Modeling to Improve Environmental System Management: Klamath River Thermal Refugia and the Sacramento-San Joaquin Delta

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ABSTRACT

As the problems facing water resource planners become increasingly complex, the people involved in decision-making and management need new tools to help them identify, manage, and evaluate potential options. It is not often feasible or prudent to experiment directly with the physical system to assess the impacts of various management options. Instead, computer models have become commonplace. Computer models enable managers to evaluate the impacts of changes, both large and small, on their system prior to implementing those changes in the field, identify changes that have the most promise, and integrate knowledge of a problem in a way that promotes practical understandings and potential management insights. Managers should become familiar and comfortable with both simulation and optimization modeling. This will allow them to use a wide range of models, and to use models that are more applicable to particular problems and conditions.

This dissertation focuses on gathering data and developing computer models to aid decision makers in managing systems for environmental purposes. Two environmentally sensitive areas are focused on: the Sacramento-San Joaquin Delta, part of the San Francisco Estuary, and thermal refugia for salmonids on the Klamath River in Northern California. A basic background on thermal refugia is provided, followed by the results from an intensive monitoring study at two refugia on the Klamath River. The results from a preliminary UnTRIM modeling effort of the Beaver Creek site indicate that the refuge can be modeled if sufficient data is available. Two optimization models representing a system of refugia were developed to maximize the number of fish reaching the spawning ground (in-migration model) and the estuary (out-migration model). The results from the model could be used to identify which refugia provide the most benefit. Finally, a CALVIN modeling study of different Sacramento-San Joaquin Delta management options is presented. Management of the Delta requires a balancing of the interests that rely on it, but results from CALVIN indicate that there is sufficient economical adaptability in the California water system to allow for changes in Delta water policies.

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CHAPTER 1: INTRODUCTION

INTRODUCTION

As the problems facing water resource planners become increasingly complex, the people involved in decision-making and management need new tools to help them identify, manage, and evaluate potential options. It is often not feasible or prudent to directly change the physical system to assess the impacts of various options. Instead, the technical management tools, such as computer models, have become commonplace. Computer models allow water system managers to evaluate the impacts of changes in operations and institutional and regulatory requirements on their system prior to implementing changes. The systems being modeled can include man-made infrastructure, the natural environment, or some combinations thereof.

This dissertation focuses on gathering data and developing computer models to aid decision makers in managing systems for environmental purposes. The Nation's environmental awareness grew in the 1960s and peaked in the 1970s with the passage of several significant pieces of environmental legislation, including the National Environmental Policy Act of 1969 (42 USC § 4321 et seq.), the Endangered Species Act of 1973 (16 U.S.C. § 1531 et seq.), and the Resource Conservation and Recovery Act of 1976 (42 USC § 6901 et seq.). Since that time State and Federal agencies, water districts, organization, and private citizens have had to consider the environmental impacts of their proposed actions.

The 1973 Endangered Species Act (ESA) is the Nation's strongest piece of environmental legislation. It was designed to protect endangered and threatened species by making it illegal to take (i.e., harming and killing, including destruction or adverse modifications of habitat) any species which is listed (16 U.S.C. § 1538(a)(1)). The ESA requires that all actions taken by any person (i.e., federal, state and/or private user) be done in a manner that will not adversely impact a listed species. The ESA is at the heart of many disagreements between private property rights advocates and environmental groups because the ESA has been used to prevent development in environmentally sensitive regions (NESARC, 2007). The mandates of the ESA have widely affected human activities. An example is the Sacramento-San Joaquin Bay-Delta, part of the San Francisco Estuary, where the migration of the endangered Delta Smelt often forces the State Water Project and Central Valley Project operators to shut down pumping from the Banks and Tracy Pumping Plants, respectively (DWR, 1996; FWUA, 2003). Another example is the Klamath River, where the Lost River and Shortnose sucker fish and Coho salmon have resulted in reduced deliveries to the irrigation project to ensure lake levels and minimum instream flows (USBR, 2003).

As managers of water projects with endangered species or environmentally sensitive areas, it is important to be able to evaluate the potential benefits and costs of each management alterative. Managers must consider the local, regional, and perhaps even statewide impacts that may result. To do that, managers require useful technical tools at all scales. This dissertation focuses on three scales for modeling: local, regional, and statewide.

Local models can be highly detailed, allowing for much more focused evaluation of the impacts on a small area. Often local models are data intensive, requiring detailed information about the site and process(es) that will be modeled. These tend to make only a few simplifying assumptions. Regional (or watershed) models allow managers to assess the impacts of their decision on a geographically wider area, but generally within a watershed or river course. These models also can be data intensive, but generally less detailed information is required than with a local model. Regional models tend to make more simplifications than local models. Statewide models are less detailed than local and regional models, but can be used by managers of large systems to evaluate how changes in one location may affect geographically distant locations. These models can require diverse data sets and tend to make the most simplifications, but can still provide information useful for managing a large water system.

STRUCTURE AND OUTLINE

This dissertation focuses on the Sacramento-San Joaquin Delta and the Klamath River as environmentally sensitive areas to be modeled. The Klamath River, downstream of Iron Gate Dam, provides spawning habitat or access to spawning habitat for the endangered Coho salmon as well as the threatened Chinook salmon. These fish rely on cold-water pools, thermal refugia, for survival when main stem water temperatures are excessive. The Sacramento-San Joaquin Delta is the hub of California’s intricate and extensive water supply system and provides habitat for endangered Delta smelt and other species.

This dissertation has seven chapters and three appendices.

- This chapter, the first one, briefly introduces the topics covered in the dissertation.
- The second chapter provides background information on thermal refugia and their importance for cold-water fish species.
- The third chapter contains the results from an intensive monitoring program at the Beaver Creek and Red Cap Creek thermal refugia on the Klamath River.
- The fourth chapter focuses on modeling the Beaver Creek thermal refuge using UnTRIM, a detailed finite difference hydrodynamic model.
- The fifth chapter describes two optimization models for a series of thermal refugia that could be managed as a system to maximize the number of fish arriving at the spawning ground or estuary.
- The sixth chapter presents the results from a CALVIN modeling study of changing Sacramento-San Joaquin Delta requirements and the impacts on California’s water supply system.

- The seventh, and final, chapter presents the major conclusions that came from the study of the Beaver Creek refuge, the optimization models of a system of thermal refugia, and the CALVIN modeling of California's water system. Also presented are some ideas for future research.

- Appendix A contains a list of acronyms used in this dissertation.

- Appendix B contains the description and information for the models evaluated for modeling a single refuge.

- Appendix C contains the variable definitions and values used for the systems models presented in Chapter 5.

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CHAPTER 2: THERMAL REFUGIA CONCEPTS AND IMPORTANCE

INTRODUCTION

This chapter is divided into two sections. The first part provides a basic background on the fundamental hydraulic processes occurring in a thermal refuge. The second part focuses on their importance for cold-water fish species. Hydraulically, a thermal refuge is an area of cool water produced by inflowing tributaries, springs, seeps, or through upwelling hyporheic flow or groundwater, in an otherwise warm channel. Fish use these refugia to avoid high main stem water temperatures. Thermal refugia are physically and biologically complex environments. The remainder of this discussion focuses on the hydraulic (water flow and temperature) properties of a thermal refuge.

The source waters that form the thermal refugia enter the main stem via surface and subsurface pathway(s) that are difficult to characterize spatially and temporally. Their ultimate size (volume, vertical, lateral, and longitudinal dimensions, and characteristics) is affected by main stem and tributary flows, water temperature and velocity distribution, local geomorphology, and meteorology. Temporally, refugia are often dynamic and unstable. Year-to-year variability in hydrologic, meteorologic, and anthropogenic conditions can change channel morphologies, flow (and velocity distribution), and temperature. Because thermal refugia are small compared to main stem regions, changes in flow regime can affect their size. Thus, variability combined with changes ranging from channel morphology alterations to riparian vegetation to benthic macro algae assemblages, can affect the effectiveness of thermal refugia for cold-water fish species.

GENERAL DESCRIPTION

A mixing zone will form as long as there is sufficient difference between the inflow and receiving water. It becomes a thermal refuge only if it allows cold-water fish to avoid periods of stress caused by exposure to excessive water temperatures. Also, the use of a thermal refuge depends on the conditions (water temperature, cover, proximity to food, flow rates, etc.) within the refuge, discussed below.

From a hydraulics point of view, a thermal refuge is a specific type of mixing zone, where waters from different sources mix. At the discharge point, the water has characteristics of the effluent. Some distance away, the water develops characteristics of the receiving water. In between is an area where the water is a mixture of both. The time and distance downstream required for the waters to become fully mixed depends on local conditions (flow, geomorphology, etc.) and the relative differences in the characteristics of the source and receiving waters. Mixing occurs in vertical, lateral (transverse) and longitudinal directions. The mixing rate is controlled by gradients in density, velocity, constituent concentration, and the local geomorphology.

Governing Equations

Mathematical modeling of mixing in a river can be represented using the governing equations: conservation of mass, momentum, and energy (Martin and McCutcheon, 1999). The conservation of mass and momentum generally states that mass or momentum "can neither be created nor destroyed, but merely transferred and transformed" (Martin and McCutcheon, 1994, pg. 8). The conservation of energy law is slightly different in that "the energy associated with matter entering any system plus the net energy added is equal to the energy leaving the system, or the net work done by the system, and the change in energy within the system" (Martin and McCutcheon, 1999, pg. 8). These three laws can be used to model movement of water and its constituents. The conservation of mass equation can be used to model constituent concentrations, conservation of momentum equation can be used to model flow, and conservation of energy is used for temperature modeling.

The concentration of a constituent in a body of water through time depends on two main processes (assuming similar buoyancy): advection and diffusion (or dispersion in one-dimensional modeling). When the receiving water is quiescent or has minimal velocity, diffusion or dispersion controls the mixing. When the receiving water has an appreciable velocity advection controls. Advection causes the tracer to move downstream. If diffusion (dispersion) is neglected, the concentration of the tracer within the parcel remains unchanged as it moves downstream (Figure 1). Advection is controlled by the velocity of the water. Diffusion is driven by two processes: concentration gradients and turbulence in the water. Molecular diffusion is caused by movement of the molecules from areas of high concentration to areas of lower concentration. Molecular diffusion can be quantified using Fick's Law and is more important in quiescent waters (Rutherford, 1994; Martin and McCutcheon, 1999). In moving waters, turbulence (small eddies) increase mixing. Moving waters generally have localized velocity fluctuations. The combined effects of molecular diffusion and turbulent velocity fluctuations result in turbulent diffusion (Rutherford, 1994).

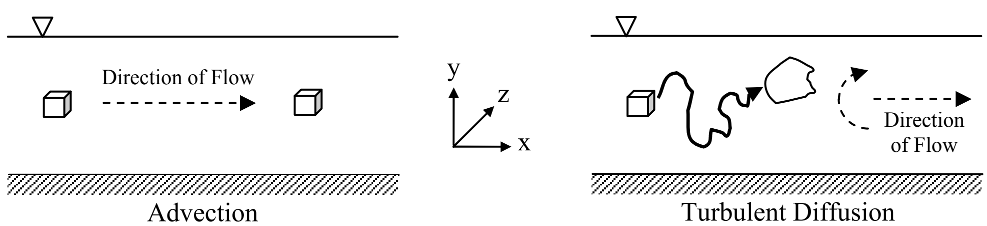

Figure 1. Movement of a Tracer Constituent Due to Advection and Diffusion (adapted from Martin and McCutcheon (1999)).

The combination of advection and diffusion describe how a concentration will change with time. For a small parcel of water, conservation of mass requires that the flux into the parcel must equal the flux out of the parcel. Let F_x, F_y, and F_z denote the flux in x-, y-, and z- directions, respectively. Let C denote the concentration and S denote any sources or sinks. Then conservation of mass can be stated as below (Eqn. 1) (adapted from Martin and McCutcheon (1999)):

$$\frac{\partial(\text{Cdxdydz})}{\partial t} = \frac{\partial F_x}{\partial x}dx + \frac{\partial F_y}{\partial y}dy + \frac{\partial F_z}{\partial z}dz \pm S \qquad (1)$$

Substituting the advection and diffusion terms for the flux (F) values, yields the generalized, three-dimension form of the advection-dispersion equation (presented below, modified from Rutherford (1994) and Martin and McCutcheon (1999)) (Eqn. 2):

$$\frac{\partial C}{\partial t} + \underbrace{\frac{\partial(uC)}{\partial x} + \frac{\partial(vC)}{\partial y} + \frac{\partial(wC)}{\partial z}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left(\frac{\partial(e_m C)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial(e_m C)}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial(e_m C)}{\partial z}\right)}_{\text{Turbulent Diffusion}} \pm S \qquad (2)$$

Where u, v, and w are the velocities in the x-, y-, and z-directions, respectively, e_m is the molecular diffusion coefficient, C is the concentration, and S is the source/sink term. If the velocity and molecular diffusion coefficient are assumed to be constant with respect to time, the equation becomes (Eqn. 3):

$$\frac{\partial C}{\partial t} + \underbrace{u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left(e_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(e_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(e_z\frac{\partial C}{\partial z}\right)}_{\text{Turbulent Diffusion}} \pm S \qquad (3)$$

Where e_i is the molecular diffusion coefficient in the x-, y-, and z-directions (from Rutherford, 1994; Martin and McCutcheon, 1999). The advection-diffusion equation determines the concentration of a conservative constituent with respect to time. Additional terms can be added to model non-conservative constituents. The advection-diffusion equation is a form of the general continuity equation (Martin and McCutcheon, 1999) (Eqn. 4).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{Q_{ss}}{\text{dxdydz}} \qquad (4)$$

Where Q_{ss} is the sum of all flow rates into the parcel (control volume) and dxdydz is the volume of the parcel. This is the basic form of the continuity equation, from which the conservation of momentum and energy equations can be derived.

One such application of the continuity equation is to model temperature within a river. Temperature can be considered a constituent of the water and the concentration term in the advection-diffusion equation needs to be modified from C to $\rho c_p T$ where ρ is the density of the water, c_p is the specific heat of the water at a given pressure, and T is the water temperature (Martin and McCutcheon, 1999). (Eqn. 5)

$$\frac{\partial(\rho T)}{\partial t} = -\frac{\partial(\rho u T)}{\partial x} - \frac{\partial(\rho v T)}{\partial y} - \frac{\partial(\rho w T)}{\partial z} + \frac{\partial}{\partial x}\left[\frac{\partial(k_c \rho T)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{\partial(k_c \rho T)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\frac{\partial(k_c \rho T)}{\partial z}\right] \pm \frac{H_{ss}}{c_p V} \qquad (5)$$

In Eqn. 5, k_c denotes the coefficient of thermal diffusivity (similar to the e_m), H_{ss} is the source/sink term, and V is the volume. In the equation above it was assumed that the specific heat of water is a physical constant and that water is an incompressible fluid. Additional assumptions can be made, such as constant density throughout the fluid, to further simplify the equation. In that case, the change in temperature with respect to time can be written as Eqn. 6:

$$\frac{\partial T}{\partial t} = -\frac{\partial(uT)}{\partial x} - \frac{\partial(vT)}{\partial y} - \frac{\partial(wT)}{\partial z} + k_c\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial y^2}\right] \pm \frac{H_{ss}}{\rho c_p V} \quad (6)$$

The equations above are presented for modeling of all three-dimensions. The number of dimensions needed to model a mixing zone depends on the level of resolution needed and the distance downstream from the source. The longitudinal distance from the source can be divided into three approximate categories: near-field, middle-field and far-field (Rutherford, 1994). In the near-field complete mixing has not occurred in any direction. In the middle-field complete vertical mixing is assumed, but complete transverse mixing has not occurred. In the far-field complete vertical and transverse mixing is assumed.

Water quality models are frequently one- or two-dimensions because the near-field is not being explicitly modeled. Instantaneous vertical mixing is assumed because shallow turbulent water mixes quickly vertically (Rutherford, 1994; Martin and McCutcheon, 1999). For those situations an average or representative depth is assumed. Far enough from the source of the constituent, in the far field, the cross section is often assumed to be homogenous (no transverse or vertical variation in concentration). In these cases the only variability occurs in the longitudinal direction.

Mixing Zones

The advection-dispersion equation can be used to calculate the concentration of a constituent in the mixing zone. While not typical, a smooth, straight, uniform, wide, rectangular channel provides a basic introduction to the mixing zone. Assume a secondary water source (for example, from a wastewater treatment plant or upwelling groundwater) flows into the channel from the middle of the channel at the bottom (Figure 2). Instantaneous vertical mixing is assumed for this simple example. As the water moves downstream it begins to mix until at some point the river is considered fully mixed (i.e., the concentration of the constituent is the same everywhere in the channel).

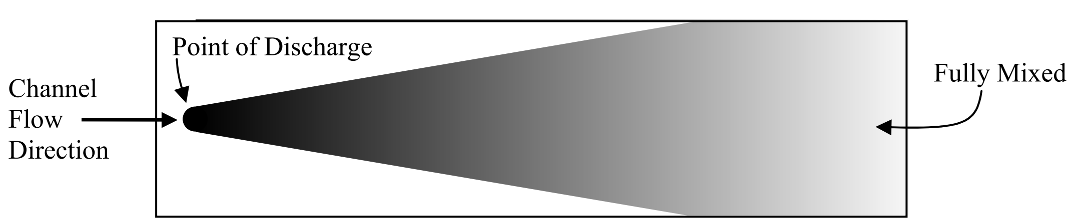

Figure 2. Simplified River with Single Point Discharge, Plan View.

For a side discharge (be it from a wastewater treatment plant or the confluence of two rivers) the theory is the same (Figure 3). At some point downstream of the confluence the water is considered fully mixed. Prior to that point, there is lateral and transverse difference in the water characteristics. Depending on the relative flow and concentration characteristics of the waters, mixing can occur relatively rapidly or take some time.

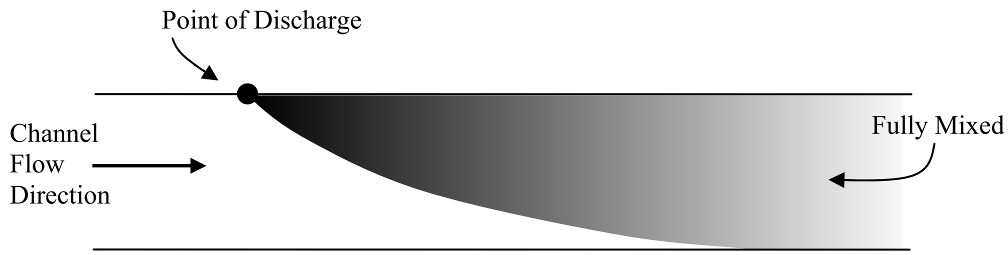

Figure 3. Simplified River with Side Discharge, Plan View.

Fischer *et al.* (1979) identified three stages of mixing:

- The initial stage where momentum and buoyancy of the discharge drive the mixing (near-field);
- The second stage when turbulence controls transverse mixing (middle-field);
- The third stage where longitudinal shear flow dispersion smoothes out the longitudinal concentrations (far-field).

Three very broad classifications of discharges are presented by Fischer *et al.* (1979): jets, plumes, and buoyant jets. Jets are momentum driven discharges, while plumes are density driven discharges. Buoyant jets are discharges driven by both momentum and density. Near the source of the discharge, regardless of the type of discharge, flow is usually controlled by the initial conditions of the discharge, but eventually all discharges behave like plumes. Jets and plumes can be either turbulent or laminar, but are generally turbulent (the motion of the fluid has local velocities and pressures that fluctuate randomly).

Fischer *et al.* (1979) state that turbulent jet behavior depends on (i) jet parameters, (ii) environmental parameters, and (iii) geometric factors (pp. 315). Jet parameters describe the condition of the discharge at the discharge point, including velocity, density, and constituent concentrations. The environmental factors refer to the ambient conditions of the receiving waters. Finally geometric parameters refer to the local geometry of the receiving water body and the geometry of the discharge device.

Wastewater discharges are generally classified as buoyant plumes. At the point of discharge, they are momentum driven, but at some distance away buoyancy-effects dominate. Natural discharges (such as surface water confluences and groundwater upwelling) also can be buoyant plumes, driven initially by momentum. There are two types of buoyant plumes: positive and negative. A positively buoyant plume has a less dense discharge than the receiving water. The discharge rises after the momentum effects are overcome. A negatively buoyant plume has a denser discharge the receiving water and sinks after the momentum effects are overcome. Theoretically, in a stratified water body, the discharge will ultimately rise (or sink) to water of similar density.

As the effects of momentum are overcome, the plume begins to spread. As it spreads, dilution occurs until at some point the concentrations of the plume constituents are the same as in the surrounding waters. At this point, the plume is fully diluted and mixing is complete.

However, rivers are rarely smooth, straight, uniform, rectangular channels. "Natural channels differ from uniform rectangular ones in three important respects: the depth may vary irregularly, the channel is likely to curve, and there may be large sidewall irregularities" (Fischer *et al.*, 1979, pg. 109). Likewise, surface water confluences and groundwater upwelling do not necessarily have the same properties as a wastewater discharge which often enter the waterway via a pipe.

In the simplified river example, the cross section was assumed to be rectangular, meaning that the depth from the water surface was the same everywhere. Most rivers have a deeper area (thalweg) and a shallower area near the banks (often part of the floodplain or connected to the floodplain) (Figure 4). Transverse variation in cross section geometry generally results in varied velocity distributions and flow conditions across the river and along the river. The velocities in the thalweg are higher than in shallower bank areas. The cross sectional shape also varies with lateral distance (Figure 4), sometimes quite drastically in terms of width and depth.

The cross section of a river is further complicated by the presence of boulders and other underwater features that can affect flow patterns. Subsurface features create complexity in the channel by providing localized areas of varying velocity gradients. Crowder and Diplas (2000) indicated that fishes use areas immediately downstream of boulders as velocity shelters, reducing energy needed to maintain their position. The sinuous shape of a river often leads to the variation in the channel size and shape with linear distance, creating localized flow separation and the formation of secondary flow cells.

