Evaluating the effectiveness of rehabilitation actions in creating fish habitat in the Trinity River

by

Darcy Christine Pickard

B.Sc., Simon Fraser University, 2002.

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department
of
Statistics and Actuarial Science

SIMON FRASER UNIVERSITY
Spring 2006

APPROVAL

Name: Darcy Christine Pickard

Degree: Master of Science

Title of project: Evaluating the effectiveness of rehabilitation actions in creating fish habitat in the Trinity River

Examining Committee: Dr. Richard Lockhart
Chair

_____

Dr. Carl Schwarz
Senior Supervisor
Simon Fraser University

_____

Dr. Boxin Tang
Simon Fraser University

_____

Dr. Derek Bingham
External Examiner
Simon Fraser University

Date Approved: _____

Abstract

Evaluating the effectiveness of different river habitat rehabilitation actions on salmonid populations is very difficult due to lack of replication, independence and effects occurring outside the river habitat. We evaluate several experimental designs to determine which designs are most likely to detect a difference in habitat creation (rather than population abundance) resulting from different mechanical rehabilitation actions. Fry-rearing habitat is believed to be the limiting type of habitat for Chinook *(Oncorhynchus tshawytscha)* in the Trinity River. This habitat is lost as growth of riparian vegetation forms permanent berms along the river edge. Cost is used as a simple measure of the complexity of a single mechanical action. We model the formation of berms using transition state matrices. The model allows for different probabilities given different rehabilitation actions, flow volumes and dependence on upstream conditions. The performance of alternative designs under different model conditions is compared and presented.

Keywords: salmonid, habitat, restoration, simulation, Pacific Northwest

To Cleo and Chinta

Acknowledgements

I would like to thank everyone in the Department of Statistics and Actuarial Science. All of the faculty and support staff have been excellent, both during courses and with advice outside of coursework.

In particular I'd like to thank: my Senior Supervisor, Carl Schwarz who provided me with very practical advice along the way, Randy Sitter who convinced me to go to graduate school in the first place, and Tim Swartz and the rest of the basketball team (even though we didn't win the t-shirt).

I'd like to thank Dave Marmorek, Marc Porter, and Ian Parnell from ESSA Technologies Ltd. Dave gave me the opportunity to work on a current problem in a field that interests me very much. Dave, Marc and Ian all provided me with excellent advice and support along the way.

Finally, I'd like to thank my family and friends.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Water is a critical resource to the human population as well as to all other life on Earth. We use it for farming, power, industry and of course to drink. In North America, many of the large rivers have been dammed in order to provide electrical power and water to the growing population. In the Trinity River of Northern California (Figure 1.1) water has been reallocated from rivers for farming, industry and drinking water. Logging of sensitive areas has resulted in erosion and increased silt in the river. The damming of the Trinity River has prevented natural flooding (Figure 1.2) that used to scour and shift the river banks. This reduction in flooding has enabled riparian vegetation to stabilize and establish permanent berms, creating narrow channels with steep banks. These changes have reduced the Trinity River salmon populations to approximately 20 percent of the pre-Lewiston Dam abundance (Trinity River Flow Evaluation-Final Report 1999).

In recent years a great deal of money has been spent trying to determine how to restore these populations. The U.S. Fish and Wildlife Service, the Hoopa Valley Tribe and other agencies completed a study in October 2000 that led to a United States Secretary of Interior Record of Decision (ROD) in December 2000 resulting in the Trinity River Restoration Program (TRRP). The TRRP is intended to restore the Trinity River fish and wildlife populations.

A major part of the TRRP is restoring salmon populations, in particular chinook salmon *(O. tshawytscha)*. The TRRP's strategy is to rehabilitate the river below

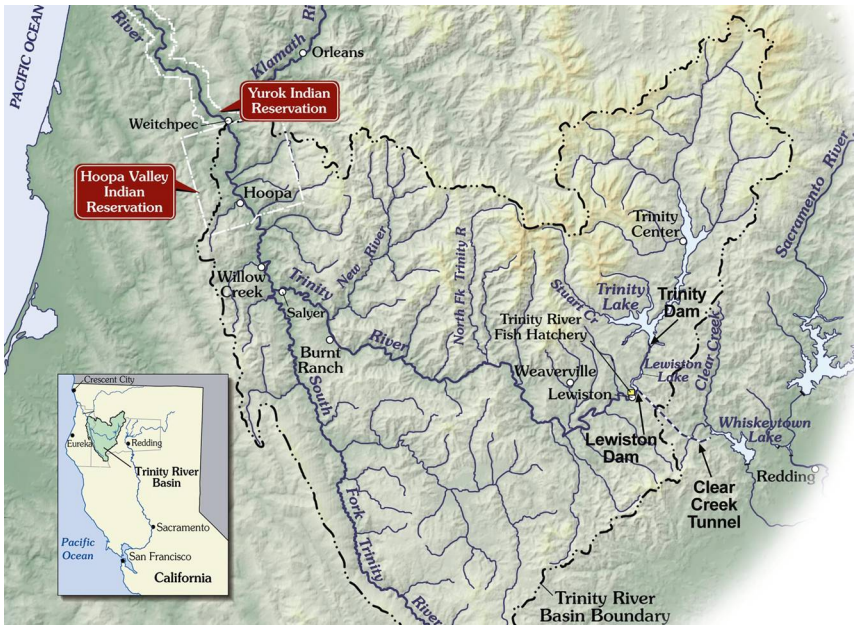


Figure 1.1: Overview of the Trinity River. Note. From TRRP Summary of the United States Secretary of the Interior Record of Decision. (p. 1), by McBain and Trush Inc. Reprinted with permission.

the Lewiston Dam so that it returns to natural pre-dam alluvial conditions. Trush et al. (2000) describe the attributes of an alluvial river and suggest that it may be possible to recreate the natural processes on a smaller scale below the Lewiston dam in the Trinity River. The concept of river rehabilitation guided by alluvial attributes is an experiment (Trush et al. 2000). The expectation is that as natural alluvial attributes are restored, habitat will be created not only at the rehabilitation site but also downstream of the site; in effect an "unzipping" of new self-maintaining habitat.

There is debate over what type/intensity of rehabilitation action is most effective. There are a number of different types and intensities of rehabilitation actions possible, with a wide range of costs. Because results from habitat rehabilitation actions may take years to be evident, we need to consider how to implement the actions in such a way that we can learn which actions are most successful while minimizing the cost of the experiment.

In this project we will use a simple simulation model to evaluate several alternative designs on their ability to detect differences in the effectiveness of rehabilitation

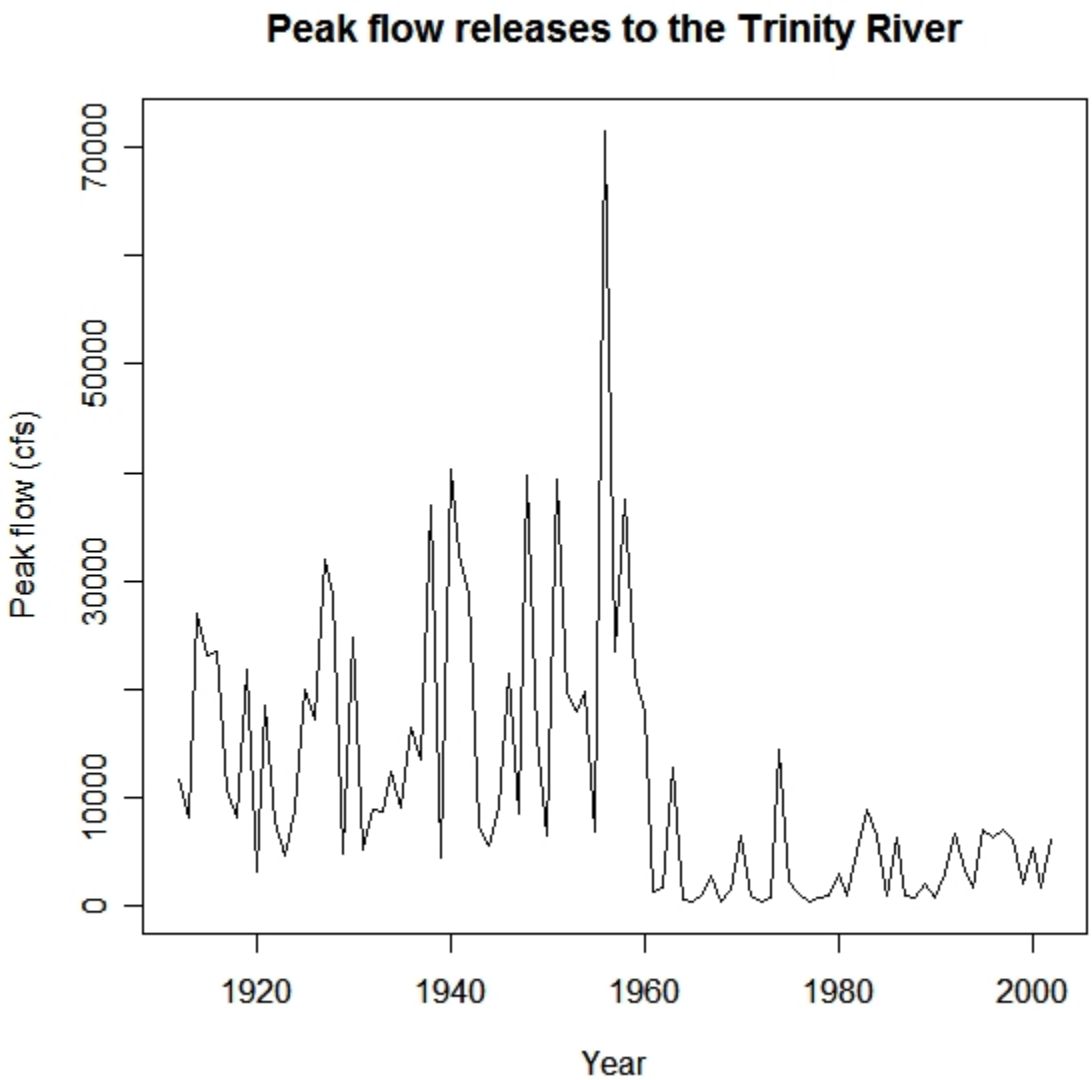


Figure 1.2: This figure illustrates the impact of the Trinity River dam and the Lewiston dam on the annual peak flows allocated to the Trinity River. The two dams were completed in 1964.

actions.

1.1 The Trinity River Restoration Program

The foundational documents of the Trinity River Restoration Program (TRRP 2005) describe its purpose as follows:

1. To restore and perpetually maintain the Trinity River's fishery resources by restoring the attributes that produce a healthy, functioning alluvial river system.
2. To restore and maintain the natural production of anadromous fish on the Trinity River's main stem downstream of Lewiston Dam.
3. To restore the basin's fish and wildlife populations to the levels that existed prior to construction of the Trinity River Dam while restoring fish and wildlife habitat.

The proposal strategy involves three types of management actions: 1) rehabilitation of the river channel and floodplains through mechanical restructuring aimed at initiating fluvial processes by lowering the threshold for bank scour; 2) implementation of high flows to re initiate fluvial processes that create fish habitat, scour encroaching riparian vegetation on constructed and scoured floodplains, and maintain appropriate temperatures for salmonids (any member of the trout and salmon family); and 3) addition of fine and coarse sediment management in both the main stem and major tributaries of the Trinity River.

An Integrated Monitoring and Evaluation Plan (IMEP) is being developed to evaluate progress toward program goals and specific objectives, and provide feedback to subsequent actions (TRRP 2005). A simplified summary of the TRRP's overall conceptual model, a general monitoring strategy and an adaptive management protocol are outlined in Figure 1.3.

This project specifically addresses the first goal of the TRRP, to restore and perpetually maintain the Trinity River's fishery resources by restoring the attributes that produce a healthy alluvial river system.

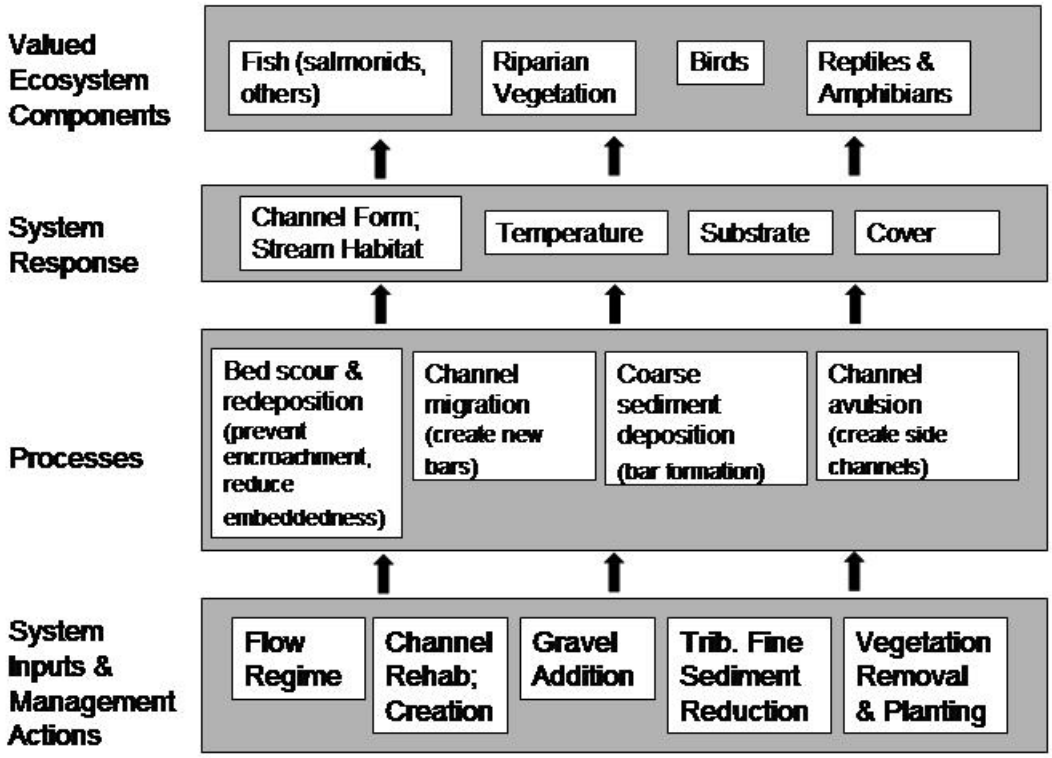


Figure 1.3: Conceptual model of overall system. Note. From the Integrated Monitoring and Evaluation Plan (IMEP), by ESSA Technologies Ltd. and North State Resources. Reprinted with permission.

