WATER ALLOCATION ON THE TRINITY RIVER USING DYNAMIC PROGRAMMING

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Introduction

Major demands for the withdrawal of water from a reservoir include those for industrial uses, agricultural uses (including irrigation), and domestic or municipal uses. Water that is stored in a reservoir can also be used for recreational use, flow augmentation (flood control, water quality control, navigation, or ecological benefits), and hydroelectric power production. These multiple purposes of water allocation may compete with one another in social and economic demands. The purpose of modeling river basins and reservoir systems is to identify the tradeoffs among the multiple purposes. Storage and release schedules of a reservoir must take into account all the beneficial uses of the stored water as well as all the social, economic, and ecological demands upstream and downstream of the reservoir.
(Loucks & Van Beek, 2005)

Project Objective

The objective of the project is to maximize the total profit from anadromous fish and rice production respectively from water releases from Lewiston dam to the Trinity River during wet (2000), normal (2002), and dry (2001) water years using a backward recursive dynamic programming methodology.

Literature Review

The purpose of this literature review is to provide a background on the use and management of the water resource on the Trinity River and to introduce the dynamic programming methodology that may be applied to manage its multiple uses. The first portion of the review covers the use of the water resource on the Trinity River and the societal and economic value of that water for environmental and irrigation purposes. The second portion describes the dynamic programming methodology and presents two case studies demonstrating the application for a multiuse reservoir.

Introduction to the Central Valley Project

The Central Valley Basin of California extends an average width of about 120 miles and 500 miles in northwest to southeast direction. The basin is surrounding by the Cascade Ranges and Sierra Nevada on the north and east (elevations up to 14,000 feet) and the Coast Ranges on the west (as high as 8,000 feet). The Sacramento River System in the north and the San Joaquin River system in the south are the two major watersheds in the basin. These river systems join at the Sacramento-San Joaquin Delta, which then flows into the San Francisco Bay and then to the Pacific Ocean. The Central Valley has a Mediterranean climate with long, warm, and dry summers and cool, moist winters. Around 80 inches of precipitation occurs annually at area of higher elevation in the north and around 35 inches in the southern mountains. (U.S. Department of the Interior Bureau of Reclamation, 2004)

The Central Valley Project (CVP) was implemented by the federal government for a water plan for the upper 1/3 of California's water supply. The CVP is composed of 20 reservoirs that when combined have a storage capacity of more than 11 million acre-feet, 500 miles of major canals and aqueducts, and 11 power plants that are generally operated as a combined project. Some purposes of the Central Valley Project are flood control, navigation, fish and wildlife protection, restoration, water for irrigation and domestic use, and power generation but not all facilities include all these purposes. The Central Valley Project Improvement Act was amended with the passage of the Reclamation Projects Authorization and Adjustment Act of 1992 to do the implement the following changes (U.S. Department of the Interior Bureau of Reclamation, 2004):

- Authorize transfers of water to service areas outside of the CVP.
- 800,000 acre-feet to be dedicated to fish, wildlife, and habitat restoration annually.
- Anadromous fish restoration program implementation.
- Making a restoration fund from water and power users.
- Increased CVP yield.
- Implementing a Shasta Temperature Control Device.
- Maintaining water supplies for Central Valley wildfires.
- Meeting Federal trust responsibilities at the Trinity River to protect fishery resources.

Introduction to the Trinity River

The Trinity River is located in the northern part of California. In the northeast part of the Trinity basin in the Trinity Alps at an elevation of 9,000 feet, the river begins moving 172 miles south and then west. Next the river moves north through Humboldt County, Hoopa Valley, and the Yurok Reservations and reaches a confluence at Weitchpec, CA with the Klamath River at an elevation of 250 feet. Forty miles from there the Klamath River drains into the Pacific Ocean (NCWQCB, 2005). The area has active local and coastal seismic activity and groundwater resources are relatively abundant. The higher elevations consist of steep, treeless mountains, while the lower elevations contain riparian vegetation and mixed conifer forests. A vast network of tributaries drains into the main stem of the Trinity River at various points along the basin as shown in Figure 1 (NCIWMP, 2007). Also Trinity and Lewiston dam, part of the Trinity River Diversion, are prominently featured along the river (Figure 1).

Both precipitation (annual precipitation is around 57 inches/year) and snowmelt sustain inflows to the Trinity River. Typically the snowpack in the Trinity Alps builds from the beginning of December to the middle of March. Then from the end of March to the end of June the snowpack melts (CDWR, 2012). Most of the precipitation that the basin receives annually occurs from November to March. Storms that last for numerous days of moderate intensity carry most of this precipitation (HVIT, 2003).

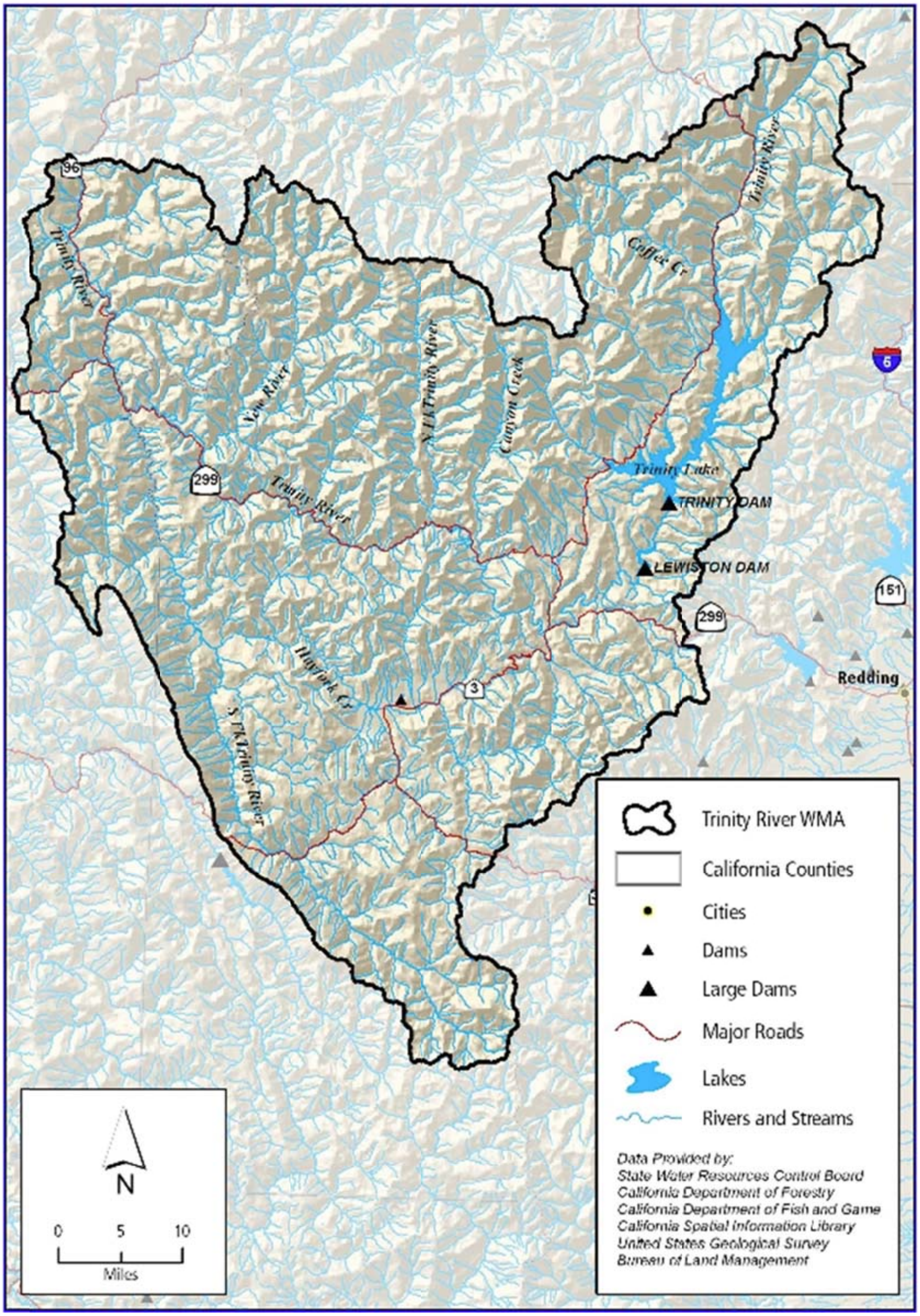

Figure 1: Trinity River Watershed Management Area (WMA) (NCIWMP, 2007).

The Trinity River Basin is split into the following seven sub-basins (Regional Water Board, 2001) (Figure 2):

- North Fork Trinity River
- New River
- Lower Trinity/Humboldt Section
- Canyon Area
- Weaverville Area
- Upstream of Weaverville (including the Trinity and Lewiston Lakes)
- South Fork Trinity

Historical & Present Use of Water from Trinity River

Infrastructure of the Trinity River Diversion

In 1955, Congress authorized the Trinity River Diversion (TRD) to move water from the Trinity River to the Sacramento River to be used for irrigation in the Central Valley and San Joaquin Valley. The U.S. Bureau of Reclamation (USBR) completed TRD in 1964 (USFWS, HVT, 1999). The entire diversion refers to Lewiston Dam, Trinity Dam, Whiskeytown Dam, and their respective reservoirs (NCWQCB, 2005). The TRD project diverts most of the upper-basin's water runoff at Lewiston. Figure 2 shows the diversion tunnel and other important infrastructure used to transfer water from the Trinity River to the Sacramento water basin.

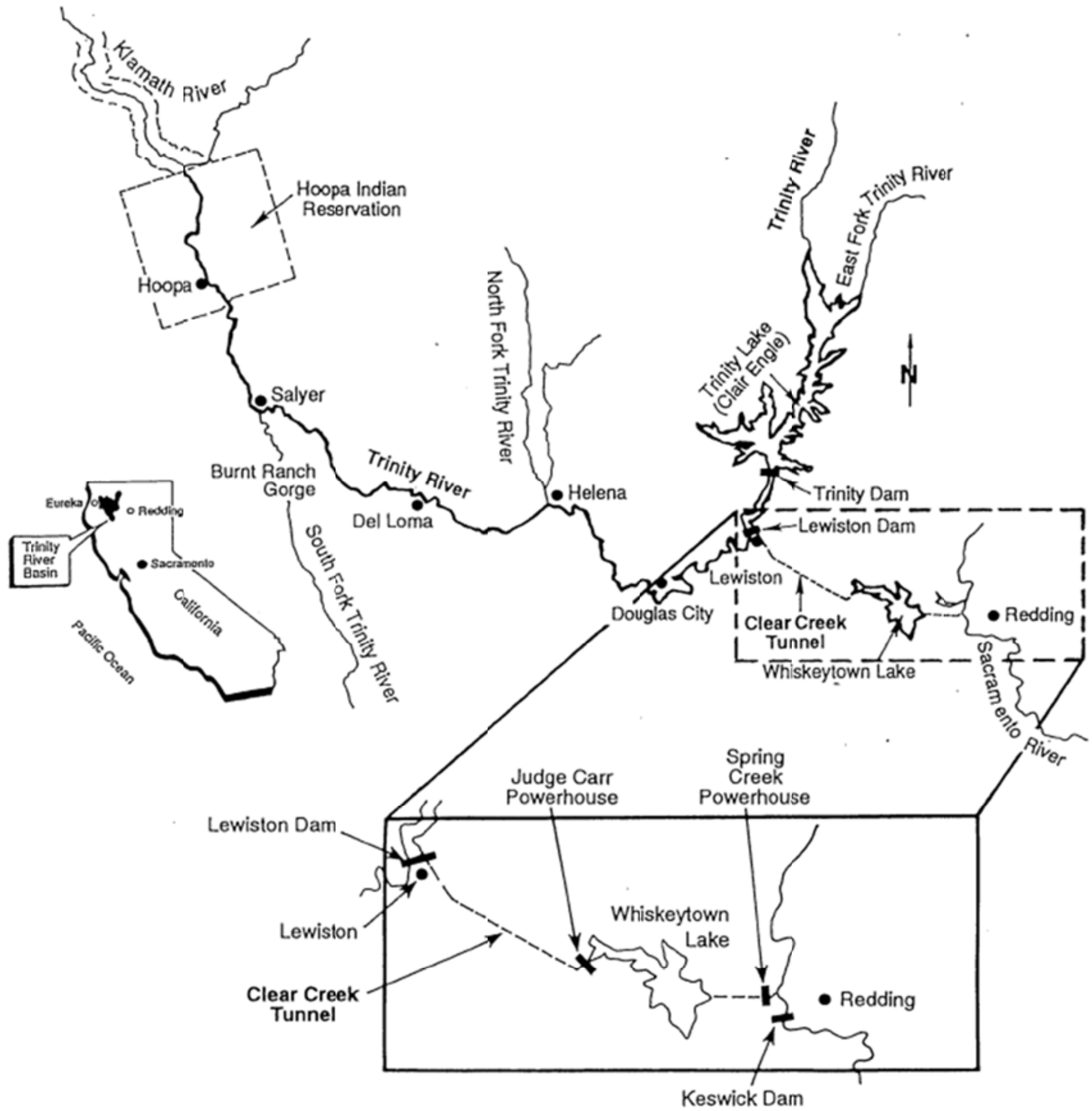

Figure 2: Trinity River diversion (Douglas, et al., 1999).

Trinity River Diversion Infrastructure

The northernmost dam on the Trinity is Trinity Dam. The dam is an earth filled with a height of 538 feet and a crest length of 2,450 feet. Behind the dam is Trinity Lake with a storage capacity of 2,448 thousand acre-feet (TAF). Recreational activities that involve the use of the lake include camping, boating, swimming, hunting, and fishing (USFWS, HVT, 1999).

The maximum permissible release from Trinity dam is smaller than the design flood inflow. To reduce the likelihood of water overtopping the dam during high water events, operators at Trinity Dam implement Safety of Dams criteria. The criteria are implemented from November to March when 2,000 TAF storage is expected. The Trinity Power Plant is located at Trinity Dam. The plant uses two generators with a total capacity of 140,000 kW and a maximum release of 3,693 cubic feet per second (cfs). (USBR, 2004).

Seven miles downstream of Trinity Dam is Lewiston Dam (USBR, 2004). The dam is an earthfilled dam 91 feet high with a crest length of 754 feet (USFWS, HVT, 1999). Safety of Dams criteria stipulates 6,000 cfs as the maximum release below the dam. The purpose of the dam is to regulate flow downstream from the Trinity Power Plant and transport water via the Clear Creek Tunnel to Whiskeytown reservoir (USBR, 2004). At the dam is Lewiston Power Plant. The plant has one generator with a 350 kW capacity. Behind Lewiston Dam is Lewiston Lake with a storage capacity of 14.66 TAF. Downstream the California Department of Fish and Wildlife (CDFW) operate the Trinity River Fish Hatchery (TRFH with a capacity of 40 million salmonid eggs (USFWS, HVT, 1999).

A trans-basin diversion to allocate water from the Trinity River to the Central Valley Project is located at Lewiston Lake through the Clear Creek Tunnel to Whiskeytown Lake (USFWS, HVT, 1999). Before reaching Whiskeytown Lake, the water passes the Judge Francis Carr Powerhouse with a total capacity 184,000 kW for the two generators (USBR, 2004). The tunnel diameter is 17.5 feet and 10.7 miles long with a capacity of 3,565 cfs (USFWS, HVT, 1999; USBR, 2004). Under Safety of Dams criteria, Judge Francis Powerhouse is used as a first choice destination for releases from Trinity Dam with Trinity in-stream flows as a second choice release destination (USBR, 2004).

Holding water from the Trinity River to Whiskeytown Lake is an earthfilled dam at 282 feet high and a crest length of 4,000 feet. The reservoir capacity is 241 TAF. From Whiskeytown Lake, water is diverted through Spring Creek Tunnel to Keswick Dam on the Sacramento River. Recreational activities centered on the lake include boating, fishing, hunting, picnicking, camping, swimming, and water skiing (USFWS, HVT, 1999).

Historical and Present Use of Trinity River Water

Since the construction of the TRD water from the Trinity River has been used for in-stream environmental and irrigation purposes. Nonetheless quantity and timing of the releases for environmental purposes has changed substantially from post TRD construction to present day. These changes in in-stream flows have been critical for restoring anadromous fish populations within the Trinity River (USFWS, HVT, 1999). As the largest tributary of the Klamath River, the Trinity River was once a major recreational and fishery resource for northern California. Above the Trinity and Lewiston dams was 109 miles of salmon and steelhead habitat (50% of the historic spawning habitat).

The historical average diversion from the Trinity River in stream flows to the Sacramento basin has been two-thirds of the annual flow (USBR, 2004). During the water years (WY) from 1964 to 1973, 88% of the in-stream flow was diverted from the Trinity River to the Sacramento River, totaling 1,234 TAF on average annually. From WY 1964 to

1973, a minimum flow of 150-250 cfs was spared for in stream flows as was deemed sufficient for Chinook salmon, the species that was the main focus at the time (USFWS, HVT, 1999).

Within 10 years of TRD operating, a significant decrease in salmonids was observed. In response from WY 1974 to 1976, 705 TAF, 275 TAF, 126 TAF were released for fisheries, respectively. From 1976-1980 the decline was investigated in depth. By 1980, an Environmental Impact Statement (EIS) by the USFWS determined the Chinook salmon and steelhead populations had declined by 80% and 60% from pre-TRD numbers, respectively, and 80-90% habitat loss. The report identified streambed sedimentation, lack of fish harvesting regulations, and most critically the low in-stream flow as cause of the decline (USFWS, HVT, 1999).

Congress passed the Trinity River Basin Fish and Wildlife Management Act in 1984, which identified in-stream flow as the principle cause of poor quality of anadromous fish habitat. The act created a fish and wildlife restoration program with the mission of restoring fish and wildlife populations to approximately the same levels that existed pre-TRD. Mainstream Trinity River restoration and maintenance of fishery resources required 1) fine and coarse sediment management, 2) increased annual in-stream volumes and variation release schedules from the reservoir, and 3) mainstream channel rehabilitation. Variable flows provide adequate temperature and habitat conditions for fish and wildlife at different life stages, build gravel bars, scour sand from pools, control riparian vegetation, as well as other ecological functions. Through monitoring fish and wildlife populations the program determines the progress of rehabilitation (USFWS, HVT, 1999).

In 1992, Congress passed the Central Valley Project Improvement Act stipulating a minimum of 340 TAF in-stream flow to the Trinity River for fisheries (USFWS, HVT, 1999). Most recently in 2002, a federal district court in the Eastern District of California issued an order to increase the minimum in-stream release to 452 TAF for all years except for critically low flow years when 368.6 TAF is to be released. The timing and amount to be released for in-stream flows is coordinated with the U.S Fish and Wildlife Service (USFWS) (USBR, 2004).

USFWS Recommended Timing and Quantity of In-stream Flow for the Trinity River

The USFWS classifies water year to consider flow availability to recommendations for meeting environmental objectives (Figure 3). In a report from 1999, the USFWS defined water years by ranking the annual water yields for the Trinity basin at Lewiston from 1912 to 1995 and calculating an exceedance probability (USFWS, HVT, 1999). Table 1 shows the water year classification from the report. The table also shows the recommended total annual in-stream flows to the Trinity River. The recommendations are based on objectives to promote the growth of the salmonid population over various life stages. The objectives are implemented by timing the release of water from Lewiston Dam for in-stream flow to regulate temperature and manage geomorphology of the river throughout the year. The successful implementation of the objectives provides ideal habitat for the salmonid populations. Figures 7-16 in the Appendix show a more detailed description of the management objectives of the USFWS in 1999 for each water year classification (USFWS, HVT, 1999).