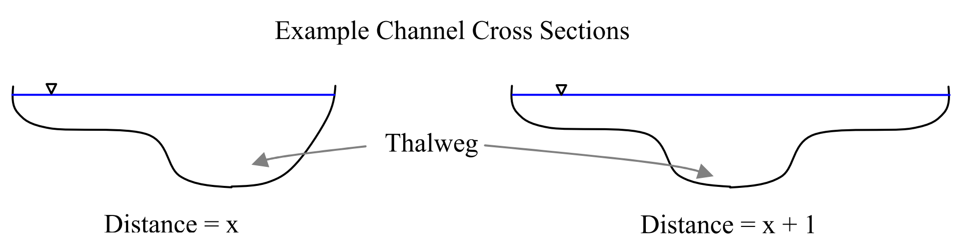

Figure 4. Examples of Irregular River Cross Sections.

The simplified example assumed vertical mixing is instantaneous. For quickly moving waters that resist strong stratification, a vertically mixed assumption is sufficient

(Rutherford, 1994; Martin and McCutcheon, 1999). For quiescent or slow moving waters with stratification incoming water will seek water of a similar density.

The simplest flow is steady, uniform, and laminar. Confluences that often form refugia in natural rivers, generally have unsteady, varied, turbulent flow. If the effects of small changes in the flow are not needed in the analysis, steady flow could be assumed, but in the field velocity changes with respect to time and space. Upstream and downstream of the confluence there might be steady, uniform flow conditions (even approximately), but natural systems are rarely laminar (Chaudhry, 1993, pg. 7).

THERMAL REFUGIA

Thermal refugia are a specialized form of a mixing zone. Physically they form in areas where a cold-water source flows into a warm river. Their usefulness depends on their proximity to and use by the fish species of interest. Their functionality depends on their location, size, stability, temperature, accessibility, and other factors.

Salmon Habitat

Despite their complexity and variability, thermal refugia provide important temperature habitat for cold-water fish survival. Cold-water dependent fishes, such as salmonids, use thermal refugia to survive during the hottest parts of the year when main stem river temperatures are excessive. Because different fish species have different temperature tolerances, a thermal refuge may be able to support only some fish species or may support different fish species at different times.

Salmonids are a class of temperature sensitive fish species with preferred tolerances that generally range from 12ºC to 18°C (Moyle, 2002; NRC, 2004). The temperature at which waters become excessively hot vary with species (Gibson, 1966; Kaya, 1977; Matthews *et al.*, 1994) and life stage (Sauter *et al.*, 2001). Three salmonids of particular interest for thermal refuge studies are coho (*Oncorhynchus. kisutch*), spring, fall and late fall-run Chinook (*O tshawytscha*), and steelhead (*O. mykiss*) trout.

Coho are the most temperature sensitive salmonid species, with an upper water temperature tolerance of 12°C (Moyle, 2002; NRC, 2004). Chinook are the next most sensitive with a preferred upper water temperature tolerance of 16°C (Moyle, 2002; NRC, 2004). Steelhead are the least sensitive (of the three presented here), with an upper temperature tolerance of 18°C (Moyle, 2002; NRC, 2004). All three species can survive short exposure to waters that range in the mid to upper 20°C range, provided other favorable factors exist (Moyle, 2002; NRC, 2004), such as low velocity and abundant (or unlimited) food. When discussing maximum water temperature tolerances, this generally refers to extended exposures. It is unlikely that water temperatures in a natural watercourse will reach levels that would be instantaneously lethal to the fishes. Rather prolonged exposure to high temperature water is a concern for managers of waters that provide salmonid habitat.

High temperature water increases fish mortality (Ebersole *et al.*, 2001), reduces reproduction (migration and spawning) and rearing capabilities (Berman and Quinn, 1991), and limits growth and development (Keller, 1995; Peterson and Rabeni, 1996). It has been postulated that the fish use the cold-water patches for thermoregulation (Matthews *et al.*, 1994; Nielsen *et al.*, 1994; Torgersen *et al.*, 1999; Ebersole *et al.*, 2003), where fish seek out colder waters to reduce their metabolic energy requirements and leave more energy available for other activities.

Numerous studies exist of various fish species (primarily salmonids) in rivers in California, Oregon, and Washington (Gibson, 1966; Kaya *et al.*, 1977; Hankin and Reeves, 1988; Berman and Quinn, 1991; Matthews *et al.*, 1994; Nielsen *et al.*, 1994; Roper *et al.*, 1994; Keller *et al.*, 1995; Belchik, 1997; Matthews and Berg, 1997; Torgersen *et al.*, 1999; Ebersole *et al.*, 2001; 2003a; 2003b). Many studies focus on the extent to which cold-water fishes use cold-water patches. Distinctions are drawn between cold-water patches that result from surface water confluences and those that occur from upwelling sub-surface flow (be it hyporheic or groundwater flows). Some studies focused on the presence or absence of fish in the theorized refugia (Gibson, 1966; Berman and Quinn, 1991; Keller, 1995; Matthews *et al.*, 1994; Roper *et al.*, 1994; Belchik, 1997; Torgersen *et al.*, 1999), while other studies focused on fish density (Kaya *et al.*, 1977; Hankin and Reeves, 1988; Nielsen *et al.*, 1994; Matthews and Berg, 1997; Ebersole *et al.*, 2001; 2003b). Finally, some studies focus on a single (or few) sites in isolation (Gibson, 1966; Kaya *et al.*, 1977; Matthews *et al.*, 1994; 1997; Nielsen *et al.*, 1994), while others focus on a suite of refugia (Berman and Quinn, 1991; Hankin and Reeves, 1988; Roper *et al.*, 1994; Keller *et al.*, 1995; Belchik, 1997; Torgersen *et al.*, 1999; Ebersole *et al.*, 2001; 2003a; 2003b).

Kaya *et al.* (1977) concluded that fish were present in a refuge only in limited numbers on cool days and in greater numbers on summer days with the warmest air temperature. On cool days main stem temperatures were lower and the fish did not need to use the cold-water patches to survive. In general, the studies of salmonids indicated that fish did use the cold-water patches when main stem temperatures were excessive. However, Ebersole *et al.* (2001) could not identify a consistent temperature threshold for fish behavior, but Nielsen *et al.* (1994) concluded that there is a weak relationship between fish behavior and the temperature of the water, indicating that other factors also influence fish behavior. Matthews *et al.* (1994, pg. 562) theorize that "proximity to competitors, predators, prey, cover, and habitat features," in addition to temperature, will influence behavior of fish and may account for some variability in individual fish behavior. Ebersole *et al.* (2001) also identified water quality (primarily dissolved oxygen) and proximity to food as other important factors affecting fish use of refugial areas.

Thermal Refuge Characterization

Thermal refugia are physically and biologically complex environments. Their size, persistence, and efficiency are all affected by main stem and tributary flows, velocity distribution and water temperature, local geomorphology, and meteorology.

One requirement of a thermal refuge is that a cold-water source flows into a body of warmer water. A formal threshold temperature difference has not been defined, but generally a pocket of cooler water is considered a thermal refuge when water temperatures are about 2 to 3°C cooler than that of the surrounding water (Ebersole *et al*., 2001; 2003a). If the cooler water is still above the temperature tolerance of the fish, the refugial value of the site would be poor, but perhaps still favorable relative to conditions in the main stem. In situations where main stem temperatures are excessive, a functioning or impaired thermal refuge may be formed wherever cooler water is present. Warm-water thermal refuges have also been identified for warm-water fish species (Peterson and Rabeni, 1996), often formed by cooling water effluents from thermal power plants. Many thermal refuge properties are the same for cold- or warm-water refugia, but the remainder of this discussion focuses on cold-water refugia.

In river systems, cold-water sources include inflowing tributaries, springs, seeps, upwelling hyporheic flow, and groundwater. The characteristics of the cold-water source and the relative differences with the characteristics of the warmer-receiving waters have a great impact on the refugia. Thus a thermal refuge may be formed along the bank, if the cold-water flows in from the side or it may form in the main stem from an upwelling or seeps.

Consider the main stem of a river augmented by a cold-water tributary (Figure 5). The main stem has a known flow (Q_{ms}) and temperature (T_{ms}). The tributary also has a known flow (Q_{cw}) and temperature (T_{cw}). Generally flow in the tributary is less than that of the main stem. If the tributary temperature is higher than that of the main stem, a warm-water temperature refuge is formed; this is of interest when studying over-wintering salmonids (Cunjak, 1996; Harper and Farag, 2004).

Two semi-distinct thermal areas are present at the confluence. One area contains water primarily from the cold-water source. This is the heart of the thermal refuge and where the coldest water is present (unless local features, such as shallow depths, woody debris, and/or groundwater and seep inflows affect water temperatures). Further out is a transition zone, where tributary and main stem waters mix. The water is neither predominately from the creek nor the main stem. Temperatures are (generally) warmer than the tributary, but cooler than the main stem. The transition zone is sometimes referred to as the mixing zone or shear line. The physical area of the thermal refuge (lateral, longitudinal, and vertical extents) is a function of the water conditions (flow and temperature) and the local geomorphology.

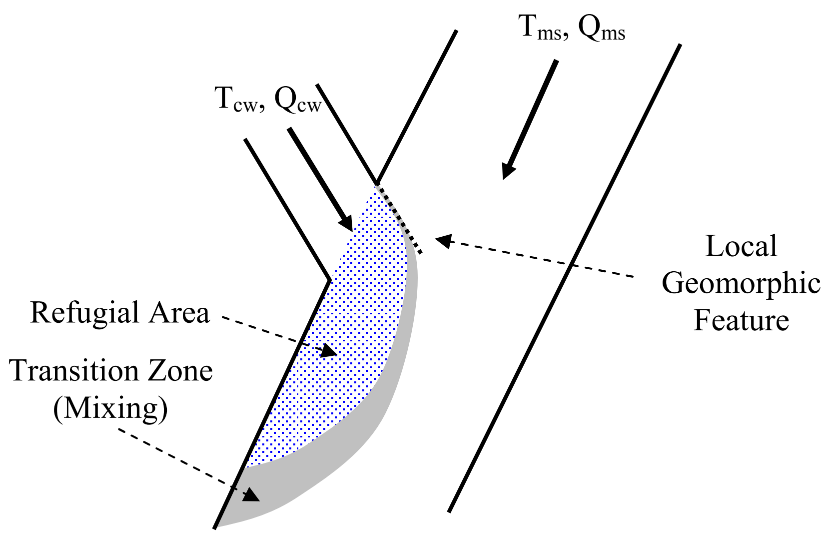

Figure 5. General Schematic of a Thermal Refuge.

Flow and Temperature Conditions

The flow and temperature difference between the main stem and the cold-water source affect both the size and efficiency of a thermal refuge. Poole and Berman (2001, pg. 788) state that, "the primary determinants of stream temperature are climatic drivers (such as solar radiation, air temperature, and wind speed), stream morphology, groundwater influences, and riparian canopy conditions." All four factors are affected by human and natural activities. Human activities can rapidly alter stream morphology and riparian canopy conditions. Stream morphology can be changed most easily by altering or augmenting gravel bars and woody debris to inhibit the mixing. Additional riparian vegetation can be planted along the stream bank to increase shading; however, due to the short residence time of water in the refugial area, such vegetation may not affect thermal conditions significantly within the refuge. Human activities have less immediate effect on climatic drivers and groundwater (though both can be influenced in the long-term).

Temperatures in the main stem and the tributary have a diurnal rise and fall. The warmest temperatures are usually in the afternoon and early evening and the coldest temperatures in the late night and early mornings. Both main stem and tributaries have a diurnal pattern, but smaller water bodies usually have a more pronounced variation; diurnal temperature variation is usually greater in the tributary. Tributaries cool and warm more quickly due to their lesser thermal mass. Subsurface flow, depending on the source, also may have a diurnal pattern, but is usually dampened. If the subsurface flow originates from the tributary (tributary waters flowing in subsurface pathways), the water will retain some of the thermal pattern of the source. As the day progresses the difference between the tributary and main stem decreases. For the thermal refuge to be present, the tributary water temperatures must be less than the main stem.

In addition to relative temperature differences, the efficiency of a thermal refuge is also affected by relative flow conditions. If a small tributary enters a large main stem, the ability to form a large thermal refuge is limited. However, small pockets of cold water with fish present have been observed (Gibson, 1966; Kaya *et al.*, 1977; Hankin and Reeves, 1988; Berman and Quinn, 1991; Matthews *et al.*, 1994; Nielsen *et al.*, 1994; Roper *et al.*, 1994; Keller *et al.*, 1995; Belchik, 1997; Matthews and Berg, 1997; Torgersen *et al.*, 1999; Ebersole *et al.*, 2001; 2003a; 2003b; Deas *et al.*, 2006). The difference in flow rates governs the initial mixing of the cold water with the main stem. If the cold-water source has greater momentum than the main stem, a band of cold water can "jet" out into the main stem. Likewise, if the main stem moves slowly or if the cold-water source enters quiescently, mixing may be slowed. Changes in flows, both in the creek and the main stem, affect the size (length, width, and depth) of the thermal refuge. Higher main stem flows may also limit tributary flows to bank sides and elongate the refuge (Deas *et al.*, 2006).

Low velocity areas, such as scour pools or backwater areas, can provide additional benefits for fishes. These areas are somewhat isolated from higher flow velocities in the main stem, but are still connected to the river. If geomorphic conditions are favorable, the backwater area can receive cold-water inflows, but because these areas are not subject to high main stem flows, mixing of the warm river water is dampened and the area of cold water is enlarged or preserved. Low velocity areas also benefit fish because of reduced energy expenditures to maintain position (Berman and Quinn, 1991). Low velocity backwater areas also accumulate macrophytes and organic matter, providing additional cover for fish.

Inflows from seeps, upwelling hyporheic flow, and groundwater also can form thermal refugia. These subsurface flows provide cold water that is relatively isolated from short-term meteorological conditions and can enter into a main stem at a variety of locations. Surface flow can create isolated pockets of cold water or provide colder water temperatures along the bed depending on how the upwelling occurs. There have been some concerns regarding quality of the water entering into the channel (primarily regarding low dissolved oxygen (DO) from groundwater sources), but even in low DO conditions fish have been observed using cold-water patches (Nielsen *et al.*, 1994; Matthews and Berg, 1997; Ebersole *et al*., 2003a).

Thermal refugia are variable in lateral, transverse, and vertical dimensions, with lateral and transverse variability getting most of the attention. However, vertical differences can significantly affect the efficiency and quality of a refuge. Upwelling subsurface flows and surface water inflows can increase vertical water temperature differences and stratification due to density differences. Where cooler, denser waters enter warmer water systems, vertical stratification can occur with warmer temperatures near the surface and colder water near the bed.

In thermal refugia stratification is caused primarily by water entering the main stem at a different temperature and by local meteorological conditions. Colder waters entering a warmer main stem seek a similar density and tend to “plunge” or “sink.” Similarly, surface warming due to meteorological conditions can result in vertical temperature stratification. However, in river systems with appreciable stream velocities, mixing in all three dimensions (vertical, lateral, and longitudinal) tends to minimize stratification, with the exception of quiescent areas or regions isolated from mixing (backwaters, areas of vegetation growth, etc.).

Geomorphology & Local Conditions

Local geomorphology also can affect the size and shape of thermal refugia. Substrate, channel slope, and channel form of both the main stem and tributary control the shape and size of the refuge area. In alluvial systems, seasonal high flows or floods may change the shape of the confluence considerably from season to season or year to year. Further, the creek water may infiltrate into the bed upstream of the confluence and emerge into the main stem as upwelling hyporheic flow or groundwater. If bedrock is prevalent, such opportunities may be limited and the refuge may be more stable than those formed by alluvial channels. Of course refugial areas occur throughout the continuum from completely alluvial to bedrock dominated. Other local factors that can influence the shape and size of refugial areas are woody debris and woody riparian vegetation, both providing complexity to channel form (as well as habitat for fish).

At the confluence, the geomorphology affects how much mixing occurs initially. Important parameters defining the confluence include the angle at which the tributary enters the river, the relative difference in water surface elevations, the width to depth ratio of the tributary, and any geomorphic features (such as gravel bars or woody debris). In Figure 6 the tributary enters almost perpendicular to the main stem and the water surface elevation (and bed surface elevation) in the tributary is significantly higher than that of the main stem. As water drops from the tributary into the main stem it gains momentum and forms a jet-like column that cuts into the main stem. Figure 7 presents a surface water source that flows into the alluvium before entering the main stem, arriving as an upwelling hyporheic flow or shoreline diffused flow. In Figure 8 the tributary enters at a gentler angle and the relative water surface elevations are not as significant as in Figure 6. Additionally, in Figure 8 the confluence is protected by a gravel bar. Local geomorphic features, like the bar in Figure 9, can impede the main stem water from interacting with the tributary.

Figure 6. Sharp Drop and Perpendicular Angle Tributary Confluence (Elk Creek, CA).

Figure 7. Surface Water Source Infiltrating into the Alluvium at the Confluence (Red Cap Creek, CA).

Figure 8. Gentle Entry Angle, with Little Elevation Difference Confluence (Beaver Creek, CA).

Figure 9. Local Geomorphic Feature (Rocky Bar) Impeding Mixing (Beaver Creek, CA).

Meteorological Conditions

Climatic conditions (air temperature, solar radiation, relative humidity, wind speed, precipitation, etc.) can significantly affect tributary and main stem water temperatures. During summer, warm weather conditions increase water temperatures due to clearer skies and increased incident solar radiation to both the overlying air and water bodies, while cold weather conditions reduce average water temperatures due to increased cloudiness and decreasing incoming solar radiation. Solar radiation refers to the amount of short-wave energy reaching the earth's surface from the sun and primarily depends on the location of the site, the time of the day, the date, atmospheric turbidity, cloud coverage, and riparian and topographic shading.

Along with influencing the overall water temperatures, meteorological conditions can also affect vertical water temperature gradients. Water temperatures at the surface are influenced more by meteorological conditions than water at the bed (if there is sufficient depth) (Deas *et al.*, 2006). Warmer water at the top and cooler water at the bed encourages vertical stratification. Strong enough temperature differences between the surface and bed can limit the fish to only part of the water column for temperature refuge.

Relative humidity (RH) is another important meteorological indicator. RH indicates how saturated the air is with water vapor and depends on the elevation of the site, air temperature, and vapor pressure. A RH of 100% indicates that the air is completely saturated with water and unable to hold additional moisture at the current air temperature, preventing evaporative cooling. Evaporative cooling is generally reduced with high RH conditions.

Wind is a source of energy that can increase mixing of surface and bed water, and reduce vertical stratification, although its effects on river systems with appreciable velocity are greatly reduced. Precipitation may temporarily increase the stage in both the tributary and the main stem depending on the location of the rainfall. Increased stage can impede or enhance mixing.

SALMONID LIFE STAGES

The Klamath River thermal refugia study, discussed below, focused on three types of salmonid: coho, Chinook, and steelhead. As mentioned above, all three are temperature sensitive species. For a detailed description of salmonid life cycle in the Klamath River basin see Brown and Moyle (1991), Moyle (2002), and NRC (2004); only a brief discussion is provided herein.

Klamath River coho have a three-year life span. Adults return to their natal habitat to spawn and die in late fall (October and November). Eggs hatch in the early winter, but the Alevins remain the gravel until spring. Peak fry emergence occurs in April and May. Coho remain in freshwater for the first year of their life before smoltification begins. As fry and parr, coho must find over-summering and over-wintering habitat. At the same time that the fry are emerging, the smolts (1+ coho) begin to move into the estuary and out into the ocean. They remain in the ocean until 3 years old, when they return to river and begin to migrate upstream.

The Klamath River hosts populations of Fall- and Spring-run Chinook salmon. Fall-Run Chinook enter the river system, hold a few weeks and then return to their natal habitat to spawn and die in the fall. Adult Spring-run Chinook return to the river in spring and summer (April through July) and hold until fall, when they spawn. Fall-run Chinook emerge from the gravels in late-winter and early-spring (February through April), while Spring-run Chinook emerge in late spring (April through July). Chinook do not have to spend the first in year freshwater, but Spring-run typically does. Fall-run fry and parr can either over-summer in the river and tributaries or migrate downstream to the estuary. Spring-run typically remains in freshwater until the next spring. Both types of Chinook remain in the ocean until three years of age, when they return to spawn.

The most common salmonid in the Klamath River basin is the steelhead. They enter the river anywhere from late summer to late winter. Spawning typically occurs in the late spring with fry emergence occurring in early summer. Steelheads generally spend two years in freshwater before smoltification begins. They spend another one to three years in the ocean before returning to spawn.

The populations of all three salmonid species are augmented by Trinity River and Iron Gate Hatcheries. In general, hatchery fish out-number wild and natural fish. Hatchery fish releases can augment an existing population, but these fish also compete with wild or natural fish for habitat and food. Hatcheries fish can have different run times from the natural or wildlife fish by weeks or months, which can allow them to out-compete wild fish for habitat and food (Busby *et al.*, 1996). The extent to which hatcheries hurt or help wild populations is still uncertain in the Klamath River basin.

CONCLUSIONS

Thermal refugia are complex and challenging environments to characterize. Refugia are highly variable in time and space, and as mentioned above, many factors can affect the size, shape, and function of refugia. They play an important role in cold-water fish survival during periods when main stem temperatures are excessive. The effectiveness of each refuge depends on several site specific parameters (geometry of the confluence, relative difference in water temperatures, presence or absence of groundwater seeps and hyporheic flow, meteorological conditions, etc.). However, a few representative refugia could be selected for intensive field studies. At these sites, the detailed field studies could help to identify the critical relationships between time of day and thermal refugia size, fish utilization, and potential flow management implications.

Although some variability among refugia is largely beyond the control of resource managers, variability is a potentially valuable characteristic of these systems. Assessing the effects that different flow regimes have on a group of refugia could be beneficial in identifying how groups of refugia would work together in the system. This suite of cool water resources that anadromous fish use seasonally may vary dramatically from year-to-year. However, because of the diversity among the various refugia, a synergistic effect of the group as a whole may be to provide the system with a robust habitat component and assist anadromous fish populations during summer months.

