# Reducing Flood Storage Space at Reservoirs: A Benefit Cost Analysis for the Mokelumne River System, California

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# ABSTRACT

Reservoir operations are increasingly being challenged to serve the diverse and growing demand for water as hydrologic, ecologic and climatic conditions change. With the recognition of environmental benefits for reservoir-floodplain connectivity and the emergence of society's awareness of water resource degradation, significant opportunities exist to update reservoir operations. In the past, limited benefits and the comprehensive analysis required to update these operations have hindered progress. This thesis provides an evaluation framework for new operating rules that integrates flood damage, water supply, hydropower and environmental releases for a pair of central California reservoirs. Transfer of various amounts of flood storage space to other purposes is used to increase overall net benefits in a benefit cost analysis. For small to moderate reductions in flood storage space – less than 50%, revenues from water supply and hydropower offset flood damages. Transfers of 25% and 50% improve net benefits ($380,000 /yr and $620,000 /yr) while providing increased environmental releases (17 and 45 additional releases over 81 years). Transfer of 75% of flood storage space results in decreased net benefits due to elevated flood damages (-$2.7 M/yr), but provides additional environmental releases (59 releases). Policy makers can use this approach to balance system economics and environmental outcomes.

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# 1. INTRODUCTION

Reservoirs are designed to provide services that benefit the society currently and in the future. These services and their relative valuation can change as the regional economy changes and as society develops new ideas and views about its use and stewardship of natural resources. Over time the negative environmental impacts of reservoirs have become increasingly clear and the continued degradation of native ecosystems has emerged as a critical problem (Collier et al. 2001, Richter et al. 2003, and Jackson et al. 2001). Understanding these negative impacts has contributed to a rethinking of benefits provided by reservoirs and proposals to change operations criteria usually referred to as reoperation.

The term reservoir reoperation is generally applied to the process of changing storage or release rules to realign benefits with changes in conditions and purposes. The need for reservoir reoperation can also be driven by shifts in hydrology and floodplain land-use. For either case, updating reservoir operations presents opportunities to improve overall reservoir benefits.

The US Army Corps of Engineers (USACE) has studied reservoir reoperation to improve benefits for a variety of uses including water supply, hydropower, recreation and wildlife (USACE 1988, 1990). In USACE 1988, sixteen historical reoperation projects were categorized by reoperation type with reduction in flood storage space found to be one of the more effective forms of reoperation. Although insightful, these studies were limited in scope and only addressed reductions in flood storage that would not significantly affect existing flood protection. Wurbs and Cabezas (1987) contributed by developing an incremental economic evaluation of flood damages and water supply benefits for different reservoir reoperation alternatives to address this issue. The use of economically-based optimization as a basis for reoperation was added by Lund and Ferreira (1996).

Opportunities can be assessed by calculating marginal changes in reservoir benefits (e.g. flood control or power generation) that result from alternative operations. This method changes the level of benefits for different reservoir purposes in an attempt to improve overall benefits. Improvements are more likely when alternatives can generate multiple benefits while forgoing or reducing individual benefits. A common example, and one studied here, is the reduction of flood storage space to improve water supply reliability, hydropower production, and environmental releases.

The mechanism that allows this type of reservoir reoperation to be feasible is the transfer of flood control responsibility from the reservoir to the downstream floodplain. This effectively enlarges the reservoir and enhances its ability to provide other benefits while at the same time extending environmental benefits to the floodplain downstream of the reservoir. The integration of reservoir – floodplain systems can produce significant environmental benefits

(Watts et al. 2011, Opperman et al. 2010). The major drawback to this strategy is increased flood risk.

Where improvements in total reservoir benefits are possible, the ability to explore benefit trade-offs between reservoir purposes can provide a range of operating strategies. The allocation of new benefits can be planned according to what is most needed. For example, in areas where environmental degradation is severe, extra benefits can be directed to improving riparian conditions. In this study a reservoir reoperation approach is evaluated with an incremental benefit cost analysis for the Mokelumne River system in California. The analysis indicates that total benefits can be increased by moderately reducing flood storage space with additional flood damage mitigation.

The Mokelumne River flows west from the Sierra Nevada Mountains into California's Sacramento-San Joaquin Delta. The river system is heavily regulated with hydropower reservoirs in the upper watershed and two large multipurpose dams in the lower watershed. These two facilities provide flood control, water supply, hydropower and environmental benefits. Reoperation alternatives include four flood control reallocations (reducing flood storage space) and a baseline case. Reductions of 25%, 50%, 75%, and 100% result in 5 flood storage alternatives: 200 thousand acre feet (taf), 150 taf, 100 taf, 50 taf, and 0 taf. 200 taf is the current flood storage requirement and is called the baseline alternative in this study.

Results show small improvements in total economic benefits for flood storage reductions of 25% and 50% ($380,000 /yr and $620,000 /yr). Along with improved economics, these alternatives significantly increase water available for environmental releases, strengthening their value compared to current operations. The 200 taf flood storage alternative (baseline) shows extra water is available for spring environmental releases in 12 of 81 years, with water available almost doubling for the 25% flood storage reduction (22 years) and tripling for the 50% reduction (39 years). The most important factor in the economic analysis – flood risk – remains significantly unchanged for flood storage reductions up to 50% of existing storage space. After this point, further reductions in flood storage become increasingly undesirable under any circumstances. The types of flood mitigation used here, property buyouts and land use conversion do not change alternative favorability or relative ranking. Water supply reliability provides a moderate economic benefit under most scenarios, and hydropower generation is mostly insignificant.

## 2. BACKGROUND

To understand the details of the type of reservoir reoperation modeled here some background information on reservoir terminology and operation can be useful. A brief summary on benefit cost analysis and the handling of non-monetized environmental benefits is also presented.

## Reservoir Terminology & Operations

Water reservoir operations have a specialized vocabulary. For multipurpose reservoirs, specific volumes of storage are often allocated for different uses. These volumes are called pools and can be thought of in stratified layers (Figure 1). Seasonal changes can affect these layers. For example, the flood control pool may increase and decrease in size with the cycle of wet and dry seasons. For consistency this study uses 'storage space' to indicate specific volumes of water or pools. A reduction in flood storage space is equivalent to a smaller flood control pool.

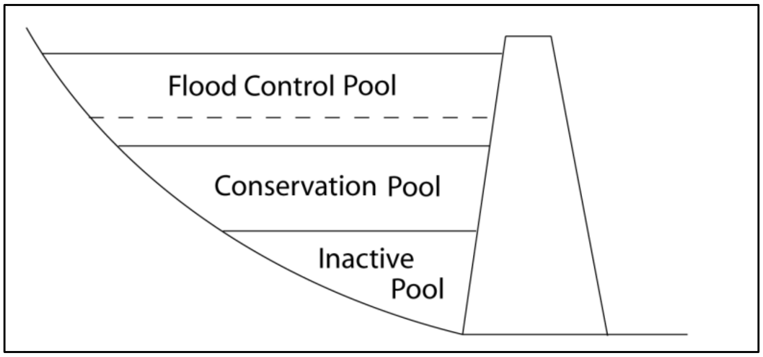
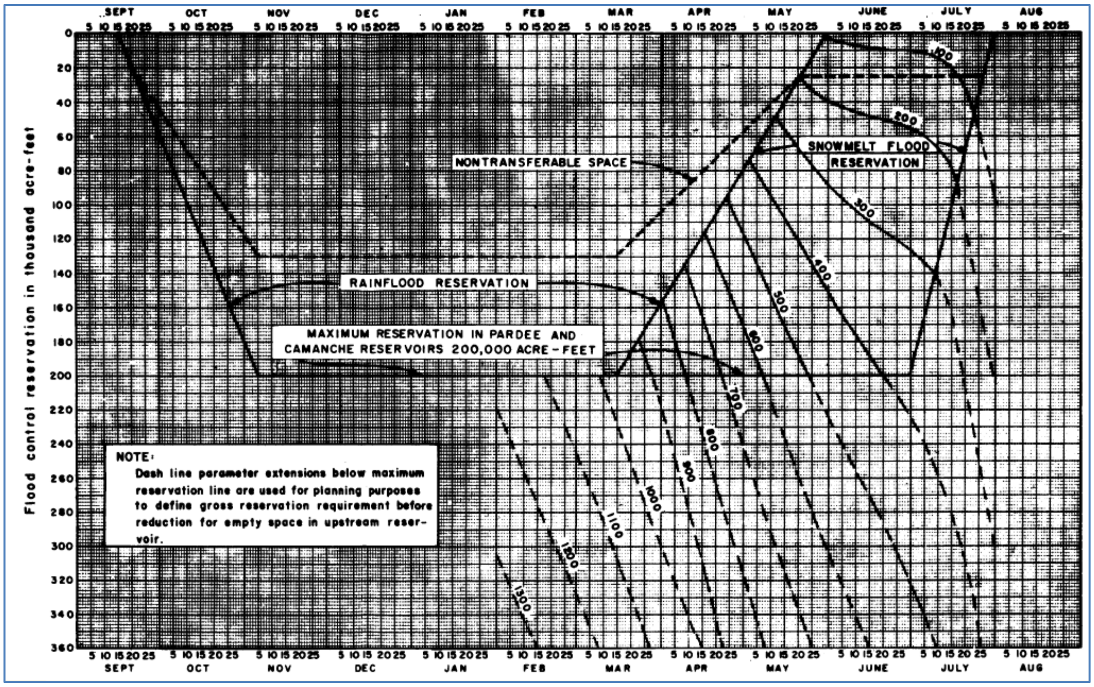


**Figure 1. Reservoir storage showing layered pools for different purposes. The dotted line represents a seasonal change in the amount of flood storage space required.**

For reservoir operations an important concept is the separation of conservation pools (i.e. hydropower, water supply, environmental releases) from the flood storage pool. These reservoir purposes are separated because they function oppositely. Conservation storage tries to conserve or store water whenever possible, while flood storage space tries to remain empty whenever possible. The separation of these two types of storage is defined by a guide curve. The guide curve tells reservoir operators how much water should be in storage at any time of the year. Figure 2 shows the guide curve from Camanche Dam, a facility analyzed in this study.



NOTE:
Dash line parameter extensions below maximum reservation line are used for planning purposes to define gross reservation requirement before reduction for empty space in upstream reservoir.

**Figure 2. Camanche dam guide curve includes a wet season drawdown in storage to increase flood storage space. Other parameters that affect the guide curve are a winter rainflood transfer pool and a spring snowmelt reserve, both of which are not modeled in this study (USACE 1981).**

## Reallocating Reservoir Storage

The concept of transferring reservoir storage capacity from flood control to other purposes is accomplished by adjusting the guide curve. In California, guide curves typically allow the reservoir to be full in the summer and store less water in the winter. For this study the guide curve was raised during the winter to correspond with each study alternative (Figure 3). This permits reservoir operators to fill part of the old flood storage space – now conservation space, with water.

The ability to consistently store water in the transferred space depends on hydrology and other factors. Although storage space is transferred to conservation space there is no guarantee that it will fill every year or even in wet years. River flow is often highly variable year-to-year and planned benefits do not always materialize. This issue is addressed by modeling a long timeseries of inflows to estimate the likelihood of filling the transferred storage space and reducing expected benefits accordingly.

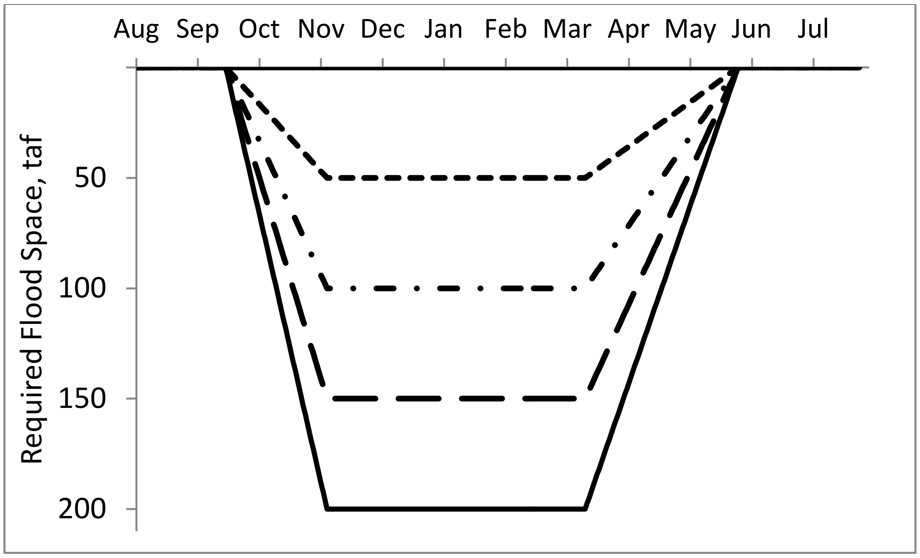


Figure 3. Reservoir guide curve with alternative levels of reduced flood storage space. The levels shown here are for the alternatives used in the Mokelumne River study. In August there are no flood storage requirements for any alternative, while in January various levels of storage space are required.

## Benefit Cost Analysis (BCA)

BCA has traditionally been used to evaluate large infrastructure projects such as dams, canals and bridges (Boardman et al. 2001). BCA includes the quantification of major benefits and costs. For dam projects, benefits and costs are commonly assigned for water supply, flood control, hydropower generation, recreation and the environment. The various benefits and costs commonly are aggregated using a net present value or equivalent annual value. In this study, benefits and costs are reported in annual terms and include water supply, hydropower and flood control, with environmental releases as a separate variable. A complicated element of the BCA is estimating expected annual damage (EAD) due to flooding.