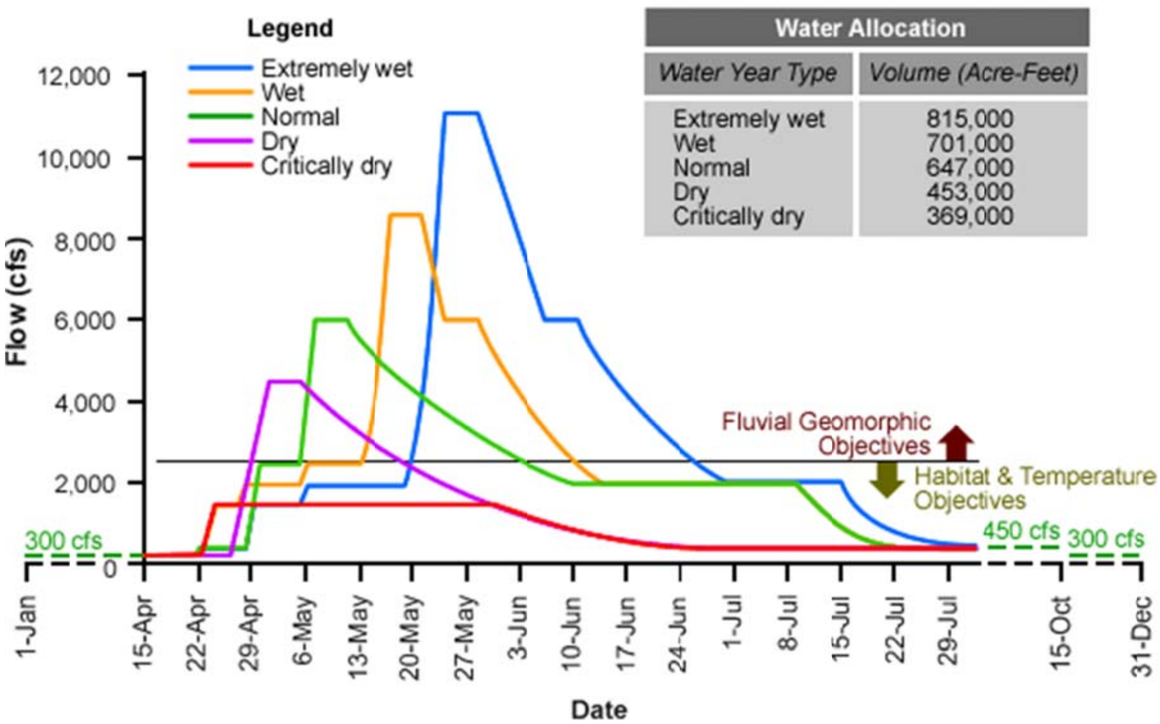

Figure 3: Typical flow releases from Lewiston dam to the Trinity River based on water-year classification (U.S. Department of Interior Bureau of Reclamation, 2013).

Table 1: Water Year Classification of Trinity (USFWS, HVT, 1999).

Water Year Classification	Probability (P)	Basin Yield (Y) (TAF)	Recommended In-stream Release to Trinity River (TAF)
Extremely Wet	P≤ 0.12	Y≥2000	815.2
Wet	0.12<P≤0.4	2,000>Y≥1,350	701.0
Normal	0.4<P≤0.6	1,350>Y≥1,025	646.9
Dry	0.6<P≤0.88	1,025>Y≥650	452.6
Extremely Dry	P>0.88	Y<650	368.6

The actual discharges (in cubic feet per second (cfs) from the Lewiston Dam to the Trinity River were measured at the USGS site 11525500 (Figure 4) (USGS , 2013). The differences between actual flow discharge and the recommended flow discharge are due to the fact that the river channel changes with time. The Bureau of Reclamation keeps levels in the Trinity Lake at lower levels during the winter to provide a safety buffer in the event of a large storm. The buffer quantity depends on the referenced hydrologic record for the basin and the amount of storage that needs to be maintained. Current conditions and forecasted weather help in the decision making process of the release schedule. Other purposes such as tribal releases or mitigation for late summer conditions for fish health purposes also are taken into account in the release schedule. The Trinity Management Council has recommended water year (WY) 2012 as a "Normal" water year. The estimated release schedule for WY2012 can be found in the following Figure 5. (U.S. Department of Interior Bureau of Reclamation, 2013)

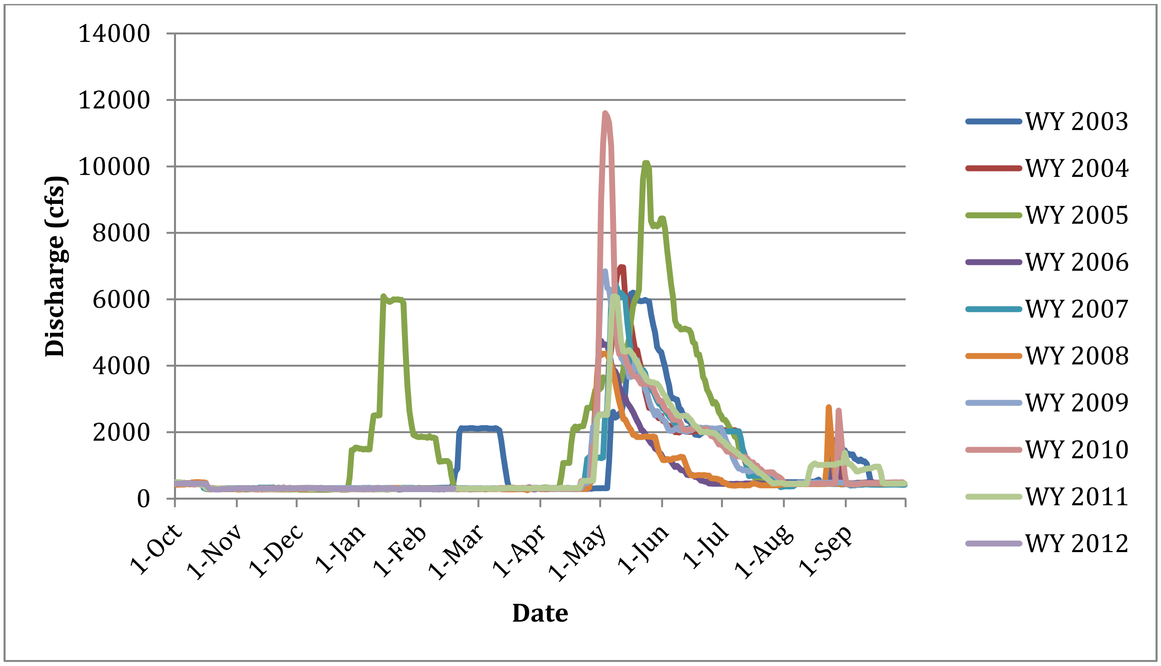

Figure 4: Actual release to the Trinity River from the Lewiston dames from USGS site 11525500 during water years 2003 to 2012 (USGS , 2013).

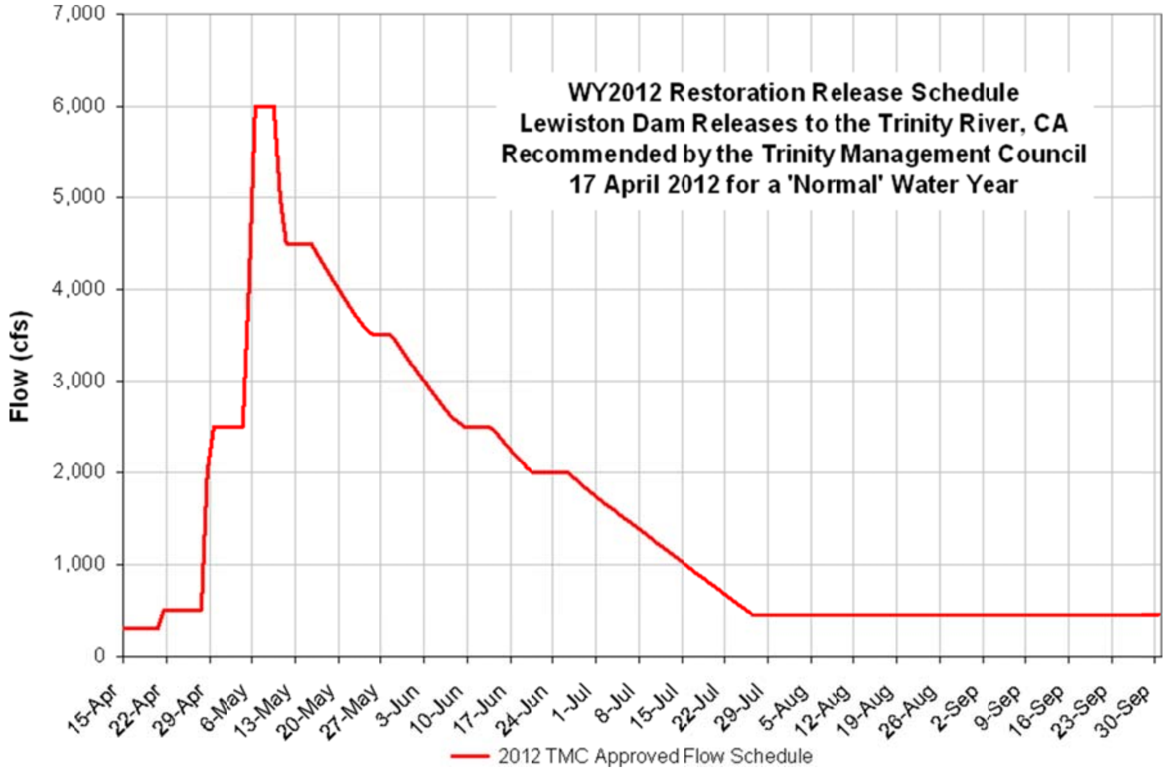

Figure 5: WY 2012 "Normal" recommended release schedule (U.S. Department of Interior Bureau of Reclamation, 2013).

Monetary Value of Trinity Water

A commonly applied technique for estimating both the public's benefits of preserving flows for endangered fish and the recreational valve of in-stream flow involves the use of a "constructed market" using an approach known as the Contingent Valuation Method (CVM). The CVM involves a hypothetical market which allows the public to buy higher levels of in-stream flow through the use of higher electricity costs, higher taxes, or a higher water bill (all clearly written out in descriptions, hydrographs, or photos). Households are asked if they would to vote to increase in-stream flow at a particular dollar amount (as well as a maximum they would pay or whether they would pay a given amount) would be determined through individual respondents. The percentage of people that would vote yes or "buy" at each dollar amount is used to statistically develop a demand-curve-like relationship to calculate a mean willingness-to-pay (WTP) for in-stream flow. The resulting hypothetical WTP can then be compared to the WTP calculated from travel cost models (respondents travel expenditures from the variation in number of trips and distances from the river) for the same river basin to test for validity. In more than one hundred comparisons it was found that the stated values in surveys across California underestimated the WTP from the travel cost models by one-half. (Loomis, 1998)

During the winter of 1993-94 Trinity River user surveys were sent out by the Planning Department of Trinity County to estimate the non-market benefits of increased Trinity River stream flows for recreational and fish run benefits by the contingent value method, which resulted in 70.79% of useable mail-back. Key survey questions involved sociodemographic background (respondent zip code, age, marital status, etc.), cross-validation, and valuation (visitor satisfaction, frequency of use, trip expenditures, etc.) questions. Five WTP bids (by monthly utility bills as payment vehicles ranging from $0 to $80 per month) inflows in terms of percentage diverted to the Sacramento River, the quality of recreational boating, and the number of adult spawning anadromous fish on the Trinity River were in the survey. The respondents were also informed of the variation in fish run sizes with flows based on the best available scientific evidence and the current marine commercial and sport harvesting regulations (impact the size of the runs). Table 2 shows an estimate of the corresponding in-stream flows with quantity of fish for five alternative annual in-stream water volumes. Table 3 shows the cost of the fish from the various alternatives along with the costs of foregoing benefits from hydropower use and irrigation. (Douglas, et al., 1999).

Table 2: Economic value of fish runs using biologist' estimates (Douglas, et al., 1999).

Alternative	In-stream Flow (TAF)	Quantity of Fish
1	120	9,000
2	240	35,000
3	360	75,000
4	600	85,00
5	840	105,000

Table 3: Comparison of values from the use of Trinity River water in millions of US dollars/year (Douglas, et al., 1999).

Scenario	Lost Hydropower Benefits	Marginal Value of Irrigation Water	Loss of Hydropower + irrigation value	Value of fish
1	2.410	3.718	6.128	106.698
2	4.821	7.435	12.256	128.613
3	7.231	11.153	18.384	249.265
4	12.052	18.589	30.641	514.812
5	16.873	26.024	42.897	803.638

In 1990 the value of crops using water supplied by the full and supplemental service from the Trinity River Diversion was valued at $2,362,691. Figure 17 in the Appendix shows the economic value of each crop type using water from the Trinity River (Stene, 1996).

Dynamic Programming

Introduction

The purpose of this next section is to provide the methodology of a water resource allocation optimization methodology called dynamic programming. There is no available evidence detailing whether dynamic programming or any optimization methodology is applied to allocate the water resource on the Trinity River. The dynamic programming methodology is described here simply as a possible tool that could be helpful in developing optimal water allocation on the river, possibly using the economic metrics presented briefly in the Monetary Value of Trinity Water section. The first part of the section introduces dynamic programming as a tool to solve water resources problems generally and the second part covers two case studies in detail that demonstrate discreet deterministic and stochastic dynamic programming, respectively.

Background on Dynamic Programming

Four methodologies are used to address reservoir water allocations problems: dynamic programming, linear programming, nonlinear programming, and simulation. Dynamic programming is focused on here because the method has been formulated for resource allocation and shows several advantages. First and foremost, a large number of water resources system problems can be formulated into a dynamic programming model (Yeh, 1985).

Additional advantages to using the dynamic programming methodology include (Yeh, 1985; Eschenbach, 2012):

- Breaks complex problems with many variables into smaller problems. The smaller problems are solved recursively
- May easily incorporate constraints to decision and state variables in contrast to other optimization methods.
- Can solve linear and nonlinear problems.
- Can include stochastic nature of problems such as inflow to a reservoir.

Disadvantages to using the dynamic programming methodology include (Yeh, 1985; Eschenbach, 2012; Yakowitz, 1982):

- Curse of Dimensionality is the reduction of computational efficiency with increase in state variables using discrete dynamic programming. For example, if there are 12 state variables and 10 discretized state spaces, the total number of discretized state nodes is 10^{12}.
- Discrete states and decisions in discrete dynamic programming when both may be continuous in reality.

Richard Bellman formulated dynamic programming (DP) in 1957 (Yeh, 1985). Belman described the methodology as the "theory of multistage decision processes" (Yakowitz, 1982). Since its first formulation DP has been used extensively to optimize water resource systems because of its relative ease in solving their most common nonlinear forms. Today dynamic programming is sometimes seen combined to other optimization methodologies for use in a variety of water resources applications (Yeh, 1985).

In 1962, Bellman and Dreyfus developed discrete dynamic programming which allowed the theory to be applied to computer programming formulations. Under the methodology state and control spaces are discretized into a finite number of values. The discreet dynamic programming methodology is focused on in this review because of its suitability of addressing water resource allocation problems. More recent developments of dynamic programming such as discrete, state incremental and state differential dynamic programming have addressed the Curse of Dimensionality problem (Yakowitz, 1982).

Knowing the relation between the main components of the dynamic programming, chiefly the stages, states, the transition equation, and the return function, is critical to understanding the methodology. A decision is made over stages, which in water allocation is the deliverance of water for some purpose changes. The decision is made via the decision variable, which again in terms of water allocation is quantity of water delivered. States are plausible results after k decisions. They rest between stages. State, stage, and/or decision variables are often bounded by constraints. States within one stage change to the next stage via the transition equation. The transition equation is a function of decision variables and state variables. A return function, also a function of decision variables and state variables, defines the transition in terms of the objective between states (Eschenbach, 2012).

A recursion process is applied either backward or forward in stages representing time or space in dynamic programing. Backward recursion is most often used and absolutely necessary for stochastic dynamic programming formulations (Yeh, 1985). Stochastic cases are used to represent inflow to reservoir and rainfall (Loucks et al, 1981). A general backward recursion equation for the deterministic case is shown in Equation 1. The equation identifies the maximum sum of the return function NB and the future value function from a later state. If the current state is at the second to last state at t+1=N-1, then the future value function from a later state is the maximum NB at state N. The stochastic form of the same general recursion equation is represented in Equation 2. The two recursion equations are only different in the addition of a "transition uncertainty" called the Markov chain for the stochastic dynamic programming problem (Loucks et al, 1981). The solution to the stochastic programming problem is the average optimal path over all possible states (Eschenbach, 2012). The case studies presented in the next sections demonstrate backward recursion.

$$f_t(s_i) = \max_k\left[NB\left(s_i, s_j, k\right) + f_{t+1}(s_j)\right] \qquad \text{[Equation 1]}$$

Where,

$f_t(s_i)$= Maximum net benefit beginning at state s_i for time period t
$f_{t+1}(s_j)$= Maximum net benefit beginning at state s_j for time period t+1
$NB\left(s_i, s_j, k\right)$= Net benefits over period t beginning at state s_i and ending in state s_j for k decision.

$$f_t(s_i) = \max_k\{\sum_{j=1}^{m} p_{i,j}^t(k)\left[NB_t(s_i, s_j, k) + f_{t+1}(s_j)\right]\} \quad \text{[Equation 2]}$$

Where,

$f_t(s_i)$= Maximum net benefit beginning at state s_i for time period t
$f_{t+1}(s_j)$= Maximum net benefit beginning at state s_j for time period t+1
$NB(s_i, s_j, k)$= Net benefits over period t beginning at state s_i and ending in state s_j for k decision.
$p_{i,j}^t(k)$= Probability that over period t+1 state is s_j knowing that state is s_i over period t and decision k is chosen.

Depending on reservoir operation horizon, inflow and outflow to and from a reservoir may be deterministic or stochastic. Hourly and daily, both may be assumed to be deterministic, while monthly or yearly inflow might be described better as be stochastic (Yeh, 1985). Uncertainty is incorporated into the transition function and the solution is the average optimal path over all possible states (Eschenbach, 2012).

A major assumption of dynamic programming is the Principle of Optimality. Principle is formulated in the following two points (Loucks et al, 1981):

1. For any state in a particular stage, an optimal solution is found by having progressed in a manner that is optimal (Loucks et al, 1981). This point requires objective functions to be summed over transition to different stages (Eschenbach, 2012).
2. For any state in a particular stage, an optimal solution is found by having arrived in a manner that is optimal (Loucks et al, 1981). This point requires the present state to have all values required to calculate optimal solution (Eschenbach, 2012).

Deterministic Dynamic Programming Case Study

An example of backward-moving deterministic water allocation problem is presented in Water Resources Systems Planning and Management: An Introduction to Methods, Models, and Applications by Stedinger et al. (2005). Firm 1, Firm 2, and Firm 3 are each allocated an amount of water equal to x_1, x_2, and x_3, respectively, from a reservoir. The objective of the discreet dynamic programming problem is to find the amount of water to allocate to each of the three firms that returns the maximum net benefit (Stedinger et al, 2005).

Figure 3 shows the possible water allocations to the three firms. The total amount available is the release subtracted from a total release, Q-R, equaling 10 units, shown to the far left in the figure. Each individual column of links between nodes is referred to as the stage. A total of three stages for the three firms are presented in this example. The set of feasible water allocations to a firm is the decision variable x_j. The decision variable is constrained to the values shown in the corresponding column of blue values along the links connecting the nodes in Figure 6. For example the possible water allocations to firm x_1 are 0, 1, and 2 (Stedinger et al, 2005).