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CHAPTER 3: THERMAL REFUGIA OF THE KLAMATH RIVER, CALIFORNIA

INTRODUCTION

In the previous chapter the basic concepts of a thermal refuge were presented, along with the importance of the cold-water habitat for the survival of salmonids during the summer periods. As stated, thermal refugia are complex and difficult to characterize because they are highly variable. The usefulness of the refugia depend on several localized parameters, including, but not limited to, main stem and tributary flow rates and temperatures, geometry of the confluence and refugial area, groundwater seeps and hyporheic flows, meteorological conditions, presence of cover, and availability of food.

Detailed studies at all thermal refugia in a system are generally not possible. However, studies of a few representative locations might be sufficient to provide managers with a generalized understanding of how different types of refugia respond to changes. This chapter presents results from two detailed field studies at known thermal refugia in the Klamath River.

BACKGROUND

The Klamath River, in Southern Oregon and Northern California (Figure 10), is a major source of water for the irrigation, hydropower, recreation, and commercial, tribal, and recreational fisheries. The free flowing river reaches also provide habitat for coho (*Oncorhynchus kisutch*), spring, fall and late fall-run Chinook (*O. tshawytscha*), and steelhead (*O. mykiss*) (USBR, 2004). The river can be divided into two portions: the upper and lower Klamath River. The upper Klamath River, from the headwaters in Southern Oregon to Iron Gate Dam at river mile (RM) 190, includes Lake Ewauna, Keno Reservoir, and the Klamath Irrigation Project. The lower river, from Iron Gate Dam to the ocean, is free flowing. Prior to reaching the ocean, the Klamath River combines with the Shasta (RM 177), Scott (RM 144), Salmon (RM 66) and Trinity (RM 43) Rivers, along with several substantial creeks. Fish passage is unblocked from the ocean to Iron Gate Dam, yet main stem water quality and water quantity conditions have come under increasing scrutiny as potential cause of the decline of Klamath River anadromous fishes.

In 2002 the National Marine Fisheries Service (NMFS) issued its Biological Opinion (BO) for the U.S. Bureau of Reclamation (Reclamation) Klamath Project Operations. In the BO, NMFS indicated that decreased flows from Iron Gate Dam to the Klamath River posed an increasing threat to the continued existence of the coho salmon, a state and federally listed endangered species. While NMFS indicated that decreasing flows posed a threat to the coho, the National Research Council (NRC, 2002) offered the hypothesis that increased main stem Klamath River releases from Iron Gate Dam might reduce the effective size of thermal refugial areas by “causing more effective mixing of the small amounts of locally derived cool water with much larger amounts of warm water from points upstream.” Thus, from a management perspective, it was necessary to assess how different flow regimes would affect thermal refugia and what could be done to protect pockets of cooler water used by anadromous fish.

To investigate the effects of different summer Iron Gate Dam flow regimes on thermal refugia habitat in the Klamath River main stem, Reclamation engaged in a multi-year study. The purpose of this study was to monitor the physical and biological characteristics of main stem thermal refugia under various hydrologic conditions. A pilot study was conducted in 2002 and 2003 and an intensive on-the-ground study at the Beaver Creek (RM 162) and Red Cap Creek (RM 53) thermal refugia was conducted in the summers of 2004 and 2005 (Sutton *et al.*, 2002; Deas *et al.*, 2003; Deal *et al.*, 2006).

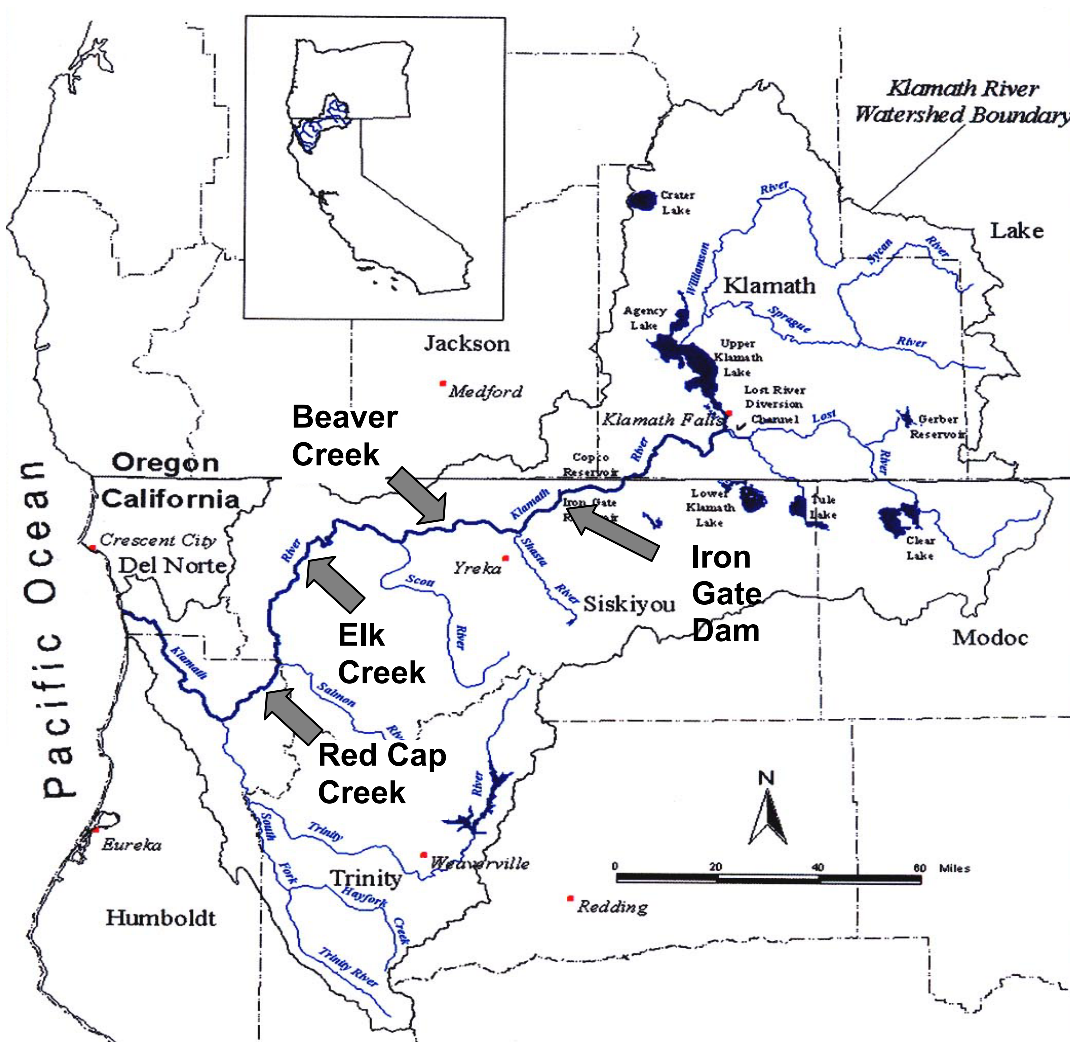


Figure 10. Project Study Area.

PILOT AND PRELIMINARY STUDIES

The intensive studies of 2004 and 2005 were based on the pilot studies of 2002 and 2003. Over the four year study period, monitoring at varying degrees of detail occurred at four sites. The most intensive monitoring occurred at Beaver and Red Cap Creeks, with some detailed work initially at Elk Creek. A fourth creek, Tom Martin, was identified in the fourth year and minimal monitoring occurred.

2002 Pilot Study

The pilot study consisted of a two day deployment in August 2002 at Elk Creek (RM 105), a readily assessable refuge. Approximately 20 thermistors were deployed in and around the refuge, main stem Klamath River, and Elk Creek. This pilot level study provided insights into deployment methods and provided some preliminary information regarding thermal refugia:

- The thermal refuge had internal spatial heterogeneity of thermal conditions over the diurnal cycle,
- The refuge had short duration temporal variation of thermal conditions, and
- Juvenile salmonids were observed in the refuge and main stem Klamath River during the morning hours, and restricted themselves to the refuge during the middle of the afternoon (Sutton *et al.*, 2002).

Detailed descriptions of study design and findings appear in Sutton *et al.* (2003).

2003 Study

The 2003 study included Elk Creek plus two additional thermal refuge sites: Beaver Creek (RM 162) and Red Cap Creek (RM 53) (Figure 10). These three creeks were intended to approximate conditions in the upper, middle, and lower portions of the Klamath River below Iron Gate Dam. Deployment methods included those from 2002, as well as the approach of deploying devices remotely on the river bed to be retrieved several days or weeks later. The deployment extended over seven days at Beaver and Elk Creeks and twelve days at Red Cap Creek in August 2003. In addition to confirming the previous findings at multiple refugia, four major conclusions were drawn from the 2003 study:

- Refugia vary in stability; some change little year-to-year while others can change significantly. Beaver Creek refuge area was the most stable, with Elk and Red Cap Creek refuge areas varying considerably year-to-year in size and temperature.
- Beaver Creek was more prone to change due from upstream flow management than Red Cap Creek or Elk Creek, because it is located closer to Iron Gate Dam.
- Vertical observations indicated that shallow subsurface flows enter the river at colder temperatures than the surface water in the tributaries.
- Refinements to the method used for device deployment were implemented to allow monitoring of a larger area for a longer period of time.

2004 and 2005 Study

The study plan for 2004 and 2005 refined and expanded the method developed during 2002 and 2003, and implemented many recommendations from the 2003 report (Deas *et al.*, 2003) (Table 1). Physical and biological characteristics of thermal refugia under various main stem hydrologic conditions were studied, with an intensive on-the-ground study at two thermal refugia: Beaver Creek and Red Cap Creek. In 2004, only four temperature monitoring devices were deployed at Elk Creek to retain continuity with previous years' studies. In 2005, no monitoring occurred at Elk Creek; instead coarser monitoring occurred at Tom Martin Creek (RM 143). Results for the intensive study at Beaver and Red Cap Creek are presented here. Results for Elk and Tom Martin Creek are omitted, but are available in Deas *et al.* (2006).

The two primary refugial areas (Beaver and Red Cap Creek) were identified as representing the upper and lower reaches of the free flowing Klamath River between Iron Gate Dam and the Pacific Ocean (Figure 10). Table 1 summarizes the recommendations from the 2003 report, and indicates which ones were incorporated in the summer of 2004/2005 fieldwork.

Table 1. List of Recommendations from the 2003 Report and Implementation in 2004 Summary.

Recommendation in 2003 Report	Implemented in 2004
Intensive Monitoring at Beaver and Red Cap Creeks	Yes
Development of Rapid Assessment Methodology	No
Extension of Study Period and Range of Flow Regimes	Yes
Deployment of Remote Loggers in Greater Density	Yes
Flow Measurements at Beaver and Red Cap Creeks	Yes[1]
Deploy a Meteorological Station at Beaver Creek	Yes
Detailed Site Surveys and Creation of Bathymetric Maps	Yes
Coordination with Fish Counts	Yes
Vertical Stratification Monitoring	Yes
Identification and Monitoring of Sub-Surface Flows	Yes
Small-Scale Manual Modifications of Refugial Areas	No
Edge Habitat Observations at Beaver Creek	No

[1] Done when safety conditions permitted.

The 2004 study period lasted 33 days (August 5 to September 7, 2004). Releases from Iron Gate Dam ranged from 600 cfs to 1,300 cfs during the 2004 deployment period, offering an unusual opportunity to assess thermal refugia conditions under variable flow regimes. In mid- to late-August 2004, a cold front passed through the area and dramatically lowered main stem Klamath water temperatures. The 2005 study period lasted 39 days (July 14 to August 22, 2005). Releases from Iron Gate Dam ranged from 920 cfs to 1,010 cfs during the 2005 deployment period.

Brief Site Descriptions

Beaver Creek

Beaver Creek originates at an elevation of over 6,000 feet in the Siskiyou Mountains of Southern Oregon and flows southward, entering the Klamath River at roughly RM 162. The refuge is a long, shallow area dominated by alluvial outwash from Beaver Creek (Figure 11). Figure 12 is a map of the confluence area with depth contours (based on 2005 data). The Beaver Creek confluence with the Klamath River is somewhat constrained by a bar of rocks, cobbles, and gravel that extends well out into the Klamath River. The bar is formed during winter and spring high flow events. Under the regulated summer low flow conditions in 2004 and 2005, the top of the bar typically exceeded the water surface elevation of the Klamath River. Under these conditions, the bar protects the colder creek water from mixing with the warmer river water.

Figure 11. Beaver Creek Site 360° Panorama, 2005, Looking from Upstream (Left) to Downstream (Right).

The Klamath River makes a left turn at the bottom of the refugial area where the river encounters bank protection adjacent to Highway 97. This turn is sufficiently sharp to create a scour pool on river right. This backwater area is dominated by rooted aquatic vegetation during the summer (Figure 13), and though this area is part of the refuge, its role has not been completely quantified due to the large quantity of aquatic vegetation and organic deposits that interfere with both fish surveys and physical characterization. Although the local gradient of Beaver Creek is moderately steep, access to the main stem Klamath River is unrestricted (i.e., fish can readily move from tributary to main stem and back).

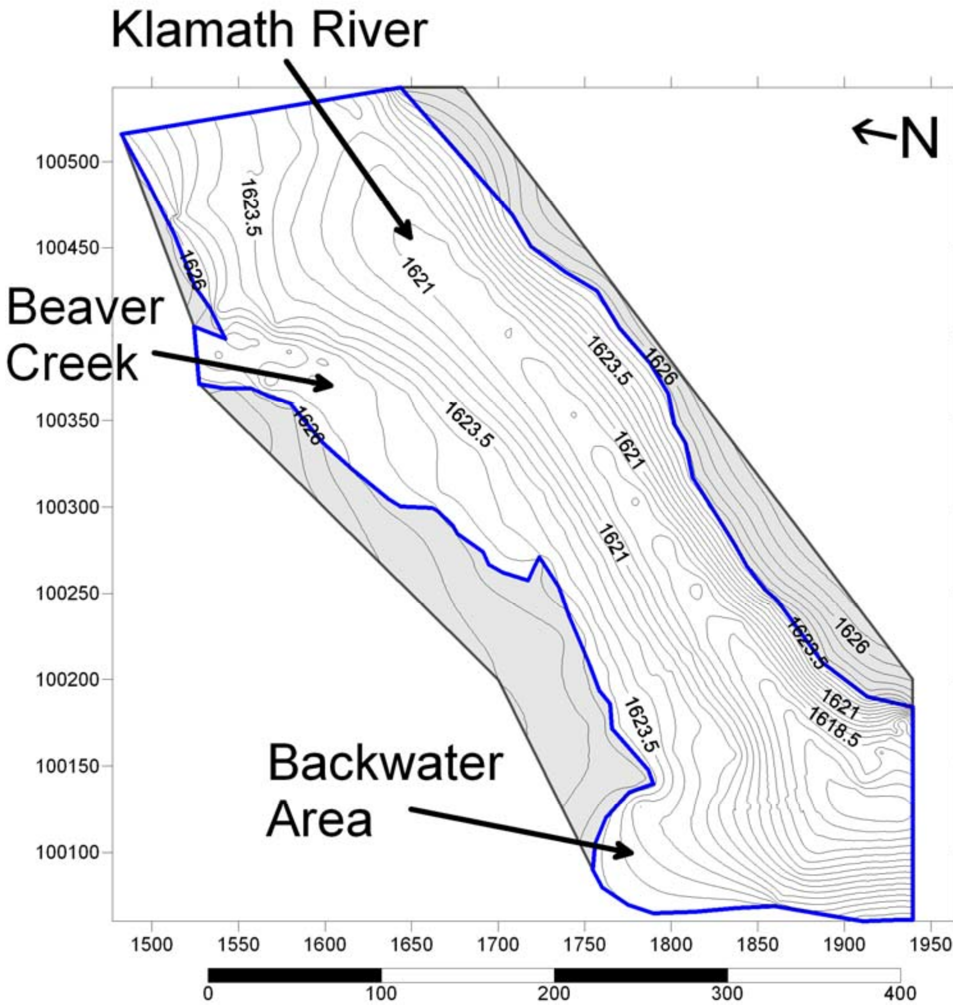


Figure 12. Beaver Creek Refugia Area, 2005 (distance and elevation measurements are in feet). (The dark line is the shoreline when Iron Gate releases were at 920 cfs.)

Figure 13. Backwater Area at Beaver Creek (September 7, 2004).

Red Cap Creek

The headwaters of Red Cap Creek are in the Salmon Mountains, with a maximum elevation of over 6,000 feet. The creek enters on river left (RM 53) after traversing an alluvial fan, which appears to be material derived from both Red Cap Creek and the

Klamath River (Figure 14). The Klamath River in the vicinity of Red Cap Creek ranges from about 150 feet to over 300 feet wide during typical summer flow conditions. Figure 15 shows a map of the area with elevation contours.

Figure 14. Red Cap Creek site 180°Panorama, 2005, Looking Upstream (Right) to Downstream (Left). Red Cap Creek is Barely Visible (located in the far right, upper half).

In 2004 and 2005 the creek split into three primary channels prior to entering the Klamath River on the left bank (Figure 16 and Figure 17). All three channels are steep, shallow, and fairly narrow. The size and location of the three channels changed between the 2004 to 2005 surveys, indicating that while the general features of the confluence remained stable from year-to-year, the actual surface water path can vary considerably. Water emerges at or near the waterline throughout the refugial area, most likely shallow subsurface flow originating from the creek, transiting through the coarse gravels and sands of the alluvial fan. The Klamath River at the confluence is generally shallow (less than 6 feet deep) and the cooler waters of Red Cap Creek form a fairly long, narrow refugial area on river left, where depths are less than 3 feet. The region well downstream of the mouth of Red Cap Creek was deeper and occupied by many adult steelhead and spring run Chinook during the 2004 survey.

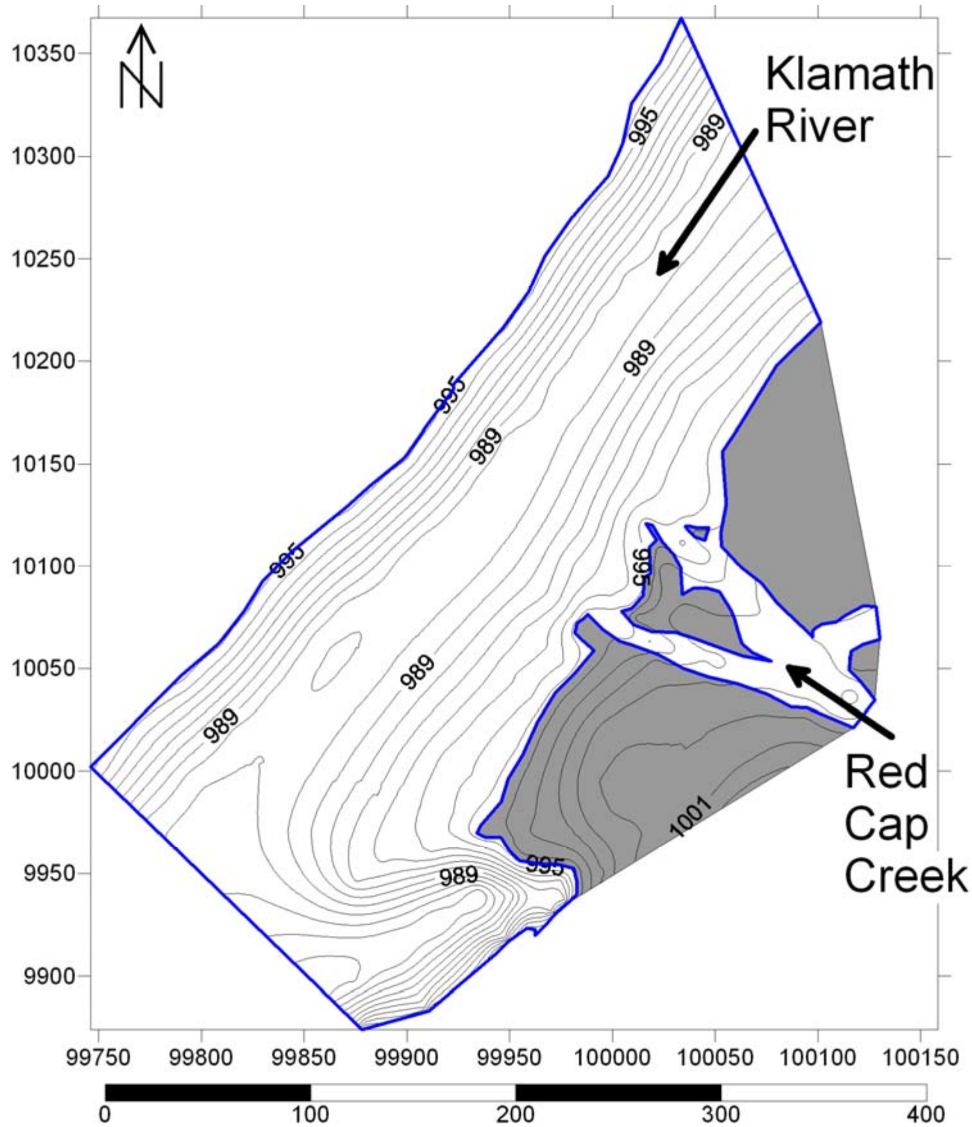


Figure 15. Red Cap Creek Refugia Area, 2004 (distance and elevation measurements in feet). (The blue line is shoreline at Iron Gate release of 615 cfs.)

Figure 16. Red Cap Creek Entering into the Klamath River, 2004.

Figure 17. Red Cap Creek Entering into the Klamath River, 2005.

Study Period and Timing

Investigations of cold-water thermal refugia coincided with the critical periods of the year (summer). The monitoring period spanned multiple days (weeks) to capture a range of flow (volume and temperature) and meteorological conditions. Ideally each distinct flow regime should be sufficiently long, so as to form a stable flow regime at the study sites. During the 2004 and 2005 field studies, all but one of the flow regimes lasted at least seven days (Table 2). The shortest duration flow regime occurred for approximately 2 days. While the flow regime changes were clearly apparent at Beaver Creek, it coincided with a cold-front that lowered overall temperatures in the area. This temperature change made it difficult to determine if changes to the refuge were due to flow change or meteorological changes. Longer flow durations might have extended beyond the cold-front and aided comparison with other representative days.

