves, Regulated, Regulated w/CU

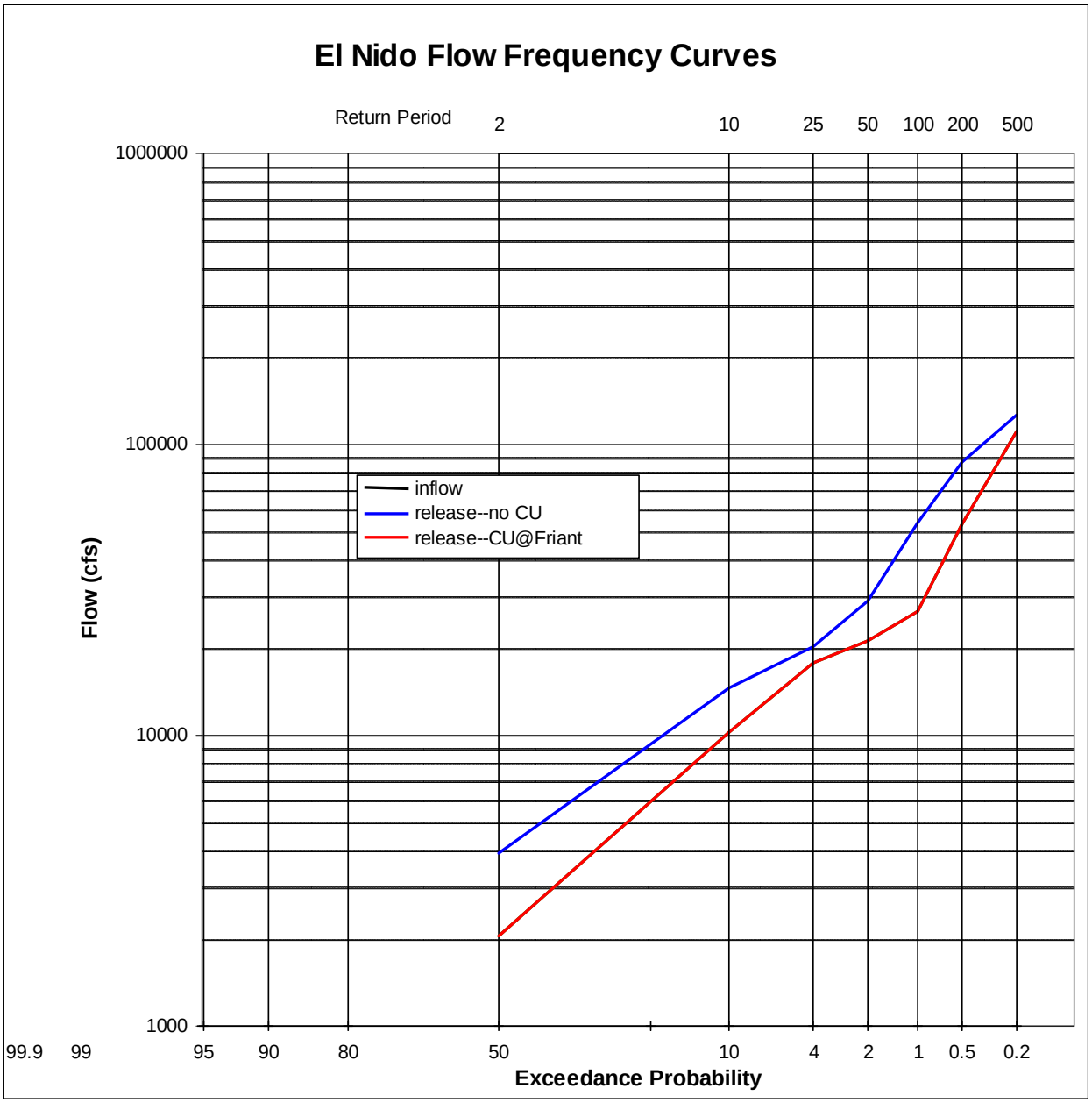


Figure B-10. El Nido Frequency Curves, Regulated, Regulated w/CU

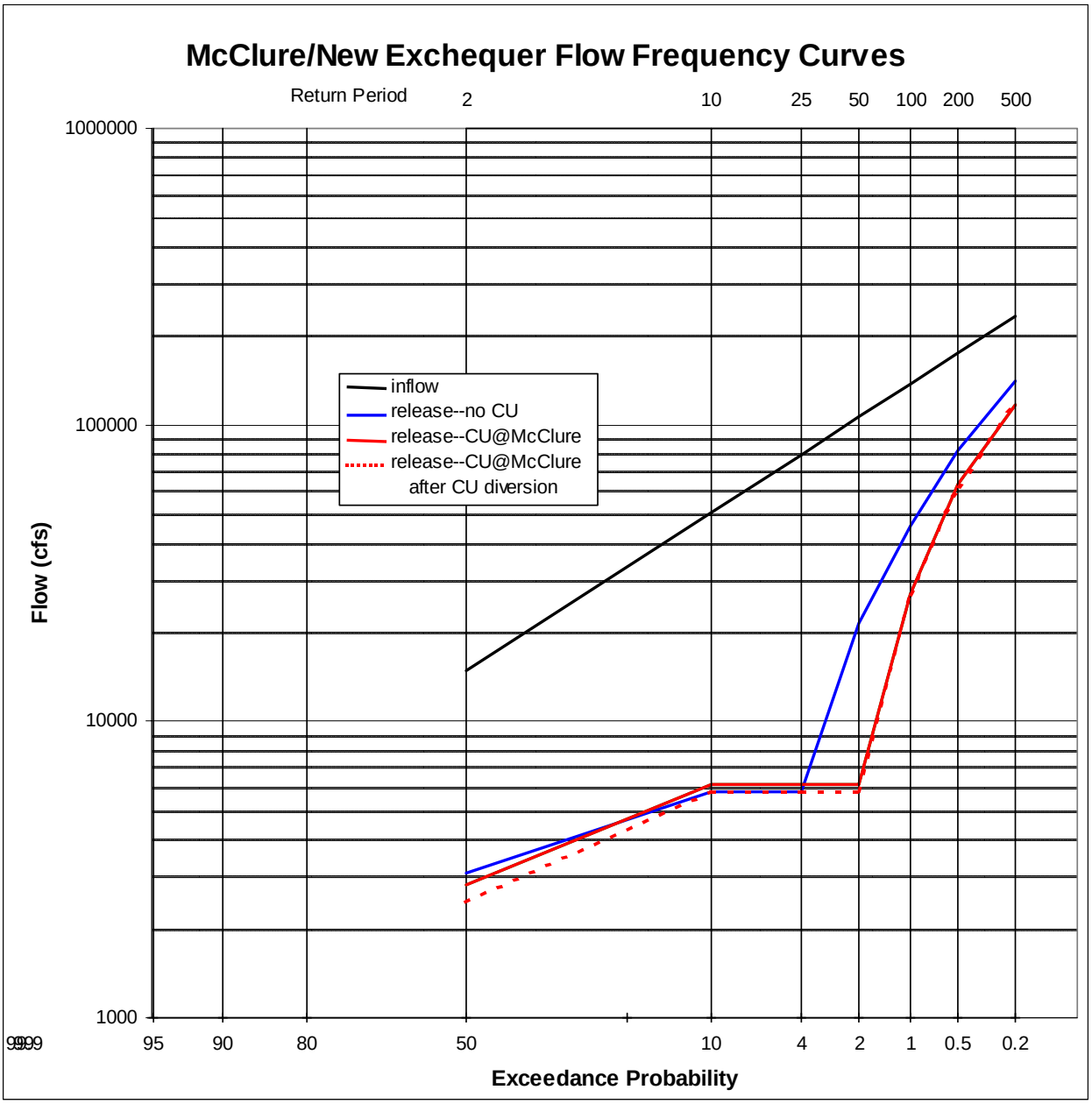


Figure B-11. McClure / New Exchequer Frequency Curves, Unregulated, Regulated, Regulated w/CU