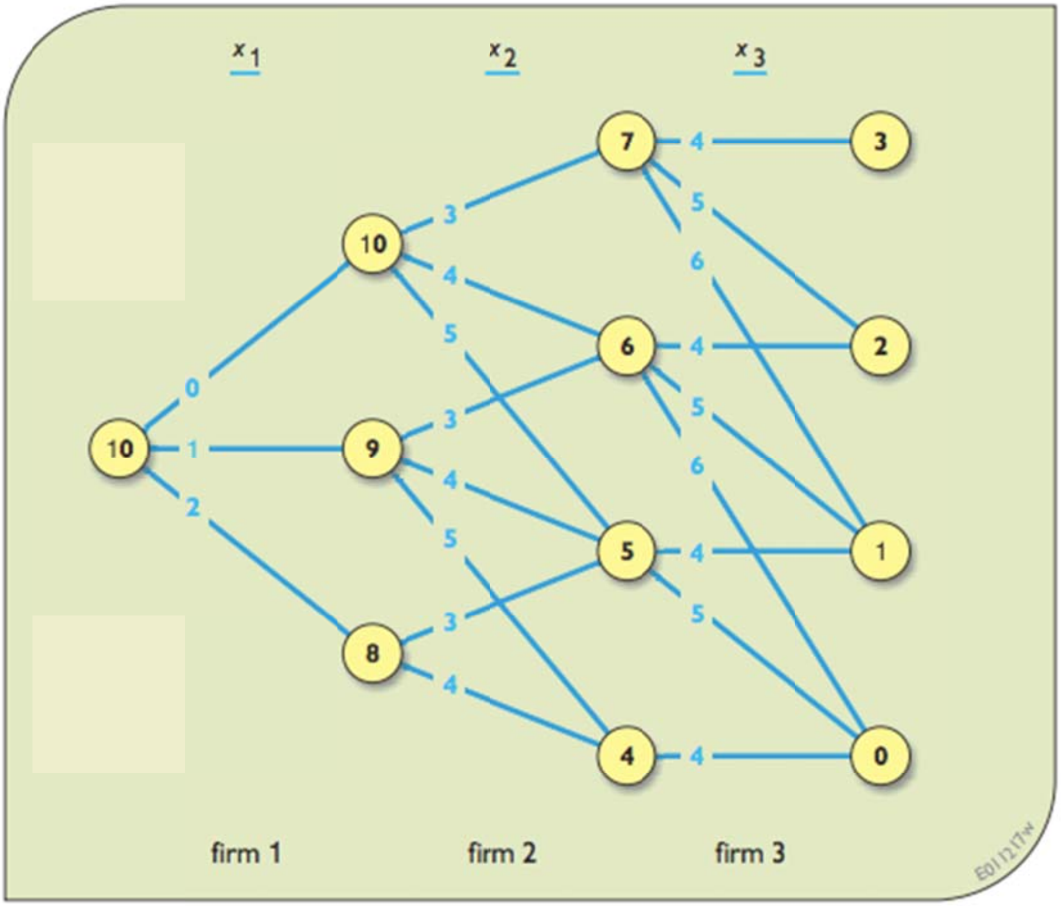

Figure 6: Nodes represent states and the value inside a state is the remaining water after allocating value in blue from nearest left linked node value moving from left to right. Each column of connections between nodes represents all feasible allocations to a particular firm and is called a stage (Stedinger et al., 2005).

The nodes in Figure 6 are the state or the amount of water in the reservoir after all previous allocations to firms or stages from immediately before the present state to the left most node with value 10. Equations 3-5 represent the continuity equations of the state S. For example, if 2 is allocated to firm 1 then 8 remains. This value is shown in the figure as the node with 8. If 4 is allocated to firm 2, then 4 remains as shown in node with value 4 (Stedinger et al, 2005).

$$Q - R - x_1 = S_2 \quad \text{[Equation 3]}$$
$$S_2 - x_2 = S_3 \quad \text{[Equation 4]}$$
$$S_3 - x_3 = S_4 \quad \text{[Equation 5]}$$

Where,

Q=Total quantity of water
R= Quantity of released water

x_1, x_2, x_3= Quantity of water allocated to Firm 1, Firm 2, and Firm 3, respectively
S_2, S_3, S_4= Water remaining after allocating x_1, x_2, x_3, respectively

As mentioned previously the objective of the dynamic programming problem is to calculate the water allocation to the three firms that maximizes the total net benefit, NB, as shown mathematically in Equation 6. NB is dependent on the amount of water allocated to each firm as shown in Equations 7-9. NB is shown for each water allocation in blue in Figure 4 (Stedinger et al, 2005).

$$\text{Maximize } \sum_{j=1}^{3} NB_j(x_j) \qquad \text{[Equation 6]}$$

Where,

$NB_j(x_j)$=Net benefit gained from allocating x_j to firm j

$$NB_1(x_1) = \max[(12 - p_1)p_1 - 3(p_1)^{1.30}], \text{where } p_1 \leq 0.4(x_1)^{0.9} \qquad \text{[Equation 7]}$$
$$NB_2(x_2) = \max[(20 - 1.5p_2)p_2 - 5(p_2)^{1.20}], \text{where } p_2 \leq 0.5(x_2)^{0.8} \qquad \text{[Equation 8]}$$
$$NB_3(x_3) = \max[(28 - 2.5p_3)p_3 - 3(p_3)^{1.15}], \text{where } p_3 \leq 0.6(x_3)^{0.7} \qquad \text{[Equation 9]}$$

Where,

NB_1, NB_2, NB_3=Maximum net benefit 1, net benefit 2, net benefit 3, respectively over feasible p space.

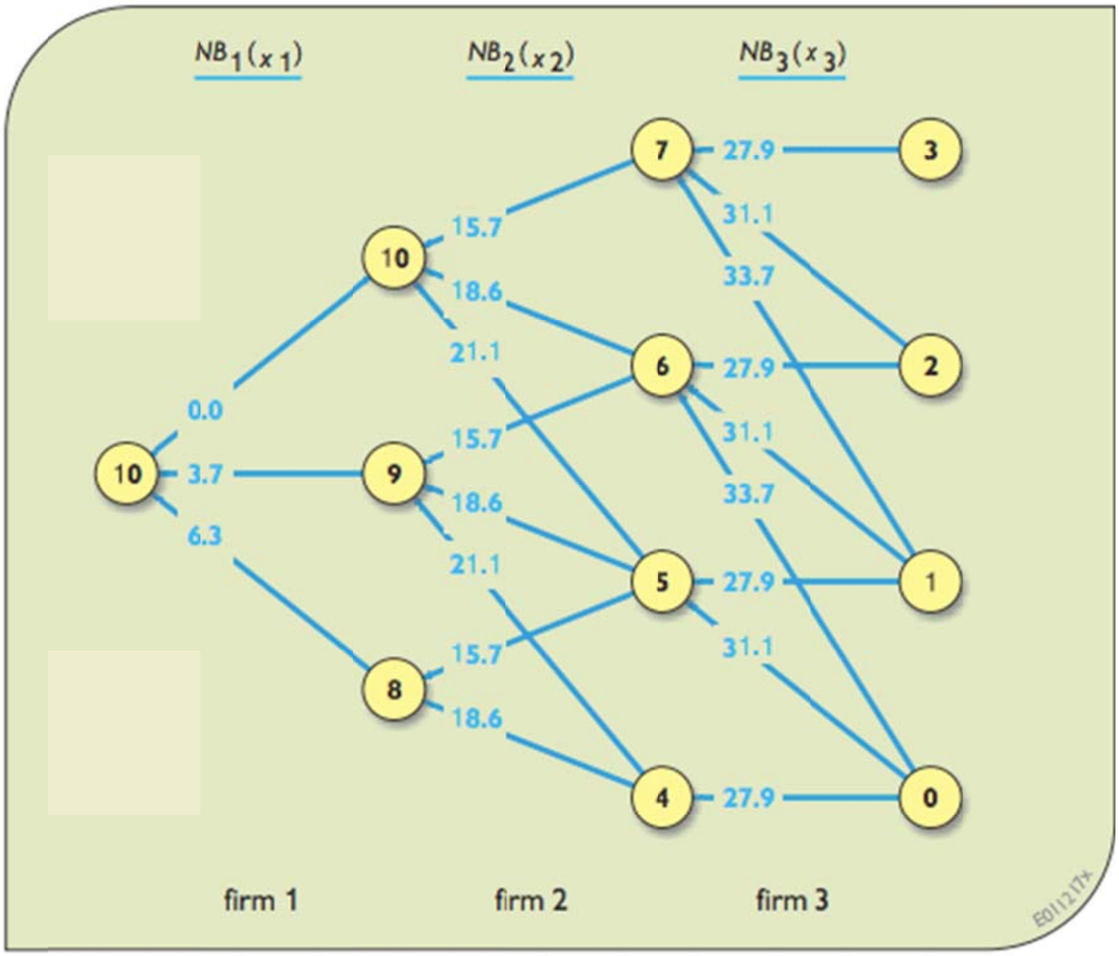

Figure 7: Values connecting states represent net benefit (NB) returned for water allocations shown in earlier figure (Stedinger et al., 2005).

Solving Equation 10 first, then Equation 11, and Equation 12 last meets the objective represented in Equation 6. This computation sequence is the backward recursion process. Figure 5 shows the value of the future value functions shown in Equations 10-12. For example, F_3 (7) =33.7 because 33.7 is the maximum NB over all water allocations to the node. Also, F_2 (10) =52.3 because the sum of $NB_2(x_2)$ =18.6 and F_3 (6) = 33.7 is greater than all other sums of net benefits and the associated future value represented above the previous right node in Figure 5 (Stedinger et al, 2005).

$$F_3(S_3) = \text{Max}\{NB_3(x_3)\} \text{ of all } x_3 \leq S_3, \text{for } 0 \leq S_3 \leq 10 \quad \text{[Equation 10]}$$

$$F_2(S_2) = \text{Max}\{NB_2(x_2) + F_3(S_3)\} \text{ of all } x_2 \leq S_2, \quad \text{[Equation 11]}$$
$$\text{for } S_3 = S_2 - x_2, \text{for } 0 \leq S_2 \leq 10$$

$$F_1(S_1) = \text{Max}\{NB_1(x_1) + F_2(S_2)\} \text{ of all } x_1 \leq S_1, \quad \text{[Equation 12]}$$
$$\text{for } S_2 = S_1 - x_1, \text{for } S_1 = 10$$

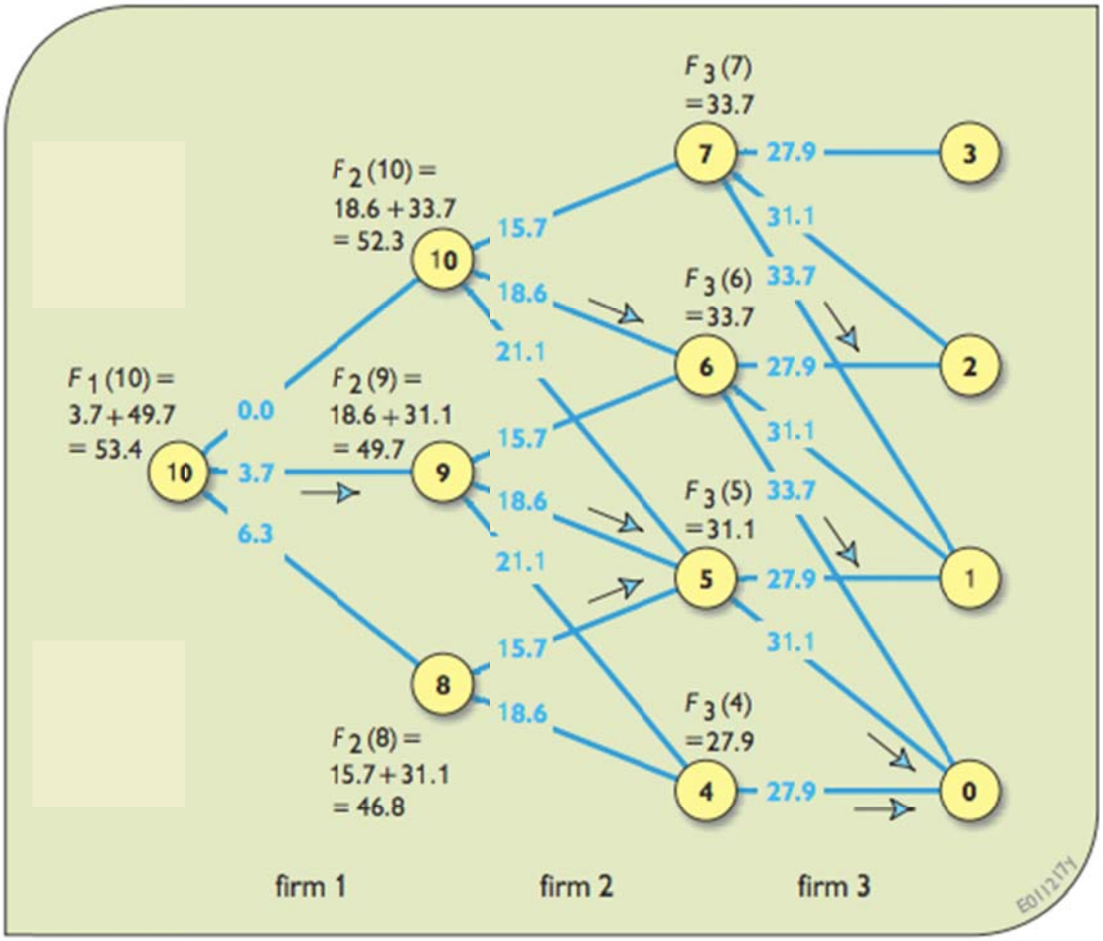

Figure 8: Backward recursive methodology showing future value function F to maximize net benefits for each state over stage, starting from right states and moving left. Arrows represent path of optimal allocation to firms (Stedinger et al., 2005).

The maximum net benefit is shown above the left most nodes as 53.4. The greatest F_1 (10) came from adding F_2 (9) =49.7 and NB_3=3.7 from allocating 1 to firm 1. Proceeding from state 9, the maximum F_2 (9) included the sum of NB_2=18.6 from allocating 4 quantities of water and F_3 (5). The remaining water to allocate is 5. The maximum F_3 (5) came from NB=31.1 from allocating 5 quantities of water. Therefore the optimal allocations to firm 1, firm 2, and firm 3 is 1, 4, and 5 units, respectively (Stedinger et al, 2005).

Stochastic Dynamic Programming Problem Water Allocation Case Study

A case study is presented by Tran et al. (2011) in "Managing Multiple-Use Resources: Optimizing Reservoir Water Use for Irrigation and Fisheries." A stochastic dynamic programming model is developed to maximize the profits for rice and/or fish production for Daton reservoir in Vietnam. The economic optimization model used is intended for policy makers (Tran et al., 2011).

In the case study Tran et al (2011) develops a stochastic dynamic programming model for managing water in a reservoir originally formulated by Tran et al. (2010). There are a total of eight stages representing different periods of the year critical for rice and fish production. The state variable is the total amount of water in the reservoir at the beginning of a stage. The decision variable is the amount of water released at a stage. The global objective is to maximize expected net present value (ENPV) of the net change in total income for a change in the release of water (Tran et al., 2011).

Two assumptions are made by Tran et al., (2011) when developing the model. First, the model assumes the production cost does not affect the maximum net change in total income. Second an assumption is made that inflows to the reservoir do not affect operation of the reservoir (Tran et al., 2011).

Even after making these assumptions, the model incorporates all variables necessary to apply to a realistic multi-use reservoir case study. Fish and rice response to time and quantity of allocated water, reservoir storage, and conditions of climate are included in the model. Also precipitation, irrigation needs, and low water necessary for fish harvests are considered (Tran et al., 2011).

The fully developed dynamic programming methodology is applied to Scenarios 1-3 listed below. Scenario three is of most concern because it identifies the optimal release for rice and fish production and partially addresses the inherent competing demands on the reservoir operation (Tran et al, 2011):

Scenario 1-Reservoir release when using water for only rice.
Scenario 2-Reservoir release when using reservoir for only fish.
Scenario 3-For reservoir release when using water resource in reservoir for fish and rice production.

The optimization problem allocates the water resource in the reservoir to partially resolve the conflict that arises from multiple uses. The conflict arises in scheduling the operation of the reservoir. During an average year, the reservoir is filled during the wet season July-November by precipitation. Often water is stored in the reservoir in case of drought and to supplement water requirements to rice during the dry season December-June, but reduces the harvest of fish typically February-May. From an economic view, the profit from fish production is far less than from rice production. However, fish production provides nutrient supplement through consumption and income for those who are in poverty (Tran et al, 2011).

The maximum ENPV of the total profit at stage n is shown in Equation 13. The total profit is the sum of the profit from the production of fish and rice. The total profit is a function of water level s_n, water release, u_n, rainfall q_n^k, and reservoir inflow i_n^k at stage n, respectively. The equation is the recursive relation that moves backward from value at stage N to stage zero to solve the global objective of maximizing the ENPV of the net change in total income for a change in the release of water. The stochastic variable considered is the quantity of rainfall that directly affects inflow to reservoir. Summing the probabilities over m discreet values at stage n should equal 1 (Tran et al, 2011).

$V_n(s_n) = \max_{u_n}\left[E\left[\sum_{k=1}^{m} p_n\{q_n^k\}\{V_n(s_n, u_n, q_n^k, i_n^k) + \alpha V_{n+1}(s_n, u_n, q_n^k, i_n^k)\}\right]\right]$ [Equation 13]

Where,

s_n=Water level at stage n (%RC)
u_n= Release at stage n (%RC)
q_n^k=Rainfall at stage n having k-th value (%RC)
i_n^k=Inflow to reservoir at stage n having k-th value (%RC)
$V_n(s_n)$ =Total profit generated at stage n
$V_{n+1}(s_n, u_n, q_n^k, i_n^k)$= Total profit generated at stage n+1
E=Expectation operator
$p_n\{q_n^k\}$=Probability of rainfall at stage n being k-th value out of m values
α=Discount factor $(1+r)^{-1}$ at a discount rate of r (%/stage)

Constraints 1-5 bound the above recursive Equation 13. The first two constraints ensure the storage and releases at stage n are within a certain bounds. The maximum reservoir capacity is 19.6 million cubic meters (MCM) while the minimum reservoir capacity is 0.4 MCM. The exact bounds on releases are not reported. The third constraint requires the release at stage n to be less than or equal to the storage. The fourth constraint requires the total water available for rice production at stage n (sum of precipitation and water released) to be less than or equal to the required water for rice production. The final constraint forces the total profit generated to zero at the last stage (Tran et al, 2011).