Table 2. Dates and Flow Regimes at Iron Gate Dam, 2004.

2004 Field Study		2005 Field Study	
Date	**Flow (cfs)**	**Date**	**Flow (cfs)**
Aug. 5 – Aug. 14	615	Jul. 14 – Jul. 30	920
Aug. 15 – Aug. 23	710	Jul. 31 – Aug. 17	1,010
Aug. 24 – Aug. 25	Transition	Aug. 18 – Aug. 22	980
Aug. 26 – Aug. 27*	1,320		
Aug. 28 – Aug. 30	Transition		
Aug. 31 – Sept. 7	908		

* August 22 to August 28, cold front.

In 2004 monitoring began in August and was carried through early September, while in 2005 monitoring began in July and ended in late August. By early September seasonal cooling, associated with shorter day length, reduced water temperatures. This makes it difficult to determine if changes in the refugia are due to flow or meteorological conditions. Likewise it is difficult to determine if the fish counts which occurred late in the study period had fewer fish because fish were redistributing themselves downstream as water temperatures fell or if it was due to the flow changes.

Creek and Main Stem Water Temperatures and Stage

Both Beaver and Red Cap Creeks have stronger diurnal temperature variations than the main stem Klamath River (Table 3, Figure 18, and Figure 19). In both years at both creeks, the water temperature of the creek was always lower than that of the Klamath River. In general, the greatest difference in temperatures occurred in the night and morning hours, and the least difference occurred in the afternoon and evening hours. Larger main stem flow rates generally reduce diurnal temperature range, wherein daily changes in water temperature are less than in the creek (Watercourse, 2003). This reduced range is a function of the larger thermal mass of the main stem, which slows the heating and cooling rates of the river. On average, Beaver Creek has a greater diurnal temperature range than Red Cap Creek in both years. Between 2004 and 2005 the average diurnal difference was similar at Beaver Creek (within 0.2°C), whereas the average diurnal difference at Red Cap Creek was slightly larger (about 0.7°C). The Klamath River was fairly similar in terms of diurnal ranges both between years and sites.

Table 3. Diurnal Range of Water Temperatures.

	Diurnal Water Temperature Range (°C)					
	2004 Field Study			2005 Field Study		
	Max	Min	Avg	Max	Min	Avg
Beaver Creek	6.5	2.5	5.5	7.0	3.0	5.7
Klamath River at Beaver Creek	3.0	0.5	1.9	2.0	0.5	1.3
Red Cap Creek	3.8	1.2	2.9	4.1	2.5	3.6
Klamath River at Red Cap Creek	2.8	0.8	2.0	2.0	1.0	1.7

Table 4. Average Water Temperatures.

	Average Water Temperature (°C)					
	2004 Field Study			2005 Field Study		
	Max	Min	Avg	Max	Min	Avg
Beaver Creek	19.4	14.1	16.4	20.0	14.3	16.9
Klamath River at Beaver Creek	23.0	21.2	22.1	23.2	21.9	22.6
Red Cap Creek	20.3	17.5	18.8	20.8	17.2	18.8
Klamath River at Red Cap Creek	23.7	21.7	22.5	24.8	23.1	23.8

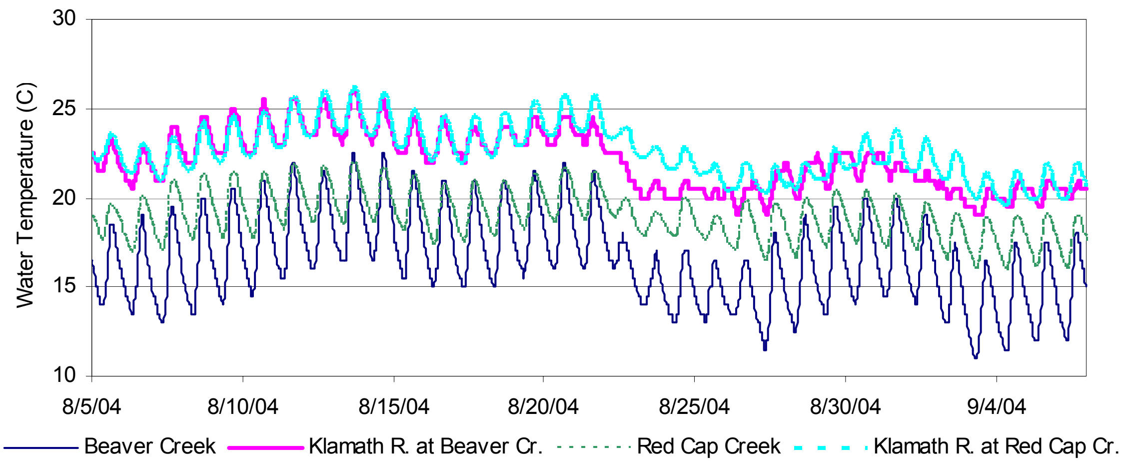


Figure 18. Water Temperature in Beaver Creek, the Klamath River at Beaver Creek, Red Cap Creek, and the Klamath at Red Cap Creek, 2004.

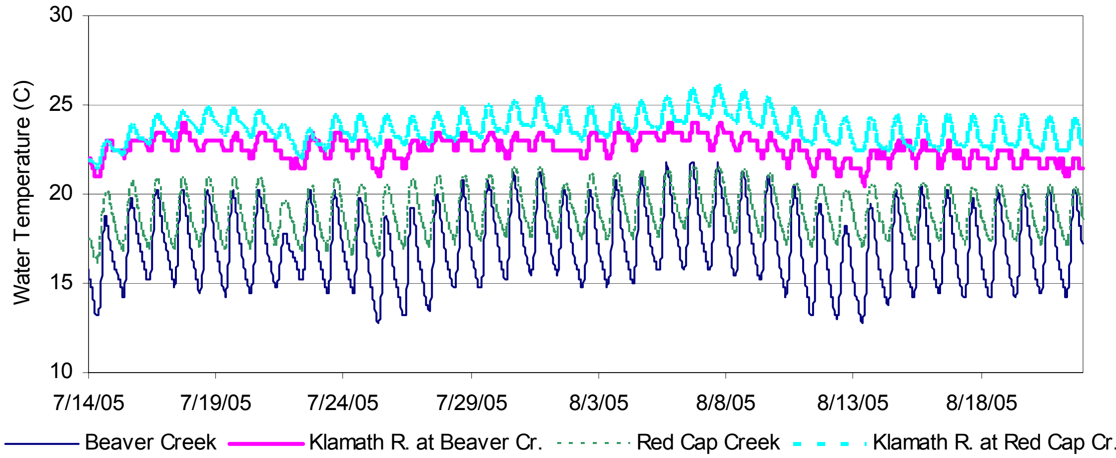


Figure 19. Water Temperature in Beaver Creek, the Klamath River at Beaver Creek, Red Cap Creek, and the Klamath at Red Cap Creek, 2005.

The diurnal pattern in tributary water temperature was accompanied by diurnal changes in stage and flow. Only three locations were selected for monitoring stage in 2004 and 2005 at the Beaver Creek site due to instrumentation limitations. Similar trends in stage were observed both upstream and downstream of the confluence, with the major difference being due to the elevation change. (There is approximately a four foot drop in elevation from the top of the Beaver Creek refuge to the bottom.) Observed water level stage in Beaver Creek had a notable diurnal pattern compared to that of the Klamath River (Figure 20 and Figure 21). On average Beaver Creek stage changed diurnally by 2 inches, while Klamath River stage changed by half an inch. The larger diurnal stage change in Beaver Creek was the result of evapotranspiration from riparian vegetation which dominates both banks of the creek. The Klamath River is significantly larger (both in width and depth) than Beaver Creek, and although riparian vegetation is present, the river stage did not show a measurable diurnal variation.

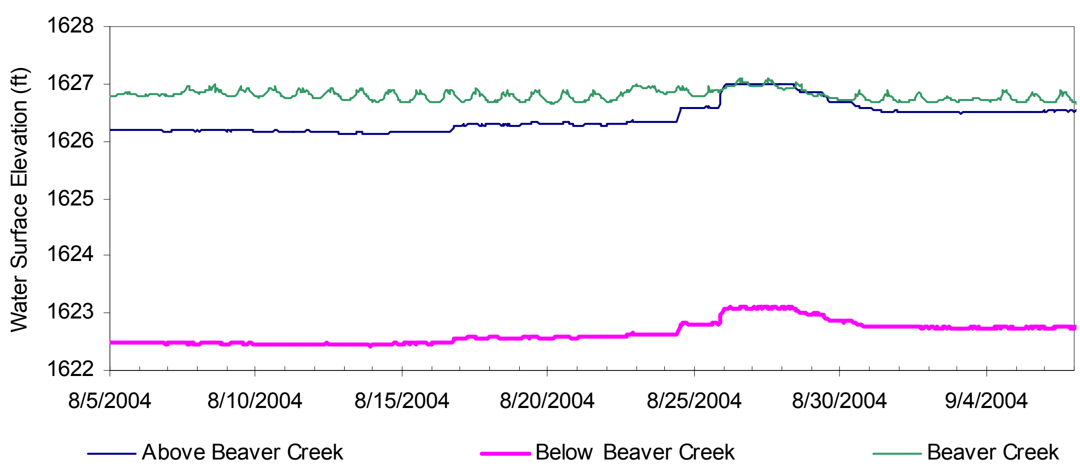


Figure 20. Relative Water Surface Elevation, 2004.

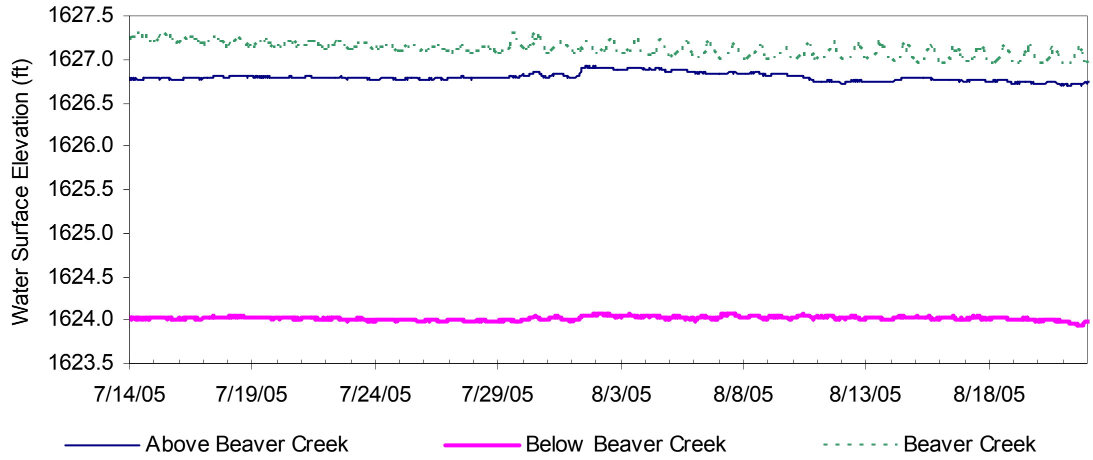


Figure 21. Relative Water Surface Elevations, 2005.

Refugia Response to Flow Conditions

Changes in flow at Iron Gate Dam affect the flow conditions at the Beaver Creek confluence more than those at Red Cap Creek. Stage data from the pressure transducer deployed in the Klamath River at Beaver Creek reflected the change in Iron Gate Dam releases (delayed due to the roughly one-day travel time from Iron Gate Dam to Beaver Creek) in both 2004 and 2005. The changes in flow regime at Iron Gate Dam were not as marked at Red Cap Creek (as depicted in the Orleans gage) because base flows are considerably larger at Red Cap Creek than at Beaver Creek from appreciable tributary accretion (Shasta River, Scott River, Salmon River, plus several substantial creeks) and a considerably larger channel to accommodate large winter flows (Figure 22). In 2004, flow conditions during the study period were confounded by rainfall in the lower basin, increasing tributary contributions. In 2005, flows at Orleans continued to fall throughout the study period even though releases from Iron Gate Dam increased. The flow increases at Iron Gate Dam were smaller than the decreasing tributary contributions between the dam and Orleans (Figure 23).

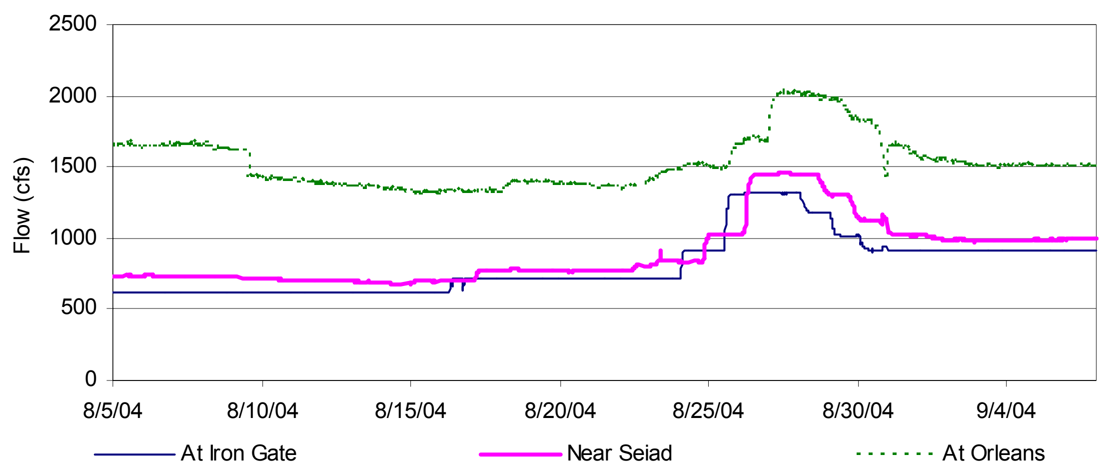


Figure 22. Klamath River Flows from August 5, 2004 Through September 7, 2004.

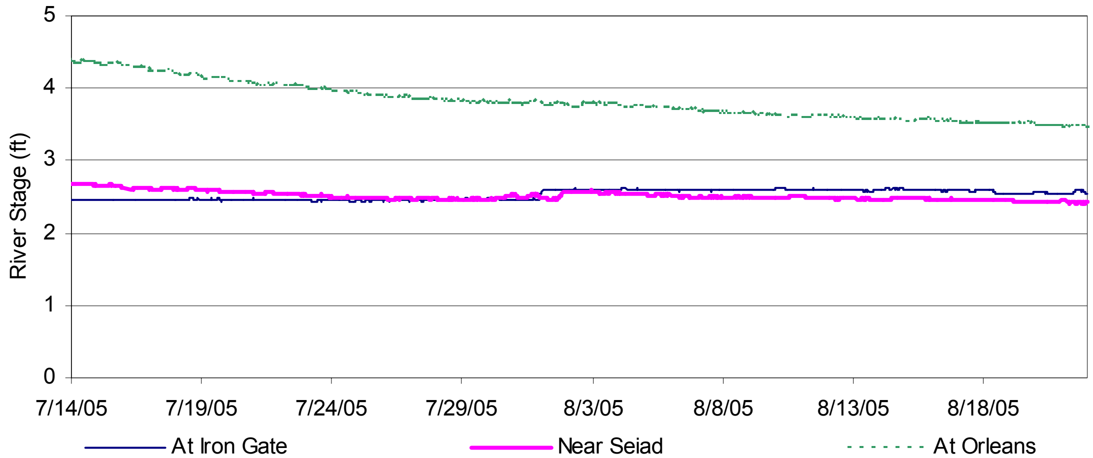


Figure 23. Klamath River Flows from July 14, 2005 Through August 22, 2005.

As discussed in Deas *et al.* (1997), Deas and Orlob (1999), and Lowney (2000), constant flow releases from main stem reservoirs under stable meteorological conditions tend to impart a periodic temperature signal consistent with the release temperature on the downstream river reach separated by travel times at one-day intervals. Thus, for these conditions, if a constant temperature release occurs at Iron Gate Dam (i.e., minimal diurnal variation), then a near constant temperature signal will occur approximately one-day travel downstream. This node of minimum diurnal variation has been identified in the Klamath River through both field observations and modeling studies (Deas and Orlob, 1999). One-day travel time for a 1,000 cfs release from Iron Gate Dam is approximately RM 156. For lower release rates, the node of minimum diurnal variation shifts upstream. Although specific flow rates have not been identified, Beaver Creek located at RM 162 probably experiences the effects of this thermal node. At low flows, the node could shift upstream towards Beaver Creek, reducing main stem diurnal temperature variation. For example, in 2004 and 2005 the maximum diurnal range was 3^{o}C and the minimum was less than 1^{o}C, while the diurnal range for the Shasta River above the confluence with the Klamath River is on the order of 5^{o}C to 6^{o}C (Deas and Orlob, 1999), suggesting that such a node is indeed present. If the node of minimum diurnal variation occurs at or near Beaver Creek, temperatures would remain relatively constant 24-hours a day, minimizing the ability of fish within the area to utilize the main stem Klamath River and increasing the value of the refugial area. This concept has not been fully explored.

Intensive monitoring in both 2004 and 2005 indicated that the thermal refuge does change diurnally in size and shape. This can be seen from the temperature plots at 3-hour intervals (Figure 24). In the early morning hours (before 09:00) the creek water is significantly cooler than the main stem. As the day progresses both the main stem and creek warm and as a result the relative difference between the two sources decrease (as the tributary heats and cools faster than the main stem). Then in the evening and night both waters cool, with the creek cooling faster. This diurnal behavior (expansion and contraction of the thermal refuge) was present for all flow rates in both years at both sites.

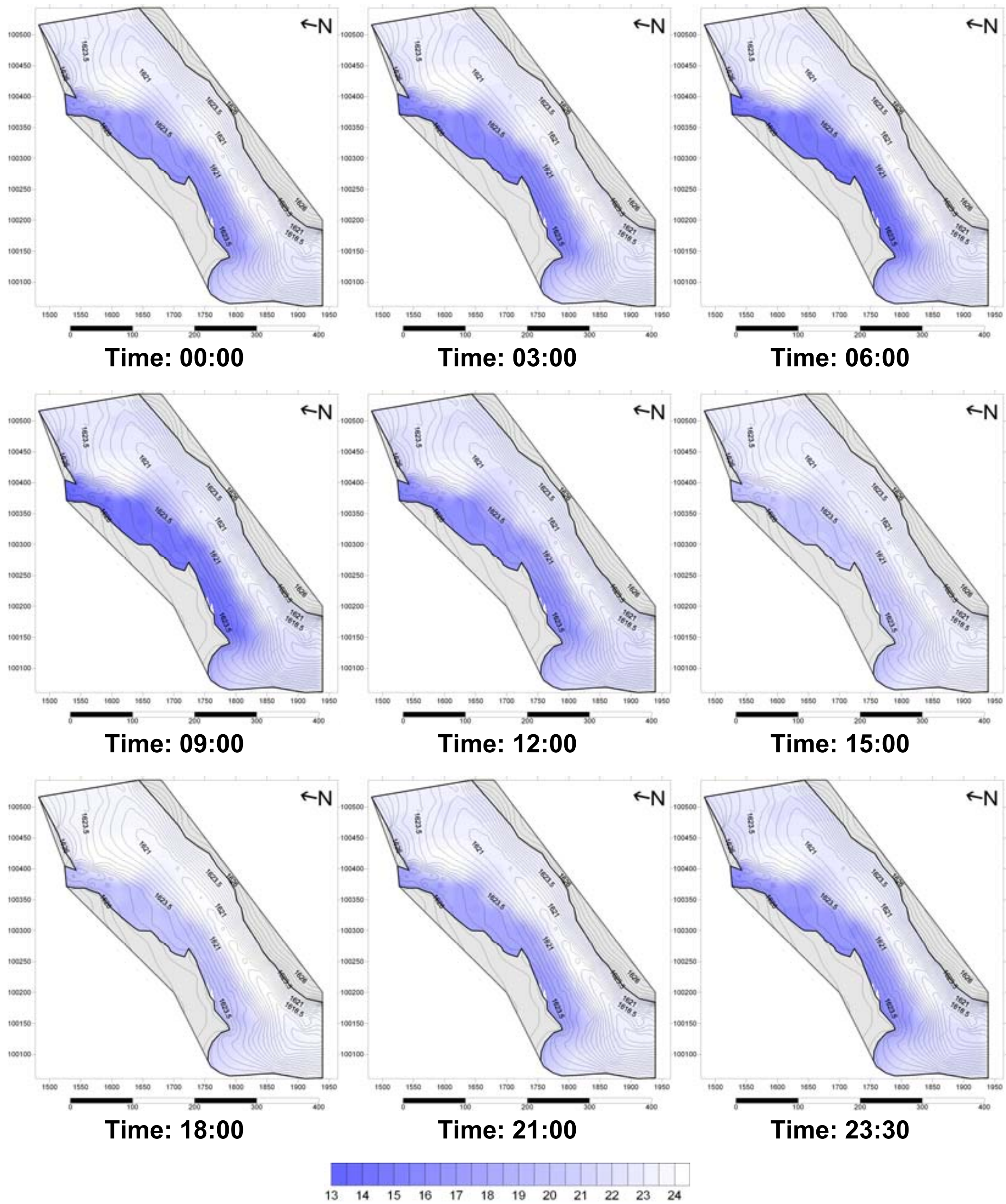


Figure 24. Beaver Creek Thermal Refuge and Main Stem Klamath River Temperatures at 3-Hour Intervals: July 19, 2005 – 930 cfs Main Stem Flow Regime (temperature scale in ºC).

Red Cap Creek also has a diurnal pattern of refuge expansion and contraction, but it is weaker than at Beaver Creek (Figure 25). The temperature observations indicate that the cool-water influences from the creek are limited to the left shore near the confluence itself, extending downstream along the shore. Colder creek inflows appear to be augmented by creek-derived groundwater underflow downstream of the confluence. This was expected given the configuration of the confluence. Unlike Beaver Creek, where the refuge is somewhat protected from mixing by a gravel bar, Red Cap Creek spills directly into the river.