## Expected Annual Damage (EAD)

A technically robust method of evaluating flood impacts is through an EAD framework (USACE 1996). This approach treats floods as uncertain and probabilistic in nature, requiring a flow distribution to describe the likelihood of occurrence (Figure 4). Each flow value on the curve is associated with a likelihood of occurrence, usually reported in probability terms of 1/(recurrence interval). These distributions can be made for unregulated or regulated rivers, with additional modeling required for the regulated case. For unregulated rivers USGS Bulletin 17b is considered the standard approach.

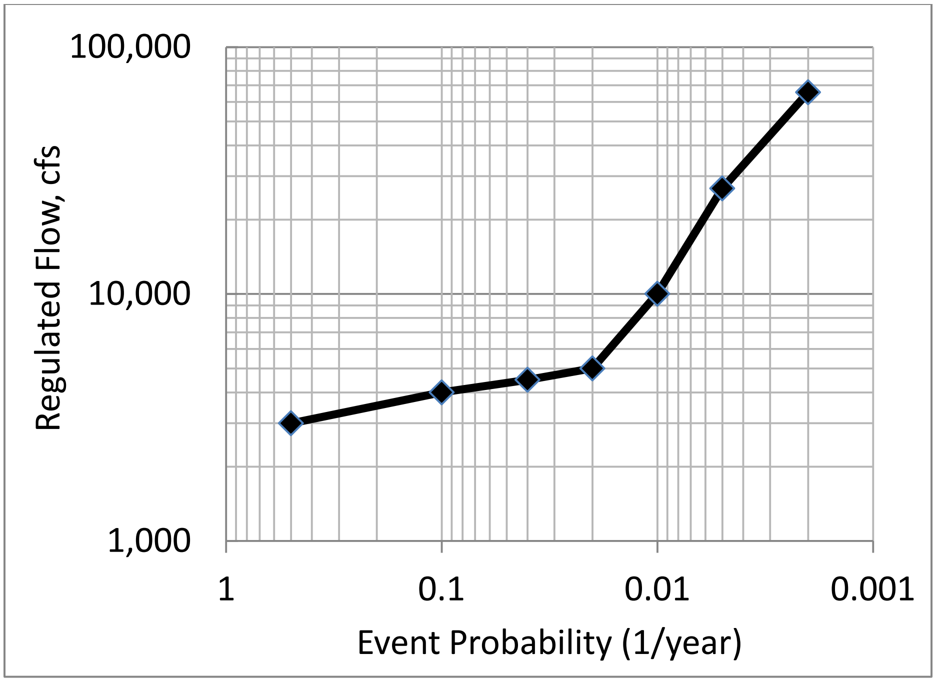


Figure 4. The Mokelumne River regulated flow frequency distribution (based on reservoir routing of unregulated inflow).

For flood damage calculations, ‘flood damage’ or ‘event damage’ is an estimate of damage from a specific flood flow. Flood damage can be multiplied by its likelihood of occurrence, selected from the flood flow distribution to calculate ‘expected flood damage’ or ‘flood risk’. This is an appropriate planning cost of a given flood event because it accounts for how often the event occurs. For example, consider a 100-year flood: first look up the 100 year flow (0.01 event probability) from the flood flow distribution (say 10,000 cfs). Then estimate damages due to 10,000 cfs flow (say damages are $50 million per event). So the event flood damage is $50 million, the likelihood of occurrence is 0.01 (or 1/100 years), and the expected flood damage or risk is $500,000/year ($50 million * 0.01/yr).

Events over the entire flood flow distribution can be analyzed in the same way to produce expected flood damage estimates for the complete distribution. These values are then integrated or summed over the entire distribution to calculate the overall expected annual damage (EAD) (Equation 1). EAD is in terms of average dollars per year and is easy to incorporate with other terms in the economic analysis.

$$EAD = \int D(q_i) * dP \qquad (1)$$

Where $D(q_i)$ is the damage sustained from the $i^{th}$ flow event. The integration step is dP indicating probability space. Practically, this integration is only done for a handful of events and the results are weighted by the probability space between them (Equation 2 and Figure 5). Where $P(q_i)$ is the probability of the $i^{th}$ flow event.

$$EAD = \sum_{i=1}^{5} \frac{1}{2}\left[D(q_i) + D(q_{i+1})\right] * \left[P(q_i) - P(q_{i+1})\right] \qquad (2)$$

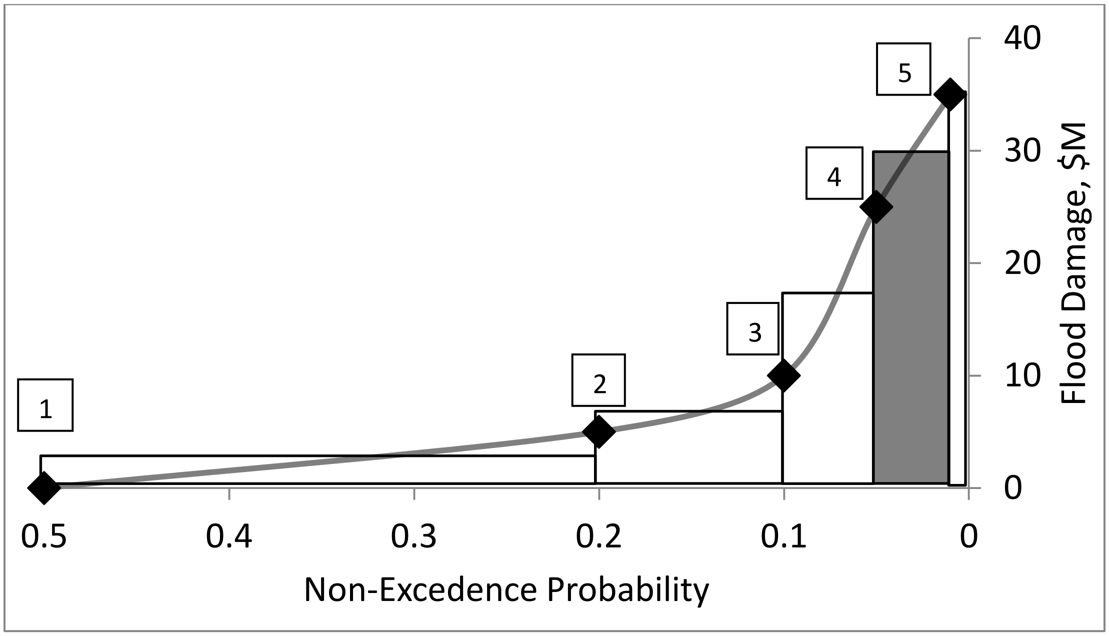


**Figure 5. EAD calculation with a distribution represented by five events (diamonds labeled 1-5). The shaded rectangle's contribution to total EAD is calculated as the average flood damage of events 4 and 5 ($ 30M) multiplied by the cumulative probability between the events (0.05-0.01) yielding $1.2 M/yr.**

## Non-Economic Variables

Quantifying environmental benefits is often difficult due to the subjective nature and uncertainty associated with these benefits. For example, consider a program to restore salmon spawning grounds in the Mokelumne River. Money is spent to place appropriately sized gravels in key locations to increase the amount of spawning area available for salmon. The cost of the work is known, but the benefits have to be estimated by evaluating the success of the program. This could be done in terms of percent utilization of new redds, or number of additional fry production. Any metric should acknowledge the impacts of unrelated factors such as ocean conditions, Delta water quality, among many others. These factors are poorly understood and add uncertainty to estimates of the cost effectiveness of restoration programs.

Economic studies that monetize environmental benefits are often controversial and challenging to justify (Morse-Jones et al. 2011). One valuation approach used in the Savannah River basin links human consumption of goods and services to ecosystems, but requires relationships of ecosystem response to hydrology, and economic response to ecosystem services (Kroeger in prep). Another approach separates economic and environmental variables into a two axis analysis to identify non-inferior (Pareto-optimal) solutions (Lund et al. 2008). This multi-objective approach results in a set of non-dominated solutions that require decision makers to confront the decision trade-offs and select the level and types of each benefit they wish to achieve. This study uses the latter approach and directly compares the economic components in monetary terms (flood damage, water supply and hydropower), while providing non-monetary quantitative analysis of environmental releases. An example would be a spring release pulse in 12 of 81 years.

# 3. SITE DESCRIPTION

The Mokelumne River originates in the Sierra Nevada Mountains and flows west to California's large Central Valley where it joins the Cosumnes River before emptying into the Sacramento-San Joaquin Delta (Figure 6). The Delta is the head of the San Francisco Estuary and receives average annual inflows of 28 million acre-feet (maf), almost half of California's total runoff (DWR 2005). The Central Valley's two largest river systems, the southward flowing Sacramento, and the northward flowing San Joaquin empty into the Delta. The Mokelumne and Cosumnes along with smaller tributaries contribute a smaller fraction (1.4 maf) to the total flow (USGS 2000). The Mokelumne watershed covers 661 square miles from its headwaters in the mountains to the Delta. Four major reservoirs regulate the Mokelumne River: Camanche, Pardee, Salt Springs, and the Lower Bear.

## Weather & Hydrology

The region has a Mediterranean climate with hot dry summers and cool wet winters. Precipitation is variable on an annual basis, but occurs predominantly from November through March. At higher elevations snow accumulates through early spring and melts by early summer (Table 1). Annual runoff averages 730 taf, but is highly variable with historical volumes as high as 1.8 maf and less than 200 taf in others years (Figure 7).

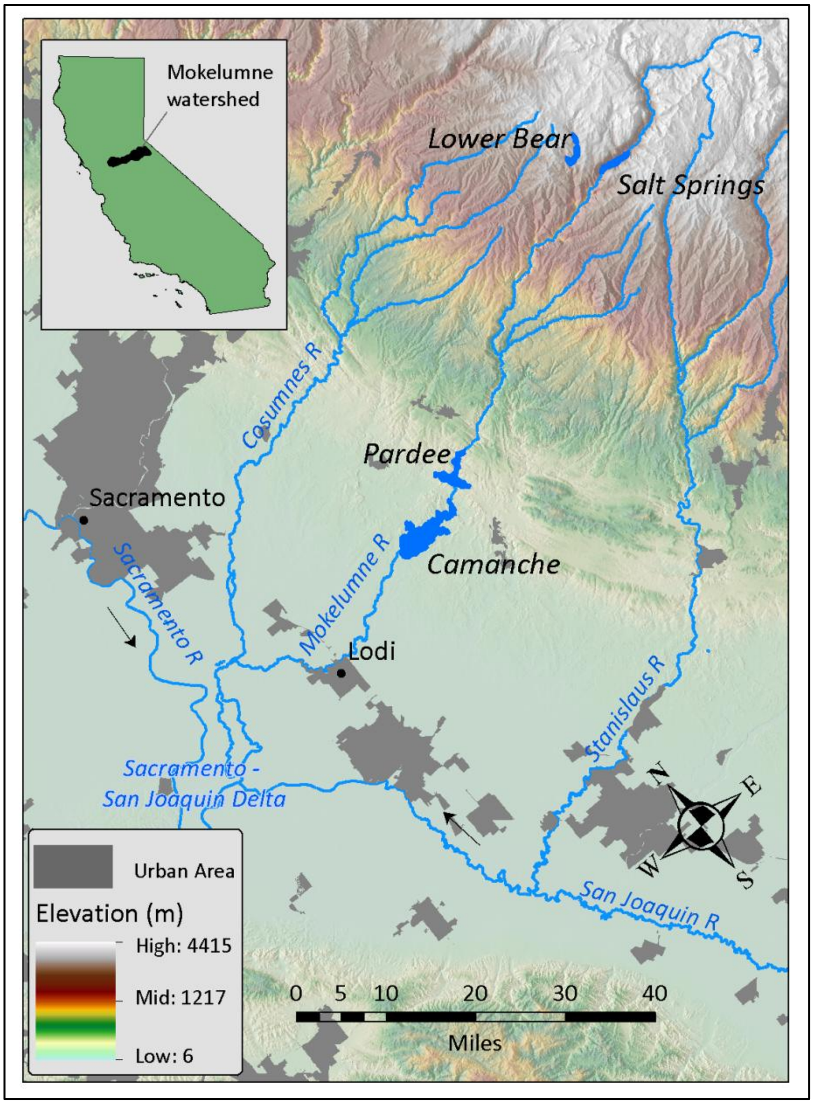


**Figure 6. The Mokelumne River watershed begins in the Sierra Nevada Mountains and ends in the Sacramento-San Joaquin delta. Its major reservoirs include the Lower Bear, Salt Springs, Pardee and Camanche.**

**Table 1. Precipitation averages for the Mokelumne watershed based on a four station average (1930-2004), snow depth measured in the upper watershed at Caples Lake (1968-2004), and average unimpaired flow at Pardee Reservoir (EBMUD 2005).**

| (inches) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation | 8.9 | 7.9 | 7.1 | 4.1 | 2.2 | 0.8 | 0.3 | 0.3 | 0.8 | 2.5 | 5.6 | 7.9 |
| Snow Depth | 58 | 76 | 73 | 51 | 11 | 0 | 0 | 0 | 0 | 1 | 22 | 44 |
| Mean River Flow (taf) | 61 | 82 | 124 | 191 | 119 | 26 | 5 | 3 | 6 | 19 | 37 | 52 |