1.2 Experimental Design and River Restoration Projects

A well thought out experimental design can greatly reduce the cost of an experiment while optimizing the potential for understanding the effects of the treatments (Box, Hunter and Hunter 1978). There are some interesting complications involved in designing an experiment for the Trinity River Restoration Project. The rehabilitation actions need to be categorized in some sensible way to allow comparison. It is reasonable to think that the location of the action in the river may affect the response due to a rehabilitation action. For example, different types of river channels respond differently to peak flows and sediment increases (Montgomery and MacDonald 2002). Hence, the channel characteristics at the site of the rehabilitation actions should be included in the design so that effects caused by location are not confounded with effects caused by rehabilitation action. The river is continuous and so it may not be appropriate to consider the different rehabilitation sites to be independent of one another. Practical obstacles regarding the timing of each rehabilitation action (there is a limit to how many sites can be completed at the same time) may lead to some concerns about time-treatment interactions. If time-treatment interactions are thought to be likely, a staircase design as described by Walters and Collie (1998) may be a suitable option. The managers have no control over how much water enters the Trinity River system each year either through snow melt or rainfall. They are able to control how much water is released from the Lewiston Dam, but there are a number of competing interests fighting for the water. Water that is not allocated to the river is available for export to the Central Valley for water supply and power generation (Trinity River Flow Evaluation Final Report 1999). The more rainfall/snow melt in a given year the more water that can be allocated to the river. The water allocation to the river is an important factor in maintaining the rehabilitation effects. Another issue that will have to be addressed is the response measure. What should the response measure be and how should it be assessed?

The rehabilitation of rivers is a relatively new practice in North America; prior to human intervention, the rivers did not need rehabilitation. While many organizations have been working to restore fish and wildlife habitat, very few have adequately

monitored the success of these projects. Bayley (2002) completed a literature survey of 2,350 papers and only found a few studies that rigorously explore the relationship between habitat restoration actions and salmonid survival. Managers are now demanding to see proof that the money that is being spent on rehabilitation actions is producing results (Wissmar and Bisson 2003).

I was only able to find a few studies that tried to statistically distinguish between the effects of different types of river rehabilitation actions. Larsen et al. (2004) look at the ability to detect a trend in several habitat indicators, given the variability around the indicators. This is interesting and may be useful in developing our simulation model, but does not link the rehabilitation actions to the habitat response. Parnell (2002) used a Before-After-Control-Impact (BACI) design to try to distinguish between two categories of habitat restoration actions: aggressive and passive. This study considered multiple streams in the Columbia River basin, and so did not have the same problem that we have of looking for differences within the same stream. Another study related the number of rehabilitation actions at a given site to parr-to-smolt survival (Paulsen and Fisher 2005). This seems like a sensible approach, but it still does not allow us to distinguish between the wide range of different rehabilitation actions possible.

1.3 Simulation

A simple model of the rehabilitation actions and hypothesized responses will be developed. This model will then be used to evaluate different ways of applying treatments to segments of the river. The model will describe the expected relationship between the rehabilitation action, covariates (flow levels, channel morphology, etc.) and the performance measure of interest. We will then input each of the designs describing the type/location/timing of rehabilitation actions to the model and determine how the performance measure of interest responds over time. We will implement the different experimental designs under many simulated random time series of water years (Section 2.2.2). Then we can complete the analysis of the simulated outcomes for each of the designs and determine which, if any, of the designs were able to detect the

differences in the mean amount of restored habitat among the treatments and after how many years. Since the model can easily be updated as new information about the relationship between the covariates and the rehabilitation actions is acquired, this method will be a useful adaptive management tool.

1.4 Project Outline

In Chapter 2 we develop a model to simulate the loss/creation of habitat under different scenarios. Then in Chapter 3 we consider several different experiments or ways of applying rehabilitation actions to the river. The results of the simulation study comparing the power of different experimental designs and the mean treatment responses are presented in Chapter 4. Finally, Chapter 5 provides an overview of the project and a discussion of possible model improvements and future work.

Chapter 2

Simulation Model

2.1 Introduction

"All models are wrong, some are useful"
-George Box (1979)

We can learn a lot from an initial imperfect model that we then update as information about the parameters is acquired. We can not learn anything if we can not agree on a model to start with.

The model should be as simple as possible in order to keep the interpretation straightforward. The model is not intended to be used as a detailed model of the river hydrology; instead it should simply provide a reasonable approximation of the behaviour of the performance measure given different covariate values. We assemble the model as follows:

1. Provide a physical description of the Trinity River and the rehabilitation actions.
2. Provide an abstraction of the system and simulation description.
3. Describe the response measure.

2.2 Physical description of the Trinity River and the rehabilitation actions

2.2.1 The Trinity River

The TRRP focuses on the 40-mile section of the Trinity River immediately below the Lewiston Dam. The TRRP scientists have grouped this 40-mile section of river into six distinct geographic regions (Figure 2.1). These regions differ in terms of gradient, valley confinement and tributary influence.

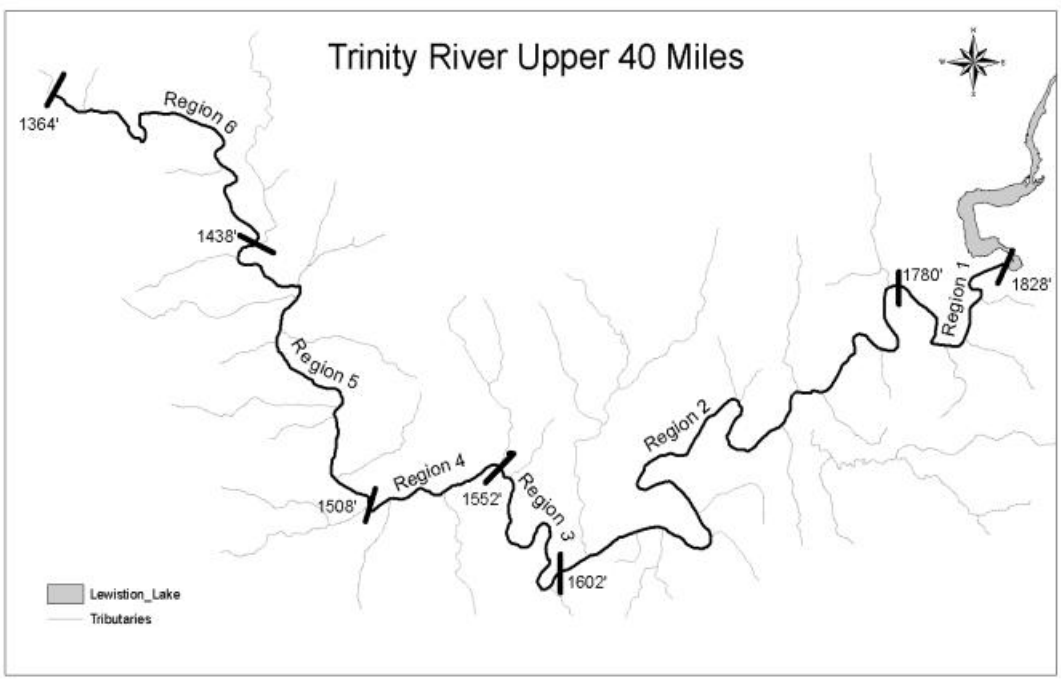


Figure 2.1: Geographic regions: The regions differ in gradient, valley confinement and tributary influence. Note. Map by Marc Porter, printed with permission.

2.2.2 Water Flows

The Lewiston Dam controls the flow levels in the Trinity River where the TRRP is interested in restoring salmon habitat. As we saw in Figure 1.2 the Lewiston Dam dramatically reduced the peak flows from an average of about 18,000 cfs to about 3,000 cfs, with some years falling below 300 cfs. Since the Record of Decision in 2000, the TRRP has developed a plan for managing the flow releases in an attempt to meet the competing needs of salmon, agriculture and the public. Based on the volume of water entering the system through snow melt and rainfall, the year is categorized as one of five water year types. For each water year type, they release water from the dam according to the flow schedule shown in Figure 2.2. This flow schedule, ensures that a peak flow of at least 1,500 cfs occurs in each year (Table 2.1). In a critically dry year most of the water is allocated to the Trinity River and very little water is allocated to the Central Valley Diversion for power and water supply.

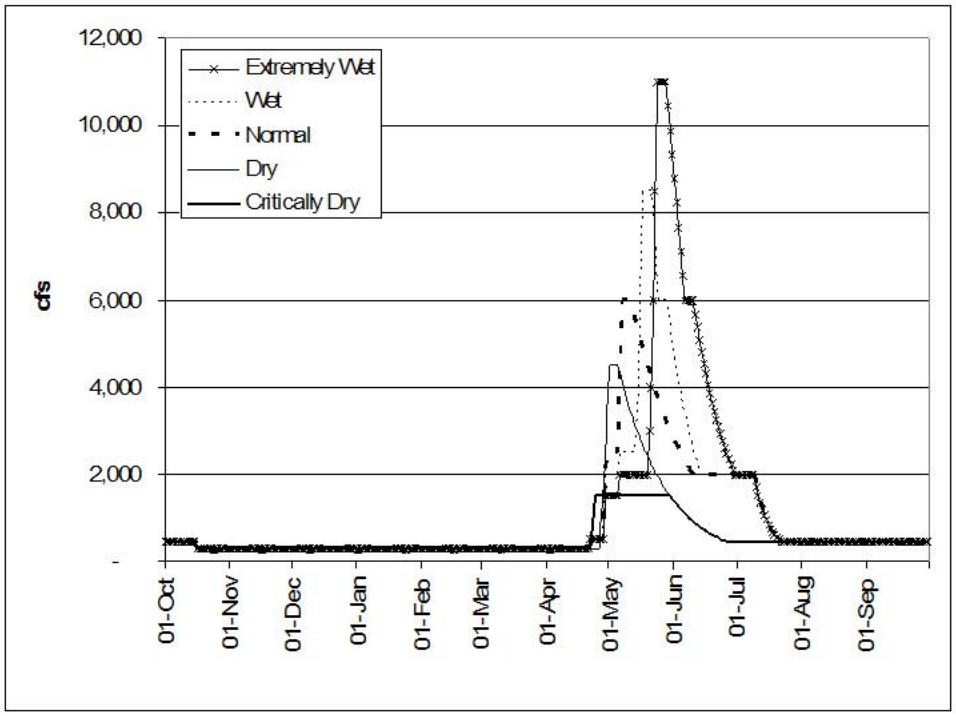


Figure 2.2: Flow Hydrograph for Five Water-Year Types. Note. Data provided by Andreas Krause, Physical Scientist-Trinity River Restoration Program.

Table 2.1: This table defines the water year type by the volume of water entering the river system and shows the corresponding TRRP proposed peak-flow release. (*AF: Acre-feet, defined as the volume of water one foot deep in one acre.)

Water Year Type	Frequency of occurrence	Incoming Volume (AF)*	Peak Release (cfs)
Critically dry	12 %	454,000	1,500
Dry	28 %	811,000	4,500
Normal	20 %	1,106,000	6,000
Wet	28 %	1,601,000	8,500
Extremely Wet	12 %	2,341,000	11,000

2.2.3 Salmon Habitat

What defines suitable salmon habitat depends on the life-stage and the species of the fish (Hemphill 2005). It is important to identify the factors that limit populations in order to most effectively focus rehabilitation efforts (Hartman et al. 1996). Fry-rearing habitat is thought to be the limiting factor for fall chinook, coho and steelhead (Trinity River Flow Evaluation 1999). Therefore, for the purpose of this project we will specifically consider fry-rearing habitat. This paper will focus on chinook salmon *(O. tshawytscha)*.

Fry emerge in the early winter months and spend the winter rearing in the river before emigrating out of the river as smolts in the spring. The fry hide among clean gravel in the shallows where the velocity is slower. Channels with long gradually sloping banks and mobile gravel bars provide suitable habitat at a range of water levels. Channels with steep permanent banks or berms provide very little fry-rearing habitat, most of which is only available when the water levels are very low (Figure 2.3, Trinity River Flow Evaluation 1999). The formation of berms occurs when the riparian vegetation encroaches on the previously mobile floodways. This happens when the young plants are not scoured away regularly. In a healthy alluvial system periodic large floods prevent riparian vegetation from dominating the river corridor and regular bankfull or greater floods ensure the channel beds are frequently mobilized (Trush and McBain 2000).

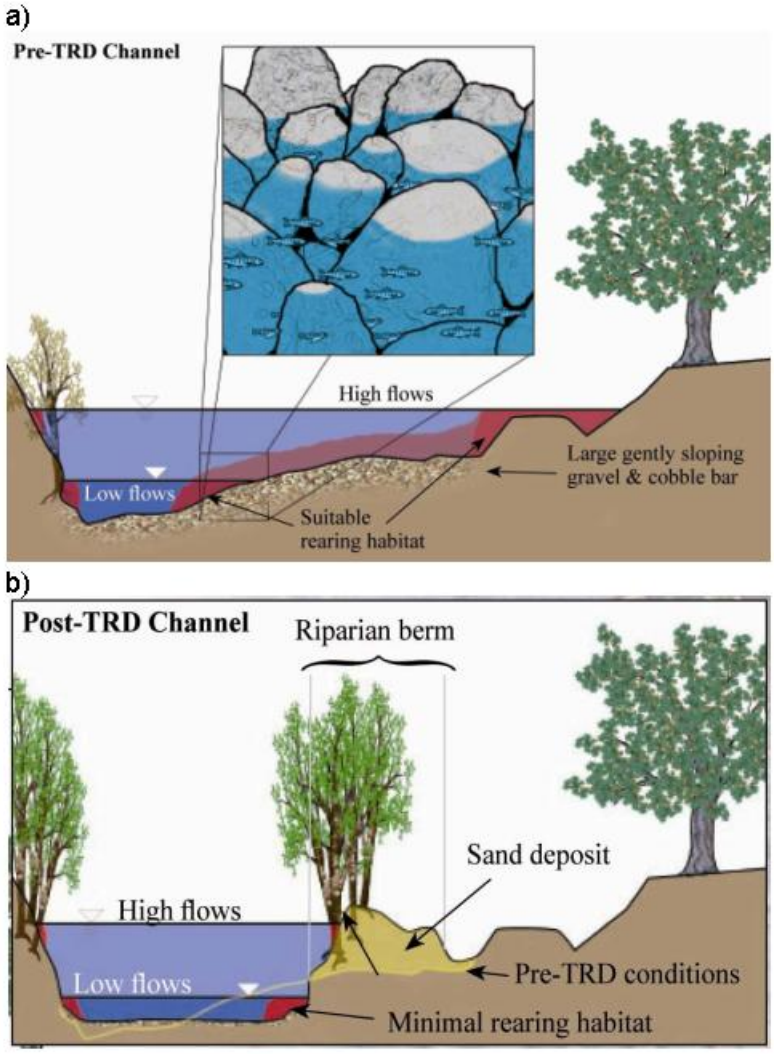


Figure 2.3: Figure a) illustrates what a healthy alluvial river should look like. We can see that there would be fry-rearing habitat available for a range of water levels. Figure b) illustrates how the shape of the channel has changed since the Trinity River was dammed. Immobile riparian berms have formed, creating steep banks with very little fry-rearing habitat. Note. From TRRP Summary of the United States Secretary of the Interior Record of Decision. (p. 4), by McBain and Trush Inc. Reprinted with permission.

2.2.4 Rehabilitation Actions

The Trinity River Restoration Program (TRRP) consists of three categories of rehabilitation action (Hemphill 2005): bank rehabilitation, sediment control, and flow actions. The focus for this project will be to compare different bank rehabilitation actions. The sediment control actions will be considered but will be simplified to two levels: with gravel or without gravel.[1] The flow actions will be assumed to follow the flow schedule described in Section 2.2.2. There are a number of possible bank rehabilitation actions ranging in sophistication from extensively engineered channel shaping projects to punching a hole in a berm with a bulldozer. Eight distinct bank rehabilitation actions have been defined. These different rehabilitation actions are listed in Table 2.2. The TRRP plans to incorporate some combination of these eight

Table 2.2: Example of the range of rehabilitation actions for TRRP bank rehabilitation projects in the Trinity River. Data source: IMEP draft 2006.