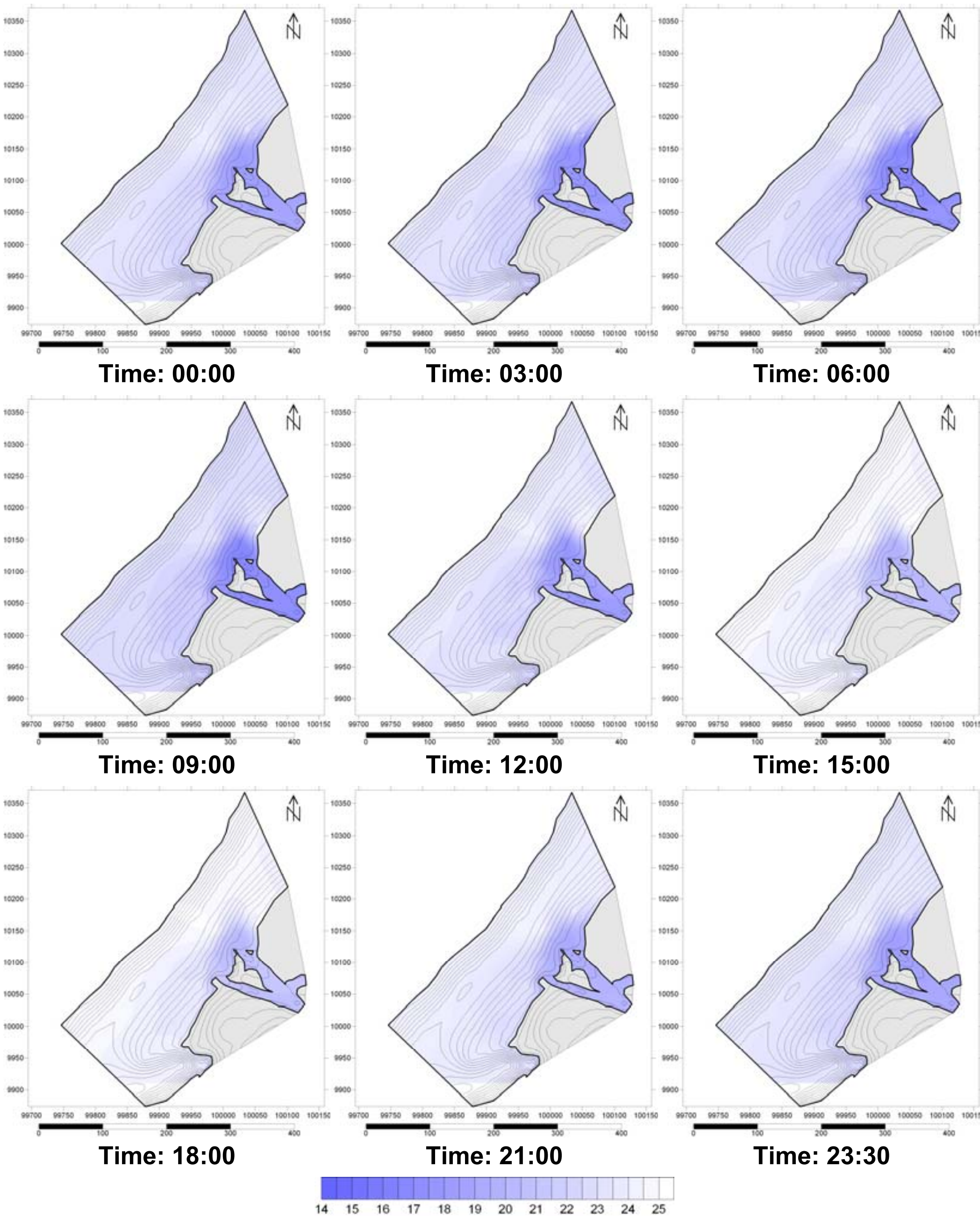


Figure 25. Red Cap Creek Thermal Refuge and Main Stem Klamath River Temperatures at 3-Hour Intervals: August 2, 2005 – 1,020 cfs Flow Regime at Iron Gate, 2,316 cfs Flow Regime at Orleans Gage (temperature scale in ºC).

Increased main stem flows thus have a greater effect on the Beaver Creek thermal refuge. The larger flow range in 2004 provides the best insight into potential effects of flow. Significant changes to the thermal refugia do not occur at relatively modest flow changes (i.e., from 615 cfs to 1,010 cfs). However, field observations show that from 1,010 cfs to 1,320 cfs the Beaver Creek refuge decreased in lateral size and volume.

While graphical depiction of results provides considerable insights into interaction of the spatial and temporal variation in the refugia and adjacent regions, a series of ANOVA (Analysis of Variation) tests were conducted on each *i*BCod data location to quantitatively assess the variability of refugia areas, comparing the main stem and creek temperatures with the temperatures in the confluence. A single-factor ANOVA analysis compares two sets of data to assess if their means are statistically similar. The ANOVA analysis is used to "see whether the apparent differences in the averages computed for the groups are significantly different, or whether these differences could be due to random sampling variability alone" (Siegel, 1988, pg. 352).

A comparison was done for both the Beaver Creek and Red Cap Creek sites (confidence level of 95%). The greatest change in number of *i*BCods that were similar to the creek and/or the Klamath River occurred when comparing the lowest observed flow with the highest observed flow (Table 5 and Figure 26) at the Beaver Creek refuge. The Red Cap Creek site was less influenced by the changes in Iron Gate Dam flow than the Beaver Creek site (Table 6). In 2004, the largest change in the number of *i*BCods in the main stem and refugial area that had the same temperature signal as Red Cap Creek occurred as a response to changes in the meteorological conditions of the site.

Table 5. Results for the Beaver Creek Site of the Single Factor ANOVA Analysis for Each Data Station, 2004 & 2005.

Representative Date	Iron Gate Flow Regime (cfs)	#of Loggers representative of the Klamath River*	#of Loggers representative of Beaver Creek*
August 10, 2004	615	3	41
August 20, 2004	710	3	40
September 6, 2004	910	2	38
August 27, 2004	1,320	11	23
July 19, 2005	930	4	35
July 28, 2005	930	5	35
August 3, 2005	1,010	10	34
August 9, 2005	1,010	3	31

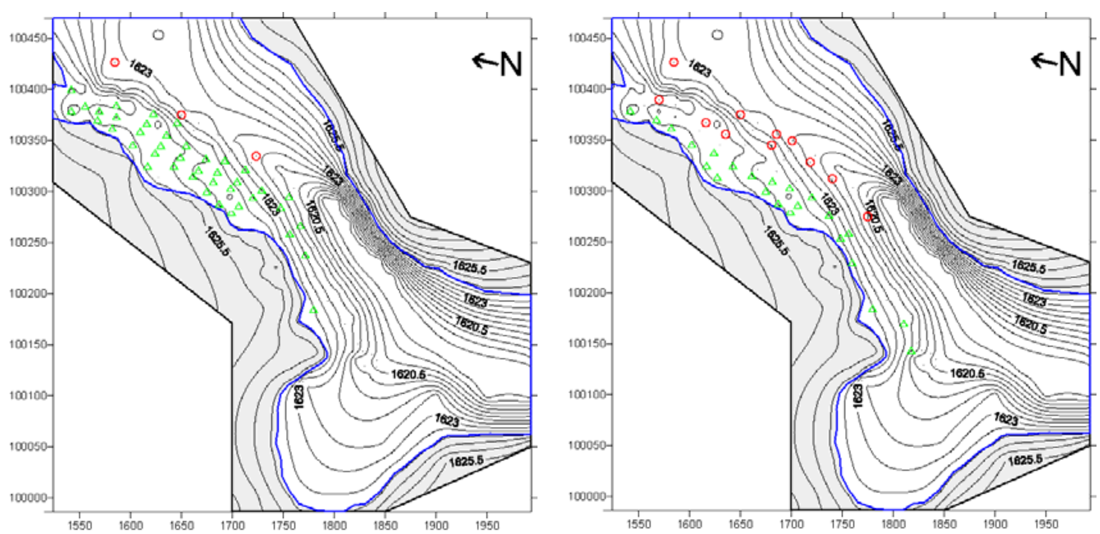
* "Same as" refers to a Single Factor ANOVA analysis between the logger deployed in the confluence and the loggers deployed to capture the temperature of the main stem and Beaver Creek.

Table 6. Results for the Red Cap Creek Site of the Single Factor ANOVA Analysis for Each Data Station, 2004 & 2005.

Representative Date	Iron Gate Flow Regime (cfs)	Measured Flow at Orleans Gage (cfs)	#of Loggers the Same as the Klamath River*	#of Loggers the Same as Red Cap Creek*
August 16, 2004	615	1,330	11	6
August 19, 2004	710	1,400	14	7
September 4, 2004	910	1,510	16	2
August 28, 2004	1,320	2,000	19	2
July 26, 2005	922	2,464	6	8
August 2, 2005	1,020	2,316	6	7
August 10, 2005	1,014	2,161	6	8
August 18, 2005	987	2,043	10	6

* "Same as" refers to a Single Factor ANOVA analysis between the logger deployed in the confluence and the loggers deployed to capture the temperature of the main stem and Red Cap Creek.

At the Beaver Creek refuge, the difference in ANOVA results between the 615 cfs and 1,320 cfs flow was largely due to main stem flow levels increasing to an elevation where the main stem flows spilled directly over the bar instead of running parallel to the river for some distance as it does under lower flow conditions. This was evident in the stage data (Figure 20). Overall flow rates or volumes may not be as important as identifying threshold flows where mixing conditions change relatively quickly for a particular thermal refuge. A challenging aspect of identifying such thresholds in a basin such as the Klamath River is the year-to year variability of tributary confluence geometry. Nonetheless, refugia inventory and assessment can provide insight to identify critical features to monitor when flow changes are considered.



Date: 081004 (Flow ~615 cfs) **Date: 082704 (Flow ~ 1,320 cfs)**

Figure 26. Extent of Cold-Water Influence from Beaver Creek for the 615 cfs and 1,320 cfs Iron Gate Dam Flow Regimes, 2004 (distance and elevation measurements in feet). (The red circles indicate loggers that were statistically the same as the Klamath River, the green triangles represent the loggers that were statistically the same as Beaver Creek.)

The limited number of refugia studied impose some limitations on conclusions regarding how the refugia respond to hydraulic and meteorological changes. However, it appears that managed upstream flows have diminishing effects on thermal refugia located further downstream due to accumulated tributary inflows (resulting in the managed flows becoming a smaller portion of the total flows), larger channel size, and less stable alluvial channel forms. Exceptions might occur due to local geomorphology (bedrock features), year-to-year changes due to hydrology, large flows that dramatically change the channel, and anthropogenic factors (e.g., road building and maintenance activity).

Tributary hydrology is also important in assessing main stem flow effects on thermal refugia, particularly in reaches where alluvial transport is active. The timing of high flow events in the tributaries and main stem can have important effects on confluence geometry. When main stem flows are high, sediment from tributaries may be deposited in the channel above summer water levels or may be transported away from confluences. However, if main stem flows are low and tributary inflows are high, alluvial contributions to the main stem may be deposited adjacent to and within the main stem, creating different confluence morphologies. Because some tributary hydrographs are rainfall dominated, while others are snowmelt (or a combined rainfall and snowmelt) dominated, variability can be expected.

For example, coarse sediment from Beaver Creek extends well out into the main stem Klamath River, creating a shallow, but broad area of cool water within the main stem. Because the headwaters of Beaver Creek exceed 6,000 feet, there is a snowmelt component to the creek's hydrograph. Irrigation practices commence in the upper Klamath River area (Klamath Falls) and Shasta River basin during early spring, and river flows at Iron Gate Dam are generally regulated throughout much of this period (and on into the summer). Thus the Klamath River hydrograph near Beaver Creek includes very little snowmelt. In some years the hydrographs for the Klamath River and Beaver Creek do not coincide; the peak of the Beaver Creek hydrograph occurring later in the year and at a time when the flows in the Klamath River are generally insufficient to move materials deposited into the main stem from Beaver Creek. Thus Beaver Creek bed load extends into the main stem, creating a shallow, complex refugial area, which is fairly stable in the main stem Klamath River.

Downstream at Red Cap Creek, refugial conditions are more variable. The Klamath River channel is considerably larger than at Beaver Creek because the river typically has significantly larger flows during winter periods in the lower river. Red Cap Creek enters from a narrow side canyon on river left, and during summer flow conditions the creek mouth in 2004 and 2005 was about 8 to 10 feet above the Klamath River. The large head difference between the creek and river sets up the potential for creek water to percolate into the bed and enter the Klamath River as shallow subsurface flows. Underflow appears to be a fairly common, but variable, feature at several Klamath River thermal refugia, entering the river at the temperature of the creek waters or cooler. For example, the Beaver Creek underflow enters several degrees cooler than the creek itself, providing habitat for over-summering juvenile coho salmon.

It is tempting to draw conclusions about the variability of thermal refugia based on simple parameters such as total distance from Iron Gate Dam or elevation of tributary headwaters (i.e., snowmelt and/or precipitation hydrograph); however, other variables such as local geology confound simple rules: Indian Creek about a mile upstream from Elk Creek is extremely stable due to a bedrock outcrop immediately upstream of the confluence with the Klamath River.

A principal objective of the thermal refugia study was to assess the potential effects of main stem flows on the size and temperature of refugial areas. For most Iron Gate Dam release rates, effects on Beaver Creek were modest and the effects of meteorological conditions or tributary contributions enroute to Red Cap Creek were more important for refugia conditions than flow changes at Iron Gate. Beaver Creek had some reduction in size at flows over 1,100 cfs, as identified by statistical analysis, but the actual impact on resident fish was not studied in sufficient detail to determine if this change was detrimental (e.g., no fish surveys occurred at the 1,320 cfs flow release from Iron Gate Dam). The algae mat, located at the lower end of the refuge in the backwater area, effectively limited mixing with main stem waters and "protected" cold-water seeps that entered in that region, even under the increased flow conditions of 2004. This is a good example of location-specific conditions having an important role in thermal refugia function.

Overall, additional monitoring at Beaver and Red Cap Creek are needed to identify stable and non-stable features, as well as the refugial response to changes in a wide range of flow rates and meteorological conditions. To better understand how a system of refugia may function additional monitoring sites are needed.

Other Observed Thermal Characteristics

Local Features

Features of the confluence and refugial area significantly affect the size of a refuge. At Beaver Creek the confluence itself is protected by a rocky bar that hinders mixing of the Klamath River with the creek waters at low flows. At the bottom of the refugial area is a backwater dominated by rooted aquatic vegetation and organic deposits. In 2005, when larger quantities of coho were present, they were observed holding in the backwater area. At the start of the 2005 study period, the temperatures within the backwater area were cooler than the Klamath River, but generally warmer than Beaver Creek. By the middle of the study period the water temperatures observed in the backwater area were similar to those of Beaver Creek, but with reduced diurnal fluctuation.

These results and field observations support the presence of seeps or underflow from the downstream edge of the alluvial fan produced by Beaver Creek. These inflows are cooler than the creek itself. Further, it appears that the rooted aquatic vegetation impedes mixing of both main stem and creek water with this cooler inflow, creating a unique attribute at the Beaver Creek thermal refuge. The presence of coho within this backwater area, but not at the mouth of the creek when colder water was present, indicate that local features such as backwater areas significantly affect the usefulness of thermal refugia.

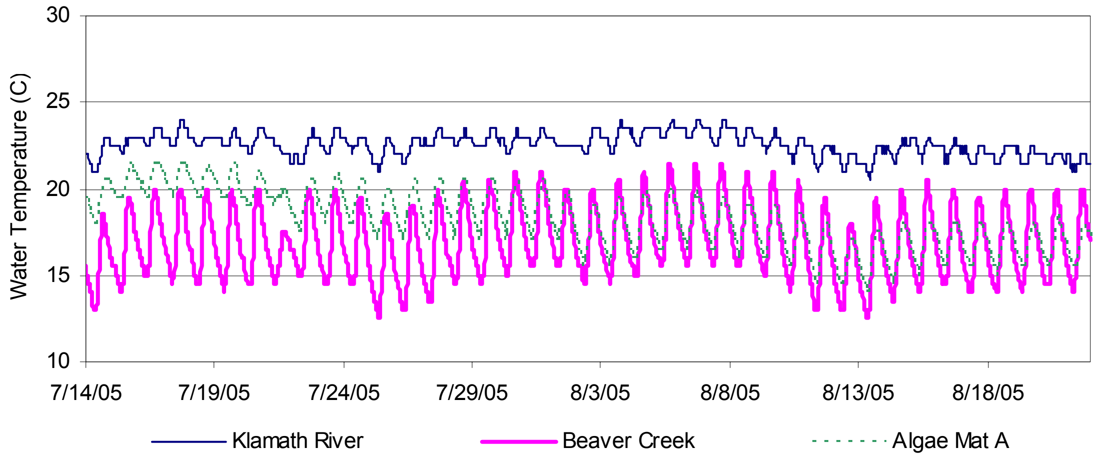


Figure 27. Comparison of Klamath River, Beaver Creek, and Algae Mat A Water Temperatures, 2005.

Vertical stratification

Limited vertical observations at both sites indicated that stratification could occur in the refuge. This stratification is primarily due to cool, denser creek waters near the bed while warm waters from the Klamath River occupy surface regions. In most areas of the refugia, velocities were sufficient to minimize vertical stratification. However, backwaters or areas of minimal velocity could stratify. In most cases these low-velocity areas were downstream of the confluence. At both Beaver and Red Cap Creeks, the most pronounced and persistent vertical stratification was associated with groundwater inflow or seeps.

Groundwater

At both creeks vertical stratification appeared to occur from shallow subsurface flow from the tributary alluvium. This subsurface tributary flow is in addition to surface inflows. The subsurface flows are usually colder than the surface water inflows from the tributaries. At both sites, diurnal patterns were apparent in some of the sub-surface water temperature measurements completed using “taps” installed adjacent to the river. The diurnal temperature variation in these shallow groundwaters was offset by approximately 12-hours from that of the creeks. This shift, or lag, may represent the travel time through the porous media.

Fish Counts

Fish counts were completed at Beaver Creek by the Karuk Tribe and at Red Cap Creek by the Yurok Tribe. Six days of intensive dives were completed at Beaver Creek in 2004 and 4 days of intensive dives were completed in 2005 (each with seven dives per day). At Red Cap Creek, four days of intensive dives were completed in both 2004 and 2005 (each with six dives per day). Three fish species (each with multiple age groups) were targeted for counting (coho, Chinook, and steelhead).

Only a few juvenile coho were observed at the Beaver Creek site in 2004 (often single fish or no fish encountered), but hundreds were counted in 2005. No adult coho were observed in either year. As the day progressed and the river water exceeded 22ºC to 23°C, more fish were observed moving into the refugial area (Figure 28). At Beaver Creek, where all three fish species were present, juvenile coho salmon were generally concentrated near an algae mat located in a backwater at the lower end of the refugia (Figure 29). Juvenile Chinook salmon were usually in the lower portion of the refuge. Juvenile and adult steelheads were generally distributed throughout the refugial area and creek. Fish counts by species and location are presented in Figure 29 for July 28, 2005 at the Beaver Creek thermal refugia.