$s_{min} \le s_n \le s_{max}$ [Constraint 1]
$u_{min} \le u_n \le u_{max}$ [Constraint 2]

$u_n \le s_n$ [Constraint 3]

$\left(\frac{u_n + q_n^k}{W_o}\right) \le 1$ [Constraint 4]

$V^*(s_n, u_n, q_n^k, i_n^k) = 0$ [Constraint 5]

Where,

s_{max}, s_{min}= Maximum and minimum reservoir capacity (%RC)
u_{max}, u_{min}= Maximum and minimum release (%RC)
V*=Value function at final stage

The recursive equation is subject to the transition represented in Equation 14. Inflow i_n is the product of the rainfall and the catchment area of the reservoir over stage n. Evaporation e_n is the product of the evaporation rate and surface area of the reservoir over stage n. Sub-Institute of Hydrometeorology and Environment of South Vietnam provided daily rainfall data 2000-2008 that allowed for inflow and precipitation to reservoir to be calculated (Tran et al, 2011).

$$s_{n+1} = s_n - u_n - e_n + q_n + i_n \quad \text{[Equation 14]}$$

Where,

e_n=Evaporation at stage n (%RC)

Models Concerning Rice Production

The profit from rice production is the difference of the return and cost (Equation 15). Return is the product of the rice yield and price of rice per weight. Both return per weight P_r and cost C_r were determined from a survey on 2008 production using 80 rice farmers farming the area around the reservoir. Additional data was supplied by the Sub-Institute of Hydrometeorology and Environment of South Vietnam (SHESV), Daton irrigation branch, and local authorities (Tran et al, 2011).

$$V_{rn} = P_r Y_r - C_r \quad \text{[Equation 15]}$$

Where,

Y_r= Rice yield (ton/ha)
V_{rn}=Profit from rice at stage n (mVND)
P_r=Price of rice (million Vietnamese Dong (mVND))/ton
C_r=Total rice production cost at stage n (mVND)

Tran et al. (2011) uses a model that calculates the response of rice yield to the amount of water applied for irrigation (Equations 16-17). The rice yield is a function of timing and quantity of release from reservoiru_n. Data was collected for 2000-2008 on rice production and area of rice cultivation by local Vietnamese authorities. A program called Cropwat calculated the water requirements for rice production given monthly climatic and crop data from 1976 to 2006 provided by SHESV. The institute also provided daily rainfall 2000-2008 to calculate quantity of water that the rice received from rainfall, which was used as input to Equation 17 (Tran et al, 2011).

$$Y_r = Y_p\left(1 - \sum_{n=1}^{N} ky_n \left(1 - \frac{W}{W_o}\right)_n\right) \quad \text{[Equation 16]}$$

Where,

Y_p= Potential rice yield (ton/ha)
ky_n=Yield response at stage n
N=Number of periods of growing rice
W_o=Water required to grow rice (%RC=Percent reservoir capacity)

$$W_n = u_n + q_n \quad \text{[Equation 17]}$$

Where,

W_n=Total water supply for rice production at stage n (%RC)
u_n=Water release (%RC)
q_n=Rainfall (%RC)

Models Concerning Fish Production

The total profit from fish production is the difference of the return and costs (Equation 18). However the form is not the same as that presented for rice production. The return for fish production is the product of the fish yield and a function modeling the response of the fish to varying water levels in the reservoir, measured in the physical concentration effect coefficient (PCE). Data was collected for 2008 production from fish farmers and the Board of Daton Aquaculture Cooperative in a survey. Additional data was supplied by SHESV and local authorities. Both return per fish P_f and cost C_f were determined from a survey for 2008 production involving the Board of the Daton Aquaculture Cooperative (Tran et al, 2011).

$$V_f = Y_f(1 + PCE_n) - C_f \text{ [Equation 18]}$$

Where,

PCE_n=Physical concentration effect coefficient at stage n
Y_f= Harvested fish yield harvest return at stage n (tonnes)
V_f=Profit from fish production at stage n (mVND)
C_f=Total cost of fish production at stage n (mVND)

The BRAVO model was used to calculate the fish yields at the reservoir for all types of fish (Equation 19). The model begins calculating the yield during the harvest period, stages 4-7. The reservoir is stocked mostly with Hypophthalmichthys molitrix (silver carp) or Cirrihinus mrigal (mrigal) (total 40-50% of fingerlings). However other fish types include Cyprinus carpio (common carp), Ctenopharyngodon idella (grass carp), and Aristichthus nobilis (bighead carp). Input to the model were derived form 2000-2008 annual reports from the Daton Aquaculture Cooperative which included time of fingerlings stocking, fish harvest and production costs (Tran et al, 2011).

$$Y_f = \sum_{n=4}^{N-1} \sum_{j=1}^{\beta} (Y_{f_{nj}} P_{f_{nj}}) \quad \text{[Equation 19]}$$

Where,

$Y_{f_{nj}}$= Weight of harvested fish type j at stage n (tonnes)
$P_{f_{nj}}$= Price of harvested fish j at stage n (mVND/ton)
β= Number of fish species

PCE may be determined using Equations 20-22. The first equation presented reveals PCE a function of water level, a parameter derived from the hypsographic curves provided by the local irrigation branch, and two parameters relating fish yield to reservoir surface area (Tran et al, 2011).

$$PCE_n = (\lambda\theta\omega A_0{}^{(\theta+1)} s_t{}^{(\lambda\theta-1)}) \left(\frac{s_t}{Y_f}\right) (\%\Delta s) \quad \text{[Equation 20]}$$

Where,

λ= Parameter derived from hypsographic curves of the reservoir
θ, ω= Parameters that relate fish yield to reservoir surface area
A_o=Surface area when reservoir is completely full (ha)
s_t=Water level of reservoir at stage n when harvest occurs (%RC)

$$s_t = \frac{s_n + s_{n+1}}{2} \quad \text{[Equation 21]}$$

Where,

$$\%\Delta s = \frac{s_t - s_{max}}{s_{max}} \quad \text{[Equation 22]}$$

Stochastic Dynamic Programming Model Results

Tran et al (2011) determined optimal release schedule for Scenario 1 that uses the reservoir for only rice production. Running the scenario returned the release schedule to return the maximum rice yield. The release schedule for stages 1-8 were 16, 5, 8, 8, 13, 8, 6, and 7 % RC, respectively. The schedule did not vary with an initial storage level of 70-100 %RC or whether releases occurred during wet or dry years because the capacity was well beyond sufficient to meet rice production water requirements (Tran et al, 2011).

The optimal release schedule was determined for Scenario 2 when the reservoir was used only for fish production. A maximum amount of water was released before the fish harvest during stages 1-4. Maximizing the release from the reservoir prior to fish harvesting increased the quantity of fish that that could be harvested and decreased the time to harvest. Optimal releases were the maximum allowed during stages 1-4. Relatively low water levels were maintained for harvesting stage 4-7 for all initial storage values 50-100 %RC. The value of the maximum ENPV depended on the initial storage level of the reservoir. With respect to initial storage levels ranging from 50 to 100 %RC, the lower the initial storage level the higher the maximum ENPV. The reason for this result was that the lowest water levels occurred earlier in stages 3 and 4 to allow for a higher fish yield. Wet and dry year also affected the fish yield, with more water able to be released at each stage during a wet year than during a dry year (Tran et al., 2011).

Of most concern in this report, a release schedule was identified for Scenario 3 concerning the optimal release for fish and rice production. Unlike in Scenario 1 the results showed the optimal release strategy heavily depended on the initial storage level. As an example, an initial storage of 100 %RC the optimal release was equal to or less than the release for scenario 2 during stages 1-4, but more than the release during this period for Scenario 1. At a lower initial storage than 70 %RC, the optimal release prioritized rice production because of its high relative value to fish production. For these lower initial storage conditions, the optimal release was at or just above the requirements necessary for rice production. Wet and dry year also affected releases. During wet years, releases were higher or equal to the release in the dry year. This results from more water being removed to concentrate fish for harvesting (Tran et al., 2011).

Methodology of Problem

The objective of the project was to maximize total monthly profits from water allocation to rice and fish from the Lewiston Dam reservoir releases. Deterministic dynamic programming using the program FORTRAN 90 was used to model the maximum total profit from water allocation to fish and rice from water releases to the Trinity River. In the dynamic program, there were a total of 12 stages that represented the different months of the year (starting with October) and 55 states and decision variables that represented the possible storages in the reservoir during a wet, normal, and dry water year (data from WY 2000, WY 2002 and WY 2001 as an example wet, normal and dry year respectively) to determine the net benefit during different periods of rice and fish production. Dynamic programming maximizes the profit from rice and fish production assuming an optimal solution exists among discretized state variables over a 12-month period. The maximum net benefit (profit) at each stage is a function of the initial storage level, the water release, and the reservoir inflow. The objective of the model is represented by the following equation:

$$\text{Maximize } \sum_{j=1}^{12} NB_j(x_j) \qquad \text{[Equation 23]}$$

Where:
$NB_j(x_j)$ =Total net benefit of all decision variables at each stage (months)

Reservoir inflow and storage values during WY 2000, WY 2002, and WY 2001 from station LEW located at Lewiston Dam can be found in Table 1, Table 2, and Table 3.

Table 1: Storage and inflow values from Lewiston Dam during WY 2000 representing a wet water year (CDEC, 2013).

Month	Days	Storage (AF)	ABS(Monthly Diff. in Storage)	Inflow (cf)	Inflow (AF)
10/1/1999	31	14210		2.26E+09	51871.74
11/1/1999	30	14023	187	2.02E+09	46407.27
12/1/1999	31	13845	178	2.87E+09	65825.45
1/1/2000	31	13926	81	3.05E+09	69917.36
2/1/2000	29	14248	322	4.33E+09	99461.16
3/1/2000	31	14128	120	1.09E+10	251071.7
4/1/2000	30	14105	23	4.49E+09	103027.4
5/1/2000	31	13926	179	8.72E+09	200247.3
6/1/2000	30	13808	118	8.85E+09	203228.4
7/1/2000	31	13462	346	9.47E+09	217507.4
8/1/2000	31	13771	309	9.39E+09	215585.5
9/1/2000	30	13956	185	4.73E+09	108482
Total		167,408			1,632,633

Table 2: Storage and inflow values from Lewiston Dam during WY 2002 representing a normal water year (CDEC, 2013).

Month	Days	Inflow (AF)	Storage (AF)	Absolute Monthly Storage Difference (AF)
10/1/2001	31	132289.59	14079.16	
11/1/2001	30	19118.68	13973.97	105
12/1/2001	31	18567.27	14021.94	48
1/1/2002	31	19511.40	13947.77	74
2/1/2002	28	17303.80	13918.54	29
3/1/2002	31	22268.43	14007.32	89
4/1/2002	30	58199.01	14115.07	108
5/1/2002	31	243929.26	14189.23	74
6/1/2002	30	151414.21	14166.97	22
7/1/2002	31	163255.54	14201.03	34
8/1/2002	31	163207.93	14177.87	23
9/1/2002	30	92344.46	14118.03	60
Total		1,101,409.59	168,916.89	

Table 3: Storage and inflow values from Lewiston Dam during WY 2001 representing a dry water year (CDEC, 2013).

Month	Days	Inflow (AF)	Storage (AF)	Absolute Monthly Storage Difference (AF)
10/1/2000	31	28466.8	14013.3	
11/1/2000	30	38584.5	14112.8	100
12/1/2000	31	52835.7	14147.4	35
1/1/2001	31	53323.6	13990.9	157
2/1/2001	28	31908.1	13946.0	45
3/1/2001	31	18085.3	13957.8	12
4/1/2001	30	60670.4	14054.5	97
5/1/2001	31	117320.3	14196.9	142
6/1/2001	30	140294.9	14192.7	4
7/1/2001	31	190714.7	14148.0	45
8/1/2001	31	188632.1	14010.7	137
9/1/2001	30	125284.0	14035.6	25
Total		1046120.3	168806.5	

The maximum and minimum monthly storage from station LEW during wet WY 2000 was found to be 14,248 AF and 13,462 AF respectively (CDEC, 2013). The minimum absolute monthly storage difference was found to be 23, which when added to the minimum monthly storage created 55 possible initial and decision storages (thus there are 55 state and decision variables). These possible state and decision variables were also used during normal and dry WY.

The dynamic program, using the program Fortran 90, uses a recursive equation that moves backward from an initial storage value at stage 12 to stage 1 to solve the objective of maximizing the total profit in the release of water. The maximum future value function was located, which gave the optimal release at that each stage, state, and decision variable. Constraints bound the recursive equation to ensure that the storage and releases at each stage were within the bounds set by the design of the dam and Clear Creek tunnel.

The recursive equation used in the program is represented by the following equation as well as the future value function at the final stage:

$$f_n(S_n) = NB_n(S_n) + f_{n+1}(S_{n+1}, R_{T,n+1}) \quad \text{[Equation 24]}$$

$$f_{12} = NB_{12}(S_{12}, R_{T,12}) \quad \text{[Equation 25]}$$

Where,

$f_n(S_n)$= Net benefit beginning for stage n given storage at stage n
$f_{12}(S_{12})$ = Net benefit at the final stage (12)
$f_{t+1}(S_{n+1}, R_{T,n+1})$= Optimal future value function at for stage n+1 with storage at stage n+1 and total release
$NB(S_n)$= Net benefits over stage n given storage at stage n

The recursive equation is subject to the following transition equation:

$$S_{n+1} = S_n - R_{T,n} + Q_n \quad \text{[Equation 26]}$$

Where:
S_{n+1} = Storage at stage n +1
$R_{T,n}$ =Total release at stage n
Q_n =Inflow at stage n

The program is subject to the following constraints:

$s_n \leq K_{max}$ [Constraint 1]
$R_n \leq R_{maxtunnel}$ [Constraint 2]
$R_{T,n} \leq R_{maxinstream}$ [Constraint 3]
$RRice \leq WR$ [Constraint 4]

Where:
K_{max} = Maximum storage capacity of the reservoir (AF)
$R_{maxtunnel}$=Maximum release to Clear Creek tunnel (AF)
$R_{maxinstream}$ = Maximum release to in-stream (AF)
$RRice$ = Water released for rice production at stage n
WR = Water required for rice production

The first constraint ensures that the storage at each stage (each month) does not exceed the maximum reservoir capacity, which is 14,660 AF (Trinity River Restoration Program , 2013). The second and third constraint ensures that the maximum monthly releases to the Clear Creek Tunnel and to in-stream flow are not exceeded. Under the Safety of Dams criteria, Clear Creek tunnel releases take priority over in-stream releases. The constraints for storage capacities for the Lewiston Dam and the Clear Creek Tunnel can be found in Table 4 and Table 5. The only difference in the maximum monthly storage capacities to in-stream and to the Clear Creek Tunnel occurs when the year is not a leap year (maximum in-stream release is 333,223 AF and maximum Clear Creek Tunnel release is 197,990 AF in February). The fourth constraint requires that the total water available for rice production at each stage to be less than or equal to the required water for rice production.

Table 4: The storage capacities of the Lewiston Dam Reservoir and the Clear Creek Tunnel (Trinity River Restoration Program , 2013).

Parameter	Value
Safety of Dams max in-stream release criteria (cfs)	6,000
Storage capacity (TAF)	14.66
Storage capacity (thousand cubic feet)	638,589.6
Clear Creek Tunnel capacity (cfs)	3,565

Table 5: Under the Safety of Dams criterion the calculated maximum releases to in-stream and to the Clear Creek Tunnel (Trinity River Restoration Program , 2013).

Month	Days	Maximum In stream Release (AF)	Maximum Tunnel Release (AF)	Maximum Total Release (AF)
10/1/1999	31	368,926	219,203	588,129
11/1/1999	30	357,025	212,132	569,157
12/1/1999	31	368,926	219,203	588,129
1/1/2000	31	368,926	219,203	588,129
2/1/2000	29	345,124	205,061	550,185
3/1/2000	31	368,926	219,203	588,129
4/1/2000	30	357,025	212,132	569,157
5/1/2000	31	368,926	219,203	588,129
6/1/2000	30	357,025	212,132	569,157
7/1/2000	31	368,926	219,203	588,129
8/1/2000	31	368,926	219,203	588,129
9/1/2000	30	357,025	212,132	569,157
Total		4,355,702	2,588,013	6,943,716

The following scenarios are used in the dynamic programming methodology:

- Scenario 1- Reservoir release when using water allocation sufficient for rice production and remaining for water allocation to fish.
- Scenario 2- Reservoir release when using reservoir for only in-stream benefits.
- Scenario 3- Reservoir release when using water allocation to satisfy minimum requirement for rice water demand for irrigation and the rest for in-stream flow

In-stream Flow Benefits

During an average year the reservoir is filled during the wet season from snow melt and precipitation in the upper Trinity watershed. The profits from fish production use the willingness to pay results from "The Economic Value of the Trinity River" (adjusted for inflation from 1999 to 2013) (Table 6). A single monthly value of fish is calculated assuming each month the value of fish remain constant which is known to vary according to the life cycles of the fish.

Table 6: Willingness to pay for in-stream flow adjusted for inflation from 1999 to 2013 (Douglas & Taylor, 1999).

In-Stream Flow (TAF)	Value of Fish (Million US$/year)	Value of Fish (Million US$/month)
0	0	0.00
10	148.69	12.39
20	179.23	14.94
30	347.36	28.95
50	717.42	59.79
70	1119.91	93.33

Graphing the value of fish to in-stream flows (Figure 9) results in the following quadratic equation that is used in the program to determine the net benefit from releasing water to in-stream flow:

$$NBF_n = 0.0094R_n^2 + 0.671R_n + 1.0167 \quad \text{[Equation 27]}$$

Where:

NBF_n =Total profit ($/month) from in-stream flow to fish at stage n
R_n = Water released to in-stream flow at stage n (= water release – water release to rice production) (TAF)

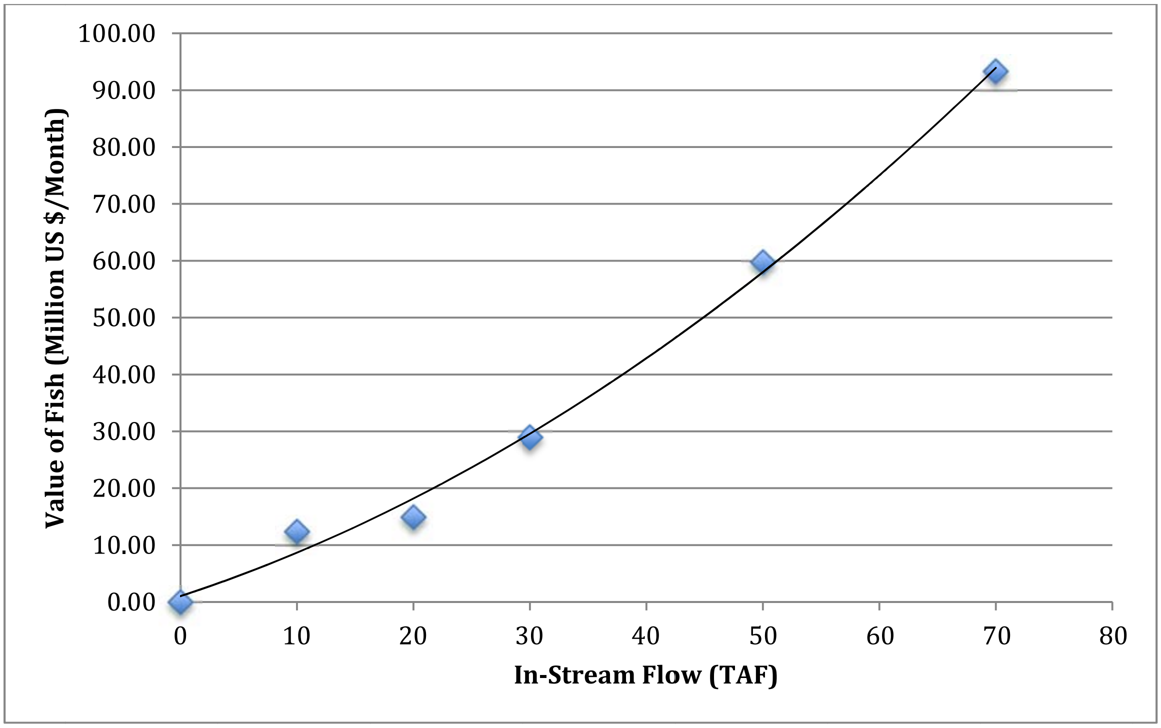

Figure 9: In stream flow versus the value of fish (Douglas & Taylor, 1999).

Recommended water releases for in-stream flow to the Trinity River during a wet, normal and dry year (in *Appendix* Figure 18, Figure 19,Figure 20, Figure 21,Figure 22, &Figure 23) were used to calculate a recommended in-stream release (in *Appendix* Table 20, Table 21, & Table 22), which are compared to the results from the program.