Rehabilitation Sophistication Categories	Rehabilitation Actions
Low cost	Berm-punching Berm removal
Moderate cost	High flow scour channels creation Low flow side channel creation Re-meander/point bar seeding (large cobbles)
High cost	Alcove/backwater creation Feather edging Floodplain recontouring

different actions at each site, based on a site-specific engineering evaluation. As a result, the response due to each of the specific types of actions may be confounded with each other. The type and scale of rehabilitation actions for each site will be completely unique. This means that no replication of individual actions will occur and therefore no inference is possible for the eight individual action types.

Given these constraints, what can we learn from the implemented rehabilitation actions? We wanted to find a simple way to classify the actions along a single gradient.

[1] Currently gravel is being added as needed (John Bair, pers. comm.), and so for the purpose of this paper we assume gravel is present throughout the river.

We decided to use cost to categorize the eight different bank rehabilitation actions. Cost should be reflective of the sophistication of the different rehabilitation actions, while still allowing the on-site scientists to choose an appropriate group of actions at a specific site. We will not learn about the detailed effect of specific types of actions, but we can learn if complex, expensive solutions are worth the effort. The different actions can be split into three basic cost/sophistication categories (Table 2.2): low, moderate and high. One concern with using cost as a surrogate for treatment actions is that the different rehabilitation sites will vary in length and therefore using absolute cost may not be sensible. Cost per unit length is a more suitable metric. For the purpose of this study the treatment is a bank rehabilitation action, with three treatment levels: low cost, moderate cost, and high cost.

2.3 Abstraction of the system

The model is a spatially explicit model of the Trinity River. The section of interest to the TRRP is the 39.6 miles below the Lewiston Dam. We divide this 39.6 miles into 396 small segments (0.1 miles long) whose behaviour we track over time (Figure 2.4). It is unreasonable to consider these arbitrarily chosen river segments independently as there are no physical barriers between them. However, experts believe that it would be reasonable to consider river segments that are separated by 2 to 3 meander lengths as independent of one another (Andreas Krause pers. comm.). Post-dam meander lengths are roughly 1,200 to 1,600 feet in length, so river segments that are greater than $(2.5 \times 1400) = 3500$ feet can be considered independent. Consequently, the rehabilitation actions in the simulation must be implemented a minimum of 7/10ths of a mile or 3,696 feet apart. This minimum separation requirement can be adjusted as new information is acquired.

We are interested in tracking the effect of the rehabilitation actions on each river segment over time. Success of a rehabilitation action is ultimately determined by an increase in fish populations. Studies to look at fry utilization of rehabilitation sites and fry densities are important and are planned by the TRRP. However, they may

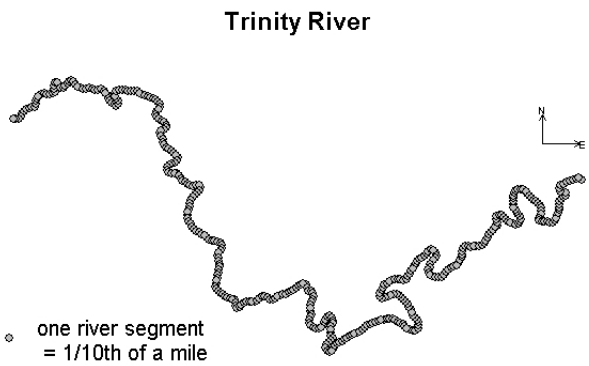


Figure 2.4: The Trinity River was split into many small segments and the model tracks the behaviour of each segment over time.

not provide us with as much information as quickly as a simple measure of the habitat created. Fry densities depend on changes that occur in the ocean habitat altering the abundance of spawners as well as fry-rearing habitat availability. Additionally, rehabilitation actions may be focused on the sites that were in the worst shape initially and so the treated sites may still have lower juvenile survival than control sites (Paulsen and Fisher 2005). For the purpose of this simulation model we will track the state of the habitat in each of the river segments over time. In particular we want to track the state of chinook fry-rearing habitat and so we need a simple measure that will reasonably approximate this. Fry-rearing habitat is lost as growth of riparian vegetation forms permanent berms along the river edge (Figure 2.3), so we will use the formation of berms as a surrogate for the loss of fry-rearing habitat. There are four possible states that each river segment can take (Table 2.3).

The probability of a individual river segment moving from one state to another is described by a probability transition matrix (Figure 2.5). The probability matrix will be quite sparse as many of the probabilities are zero. For example, if a river segment has one-year old vegetation this year, there is zero probability of it having three-year old vegetation next year and if a river segment has three-year old vegetation this year,

Table 2.3: Definition of the four habitat states possible in this model.

State	Description	Habitat quality
1	The bank is scoured bare of riparian vegetation.	Good
2	The bank has one-year old riparian vegetation.	Good
3	The bank has two-year old riparian vegetation.	Good
4	The bank has three-year old or older riparian vegetation.	Poor, riparian berms have formed

State of vegetation in following year

Initial State of vegetation	bare	1 yr	2 yr	3 yr +
bare	$p_{1,1}$	$1-p_{1,1}$	0	0
1 yr	$p_{2,1}$	0	$1-p_{2,1}$	0
2 yr	$p_{3,1}$	0	0	$1-p_{3,1}$
3 yr +	$p_{4,1}$	0	0	$1-p_{4,1}$

Figure 2.5: This is a generic example of a probability transition matrix for this four-state system.

there is zero probability of that vegetation being two-years old next year (plants can't get younger).

There are a number of factors that affect the probability of a river segment being scoured bare of vegetation. The most important event in determining the probability of scour is the annual peak-flow event (C. Alexander pers. comm.). The presence of gravel is also an important mechanism in scouring action. The geographic region of a river segment and the state of the river segments immediately upstream are believed to affect the probability of scour. It is hoped that habitat rehabilitation actions will increase the probability of scour. The key features of the model are summarized in Table 2.6 at the end of this Section.

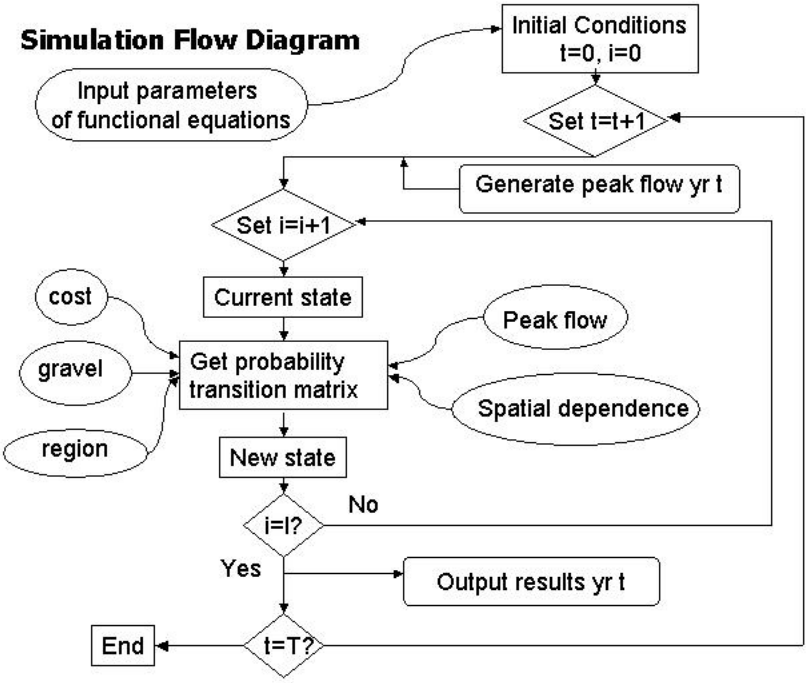


Figure 2.6: Simulation flow diagram: i=1,2,...,396 river segments and t=1,2,...,T time in years. For each simulation run, we generate a random time series of water years based on historical flow data (Appendix A) and the corresponding peak-flow is recorded.

The simulation process is outlined in Figure 2.6. Given the state of the habitat in the previous year and the treatment and covariate combination, the model calculates a probability that the river segment is scoured bare using a probability transition

matrix that depends upon the treatment and covariate values in the current year.

The probabilities: $p_{1,1}$, $p_{2,1}$, $p_{3,1}$, and $p_{4,1}$ in the transition matrices (Figure 2.5) were estimated with the help of John H. Bair, a riparian botanist with McBain and Trush Inc. working on the TRRP. I presented him with the question of how the probability of scouring riparian vegetation of various age-classes changes for different flows and regions. He generated expert guesses for the probability transition matrices for each of the five water years and for each of the six regions. We then fit a model to the data he provided to allow us to infer the probabilities for each region at any value of flow.

As we are not sure how the cost of different rehabilitation actions will affect the probability transition matrices, we looked at a range of costs and arbitrarily chose a coefficient for cost that was large enough to make a difference to the probability matrices.

Figure 2.7 illustrates several possible transition matrices and Figure 2.8 illustrates possible behaviour for a single river segment. We use a continuation-ratio logit model to relate the different covariates to the probabilities in the matrix. The continuation-ratio logit model is useful when the categories are ordinal in nature, such as survival through various age periods (Agresti 2002). This is very similar to our scenario where we are interested in categories or states defined by the age of riparian growth. The continuation-ratio logit is found by first calculating the conditional probabilities π_j (Equation 2.1) , where p_1 is the probability of ending up in state 1 for a particular row of the probability transition matrix.

$$\pi_j = \frac{p_j}{p_j + ... + p_J}, j = 1, ..., J-1 \tag{2.1}$$

Then, we simply take the ordinary logit of the conditional probabilities (π_j) from equation 2.1.

$$log\frac{\pi_j}{1-\pi_j} = log\frac{p_j}{p_{j+1} + ... + p_J} \quad , j = 1, ..., J-1 \tag{2.2}$$

Equation 2.2 is one way of defining the continuation-ratio logit (Agresti 2002). The continuation-ratio logit can take values between $(-\infty, +\infty)$, so now we can use standard linear regression methods to relate the covariates to the response value Y_j (see

Markov Probability Transition Matrix:
Flow year= normal
Treatment=none
Region=3

State of vegetation in following year

Initial State of vegetation

$$\mathbf{P} = \begin{array}{c|cccc} & \text{bare} & \text{1 year} & \text{2 year} & \text{3 year +} \\ \hline \text{bare} & .75 & .25 & 0 & 0 \\ \text{1 year} & .85 & 0 & .15 & 0 \\ \text{2 year} & .2 & 0 & 0 & .80 \\ \text{3 year +} & .00001 & 0 & 0 & .99999 \end{array}$$

Markov Probability Transition Matrix:
Flow year= critically dry
Treatment=none
Region=3

State of vegetation in following year

Initial State of vegetation

$$\mathbf{P} = \begin{array}{c|cccc} & \text{bare} & \text{1 year} & \text{2 year} & \text{3 year +} \\ \hline \text{bare} & .001 & .999 & 0 & 0 \\ \text{1 year} & .0001 & 0 & .9999 & 0 \\ \text{2 year} & .00001 & 0 & 0 & .99999 \\ \text{3 year +} & .00001 & 0 & 0 & .99999 \end{array}$$

Markov Probability Transition Matrix:
Flow year= normal
Treatment=high(3)
Region=3

State of vegetation in following year

Initial State of vegetation

$$\mathbf{P} = \begin{array}{c|cccc} & \text{bare} & \text{1 year} & \text{2 year} & \text{3 year +} \\ \hline \text{bare} & .98 & .02 & 0 & 0 \\ \text{1 year} & .99 & 0 & .01 & 0 \\ \text{2 year} & .83 & 0 & 0 & .17 \\ \text{3 year +} & .0002 & 0 & 0 & .9998 \end{array}$$

Markov Probability Transition Matrix:
Flow year= critically dry
Treatment=high(3)
Region=3

State of vegetation in following year

Initial State of vegetation

$$\mathbf{P} = \begin{array}{c|cccc} & \text{bare} & \text{1 year} & \text{2 year} & \text{3 year +} \\ \hline \text{bare} & .02 & .98 & 0 & 0 \\ \text{1 year} & .002 & 0 & .998 & 0 \\ \text{2 year} & .0002 & 0 & 0 & .9998 \\ \text{3 year +} & .0002 & 0 & 0 & .9998 \end{array}$$

Figure 2.7: Example of how the probability transition matrix changes for different values of flow and treatment size for a fixed region, spatial dependence, gravel and treatment persistence. According to the top left matrix, if the initial state is bare, then in the next time step you can either move to the next state (1 year old vegetation) with probability 0.25 or remain bare with probability 0.75. Additional probability transition matrices are found in Appendix B.1.

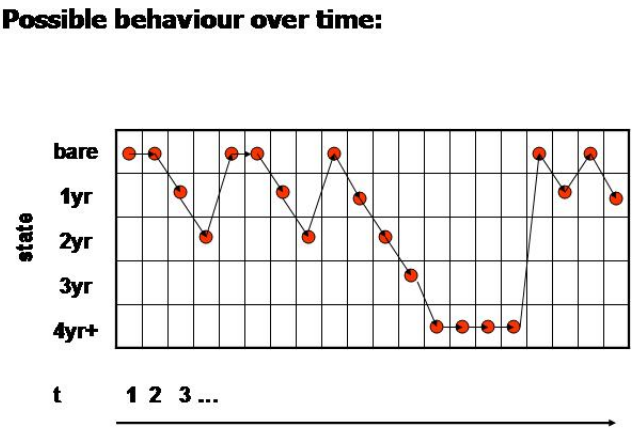


Figure 2.8: This illustrates possible behaviour for a single river segment over time. The state of the segment at time $t = 2$ is dependent on the state at time $t = 1$ and the probabilities defined in the probability transition matrix.

Equation 2.3),

$$Y_j = log\frac{p_j}{p_{j+1} + ... + p_J} = \boldsymbol{x}_j^T \boldsymbol{\beta}_j \tag{2.3}$$

where Y_j is the continuation-ratio logit for initial state j (or row j in the transition matrix), x_j are the covariate values and β_j are the coefficients that describe the relationship between the covariates and Y. Recall that larger Y_j indicates larger probability of returning to state 1, or of scouring the bank. Y_j represents the relationship for the jth initial state.

Our final model consists of the following parameters: flow (continuous), cost or size of treatment (3 levels plus the baseline, no treatment), gravel (baseline=presence, 1=absence), region (categorical, region 6 is the baseline), and spatial dependence (proportion) (Equation 2.4). If necessary, second-order terms or interactions could be added in future generations of the model. The coefficient values for each initial state, or row of the transition matrix are summarized in Table 2.4.

$$\begin{aligned} Y_j \;=\; & \beta_{1j} + \text{flow} \times \beta_{2j} + \text{region1} \times \beta_{3j} + \text{region2} \times \beta_{4j} + \text{region3} \times \beta_{5j} + \text{region4} \times \beta_{6j} \\ & + \text{region5} \times \beta_{7j} + \text{gravel} \times \beta_{8j} + \text{spatial.dependence} \times \beta_{9j} \\ & + \text{cost} \times \beta_{10j} + \text{flow}^2 \times \beta_{11j} \qquad , j = 1, 2, 3, 4 \end{aligned} \tag{2.4}$$

Table 2.4: Coefficients for the final model, given the current best guess of how the probability of scour changes for each of the covariates. Notice that with the current guess regions 1 and 2 are the same and regions 3, 4 and 5 are the same as region 6, the baseline. The coefficients for gravel and spatial dependence were assumed to be the same regardless of the initial state and the values were arbitrarily chosen.