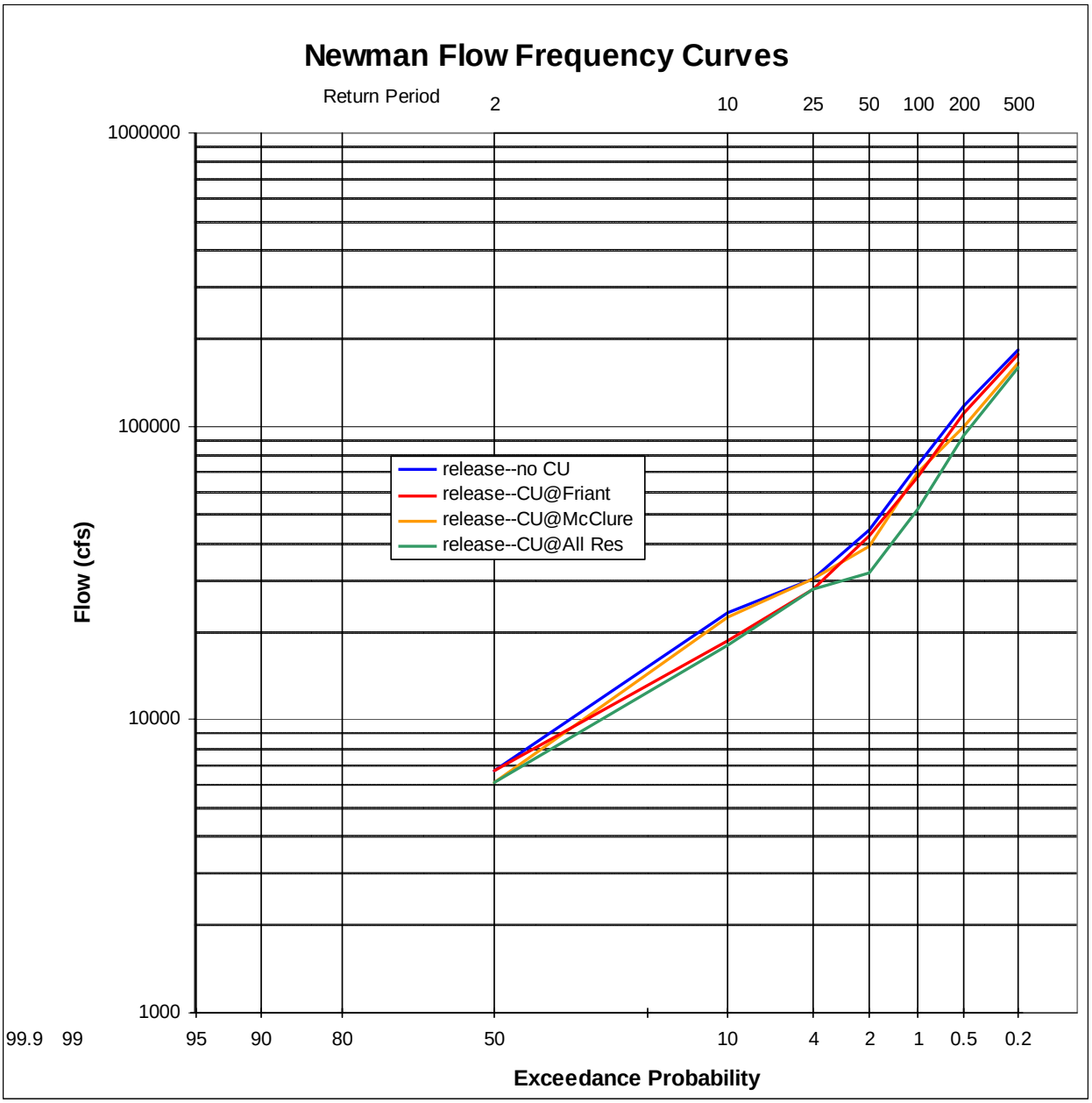


Figure B-12. Newman Frequency Curves, Regulated, Regulated w/CU

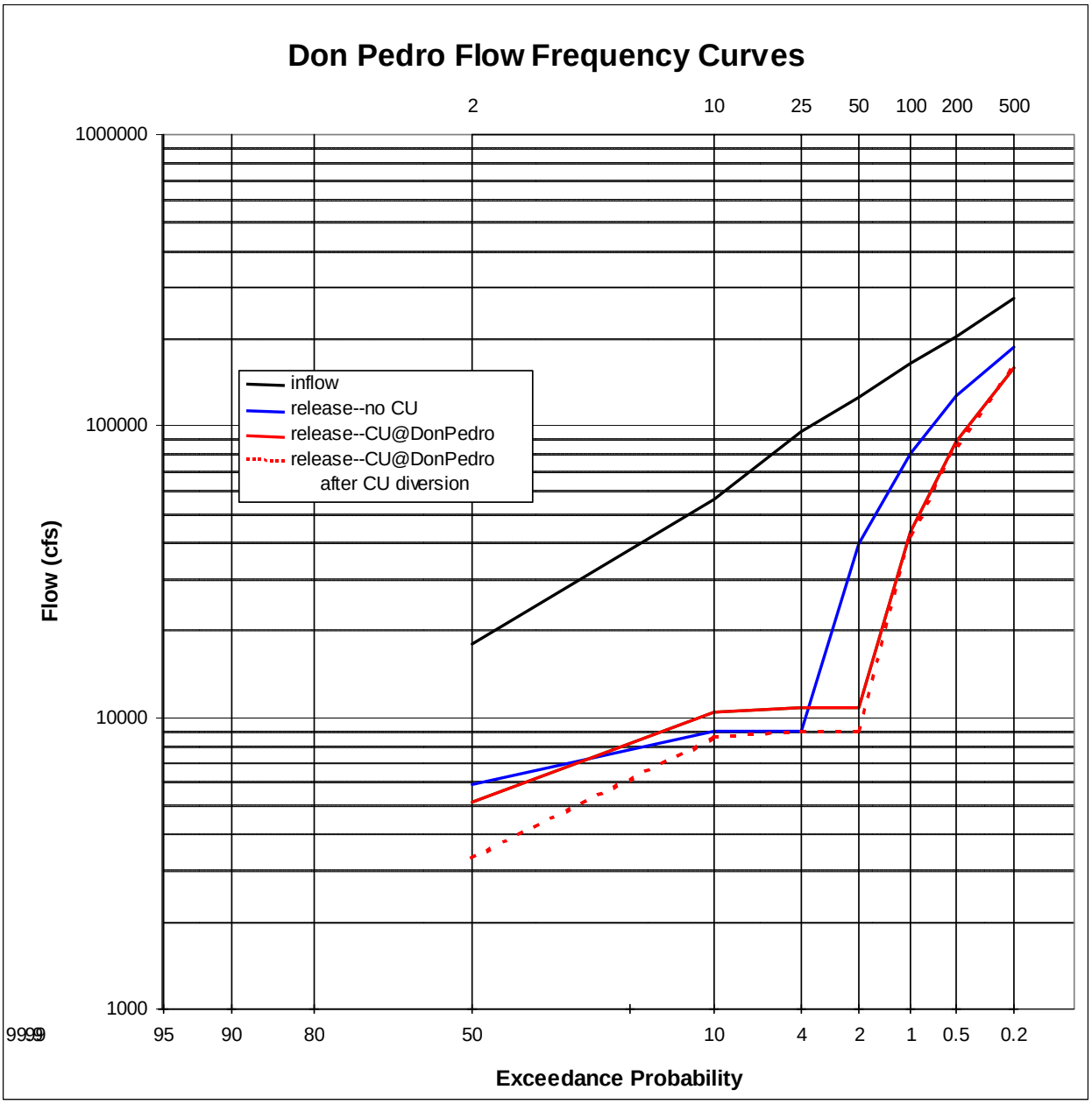


Figure B-13 Don Pedro Frequency