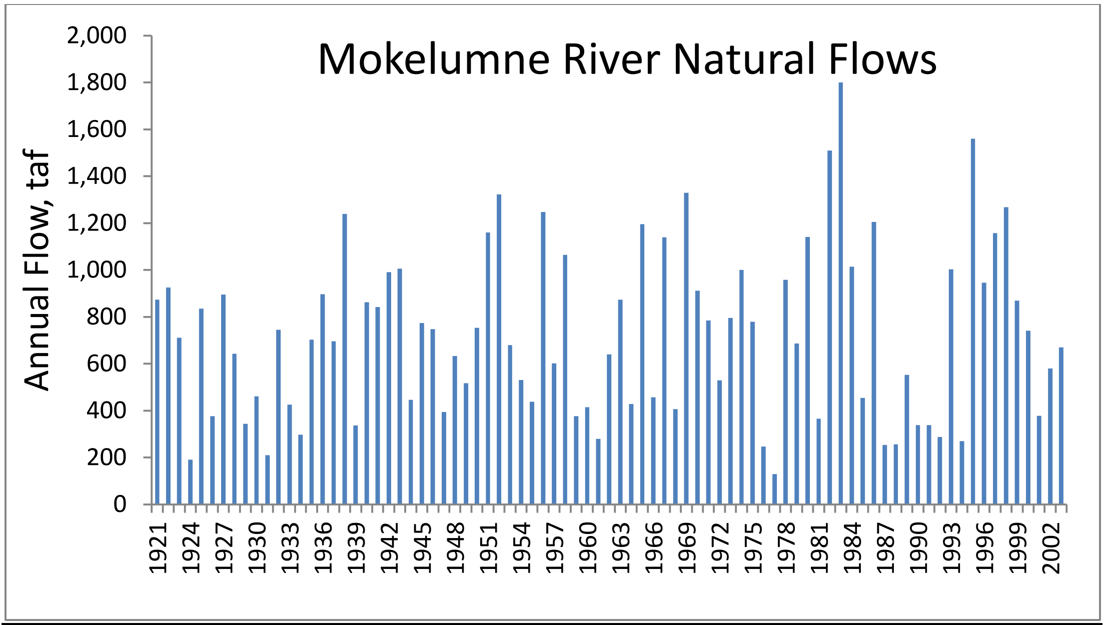


**Figure 7. The Mokelumne River annual runoff based on unimpaired flow shows high variability. Data from the California DWR Central Valley Unimpaired Flows 4th edition report (DWR 2006).**

## Reservoirs

Dams in the Mokelumne watershed primarily provide hydropower, water supply, and flood control. Regulation in the upper watershed is for hydropower via many small dams and two larger ones, the Lower Bear at 52,000 acre-feet, and Salt Springs at 142,000 acre-feet. These reservoirs begin storing water in early spring, fill by summer, and slowly drawdown through the fall. There are no flood storage space requirements at these facilities. Downstream is Pardee Reservoir which is a multipurpose water supply, hydropower, and flood control reservoir. It operates in tandem with Camanche, the terminal reservoir in the system with similar purposes. Pardee has a capacity of 197,000 acre-feet and Camanche 417,000 acre-feet.

## Water Supply

Pardee and Camanche provide water supply for a variety of user types, each with a unique shortage cost curve. Users have a year-to-year normal range of water deliveries where supply approximately meets demand and no shortages occur, however during drought periods users may cut back deliveries (forgo beneficial uses) and incur shortage costs. These costs are the largest for high value users, typically commercial and industrial.

Pardee Reservoir delivers water via aqueduct to urban users in San Francisco's East Bay area. Between 1970 and 2005 average annual deliveries ranged from 200 to 225 million gallons per day (MGD) (224 to 252 taf) with drought years ranging from 180 to 200 MGD (202 to 224 taf) and dropping as low as 150 MGD (168 taf) (EBMUD 2005). During normal years no shortage costs are assigned, however during droughts when water use is cut back, monthly costs of $8.4

M to $24.4 M occur (Draper 2003). Three significant droughts have occurred (various months in: 1976-77, 1988-93, and 2007-2009) where shortage costs could be assigned.

Camanche Reservoir provides water to downstream users by releasing water when required. Downstream users generally have senior rights to the Pardee diversion and are mostly irrigators. Demand follows a strong seasonal pattern of high use in the spring and summer and low use in the winter. The yearly range of water use is approximately 60 to 105 taf (EBMUD 2005). No shortage costs have been developed for these users because their demands have the highest priority and are almost always met (also the case in this study).

## Flood Control

Currently, 200,000 acre-feet of combined flood control space is required from November through March for Pardee and Camanche Reservoirs. No other facilities on the Mokelumne River are required to maintain flood control space. Most flood control space is at Camanche. Pardee is sometimes drawn down as much as 32,000 acre-feet in winter to reduce spill for hydropower generation. The US Army Corps of Engineers Water Control Manual for Camanche Dam details flood storage requirements during the wet season as well as maximum flood releases (USACE 1981).

Historically, the amount of flood storage space on the Mokelumne River has minimized flood flows. Since 1963 (the construction of Camanche Dam) no flood event has significantly exceeded 5,000 cfs (the channel capacity). Before Camanche Dam, flows in excess of 10,000 cfs occurred once or twice a decade (Figure 8). When flooding does occur it is minor and usually associated with levee failure in the lower agricultural areas near the river.

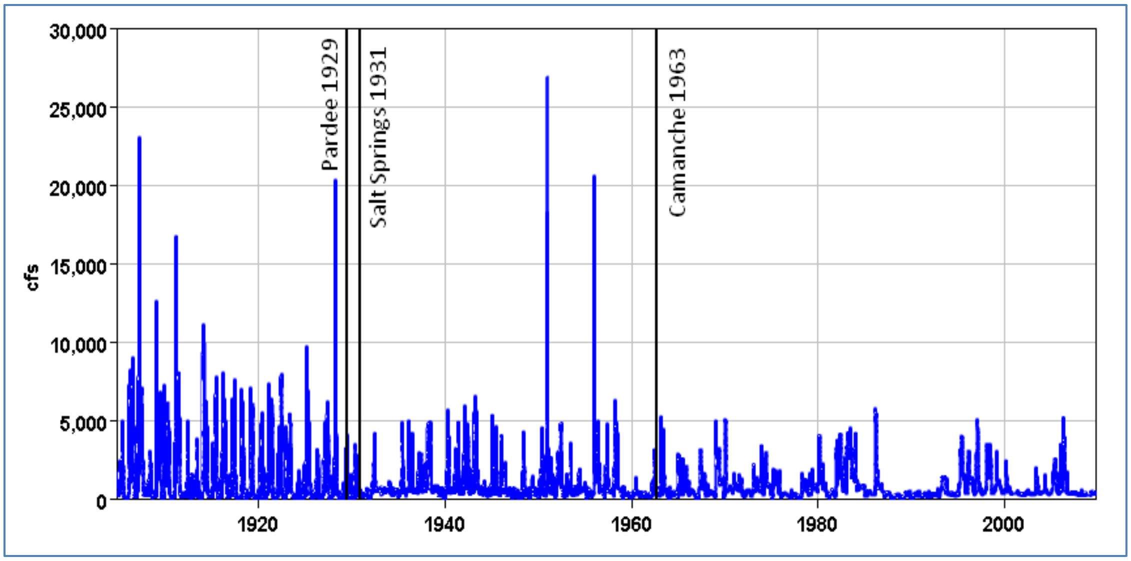


Figure 8. Mokelumne River flow (CFS) below Camanche dam. Pardee and Salt Springs dams were constructed around 1930 and Camanche dam in 1963.

Another component of flood control along the Mokelumne River are agricultural levees. These are mainly located in low lying areas and are only designed to handle 5,000 cfs (or less in some areas). Overall reliability of these levees is low and many fail during high flows that are sustained for several weeks. In the spring of 2006 a 5,000 cfs flow lasted 20-30 days, saturating levees along the Mokelumne River and causing failures from overtopping, seepage, and levee breaks (EBMUD 2006).

## Hydropower

Hydropower generation on the Mokelumne River can be divided into two categories: facilities using peaking operations and those constrained by multiple purposes. Peaking refers to hydropower peaking operations where releases are made during peak price hours to generate maximum revenues. The smaller reservoirs in the upper watershed (including Salt Springs and the Lower Bear) are primarily peaking facilities. These reservoirs have no required flood control storage and are outside the scope of the model. The second type of hydropower facility operates with constraints on energy generation. This type includes Pardee and Camanche reservoirs. Although Pardee operates as a peaking facility at times, it has downstream release obligations for Camanche. Pardee generates 110,000 MW-hrs of power in an average year while Camanche (with a lower head) generates 40,000 MW-hrs per year (EBMUD 2005). It is estimated that Pardee makes $ 5-6 M/year in revenues and Camanche around $ 2 M/year. There is no peaking at Camanche due to downstream constraints; it is considered a baseload facility.

## Floodplain Land Use

Land use in the Mokelumne River's floodplain is primarily agricultural with the exception of the City of Lodi. The shape of the floodplain is defined by high terraces (20-40 feet) near Camanche dam that gradually disappear as the floodplain widens near Lodi, approximately 40 miles downstream from Camanche Dam (Wheaton et al. 2004). Channel width ranges from 62 to 141 feet, larger upstream and narrower downstream where levees protect homes and farmland (Jeffres 2006). The crops grown in the floodplain include field, row and permanent crops with vineyards and walnuts being prominent. Crop acreages from the 1996 San Joaquin County DWR crop survey are shown in Table 2. The table is arranged by cumulative floodplain inundation flows. For example, the 7,000 cfs row is the acres of all the crops that would be damaged if 7,000 cfs passed downstream. These acreages were calculated in this study as an intermediate step to estimate flood damages for various high flow events.

Table 2. Floodplain agricultural acreage inundated for various river flows.

| Flow, cfs | Walnuts | Almonds | Vineyard | Apples | Melons | Cherries | Beans | Alfalfa | Totals |
|---|---|---|---|---|---|---|---|---|---|
| 4,000 | 135 | 0 | 193 | 0 | 45 | 40 | 5 | 17 | 435 |
| 5,000 | 164 | 0 | 205 | 0 | 45 | 50 | 14 | 25 | 503 |
| 7,000 | 205 | 0 | 207 | 7 | 46 | 60 | 28 | 36 | 589 |
| 10,000 | 653 | 9 | 297 | 13 | 54 | 71 | 63 | 111 | 1,270 |
| 20,000 | 743 | 12 | 485 | 19 | 65 | 111 | 106 | 136 | 1,677 |
| 60,000 | 1,089 | 12 | 727 | 48 | 153 | 137 | 165 | 171 | 2,503 |

Downstream of Camanche dam (approximately 24 miles) is Lodi, home to 61,000 people. Lodi is built in a low spot along the river making it vulnerable to flooding. FEMA flood maps show most of Lodi within the 500 year floodplain and most waterfront areas within the 100 year floodplain (FEMA 2009). Figure 9 shows an aerial image of central Lodi and the FEMA flood map for the same location.

Figure 9. Aerial photo (left) of the Lodi peninsula and the FEMA 100 year floodplain (north of white line). FEMA map (right) indicates different levels of flood risk with shaded areas (100 year) and non-shaded (500 year). Most of Lodi is within the 500 year floodplain.

## Ecosystem

The Mokelumne River is part of California's Central Valley network of rivers and floodplains. Historically, the Central Valley contained large connected areas of seasonal floodplain habitat and riparian forests (Kelley 1989). The construction of levees to protect floodplain development and the clearing of riparian areas for farming has reduced floodplain habitat by over 95% (Hunter 1999). Furthermore, large dams that ring the Central Valley have significantly altered natural flow regimes and removed or reduced small and medium sized floods – important ecological flow components, from the hydrograph (Wang et al. 2011). This large-scale transformation has degraded native ecosystems, evident by dramatic population reductions and some species extinction (Brown and Bauer 2010). The Mokelumne River's connection to the Central Valley's ecosystem is through its direct outflow to the Delta and its historical provision of riparian and floodplain habitat.

The lower Mokelumne River (LMR) watershed between Camanche Dam and the Delta is the primary river-floodplain area that would benefit from additional environmental releases. This section of river covers approximately 35 miles and historically provided excellent habitat for a variety of fish species (Merz and Setka 2004). Of the 34 species of fish that utilize the LMR, fall-run Chinook salmon has been a focal point due to large declines in Central Valley populations (Gustafson 2007) and potential future government protections. Primary spawning habitat for the Chinook is a six mile reach immediately downstream of Camanche Dam where riparian vegetation and the lack of levees could support a functioning floodplain ecosystem (Merz 2001). To achieve this state, or improve current conditions, increased reservoir releases that inundate floodplains and move sediment are required.

East Bay Municipal Utility District (EBMUD) – operator of Pardee and Camanche Dams, may release environmental flow pulses during important Chinook life cycle periods (when they have surplus water). These pulses have occurred in the spring to simulate spring snowmelt, and the fall to simulate rainstorm events. Typical fall pulse flow events occur over one to two weeks with a peak flow between 2,000 to 3,000 cfs and total volume around 20,000 acre-feet (af) (EBMUD 2001). Spring releases are larger, longer in duration and more variable. They depend on the timing of reservoir inflow and the current reservoir storage. By comparing guide curve operations with actual releases during wet years, volumes of 20,000 to 60,000 af over two to three months can be estimated. In these cases EBMUD has flexibility to release water earlier in the spring or store it and release according to flood operations. The first option allows for spring environmental flow pulses that mimic natural river flow. These spring and fall environmental releases are used as an example for releases modeled in this study.

## 4. METHODS

This study quantifies economic and environmental impacts of reallocation of reservoir flood storage space for water supply and environmental uses. The economic components in the analysis include: flood damage, hydropower, and water supply. Environmental components have been combined into seasonal environmental releases. These components have been estimated with enough detail to illustrate the reservoir reoperation concept and method, but remain too coarse for implementation.

The study follows traditional economic analysis procedures for infrastructure projects with multiple benefits and costs. All values are incremental or relative to the baseline case. The economic components are measured by estimating dollar values, while environmental releases are quantified using a frequency approach. This allows the subjective nature of environmental releases to be evaluated independent of the more traditional economic components. The analysis framework therefore has two axes: economic benefits (or costs) and environmental releases. This approach generates a trade-off curve between the two types of benefits, providing more information for decision makers than a single solution.