Covariate	Coefficient	Value of coefficients for each initial state or row of the probability transition matrix			
		Y_1	Y_2	Y_3	Y_4
intercept	β_1	-8.66	-11.20	-13.13	-10.24
flow	β_2	0.13	0.15	0.14	-0.09
region1	β_3	1.62	1.63	1.30	1.84
region2	β_4	1.62	1.63	1.30	1.84
region3	β_5	0	0	0	0
region4	β_6	0	0	0	0
region5	β_7	0	0	0	0
gravel	β_8	-0.5	-0.5	-0.5	-0.5
spatial dependence	β_9	1	1	1	1
cost	β_{10}	1	1	1	1
flow^2	β_{11}	0	0	0	0.0012

The cost or treatment size variable requires further explanation to clarify how it is used in the Chapter 4 experiments. Cost is a categorical variable with four possible levels: no treatment, low cost, moderate cost or high cost. I chose to use a single predictor variable for cost, because I wanted to minimize the number of variables to keep the model from being too overwhelming. Two problems with this is it suggests that the treatments are ordered and have fixed spacing (Weisberg 1985). In our case, we do believe that the effect of no treatment < low cost < moderate cost < high cost, so the first assumption is reasonable. We do not know how big the three different treatments are and we don't know how they relate to one another. We will test two different spacing possibilities: equal spacing and unequal spacing (Table 2.5).

Table 2.5: Comparison of the equally spaced and unequally spaced treatment variables.

Equally spaced rehabilitation action cost or treatment levels			
Cost or treatment level	β_{10j}	Dummy Variable	Effect on Y $= \beta_{10j} \times$ Dummy Variable
no treatment	1	0	$1 \times 0 = 0$
low cost	1	1	$1 \times 1 = 1$
moderate cost	1	2	$1 \times 2 = 2$
high cost	1	3	$1 \times 3 = 3$
Unequally spaced rehabilitation action cost or treatment levels			
Cost or treatment level	β_{10j}	Dummy Variable	Effect on Y $= \beta_{10j} \times$ Dummy Variable
no treatment	1	0	$1 \times 0 = 0$
low cost	1	1	$1 \times 1 = 1$
moderate cost	1	3	$1 \times 3 = 3$
high cost	1	9	$1 \times 9 = 9$

Table 2.6: Summary of the key features involved in this model.

Key Model Features	Description
Study Area	39.6 miles of the Trinity River below the Lewiston dam.
River segments	396 segments: each one tenth of a mile long
Geographic region	6 regions, with 67, 72, 27, 38, 150, 42 segments in region 1,2,3,4,5,6 respectively
Current estimate of good habitat by region	4%, 8%, 15%, 21%, 22%, 26%
Peak flow	5 possible water years, each with a minimum peak flow release
Gravel	presence or absence of gravel is tracked for each segment.
Spatial Dependence	Proportion of good habitat in the 3 sections (1584 feet) immediately upstream.
Length	All rehabilitation actions are 0.2 miles long.
Parameters associated with the cost of Rehabilitation actions:	
Size	The size of the effect for different cost/sophistication actions in the first year after implementation.
Persistence	A weight that reduces the "Size" of the effect over time. $\text{effect}_t = (1 - (\frac{1}{persistence} \times t)) \times \text{effect}_{t_1}$

The following four steps summarize the procedure used to calculate the probability transition matrices.

1. Determine what covariates are expected to affect the probability of the event of interest occurring. In our case we believe that peak flow, region, gravel, and spatial dependence affect the probability of scour.

2. Ask the scientists to provide an estimate of the probabilities for a sample of covariate values. The estimate may be based on data, theory or simply a best guess based on their experience. Providing an educated guess of the probability for several specific scenarios is much easier than trying to guess the overall relationship, which may be quite complex. For example, we asked the experts "Given that a river segment is bare of vegetation this year, what is the probability that it is still bare next year if the peak flow is 1500 cfs, 4500 cfs, 6000 cfs etc...?"

3. Now you have 'guess data' for a range of covariate combinations, and so a generalized linear model can be fit to the data using standard techniques as described earlier in this section.

4. Once a model is fit, we can calculate the probability transition matrix for any combination of covariates. This can be done by taking the covariate values for a given river segment in a given year and then calculating the value of Y for initial state j using the jth coefficient values from Table 2.4 and Equation 2.4. Then, calculate the probability $p_{j,1}$ using the relationship described in Equation 2.3. Do this for each of the j initial states or rows and you will have the entire probability transition matrix.

2.4 Response Variable

A natural response measure is the amount of good quality habitat. However, all levels of habitat rehabilitation action initially result in good quality habitat at the rehabilitation site. Consequently, we are interested in whether a habitat rehabilitation action results in the creation of good quality habitat downstream and how long the actual rehabilitation site remains as good quality habitat.

We consider the treatment section (0.2 miles) plus the next 0.5 miles downstream as the 0.7 mile response area of interest. At 5, 10 and 15 years after the treatment was implemented we count how much of the 0.7 mile response area is good quality habitat, compared with how much was treated (Equation 2.5 and Figure 2.9). We will call this response, the Rehabilitation Action Effectiveness Index (RAEI).

$$RAEI = \frac{length\ of\ good\ habitat\ at\ time\ t}{length\ of\ rehabilitation\ action\ at\ time\ t_0} \tag{2.5}$$

If the RAEI is greater than one, then the amount of good habitat increased since the rehabilitation action. If the RAEI is less than one, the rehabilitation action was not self maintaining. Good habitat is defined as all sites where the state of the riparian vegetation growth is less than three years old. Poor habitat is defined as all sites where there is vegetation three-years old or more, forming permanent riparian berms. States 1 to 3 from the model (see Table 2.3) correspond to good habitat. State 4 corresponds to poor habitat.

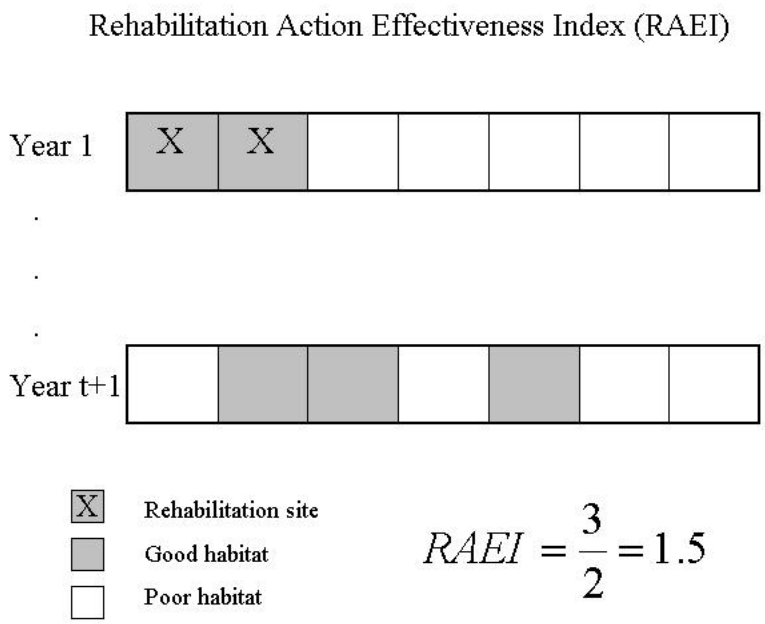


Figure 2.9: Illustration of the Rehabilitation Action Effectiveness Index (RAEI). In year 1, the rehabilitation action occurred on segments 1 and 2. The system is simulated for t years. In year t+1 three segments of good quality habitat remain. The response measure is $RAEI = \frac{3}{2}$.

Chapter 3

Description of Experiments

The goal of this study is to design an experiment that provides the most information about the success of the different rehabilitation actions given certain constraints. In the first experiment we compare rehabilitation sites to control sites. Experiments 2 through 4b compare three levels of rehabilitation actions. The last experiment compares three treatment levels under several scenarios of interest.

3.1 Hypotheses of Interest

For each experiment, we are interested in determining if the mean Rehabilitation Action Effectiveness Index (RAEI) differs among the treatments and if the difference can be detected. In the designs where we compare treatment versus control sites, the hypotheses we are testing are:

$$H_0 : \mu_{control} = \mu_{treatment} \tag{3.1}$$

$$H_A : \mu_{control} \neq \mu_{treatment} \tag{3.2}$$

In the designs where we consider multiple treatment levels, the hypotheses are:

$$H_0 : \mu_{low} = \mu_{moderate} = \mu_{high} \tag{3.3}$$

$$H_A : \text{at least one of the three pairs of treatment means are not equal.} \tag{3.4}$$

We are also interested in testing each of the pair-wise comparisons: $\mu_{low} = \mu_{moderate}$, $\mu_{low} = \mu_{high}$, and $\mu_{moderate} = \mu_{high}$. We use the Bonferonni method, which is one of several common methods used for multiple comparisons (Wu and Hamada 2000).

3.2 Experiment 1

In Experiment 1, we investigate the power to detect a difference in the mean RAEI over control and treatment sites after 5, 10 and 15 years. The experiment was run as a completely randomized design with 9 control sites and 9 treatment sites (Figure 3.1). We use a total of 18 sites for each of Experiments 1-4, in order to maintain roughly the same overall cost. We chose this number of sites, because it works conveniently with each of the proposed experiments (i.e. the randomized complete block design requires a minimum of 18 sites) and because it is close to the number of sites (24) proposed for phase 1 by the TRRP. We then investigate how the power changes with a range of rehabilitation actions. Recall from Table 2.6 that there are two parameters (related to the cost of the habitat rehabilitation action) in the simulation model that affect the response:

1. The size of the rehabilitation action effect in the first year post treatment.
2. The persistence of the rehabilitation action effect over time.

Persistence is not a factor under our control but is intimately tied up with the cost of the rehabilitation action. A more costly rehabilitation action is expected to last longer (John Bair pers. comm.). The power to detect a difference in mean RAEI was estimated for combinations of parameter settings through 100 replications of the simulation experiment. We only used 100 replications for this experiment because it was simply an exploratory look at how the power changed with a range of parameter settings and this greatly reduced the computing time. We use the results from this experiment to help choose a persistence level that seems sensible for our simulation system. Based on the results from this experiment we fixed the persistence value to be used for later experiments at: 5 years, 10 years, and 100 years, to correspond with low cost, moderate cost, and high cost treatments.

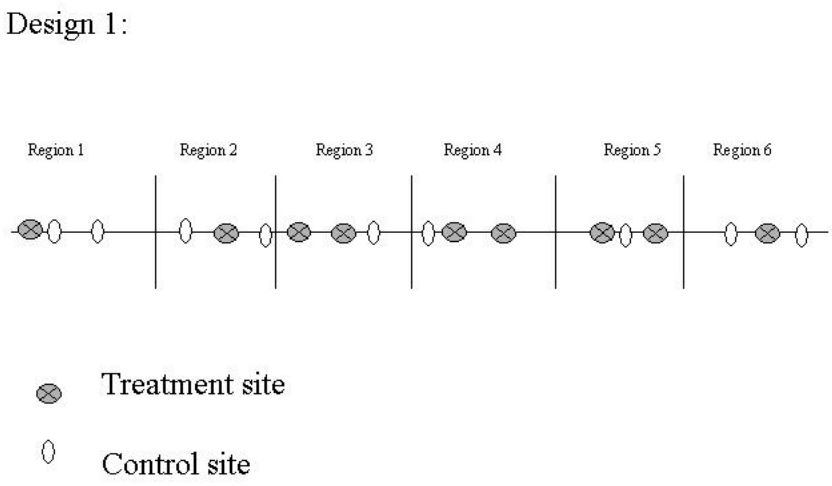


Figure 3.1: Experiment 1: Treatment and control sites are placed throughout the river in a completely randomized design, but must be at least 0.7 miles apart.

3.3 Experiment 2

Experiments 2 through 4 compare the mean RAEI among three different levels of rehabilitation actions (low, moderate, and high). In each experiment we try two different spacings for the cost effect: equally spaced effects where the coefficient of the cost levels are equally spaced (low=1, moderate=2, high=3) and unequally spaced effects where the coefficients of the cost levels are unequally spaced (low=1, moderate=3, high=9) (Table 2.5).

Experiment 2, was run as a completely randomized design with six replicates for each of the low, moderate and high cost treatments. An example of a possible design based on this procedure is seen in Figure 3.2.

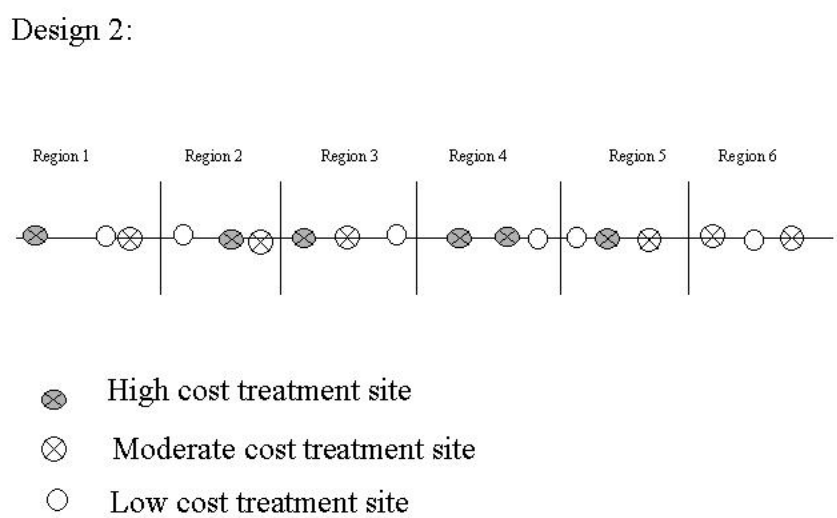


Figure 3.2: Experiment 2: Low, moderate and high cost treatments are compared in a completely randomized design, but all treatments must be at least 0.7 miles apart.

3.4 Experiment 3

Experts from various disciplines involved with the Trinity River Restoration Project (TRRP) have grouped the river into six different geographic regions (Section 2.2.1) and the region is believed to have an effect on the probability of scour. Our third experiment is run as a randomized complete block design (RCBD). This design is one of the most widely used experimental designs (Montgomery 1997). Each of the six geographic regions is treated as a block and one replicate of each of the three treatment levels (low, moderate, high) is applied to each block for a total of 18 treatment sites. The location of the treatment within each block is random. A possible treatment allocation is shown in Figure 3.3.