Curves, Unregulated, Regulated, Regulated w/CU

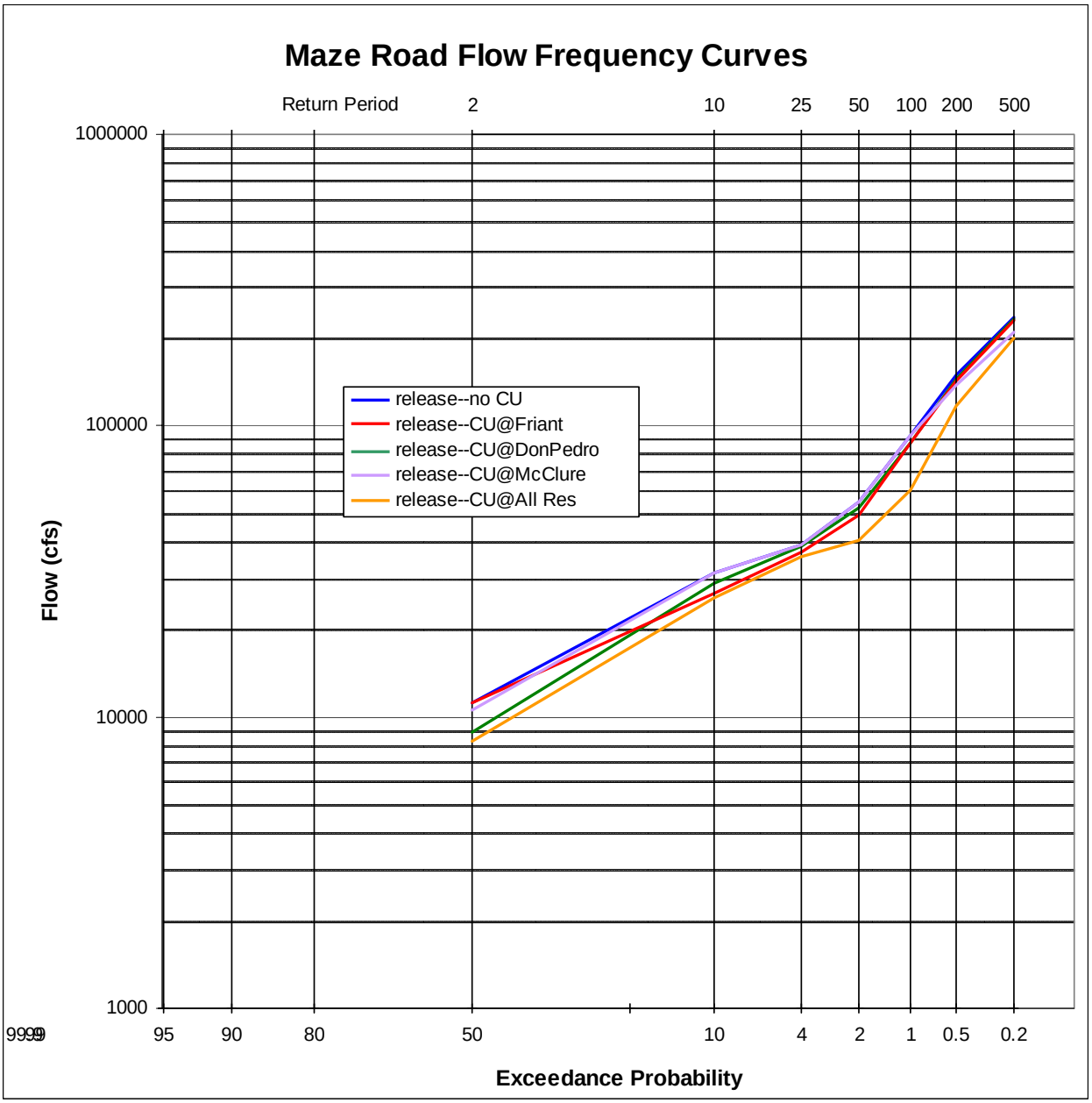


Figure B-14 Maze Road Frequency Curves, Regulated, Regulated w/CU

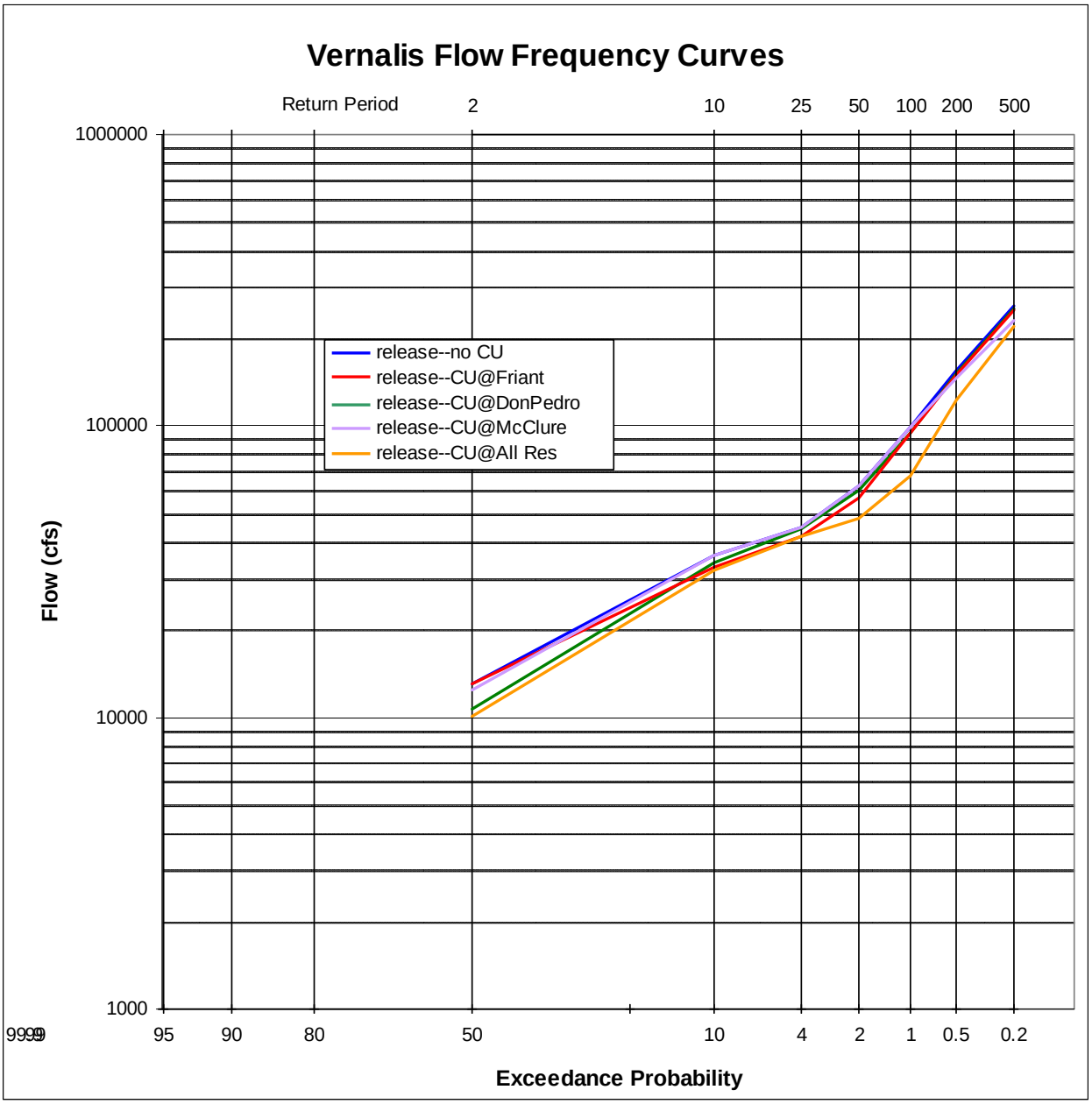