To set up the analysis, system alternatives are developed. The alternatives include values for: flood storage space, agricultural floodplain land-use, urban floodplain land-use, and desired level of environmental releases. These values determine the economic and environmental outcomes for each alternative. To further simplify alternatives, agricultural and urban floodplain land-uses are developed as a function of flood storage space, as downstream flood losses are strongly tied to reservoir operations and allocated flood storage capacity. Lastly, each alternative specifies the desired level of environmental release: none, half of extra water available, or full release. This provides the economic-environmental trade-off; extra water available is also a source of benefits for water supply and hydropower. Five flood storage levels are examined, beginning with the current (or baseline) amount and stepping down in 25 percentage point increments to zero flood storage (100%, 75%, 50%, 25%, 0%), or in terms of reservoir volume: 200, 150, 100, 50, 0 taf.

For each alternative, each component of the economic-environmental framework is estimated. Flood damage is calculated as expected annual damage. The flood damage analysis follows a frequency approach as shown in the top row of Figure 10, using a daily flood routing simulation model. A period of record (POR) or timeseries approach is used for modeling water supply, hydropower and environmental releases (bottom of Figure 10), using a monthly water balance simulation model.

Two models are used due to the time scale differences in performance for different management purposes. This approach is supported by the reoperation literature (USACE 1988, Wurbs and Cabezas 1987). Flood damage calculations must include very large and rare flood events. Few such events exist in the POR timeseries, so these extreme events are generated using frequency methods. The POR approach is useful to show long-term trends such as reservoir levels, water supply shortages, hydropower production, and the likelihood of environmental releases over the time. The following subsections outline the calculations for each economic or environmental component in the analysis.

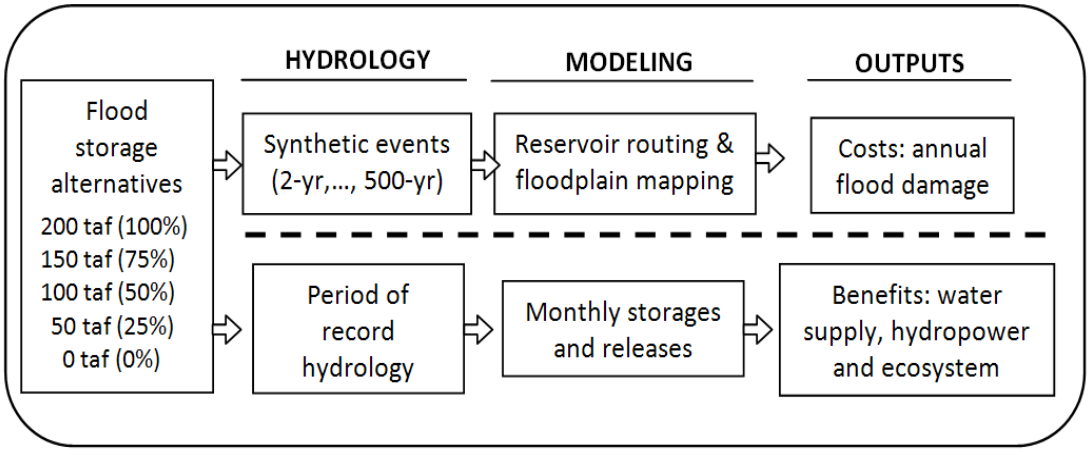


**Figure 10. Flow Chart. Flood storage alternatives are evaluated in two ways: a frequency approach for flood damage (above dotted line) and a period of record approach for water supply, hydropower and environmental releases (below line).**

## Flood Damage Modeling

Flood damage calculations here follow an expected annual damage (EAD) approach which includes floodplain mitigation. This process begins by estimating an unregulated inflow frequency and generating return interval events (e.g. 100 year event). These events are routed through the reservoir system to quantify areas of downstream flooding. Flood maps are created and combined with land-use data to estimate specific event flood damages. Probability of an event occurring is transferred from the flood inflow. All flood damage estimates are then integrated over the transferred probability distribution to calculate an overall EAD value for each alternative. These steps are explained below.

### A. Upstream Flood Frequency

The EAD calculation begins by estimating the upstream flood frequency for the project. This is done by fitting a Pearson Log-III distribution to unregulated yearly peak inflows then selecting standard return interval peak flows from the resulting distribution (Figure 11) (USGS 1982). Once peak flows have been identified they are fitted to a balanced or representative hydrograph often called synthetic hydrographs. Hydrographs, not peak flows are required for reservoir modeling.

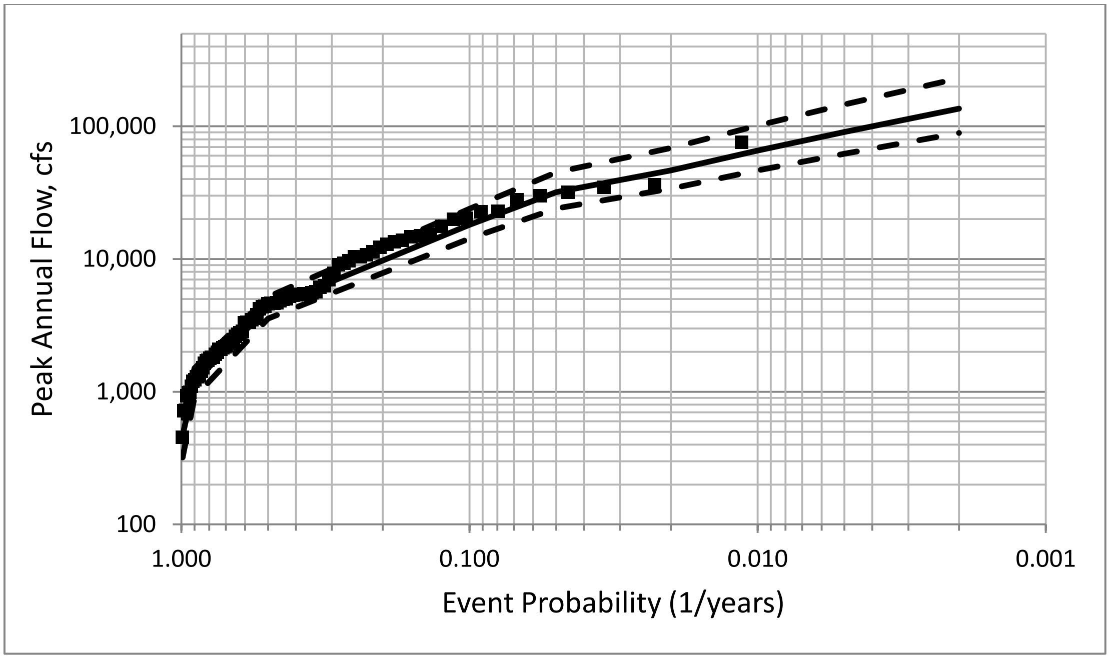


Figure 11. Natural annual peak flow distribution for the Mokelumne River with actual events (squares) and confidence intervals (95%) around the calculated distribution (black line).

Instead of creating new synthetic hydrographs, this study uses USACE hydrographs generated for the Mokelumne River (Figure 12). The 2-year through 500-year unregulated peak flows are estimated and combined with a region specific hydrograph shape, in this case the January 1997 storm event, to construct synthetic hydrographs (USACE 2002). The USACE hydrographs have smaller high-flow events before and after the peak event to create more realistic conditions.

In this study, seven events are routed through the reservoir flood model (2-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, and 500-yr) to generate a downstream flow frequency distribution. An important consideration for EAD calculations is to include as much of the inflow distribution as practical. Doing so better characterizes the final flood damage curve used to compute EAD. More elaborate methods of generating synthetic flood hydrographs are possible (Ji 2011).

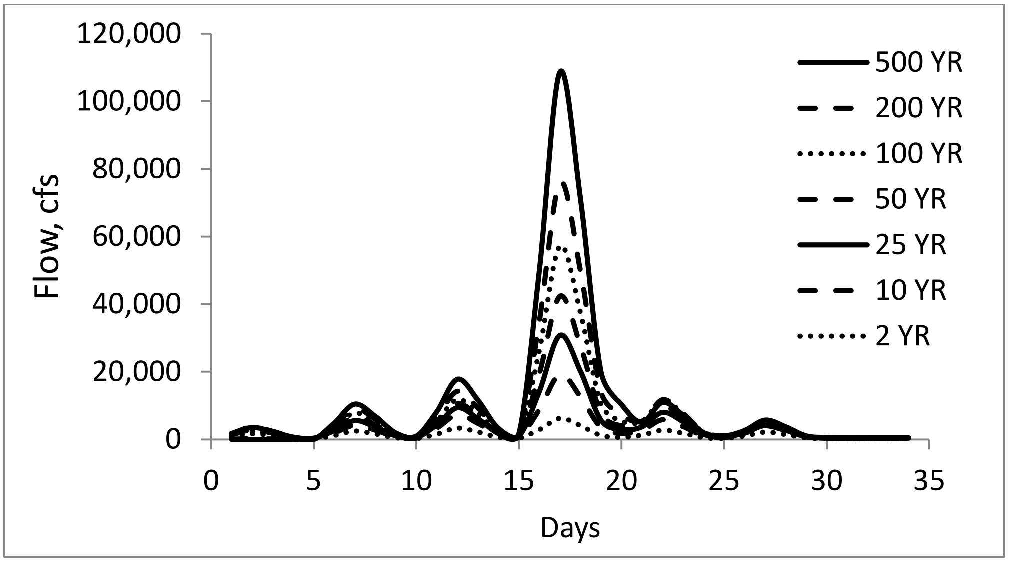


Figure 12. USACE synthetic hydrographs for the 2-year through 500-year event upstream of project.

## B. Reservoir Flood Routing

After synthetic hydrographs are constructed they are routed through a reservoir model (USACE's HEC-ResSim) with flood operation rules. The peak outflow for each synthetic hydrograph is paired with its unregulated peak inflow probability to translate the flood event probability downstream. For example, if a 30,000 cfs inflow event with a return period of 100 years is regulated to 5,000 cfs downstream, this implies 100 year status (0.01 annual exceedance probability) for the 5,000 cfs event. The two components of this process are the inflow – outflow relationship defined by the reservoir operations (Figure 13 (a)), and the translation of the probabilities to the downstream events (Figure 13 (b)).

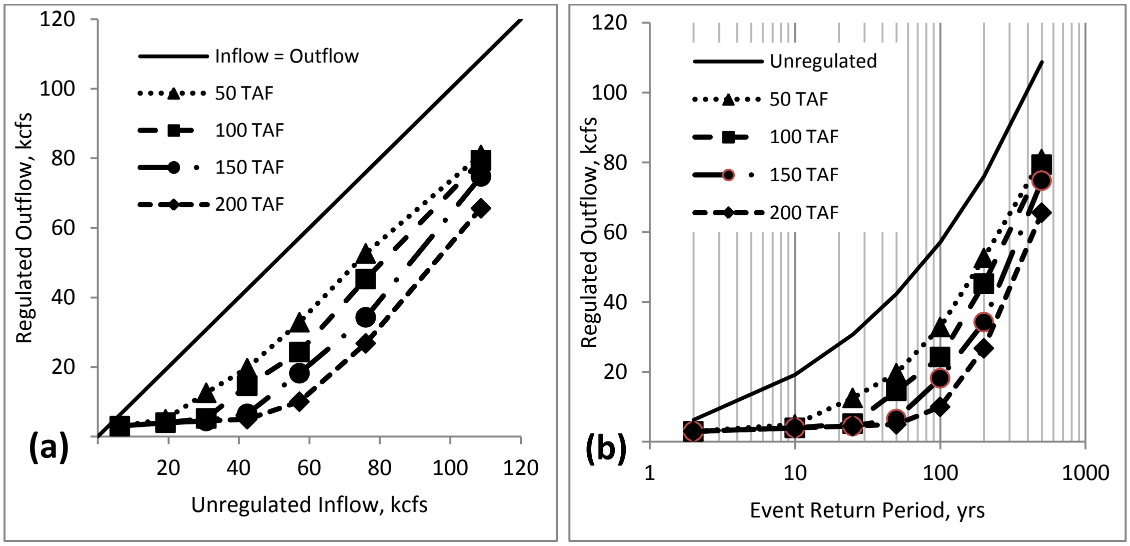


Figure 13. (a) Unregulated versus regulated reservoir plot for each flood storage alternative. (b) Regulated outflow probability curves for each alternative.

Reservoir flood operations are modeled with the USACE's HEC-ResSim software. This software allows the user to enter many types of operations as well as physical parameters for the dam and reservoir. Seven synthetic event hydrographs (2-year through 500-year) were routed for the flood storage alternatives (200, 150, 100, 50 and 0 taf) to generate the 28 values shown in Figure 13. For the zero flood storage space alternative, the inflow values were used in place of modeling outflows. This neglects the effects of pool routing and over-estimates the magnitude of outflow events. Daily and hourly model runs were completed with daily results used in the study. Hourly values provide an unrealistic level of accuracy given other input data. The next step requires the peak outflows and their probabilities to be carried forward to the flood mapping portion of the analysis.

### C. Mapping Flooded Areas

The technique used to map flooded areas includes building a hydraulic model based on elevation data, routing flood events downstream, and using water stage with land elevation to determine the extent of flooding. This process begins in ESRI's ArcGIS (ESRI 2011) program using an add-in tool called HEC-GeoRAS (USACE 2011).