Rice Production Benefit and Requirements

For the Trinity River the total area assumed to be dedicated toward rice crop is 5,796 acres (See Figure 26) (Stene, 1996). The profit of the rice production was determined from the difference between the return and the cost. The return of the rice production was calculated by the following equation using the price per unit weight (throughout a 5 month cycle) per acre of land (see Table 7 for production and yield costs) (Tran et al., 2011):

$$NBR_n = P_r Y_r - C_r \qquad \text{[Equation 28]}$$

Where,

Y_r= Rice yield (cwt/acre)
NBRn=Profit from rice at stage n ($/cwt)
P_r=Price of rice ($/cwt)
CR_n=Total rice production cost at stage n ($/cwt)

Tran et al. (2011) uses a model that calculates the response of rice yield to the amount of water applied for irrigation (Equations 16-17). The rice yield is a function of timing and quantity of release from reservoir R_n. The following equation was used in the dynamic program to determine the potential rice yield (Tran et al., 2011):

$$Y_r = Y_p\left(1 - k_{c,n}\left(1 - \frac{RRice}{WR}\right)_n\right) \quad \text{[Equation 29]}$$

Where,

Y_p= Potential rice yield
$k_{c,n}$ =Crop stage coefficient at stage n
N=Number of periods of growing rice
WR=Water required for rice production at stage n
$RRice_n$ =Water released for rice production at stage n

Table 7: Rice yield, price, and rice production costs used to determine rice production benefits (Livezey, Foreman, & USDA, 2004)

Parameter	Value
Rice Yield (cwt/acre)	13
Price of rice ($/cwt)	1.34
Rice production cost ($/cwt)	0.89

The water required at each stage for rice production is determined by calculating the water demand for rice production minus the possible precipitation to the rice crop over the area, which is taken into consideration by the Blaney-Criddle Method. The Blaney-Criddle Method is represented by the following equation (Gupta, 2008):

$$U = \sum K_T * K_c * t_m\left(\frac{P}{100}\right) \quad \text{[Equation 30]}$$

Where,

U = Water demand (in. /month)
K_T = The climatic coefficient (Kt=0.0173tm-0.314)
K_c =Crop growth stage coefficient
t_m =Average monthly temperature of area (^{o}F)
P =Monthly average percent of annual daytime hours

The crop coefficient for rice, K_c, for each of its growth stages can be seen in Table 8. Rice is usually planted in May and harvested in October with 150 days of growth. Rice in this model will be assumed to be growing for either 1 cycle (5 months) or two cycles (10 months) with each growing stage represented by its corresponding crop coefficient. The planting schedule that was used in the program when using two cycles can be found in Table 9.

Table 8: Rice crop coefficients based on its growth stages (United States Department of Agriculture (USDA) , 1993)

Growth Stage	Rice Crop Coefficient, K_c
0-2 Months	1.15
3-4 Months	1.35
5 Months	1.05

Maximum and minimum temperature data and precipitation data were taken from Modesto, CA (station located at 37.5031˚N and 121.5747˚W) during years 1971 to 2000 was averaged to determine the average temperature and average precipitation (used to calculate volume of water to the reservoir from precipitation) of the Trinity River area. Temperature coefficients were calculated using the following equation (see Table 9) (Gupta, 2008):

$$K_T = 0.0173 * T_{ave} - 0.314 \qquad \text{[Equation 28]}$$

Where:

T_{ave} =Average temperature (degrees F)

The monthly percent of annual daytime hours were determined using averages from 38˚ north of the equator based on the location of the Lewiston Dam (Table 9).

Table 9: Average temperature and precipitation values taken from the station located in Modesto, CA used to calculate monthly temperature coefficients and volume of precipitation (Wester Regional Climate Center WRCC, 2010). Monthly percent of annual daytime hours were taken 38˚ N of the equator (Gupta, 2008).

Planting Schedule	Month	Days	Average Min Temp (˚F)	Average Max Temp (˚F)	Average Temp. (˚F)	Average Total Precip. (in.)	Water Volume of Precip. (cf)	Daytime Hours of the Year Using 38˚ North of equator) (%)	K_t	K_C
	10/1/1999	31	51.5	78.3	64.9	0.73	15358820	0.078	0.8088	None
Begin Crop 1	11/1/1999	30	42.2	62.2	52.2	1.5	31559220	0.0682	0.5891	1.15
	12/1/1999	31	38.3	54.6	46.45	1.74	36608695	0.0666	0.4896	1.15
	1/1/2000	31	39.4	54.8	47.1	2.53	53229884	0.0687	0.5008	1.35
	2/1/2000	29	42.6	62	52.3	2.55	53650674	0.0679	0.5908	1.35
	3/1/2000	31	45.4	67.9	56.65	2.1	44182908	0.0834	0.6660	1.05
	4/1/2000	30	48.3	74.1	61.2	0.98	20618690	0.089	0.7448	None
Begin Crop 2	5/1/2000	31	53.2	81.6	67.4	0.59	12413293	0.0992	0.8520	1.15
	6/1/2000	30	57.9	88.6	73.25	0.15	3155922	0.0995	0.9532	1.15
	7/1/2000	31	61.2	93.5	77.35	0.05	1051974	0.101	1.0242	1.35
	8/1/2000	31	60.7	92.2	76.45	0.07	1472764	0.0947	1.0086	1.35
	9/1/2000	30	57.7	87.6	72.65	0.24	5049475	0.0838	0.9428	1.05

The monthly gross water demand for rice irrigation was calculated using the calculated monthly temperature coefficients, the crop coefficients (depending on planting schedule), average monthly precipitation, and average daily percent of annual daytime hours. The net irrigation required for area assumed from growing rice (5796 acres) was then calculated by subtracting the average monthly effective precipitation from the gross irrigation required. The on-farm delivery was calculated by dividing the net irrigation required for 5796 acres of rice by the assumed on-farm efficiency of 59% (Gupta, 2008). The final calculation for the gross requirement for rice irrigation was then calculated by dividing the farm delivery by the assumed off-farm efficiency of 83% (Gupta, 2008). All resulting calculations and rice water demand for irrigation can be found in Table 10.

Table 10: Water demand for rice irrigation calculation results (Gupta, 2008).

Month	Gross irrigation Required (in.)	Monthly Effective Rainfall (in.)	Net Irrigation Required (IR) (in.)	IR for Area (cf)	Farm Delivery (cf)	Gross Requirement (cf)	Gross Req. (AF)
10/1/1999	0.000	0	0.000	0	0	0	0
11/1/1999	2.412	1.25	1.162	2E+07	4.1E+07	49,908,669	1146
12/1/1999	1.742	1.25	0.492	1E+07	1.8E+07	21,127,569	485
1/1/2000	2.188	1.85	0.338	7E+06	1.2E+07	14,511,975	333
2/1/2000	2.832	1.95	0.882	2E+07	3.1E+07	37,906,906	870
3/1/2000	3.304	1.35	1.954	4E+07	7E+07	83,957,837	1927
4/1/2000	0.000	0	0.000	0	0	0	0
5/1/2000	6.551	0.4	6.151	1E+08	2.2E+08	264,279,197	6067
6/1/2000	7.990	0	7.990	2E+08	2.8E+08	343,264,484	7880
7/1/2000	10.801	0	10.801	2E+08	3.9E+08	464,072,729	10654
8/1/2000	9.858	0	9.858	2E+08	3.5E+08	423,524,599	9723
9/1/2000	6.027	0	6.027	1E+08	2.1E+08	258,948,939	5945

Project Assumptions

The following assumptions were made for the project:

- No precipitation or evaporation occurs over the reservoir.
- Release from the reservoir is constant over entire day.
- The monthly potential value from rice and fish production is constant over growing period and life stages, respectively.
- The value of in-stream benefits is constant over all months.
- There are 2 cycles of 5-months used for rice production.
- All the land available for crop production is used for rice.

Results and Discussion

Results illustrated that scenarios 1 and 2 had the largest total net benefits which, signifies that the largest profits come from allocating as much water to in-stream flow as possible (Figure 10). These results also illustrate that there is around $9,187,142 lost when allocating between the extremes for rice production and in-stream flow (scenario 1) and allocating all of the water to in-stream flow (scenario 2) during a wet year. Similar results are illustrated during normal and dry water years except that the total net benefits decrease from the wet to the normal and dry year due to less inflow contributing to in-stream release (Figure 11 & Figure 12). Due to the fact that the amount of water that is allocated to rice is a requirement in practice, net benefits from scenario 3 are calculated for the dry, normal and dry water years. To make these results as accurate as possible, further analysis should be performed on the economic valve of fish production rather than just a societal value or a societal value should be given for rice production. Real-life models would have to take into account more factors in the allocation of water releases to rice and fish production.

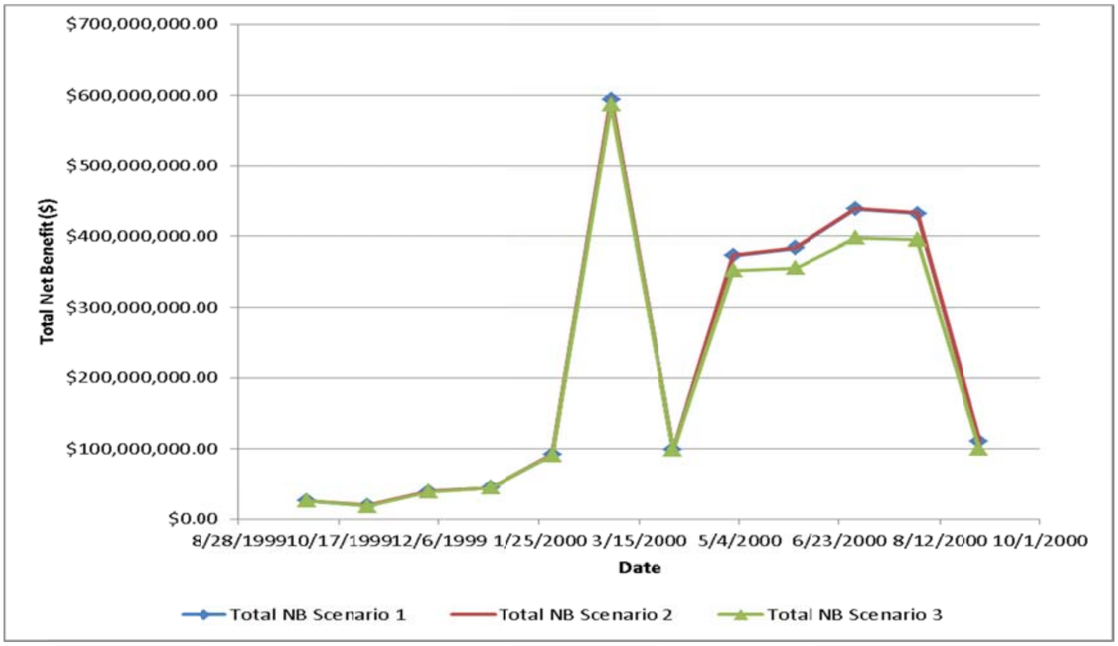

Figure 10: Total net benefit results using deterministic dynamic programming (using FORTRAN 90) from release to rice irrigation and in-stream flow for scenarios 1, 2 and 3 during a wet year.

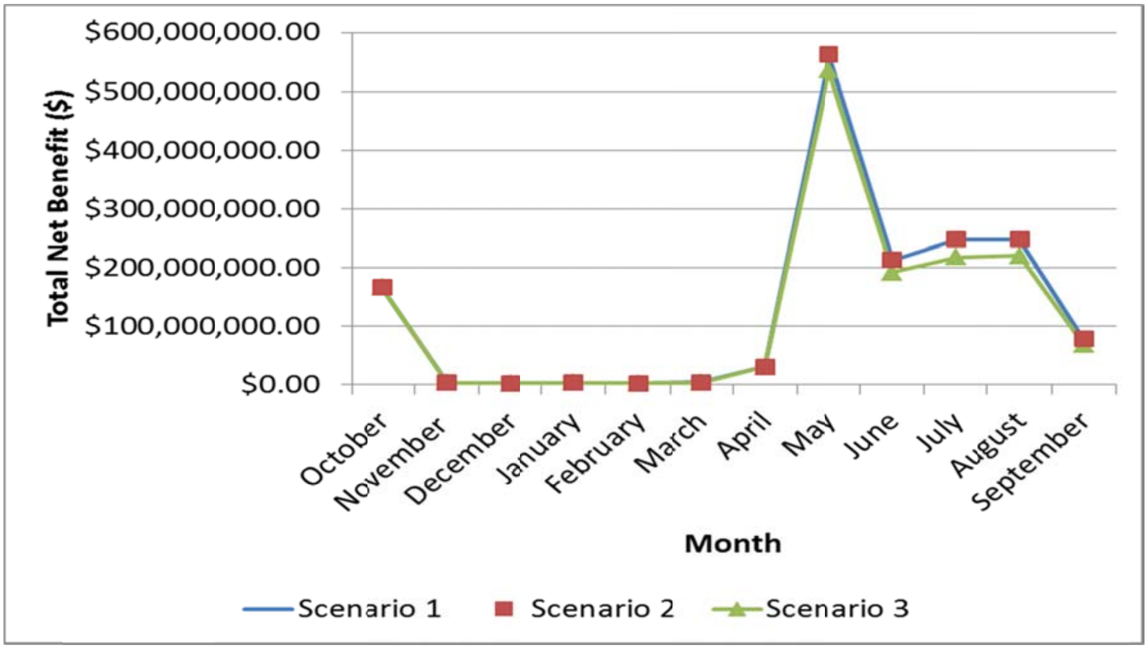

Figure 11: Total net benefit results using deterministic dynamic programming (using FORTRAN 90) from release to rice irrigation and in-stream flow for scenarios 1, 2 and 3 during a normal year.

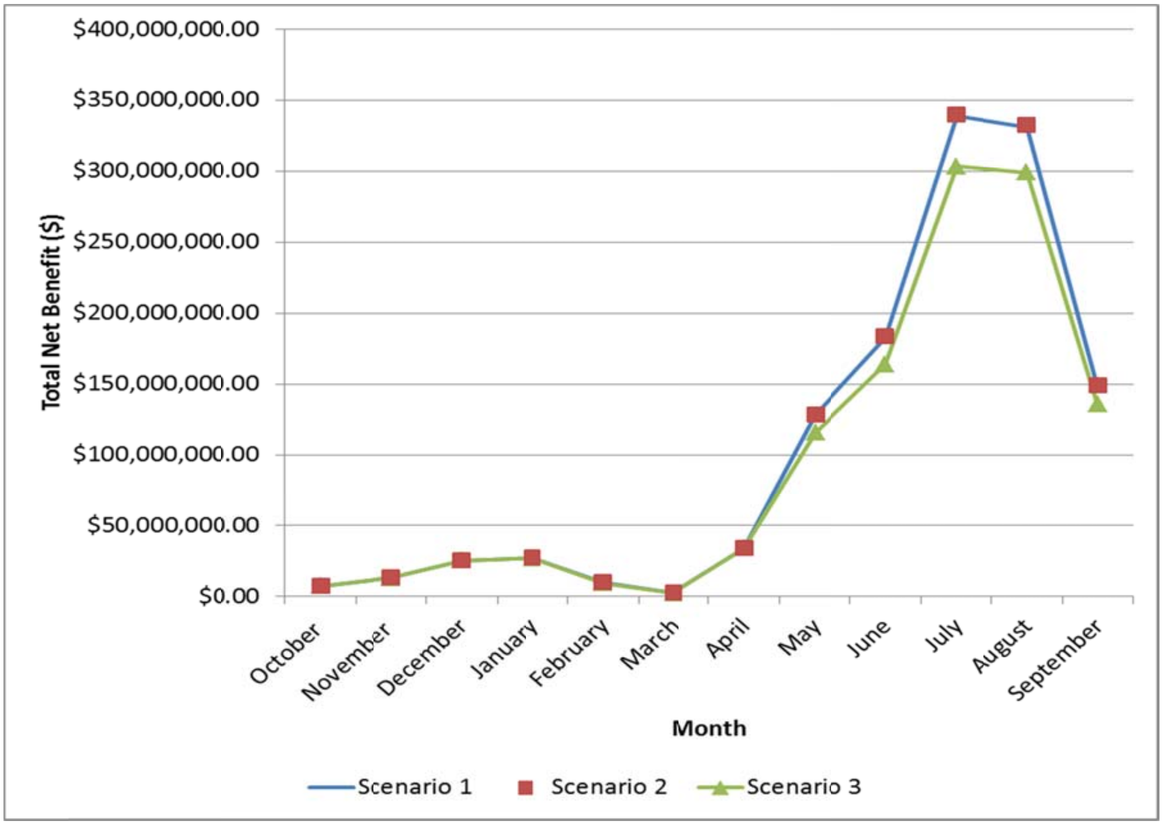

Figure 12: Total net benefit results using deterministic dynamic programming (using FORTRAN 90) from release to rice irrigation and in-stream flow for scenarios 1, 2 and 3 during a dry year.

Large decreases in profit are calculated when using only 1 cycle of rice production for scenarios 1 and 3 (Table 11). These results illustrate that using 2 cycles of rice production results in higher net benefits from water allocation. The area has optimal climate for 2 cycles of rice production, thus 2 cycles is used in the remainder of the analysis to maximize net benefit.

Table 11: Differences in total net benefits of scenarios 1, 2 and 3 when only using 1 cycle of rice production during a wet year.

Net Benefit Scenario 1 Difference ($)	Net Benefit Scenario 2 Difference ($)	Net Benefit Scenario 3 Difference ($)
$0.00	$0.00	$0.00
$0.00	$0.00	$0.00
$0.00	$0.00	$0.00
$0.00	$0.00	$0.00
$0.00	$0.00	$0.00
-$108,748.25	$108,892.24	$0.00
$0.00	$0.00	$0.00
-$1,257,116.55	$0.00	-$22,315,873.63
-$1,276,525.13	$0.00	-$29,304,979.86
-$1,384,597.23	$0.00	-$42,169,872.06
-$1,374,028.66	$0.00	-$38,264,451.89
-$680,888.49	$0.00	-$11,757,093.11
$0.00	$0.00	$0.00

The highest monthly net benefits for rice occurred during scenario 3, but the water that was allocated to rice procured some of the profits from in-stream flow (Table 12, Table 13, & Table 14). The net benefits for the allocation to rice remained the same for all water years due to the fact that only requirements were met in all scenarios. As expected, the net benefits from in-stream flow increased as the amount of inflow increased. Scenarios 1 and 2 resulted in higher net benefits due to the higher allocation of water to in-stream flow.

Table 12: Resulting Rice and Fish net benefits for scenarios 1, 2 and 3 during a wet year.

Month	Scenario 1		Scenario 2		Scenario 3	
	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)
October	$0.00	$26,119,090.40	$0.00	$26,119,090.40	$0.00	$26,119,090.40
November	$18,593.30	$19,450,666.66	$0.00	$19,736,486.42	$100,965.43	$18,761,612.43
December	$64,575.92	$39,376,840.34	$0.00	$39,783,072.62	$100,965.43	$39,192,105.95
January	$100,965.43	$44,632,430.44	$0.00	$45,064,856.24	$100,965.43	$44,632,430.44
February	$16,832.63	$91,706,806.81	$0.00	$92,326,205.72	$100,965.43	$90,712,347.91
March	$13,270.92	$594,512,934.79	$0.00	$596,197,282.91	$100,965.43	$587,108,495.82
April	$0.00	$98,823,671.79	$0.00	$98,823,671.79	$0.00	$98,823,671.79
May	-$8,772.83	$373,135,420.48	$0.00	$374,383,764.20	$100,965.43	$351,966,925.14
June	-$10,239.10	$383,947,663.83	$0.00	$385,213,949.86	$100,965.43	$355,808,004.57
July	-$31,078.79	$438,715,392.17	$0.00	$440,068,910.61	$100,965.43	$397,798,073.12
August	-$30,670.85	$432,148,355.13	$0.00	$433,491,712.94	$100,965.43	$395,126,295.62
September	$889.04	$111,142,467.36	$0.00	$111,824,244.89	$100,965.43	$99,966,186.35
Total	**$134,365.67**	**$2,653,711,740.20**	**$0.00**	**$2,663,033,248.60**	**$1,009,654.30**	**$2,506,015,239.54**

Table 13: Resulting Rice and Fish net benefits for scenarios 1, 2 and 3 during a normal year.