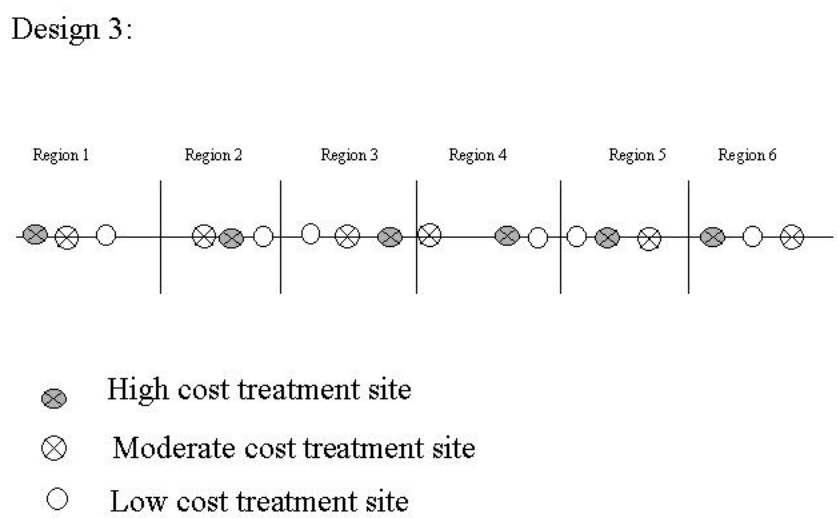


Figure 3.3: Experiment 3: The three treatments are compared in a completely randomized block design. Each treatment level is applied to each of the six geographic regions in the river. All treatments must be 0.7 miles apart.

3.5 Experiment 4

The design in Experiment 3 seems like an obvious choice, but what should be done if it is not feasible to complete all 18 of the treatments in the same year? We know that the peak flow varies from year to year and that peak flow is the driving force behind the scouring of riparian vegetation. Even with a restoration action, if there is very low flow there will not be much scouring action. The year in which the actions are implemented should affect the outcome of the experiment. There are many factors limiting the number of sites completed each year. Cost, construction time and logistics restrict the number of sites that can be completed each year. Currently the TRRP is planning to complete roughly 6-8 sites per year. The actions may actually take several years from the initial planning/permitting to the final completion date. In Experiment 4, the same design as Experiment 3 is used, except that the number of modified sites are limited to six per year. We can consider the implementation year as a second blocking factor, with three levels. As in Experiment 3, we apply each treatment to each block for a total of 18 sites. However we now need to decide which blocking factor we should apply first. We consider two alternative designs. First, we use two 3x3 latin squares to account for the blocking variables: region and treatment year. In this implementation design, the two blocks are orthogonal. Second, we complete all three treatments in two randomly selected regions each year. This design is likely more convenient to implement, but the year effects are fully confounded with some of the region effects. The two alternatives are illustrated in Figures 3.4 and 3.5.

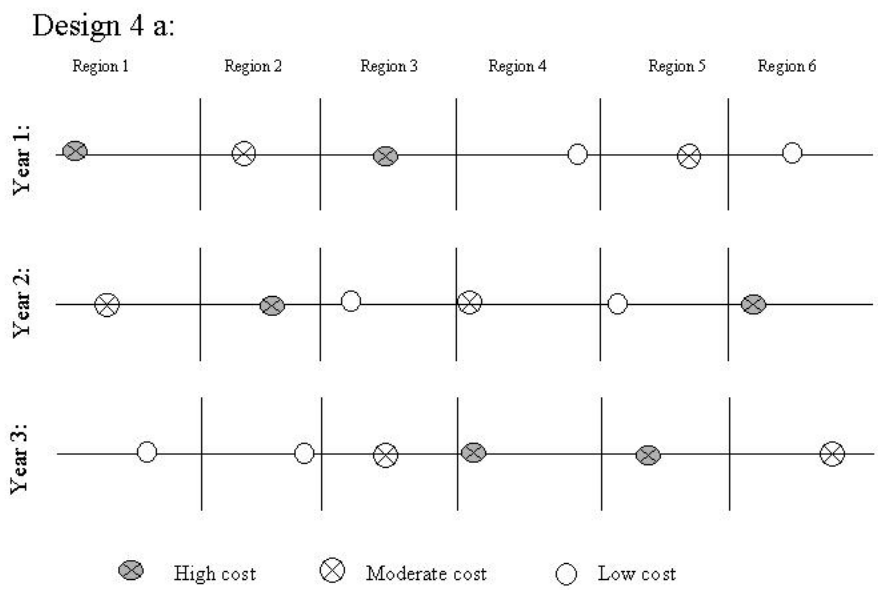


Figure 3.4: Experiment 4a: The treatments are placed according to a 3x6 latin square design, where year and region are the blocking variables. Two 3x3 latin squares are generated and then each of the six regions is randomly assigned to one of the columns in the two latin squares. All treatments are at least 0.7 miles apart.

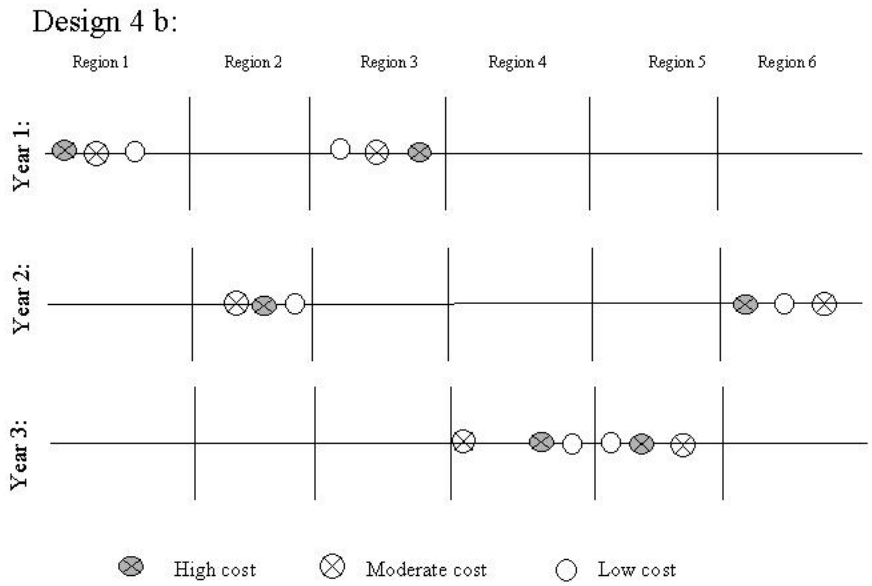


Figure 3.5: Experiment 4b: Randomly choose two regions and apply all three treatments to those 2 regions in the first year, then choose two more regions and apply all three treatments in the second year and finally apply all three treatments to the remaining two regions in the third year. All treatments are at least 0.7 miles apart.

3.6 Experiment 5

The extremely small probabilities in the probability transition matrices for Critically Dry (Figure 2.7) and Dry (Appendix B.1) water years beg the question: "What would happen if there is a drought of three years (the time needed for a riparian berm to establish) or more?" Another interesting question is "What would happen if we forced a flood (peak flow $\geq 11,000$ cfs) to occur at some regular interval?" In Experiment 5 we measure the Rehabilitation Action Effectiveness Index (RAEI) after fifteen years for nine randomly chosen treatment sites under three scenarios: a three year drought, a flood every five years and the normal TRRP flow schedule. This is repeated for the three unequally spaced treatment levels.

Chapter 4

Results

4.1 Experiment 1

Figure 4.1 illustrates how the power to detect a difference between treatment sites and control sites varies with different values of the two parameters:

1. The size of the treatment effect in the first year.
2. The persistence of the treatment effect over time.

These results were used to help choose appropriate values for the size and persistence of the treatment effect in later experiments.

Figure 4.1 illustrates that after five years, the power to detect a difference in mean RAEI between the treatment and control sites was at least 0.8 for most size and persistence combinations. This is not surprising, since all of the actions result in good habitat in the first year and it takes at least three years for riparian berms to form. The power dropped below 0.8 after ten years for treatments with cost < 2 and/or persistence < 5 years. The power remained above 0.8 after fifteen years only for treatments with: cost=3 and persistence=100 years or cost=6 and persistence=20 years.

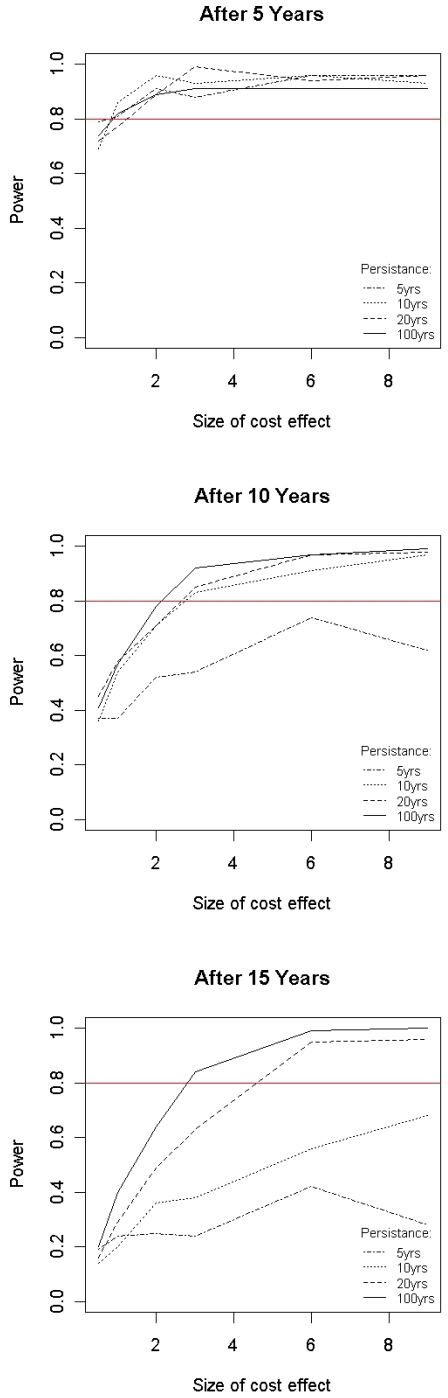


Figure 4.1: Experiment 1: This illustrates how the power (when $\alpha = 0.05$) to detect a difference in mean RAEI changes for a range of size and persistence values.

4.2 Experiment 2

The results of the power analysis for Experiment 2, are shown in Table 4.1. The mean Rehabilitation Action Effectiveness Index (RAEI) is plotted for each of 1000 runs of the simulation in Figure 4.2.

Table 4.1: Experiment 2: The power to detect a difference in mean RAEI among low, moderate and high cost treatment levels in the short term (5 years), the medium term (10 years), and the longer term (15 years). The power values have an accuracy of roughly ± 0.03 based on 1000 runs and were calculated for $\alpha = 0.05$.

	Equal spacing (L,M,H) effects= (1,2,3)			Unequal spacing (L,M,H) effects=(1,3,9)		
	Short term	Medium term	Long term	Short term	Medium term	Long term
Overall Power	0.15	0.27	0.23	0.27	0.61	0.78
Low vs. Moderate	0.04	0.07	0.07	0.12	0.18	0.08
Low vs. High	0.09	0.24	0.20	0.22	0.58	0.74
Moderate vs. High	0.05	0.12	0.16	0.08	0.34	0.60

The results indicate that it is very difficult to detect a difference in mean RAEI among treatments regardless of the size and persistence after only five years. The power to detect a difference in mean RAEI among equally spaced treatments was poor (< 0.27) regardless of how many years were observed. The greatest power (0.78) to detect a difference in mean RAEI among unequally spaced treatments occurred after fifteen years. Figure 4.2 shows that after five years the median RAEI is about one or slightly greater for all treatments, indicating that all treatments maintain themselves for at least five years. After ten years the median RAEI for all treatment levels with a cost < 3 is less than one, indicating that the habitat has begun to recede. After fifteen years only the highest treatment (cost=9), still has a mean RAEI of about one and is therefore maintaining itself.

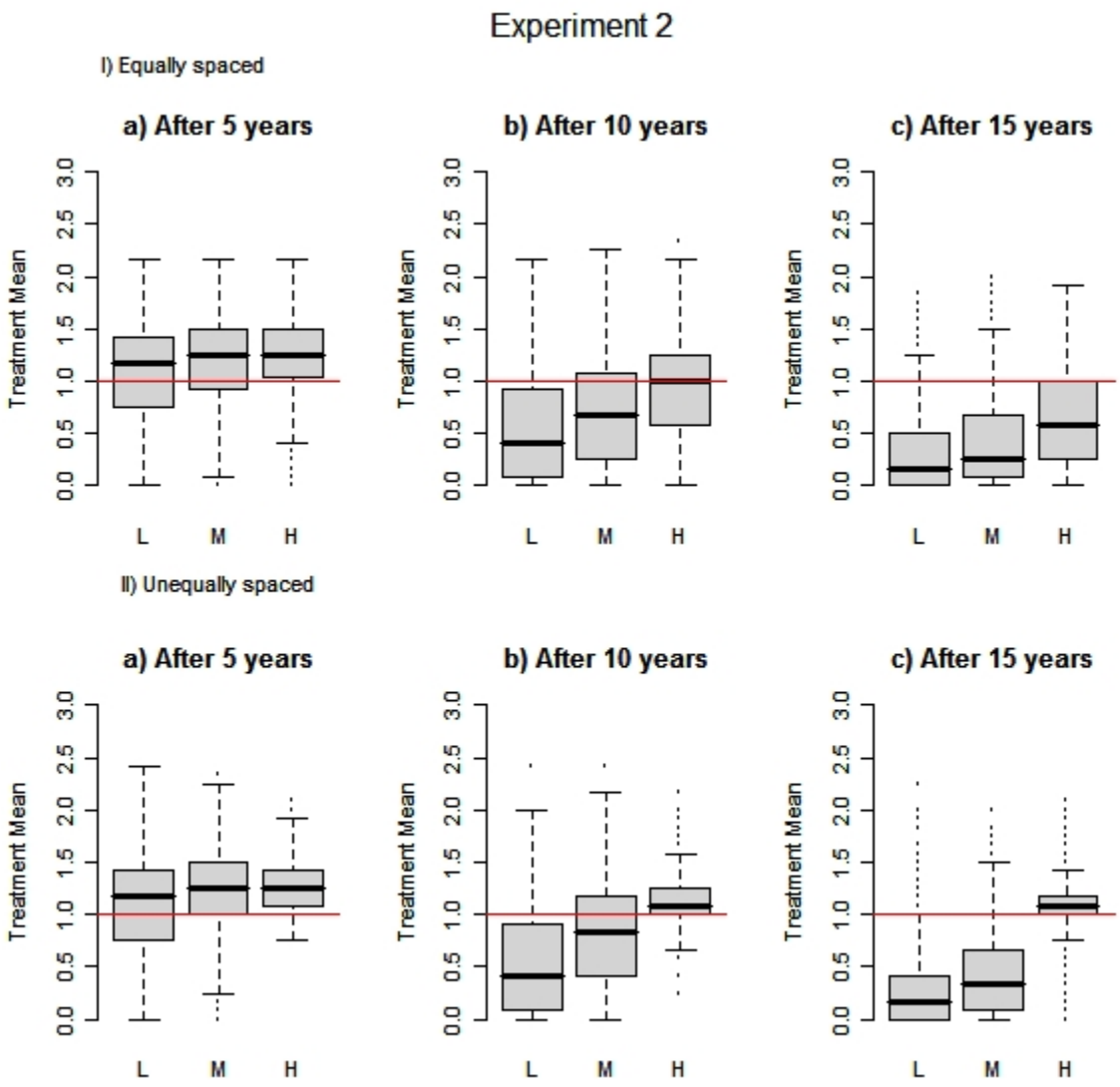


Figure 4.2: Experiment 2: Box plots comparing the mean RAEI resulting from low, moderate and high cost treatments for short, medium and long term responses. Plots I) a, b, and c are generated with equally spaced treatment levels: L=1, M=2, H=3. Plots II) a, b, and c are generated with unequally spaced treatment levels: L=1, M=3, H=9. Typical standard errors for the mean RAEI within a simulation ranged from 0.12-0.16 decreasing with years, except for when cost=9, they ranged from 0.09-0.13.