HEC-GeoRAS is an ArcGIS tool that extracts data from a digital elevation model (DEM) and collects information to build a HEC-RAS model. This approach to building a HEC-RAS model is useful for studies involving large cross sections that would be impractical to manually survey. Variables such as channel centerline and banks need to be drawn in GIS and roughness values estimated before export to HEC-RAS. The quality of the HEC-RAS input data is directly related to the resolution of the DEM. In this study a 3 meter USGS Seamless Server DEM was the best available public data set (USGS 2010). After calibration model runs it was determined that the river's capacity was too low so manual changes were made to the underlying DEM. The channel centerline was lowered by 4 meters and the banks by 3 meters. This produced more realistic flood inundation maps based on historical data (EBMUD 2006). The need for this alteration is thought to result from poor incorporation of bathymetry data into the USGS DEM. However further investigation is required.

Once the input data is transferred to HEC-RAS, water stage and lateral extents at downstream cross sections are modeled based on an assumption of steady peak outflow. Figure 14 shows stage results for a typical agricultural floodplain cross-section. These cross-sections, which store information including water stage and inundation areas, are loaded back into ArcGIS and the HEC-GeoRAS tool interpolates flooded areas between cross sections based on the underlying DEM and creates inundation maps.

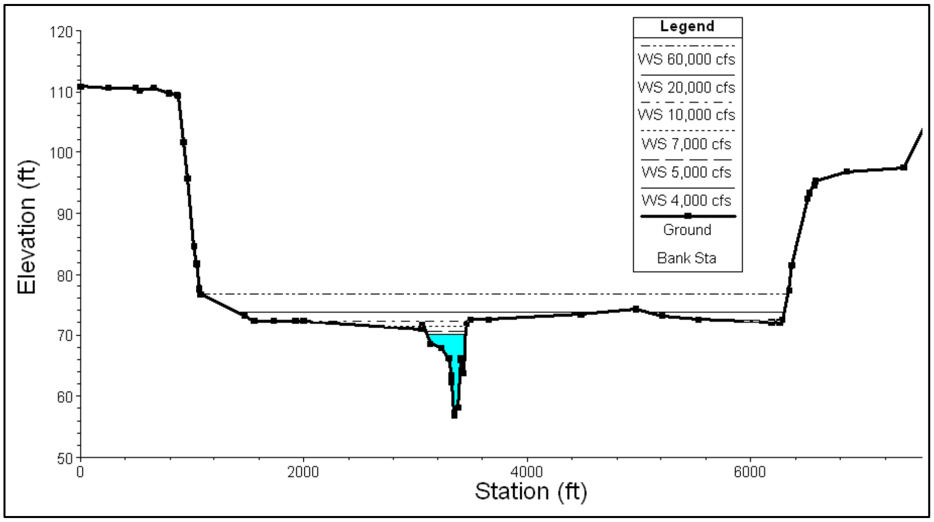


**Figure 14. HEC-RAS cross section of Mokelumne River floodplain upstream of Lodi, CA. Six water surface stages are calculated based on steady state routing of peak outflow events.**

Instead of modeling and calculating flood damages for five alternatives (200, 150, 100, 50, 0 taf) each with seven synthetic events (2-yr through 500-yr), six flood events are modeled that inundate various amounts of the floodplain and the 35 flood events are interpolated based on the six modeled events. It is important that the six events do a good job describing the alternatives so interpolation distances are small and all events are bracketed. In many circumstances, a larger number of events might be desirable for these calculations.

## D. Flood Damages

For each of the six modeled flood events, a flood damage cost is estimated. Within the Mokelumne River floodplain are two types of flood damage, urban and agricultural. Urban damage is calculated based on number and type of structure, cost to rebuild, depth of inundation, and duration of flooding. Agricultural damage is calculated based on crop type, season of flooding, duration of flooding, and acreage inundated. The California Department of Water Resources (CDWR) and this study uses a flood damage economics spreadsheet called the Flood Rapid Assessment Management (F-RAM) to estimate damages. The spreadsheet includes the above factors coupled with a composite Central Valley flood frequency to generate one EAD value for each flood storage space alternative. The final F-RAM equation is based on the EAD equation presented in equation 2 with urban and agricultural costs added together as the event's total flood damage.

Urban flood damage estimates are driven by the number of residential properties within an inundation zones and the flood control alternative's downstream flow frequency. Table 3 shows the number of residential properties in each inundation zone (i.e. 4,000 cfs flooding zone contains 46 high value properties). If a property is within a smaller inundation zone it is also counted within larger inundation zones. Two averages of property values, $600,000 and $300,000 are used to capture the difference between higher cost river front properties and lower cost interior city properties. For a more rigorous study this level of detail needs to be increased. The dividing line between the two is poorly defined, but is based on aerial images of home size and online surveys of recently bought and sold homes in Lodi, CA.

**Table 3. Number of high and low value residential properties inundated for each downstream flow. The total number of high value residential properties near the waterfront is 65.**

| No. of Properties @ | Downstream flow, cfs | | | | | |
|---|---|---|---|---|---|---|
| | 4,000 | 5,000 | 7,000 | 10,000 | 20,000 | 60,000 |
| $600,000 ea | 46 | 60 | 65 | 65 | 65 | 65 |
| $300,000 ea | 0 | 9 | 38 | 79 | 585 | 835 |

Agricultural flood damages are estimated similarly. For each flood inundation zone, acres of crop types are estimated. Table 4 shows the acres for each crop for each inundation zone. These nine crop types provide more detail than is required for this feasibility study. Following the grouping of crop types in the USACE Comprehensive Study these nine crops are grouped into three categories: field crops, vegetable crops, and fruit and nut crops.

**Table 4. Acreages of crops inundated for each flood flow.**

| Flow kcfs | Corn | Walnuts | Almonds | Vineyard | Apples | Melons | Cherries | Beans | Alfalfa | Totals |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 0 | 135 | 0 | 193 | 0 | 45 | 40 | 5 | 17 | 435 |
| 5 | 0 | 164 | 0 | 205 | 0 | 45 | 50 | 14 | 25 | 503 |
| 7 | 0 | 205 | 0 | 207 | 7 | 46 | 60 | 28 | 36 | 589 |
| 10 | 0 | 653 | 9 | 297 | 13 | 54 | 71 | 63 | 111 | 1,270 |
| 20 | 0 | 743 | 12 | 485 | 19 | 65 | 111 | 106 | 136 | 1,677 |
| 60 | 9 | 1,089 | 12 | 727 | 48 | 153 | 137 | 165 | 171 | 2,512 |

Table 5 shows the grouped acres for agricultural products. The economic values for revenue, re-establishment cost, and EAD for each crop group is taken as the average of all included crops. Crops not grown in the floodplain such as tomatoes, asparagus and wheat have been included because they are widely grown in the region and generate a better crop group average (SJ County 2010). Table 6 shows revenues for field crops, Table 7 for vegetable crops, and Table 8 for fruit and nut crops. For agriculture’s addition to EAD, fruit and nut crops have the highest EAD, followed by vegetable crops and field crops.

**Table 5. Acreages of crop groups for each flood flow.**

| Flood flow, cfs | 4,000 | 5,000 | 7,000 | 10,000 | 20,000 | 60,000 |
|---|---|---|---|---|---|---|
| Field Crops (acres)<br>(corn, bean, alfalfa, pasture, wheat) | 22 | 39 | 64 | 173 | 242 | 346 |
| Vegetable Crops (acres)<br>(melons, tomatoes, asparagus) | 45 | 45 | 46 | 54 | 65 | 153 |
| Fruit & Nut Crops (acres)<br>(walnuts, grapes, apples, almonds, cherries) | 368 | 419 | 480 | 1,043 | 1,370 | 2,013 |
| Totals | 435 | 503 | 589 | 1,270 | 1,677 | 2,512 |

**Table 6. Economic values for the field crop group. An equally weighted average of all crops in the floodplain is used instead of a crop area weighted average because these crops are considered equivalent for this analysis.**

| Field Crop | EAD ($/yr/ac) | Re-establishment Cost ($/ac) | Gross Income ($/ac) | Variable Costs ($/ac) | Net Income ($/ac) |
|---|---|---|---|---|---|
| Corn | 36 | 0 | 521 | 487 | 34 |
| Beans | 143 | 0 | 1000 | 742 | 258 |
| Wheat | 442 | 0 | 655 | 447 | 208 |
| Alfalfa | 1020 | 531 | 1588 | 675 | 913 |
| Pasture | 7 | 112 | 107 | 143 | -36 |
| Average | 330 | 129 | 774 | 499 | 275 |

**Table 7. Economic values for the vegetable crop group.**

| Vegetable Crop | EAD ($/yr/ac) | Re-establishment Cost ($/ac) | Gross Income ($/ac) | Variable Costs ($/ac) | Net Income ($/ac) |
|---|---|---|---|---|---|
| Melons | 1,633 | 0 | 6,303 | 5,424 | 879 |
| Tomatoes | 2,150 | 0 | 8,070 | 6,419 | 1,651 |
| Asparagus | 1,239 | 2,045 | 5,014 | 4,680 | 334 |
| Average | 1,674 | 682 | 6,462 | 5,508 | 955 |

**Table 8. Economic values for the fruit and nut crop group.**

| Fruit & Nut Crop | EAD ($/yr/ac) | Re-establishment Cost ($/ac) | Gross Income ($/ac) | Variable Costs ($/ac) | Net Income ($/ac) |
|---|---|---|---|---|---|
| Walnuts | 2,449 | 5,705 | 4,250 | 1,946 | 2,304 |
| Almonds | 1,681 | 5,049 | 3,000 | 2,128 | 872 |
| Vineyards | 1,256 | 12,802 | 2,925 | 1,989 | 936 |
| Apples | 10,075 | 10,527 | 18,180 | 9,234 | 8,946 |
| Cherries | 2,354 | 6,429 | 12,740 | 11,525 | 1,215 |
| Average | 3,563 | 8,102 | 8,219 | 5,364 | 2,855 |

Agricultural damage includes variable crop damage based on season of flooding, a layer of complexity not needed in urban flood damage. For example, if tomatoes are planted in March and flooding occurs in February, crop damage is zero. This seasonal flood issue presents a problem for a frequency based approach. In the F-RAM spreadsheet CDWR's solution is to multiply each month's damage by a probability that the flood event occurs during a specific month. These monthly probabilities sum to one and are based on California's Central Valley hydrology. This multiplication happens in addition to the initial multiplication of the flow frequency, so 1.0 does not mean a flood happens every year; if a flood happens (based on the flow frequency), the additional probability weights when that flood event will occur during the year.

## E. Expected Annual Damage

Once flow frequencies, inundated land acreages, and crop values have been estimated, the expected annual damage for each alternative can be calculated. This is done based on equation 2 and figure 5. Urban and agricultural sectors are calculated separately and then combined in the final economic analysis. An important add-on for evaluating alternatives is the floodplain response to changing conditions, more specifically floodplain mitigation that can significantly reduce EAD.

## F. Floodplain Mitigation

For simplicity, floodplain mitigation takes two forms in this study: residential home purchases, and agricultural land-use conversion. The guiding principle for floodplain mitigation is economic feasibility: unmitigated damages should exceed mitigated damages plus mitigation costs. On the residential side, property values are divided into two categories: (1) high value waterfront – near waterfront homes, and (2) lower value interior city homes with values of $600,000 and $300,000/property respectively. These values are averages of recent home sales in Lodi, CA. The mitigation decision to purchase residential properties is based on repaying a typical government-sponsored project loan over a 50 year time period with a 6% interest rate. A capital repayment factor (CRF) of 0.0634 is used to annualize payments.

The decision to buyout residential properties in a particular flood inundation zone can be simplified to all or nothing for each property category ($300k and $600k). For example if the benefit of buying one $600,000 property within the 4,000 cfs inundation zone (for a given flood storage alternative) is $6,913/year, then each additional property will net the same benefit due to an unchanging probability of flooding for that zone. For flood storage alternatives of 200, 150, 100 and 50 taf no buyouts are feasible. For the no flood storage space alternative, all properties within 10,000 cfs floodplain are purchased (191 properties).

Agricultural land conversion is the second type of floodplain mitigation. Agricultural flood mitigation is implemented when a net benefit occurs from converting high flood cost land to lower flood cost uses, such as switching from fruit and nut crops to vegetable crops. Both the benefit of reducing agricultural EAD and the cost of switching land use from one crop group to another are considered. In general, land uses with high flooding costs also generate more revenue per acre, so changing crops often reduces crop revenue. These two factors are balanced within the flood storage alternative being analyzed to establish the optimal crop pattern across the affected floodplain. In reality, farmers individually make this decision considering many other factors not modeled here such as field topography, soil conditions, water availability, and a farms' crop diversity. Nevertheless, this approach is useful for approximating crop land use with large changes in flood frequency.

Tables 9 (a), (b), and (c) show the optimized crop mix for all flood storage alternatives. Results for the 200, 150, and 100 taf flood storage alternatives are the same. Overall, high value fruit and nut crops dominate the floodplain at larger amounts of flood storage space (200, 150, 100 taf) and transition (50 taf) to less expensive crops at lower levels of flood protection. This shift is driven by the economic loss each time flooding triggers a re-establishment cost (highest for fruit and nut crops).