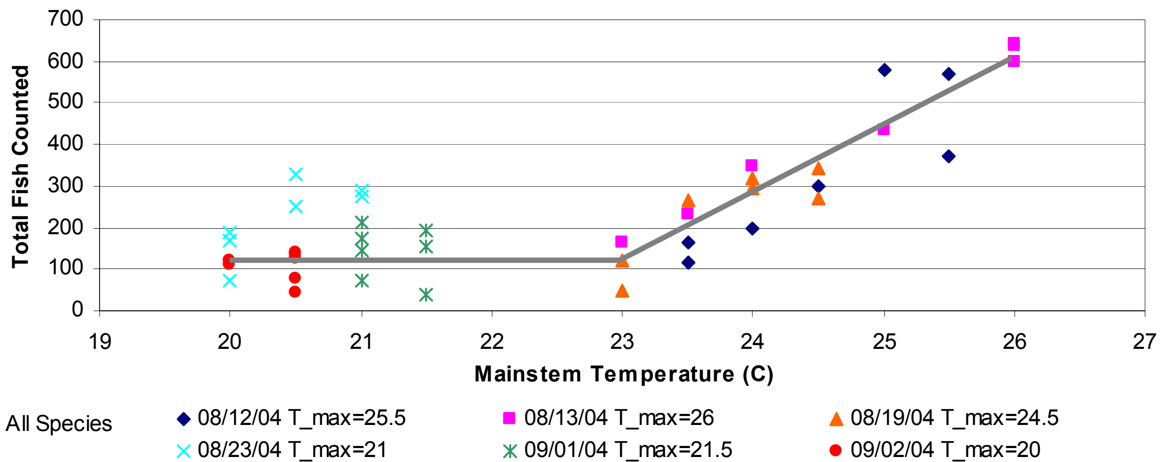
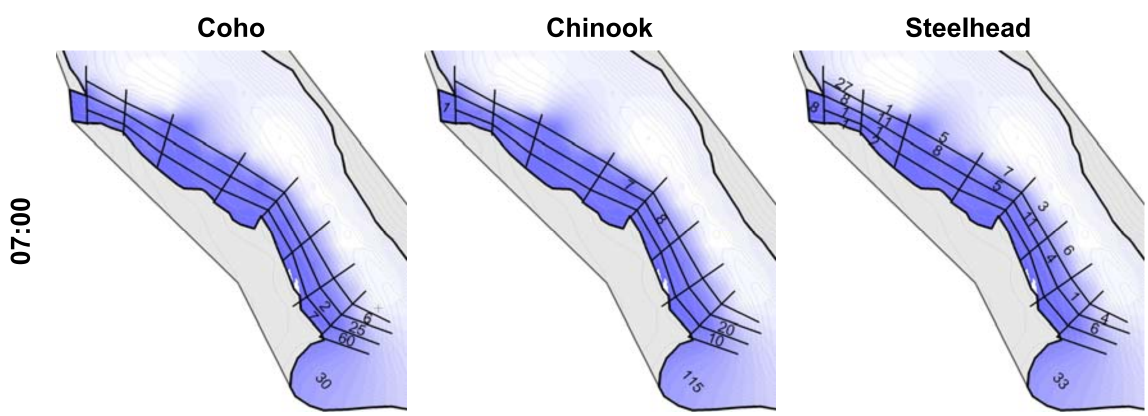
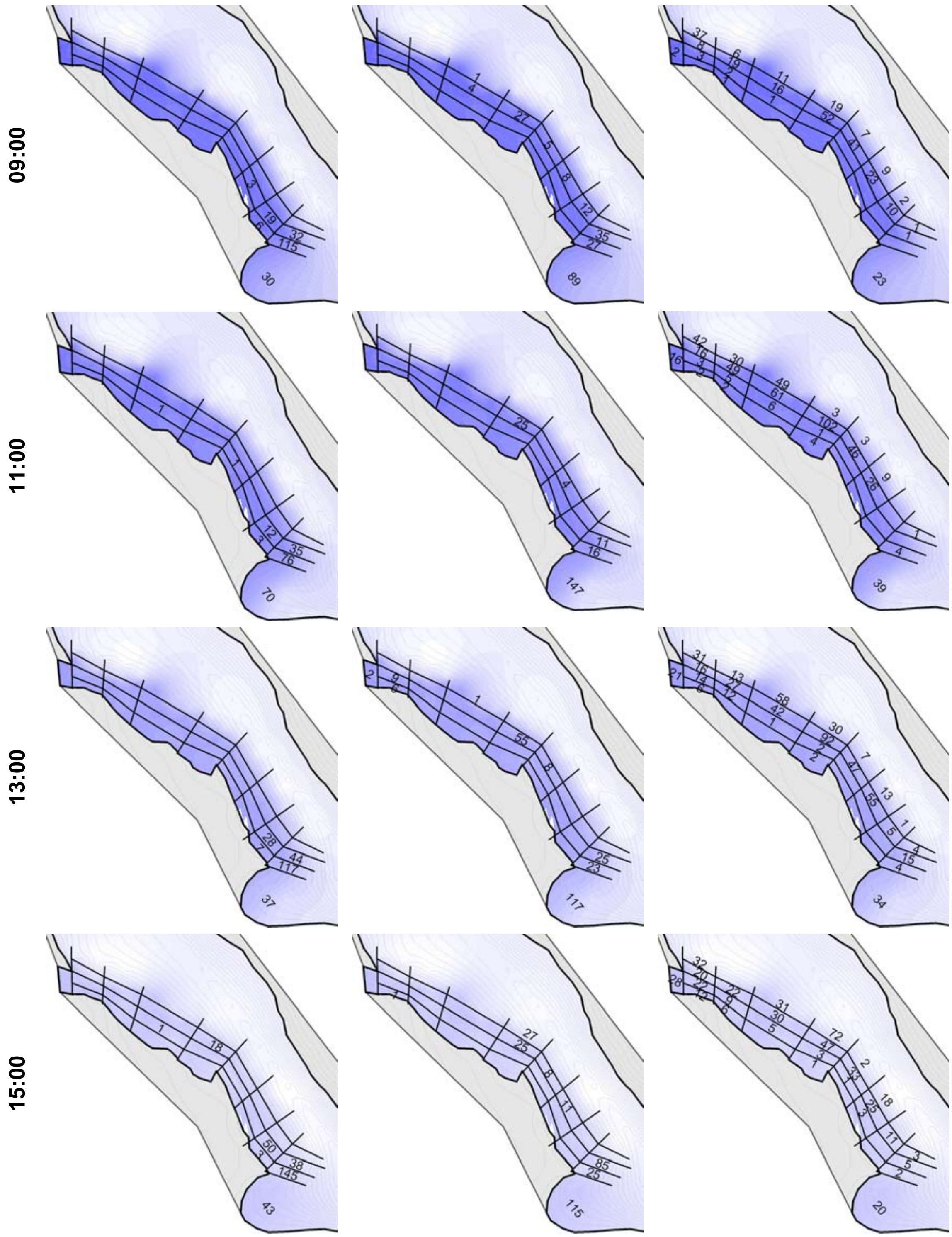


Figure 28. Total Number of Fish Observed in the Beaver Creek Refugial Area with Main Stem Temperature, 2004. (T_max denotes the maximum main stem temperature recorded for the intensive dive date. Trendline added for illustration purposes and has no statistical significance.)

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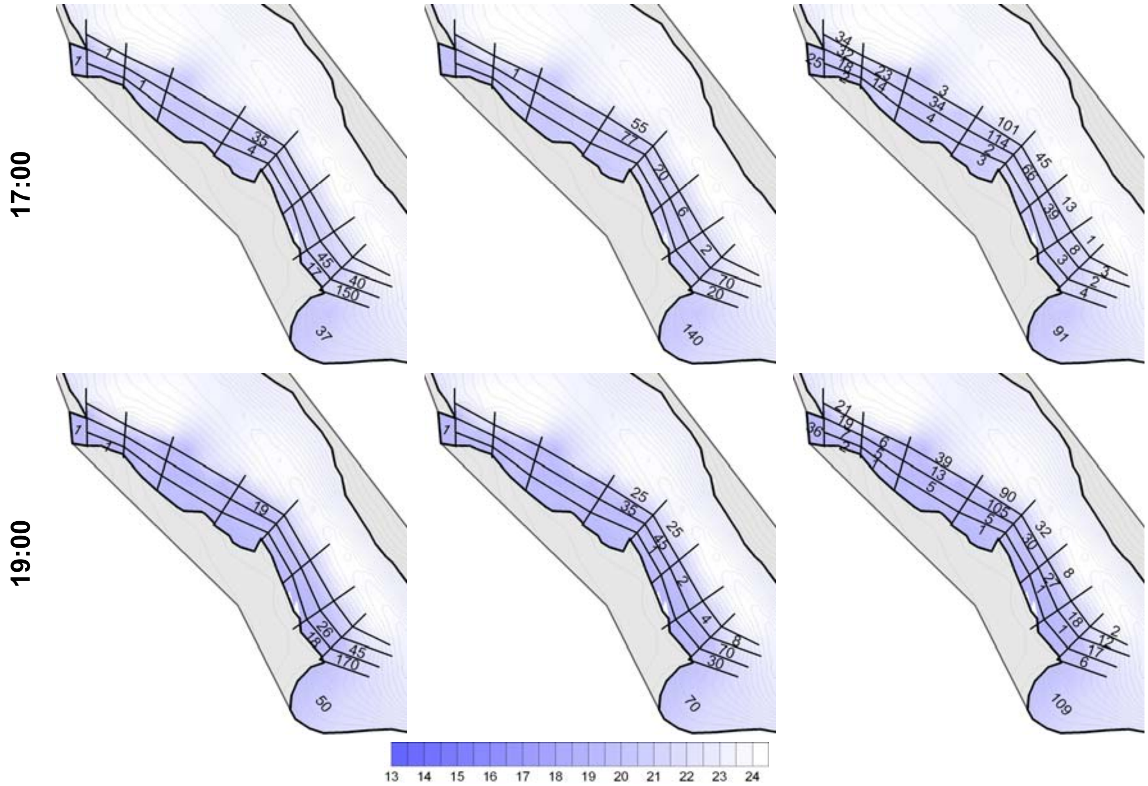

Figure 29. Fish Counts by Species for July 28, 2005 at the Beaver Creek Site.

No coho were observed at the Red Cap Creek site in either 2004 or 2005. As with Beaver Creek, observations suggested that as the day progressed and the river water exceeded 22ºC to 23ºC, more fish were observed moving into the refugial area. At Red Cap Creek the calm water area downstream of the confluence on river left was generally warmer than the confluence and similar in temperature to the Klamath River. Fish were observed at this location in early morning, but usually moved away by afternoon with higher densities closer to the mouth of the creek as the day progressed and water temperatures increased in the main stem.

Cooperation with the Karuk and Yurok Tribes and incorporation of a grid system was pivotal in characterizing the spatial and temporal distribution of fish by species, in the refugial areas. This quantification allowed direct comparison of fish distribution the temperature conditions throughout the dive days. Both the Karuk and Yurok Tribes had previously identified the 22ºC to 23ºC threshold main stem temperature range when fish densities within thermal refugia begin to increase and implementing the counting grids provided a means to quantify this threshold.

CONCLUSIONS

The detailed studies at Beaver Creek and Red Cap Creek emphasized that thermal refugia can vary considerably from site-to-site and from year-to-year. Despite their variability, some features of the refugia were consistent between the two sites. Both refugia cold-water pools expanded during the night and early morning hours. As the main stem and tributary water temperatures increased, the lateral size of the refugia decreased, as did the difference in temperature between the main stem and the tributary. The refugia were not subject to strong vertical stratification and at both sites the presence of groundwater seeps and hyporheic flow provided cold-water sources at locations other than the confluence. Local features, such the backwater area at Beaver Creek, are important to the usefulness of the refugia because fish behavior is governed by more than temperature.

Intensive monitoring of the refugial areas of interest can provide managers with valuable information on how the refuge will respond to changes. While managers cannot control meteorological conditions, they can alter flow conditions and the local geometry. Field studies can only monitor and report the observed responses of the refuge for those conditions that occurred. However, it is not always prudent or possible to test a full range of conditions and as such managers need additional ways to estimate how a refuge will respond without having to make changes to the physical system. The information gathered in the field studies can provide the ground work for development of a thermal refuge computer model that could be used by water managers to assist them in making decisions on how to maximize the usefulness of the refugial area.

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CHAPTER 4: MODELING AT A LOCAL LEVEL - A SINGLE THERMAL REFUGE

INTRODUCTION

The ad hoc science panel convened on June 27, 2002 recommended investigating flows that ranged from approximately 700 cfs to 1,300 cfs at Iron Gate Dam, wherein the minimum duration of any particular flow regime be seven days (Sutton *et al.*, 2002). Although the observed flow regimes ultimately provided a sufficient range of conditions to assess the potential impacts of flow on thermal refuge size and quality, a still broader range of flow experiments would provide greater insight into thermal refuge response to Iron Gate Dam flows; particularly refugia closer the Iron Gate Dam where the potential impacts of flow change would generally be larger. However, given the intra and inter-annual variability of water availability, upstream demands, and instream fisheries concerns, it may be neither feasible nor prudent to release a wide range of flows for this purpose.

Development of a simulation model of the Beaver Creek thermal refuge would enable managers to assess the effects of various flows on the thermal refuge. Flows above 1,000 cfs could be modeled and analyzed in greater detail (recall that the 1,320 cfs event only occurred for two days which was insufficient to create a stable situation at the Beaver Creek site). Likewise, extremely low flows could also be modeled to determine flow levels that severely reduce the refuge.

A local, detailed, model could be used by managers to assess the effects of changes on the refuge due to different operations. Different flow conditions (in the main stem) could be investigated, as well as different site configurations.

NUMERICAL MODELING BACKGROUND

Computer models range from the relatively simple to the highly complex. They can be created on a spreadsheet designed for the average individual to use, or created in a high-level computer programming language where only an expert can run the model, or somewhere in between. The level of effort to implement, test, and apply models can be considerable as well.

Numerical models refer to a wide range of computer schemes used to solve complex systems of mathematical equations. The mathematical equations that form the basis for flow and temperature models include fundamental conservation laws (conservation of momentum, mass, and energy, as well as more empirical relationships such as fluid friction (e.g., Manning's equation)). These equations are represented mathematically as partial differential equations (PDE). PDEs can only be solved directly (i.e., closed form solutions) for special, generally simplified, cases or conditions. The primary challenge solving PDEs is to create a formulation which approximates the equation to be studied, but which is numerically stable. A solution is numerically stable when errors in the input data and intermediate calculations do not accumulate and cause the resulting output to be erroneous (i.e., the result produces a good approximation to the true solution).

Many numerical methods can be used to approximate solutions to PDEs, all with advantages and disadvantages. Generally, numerical methods are employed to represent these equations in forms that are readily solved on computers. Common numerical methods applied to fluid dynamics problems include finite volume, finite element, and finite difference. These methods are discussed by Anderson (1995), Veersteg and Malalasekra (1996), Chung (2002), Smith (2004), and Zienkiewicz (2005).

Another aspect of numerical models is the spatial and temporal representation. Aquatic systems vary spatially in three principal directions: longitudinal, vertical, and lateral. One-, two-, and three-dimensional models are available for application, with higher dimensional models requiring increasing levels of complexity, data, and resources to implement and apply. Within any of these models, the spatial scale refers to the distance between nodes or grid points where physical information is supplied or calculated. In addition to spatial scale or resolution, temporal scale can be an important aspect of a numerical model. Selection of spatial and temporal scales can greatly affect model performance. Spatial and temporal resolution also directly affect the computational time for computer models. Finer resolution representations, while potentially yielding more detailed results, also increase the computational burden. A tradeoff between resolution and computational effort may be important when selecting spatial and temporal time scales.

AVAILABLE MODELS

To capture the geometric, hydrodynamic, and thermal complexities of the Beaver Creek refuge, several numerical models were considered. Roughly a dozen models were briefly investigated to determine their applicability to modeling the Beaver Creek thermal refuge and thermal refugia in general. These models were assessed using several metrics:

- Ability to assess multiple dimensions: lateral and longitudinal representation was critical, with the possibility of the vertical dimensions (full three-dimensional modeling) being a further benefit;

- Ability to represent temperature (or density): models were required to assess temperature. A more desirable feature was explicitly considering density in the solution of the governing hydrodynamic equation, providing the ability to model density driven flows;

- Wetting and drying capabilities: to accommodate variable flow regimes;

- Proprietary or open source code: ideally the code should be available for peer review;

- Cost: costs of some of these computer codes is considerable (tens of thousands of dollars), and may be a consideration should future modeling be considered;

- Ease of Use: because most models require some expertise and training, this metric was not given appreciable weight, but may be considered in future model applications;

- Support: often critical to implementing and applying models is the level of technical support. Technical support can greatly assist in assuring proper system representation, model testing, and interpretation of results.

This information was used to assess the applicability of each model to the hydrodynamics of thermal refugia (Table 7). Further details on the individual models can be found in the model documentation and Appendix B.

Table 7. Comparison of Model Features.

	Number[1] of Dimensions	Temp. or Density	Wetting and Drying	Open Source Code[2]	Cost	Ease of Use	Support	Overall Rank (1-low 5-high)
CORMIX	X, Y	Yes	No	No	Fee		Yes	2
CE-QUAL-RIV1	X	Yes	-	-	-	-	-	1
CE-QUAL-W2	X, Z	Yes	-	-	-	-	-	1
CWR-ELCOM	X, Y, Z	Yes	Yes	Yes	Fee[3]		Yes	5
EDFC	X, Y, Z	Yes	Yes		Free		Limited	5
MIKE 3	X, Y, Z	Yes	Yes	No	Fee[3]		Yes	5
MIKE 11	X, Y, Z	Yes	Yes[4]	No	Fee[3]		Yes	5
RMA 2	X, Y	No	Yes	Yes	Fee[3]		Yes	4
RMA 11	X, Y	Yes	Yes	Yes	Fee[3]		Yes	4
RMA 10	X, Y, Z	Yes	Yes	Yes	Fee[3]		Yes	5
UnTRIM	X, Y, Z	Yes	Yes	No	Fee[3]		Yes	5

[1] X,Y,Z represent longitudinal, lateral, and vertical dimensions, respectively.
2 Open source code refers to non-proprietary model codes
[3] License fee. Current costs must be requested from the model owner.
[4] Not explicitly stated in documentation, but implied through available features of the model.

After review of the model documentation and interviewing selected model authors, UnTRIM was selected to explore numerical modeling of a thermal refuge. Although a proprietary model, an important consideration was the generous support offered by Dr. Ralph Cheng at USGS, one of the model developers.

UNTRIM

The Unstructured Grid Tidal, Residual, Inter-Tidal Mudflat (UnTRIM) model is an unstructured grid, three-dimensional, semi-implicit, finite-difference hydrodynamic model (for details see Cheng and Casulli, 2001). Developed in 1990, the UnTRIM model solves the continuity and momentum (Navier-Stokes) equations for shallow waters, while assuming that water is an incompressible fluid and that the vertical pressure distribution is hydrostatic (Cheng *et al.*, 1993). Mass transport is represented through the three-dimensional transport equation for salt, heat, dissolved matter and suspended sediments. While designed as a three-dimensional model, UnTRIM can be run for one- or two-dimensional scenarios as well.

Using a characteristic analysis, Casulli (1990) found that numerical stability of the solution for the governing equations was controlled by the gravity wave and transport terms of the momentum and continuity equations, respectively. Therefore, UnTRIM uses a semi-implicit finite-difference solution method. The more accurate, but numerically intensive semi-implicit finite-difference method is applied to terms having the greatest effect on the stability, while the remaining terms are treated explicitly (Casulli, 1990). This approach leads to a representation of the governing equation that is both accurate and computational efficient.

In its original form, UnTRIM required a structured grid of four-sided polygons to be used to describe the area being modeled. Recent updates to the UnTRIM model have added the ability to handle three or four sided orthogonal polygons. An unstructured grid improves computational efficiency by allowing users to specify different size polygons depending on where greater detail is needed to represent an area (Cheng *et al.*, 2001). Additional tools are available to ease the creation of input files, but these are not included as part of the UnTRIM package. User's manuals and technical documentation are available and the theoretical background of the model was been presented in Casulli (1990), Cheng *et al.* (1993), Casulli and Walters (2000), Cheng *et al.* (2001) and Cheng (2004).

UnTRIM Application: Beaver Creek

To explore the potential application of numerical models to thermal refugia, the UnTRIM was applied to the Beaver Creek site using 2004 data. Model implementation required discretization of the site bathymetric map into unstructured orthogonal grids. The water's edge was specified within the grid file, along with the water high water mark (to serve as a reference datum). A computational mesh was generated using Argus ONE (a general purpose graphical pre- and post-processor software package that can be used to generate grids or meshes). A separate utility was used to convert the Argus ONE grid format to the UnTRIM format. The final Beaver Creek mesh consisted of over 5,000 polygons (Figure 30).

Beyond the geometry file, several additional files are required to run UnTRIM. However, few require modification. Exceptions include the configuration file and the input file. Information in these files includes initial water surface elevation (below the reference datum) at open boundaries, initial temperatures and concentrations at open boundaries, bed roughness (variable throughout the mesh), time step, as well as other model control parameters. (At open boundaries water is allowed to enter or leave the modeling domain. The remaining boundaries are considered 'closed' to flow across the boundary). Groundwater sources were not considered in this application.

For the Beaver Creek application the assumed initial conditions were from midnight on August 10, 2004. Initial creek water temperature was set to 17.0°C, main stem river water temperature was set to 23.0°C, and the reference elevation of 1627.0 m was applied. The mesh consisted of 5,114 polygons, with 56 open boundary points (creek, river upstream of confluence, and river downstream of confluence). The initial elevations (with respect to the reference datum) of the creek, upstream river, and downstream river were set at 0.10 m, 0.05 m, and -1.25 m, respectively. Because flow changes over the course of a day are small, and to reduce simulation time, the model was run for steady-state conditions. The model was run at 30 seconds time steps until stable conditions were achieved.

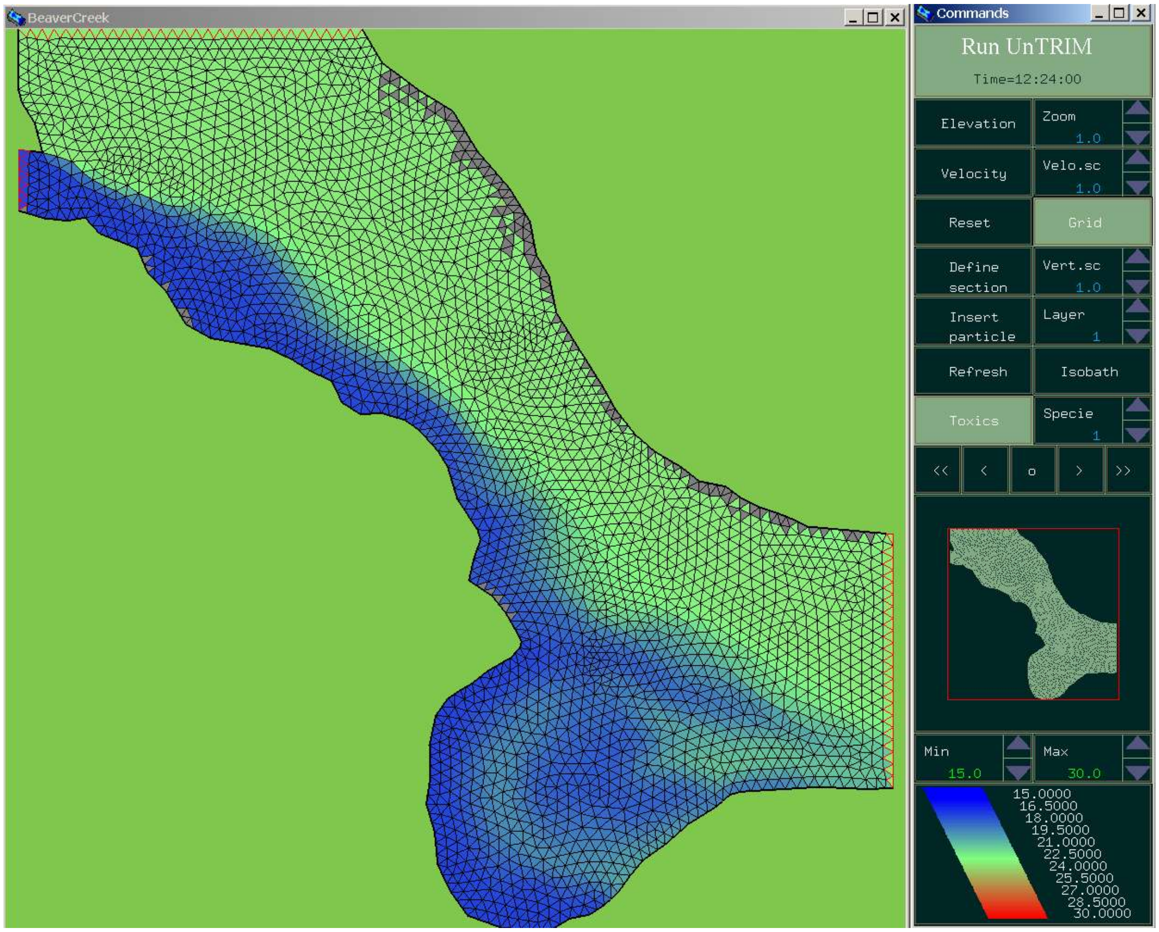


Figure 30. UnTRIM Grid for the Beaver Creek site, 2004.