Figure B-15 Vernalis Frequency Curves, Regulated, Regulated w/CU

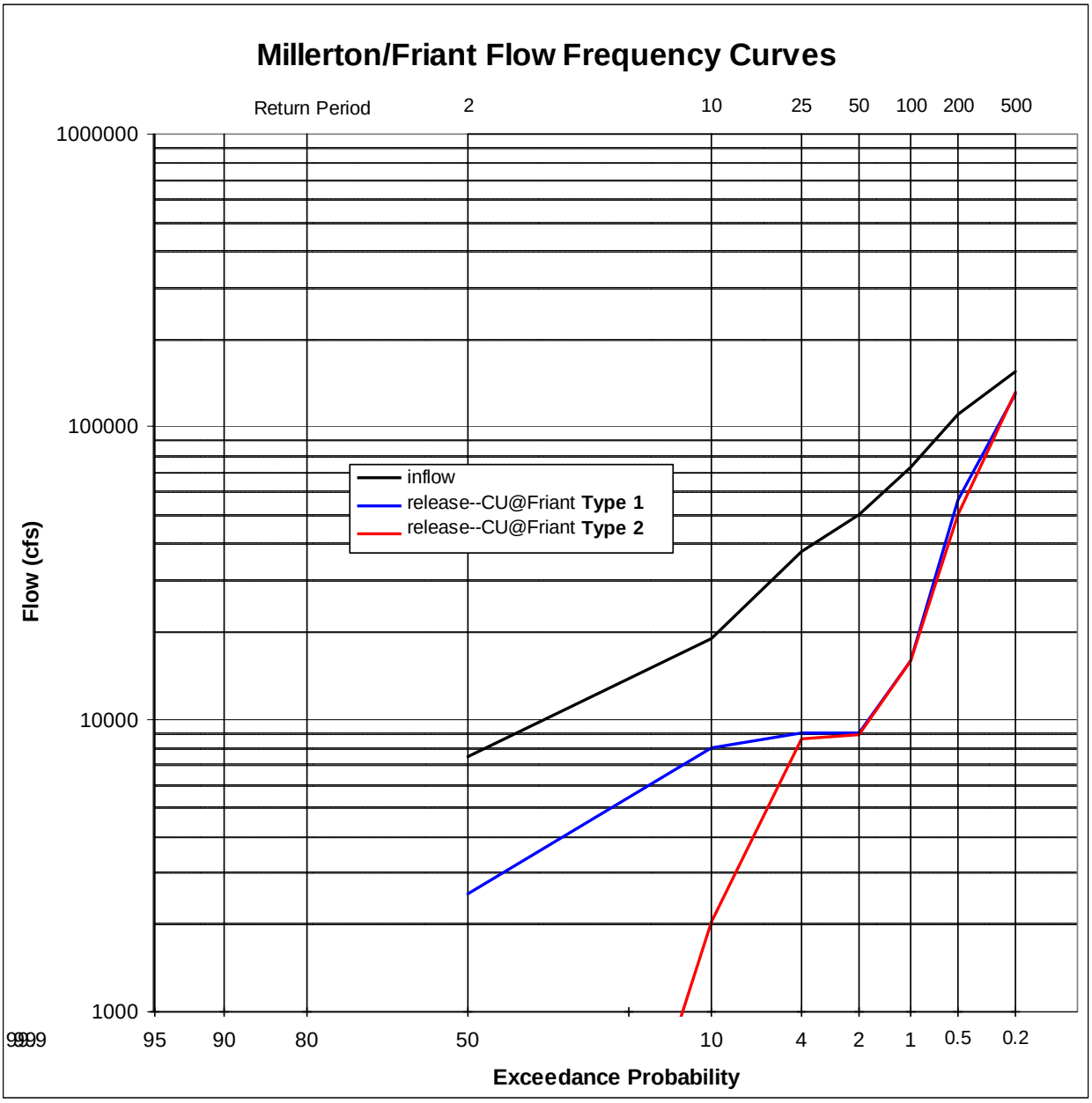


Figure B-16 Millerton / Friant Flow Frequency Curves, Type 1 vs Type 2 Conjunctive Use Operations