**Tables 9 (a) Optimized agricultural floodplain land use based on crop group and flood frequency. Tables report acreages of each crop group located within inundation zones. Flood storage alternatives: 200 taf, 150 taf and 100 taf result in the same land use – all fruit & nuts.**

| Optimized Land | Floodplain inundated @ | | | | | |
|---|---|---|---|---|---|---|
| Use (acres) | 4,000 cfs | 5,000 cfs | 7,000 cfs | 10,000 cfs | 20,000 cfs | 60,000 cfs |
| Field Crops | 0 | 0 | 0 | 0 | 0 | 0 |
| Vegetables | 0 | 0 | 0 | 0 | 0 | 0 |
| Fruit & Nuts | 435 | 503 | 589 | 1,270 | 1,677 | 2,512 |
| Total | 435 | 503 | 589 | 1,270 | 1,677 | 2,512 |

**(b) The 50 taf flood storage alternative shows a shift to vegetables for frequently flooded areas.**

| Optimized Land | Floodplain inundated @ | | | | | |
|---|---|---|---|---|---|---|
| Use (acres) | 4,000 cfs | 5,000 cfs | 7,000 cfs | 10,000 cfs | 20,000 cfs | 60,000 cfs |
| Field Crops | 0 | 0 | 0 | 0 | 0 | 0 |
| Vegetables | 435 | 435 | 435 | 435 | 435 | 435 |
| Fruit & Nuts | 0 | 69 | 154 | 836 | 1,243 | 2,078 |
| Total | 435 | 503 | 589 | 1,270 | 1,677 | 2,512 |

**(c) The no flood storage alternative transitions to field crops that sustain less damage from high frequency floodplain inundations.**

| Optimized Land | Floodplain inundated @ | | | | | |
|---|---|---|---|---|---|---|
| Use (acres) | 4,000 cfs | 5,000 cfs | 7,000 cfs | 10,000 cfs | 20,000 cfs | 60,000 cfs |
| Field Crops | 435 | 503 | 589 | 1,270 | 1,270 | 1,270 |
| Vegetables | 0 | 0 | 0 | 0 | 407 | 407 |
| Fruit & Nuts | 0 | 0 | 0 | 0 | 0 | 835 |
| Total | 435 | 503 | 589 | 1,270 | 1,677 | 2,512 |

## Water Supply Modeling

Modeling water supply shortages, hydropower generation and environmental water volumes for each reservoir alternative is done with a POR approach. A time series of 81 water years from USGS is used to study trends in reservoir operations for each flood storage space alternative. A water balance spreadsheet model operating on a monthly time step is used to analyze these trends.

A time series of regulated stream flow is available from USGS (Gage 11139500) for a location just upstream of Pardee reservoir. These data include upstream regulation by hydropower operations and small water supply diversions. A shortcoming of POR approaches are the possible exclusion of extreme events that have not occurred in the period of record. For the Mokelumne River, three multi-year droughts and a few very wet periods are included in the stream flow record. However, for estimating long-term average performance not dependent on extreme events (water supply, hydropower, recreation, etc.), period-of record analysis with records longer than six or seven decades has been shown to be adequate (Lund and Ferreira 1996).

The monthly reservoir model developed for this study operates a pair of reservoirs together. The upstream reservoir contains the primary water supply diversion, with the lower reservoir providing flood control, fisheries releases, and other downstream water supply releases. The two reservoirs are linked through release rules at the upper reservoir that prevent the lower reservoir from dropping below 50,000 acre-feet. In this way, flood storage at the lower reservoir alters the frequency of water shortage periods at the upper reservoir. Flood routing is not included in this model, typically a high monthly release will mask most flood operations.

Water supply benefits are calculated based on reductions in shortages and shortage costs. Alternatives with less flood storage space typically maintain higher reservoir levels throughout the year. This better prepares the system for droughts. Benefits from decreased shortages are only realized when the system is going into or coming out of a drought. For each time step in the monthly model, deliveries are reduced if water supply storage falls below a specified level. A summary table calculates shortages by month, multiplies these by estimated shortage costs, and sums across all months for a cumulative shortage cost for the POR (Table 10). This is then annualized so it can be included with hydropower and flood damage values.

Shortage cost curves were obtained from the California Value Integrated Network (CALVIN) model (Draper et al. 2003). Shortage costs are based on data available for the largest water user in the Mokelumne, EBMUD. Continuous cost curves are available ranging from 0% shortage to 30% shortage, however the model only uses a 15% shortage. The other water supply use in the system is primarily downstream agriculture and use is much less than EBMUD, although they often have more senior water rights. Shortages for these other users are tracked in the model and reported, but no costs are assigned because they are insignificant compared to EBMUD.

**Table 10. EBMUD levels of delivery and shortage costs per month.**

| Month | Full Delivery taf/mo | Reduced Delivery taf/mo | Shortage Cost $ (x 1000) |
|---|---|---|---|
| Jan | 14.23 | 11.86 | 22,951 |
| Feb | 12.86 | 10.71 | 20,764 |
| Mar | 14.76 | 12.30 | 23,727 |
| Apr | 16.84 | 14.03 | 10,584 |
| May | 19.51 | 16.26 | 8,401 |
| Jun | 21.94 | 18.28 | 9,461 |
| Jul | 24.25 | 20.21 | 10,434 |
| Aug | 23.72 | 19.77 | 10,223 |
| Sep | 21.43 | 17.86 | 9,240 |
| Oct | 18.98 | 15.82 | 11,925 |
| Nov | 15.31 | 12.75 | 24,448 |
| Dec | 14.23 | 11.86 | 22,769 |
| Totals | 218 | 180 | |

## Hydropower Modeling

Reservoir hydropower generation is simplified due to the limitations of a monthly time step. Average monthly prices including peak and off-peak factors are used to estimate revenue changes using baseload generating rules at Camanche dam. In general, there are more sophisticated methods to analyze hydropower revenue generation, but this approach is sufficient to capture revenue changes from reductions in flood storage. Two sets of price values are used to reflect the impact of wet and dry year types on hydropower generation. Generation at Pardee dam is assumed unchanged because flood storage space reductions occur at the lower reservoir and have an indirect effect on the upstream reservoir. Table 11 shows the generation prices for each year type, month, and rate. Peak and non-peak hours are based on a 10 hour mid-day peak and 14 hour off peak per day rate structure.

**Table 11. Monthly energy prices for wet and dry years, including peak and off-peak pricing. Values estimated based on 4 years of hourly price data available through the California Independent System Operator (CAISO).**

| Month | Wet Year (WY flow > 730 TAF) Peak ($/MW-hr) | Wet Year (WY flow > 730 TAF) Off-peak ($/MW-hr) | Dry Year (WY flow < 730 TAF) Peak ($/MW-hr) | Dry Year (WY flow < 730 TAF) Off-peak ($/MW-hr) |
|---|---|---|---|---|
| Jan | 44.54 | 41.02 | 64.17 | 57.62 |
| Feb | 37.59 | 37.59 | 67.91 | 57.96 |
| Mar | 38.04 | 34.87 | 67.92 | 58.09 |
| Apr | 37.86 | 37.86 | 82.21 | 64.11 |
| May | 38.51 | 32.38 | 74.55 | 63.08 |
| Jun | 42.43 | 35.51 | 91.26 | 69.04 |
| Jul | 65.47 | 40.71 | 85.18 | 55.53 |
| Aug | 65.30 | 47.13 | 89.21 | 53.05 |
| Sep | 43.89 | 37.28 | 65.23 | 42.82 |
| Oct | 55.63 | 47.46 | 63.00 | 46.69 |
| Nov | 60.91 | 47.10 | 56.71 | 47.72 |
| Dec | 55.96 | 53.02 | 61.16 | 52.07 |

For each monthly time step the flow through the dam is checked to make sure it does not exceed generation capacity. Then it is included in the hydropower generation equation (Equation 3). This generation assumes constant efficiency operations for an entire time step.

$$P = Q * h * \gamma * \eta \qquad (3)$$

Where P is power (ft-lb/sec), Q is flow (ft^3/sec), h is head (ft), γ is specific weight of water (62.4 lb/ft^3), and η is turbine efficiency (0.87). Power is converted to MW by multiplying ft-lb/sec by 1.356 x 10^ (-6). This calculation is done for each time step in the reservoir model release time series. Generation in MW-hrs is then calculated based on 24 hours of generation per day for a month at the calculated MW rate.

## Environmental Release Modeling

Environmental benefits are derived through specific releases of water stored for environmental purposes. The POR model tracks water stored above the baseline (200 taf alternative) and releases water in specific months as pulse flows. Water is only released if it is stored in the 200 taf of transferable storage space. Therefore, environmental releases cannot reduce water supply reliability below the baseline case. Levels of releases for environmental flows are included in the model to explore the trade-off between water supply and environmental flows for the additional water made available. Table 12 shows the timing and volumes for these releases in taf. These volumes are based on pulse flow releases by EBMUD to study the benefits of targeted environmental releases (EBMUD 2001).

**Table 12. Environmental releases pulse schedule. Releases are only made if water is stored above the 200 taf baseline guide curve.**

| Spring Releases (taf) | | | | Fall Releases (taf) | | | |
|---|---|---|---|---|---|---|---|
| Month | Full | Half | None | Month | Full | Half | None |
| April | 15 | 7.5 | 0 | September | 5 | 2.5 | 0 |
| May | 30 | 15 | 0 | October | 10 | 5 | 0 |
| June | 15 | 7.5 | 0 | November | 5 | 2.5 | 0 |
| total | 60 | 30 | 0 | total | 20 | 10 | 0 |

Not having to specify a daily or hourly hydrograph for environmental flows is a benefit of monthly modeling. These volumes are released at specific times of the year for species of interest or for geomorphic purposes. Studies in these fields can be used to best make use of the volumes presented in this analysis. Furthermore, other volumes and timing regimes can easily be substituted into the monthly model and analyzed.

# 5. RESULTS

## Operating Performance

Each flood storage alternative (200, 150, 100, 50 and 0 taf) has two outputs: an economic value and an environmental flows value. The economic value is the combined marginal benefit (or cost) of flood damage, water supply reliability, and hydropower revenue (Figure 15). The environmental value is presented as environmental pulse flows made possible by extra stored water (Figure 16).

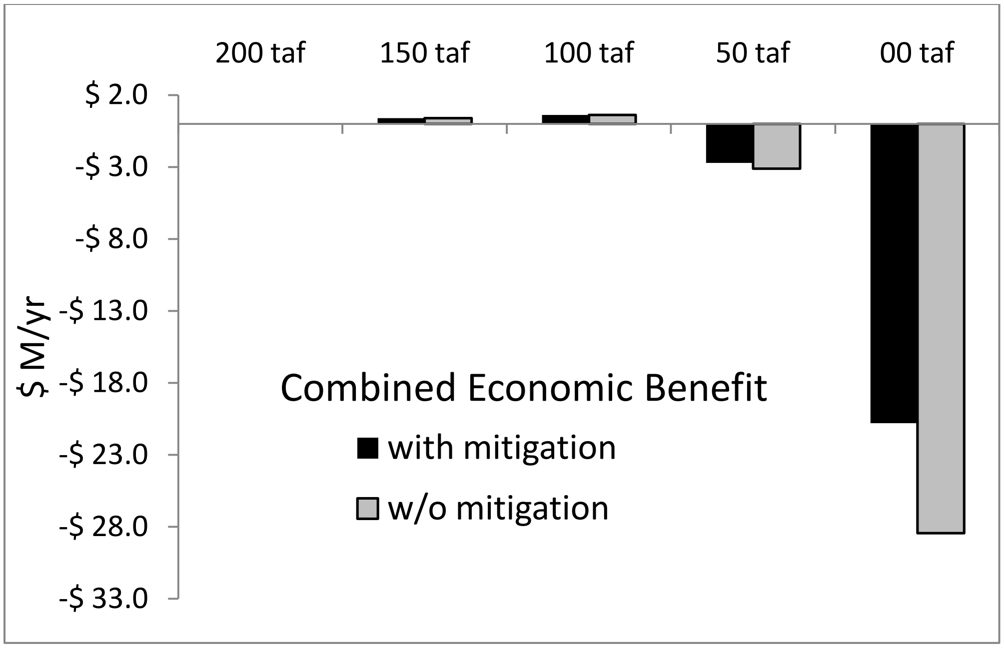


**Figure 15. Combined economic benefit of reductions in flood storage space. Alternatives are in 2010 dollars and relative to 200 taf baseline.**

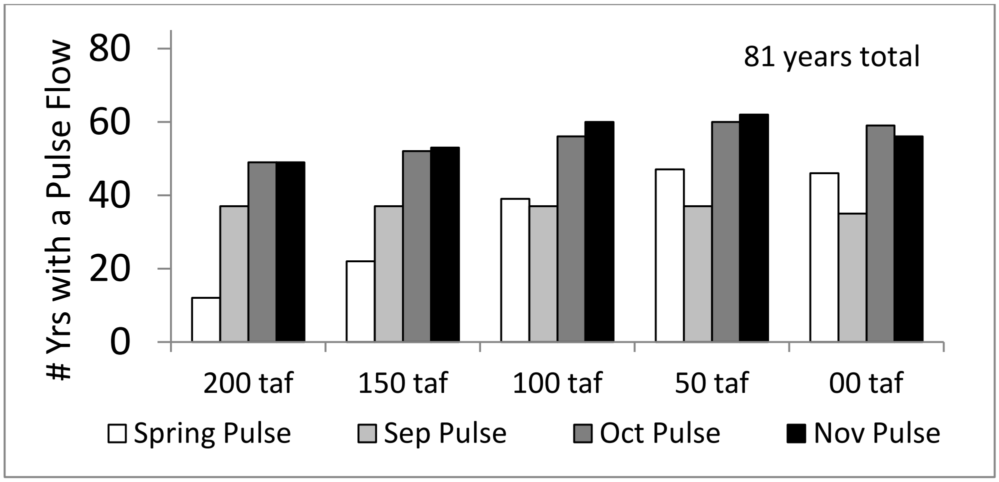


**Figure 16. Environmental pulse flows released from Camanche Dam based on simulating 81 years of data. Spring pulses show the greatest increase potential, while fall pulses show a muted response and tend to increase later in the season.**

The economic results indicate a clear region of similar performing alternatives (200, 150, and 100 taf). These three alternatives differ by a small percentage and provide increased flexibility for policy makers. The 150 and 100 taf alternatives generate positive net revenues of $380,000/yr and $620,000/yr respectively. While these alternatives show promise, the oppressive weight of flood damages is very noticeable in the combined results, with water supply and hydropower benefits only shifting the estimates up slightly.