	Scenario 1		Scenario 2		Scenario 3	
Month	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)
October	$0.00	$166,255,812.69	$0.00	$166,313,323.27	$0.00	$166,255,812.69
November	$18,593.30	$3,536,201.77	$0.00	$3,658,668.91	$100,965.43	$3,245,963.37
December	$64,575.92	$2,927,866.33	$0.00	$3,039,396.55	$100,965.43	$2,877,650.60
January	$100,965.43	$3,672,405.05	$0.00	$3,797,188.54	$100,965.43	$3,672,405.05
February	$16,832.63	$2,495,235.89	$0.00	$2,591,093.03	$100,965.43	$2,333,462.06
March	$13,270.92	$4,275,370.02	$0.00	$4,409,925.99	$100,965.43	$3,660,152.66
April	$0.00	$31,301,488.80	$0.00	$31,301,488.80	$0.00	$31,301,488.80
May	-$8,772.83	$561,537,675.27	$0.00	$563,068,845.08	$100,965.43	$535,499,135.54
June	-$10,239.10	$213,290,770.68	$0.00	$214,234,840.18	$100,965.43	$192,453,718.31
July	-$31,078.79	$248,281,951.99	$0.00	$249,300,438.87	$100,965.43	$217,748,599.14
August	-$30,670.85	$248,065,066.76	$0.00	$249,083,109.15	$100,965.43	$220,216,315.96
September	$889.04	$78,571,364.31	$0.00	$79,303,553.45	$100,965.43	$69,369,993.65
Total	**$134,365.67**	**$1,564,211,209.56**	**$0.00**	**$1,570,101,871.82**	**$1,009,654.30**	**$1,448,634,697.83**

Table 14: Resulting Rice and Fish net benefits for scenarios 1, 2 and 3 during a dry year.

	Scenario 1		Scenario 2		Scenario 3	
Month	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)	RICE NB ($)	FISH NB ($)
October	$0.00	$7,307,442.91	$0.00	$7,307,442.91	$0.00	$7,307,442.91
November	$18,593.30	$13,401,745.41	$0.00	$13,639,172.27	$100,965.43	$12,830,839.58
December	$64,575.92	$25,449,557.92	$0.00	$25,776,345.74	$100,965.43	$25,301,086.48
January	$100,965.43	$27,030,699.50	$0.00	$27,367,453.87	$100,965.43	$27,030,699.50
February	$16,832.63	$9,723,712.91	$0.00	$9,926,106.57	$100,965.43	$9,401,721.91
March	$13,270.92	$2,747,900.91	$0.00	$2,855,981.66	$100,965.43	$2,259,414.84
April	$0.00	$33,961,573.57	$0.00	$33,961,573.57	$0.00	$33,961,573.57
May	-$8,772.83	$127,766,887.73	$0.00	$128,497,803.13	$100,965.43	$115,508,103.93
June	-$10,239.10	$183,022,576.16	$0.00	$183,897,174.01	$100,965.43	$163,760,006.08
July	-$31,078.79	$339,106,742.25	$0.00	$340,296,851.73	$100,965.43	$303,254,119.47
August	-$30,670.85	$331,222,426.01	$0.00	$332,398,631.14	$100,965.43	$298,913,770.83
September	$889.04	$148,360,850.96	$0.00	$149,148,391.68	$100,965.43	$135,402,158.37
Total	**$134,365.67**	**$1,249,102,116.24**	**$0.00**	**$1,255,072,928.28**	**$1,009,654.30**	**$1,134,930,937.47**

As expected due to highest inflow, the most net benefit occurs during the wet water year (WY) and conversely for the dry WY (Figure 13 & Table 15). There were higher net benefits during from April to September due to the larger amount of water being released.

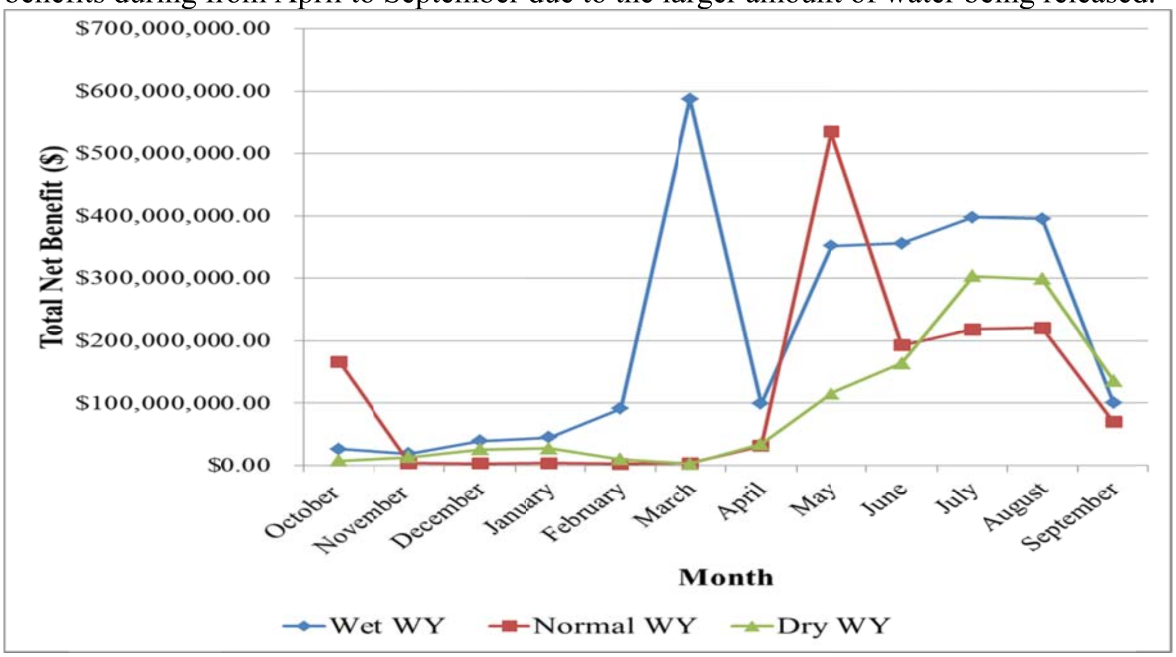

Figure 13: Monthly total net benefit results based on a wet, normal and dry water year.

Table 15: Total net benefits based on a wet, normal, and dry water year.

	Total Net Benefit Wet WY ($)	Total Net Benefit Normal WY ($)	Total Net Benefit Dry WY ($)
Total	$2,507,024,893.84	$1,449,644,352.13	$1,135,940,591.77

The largest net benefit from in-stream release occurred during the wet water year (Table 16).

Table 16: Total monthly rice and fish net benefit results based a wet, normal and dry water year.

	Wet WY		Normal WY		Dry WY	
Month	**Rice Net Benefit ($)**	**Fish Net Benefit ($)**	**Rice Net Benefit ($)**	**Fish Net Benefit ($)**	**Rice Net Benefit ($)**	**Fish Net Benefit ($)**
Oct	$0	$26,119,090	$0	$165,030,459	$0	$7,307,443
Nov	$100,965	$18,761,612	$100,965	$2,821,677	$100,965	$12,830,840
Dec	$100,965	$39,192,106	$100,965	$2,872,061	$100,965	$25,301,086
Jan	$100,965	$44,632,430	$100,965	$3,486,061	$100,965	$27,030,700
Feb	$100,965	$90,712,348	$100,965	$2,329,613	$100,965	$9,401,722
Mar	$100,965	$587,108,496	$100,965	$3,662,379	$100,965	$2,259,415
Apr	$0	$98,823,672	$0	$31,302,574	$0	$33,961,574
May	$100,965	$351,966,925	$100,965	$533,275,808	$100,965	$115,508,104
Jun	$100,965	$355,808,005	$100,965	$192,451,028	$100,965	$163,760,006
Jul	$100,965	$397,798,073	$100,965	$217,740,015	$100,965	$303,254,119
Aug	$100,965	$395,126,296	$100,965	$220,210,561	$100,965	$298,913,771
Sep	$100,965	$99,966,186	$100,965	$69,371,609	$100,965	$135,402,158
Total	**$1,009,654**	**$2,506,015,240**	**$1,009,654**	**$1,444,553,845**	**$1,009,654**	**$1,134,930,937**

The greatest releases contributing to the highest net benefit (NB) for the wet WY occurs March, July, and August, and conversely for the dry WY in October and March (Figure 14). Actual releases were determined by subtracting the storage at stage n+1 from the inflow and storage at stage n. The actual releases during wet WY 2000, normal WY 2002, and dry WY 2001 were very similar to the resulting releases from the dynamic program, which signifies that the resulting releases are optimal for the Trinity River. Cumulative releases in May during the normal WY result in surpassing the cumulative annual release during the dry WY (Table 17), which illustrates why the normal and dry water years are classified as such.

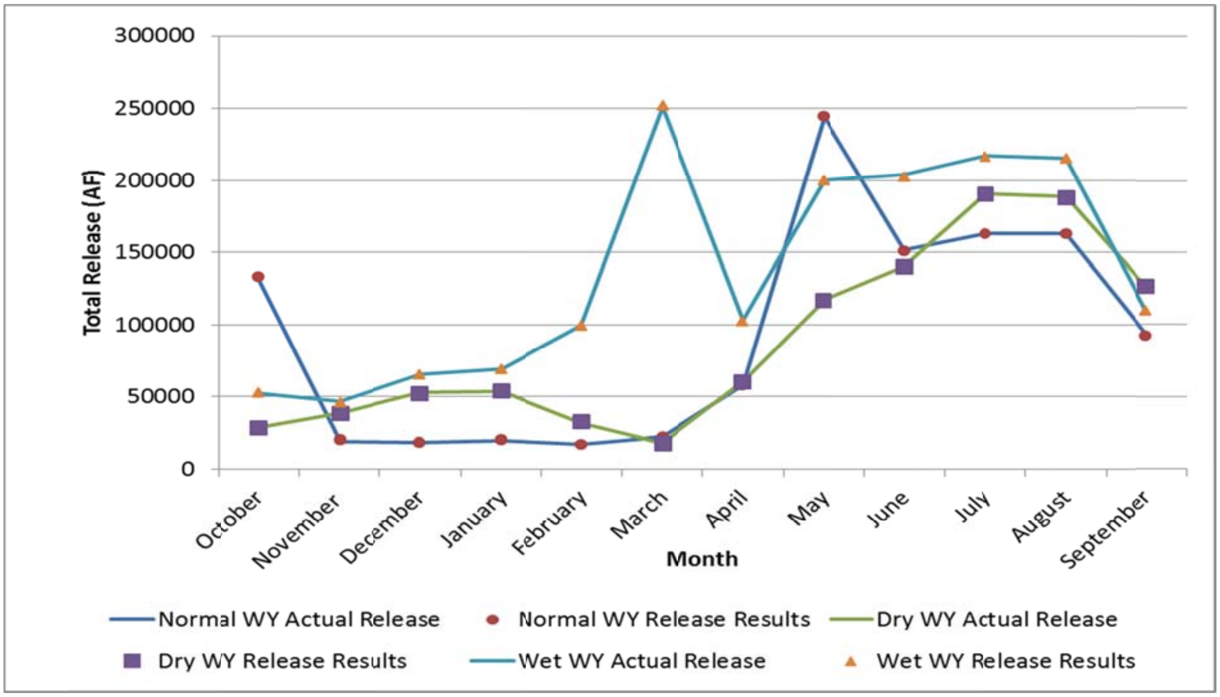

Figure 14: Total monthly release results based on a wet, normal, and dry water year classification versus the actual releases during wet WY 2000, Normal WY 2002, and Dry WY 2001. (CDEC, 2013)

During all water years optimal in-stream releases are above recommended except for May during all WY and June in normal and dry WY (Figure 15). These results illustrate that the recommended in-stream releases may have to be considered in the dynamic program as a constraint during periods of low flow. However, annual optimal in-stream releases are at minimum nearly double the recommended and actual in-stream releases (Table 17). Exceeding recommended and actual in-stream releases contribute to a higher net benefit from fish production.

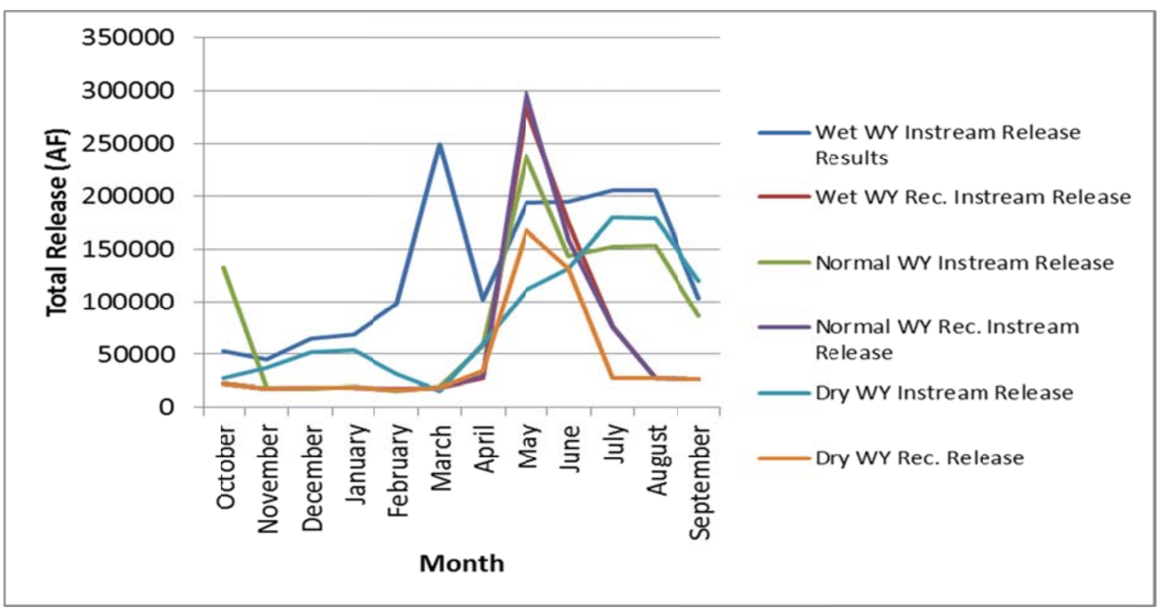

Figure 15: Optimal releases for in-stream (fish) results from the dynamic program versus the recommended in-stream releases (Douglas & Taylor, 1999).

Table 17: Annual total release during a wet, normal, and dry WY.

WY	Result Total Release (AF)	Recommended In-stream Releases (AF)	Actual Total In-stream Release (AF)
Wet	1,583,046	731,058	560,000
Normal	1,054,534	729,074	482,700
Dry	997,939	528,694	383,800

The amount of water allocated for rice remained the same for all water years. The amount of water allocated for in-stream release increased as the water year became wetter mostly due to higher inflows (

Table **18**).

Table 18: Monthly rice and fish release results based on a wet, normal and dry water year.

	Wet WY		Normal WY		Dry WY	
Month	**Rice Release (AF)**	**Fish Release (AF)**	**Rice Release (AF)**	**Fish Release (AF)**	**Rice Release (AF)**	**Fish Release (AF)**
October	0	52677	0	132465	0	27846
November	1146	44640	1146	17290	1146	36910
December	485	64535	485	17444	485	51845
January	333	68871	333	19222	333	53589
February	870	98200	870	15707	870	31590
March	1927	249881	1927	19703	1927	15468
April	0	102498	0	57671	0	60072
May	6067	193467	6067	238148	6067	110816
June	7880	194520	7880	143050	7880	131954
July	10654	205680	10654	152161	10654	179578
August	9723	204988	9723	153022	9723	178288
September	5945	103089	5945	85871	5945	119983
Total	45030	1583046	45030	1051754	45030	997939

Resulting final storages in the reservoir at Lewiston Dam were found to be very similar throughout the water years, which signifies that the maximum possible allocation to in-stream release was performed (Table 19).

Table 19: Monthly initial and final storage results based on a wet, normal and dry water year.

	Wet WY		Normal WY		Dry WY	
Month	Initial Storage (AF)	Final Storage (AF)	Initial Storage (AF)	Final Storage (AF)	Initial Storage (AF)	Final Storage (AF)
October	14205	13400	14076	13900	14021	14642
November	14021	14642	13966	14648	14113	14642
December	13837	14642	14010	14648	14136	14642
January	13929	14642	13944	13900	13998	13400
February	14251	14642	13922	14648	13952	13400
March	14136	13400	14010	14648	13952	14642
April	14113	14642	14120	14648	14044	14642
May	13929	14642	14186	13900	14205	14642
June	13814	14642	14164	14648	14182	14642
July	13469	14642	14208	14648	14159	14642
August	13768	14642	14186	14648	14021	14642
September	13952	13400	14120	14648	14044	13400

Conclusions

- As guaranteed by dynamic programming methodology, an optimal monthly release schedule was identified (with scenario 3 chosen due to the fact that rice production requirements must be met to simulate in the allocation model what would be done in practice).
- As expected, total net benefits increase with higher inflows as shown in WY type analysis due to the higher allocation to in-stream flow, which may signify that a societal value should be given to rice production or instead an economic value to fish production.
- Releases remained the same for all water year types for rice production to maximize the net benefit from in-stream releases, which resulted in similar final storages in the reservoir.
- May optimal in-stream releases during a wet WY and June during normal and dry water years optimal in-stream releases are below recommended in-stream releases, but annual optimal in-stream releases always exceed recommended and actual for all WY types.

Recommendations for Further Analysis

- Monthly recommended in-stream releases by the USFWS should constrain optimal releases.
- Substitute the economic value of rice production with a societal value to weigh directly against the societal value of fish or substitute the societal value of fish production with an economic value.
- Meaningful comparisons between optimal total releases and actual can be conducted when accounting for evaporation and precipitation over reservoir.
- Extend analysis to an extremely wet and an extremely dry WY to determine how they would impact the total net benefit results from the program.
- Incorporate value of hydropower in the allocation of water release in the net benefit analysis.
- Increase the area to be used for rice production (if increased to 250 times the area currently used for rice production the net benefits from rice production surpasses the net benefits from fish production).
- Incorporate other crops in the net benefit analysis to determine if higher net benefits would result.