UnTRIM Results and Analysis

UnTRIM results were processed for twelve locations at the Beaver Creek site (Figure 31); however, any number of locations could be examined. In addition to water temperature, UnTRIM calculates velocities and simulated constituents. Velocity, depth, and temperature were the parameters simulated in this study.

Simulated temperatures, shown in Figure 32, indicate that these initial model results depict conditions similar to observations (temperatures range from approximately 17.0°C (blue) to 23.0°C (green)). Model results indicate that the cold water is primarily concentrated along the right shoreline and in the algae mat. The transition zone occurs relatively close to shore, as in the prototype. Comparing the simulated results with field data, it appears that UnTRIM underestimates the extent to which the cooler water from Beaver Creek extends out in to the main stem Klamath River (Figure 33). It is postulated that local geometry and improved representation in the region near the algae mat may reduce this discrepancy. Modifications to boundary elevations for both the Klamath River and Beaver Creek boundaries to avoid drying of regions in and around the algae mat support this argument. In 2005 both the upstream and downstream areas of the main stem were mapped in greater detail. One critical finding was that the size of the backwater region had been considerably over-estimated in 2004. Although this updated bathymetry has not been included in the latest UnTRIM simulations, it is presumed that these updates would likely improve overall representation of the thermal refuge.

Despite the coarse representation of certain geometric features (including the absence of microtopography, such as boulders and other small scale changes in the bed), UnTRIM did capture much of site details. For example,

- the overall extent of the refugia along the right shoreline as a long, narrow feature,
- minimal mixing and persistence of cold water in the upper half of the refugia,
- retention of cold water in the region of the algae mat, and
- dissipation of the cold water impacts at the lower most reaches of the refugia,

The model results also suggest a small magnitude clockwise circulation in the backwater at the lower end of the refugia. Biologists completing fish counts in this backwater area had previously identified such circulation (A. Corum, pers. comm.).

Temperature results were output at nine locations for this exploratory effort. Generally, the results from the UnTRIM model were consistent with the temperatures recorded by the iBCods (Table 8). In general the UnTRIM results were within 0.5°C of the observed values, except at location 12 where the field temperature was 1.5°C lower than that of the creek. The temperature of this logger registered 0.5°C lower than observed Beaver Creek water upstream of this site. Discrepancies may be a result of logger resolution (±0.5°C), due to groundwater inflow (not incorporated into this modeling analysis), and/or geometric representation of the site in the model.

Local velocity measurements were unavailable on August 10, 2004. Limited data in the shallower areas of Beaver Creek and the refuge area within the main stem were available for the deployment and retrieval date. In general, the UnTRIM simulated velocity field indicates that the greatest velocities occur in the thalweg of the Klamath River and in the vicinity of the creek mouth. The values were consistent with those recorded over the iBCods. No measurements were made in the thalweg, so the comparison is qualitative. Local discrepancies could be considerable because the actual river bottom has local discontinuities and large boulders, not reflected in the smooth bottom geometry used for the 2004 model run. Further, more extensive 2005 surveys indicate the thalweg may be further from the right bank, more towards the center of the channel, then estimated in the 2004 survey (and model bathymetry). Finally, examination of Figure 34 indicates that simulation predicted high velocities close to the right shoreline near the transition from the upper to the lower refugia areas. These high velocities seem inconsistent with field conditions present at the Beaver Creek refuge in this region. Refinement of the model geometry or re-assessment of model bed roughness representation may improve the overall representation of the thermal refuge extent.

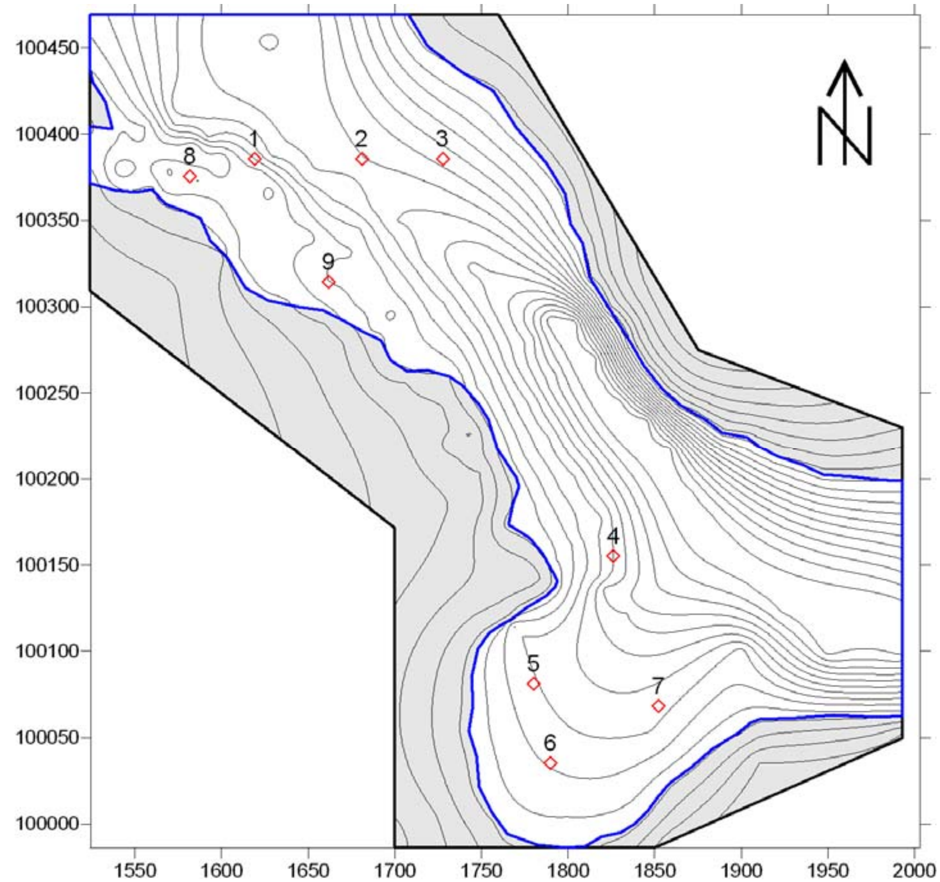


Figure 31. Location of UnTRIM Results Stations, 2004.

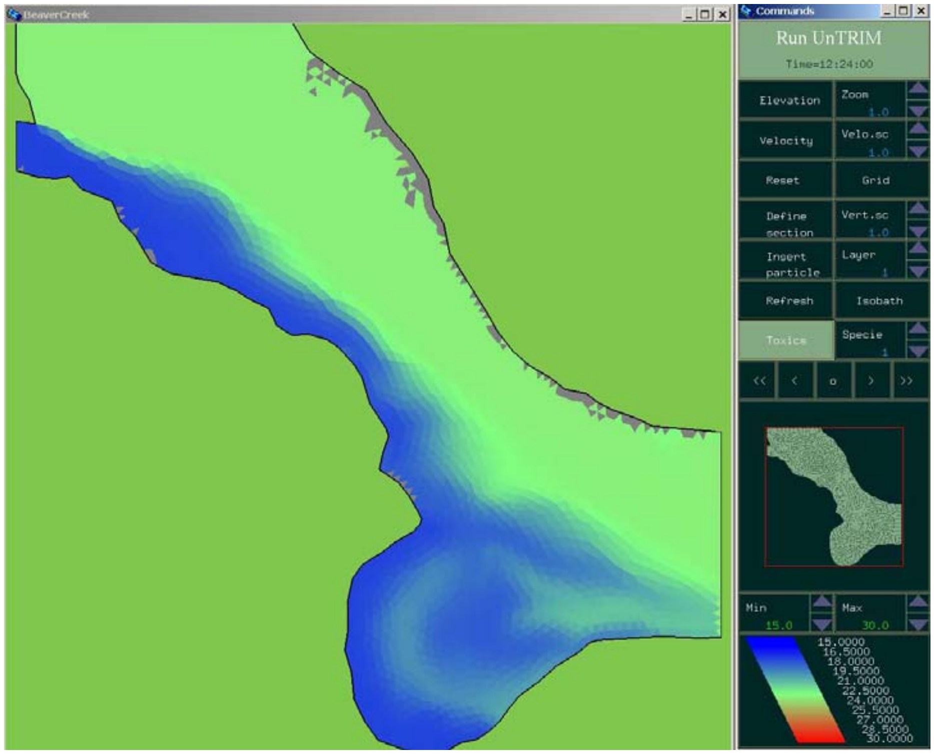
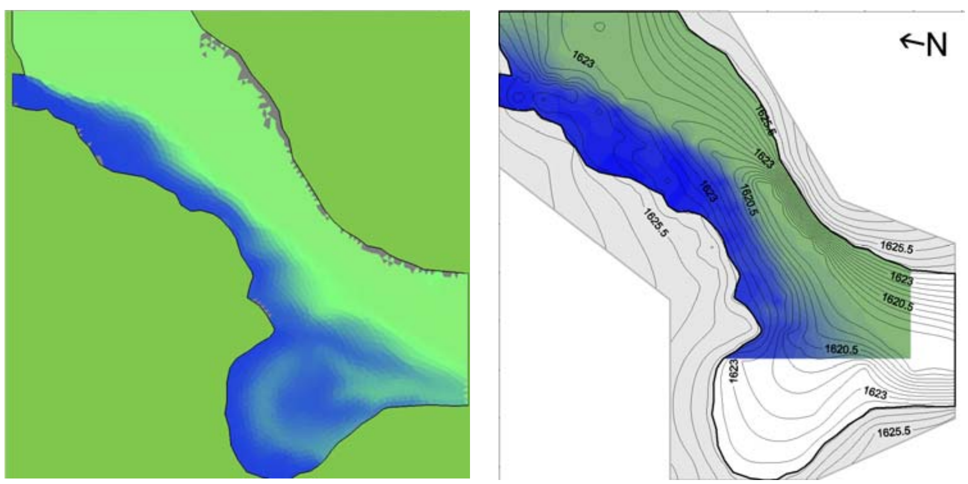


Figure 32. UnTRIM Water Temperature Results, 2004.



(a) UnTRIM Results (b) iBCod Data

Figure 33. Comparison of UnTRIM Simulated Water Temperature and Field Observations (*i*BCod Data) for August 10, 2004.

Table 8. Simulated UnTRIM and Field (iBCod Data) Temperature Comparison, 2004.

UnTRIM Location	iBCod #	Temperature (°C)	
		UnTRIM1	iBCod
1	269	23.0	22.5
2	291*	23.0	23.0
3	291*	23.0	23.0
6	287	19.2	19.5

8	n/a	19.1	-
9	n/a	19.3	-
10	n/a	19.2	-
11	203	17.3	17
12	213	17.8	16.5

* Not available (no iBCod at location) set equal to the Klamath River upstream, iBCod #291

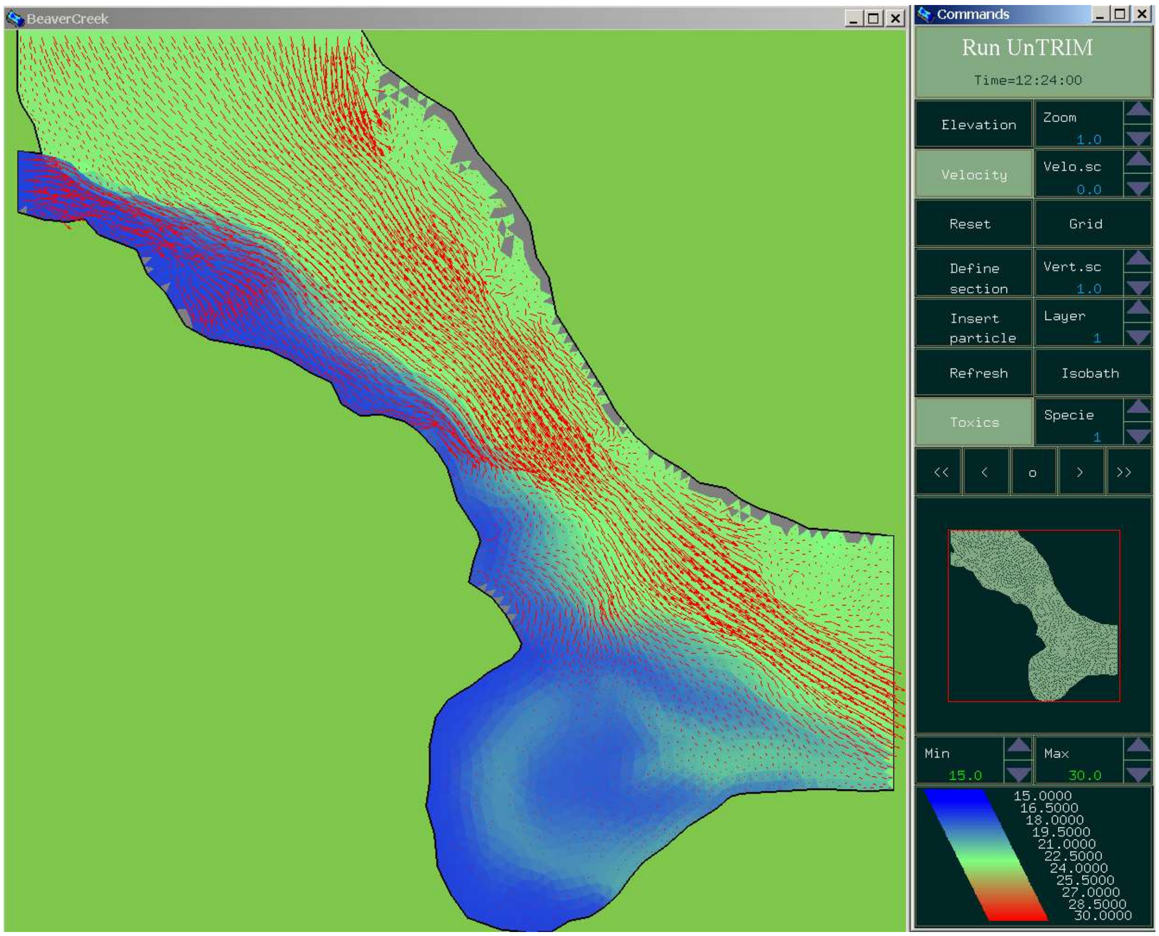


Figure 34. UnTRIM Simulated Velocity at the Beaver Creek Site, 2004.

CONCLUSIONS

While not extensive or detailed, the preliminary UnTRIM model indicates that the Beaver Creek site could be modeled if additional refinements were made to the model data, especially regarding the site bathymetry. Among the major issues with the model is that the water elevations had to be changed to force the algae mat area to remain watered. This is unsurprising because a comparison of the 2004 bathymetery and the 2005 bathymetery indicated that the 2004 bathymetery data over-estimated the algae mat volume. The 2005 bathymetry may reduce the need to modify the initial water elevation to avoid drying out the algae mat area in the model.

The initial comparisons were either qualitative in nature or based on a limited number of comparison points. Still it indicated that many of the major features of the site are correctly represented with UnTRIM. The reverse circulation within the algae mat and the general shape and size of the refugial area were represented closely. Additional output points (locations in the model where velocity and temperature are reported) would be necessary to quantify how well UnTRIM represented the refugial area.

If a model of the Beaver Creek site were to be developed and refined it would possible to model the response of the site to different flow and temperature conditions or different site configurations. Also, different options to change the physical size of the refuge (from adding woody debris to raising the size of a rock bar) could be evaluated. The preliminary model was run for steady-state conditions, using data from a single flow and temperature combination. All of the boundary conditions (stage and temperature) could vary with time enabling managers to assess the impacts of their actions on a refuge for a continuous period of time.

Overall, computer modeling can give managers the ability to estimate the response of the refuge to different management options prior to making changes in the field. Models, such as the one of Beaver Creek, are highly detailed and can be used to help decision makers manage very localized systems. The information and data from the detailed, local models can be used by itself for management of that location alone or be used in models that represent a larger system.

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CHAPTER 5: MODELING AT A REGIONAL LEVEL - A SYSTEM OF THERMAL REFUGIA

INTRODUCTION

The physical and biological structure and function of individual thermal refugia have been presented previously. This chapter focuses on how a system of refugia functions for two stages in the salmonid life-cycle. The major purpose of this chapter is to present and demonstrate a framework and model for understanding the function of a system of thermal refugia. This framework and model can be expanded and improved to integrate improvements in understanding of fish use and behavior regarding thermal refugia.

A brief overview of systems modeling is presented first. Then two different fish migration models are presented. Both models share a common flow and temperature routing method, the same refuge capacity and cost method, and the same refuge sizing method. The common methods are presented first, followed by the two models and examples.

SYSTEMS MODELING BACKGROUND

Historical modeling efforts revolve around simulation models, which are "usually characterized by a representation of a physical system used to predict the response of the system under a given set of conditions" (Simonovic, 1992, pg. 264). UnTRIM, the model presented previously, is a simulation model. Labadie (1997) states that "simulation or descriptive models are particularly attractive for answering what if questions regarding the performance of alternative operational strategies . . . [but] are ill-suited to prescribing the best or optimal strategies when flexibility exists in coordinated system operations." Optimization or prescriptive models are well suited to evaluating alternatives and determining those that have the most promise.

Even though optimization has the potential for widespread application, it is not often used in decision making. Reasons include, but are not limited to, a lack of trust by decision makers in the models, lack of interaction and communication between model users and developers, conflicting objectives that make it difficult to develop optimization models, and time, money and data limitations (Friedman *et al.*, 1984; Rogers and Fiering, 1986; Loucks, 1992; Simonovic, 1992; Labadie, 1997). Despite the limitations and drawbacks, some agencies and organizations have begun to develop or utilize optimization models (HEC, 1991; Watkins *et al.*, 2004).

Optimization modeling has been actively used and discussed since the 1960s (Labadie, 1997), but up until the late 1990s large-scale optimization was nearly impossible. Recent advances in computer processors and memory have made it possible to run large scale optimization programs on desktop computers. Many types of optimization models exist, ranging from relatively simple to highly complex. Each modeling method has strengths and weaknesses.

One of the most common types of optimization modeling is linear programming. Linear programming guarantees a global optimal solution and dual values for sensitivity analysis, among other benefits (Simonovic, 1992; Labadie, 1997). The drawback is that pure linear programming models require that the objective function and all constraints be linear. Additionally, very large linear programming models can be computationally burdensome. One specialized form of linear programming is network flow programming or network flow optimization. Network flow models represent everything as interconnected nodes and links.

All optimization models have some similar characteristics: an objective function and specified constraints. The objective function specifies the stated goal of the model in mathematical terms. The constraints mathematically represent the physical and institutional bounds that the solution is subject too. Traditional constraints include "conservation equations" requiring that the flow from node *i* equals the flow into node *j* (Ford *et al.*, 1962). More recent network flow programming allows for gains and losses to take place on links. These network-with-gains or generalized network models have gain parameters on the links that allow flow to be increased or decreased (Jensen *et al.*, 1980). Parameters greater than one represents gains, while parameters less than one represent loses.

Optimization requires that all components of the system represented in the model be specified mathematically. In pure network flow, the weights on the different links specify the relative value of one component compared to the rest of the system. However, it is easier to specify the economic value of water to a farmer than it is to a fish. The value of the land or the crop can be translated to a volume of water and then put into an optimization model. For the fish, or many other non-economic water uses, determining the correct value of the water is far more difficult. There are different ways by which the economic value of environmental services may be determined. These include, but are not limited to, contingent valuation method, market comparisons of similar goods with and without environmental components, and travel costs to environmental locations (Loomis, 2000). However, establishing economic values for environmental water uses remains controversial (Shabman and Stephenson, 2000). Optimization modeling can avoid representing environmental water needs economically by imposing them as constraints on the system (the river needs *X* units of water).

There are two optimization models presented below. The upstream adult migration model is pure optimization. The downstream juvenile migration model is a combination of simulation and optimization. Both models are represented by network flow with gains and losses and solved using Microsoft Excel's built-in Solver. To avoid economic valuation of fish survival, cost is only used to determine how much expansion is possible given a specific budget. There is no economic competition between fish survival and any other use of the water or refugial area.

SYSTEM OF REFUGIA

Along rivers, such as the Klamath River in California, tributary inflows form potential thermal refugia (Figure 2). Fish use such a system of thermal refugia to survive warm water conditions in the main stem as they move up and down the river system. Salmonid (coho, Chinook and steelhead) life cycles were discussed in Chapter Two, but will briefly be reviewed. Depending on the salmonid species, fry that emerge from the gravels in the spring can either remain in the freshwater system or migrate to the estuary. Those that remain in the freshwater system through the summer must find over-summering habitat. In the fall, spawning salmonids return to the freshwater and begin to migrate upstream. Main stem temperatures may not have yet begun to cool or may not have cooled enough and these fish seek out cold water habitat as they move upstream. This results in cold water thermal refugia being generally necessary for two stages of salmonid movement in the system: over-summering habitat for young salmonids moving down the river system toward the estuary or over-wintering habitat locations and for upstream migrating adult fish. In both cases, movement generally occurs as the main stem of the river cools.

Returning adult fish are more likely to be affected by diurnal cooling because adults travel mainly in the night and early morning when temperatures are lowest. In this sense they use the refugia in a 'hopscotch' manner, moving from one refuge to the next. Over-summering salmonids, between zero and one year old, generally remain in the same refuge for extended periods and are theorized to move out of the refuge, into the main stem to feed during cool periods of the day (night and early morning) and then return to the refuge when main stem temperatures increase (afternoon and evening) (Sutton *et al.*, 2002; 2007).