Environmental release results show significant gains can be realized in the spring with smaller gains possible in the fall. This is due to the seasonality of releases relative to the river's hydrology and the current demand patterns of water users. Once the snow melts and rainfall stops in the spring, reservoir storage must carry the system through until the winter brings more precipitation.

Combining these two results in one plot creates a valuable analysis tool (Figure 17), capable of displaying different system alternatives and the resulting trade-offs between economic and environmental uses of reservoir storage. The environmental axis is the total number of pulse flow releases divided by the 200 taf baseline alternative. Different metrics can be used to emphasize different aspects of the environmental variable. Here, a linear assumption of benefits for additional environmental releases is an over simplification of environmental response, however it illustrates the point of creating a trade-off plot that ranks alternatives by multiple parameters.

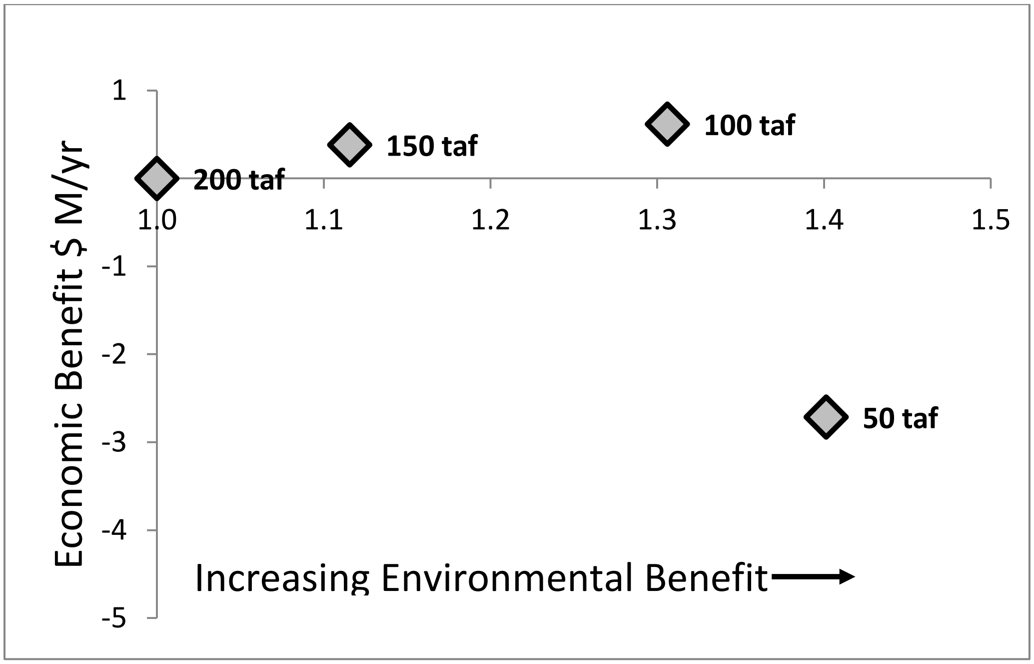


**Figure 17. Economic-environmental trade-off plot for reoperation alternatives. Environmental axis is total environmental releases divided by baseline (200 taf) case releases. The 00 taf alternative (not shown) is at -$21 M/yr and 1.4.**

Finally, individual results for each component of the economic analysis are presented below. These details provide insight into modeling limitations and possibilities for future work. Also presented is a future water demand analysis ("Changes in demand"). To gain a better understanding of the results– which are a snapshot in time (2010), and how they might change, economic values were estimated for EBMUD demand for years: 1995, 2010, 2020 and 2040.

## Flood Damages

The expected cost of flooding was calculated with and without floodplain mitigation. For the Mokelumne watershed significant flood storage space currently exists (relative to system inflows) to regulate all but the largest floods. This is true for agricultural flood damages (Figure 18) as well as urban flood damages (Figure 19) with both indicating floodplain mitigation activities are too expensive for the 200, 150, 100 taf alternatives, and only becomes feasible when flood storage is 50 taf or less.

Agricultural land use changes begin when flood storage space is reduced to 50 taf. The shift observed in tables 9a and 9b removes high value fruit and nut crops and replaces them with vegetable crops for the more flood prone areas (inundation zones). Referencing the crop group economics (tables 6-8); re-establishment costs due to elevated flood frequencies begin to reduce overall revenues. The same process occurs again as flood storage is reduced to zero, except vegetable crops are replaced by the lowest cost field crops.

For urban flood damage mitigation, residential buyouts only occur for the no flood storage alternative. The total cost of this alternative is unreasonably high and therefore shows that residential property buyouts are not an effective method to reduce flood damage in this river system. Other methods such as levees and or bypasses may provide a more cost effective solution.

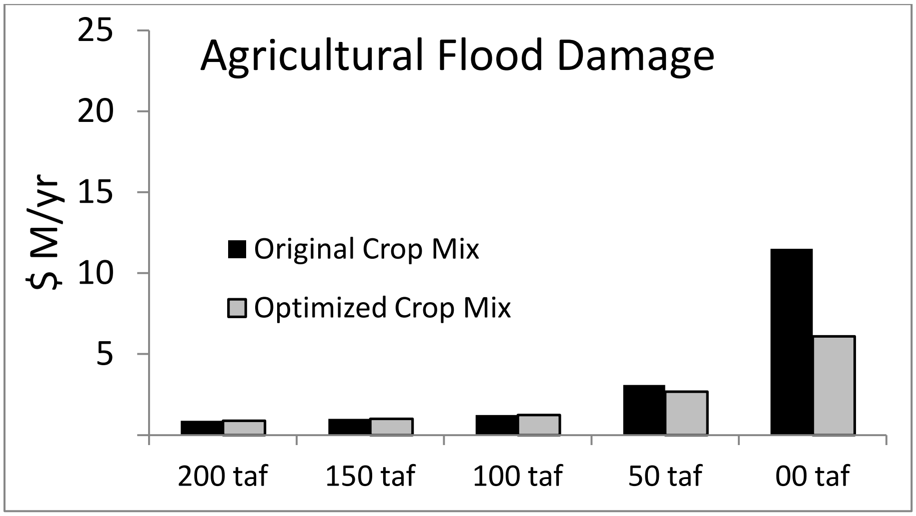


Figure 18. Agricultural flood damages (EAD values) for original floodplain land use and optimized (mitigated) land use.

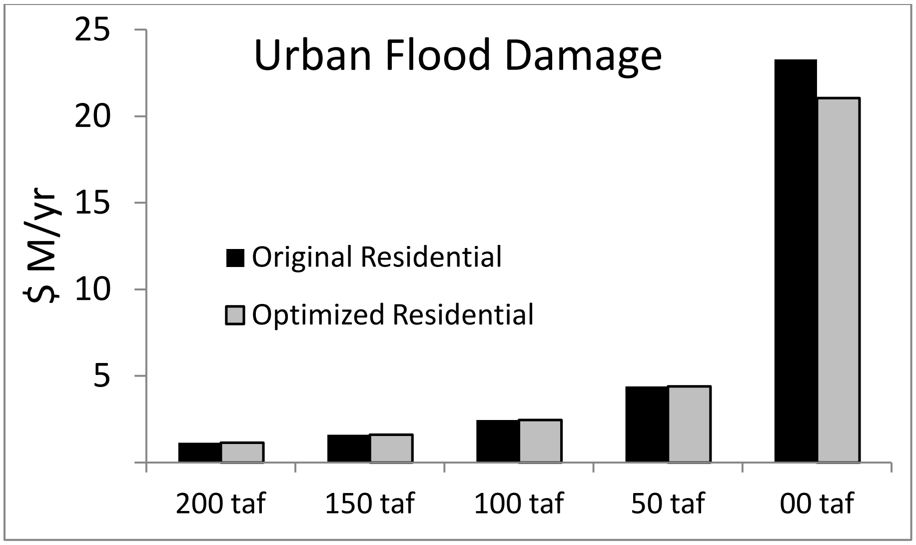


Figure 19. Urban flood damages based on current residential land use and for optimized land use.

## Environmental Releases

Environmental pulse flows during the spring and fall periods depend on the timing of inflows, the seasonal demands of water users, and reservoir guide curves that limit water storage. As seen in Figure 16, the major change in environmental pulse flows is during the spring. This is from flood storage requirements in winter – any reduction in the requirement and resulting stored water can be immediately used in the spring.

## Water Supply Reliability

Water supply reliability benefits arise from reduced water shortage costs for EBMUD. Water supply benefits are moderately important in the overall economic analysis at small to medium levels of flood storage reallocation. Using cost curves and the historical record of inflows, costs were estimated for each flood storage level (Figure 20). The incremental benefit is very sensitive to the periods entering and exiting droughts since there are only three significant droughts in the historical record. These periods are the most likely to shift from shortage to normal operations (or vice versa) for different alternatives. No change is observed between 100 taf and 50 taf because small differences in reservoir levels during these periods did not trigger changes in shortages. Both alternatives triggered drought conservation measures during the same months and for the same durations.

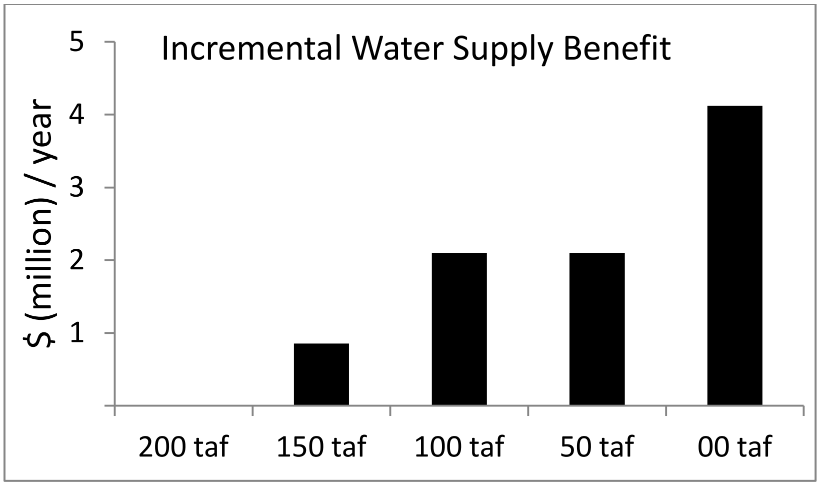


Figure 20. Average annual benefit of reduced water supply shortage costs for EBMUD (relative to 200 taf baseline).

## Hydropower

In the Mokelumne system, economic benefit from the reoperation of hydropower is fairly small, less than $300,000 per year. Figure 21 shows the impact of each alternative relative to the baseline (200 taf). The drop in benefits for no flood storage (00 taf) is due to flood releases and reservoir spill. This result includes two counter-acting processes. The first is an increase in generation from more reservoir head (00 taf relative to 50 taf), and the second is a decrease in generation due to water not going through turbines – spilled water (5,000 cfs turbine capacity). From a revenue perspective, water loss due to spill (flows bypassing the turbines) is more significant.

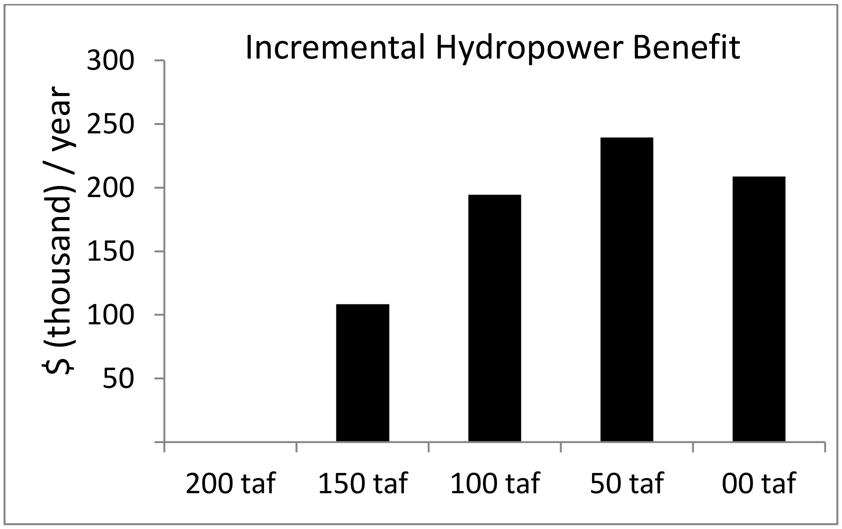


Figure 21. Average annual change in hydropower revenues at Camanche Dam for each flood storage alternative.

## Changes in Demand

Over time demands on water resource systems usually change. In the case of the Mokelumne River, EBMUD has had fairly stable water use from 1970-2005, averaging between 200 and 225 million gallons per day (224 to 252 taf/year) (EBMUD 2005). These urban demands are expected to change in the future as the population increases and demand hardens. Projections for 2020 and 2040 are 221 MGD and 230 MGD respectively (248 and 258 taf/year) after conservation and recycling savings (EBMUD 2009). These higher demands change performance results with different flood storage pool levels. Table 13 shows the total marginal benefit for EBMUD demand levels based on years 1995, 2010, 2020, and 2040. In the table the optimal economic storage level shifts from 150 taf to 100 taf from 1995 to 2010. This shows the increasing value of the water supply improvements for EBMUD. The trend then shifts back toward more flood storage space for years 2020 and 2040, due to a reduction in the length of time water is stored in the transferred space creating a benefit. Higher demands effectively increase the rate of reservoir drawdown and make it more likely that empty storage space will be present (so reductions in flood storage allocation become less effective at creating additional benefits).