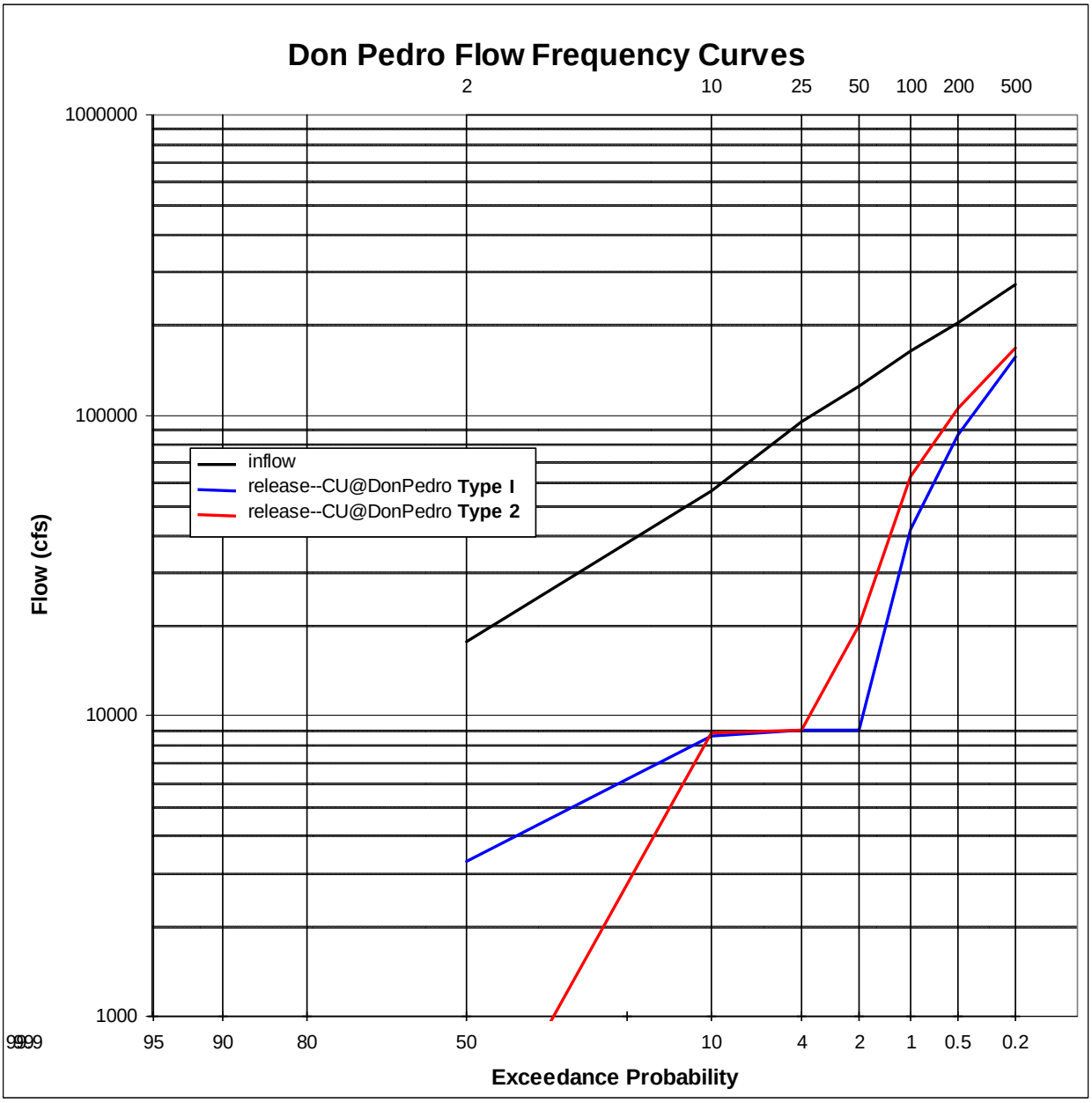


Figure B-17. Don Pedro Flow Frequency Curves, Type 1 vs Type 2 Conjunctive Use Operations

Appendix C. CU Project Cost Tables

Table C-1. Costs of Agricultural Lands Grouped by Counties

A. Butte County.

Index Letter 'E' for the 'Chico Fan' site and Index Letter 'F' for the 'Butte Creek' site

Ag Land Type	Price Range ($/ac)
Rice	$1,500 to $3,300
Vegetable Crops	$3,000 to $4,000
Irrigated Field Crops	$1,400 to $2,600
Rangeland	$ 200 to $1,100
Almonds	$2,500 to $8,000
Walnuts	$4,000 to $8,000
Prunes	$3,000 to $7,500
Olives	$3,900 to $6,000

B. Sutter County.

Index Letter 'I' for the 'Yuba City' site, Index Letter 'K' for the 'Best Slough' site and Index Letter 'M' for the 'American Basin' site

Ag Land Type	Price Range ($/ac)
Rice	$2,200 to $3,200
Vegetable Crops	$2,200 to $3,200
Irrigated Field Crops	$2,200 to $3,200
Walnuts	$5,000 to $8,000
Prunes	$5,000 to $7,000
Peaches	$3,000 to $11,000

C. Yolo, Solono, and Sacramento Counties

Index Letter 'N' for the 'Cache-Putah Plain' site, Index Letter 'O' for the 'South Fork Putah Creek' site and Index Letter 'P' for the 'Elk Grove' site

Ag Land Type	Price Range ($/ac)
Rice	$1,500 to $4,000
Vegetable Crops	$1,800 to $4,500
Irrigated Field Crops	$1,900 to $4,000
Rangeland	$ 350 to $ 700
Walnuts	$5,000 to $7,000
Pears	$4,000 to $8,000
Vineyards	$12,000 to $20,000

Table C-1 (Continued). Costs of Agricultural Lands Grouped by Counties

D. Modesto and Turlock Counties

Index Letter 'S' for the 'Hetch Hetchy Aqueduct' site, Index Letter 'T' for the 'Dry Creek' site and Index Letter 'U' for the 'Montpellier' site