4.3 Experiment 3

The results of the power analysis for Experiment 3, are shown in Table 4.2. The mean Rehabilitation Action Effectiveness Index (RAEI) is plotted for each of 1000 runs of the simulation in Figure 4.3.

Table 4.2: Experiment 3: The power to detect a difference in mean RAEI among low, moderate and high cost treatment levels in the short term (5 years), the medium term (10 years), and the longer term (15 years). The power values have an accuracy of roughly ± 0.03 based on 1000 runs and were calculated for $\alpha = 0.05$.

	Equal spacing (L,M,H) effects= (1,2,3)			Unequal spacing (L,M,H) effects=(1,3,9)		
	Short term	Medium term	Long term	Short term	Medium term	Long term
Overall Power	0.14	0.31	0.26	0.30	0.65	0.82
Low vs. Moderate	0.04	0.06	0.06	0.14	0.14	0.08
Low vs. High	0.10	0.26	0.23	0.25	0.60	0.78
Moderate vs. High	0.02	0.10	0.15	0.09	0.37	0.67

The results from Experiment 3, mimic those of Experiment 2. It is very difficult to detect a difference in mean RAEI among treatments regardless of the size and persistence after only five years. The power to detect a difference in mean RAEI among equally spaced treatments was poor (< 0.31) regardless of how many years were observed. The greatest power (0.82) to detect a difference in mean RAEI among unequally spaced treatments occurred after fifteen years. Figure 4.3 shows that all treatments maintain themselves for at least five years. After ten years the median RAEI for all treatment levels with a cost < 3 is less than one, indicating that the habitat has begun to recede. After fifteen years only the highest treatment (cost=9), still has a mean RAEI of about one and is therefore maintaining itself. The power to detect a difference in mean RAEI is consistently greater for Experiment 3, the randomized complete block design than for Experiment 2, the completely randomized design. However, the difference between the power (≤ 0.04) of the two designs is on

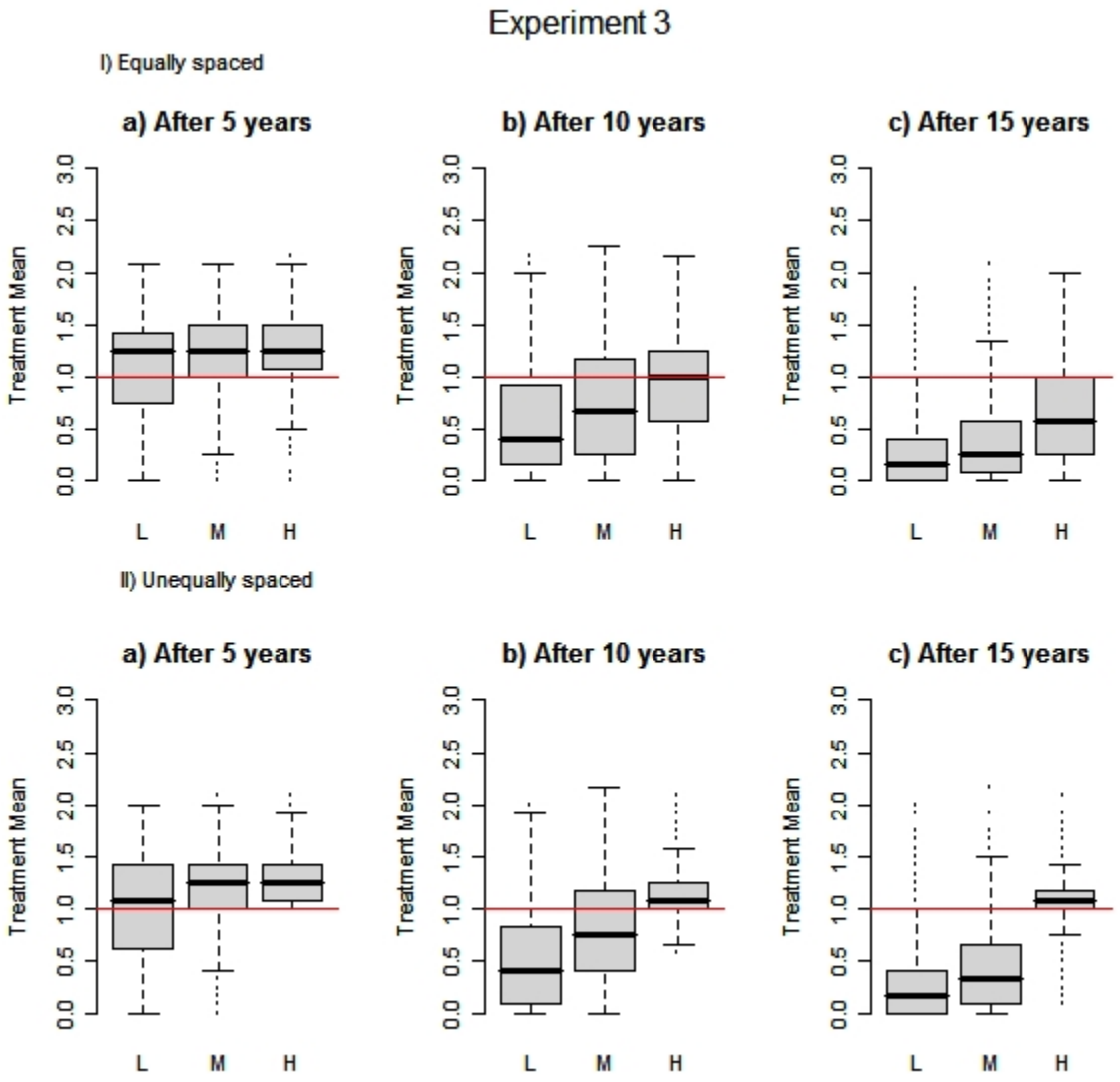


Figure 4.3: Experiment 3: Box plots comparing the mean RAEI resulting from low, moderate and high cost treatments for short,medium and long term responses. Plots I) a, b, and c are generated with equally spaced treatment levels: L=1, M=2, H=3. Plots II) a, b, and c are generated with unequally spaced treatment levels: L=1, M=3, H=9. Typical standard errors for the mean RAEI within a simulation ranged from 0.12-0.17 generally decreasing with years, except for when cost=9, they ranged from 0.09-0.13.

the same order as the precision of the power estimates and so should likely not be over interpreted.

4.4 Experiments 4a and 4b

The results of the power analysis for Experiments 4a and 4b, are shown in Tables 4.3 and 4.4. The mean Rehabilitation Action Effectiveness Index (RAEI) for each experiment is plotted for each of 1000 runs of the simulation in Figures 4.4 and 4.5 .

Table 4.3: Experiment 4a: The power to detect a difference in mean RAEI among low, moderate and high cost treatment levels in the short term (5 years), the medium term (10 years), and the longer term (15 years). The power values have an accuracy of roughly ± 0.03 based on 1000 runs and were calculated for $\alpha = 0.05$.

	Equal spacing (L,M,H) effects= (1,2,3)			Unequal spacing (L,M,H) effects=(1,3,9)		
	Short term	Medium term	Long term	Short term	Medium term	Long term
Overall Power	0.14	0.37	0.29	0.22	0.62	0.79
Low vs. Moderate	0.04	0.06	0.06	0.08	0.16	0.07
Low vs. High	0.09	0.26	0.24	0.17	0.59	0.76
Moderate vs. High	0.03	0.11	0.16	0.05	0.36	0.62

Table 4.4: Experiment 4b: The power to detect a difference in mean RAEI among low, moderate and high cost treatment levels in the short term (5 years), the medium term (10 years), and the longer term (15 years). The power values have an accuracy of roughly ± 0.03 based on 1000 runs and were calculated for $\alpha = 0.05$.

	Equal spacing (L,M,H) effects= (1,2,3)			Unequal spacing (L,M,H) effects=(1,3,9)		
	Short term	Medium term	Long term	Short term	Medium term	Long term
Overall Power	0.12	0.33	0.26	0.22	0.61	0.80
Low vs. Moderate	0.03	0.04	0.04	0.08	0.13	0.06
Low vs. High	0.07	0.27	0.24	0.17	0.57	0.76
Moderate vs. High	0.03	0.12	0.15	0.05	0.35	0.64

Once again, the results from Experiment 4a and 4b, mimic those of Experiments 2 and 3. It is very difficult to detect a difference in mean RAEI among treatments regardless of the size and persistence after only five years. The power to detect a difference in mean RAEI among equally spaced treatments was poor (4a:< 0.37, 4b:< 0.33) regardless of how many years were observed. The greatest power (4a: 0.79, 4b: 0.80) to detect a difference in mean RAEI among unequally spaced treatments occurred after fifteen years. Figure 4.4 and 4.5 show that all treatments maintain themselves for at least five years. After ten years the median RAEI for all treatment levels with a cost < 3 is less than one, indicating that the habitat has begun to recede. After fifteen years only the highest treatment (cost=9), still has a mean RAEI of about one and is therefore maintaining itself. Experiments 4a and 4b do not appear to differ in terms of their ability to detect a difference in mean RAEI among treatments. If we were limited to six treatment sites per year and we still want to block on the six regions, then given the current model assumptions we could use the more convenient of Experiments 4a and 4b.

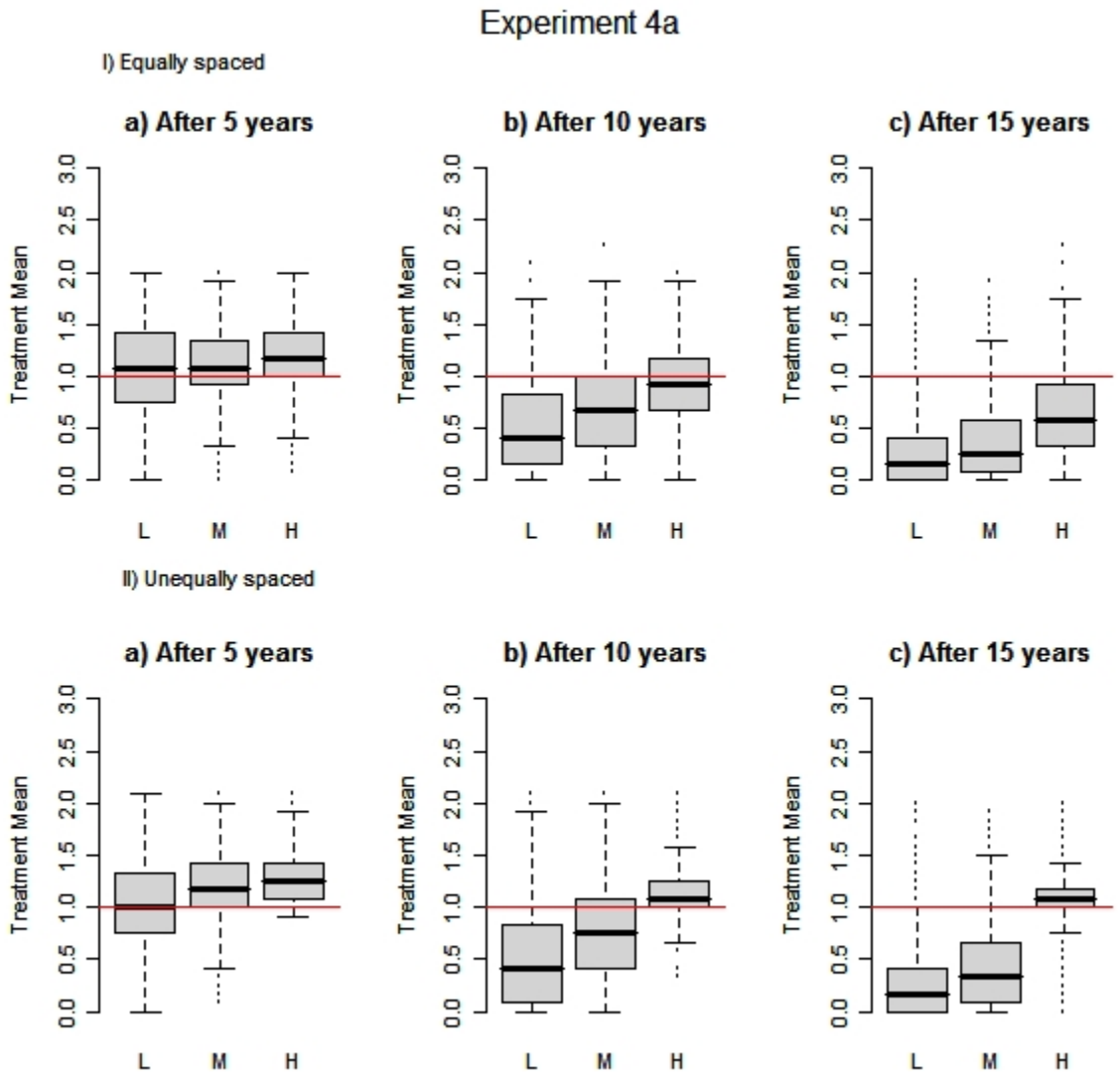


Figure 4.4: Experiment 4a: Box plots comparing the mean RAEI resulting from low, moderate and high cost treatments for short,medium and long term responses. Plots I) a, b, and c are generated with equally spaced treatment levels: L=1, M=2, H=3. Plots II) a, b, and c are generated with unequally spaced treatment levels: L=1, M=3, H=9. Typical standard errors for the mean RAEI within a simulation ranged from 0.13-0.18 generally decreasing with years, except for when cost=9, they ranged from 0.09-0.13.