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Appendix A: Project Tables

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
Oct 1 - Oct 15	450	Fall baseflow	≤56°F at confluence of the North Fork Trinity River	Provide optimal holding/spawning temperatures for spring- and fall-run chinook adults	Provide suitable temperatures, reducing pre-spawning mortality and increasing egg viability
Oct 16 - Apr 22	300	Winter baseflow	Provide maximum amount of spawning habitat	Provide best balance of spawning and rearing habitats for all anadromous salmonids in the existing channel	Increase spawning habitat while minimizing dewatering of redds (dewater less than 5% of redds) of salmonids
Apr 22 - Apr 28	500	Spring baseflow	≤ 55.4°F at Weitchpec	Provide optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production
Apr 29 - May 5	1,500	Spring baseflow/ Ascending limb	≤ 55.4°F at Weitchpec	Provide optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production
May 6 - May 19	2,000	Spring baseflow/ Ascending limb	≤ 55.4°F at Weitchpec	Provide optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production Reduce travel time of outmigrating steelhead smolts
May 19 - May 24	2,000 - 11,000	Ascending limb	Reach peak flow	Ramp to peak flow (according to OCAP) safely for human use	Reduce travel time of outmigrating steelhead smolts
May 24 - May 28	11,000	Snowmelt peak	Peak: Mobilize ≥2 D84 deep on flanks of alternate bars (more on lower channel than upper) cleanses gravels and transports all sizes of sediments Initiate channel migration at bank rehabilitation sites Duration: Transport coarse sediment (>8mm) through mainstem at a rate equal to tributary input downstream of Rush Creek Transport fine sediment (< 8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (< 8mm) storage within surface and subsurface channel bed Increase sinuosity through channel migration Create and maintain alternate bar morphology Create floodplains by bar building and fine sediment deposition Encourage establishment and growth of riparian vegetation on floodplains Scour up to 3 yr old riparian vegetation along low flow channel margins and scour younger plants higher on bar flanks	Increase fry production through improved egg-to-emergence success Increase fry production by creating and maintaining rearing habitat along channel margins Increase smolt production by increasing year-round rearing habitat quality, quantity, and reducing outmigration travel time Increase species and age diversity of riparian vegetation

Figure 16: Recommended releases from Lewiston Dam over the course of an Extremely Wet water year along with explanations (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
May 28 - June 6	11,000 - 6,000	Descending limb	Ramp to 6,000 cfs	Reduce fine sediment (< 8mm) storage stored within surface channelbed	Increase fry production through improved egg-to-emergence success
June 6 - June 10	6,000	Descending limb bench	Transport fine sediment (< 8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (< 8mm) storage within surface channelbed while minimizing coarse sediment (>8mm) transport	Improve spawning production through improved egg-to-emergence success Discourage riparian vegetation initation along low water channel margins
June 10 - Jun 30	6,000 - 2,000	Descending limb	Descend at a rate mimicking pre-TRD descent	Inundate point bars Minimize river stage change to preserve yellow legged frog egg masses Maintain seasonally variable water surface levels in sidechannels and off-channel wetlands	Prevent riparian initiation along low water channel margins Reduce fine sediment (< 8mm) storage stored within surface channelbed Improve juvenile chinook growth Increase riparian vegetation and future LWD recruitment
Jun 30 - Jul 9	2,000	Descending limb bench	Provide optimal water temperatures ($\leq$62.6°F) to Weitchpec for chinook salmon smolts	Providing optimal temperatures for their survival Inundate point bars	Improve chinook smolt production Prevent riparian initiation along low water channel margins
Jul 9 - Jul 22	2,000 - 450	Descending limb	Decline to summer baseflows	Minimize stranding behind berms	Increase survival of steelhead fry Provide emigration cues for chinook salmon smolts
Jul 22 - Sep 30	450	Summer baseflows	$\leq$ 60°F @ Douglas City through Sep 14 $\leq$ 56°F @ Douglas City from Sep 15 through Sep 30	Increase survival of holding adult spring-run chinook salmon by providing optimal thermal refugia	Increase production of coho salmon and steelhead by providing water temperatures conducive to good growth

Figure 17: Recommended releases from Lewiston Dam over the course of an Extremely Wet water year along with explanations continued (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
Oct 1 - Oct 15	450	Fall baseflows	≤56°F at confluence of the North Fork Trinity River	Provide optimal holding/spawning temperatures for spring- and fall-run chinook adults	Provide suitable temperatures, reducing pre-spawning mortality and increasing egg viability
Oct 16 - Apr 21	300	Winter baseflows	Provide maximum amount of spawning habitat	Provide best balance of spawning and rearing habitats for all anadromous salmonids in the existing channel	Increase spawning habitat while minimizing dewatering of redds (dewater less than 5% of redds) of salmonids
Apr 22 - Apr 28	500	Spring baseflow	≤ 55.4°F to Weitchpec	Providing optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production
Apr 29 - May 5	2,000	Spring baseflow/ Ascending limb	≤ 55.4°F to Weitchpec	Providing optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production
May 6 - May 13	2,500	Spring baseflow/ Ascending limb	≤ 55.4°F to Weitchpec	Providing optimal temperatures for survival of steelhead smolts	Improve steelhead smolt production Reduce travel time of outmigrating steelhead smolts
May 13- May 17	2,500 - 8,500	Ascending limb	Reach peak flow	Ramp to peak flow (according to OCAP) safely for human use	Reduce travel time of outmigrating steelhead smolts
May 17- May 21	8,500	Snowmelt peak	Peak Threshold: Mobilize ≥1 D84 deep on flanks of alternate bars (more on lower channel than on upper) cleanses gravels and transports all sizes of sediments Initiate channel migration at bank rehabilitation sites Duration: Transport coarse sediment (>8mm) through mainstem at a rate equal to tributary input downstream of Rush Creek Transport fine sediment (< 8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (< 8mm) storage within surface and subsurface channel bed Increase sinuosity through channel migration Create and maintain alternate bar morphology Create floodplains by bar building and fine sediment deposition Encourage establishment and growth of riparian vegetation on floodplains Scour up to 2 yr old woody riparian vegetation along low flow channel margins	Increase fry production through improved egg-to-emergence success Increase fry production by creating and maintaining rearing habitat along channel margins Increase smolt production by increasing year-round rearing habitat quality, quantity, and quantity and reducing outmigration travel time Increase species and age diversity of riparian vegetation

Figure 18: Recommended releases from Lewiston Dam over the course of a Wet water year along with explanations (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
May 21 - May 24	8,500 - 6,000	Descending limb	Ramp to 6,000 cfs	Reduce fine sediment (< 8mm) storage stored within surface channelbed	Increase fry production through improved egg-to-emergence success
May 24 - May 28	6,000	Descending limb bench	Transport fine sediment (< 8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (< 8mm) storage within surface channelbed while minimizing coarse sediment (> 8mm) transport	Increase fry production through improved egg-to-emergence success Discourage riparian vegetation initiation along low water channel margins
May 28 - Jun 14	6,000 - 2,000	Descending limb	Descend at a rate mimicking pre-TRD descent Descend at a rate less than 0.1 ft/day	Inundate point bars Minimize river stage change to preserve yellow legged frog egg masses. Maintain seasonally variable water surface levels in sidechannels and off-channel wetlands	Prevent riparian initiation along low water channel margins Reduce fine sediment (< 8mm) storage stored within surface channelbed Improve juvenile chinook growth
Jun 14 - Jul 9	2,000	Descending limb bench	Provide optimal water temperatures (≤62.6°F) to Weitchpec for chinook salmon smolts	Providing optimal temperatures for their survival Inundate point bars	Improve chinook smolt production Prevent riparian initiation along low water channel margins
Jul 9 - Jul 22	2,000 - 450	Descending limb	Decline to summer baseflows	Minimize stranding behind berms	Increase survival of steelhead fry Provide emigration cues for chinook salmon smolts
Jul 22 - Sep 30	450	Summer baseflows	≤ 60°F @ Douglas City through Sep 14 ≤ 56°F @ Douglas City from Sep 15 through Sep 30	Increase survival of holding adult spring-run chinook salmon by providing optimal thermal refugia	Increase production of coho salmon and steelhead by providing water temperatures conducive to good growth

Figure 19: Recommended releases from Lewiston Dam over the course of a Wet water year along with explanations continued (USFWS, HVT, 1999).

Table 20: Calculated recommended in-stream volume for in-stream flow during a wet year to the Trinity River.

Month	Days	Recommended Instream Volume (cf)	Recommended In-stream Volume (AF)
10/1/1999	31	1,205,280,000.00	27669
11/1/1999	30	777,600,000.00	17851
12/1/1999	31	803,520,000.00	18446
1/1/2000	31	803,520,000.00	18446
2/1/2000	29	751,680,000.00	17256
3/1/2000	31	803,520,000.00	18446
4/1/2000	30	1,192,320,000.00	27372
5/1/2000	31	12,420,000,000.00	285124
6/1/2000	30	7,603,200,000.00	174545
7/1/2000	31	3,319,920,000.00	76215
8/1/2000	31	1,205,280,000.00	27669
9/1/2000	30	1,166,400,000.00	26777

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
Oct 1 - Oct 15	450	Fall baseflow	≤56°F at confluence of the North Fork Trinity River	Provide optimal holding/spawning temperatures for spring- and fall-run chinook	Provide suitable temperature, reducing pre-spawning mortality and increasing egg viability
Oct 16 - Apr 21	300	Winter baseflow	Provide the maximum amount of spawning habitat	Provide best balance of spawning and rearing habitats for all anadromous salmonids in the existing channel	Increase spawning habitat while minimizing dewatering of redds (dewater less than 5% of redds) of salmonids
Apr 22 - Apr 28	500	Spring baseflow	≤ 55.4°F at Weitchpec	Providing optimal temperatures for enhanced survival of steelhead smolts	Improve steelhead smolt production
Apr 29 - May 5	2,500	Spring baseflow/ Ascending limb	≤ 55.4°F at Weitchpec	Providing optimal temperatures for enhanced survival of steelhead smolts	Improve steelhead smolt production
May 5 - May 7	2,500 - 6,000	Ascending limb	Reach peak flow	Ramp to peak flow (according to OCAP) safely for human use Provide optimal temperatures for survival of steelhead smolts	Reduce travel time of outmigrating steelhead smolts Improve steelhead smolt production
May 7 - May 11	6,000	Snowmelt Peak	<u>Peak threshold:</u> Mobilize D84 on most alluvial features (general channel mobility) <u>Duration:</u> Transport coarse sediment (> 8mm) through mainstem at a rate equal to tributary input downstream of Rush Creek Transport fine sediment (<8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (< 8mm) storage within surface channelbed Create and maintain alternate bar morphology Create floodplains by bar building and fine sediment deposition Encourage establishment and growth of riparian vegetation on floodplains Scour up to 1 yr old woody riparian vegetation along channel margins	Improve spawning production through improved egg-to-emergence success Discourage riparian vegetation initiation along low water channel margins Increase smolt production by increasing year-round rearing habitat quality and quantity; reducing outmigration transport time

Figure 20: Recommended releases from Lewiston Dam over the course of Normal Wet water year along with explanations (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
May 11 - Jun 10	6,000 - 2,000	Descending limb	Descend at a rate mimicking pre-TRD Descend at a rate less than 0.1 ft/day	Inundate point bars to prevent riparian initiation and encroachment along channel margins Minimize river stage change to preserve Yellow Legged Frog egg masses Maintain seasonal variation of water surface levels in sidechannels and off-channel wetlands	Reduce fine sediment (< 8mm) storage stored within surface channelbed Improve juvenile chinook growth Increase riparian vegetation and future LWD recruitment
Jun 10 - Jul 9	2,000	Descending limb bench	Provide optimal water temperatures (≤ 62.6°F) to Weitchpec for chinook salmon smolts	Improve chinook smolt production by providing optimal temperatures for their survival Inundate point bars to prevent riparian initiation along channel margins	Improve chinook smolt production Prevent riparian initiation along channel margin
Jul 9 - Jul 22	2,000 - 450	Descending limb	Decline to summer baseflow	Minimize stranding behind berms	Increase survival of steelhead fry Provide emigration cues for chinook salmon smolts
Jul 22 - Sep 30	450	Summer baseflow	≤ 60°F @ Douglas City through Sep 14 ≤ 56°F @ Douglas City from Sep 15 through Sep 30	Increase survival of holding spring-run chinook salmon adults by providing optimal thermal refugia	Increase production of coho salmon and steelhead smolts by providing water temperatures conducive to good growth

Figure 21: Recommended releases from Lewiston Dam over the course of a Normal water year along with explanations continued (USFWS, HVT, 1999).

Table 21: Calculated recommended in-stream volume for in-stream flow during a normal year to the Trinity River.

Month	Days	Recommended In-stream Volume (cf)	Recommended In-stream Volume (AF)
10/1/2001	31	997920000	22909.09091
11/1/2001	30	777600000	17851.23967
12/1/2001	31	803520000	18446.28099
1/1/2002	31	803520000	18446.28099
2/1/2002	29	751680000	17256.19835
3/1/2002	31	803520000	18446.28099
4/1/2002	30	1278720000	29355.3719
5/1/2002	31	9568800000	219669.4215
6/1/2002	30	6739200000	154710.7438
7/1/2002	31	3045600000	69917.35537
8/1/2002	31	1205280000	27669.42149
9/1/2002	30	1166400000	26776.8595

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
Oct 1 - Oct 15	450	Fall baseflow	≤56°F at confluence of the North Fork Trinity River	Provide optimal holding/spawning temperatures for spring- and fall-run chinook adults	Provide suitable temperatures reducing pre-spawning mortality and increasing egg viability
Oct 16 - Apr 26	300	Winter baseflow	Provide the maximum amount of spawning habitat	Provide best balance of spawning and rearing habitats for all anadromous salmonids in the existing channel	Increase spawning habitat while minimizing dewatering of redds (dewater less than 5% of redds) of salmonids
Apr 26 - May 1	300 - 4,500	Ascending limb	Reach peak flow	Ramp to peak flow (according to OCAP) safely for human use	Reduce travel time of outmigrating steelhead smolts
May 1 - May 5	4,500	Peak flow	Peak threshold: Mobilize D84 on bar flanks features (median bars, pool tails) Duration: Transport coarse sediment (> 8mm) through mainstem at a rate equal to tributary input downstream of Rush Creek Transport fine sediment (<8mm) through mainstem at a rate greater than tributary input (as measured at Limekiln Gulch Gaging Station)	Reduce fine sediment (<8mm) storage within surface of the channelbed	Increase salmonid fry production through improved egg-to-emergence success Discourage riparian vegetation initation along low flow channel margins

Figure 22: Recommended releases from Lewiston Dam over the course of a Dry water year along with explanations (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
May 5 - Jun 26	4,500 - 450	Descending limb	Descend at a rate mimicking the pre-TRD descent Provide non-lethal water temperatures to Weitchpec for coho smolts (≤ 62.6°F) until June 4, and chinook salmon smolts (≤ 68°F) until mid-June	Inundate point bars Minimize river stage change to preserve yellow legged frog egg masses Maintain seasonal variable water surface levels in sidechannels and off-channel wetlands Improve salmonid smolt production by providing temperatures necessary for survival of steelhead, coho, chinook smolts	Prevent riparian initiation along channel margins Reduce fine sediment (<8mm) storage stored within surface channelbed Improve juvenile chinook growth Increase survival of steelhead fry Provide emigration cues for chinook salmon smolts
Jun 26 - Sep 30	450	Summer baseflow	≤ 60°F @ Douglas City through Sep 14 ≤ 56°F @ Douglas City from Sep 15 through Sep 30	Increase survival of holding spring-run chinook salmon adults by providing optimal thermal refugia	Increase production of coho salmon and steelhead smolts by providing water temperatures conducive to good growth

Figure 23: Recommended releases from Lewiston Dam over the course of a Dry water year along with explanations continued (USFWS, HVT, 1999).

Table 22: Calculated recommended in-stream volume for in-stream flow during a dry year to the Trinity River.

Month	Days	Recommended In-stream Release (AF)
10/1/2000	31	22909
11/1/2000	30	17851
12/1/2000	31	18446
1/1/2001	31	18446
2/1/2001	29	16661
3/1/2001	31	18446
4/1/2001	30	34512
5/1/2001	31	168099
6/1/2001	30	131207
7/1/2001	31	27669
8/1/2001	31	27669
9/1/2001	30	26777

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
Oct 1 - Oct 14	450	Fall baseflow	≤56°F at confluence of the North Fork Trinity River	Provide optimal holding/spawning temperatures for spring- and fall-run chinook adults	Provide suitable temperatures, reducing pre-spawning mortality and increasing egg viability
Oct 15 - Apr 22	300	Winter baseflow	Provide the maximum amount of spawning habitat.	Provide best balance of spawning and rearing habitats for all anadromous salmonids in the existing channel	Increase spawning and rearing habitat while minimizing dewatering of redds (dewater less than 5% of redds) of salmonids
Apr 22 - Apr 24	300 - 1,500	Ascending limb	Reach peak flow	Ramp to peak flow (according to OCAP) safely for human use	Reduce travel time of outmigrating steelhead smolts
Apr 24 - May 29	1,500	Peak flow	Provide non-lethal water temperatures to Weitchpec for steelhead smolts (≤ 59°F) until May 22, and coho salmon smolts (≤ 62.6°F) until May 29 Inundate bar flanks (1,500 cfs)	Sustain steelhead and coho salmon smolt production by providing non-lethal temperatures for survival Discourage riparian vegetation establishment along channel margins	Transport limited amounts of surface fine sediment (<8mm)

Figure 24: Recommended releases from Lewiston Dam over the course of a Critically Dry water year along with explanations (USFWS, HVT, 1999).

Date	Release (cfs)	Hydrograph Component	Management Target	Purpose	Benefits
May 29 - Jun 26	1,500 - 450	Descending limb	Descend at a rate mimicking pre-TRD descent Provide non-lethal water temperatures to Weitchpec for coho salmon smolts (≤62.6°F) until June 4, and chinook salmon smolts (≤ 68°F) until mid-June	Minimize river stage change to preserve yellow legged frog egg masses Inundate point bars Provide non-lethal temperatures for survival of steelhead, coho, chinook smolts	Reduce fine sediment (<8mm) storage stored within surface channelbed Prevent riparian initiation along low water channel margins Maintain seasonal variable water surface levels in sidechannels and off-channel wetlands Sustain/improve salmonid smolt production
Jun 26 - Sep 30	450	Summer baseflow	≤ 60°F @ Douglas City through Sep 14 ≤ 56°F @ Douglas City from Sep 15 through Sep 30	Increase survival of holding spring-run chinook salmon adults by providing optimal thermal refugia	Increase production of coho salmon and steelhead smolts by providing water temperatures conducive to good growth

Figure 25: Recommended releases from Lewiston Dam over the course of a Critically Dry water year along with explanations continued (USFWS, HVT, 1999).

Trinity River Division: Full and Supplemental Service			
Crops	Acres	Total Crop Values $	
Oats	76	$	9,310
Alfalfa Hay	136	$	96,480
Other Hay	718	$	266,300
Irrigated Pasture	3,324	$	627,700
Corn, Sweet (Processing)	13	$	1,404
Corn, Sweet (Fr. Market)	9	$	28,800
Melons, Cantaloupe, Etc.	8	$	11,200
Honeydew, Honey Ball, Etc.	7	$	9,800
Watermelon	6	$	8,400
Squash	6	$	14,400
Tomatoes (Fr. Market)	8	$	35,200
Nursery	20	$	99,115
Apples	17	$	6,336
Apricots	6	$	1,800
Grapes, Table	13	$	29,570
Olives	810	$	550,800
Peaches	3	$	1,650
Pears	1	$	432
Prunes and Plums	150	$	45,000
Other Fruits	56	$	76,764
Almonds	6	$	8,450
Pecans	20	$	45,580
Walnuts	5	$	27,000
Other Nuts	67	$	205,700
Family Gardens and Orchards	311	$	155,500
Totals	5,796	$	2,362,691

Figure 26: 1990 Crop values from the use of Trinity Water (Stene, 1996).

Parameters	Unit	Value	Descriptions
N		8	Stages of SDP
P_a	mVND/ton	2.5	The price of rice
β		5	Number of fish species
A_0	ha	350	Reservoir surface area at full level of water
Rc	Km^2	21	Reservoir catchment area
λ		0.5732	Hypsographic coefficient
θ		-0.7446	Coefficient obtained from Nguyen et al (2001)
ω		0.7422	Coefficient obtained from Nguyen et al (2001)
s_{min}	MCM	0.4	Minimum reservoir capacity
s_{max}	MCM	19.6	Maximum reservoir capacity
u_{min}	%RC	0	Minimum release
u_{max}	%RC	27	Maximum release
r	%/stage	0.05	Discount rate

Figure 27: Parameters of stochastic dynamic programming model (Tran et al., 2011).

Fish species	Price (mVND/ton)	Fish yields (ton)							
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
1	16	0	0	0	3.506	3.026	2.636	2.262	0
2	6	0	0	0	8.861	7.666	6.693	5.758	0
3	8.5	0	0	0	7.043	6.239	5.573	4.887	0
4	6	0	0	0	4.477	3.93	3.479	3.027	0
5	8.5	0	0	0	4.154	3.584	3.121	2.678	0

Figure 28: Price and yield of fish at each stage (Tran et al., 2011).