Ag Land Type	Price Range ($/ac)
Cropland-Well & USBR	$3,000 to $6,000
Cropland-District Water	$4,000 to $8,500
Almonds	$5,000 to $14,000
Walnuts	$8,500 to $14,000
Cling Peaches	$7,000 to $13,500
Apricots	$6,500 to $8,000
Rangeland - For Year 2000	$ 900 to $2,500

E. Merced County

Index Letter 'V' for the 'Owens Creek' site

Ag Land Type	Price Range ($/ac)
Cropland-Well Water	$1,750 to $3,500
Cropland-District Water	$2,500 to $5,000
Cropland-West County	$2,500 to $4,500
Rangeland	$ 400 to $ 650
Almonds	$5,000 to $8,500
Walnuts	$5,000 to $9,000

F. Chowchilla and Madera Counties

Index Letter 'X' for the 'Berenda Creek' site, Index Letter 'Y' for the 'Chowchilla Bypass' site, Index Letter 'Z' for the 'Gravelly Ford' site and Index Letter 'AA' for the 'Little Dry Creek' site

Ag Land Type	Price Range ($/ac)
Almonds	$3,500 to $8,500
Pistachios	$5,000 to $10,000
Raisin Grapes	$5,000 to $8,000
Table Grapes	$6,000 to $8,500
Wine Grapes	$3,500 to $8,000
Cropland-Madera ID	$2,500 to $4,500
Cropland-Chowchilla ID	$2,500 to $3,500
Cropland-Well Water	$1,500 to $3,000
Rangeland	$ 500 to $ 850
Native Pasture (Valley Floor)	$ 800 to $1,000

Table C-1 (Continued). Costs of Agricultural Lands Grouped by Counties

G. Kings County

Index Letter 'BB' for the 'James Bypass' site

Ag Land Type	**Price Range ($/ac)**
Cropland-General	$ 750 to $5,500
Cropland-North & Central	$3,000 to $5,500
Cropland-West	$1,200 to $2,650
Cropland-Lake Bottom	$ 600 to $1,600
Walnuts	$5,000 to $7,000
Grazing-West	$ 75 to $ 125
Tree Fruit	$4,500 to $7,000