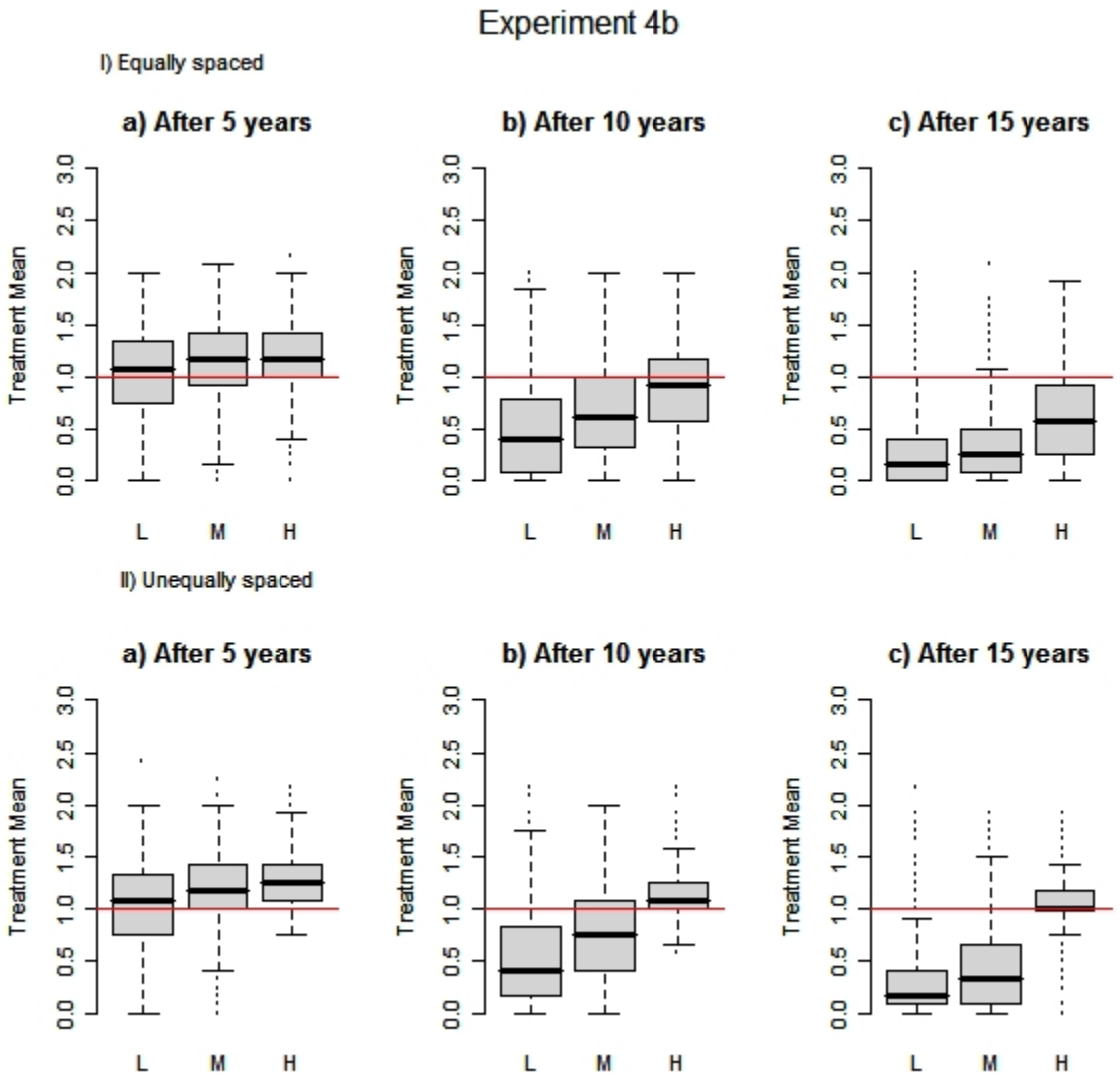


Figure 4.5: Experiment 4b: Box plots comparing the RAEI resulting from low, moderate and high cost treatments for short,medium and long term responses. Plots I) a, b, and c are generated with equally spaced treatment levels: L=1, M=2, H=3. Plots II) a, b, and c are generated with unequally spaced treatment levels: L=1, M=3, H=9. Typical standard errors for the mean RAEI within a simulation ranged from 0.12-0.19 generally decreasing with years, except for when cost=9, they ranged from 0.09-0.13.

4.5 Experiment 5

Now we present the results from several scenarios of interest. First, what happens if there is a three year drought? Second, what happens if there is a flood every five years? How do the mean RAEI differ under these two scenarios and how do they compare to the mean RAEI under the current TRRP flow schedule? The mean Rehabilitation Action Effectiveness Index (RAEI) after 15 years is plotted for each of 1000 runs of the simulation in Figure 4.6. The mean and standard error of the 1000 mean RAEI's for each treatment is presented in Table 4.5 for each of the three scenarios.

Table 4.5: Experiment 5: Mean and standard error of 1000 simulated mean RAEI values under several interesting flow patterns

	RAEI: Mean (Standard Error) after 15 years		
Flow pattern	Cost Effect= 1	Cost Effect= 3	Cost Effect= 9
3 year drought	0.08 (0.003)	0.20 (0.007)	1.05 (0.002)
Natural flow	0.33 (0.012)	0.50 (0.014)	1.13 (0.005)
Flood every 5 years	0.82 (0.018)	0.98 (0.017)	1.35 (0.008)

The results from Experiment 5 show that if a three year drought occurs, the mean Rehabilitation Action Effectiveness Index (RAEI) at 15 years post-treatment for low and moderate cost treatments are very low, 0.08 and 0.20 respectively (Table 4.5). Under the TRRP flow schedule, these treatments would result in a RAEI of 0.33 and 0.50 after fifteen years. However, if we force a flood to occur every five years the RAEI is 0.82 and 0.98 for the low and moderate cost treatments. In other words, under the flood scenario the low and moderate actions are roughly self maintaining. As we saw in the earlier experiments, the highest treatment (cost=9) was able to maintain itself regardless of the scenario. However, under the flood scenario the high cost treatment was also able to generate some new habitat downstream as the mean RAEI value was 1.35. The box-plots in Figure 4.6 illustrate that the five year floods result in a big increase to the median RAEI resulting from low and moderate

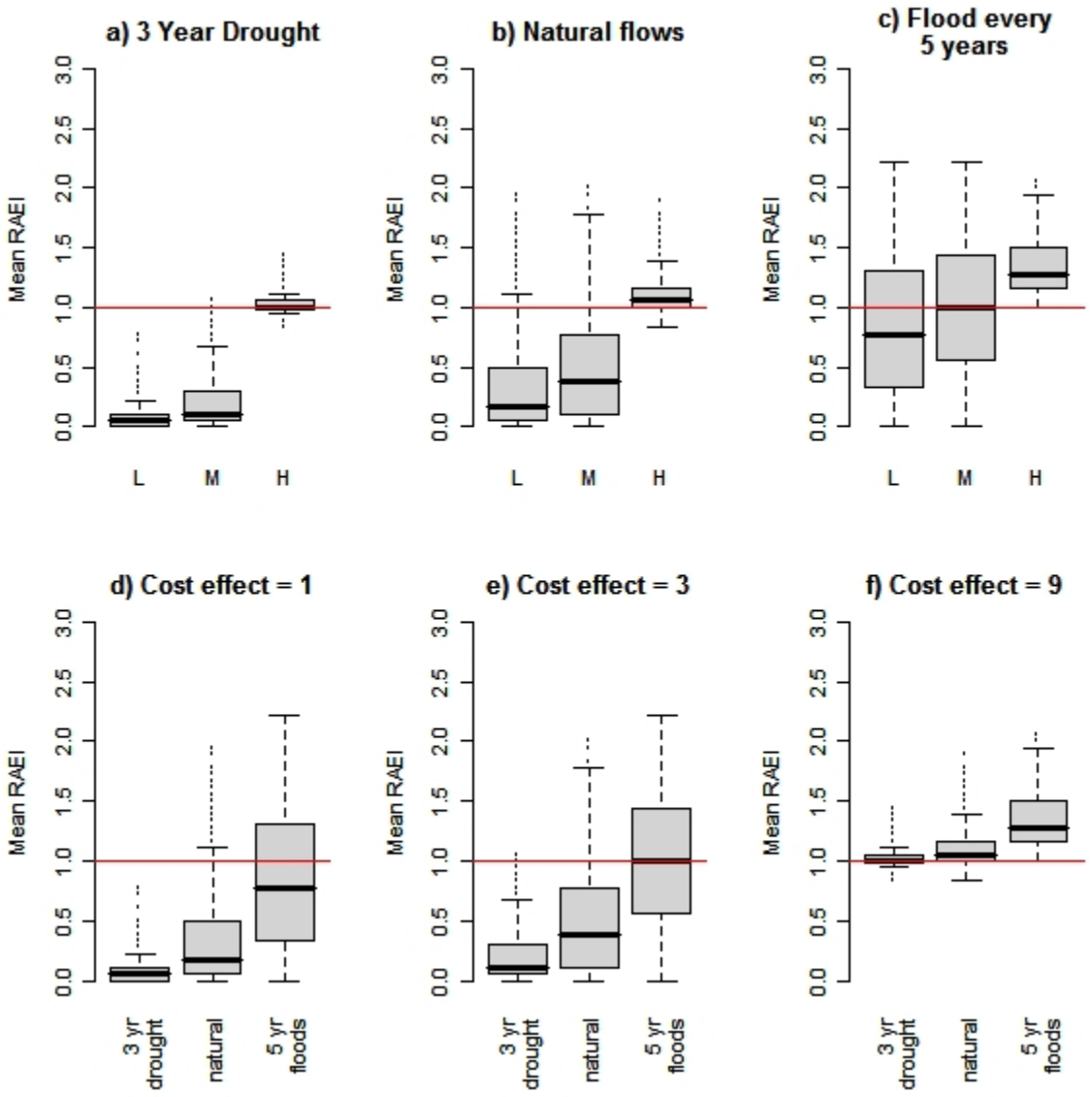


Figure 4.6: Plots a, b, and c compare all three treatment levels (L=1, M=3, H=9) on a single plot for each flow regime respectively. Plots d, e, and f are from the same data, but are plotted so that all three scenarios for a single treatment level are on a single plot.

cost actions. It may be worth examining the cost/benefit of implementing many low and/or moderate cost actions along with regular floods compared with more costly mechanical rehabilitations under the current TRRP flow schedule.

Chapter 5

Discussion

5.1 Conclusions

This simulation study was used to investigate the effectiveness of rehabilitation actions in creating salmon habitat in the Trinity River. Keep in mind that it is not intended to be a perfect reflection of reality, but instead a study of the gross effects.

Comparisons of the mean RAEI at treatment and control sites indicate that the mean habitat restoration under most treatment levels is found to be greater than those in control sites after five years, but for a difference to still be detectable in the long-term (> fifteen years) either the persistence or the size of the rehabilitation action effect must be very large.

Experiments 2 through 4 showed that it is very difficult to detect a difference in the mean RAEI among treatments regardless of the size and persistence after only five years. Additionally, Experiments 2-4 showed that if the size of the rehabilitation action effects are equally spaced, there is very little power (< 0.3 in general) to detect a difference in mean RAEI among treatment levels. The only scenario where we consistently obtained power estimates close to 0.8 occurred when the size of the rehabilitation actions had unequal spacing. In other words, when the effect of the 'high cost' treatment level was assumed to be three times the size of the 'moderate cost' treatment and nine times the size of the 'low cost' treatment. If it is realistic to believe that the different rehabilitation actions differ this much or more in their

effectiveness, then we should be able to detect a difference in the medium to long-term (ten to fifteen years).

We were also interested in determining if one experimental design would have greater power than another to detect a difference between treatments. The randomized complete block design in Experiment 3 had comparable power to the completely randomized design in Experiment 2 in its ability to detect a difference in the mean RAEI among treatments. There is strong expert opinion that the regions differ and so it would still be prudent to block on the regions, at least until we learn more about the relationship between the regions and the mean RAEI. The results suggest that there is little difference in power between Experiment 4a and 4b. In fact the power of Experiments 4a and 4b to detect a difference in mean RAEI are similar to Experiments 2 and 3 as well. This is not too surprising, since the start years are only staggered by one year and so the treatment sites share most of the annual flows. This might change if we were to separate the implementation years by more than one year, or if the expert opinion probability of scour transition matrices are changed. The current model suggests that if we are limited to six treatment sites per year and we wish to block on the six regions, we can choose to use the most convenient or cost effective of the designs in Experiments 4a and 4b.

The additional questions in Experiment 5 provided some interesting insights. First, under three year drought patterns, the mean Rehabilitation Action Effectiveness Index (RAEI) is very low for low and moderate cost actions. Since 1912, there have been three droughts of three or more consecutive years, so this is a very relevant scenario. Second, if we force a flood to occur every five years all treatment levels are able to maintain or increase the habitat area for at least fifteen years. These results suggest that good habitat will only persist through a drought if high cost rehabilitation actions are implemented. If five year floods are implemented, there is little change in the median RAEI for the high cost action but there is a large increase in the median RAEI for the low and moderate cost actions. This information should be used to improve the Trinity River rehabilitation strategy. For example, one possibility could be to complete a quick/cheap repair to the treatment sites if several years of drought occur. Another possibility could be to assess the cost/benefit of releasing a significant volume every five years even if it is not an extremely wet water

year. For example, would it be more cost effective to combine regular floods with low and moderate cost bank rehabilitation actions or the current TRRP flow regime with more expensive actions?

5.2 Discussion

One phenomenon of the current model is that it quickly tends toward poor habitat, except where there are rehabilitation actions. Currently about 14% of the Trinity River is believed to have good habitat, but when the simulation model is run for more than five years without rehabilitation actions this habitat usually disappears. This is not surprising given the extremely low probability of removing riparian vegetation in dry and critically dry years and since the three-year and older state is almost an absorbing state (Figure 2.7). It is worth asking if it is realistic for the habitat to deteriorate so quickly. If the current levels of good quality habitat are remnants from the pre-dam years that are still declining then perhaps our model is realistic. If the current level of good habitat has been stable for many years this may be an indication that further tuning is needed. For example, it is possible that the probabilities in the transition matrices are too pessimistic. It is also possible that we are missing an additional significant factor. In discussion with John Bair the riparian botanist who helped generate the model, one factor that might account for the discrepancy is rainfall on peak flow events. If a rainfall occurs simultaneously with a peak flow event the flow will be greater than those specified by the TRRP flow schedule.

The TRRP hopes to implement rehabilitation actions that are not only self-maintaining, but create habitat downstream as well. We should get clarification on how much downstream habitat they expect to create with a given action. Our model found that only the largest effect (we considered) with the longest persistence had a mean RAEI > 1 after fifteen years. If the TRRP is correct, that such actions are possible, we need to tune the model to try to capture this. There are several parameters in the model that should be reviewed with the biologists again, to see if we can address this problem. First, perhaps the dependence on upstream river segments have a bigger effect on the probability of scour. Second, we could allow

each treatment level to have a different effect on downstream river segments. Currently, the spatial dependence is strictly based on the amount of good quality habitat upstream, as opposed to the type of action that occurred upstream. Finally, the size and persistence of actions should be reviewed to ensure they are realistic.

The parameters in our current model are estimates based on our current best guess of reality. The experts are quite confident in the value of some of the parameters, but other parameters estimates were at best educated guesses. It would be interesting to consider a bayesian approach where we draw the parameter values from a distribution instead of using a point estimate. For example, if the expert believed that the probability of some event ranged from 0.2 to 0.4, we could simply draw from a uniform(0.2, 0.4) or a truncated normal distribution with mean = 0.3 rather than using 0.3 each time. Incorporating variability in the parameter estimates should result in more robust conclusions.

A concern with this study is that the experiment results rely on the placement of treatments being random. In reality, this may be difficult to implement. Treatment sites are chosen based on suitability of a site for a particular rehabilitation action and logistics such as getting permission to use and often flood the land. I would suggest that the TRRP split each region into large sections and then randomly choose a large section for a particular treatment. Hopefully within each of the large sections they can find a suitable site to implement the rehabilitation action.