Table 13. The effect of changing water demands on total annual economic benefits. Bold/Italics show the optimal level of flood storage.

| Flood Storage | 1995 | 2010 | 2020 | 2040 |
|---|---|---|---|---|
| 200 taf | $0 | $0 | $0 | ***$0*** |
| 150 taf | ***$250,000*** | $380,000 | ***$430,000*** | -$630,000 |
| 100 taf | -$750,000 | ***$620,000*** | $300,000 | -$730,000 |
| 50 taf | -$3,450,000 | -$2,700,000 | -$1,650,000 | -$4,100,000 |
| 00 taf | -$23,000,000 | -$20,800,000 | -$19,700,000 | -$20,700,000 |

The second factor contributing to the reversal of the least-cost flood storage level is a static flood damage curve that does not vary with actual or average reservoir storage. In reality there would be a reduction in flood damage as the reservoir is drawn down more often. However, the flood model in this study is based on the maximum allowable water level of each alternative, so this effect is not captured. This approach underestimates the effectiveness of flood storage reductions, if the flood damage curves were adjusted to reflect the lower reservoir levels, the trend would not reverse in 2020. Least-cost flood storage space would likely remain at 100 taf or possibly shift to 50 taf.

# 6. DISCUSSION

The results shown in Figure 17 have two optimal operation points that occur at 50 and 100 taf of flood storage space. The 50 taf alternative performs best for environmental purposes although it requires a substantial overall economic loss (-$2.7 M/yr). The 100 taf alternative performs best for economic purposes and provides increased environmental benefits relative to the baseline (200 taf) alternative. Based on the level of environmental restoration needed, a solution that is bracketed by these end points represents the best way of operating the system to take advantage of maximum total benefits.

An important non-modeling aspect of this type of reoperation is the financial compensation framework that must be established to make all stakeholders whole. The idea of increasing total benefits is not meant to mask the fact that some stakeholders will be harmed in this process. Having a strong public relations program to accompany the technical work will help this process be less uncertain and more trusted by local residents who could be negatively affected.

An interesting byproduct of reducing reservoir flood storage is the increase in passive flood releases. These releases are generally considered negative from a flood control perspective because they occur in an uncontrolled fashion and may cause flood damage. However, their variability and uncertain nature can provide environmental benefits (Poff et al 1997). Modeling used in this study focused on managed environmental releases based on water made available, but it is important to recognize the additional environmental benefits these releases will generate. The benefits of passive flood releases are high for alternatives with less flood storage and decrease to zero for the 200 taf alternative (no uncontrolled releases). The consideration of passive flood releases does not change the optimal operating range. The 50 and 0 taf flood storage alternatives would shift further right (higher environmental benefits) in figure 19 if passive environmental benefits were included, but the 0 taf flood storage alternative's high economic cost still excludes it as a feasible alternative.

# 7. FUTURE WORK

## Historical Land Use

Modeling historical land use can provide insight into economic trends and quantify the connection between floodplain development and increased flood risk. Conceptually, adding damage-prone property (particularly urban) in the floodplain increases flood risk and mitigation costs. Modeling 1950, 1970, and 1990 land use practices and home values would show the relationship between development and increases in flood risk. Such work would likely display the advantages of beginning a reoperation program sooner, rather than later. Expensive development vulnerable to flooding restricts future flexibility and options. Permanent high-value flood-prone investments on the floodplain removes the ability to transfer flood control to the floodplain and makes it more critical that flood storage space remains or even increases.

## High Flow Bypass System

A high flow bypass system around urban Lodi is a capital-intensive floodplain mitigation option that should be considered. This option would function similarly to bypasses in the Sacramento Valley, allowing high flows to safely pass around developed areas, while providing the environmental benefits from a more dynamic river. Figure 22 shows a possible location for a weir and bypass around Lodi, CA. The weir would be designed to allow flows above a threshold (likely 5,000 cfs) to spill into a bypass around the urban reach of the river. The weir threshold would allow annual crops to be grown in the bypass in most years, as is the case with the Yolo Bypass on the Sacramento River. With an adequate bypass system, major reservoir reoperation could occur with little increase in downstream flood damage. Alternatives including limited or no flood storage space in the reservoir might become feasible with significant increases in water supply and eco-system benefits. Because the Mokelumne River is not a tributary to the San Joaquin or Sacramento River, there are less combined flooding consequences from large releases. Delta issues such as flooding and water quality would need to be considered for a thorough study.

Figure 22. High flow bypass system around urban Lodi, CA

## Camanche Outlet Capacity

Increasing Camanche's outlet capacity has potential environmental and flood reduction benefits. A larger outlet capacity that results in higher flow events supports significant opportunities for restoring elements of the Mokelumne River's natural flow regime (Florsheim and Mount 2003). Since the current channel capacity is 5,000 cfs and the maximum controlled release is also 5,000 cfs, additional outlet capacity is required to exceed channel capacity and cause the river to connect with the floodplain.

Flood risk reductions would require downstream mitigation actions to allow larger controlled releases (i.e. 7,000 or 10,000 cfs). Once this is done, Camanche's ability to prevent uncontrolled releases is improved. By releasing a higher controlled flow – a flow for which floodplain users are prepared, the dam can likely route larger flood events with less uncontrolled spill and a lower peak flow. This becomes increasingly important for greater reductions in flood storage space because the reservoir loses its ability to stop flood events.

## Agricultural Levees

Understanding how floodplains function with varying degrees of agricultural levees would provide useful information for selecting alternatives. Desired floodplain processes rely on coordinating the reservoir flow regime with the planned river and floodplain topography. If levees are completely removed and an aggressive flow regime (a small flood storage alternative) is selected, flooding losses might overshadow environmental benefits. Alternatively, if levees are strengthened and a conservative flow regime is selected, environmental benefits might be insufficient. In general, the ability to change the static elevation of floodplain land, add and remove levees, and otherwise manipulate modeled topography is valuable for refining alternatives.

There is also an opportunity to combine this idea with changes in Camanche's outlet capacity. If existing floodplains could be sufficiently reconnected by degrading some existing levees, the need to increase Camanche's outlet capacity would be reduced. A combination of selective levee degradation or setting levees back and increased outlet capacity might provide the most economical solution for achieving desirable river-floodplain connection. The best alternatives will strike a balance between outlet capacity and floodplain-levee changes.

## Current Study Improvements

Mapping large floodplain inundation flows is important yet difficult. Typically, there are few historical events to test or calibrate a hydraulic model and small differences in water surface elevations can greatly change flood damage estimates. In this study, three meter vertical resolution is the best that could be obtained (publicly) for the river and floodplain system. This is too coarse for realistic urban floodplain work, but does illustrate the methodical approach and the conceptual and practical basis for beneficial reoperation and storage reallocation policies. Much of Lodi, CA lies within one elevation band, and while linear interpolation provides some differentiation between intermediate elevations, it masks a gap in information. Figure 23 shows historical flooded areas after a long duration high flow (5,000 cfs) in the spring of 2006 (EBMUD 2006). This can be compared with a similar flood flow generated from modeled output (same figure).

Small river bank levees are not captured in the model resulting in water spreading further across fields and riparian properties than is realistic. Manual modifications to the underlying elevation model can help correct this problem, but using higher resolution data which captures agricultural levees is preferable. For this study, areas disconnected from the river that are indicated as flooded were not included in crop agricultural estimates. FEMA flood maps were consulted to adjust urban flood damage estimates.

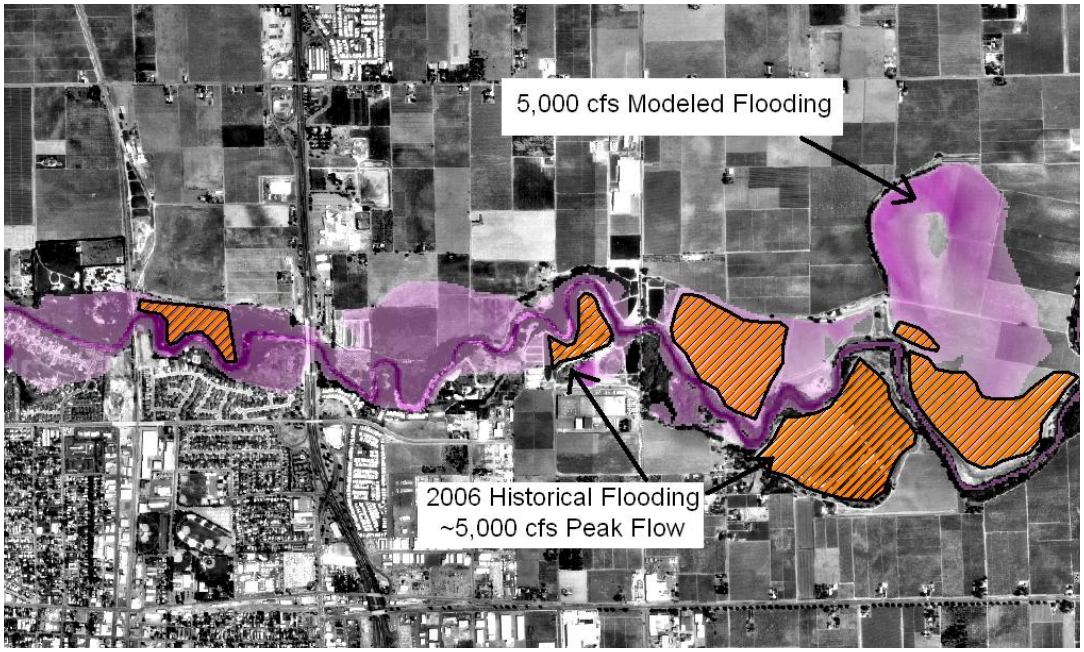


Figure 23 - Flood inundation mapping of historical and modeled 5,000 cfs events.

Another improvement is to incorporate unsteady flow analysis. The use of steady flow modeling of peak reservoir outflows over-estimates flood damages and precludes estimates of duration of inundation. In this study agricultural and urban properties with damage functions based partly on duration of inundation are used with the assumption of long duration flooding. This increases damage estimates. Modeling with unsteady flow routing would avoid this issue and create more accurate flooding hydrographs. Locations along the agricultural reaches can historically pass short duration peak flow events (4,000 cfs or more) without damage. However, the same peak flow event may cause flooding for longer duration flows. In 2006 flows remained above 4,000 cfs for 20 to 30 days, causing levees to saturate through their entire thickness and fail under seepage.

A final improvement would be to refine drought management in the POR model to better predict the start and end of droughts. Shortage costs during droughts drive water supply economics and occur infrequently enough (2 to 3 times in the historical record) to make them very sensitive to modeling issues. Currently, the POR model only has a few layers of drought management that fail to mitigate severe droughts and result in empty reservoirs under some scenarios. The economic analysis methods used here are for calculating small water supply changes not drastic, behavior-altering conditions that result from empty reservoirs. Updated water shortage costs to reflect present water supply conditions for EBMUD, including increased system reliability from the Regional Freeport Water Project on the Sacramento River would help this issue. The Freeport Project will reduce EBMUD's shortage costs for Mokelumne River water during drought conditions and reduce the occurrence of empty reservoirs in the model.

# 8. CONCLUSIONS

Reservoir operations have evolved over the last century. Beginning with single purpose water supply diversions and hydropower dams and progressing to multi-purpose facilities that provide a variety of benefits under many environmental and regulatory restrictions. Reservoir reoperation by reducing flood storage space is another step in this evolution. It seeks to bring the operations of reservoirs into alignment with the larger environmental goals of modern society. Through the process of conducting this study many issues where encountered and negotiated. The following subsections provide general as well as Mokelumne River specific reflections.

## Reservoir Reoperation

Reservoir reoperation through reduction of flood pools increases downstream flood risk. However, if floodplain mitigation and smart land use practices complement a reoperation program, significant benefits can be realized through increased flexibility for releases while limiting increases or even decreasing flood risk. This type of program is also effective to adapt to climate change, both in terms of managing higher peak flow events and handling seasonal shifts in runoff. Institutional mechanisms for combining flood mitigations with reservoir storage reallocation are needed, however.

Reservoir purposes such as water supply and hydropower can be protected and likely enhanced while environmental benefits are increased. This approach changes the isolated and disconnected view of reservoirs accomplishing goals like flood control, water supply, hydropower and other purposes independent of their surrounding watersheds. Reoperation can integrate the river system and floodplain rather than relying completely on reservoirs, allowing better utilization of reservoir storage space.

## Mokelumne River Reoperation

Analysis of reductions in flood storage space show small to moderate changes can improve economics and provide significant environmental flow management flexibility. However, when reoperation alternatives drive flood risk too high, this benefit cannot economically overcome increased flood damages. Reoperation's effect on flood risk is by far the most important factor in the analysis and can overwhelm other elements of performance in many cases.

Reducing the flood storage volume makes additional water for managed environmental uses available on the Mokelumne River. In wet years this effect is already put into play as EBMUD uses surplus water for these purposes. However, with small to moderate reductions in flood storage space considerable increases in spring environmental releases are possible in many years. Generating large amounts of extra water in the fall is more difficult due to the seasonal pattern of water diversions and rights to Mokelumne River water. Although the seasonal uses of water are unlikely to change due to high value urban and agricultural water uses, environmental needs in the fall require less water to meet environmental targets and therefore still show promise of improvement.

This study is done at a proof of concept level and illustrates the benefits and costs of reducing flood storage space. Ultimately, a more in-depth feasibility level study needs to be conducted to better understand the economic and environmental components, especially flood damage which has been shown to drive the entire process. This approach is a new way of thinking about reservoir-floodplain interactions. Historically, the two were separated solely for human benefit, but the future holds promise for a more integrated system that improves environmental conditions and increases total benefits for society.

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