Table C-2. Cost of Purchasing Lands for Full-Sized Recharge Basins

	Project Area		Range lands		Irrigated lands		Average	Total Purchase
			low	high	low	high	Price	Price
Index	sq miles	acres	$/acre	$/acre	$/acre	$/acre	$/acre	$
E	8	5120	200	1100	1400	2600	1100	5,632,000
F	8	5120	200	1100	1400	2600	1100	5,632,000
G	2	1280	200	1100	1400	2600	1100	1,408,000
I	8	5120			2200	3200	2700	13,824,000
K	4	2560			2200	3200	2700	6,912,000
M	8	5120			2200	3200	2700	13,824,000
N	8	5120	350	700	1900	4000	1333	6,826,667
O	8	5120	350	700	1900	4000	1333	6,826,667
P	6	3840	900	2500	3000	6000	2633	10,112,000
S	4	2560	900	2500	3000	6000	2633	6,741,333
T	4	2560	900	2500	3000	6000	2633	6,741,333
U	4	2560	900	2500	3000	6000	2633	6,741,333
V	8	5120	400	650	1750	3500	1225	6,272,000
X	4	2560	500	850	1500	3000	1200	3,072,000
Y	4	2560	500	850	1500	3000	1200	3,072,000
Z	4	2560	500	850	1500	3000	1200	3,072,000
AA	4	2560	500	850	1500	3000	1200	3,072,000
BB	4	2560	75	125	1200	2650	708	1,813,333
								$ 111,594,667

Table C-3a. Cost of Constructing Conveyance: Low Capacity

		River to Aquifer				Aquifer to River				Excavation Costs			Right of Way Costs			Total Conveyance Cost
Index	Aquifer Name	Distance (miles)	Flow (cfs)	Channel Width (feet)	Channel Depth (feet)	Distance (miles)	Flow (cfs)	Channel Width (feet)	Channel Depth (feet)	Excavation Vol. (ft^3)	Excavation Vol. (yards^3)	Excavation Cost @24$/yd	Land Needed (ac)	Land Cost ($/acre)	Right of Way Cost ($)	($)
E	chico fan	19	600	25	12.5	15	350	20	10	47190000	1747778	41,946,667	165	1,100	181,333	42,128,000
F	Butte Creek	6	200	15	7.5	8	350	20	10	12012000	444889	10,677,333	68	1,100	74,667	10,752,000
G	Feather River	5	150	15	7.5	5	100	15	7.5	5940000	220000	5,280,000	36	1,100	40,000	5,320,000
I	Yuba City	2	300	20	10	2	350	20	10	4224000	156444	3,754,667	19	2,700	52,364	3,807,030
K	Best Slough	9	375	20	10	2	175	15	7.5	10692000	396000	9,504,000	40	2,700	108,000	9,612,000
M	American Basin	1	600	25	12.5	1	350	25	12.5	3300000	122222	2,933,333	12	2,700	32,727	2,966,061
N	Cache Creek Drainage	3	300	20	10	3	350	20	10	6336000	234667	5,632,000	29	1,333	38,788	5,670,788
O	South-Fork	8	400	20	10	8	350	20	10	16896000	625778	15,018,667	78	1,333	103,434	15,122,101
P	Elk Grove	4	550	25	12.5	5	250	20	10	11880000	440000	10,560,000	44	2,633	114,909	10,674,909
S	H&H Aqueduct	0.04	200	15	7.5	2	175	15	7.5	1211760	44880	1,077,120	7	2,633	19,535	1,096,655
T	Dry Creek	1	300	20	10	1	175	15	7.5	1122000	41556	997,333	5	2,633	14,364	1,011,697
U	Montpellier	2	300	20	10	2	175	15	7.5	3300000	122222	2,933,333	15	2,633	38,303	2,971,636
U'	Montpellier	9	400	20	10	7	350	20	10	16896000	625778	15,018,667	78	2,633	204,283	15,222,949
X	Berenda Creek	5	175	15	7.5	5	175	15	7.5	5940000	220000	5,280,000	36	1,200	43,636	5,323,636
Y	Chowchilla By pass	0.3	175	15	7.5	0.3	175	15	7.5	356400	13200	316,800	2	1,200	2,618	319,418
Z	Gravelly Ford	7	175	15	7.5	8	175	15	7.5	8910000	330000	7,920,000	55	1,200	65,455	7,985,455
AA	Little Dry Creek	0.3	175	15	7.5	0.3	175	15	7.5	356400	13200	316,800	2	1,200	2,618	319,418
BB	James Bypass	14	175	15	7.5	13	175	15	7.5	16038000	594000	14,256,000	98	708	69,545	14,325,545
												$ 150,000,000			1,200,000	150,000,000