Parameter	Unit	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Y_p	Ton/ha	6.5	6.5	6.5	6.5	6	6	6	6
k_y		1	1.09	1.32	0.5	1	1.09	1.32	0.5
W_0	mm	252.5	80.3	124.6	132.1	209	131.7	85.1	103.7
e_n	mm	5.34	6.85	8.30	9.30	8.3	5.59	3.99	3.59

Figure 29: Potential rice yield (Y_p) , yield response factor (k_y), rice water requirements (W_o), and evaporation (e_n) at each stage (Tran et al., 2011).

k	Rainfall q_n^k (mm)	Rainfall probability $p_n\{q_n^k\}$ Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
1	0	0.955	0.98	0.98	0.95	0.865	0.745	0.635	0.545
2	37.5	0	0	0	0	0.005	0.005	0.015	0.03
3	87.5	0.005	0	0.01	0	0.015	0.01	0.035	0
4	137.5	0	0	0.005	0.015	0.01	0.03	0.025	0.025
5	187.5	0.01	0.005	0	0	0.025	0.01	0.035	0.04
6	237.5	0.005	0	0.005	0	0.03	0.005	0.01	0.035
7	287.5	0	0	0	0.005	0.005	0.01	0.015	0.02
8	337.5	0	0	0	0.01	0	0.01	0.02	0.03
9	387.5	0.005	0	0	0.015	0.005	0.02	0.005	0.03
10	437.5	0.01	0.01	0	0	0	0.01	0.01	0.005
11	487.5	0	0.005	0	0	0.01	0.02	0.02	0.03
12	537.5	0	0	0	0.005	0	0.005	0.01	0.02
13	587.5	0.005	0	0	0	0.005	0.005	0.015	0.015
14	625.0	0.005	0	0	0	0.025	0.115	0.15	0.175

Figure 30: Rainfall and its associated probability (Tran et al., 2011).

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Average	16.13	7.63	2.56	15.31	44.88	177.56	272.75	316.00
Min	0	0	0	0	7	48	57	64
Max	47	35	10.5	46.5	105	289	515	623

Figure 31: Rainfall over the Daton reservoir from 2000-2008 (mm) (Tran et al., 2011).

Appendix B: Dynamic Program

```
PROGRAM TRINITY_WATER_ALLOCATION2
IMPLICIT NONE
DOUBLE
PRECISION::TEMPREL,STORCAP,TOL,TOL2,PRICE,COSRICE,YIELD,WDRAW,NBRTEMP,NBFTEMP,
MAXNBTOTTEMP,RRELEASETEMP,&
        DELTARELALLOC,RNEEDMIN,FISHMAXNBTEMP,RICMAXNBTEMP
INTEGER::M,N,O,P,J,K,L,E,G,W,FLOCNEW,COUNTS,ECRIT,CYCLES,Z,ZEND,NBSIG
INTEGER,DIMENSION(1)::FLOC
```

```
DOUBLE
PRECISION,DIMENSION(:),ALLOCATABLE::INFLOW,SIGNAL,RNEED,INRELREC,DAYINMONTH,MA
XTUNREL,MAXINREL,MAXTOTREL,RCROPCOEF
DOUBLE PRECISION,DIMENSION(:,:),ALLOCATABLE::FOPT,STORAGE,DIFFS
DOUBLE
PRECISION,DIMENSION(:,:,:),ALLOCATABLE::TOTRELEASE,RICRELEASE,NB,NBORIG,ROPT,ROPT
OLD,RICMAXNB,FISHMAXNB


!Read in all input
OPEN(UNIT=15,FILE="INPUT.TXT")

M=12

!Read in number of stages, states, decisions
READ(15,*) O,P,NBSIG
READ(15,*) TOL
ALLOCATE(INFLOW(M),FOPT(M,O),ROPT(M,P,O),STORAGE(M,O),TOTRELEASE(M,P,O),RICRELEAS
E(M,P,O),NB(M,P,O),ROPTOLD(M,P,O),&

DIFFS(P,O),SIGNAL(M),DAYINMONTH(M),MAXTUNREL(M),MAXINREL(M),MAXTOTREL(M),RNEE
D(M),INRELREC(M),RCROPCOEF(M),&
     NBORIG(M,P,O),RICMAXNB(M,P,O),FISHMAXNB(M,P,O))
!WRITE(*,*) M,O,P

DAYINMONTH=999999999
RNEED=999999999

READ(15,*)(DAYINMONTH(J),J=1,M)

!READ IN RICE CHARACTERISTICS
READ(15,*)PRICE,COSRICE,YIELD,CYCLES
READ(15,*)(RNEED(J),J=1,M)
!WRITE(*,*)"RNEED"
!WRITE(*,'(6F10.2)')(RNEED(J),J=1,M)

MAXTUNREL=999999999
MAXINREL=999999999
MAXTOTREL=999999999

!READ IN LEWISTON SPECIFICATIONS
READ(15,*)(MAXTUNREL(J),J=1,M)
READ(15,*)(MAXINREL(J),J=1,M)
MAXTOTREL=MAXTUNREL+MAXINREL
!WRITE(*,*)"MAXTOTREL"
!WRITE(*,'(6F10.2)')(MAXTOTREL(J),J=1,M)

INRELREC=999999999
INFLOW=999999999
STORAGE=999999999

!Read in instream recommendations
READ(15,*)(INRELREC(J),J=1,M)

!Read in storage
READ(15,*)(STORAGE(1,K),K=1,P)
DO J=2,M
 STORAGE(J,:)=STORAGE(1,:)
```

```
END DO
!WRITE(*,*)"STORAGE"
!WRITE(*,'(10F10.2)') (STORAGE(1,K),K=1,P)


READ(15,*) (INFLOW(J),J=1,M)
!WRITE(*,*) "INFLOW"
!WRITE(*,'(6F10.2)')(INFLOW(J),J=1,M)

CLOSE(15)

IF(CYCLES==0) THEN
  RCROPCOEF=(/
DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DBLE(0),DB
LE(0) /)
ELSE IF (CYCLES==1) THEN
  RCROPCOEF=(/
DBLE(0),DBLE(1.15),DBLE(1.15),DBLE(1.35),DBLE(1.35),DBLE(1.05),DBLE(0),DBLE(0),DBLE(0),DBLE(
0),DBLE(0),DBLE(0) /)
ELSE IF (CYCLES==2)THEN
  RCROPCOEF=(/
DBLE(0),DBLE(1.15),DBLE(1.15),DBLE(1.35),DBLE(1.35),DBLE(1.05),DBLE(0),DBLE(1.15),DBLE(1.15),
DBLE(1.35),&
              DBLE(1.35),DBLE(1.05) /)
ELSE
  WRITE(*,*)'RCROPCOEF ERROR'
  STOP
END IF

!WRITE(*,'(6F10.2)') (RCROPCOEF(J),J=1,M)

TOTRELEASE=999999999

!Calculates releases from storage and inflow

DO J=1,M
  E=J+1
  DO K=1,P
    DO L=1,O
      IF(E>M) THEN
        E=1
      END IF
      TEMPREL=STORAGE(J,L)-STORAGE(E,K)+INFLOW(J)
!      WRITE(*,*)TEMPREL
      IF(TEMPREL<=MAXTOTREL(J)) THEN
        TOTRELEASE(J,K,L)=TEMPREL
      ELSE
        TOTRELEASE(J,K,L)=999999999
      END IF
    END DO
  END DO
END DO

!WRITE(*,*)"TOTRELEASE"
!WRITE(*,'(10F10.2)')((TOTRELEASE(2,K,L),K=1,P),L=1,O)

RNEEDMIN=999999999
```

```
DO J=1,M
  IF(RNEED(J)>DBLE(0) .AND. RNEED(J)<RNEEDMIN) THEN
    RNEEDMIN=RNEED(J)
  END IF

END DO

RICRELEASE=DBLE(0)
NB=DBLE(0)

DO J=1,M
  DO K=1,P
    DO L=1,O
      IF(TOTRELEASE(J,K,L)<=MAXTOTREL(J)) THEN
        IF(RCROPCOEF(J)==DBLE(0)) THEN
          IF(TOTRELEASE(J,K,L)<=MAXINREL(J)) THEN
           NB(J,K,L)=0.0094*(TOTRELEASE(J,K,L)**2)+0.671*TOTRELEASE(J,K,L)+1.0167
           RICRELEASE(J,K,L)=DBLE(0)
           RICMAXNB(J,K,L)=DBLE(0)
           FISHMAXNB(J,K,L)=NB(J,K,L)
!            WRITE(*,*) "ONLY FISH"
!            WRITE(*,*) J
          ELSE
            NB(J,K,L)=999999999
          END IF
        ELSE IF(NBSIG==1 .AND. RCROPCOEF(J)>DBLE(0))THEN
          ZEND=INT(TOTRELEASE(J,K,L)/RNEEDMIN)
          DELTARELALLOC=INT(RNEEDMIN)
!           IF(J==2)THEN
!             WRITE(*,*) "DELTARELALLOC"
!             WRITE(*,*) DELTARELALLOC
!             WRITE(*,*) "ZEND"
!             WRITE(*,*) ZEND
!           END IF
          MAXNBTOTTEMP=DBLE(0)
          RRELEASETEMP=999999999
          WDRAW=0.D0
          DO Z=1,(ZEND+1)
            IF(Z==(ZEND+1)) THEN
              IF(WDRAW<=MAXTUNREL(J) .AND. WDRAW<=RNEED(J)) THEN
                NBRTEMP=PRICE*(DBLE(5796)*(YIELD*(1-RCROPCOEF(J)*(1-WDRAW/RNEED(J)))))-
COSRICE
                NBFTEMP=0.D0
               IF((NBRTEMP+NBFTEMP)>MAXNBTOTTEMP)THEN
                MAXNBTOTTEMP=NBFTEMP+NBRTEMP
                RRELEASETEMP=WDRAW
               END IF
              END IF
!             IF(J==2) WRITE(*,*) "ENTERED"
            ELSE IF(Z>1 .AND. Z<(ZEND+1)) THEN
              IF((TOTRELEASE(J,K,L)-WDRAW)<=MAXINREL(J) .AND. WDRAW<=MAXTUNREL(J) .AND.
WDRAW<=RNEED(J)) THEN
               NBFTEMP=0.0094*((TOTRELEASE(J,K,L)-WDRAW)**2)+0.671*(TOTRELEASE(J,K,L)-
WDRAW)+1.0167
               NBRTEMP=PRICE*(DBLE(5796)*(YIELD*(1-RCROPCOEF(J)*(1-(WDRAW/RNEED(J))))))-
COSRICE
!                WRITE(*,*)"ENTERED"
!                IF(J==2)THEN
```

```
!               WRITE(*,*)"NBFTEMP"
!               WRITE(*,*) NBFTEMP
!               WRITE(*,*) "NBRTEMP"
!               WRITE(*,*) NBRTEMP
!             END IF
            IF((NBRTEMP+NBFTEMP)>MAXNBTOTTEMP)THEN
!               WRITE(*,*)"ENTERED"
              MAXNBTOTTEMP=NBFTEMP+NBRTEMP
              RRELEASETEMP=WDRAW
              RICMAXNBTEMP=NBRTEMP
              FISHMAXNBTEMP=NBFTEMP
!               IF(J==2)THEN
!                 WRITE(*,*) "WDRAW"
!                 WRITE(*,*) WDRAW
!               END IF
            END IF
          END IF
        END IF
        WDRAW=DELTARELALLOC+WDRAW
!         IF(J==2 .AND. K==1 .AND. L==1)THEN
!           WRITE(*,*)"WDRAW"
!           WRITE(*,*) WDRAW
!            WRITE(*,*) "RRELEASETEMP"
!            WRITE(*,*)RRELEASETEMP
!         END IF
      END DO
      IF(MAXNBTOTTEMP==DBLE(0)) THEN
        NB(J,K,L)=999999999
        RICRELEASE(J,K,L)=999999999
      ELSE
        NB(J,K,L)=MAXNBTOTTEMP
        FISHMAXNB(J,K,L)=FISHMAXNBTEMP
        RICMAXNB(J,K,L)=RICMAXNBTEMP
        RICRELEASE(J,K,L)=RRELEASETEMP
      END IF
    ELSE IF(RCROPCOEF(J)>DBLE(0) .AND. NBSIG==2) THEN
      IF(TOTRELEASE(J,K,L)<=MAXINREL(J)) THEN
        NBFTEMP=0.0094*(TOTRELEASE(J,K,L)**2)+0.671*TOTRELEASE(J,K,L)+1.0167
        NB(J,K,L)=NBFTEMP
        FISHMAXNB(J,K,L)=NBFTEMP
        RICMAXNB(J,K,L)=DBLE(0)
        RICRELEASE(J,K,L)=DBLE(0)
      ELSE
        NB(J,K,L)=999999999
        RICRELEASE(J,K,L)=999999999
      END IF
    ELSE IF(RCROPCOEF(J)>DBLE(0) .AND. NBSIG==3)THEN
      IF(RNEED(J)<=MAXTUNREL(J) .AND. (TOTRELEASE(J,K,L)-RNEED(J))<=MAXINREL(J)) THEN
        NBFTEMP=0.0094*((TOTRELEASE(J,K,L)-RNEED(J))**2)+0.671*(TOTRELEASE(J,K,L)-
RNEED(J))+1.0167
        NBRTEMP=PRICE*(DBLE(5796)*(YIELD*(1-RCROPCOEF(J)*(1-(RNEED(J)/RNEED(J))))))-
COSRICE
        NB(J,K,L)=NBFTEMP+NBRTEMP
        RICRELEASE(J,K,L)=RNEED(J)
        FISHMAXNB(J,K,L)=NBFTEMP
        RICMAXNB(J,K,L)=NBRTEMP
!         IF(J==2 .AND. K==1 .AND. L==1) THEN
!           WRITE(*,*)"NBFTEMP"
```

```
!           WRITE(*,*) NBFTEMP
!           WRITE(*,*) "NBRTEMP"
!           WRITE(*,*) NBRTEMP
!           WRITE(*,*) "TOTRELEASE"
!           WRITE(*,*) TOTRELEASE(J,K,L)
!           WRITE(*,*) "RNEED"
!           WRITE(*,*) RNEED(J)
!          END IF
        ELSE
          NB(J,K,L)=999999999
          RICRELEASE(J,K,L)=999999999
        END IF
      END IF
     ELSE
!       WRITE(*,*)"ENTERED"
      NB(J,K,L)=999999999
      RICRELEASE(J,K,L)=999999999
     END IF
   END DO
  END DO
END DO

NBORIG=NB

!WRITE(*,*) "TOTRELEASE, RNEED"
!WRITE(*,'(2F12.2)') TOTRELEASE(1,1,1),RNEED(2)
!WRITE(*,*) "NB"
!WRITE(*,'(1F12.2)') NB(2,1,1)
!WRITE(*,'(10F12.2)')((NB(1,K,L),L=1,P),K=1,O)
!WRITE(*,*)"RICRELEASE"
!WRITE(*,'(10F12.2)')((RICRELEASE(1,K,L),L=1,P),K=1,O)



FOPT=999999999
FLOC=999999999
ROPT=999999999
!NBOPT=999999999
!OPTFINSTORAGE=999999999
!RICOPT=999999999
ROPTOLD=999999999
DIFFS=999999999
SIGNAL=0
TOL2=0.001

!COUNTS=0
!Calculates the optimal release


!WRITE(*,*) M,O,P

N=1
W=1
ECRIT=1

DO
  DO J=M,1,-1
```

```
    E=J+1
    IF(E>M)THEN
     E=1
    END IF
    DO L=1,O
     IF(N>1)THEN
      DO K=1,P
       IF(NB(J,K,L)<999999999)THEN
        NB(J,K,L)=NB(J,K,L)+FOPT(E,K)
       END IF
      END DO
     END IF
     FOPT(J,L)=MAXVAL(NB(J,1:P,L))
     FLOC=MAXLOC(NB(J,1:P,L))

!     RICOPT(J,:,L)=999999999
!     NBOPT(J,:,L)=999999999
!     OPTFINSTORAGE(J,:,L)=999999999
     ROPT(J,:,L)=999999999
!     WRITE(*,*) ROPT(J,:,L)
!     NBOPT(J,FLOC(1),L)=NBORIG(J,FLOC(1),L)
!     OPTFINSTORAGE(J,FLOC(1),L)=STORAGE(E,FLOC(1))
     ROPT(J,FLOC(1),L)=TOTRELEASE(J,FLOC(1),L)
!     RICOPT(J,FLOC(1),L)=RICRELEASE(J,FLOC(1),L)
     FLOCNEW=FLOC(1)+1
!     WRITE(*,*) FLOC(1)
!     WRITE(*,*) FLOCNEW
!     WRITE(*,*) FOPT(J,L)
!     WRITE(*,*) P
!     WRITE(*,'(F6.2)') ROPT(J,FLOC(1),L)
     IF(FLOCNEW<=P)THEN
!       WRITE(*,*) "ENTERED"
      DO G=FLOCNEW,P
       IF(FOPT(J,L)==NB(J,G,L))THEN
        ROPT(J,G,L)=TOTRELEASE(J,G,L)
!         NBOPT(J,G,L)=NB(J,G,L)
!         OPTFINSTORAGE(J,G,L)=STORAGE(E,G)
!         RICOPT(J,G,L)=RICRELEASE(J,G,L)
       END IF
      END DO
     END IF
    END DO
    COUNTS=COUNTS+1
!    WRITE(*,'(A,I5)') "MONTH",J
!    WRITE(*,'(4F10.2)')((ROPT(J,K,L),K=1,P),L=1,O)
    N=2
    IF(W==1) THEN
     ROPTOLD(J,:,:)=ROPT(J,:,:)
    ELSE
     DIFFS=ABS(ROPT(J,:,:)-ROPTOLD(J,:,:))
     IF(SUM(DIFFS)<TOL)THEN
      SIGNAL(J)=1
      IF(ABS(M-SUM(SIGNAL))<TOL2)THEN
!        WRITE(*,*) "SIGNAL"
!        WRITE(*,*) SIGNAL
!        WRITE(*,*)"COUNT TO CONVERGE"
!        WRITE(*,*) COUNTS
       ECRIT=2
```

```
        EXIT
      END IF
    ELSE
      SIGNAL(J)=0
      ROPTOLD(J,:,:)=ROPT(J,:,:)
    END IF
  END IF
 END DO

W=2

IF(ECRIT==2) EXIT

END DO

WRITE(*,*) "FINAL OPTIMAL ALLOCATION"
WRITE(*,*) "END USE ALLOCATION OPTION", NBSIG
WRITE(*,*) "CROP CYCLES", CYCLES
WRITE(*,*) "NET BENEFIT ($),  RICE NET BENEFIT ($), FISH NET BENEFIT ($) TOTAL RELEASE
(AF),  RICE RELEASE, FISH RELEASE (AF), &
        & INITIAL STORAGE (AF), FINAL STORAGE (AF)"
DO J=1,M
 E=J+1
 IF (E>M)THEN
  E=1
 END IF
 DO L=1,O
  WRITE(*,'(A6,I3,A6,I6)') "MONTH",J,"STATE",L
  DO K=1,P
   IF(ROPT(J,K,L)<999999999) THEN
    WRITE(*,'(F12.2,A2,F12.2,A2,F12.2,A2,F12.2,A2,F12.2,A2,F12.2,A2,F12.2,A2,F12.2)')
NBORIG(J,K,L),",",RICMAXNB(J,K,L),",", &
                                          FISHMAXNB(J,K,L),",",ROPT(J,K,L), &
                                          ",",RICRELEASE(J,K,L),",", &
                                          (ROPT(J,K,L)-RICRELEASE(J,K,L)),",",&
                                          STORAGE(J,L),",",STORAGE(E,K)
   END IF
  END DO
 END DO
END DO


END PROGRAM TRINITY_WATER_ALLOCATION2
```