5.3 Future Work

I will be working with the TRRP to further develop this model and address the concerns mentioned in Section 5.2. We should be able to make the model more realistic by allowing for rainfall on top of peak flow events. This should be fairly simple to accomplish by simply increasing the peak flow release volume in some years by some randomly generated rainfall event. It would then be interesting to compare the total habitat created by different implementation plans. For example we could compare many small/cheap actions versus a few expensive actions or a cheap action repeated every five years versus an expensive action completed every ten years. As the results

from Experiment 5 suggested, we could consider a repair strategy whenever several years of drought occur, or we could look at the cost of ensuring that a flood occurs at least once every five years. We can look at how increasing the number of years between implementation of different actions affects the power to detect a difference in mean RAEI among treatments. Additionally, the model can be generalized to allow for: unequal treatment lengths, different size river segments, different cost levels, alternative persistence functions and different downstream effects for different actions.

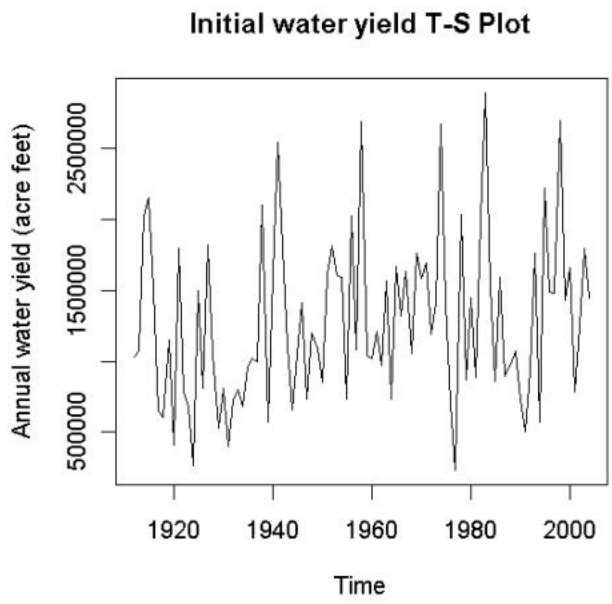
Appendix A

Analysis of Historical Water Yield Data

The annual water yield is a measure of the volume of water in acre feet that enters the Trinity River system annually. Unlike the flow measurements downstream of the dams, the annual water yield is independent of the dams. The annual water yields are available from 1912 to present. The TRRP determines which water year class each year belongs to based on the annual water yield (Section 2.2.2). In our simulation model, one of the inputs is a randomly generated water year. In order to generate realistic sequences of water years we first randomly generate an annual water yield and then use the TRRP criteria to choose the appropriate water year category. In order to generate a realistic sequence of annual water yields we fit a model to the historical annual water yield data and then generate our data from this model.

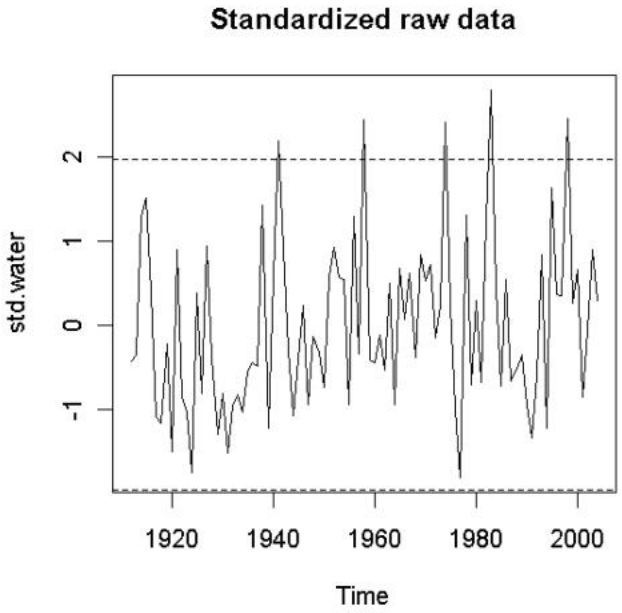
This appendix provides a brief overview of the analysis.

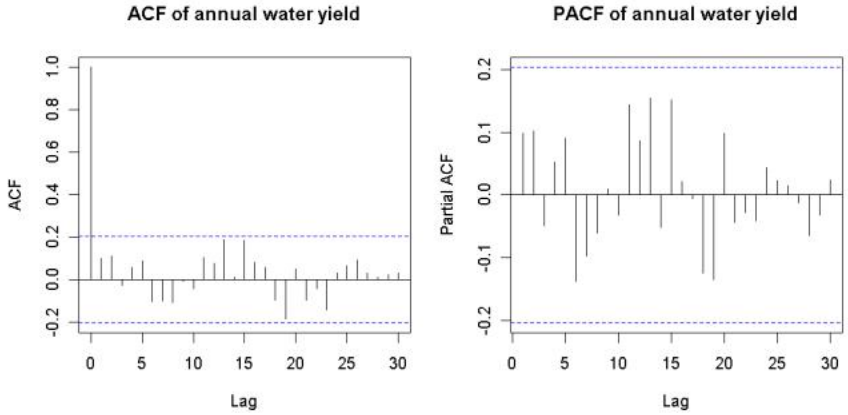
1a) Plot the raw data and look for obvious trends:



There is no obvious periodic behaviour in this plot. There is no obvious trend up or down over time. The plot looks like it might have a bit more variation for high values (except for a low value at 1978).

1b) Plot the standardized data and the ACF/PACF plots:

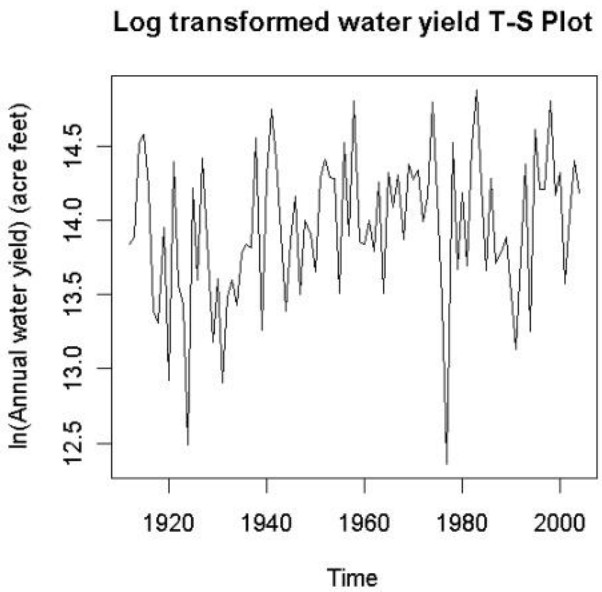




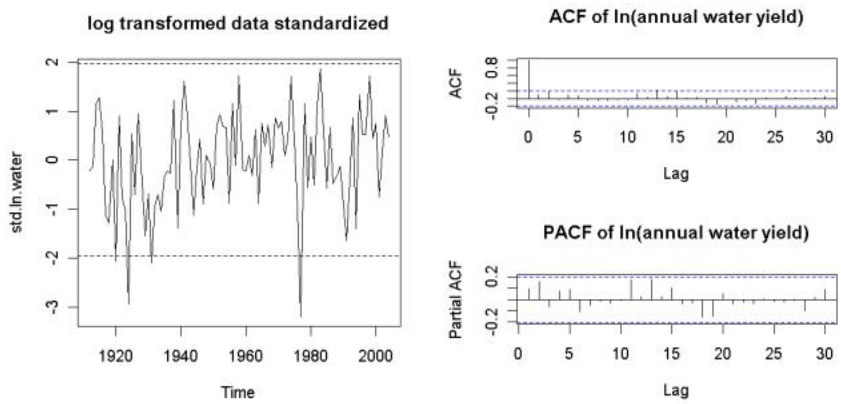
Only 5 points out of 93 are outside of ± 1.96 which is about 5%. If the standardized data is from a N(0,1) distribution, then we would expect to see only about 5% of

the values falling beyond ±1.96 or 2SE. The ACF/PACF indicate that the data has no underlying AR(p) or MA(q) process. However, I am a little concerned about the fact that all of the points beyond ±1.96 are all on the positive side, so I will look at transforming the data.

2a) Plot the log transformed data:

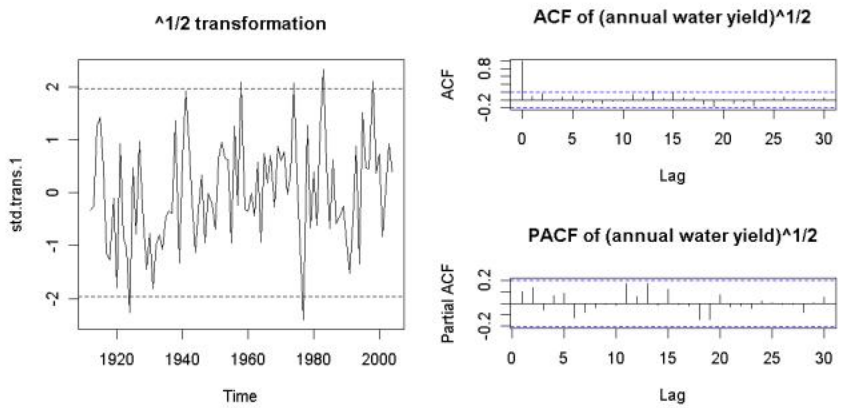


2b) Plot the standardized log(data) and the ACF and PACF of the data:



Again, there are only about 5% of the points outside of ± 1.96, but now they are all on the negative side, perhaps the log transformation was too strong.

3) Try data$^{1/2}$ transformation:



The transformed, standardized data is a bit more symmetric although now 6 points outside the lines, but that is not too unreasonable for roughly 100 years of data.

Conclusion: I will work with this transformation (data$^{1/2}$). Using this will also keep me from getting negative results when I randomly generate the data. The flow data is generated by randomly generating data from a N(0,1) distribution and then back-transforming the simulated data. The water year is then determined based on the value of the randomly generated annual water yield. I ran some checks using this transformation to generate water years and tested them against the TRRP expected frequency of 12, 28, 20, 28, 12 of each of the 5 water year types. I end up getting very close to this on average, here is an example of what I got on average from 1000 runs: 13, 24, 23, 30, 11.

Appendix B

Scour Probabilities

Table B.1: Probability of remaining bare for a given region.

Peak Flow Release	R1	R2	R3	R4	R5	R6
`Initial state` = 1						
1500	0.010	0.010	0.001	0.001	0.001	0.001
4600	0.050	0.050	0.010	0.010	0.010	0.010
6000	0.900	0.900	0.750	0.750	0.750	0.750
8500	0.950	0.950	0.900	0.900	0.900	0.900
11000	0.999	0.999	0.990	0.990	0.990	0.990
`Initial state` = 2						
1500	0.0010	0.0010	0.0001	0.0001	0.0001	0.0001
4600	0.0100	0.0100	0.0010	0.0010	0.0010	0.0010
6000	0.9000	0.9000	0.8500	0.8500	0.8500	0.8500
8500	0.9500	0.9500	0.9000	0.9000	0.9000	0.9000
11000	0.9990	0.9990	0.9900	0.9900	0.9900	0.9900
`Initial state` = 3						
1500	0.00010	0.00010	0.00001	0.00001	0.00001	0.00001
4600	0.00100	0.00100	0.00010	0.00010	0.00010	0.00010
6000	0.30000	0.30000	0.20000	0.20000	0.20000	0.20000
8500	0.80000	0.80000	0.70000	0.70000	0.70000	0.70000
11000	0.90000	0.90000	0.80000	0.80000	0.80000	0.80000
`Initial state` = 4						
1500	0.00010	0.00010	0.00001	0.00001	0.00001	0.00001
4600	0.00010	0.00010	0.00001	0.00001	0.00001	0.00001
6000	0.00010	0.00010	0.00001	0.00001	0.00001	0.00001
8500	0.00100	0.00100	0.00010	0.00010	0.00010	0.00010
11000	0.01000	0.01000	0.01000	0.01000	0.01000	0.01000

Bibliography

[1] Agresti, A. (2002). *Categorical Data Analysis*. John Wiley and Sons, New Jersey.

[2] Box, G.E.P. (1979). Robustness in the strategy of scientific model building. In R.L. Launer and G.N. Wilkinson, *Robustness in Statistics* (pp 201-236). Academic Press, New York.

[3] ESSA Technologies Ltd. and North State Resources. 2006. *Integrated Monitoring and Evaluation Plan - preliminary report*. Trinity River Restoration Program, Weaverville, CA. 315 pp.

[4] Hartman G.F, J.C. Scrivener, and M.J. Miles. (1996). Impacts of logging in Carnation creek, a high-energy coastal stream in BC, and their implication for restoring fish habitat. *Canadian Journal of Fisheries and Aquatic Sciences*, 53:237-251.

[5] Hemphill, N. (2005). Smolt Abundance. In ESSA Technologies Ltd. and North State Resources, *Integrated Monitoring and Evaluation Plan-draft*. Section 6.6. Trinity River Restoration Program, Weaverville, CA.

[6] Larsen, D.P., P.R. Kaufmann, T.M. Kincaid, and N.S. Urquhart. (2004). Detecting persistent change in the habitat of salmon-bearing streams in the Pacific Northwest. *Canadian Journal of Fisheries and Aquatic Sciences*, 61:283-291.

[7] Lorenzen, T.J. and V.L. Anderson (1993). *Design of Experiments: A No-Name Approach*. M. Dekker, New York.

[8] McBain and Trush Inc. *Summary of the United States Secretary of the Interior Record of Decision*, Trinity River Restoration Program.

[9] Montgomery, D.C. (1997). *Design and Analysis of Experiments.* 4th edn. John Wiley and Sons, New York.

[10] Montgomery, D.R., and L.H. MacDonald. (2002). Diagnostic approach to stream channel assessment and monitoring. *Journal of American Water Resource Association*, 38:1-16.

[11] Parnell, I.J. (2002). *Use of decision analysis to design a habitat restoration experiment.* M.R.M. research project no. 276, School of Resource and Environmental Management. Simon Fraser University.

[12] Paulsen, C.M. and T.R. Fisher. (2005). Do habitat actions affect Juvenile survival? An information theoretic approach applied to endangered Snake river Chinook Salmon. *Transactions of the American Fisheries Society*, 134:68-85.

[13] Roper, B.B., J.L. Kershner, E. Archer, R. Henderson and N. Bouwes. (2002). An evaluation of physical stream habitat attributes used to monitor streams. *Journal of American Water Resources Association*, 38:1637-1646.

[14] Ross, S. M.(2000). *Introduction to Probability Models.* 7th edn. Academic Press, San Diego.

[15] Solazzi, M.F., T.E. Nickelson, S.L. Johnson, and J.D. Rodgers. (2000). Effects of increasing winter rearing habitat on abundance of salmonids in two coastal Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences*, 57:906-914.

[16] Trush, W.J., S.M. McBain, and L.B. Leopold. (2000). Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences*, 97:11858-11863.

[17] U.S. Fish and Wildlife Service and Hoopa Valley Tribe. (1999). *Trinity River Flow Evaluation- Final Report.*

[18] Walters, C.J. and J.S. Collie. (1987). Experimental Designs for Estimating Transient Responses to Management Disturbances. *Canadian Journal of Fisheries and Aquatic Sciences*, 45:530-538.

[19] Weisberg, S. (1985). *Applied Linear Regression.* John Wiley and Sons, New York.

[20] Wissmar, R.C. and P.A. Bisson, editors. (2003). *Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems.* American Fisheries Society, Bethesda, Maryland.