Table C-3b. Cost of Constructing Conveyance: High Capacity

		River to Aquifer				Aquifer to River				Excavation Costs			Right of Way Costs			Total Conveyance Cost
Index	Name	Distance (miles)	Flow (cfs)	Channel Width (feet)	Channel Depth (feet)	Distance (miles)	Flow (cfs)	Channel Width (feet)	Channel Depth (feet)	Excavation Vol. (ft^3)	Excavation Vol. (yards^3)	Excavation Cost @24$/yd	Land Needed (ac)	Land Cost ($/acre)	Right of Way Cost ($)	($)
E	chico fan	19	2000	40	20	15	350	20	10	96096000	3559111	85,418,667	165	1,100	181,333	85,600,000
F	Butte Creek	6	2000	40	20	8	350	20	10	33792000	1251556	30,037,333	68	1,100	74,667	30,112,000
G	Feather River	5	400	20	10	5	100	15	7.5	8250000	305556	7,333,333	36	1,100	40,000	7,373,333
H	Sutter Butter															
I	Yuba City	2	400	20	10	2	350	20	10	4224000	156444	3,754,667	19	2,700	52,364	3,807,030
K	Best Slough	9	375	20	10	2	175	15	7.5	10692000			40	2,700	108,000	108,000
M	American Basin	1	750	30	15	1	350	25	12.5	4026000	149111	3,578,667	12	2,700	32,727	3,611,394
N	Cache Creek Drainage I	3	2000	40	20	3	350	20	10	15840000	586667	14,080,000	29	1,333	38,788	14,118,788
O	South-Fork	8	400	20	10	8	350	20	10	16896000	625778	15,018,667	78	1,333	103,434	15,122,101
P	Elk Grove	4	550	25	12.5	5	250	20	10	11880000	440000	10,560,000	44	2,633	114,909	10,674,909
S	H&H Aqueduct	0.04	750	30	15	2	175	15	7.5	1283040	47520	1,140,480	7	2,633	19,535	1,160,015
T	Dry Creek	1	950	30	15	1	175	15	7.5	1782000	66000	1,584,000	5	2,633	14,364	1,598,364
U	Montpellier	2	950	30	15	2	175	15	7.5	5940000	220000	5,280,000	15	2,633	38,303	5,318,303
U'	Montpellier	9	950	30	15	7	350	20	10	28776000	1065778	25,578,667	78	2,633	204,283	25,782,949
X	Berenda Creek	5	850	30	15	5	175	15	7.5	14850000	550000	13,200,000	36	1,200	43,636	13,243,636
Y	Chowchilla By pass	0.3	650	30	15	0.3	175	15	7.5	891000	33000	792,000	2	1,200	2,618	794,618
Z	Gravelly Ford	7	950	30	15	8	175	15	7.5	21384000	792000	19,008,000	55	1,200	65,455	19,073,455
AA	Little Dry Creek	0.3	950	30	15	0.3	175	15	7.5	891000	33000	792,000	2	1,200	2,618	794,618
BB	James Bypass	14	950	30	15	13	175	15	7.5	40986000	1518000	36,432,000	98	708	69,545	36,501,545
												$ 270,000,000			1,200,000	270,000,000

Table C-4a. River Turnout Locations and Distances to Aquifer Sites

Aquifer Storage Site						River Turnout Location					
Index	Name	Basin	UTM (E)	UTM (N)	Elev-ation	UTM (E)	UTM (N)	Elev-ation	Comment	Distance (Miles)	Elevation Loss (feet)
E	Chico Fan	butte	**598196**	**4391697**	40	625307	4377964	150	from Thermalito Diversion	18.9	110
F	Butte Creek	Butte	**599046**	**4349403**	20	600415	4359493	25	Via Cherokee Canal	6.3	5
G	Feather River	Butte	**609999.4**	**4349616**	19	618073	4351142	22	Feather R.	5.1	3
I	Yuba City	Sutter	**617123.7**	**4336941**	15	619476	4337690	15	Feather River N. of Yuba City	1.5	0
K	Best Slough	Placer-Yuba	**628564**	**4319013**	18	621243	4331249	20	Yuba City	8.9	2
M	American Basin	Sutter	**629748.4**	**4291217**	10	627543	4291157	10	Via North Main Canal	1.4	0
N	Cache Creek Drainage	Solona-Yolo	**613855.1**	**4283058**	5	618968	4283333	5	Sacramento R. Due east	3.2	0
			614392	**4283058**							0
O	South-Fork	Solano-Yolo	**610848.4**	**4259217**	8	623540	4259052	0	Sac R. Deep Water Ship	7.9	**-8**
P	Elk Grove	Sac	**637483**	**4254053**	8	630672	4255638	10	Sac R. Freeport Bend	4.3	2
S	H&H Aqueduct	Modesto	**666135.3**	**4169580**	10	666110	4169522	10	Lateral #3	0.04	0
T	Dry Creek	Modesto	**682184.7**	**4167970**	30	682203	4168750	35	Lateral #2 from Modesto Main	0.5	5
U	Montpellier	Turlock	**704583.3**	**4159638**	75	701040	4161475	50	High Line Canal	2.5	**-25**
U'	Montpellier	Turlock	**704583.3**	**4159638**	76	717072	4153367	78	from Merced River	8.7	2
			753577.3	**4119224**							
X	Berenda Creek	Madera	**747623**	**4102587**	68	751393	4096370	70	from Fresno River	4.5	2
Y	Chowchilla By pass	Chochilla	**730334.4**	**4096826**	48	730788	4096918	49	from Ash Slough	0.3	1
Z	Gravelly Ford	Madera	**751083.7**	**4086406**	64	759419	4078691	65	from SJ River	7.1	1
AA	Little Dry Creek	MAdera	**779976.7**	**4092224**	110	780186	4091757	112	off Madera Canal	0.3	2
BB	James Bypass	Kings	**761179.7**	**4054732**	55	757834	4077797	60	from SJ River	14.5	5

pumping required

Table C-4b. River Return Locations and Distances to Aquifer Sites

	River Return Location					
Index	UTM	UTM	Elev-ation	Comment	Distance (Miles)	Elevation Loss (feet)
E	61305	437337	35	to Thermalito	14.7	5
F	59182	433868	15	Sac R. nr Moons	8.0	5
G	61805	434976	18	Feather	5.0	1
I	61947	433769	14	Sutter	1.5	1
K	62618	431814	15	Agoon Slough to Bear	1.6	3
M	62754	429115	9		1.4	1
N	61896	428333	4	Sacrmento	3.2	1
						0
O	62354	425905	0	Sac R. Deep Water	7.9	8
P	62992	425070	5	Sac R. Near Stone	5.1	3
S	66619	416696	9	Lateral #4 to San	1.6	1
T	68130	416858	25	Dry	0.7	5
U	70104	416147	50	High Line	2.5	25
U’	71237	415206	50	back to Merced	6.8	26
X	74688	409515	61		4.6	7
Y	73054	409718	47	to Ash	0.3	1
Z	73895	408495	62	to E.Side	7.6	2
AA	77996	409175	109	to Madera	0.3	1
BB	75094	407361	53	to San	13.3	2