While it is important to maximize the benefits of each thermal refuge, it is also important to consider their interactions as a system of refugia. Determination of which refugia provide the greatest benefits for system-wide fish survival and production would be useful for managers who want to improve overall river system conditions. It should be noted that the system must still be managed to provide high-quality habitat for as many fish as possible. Ecologists warn against creating ecological (or evolutionary) traps (Coutant, 1997; Donovan and Thomspon, 2001; Schlaepfer *et al.*, 2002). These are areas that appear to be good habitat, but become traps for fish as they mature or as conditions change. If modifications to the thermal refugia occur, it should be to provide both cold water and other necessary habitat needs.

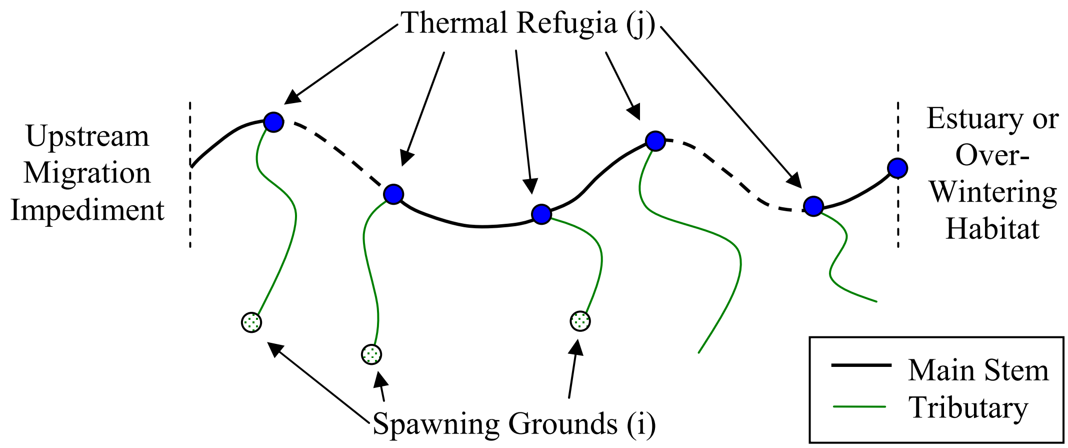

Figure 35. Theoretical River System with Multiple Thermal Refuge Locations.

Two system models are presented below. One model represents adult fish moving upstream toward the spawning grounds in the early fall. The second model represents young fish moving downstream during the summer. Both models use the same logic for flow and temperature routing and use the same capacity expansion optimization model. In both models the spawning locations are denoted with an "*i*" and the refugia are denoted with a "*j*".

River Flow and Temperature Representation

The river system is represented using nodes and links. Each confluence (location where the tributary flows into the main stem) is represented by a node. The spawning grounds and estuary are also represented as nodes. Each link represents a river or tributary reach. For both models, a basic river routing model determines the flow rate and temperature in each reach of the river system. Flow rates determine the temperature in each reach of river between thermal refugia. River reach temperature and travel times then determine the loss rates of fish in each reach.

Each node (excluding the spawning grounds and estuary) has the potential for a tributary inflow (Figure 36). Not all tributaries can function as spawning grounds. Access and local conditions preclude use of some tributaries as spawning grounds for salmonids.

The inflow from the tributary has both a flow and a temperature. Additionally, each river reach can gain or lose water depending on the conditions along the length of the river reach. However, distributed flows along the length of the river are not included in the model; as such, the miscellaneous gains and losses are represented as a single additional flow into or out of a node. As with the tributary, the miscellaneous gains and losses have a flow and a temperature.

None of the nodes in the river system can store water, so inflows must equal outflows at each node. The water mass balance assumes that all flows into the refuge (node) must equal all flows out of the refuge (node) (Eqn. 7).

$$Q_{j+1,j} + Q_{Tj} + Q_{Mj} = Q_{j,j+1} \tag{7}$$

The flow into refuge *j* from the upstream refuge (*j* – 1) is represented by $Q_{j-1,j}$, while the flow to the next downstream refuge (*j* +1) is denoted by $Q_{j,j+1}$. The tributary also contributes flow (Q_{Tj}) into refuge *j*, as does the miscellaneous gains and losses (Q_{Mj}).

Temperature is represented as a conservative and perfectly mixed substance, so simple weighting is used. The river channel is assumed to be vertically homogenous. In river systems, heating and cooling occurs within the river reach due to meteorological conditions (primarily driven by solar radiation). For this simplified flow and temperature representation, a simple value is used to indicate the amount of heat added to the river in each reach.

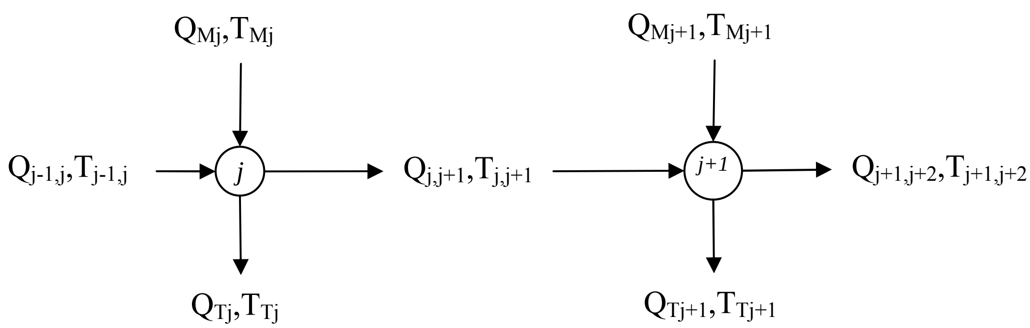

Figure 36. Representative Node for Flow and Temperature Mass Balance.

Each water flow has an associated temperature. The temperature of the tributary (T_{Tj}) and miscellaneous gains and losses (T_{Mj}) are inputs to the model, while the river temperature from the upstream node ($T_{j-1,j}$) is augmented to account for heating in the reach ($\lambda_{j-1,j}$) due to meteorological conditions. The downstream reach temperature ($T_{j,j+1}$) is then calculated. Water temperature is modeled as a perfectly mixed conservative substance and the overall outflow temperature is an inflow weighted average (Eqn. 8).

$$T_{j,j+1} = \left(\frac{Q_{Tj} T_{Tj} + Q_{Mj} T_{Mj} + Q_{j-1,j} \lambda_{j-1,j} T_{j-1,j}}{Q_{j,j+1}} \right) + \lambda_{j,j+1} \tag{8}$$

The temperatures of tributary inflows and miscellaneous gains and losses are specified by the user. The temperature of the flow into refuge *j* from the upstream refuge is calculated, unless the upstream node represents the inflow boundary in which case the temperature is an input to the model.

The flow and temperature of the water in the river channel are two major factors influencing fish survival during the summer. For this model, these two factors (along with predation) are used to determine fish loss rates between and within refugia.

CAPACITY EXPANSION OPTIMIZATION

Both the upstream and downstream optimization models seek to maximize the number of fish that reach a target location. For both models the capacities (i.e., sizes) in the refugia network limit the number of fish that can survive warm water conditions in the main stem. The method of calculating fish numbers entering each refuge differs between the in-migrating and out-migrating models, but the refugia sizing and expansion methods are similar.

The size of the refuge can be affected by the human activities. Examples include increasing the gravel bar or woody debris at the upstream end of the confluence and increasing the amount of the refuge shaded by riparian vegetation. Each of these activities has cost (for materials, labor, maintenance, etc.). These costs can vary between refuge sites. With this information it is possible to build a relationship between refuge size (i.e., number of fish that the refuge can sustain) and cost. These cost curves will help decision-makers to decide how much to invest to expand each refuge area.

Cost of Expansion

The cost curves are assumed to increase non-linearly (Figure 37), but can be represented in a piece-wise linear fashion. The area (size) of the refuge will be related to fish density (i.e., a refuge can support *X* fish per unit area). Therefore the size of the refuge predicted by the thermal refuge model can be translated into the number of fish that can be sustained. Then the cost per fish value of expansion can be estimated (as the slope of a linear segment). For example, if it is known that it costs *Y* dollars to add a rock bar that increases the size of the refuge by *Z*, then it can be determined how many additional fish could be in the refuge given *Y* dollars. A localized site model, like the one presented in Chapter 4, could be used to estimate the change in the size of the refuge for a given activity. Expansion is only necessary if the number of fish seeking refuge exceeds the refuge capacity. Figure 3 is an example of the size of refuge versus cost of expansion curve.

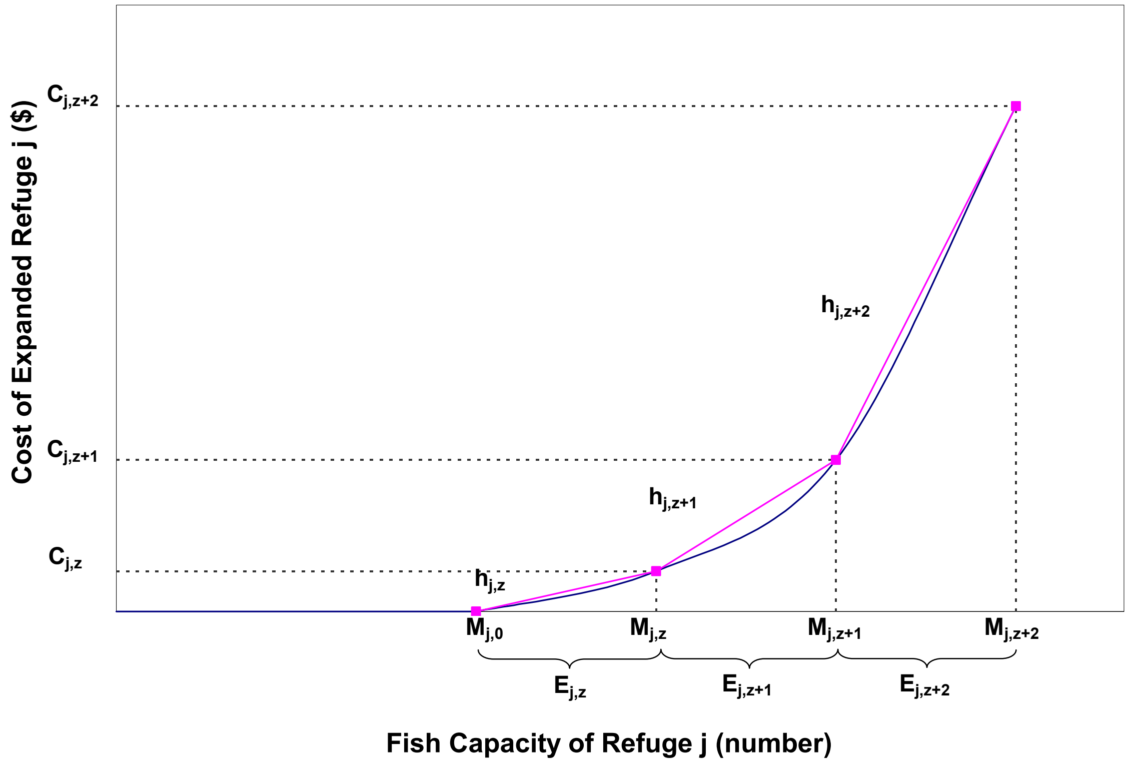

Figure 37. Example Size of Refuge v. Cost of Expansion Curve

From the above figure, the cost of expansion slope ($h_{j,z}$) (dollars per fish) can be calculated where *j* refers to the refuge number and *z* denotes the segment of the curve (Eqn. 9).

$$h_{j,z} = \frac{C_{j,z} - C_{j,z-1}}{M_{j,z} - M_{j,z-1}} \tag{9}$$

With unit costs of expansion ($h_{j,z}$) known, the total cost of expansion and the amount of expansion can be specified. $E_{j,z}$ denotes the expansion that has taken place at refuge *j* at the z^{th} cost segment. Adding this to the existing size of the refuge ($M_{j,0}$) denotes the total size of the refuge. The total cost (TC_j) for the expansion of the j^{th} refuge is the sum of the unit cost of expansion times the amount of expansion (Eqn.10). TE_j represents the total final expanded size of refuge *j* (Eqn. 11).

$$TC_j = \sum_z h_{j,z} E_{j,z} \tag{10}$$

$$TE_j = M_{j,0} + \sum_z E_{j,z} \tag{11}$$

For Figure 3, the total cost (Eqn. 12) and total expanded size of refuge *j* (Eqn. 13) would be:

$$TC_j = h_{j,z}E_{j,z} + h_{j,z+1}E_{j,z+1} + h_{j,z+2}E_{j,z+2} \quad (12)$$

$$TE_j = M_{j,0} + E_{j,z} + E_{j,z+1} + E_{j,z+2} \quad (13)$$

$E_{j,z}$ must equal $M_{j,z}$ before $E_{j,z+1}$ can be greater than zero. Likewise the amount of expansion for a given cost interval ($E_{j,z}$) cannot exceed the amount of expansion available at that cost ($M_{j,z} - M_{j,z-1}$) (Eqn. 14).

$$0 \le E_{j,z} \le M_{j,z} - M_{j,z-1} \quad (14)$$

As a property of linear optimization with a cost constraint, the model automatically attempts to fill the lowest unit cost segments first. It is assumed that the cost curve will be a well-behaved function where the marginal returns decrease with expansion (refuge capacity expansion does not have economies of scale).

The total capacity of the refuge cannot exceed the maximum theoretical size of the refuge ($TE_{j,max}$) nor can it be less than the initial capacity ($M_{j,0}$) (Eqn. 15).

$$M_{j,0} \le TE_j \le TE_{j,max} \quad (15)$$

Budget

The total monetary ($) budget available for expansion is value B. The total costs of expansion for all of the refugia cannot exceed this budget (Eqn. 16).

$$\sum_{j=0}^{n} TC_j \le B \quad (16)$$

FISH SURVIVAL IN A REFUGE

In a refuge, the salmonids are subject to losses (death) due to over-capacity, crowding, temperature, predation, and other factors. Each refuge has a capacity (TE_j) determined by the initial capacity plus any expansion. This will determine how many of the fish that arrive (FI_j) survive crowding. If more fish than arrive than can be sustained, the excess fish are lost.

$$\text{If } FI_j > TE_j \text{ then } OC_j = FI_j - TE_j \text{ else } OC_j = 0$$

Linear optimization cannot directly represent true/false logic, such as the one above. One method to resolve true/false statements is the use of a binary or integer variables.

However, that can be computationally burdensome. Another method is to transform the binary or integer variable into a set of linear constraints, as long as the survival rates are convex functions.

The refuge is divided into "crowding blocks" with each block having a different survival or loss rate. In Figure 38 the capacity of the refuge is broken into four "blocks" and each block has a lower survival rate. In an ideal world, every fish that arrives at a refuge would survive, but as the refuge fills to capacity (and over) mortality increases (Figure 39).

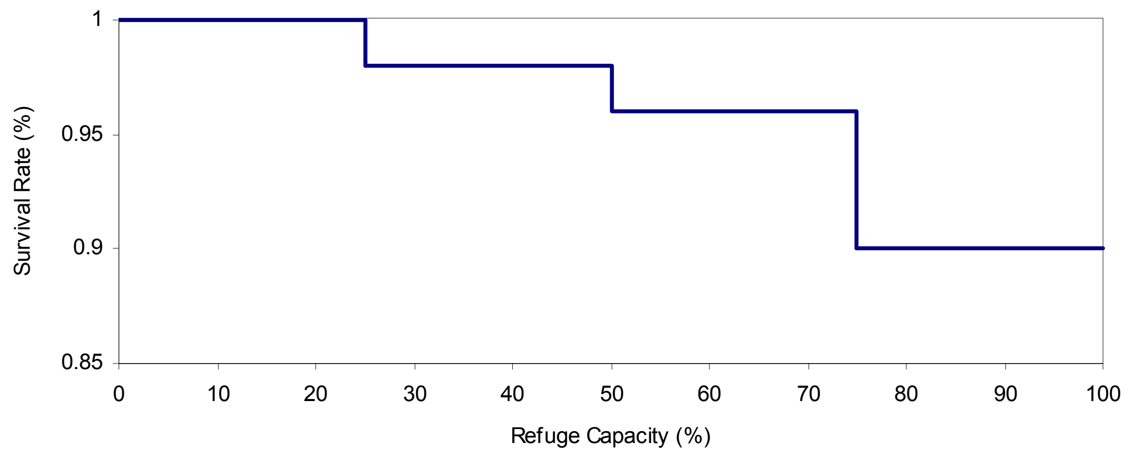

Figure 38. Example Survival Rates for Different Capacity Blocks.

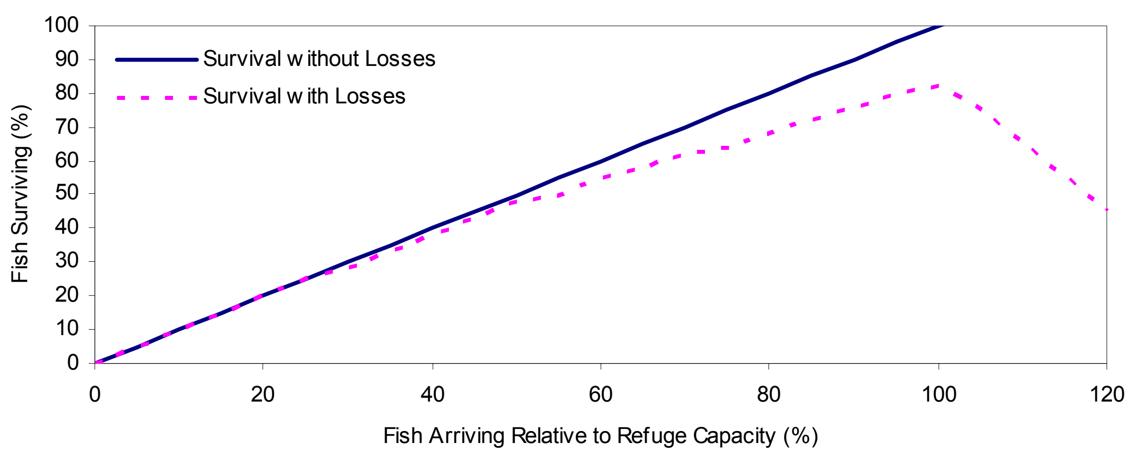

Figure 39. Fish Survival in a Refuge as Capacity Is Reached.

To represent increasing mortality as capacity is reached and the loss of all over-capacity fish a new set of decision variables (CB_b) is needed. The total size of the capacity blocks must equal the number of fish arriving at refuge *j* (Eqn. 17).

$$\left(\sum_{b=1}^{cb} CB_{j,b}\right) + CB_{j,oc} = FI_j \tag{17}$$

$CB_{j,b}$ is the number of fish in crowding block *b*, $CB_{j,oc}$ is the number of fish exceeding the capacity, and FI_j is the number of fish seeking refuge in refuge *j*. To better constrain the number of fish in each crowding block, the upper limits of each block are specified as a percent of the total expanded capacity (TE_j) (Eqn.19). Let $\theta_{j,b}$ be the percent of the total expanded capacity that each crowding block represents. The sum of the $\theta_{j,b}$ must be one (Eqn. 18). The loss of fish due to capacity crowding cannot exceed the available fish (Eqn. 20); let $\gamma_{j,b}$ be the survival rate for each block and $\gamma_{j,oc}$ be the loss rate associated with the amount over-capacity.

$$\sum_{b=1}^{cb} \theta_{j,b} = 1 \tag{18}$$

$$CB_{j,b} \le \theta_{j,b} TE_j \text{ for all } b \tag{19}$$

$$\sum_{b=1}^{cb} \gamma_{j,b} CB_{j,b} \ge \gamma_{j,oc} CB_{j,oc} \tag{20}$$

The number of fish that survive can then be determined (Eqn. 21).

$$FSC_j = \left(\sum_{b=1}^{cb} \gamma_{j,b} CB_{j,b}\right) - \gamma_{j,oc} CB_{j,oc} \tag{21}$$

In Figure 38, the capacity of the refuge is divided into four blocks; each equally sized (25% of the capacity). So the equations for the optimization model would be (Eqn. 22 through 25):

$$CB_{j,1} + CB_{j,2} + CB_{j,3} + CB_{j,4} + CB_{j,oc} = FI_j \tag{22}$$

$$CB_{j,1} \le 0.25TE_j, CB_{j,2} \le 0.25TE_j, CB_{j,3} \le 0.25TE_j, CB_{j,4} \le 0.25TE_j \tag{23}$$

$$\gamma_{j,1} CB_{j,1} + \gamma_{j,2} CB_{j,2} + \gamma_{j,3} CB_{j,3} + \gamma_{j,4} CB_{j,4} \ge \gamma_{j,oc} CB_{j,oc} \tag{24}$$

$$FSC_j = \left(\gamma_{j,1} CB_{j,1} + \gamma_{j,2} CB_{j,2} + \gamma_{j,3} CB_{j,3} + \gamma_{j,4} CB_{j,4}\right) - \gamma_{j,oc} CB_{j,oc} \tag{25}$$

Note, in the equations above it is possible that the number of fish lost due to over-crowding ($\gamma_{j,oc} CB_{j,oc}$) could exceed the number of fish surviving in each capacity block ($\gamma_{j,1} CB_{j,1} + \gamma_{j,2} CB_{j,2} + \gamma_{j,3} CB_{j,3} + \gamma_{j,4} CB_{j,4}$). For this to happen, the number of fish arriving over the expanded capacity would have to be very large or the survival rates of each capacity block would have to be very low. The refuge must have sufficient capacity to sustain all the fish that survived crowding (FSC_j) (Eqn. 26).

$$FSC_j \leq TE_j \tag{26}$$

Fish also can die due to high water temperatures within the refugial areas ($T_{j,T}$) and in-refuge predation (P_j) (Eqn. 27).

$$FS_j = (1 - T_{j,T})(1 - P_j)(FSC_j) \tag{27}$$

Where FS_j is the number of fish surviving in refuge *j*. In short the fish that arrive at refuge *j* minus the amount that die due to crowding, predation and temperature must equal the number of fish that leave refuge *j* (Eqn. 28 and 29):

$$\left(\left(\sum_{b=1}^{m} \gamma_{j,b} CB_{j,b}\right) - \gamma_{j,oc} CB_{j,oc}\right)(1 - P_j)(1 - T_{j,T}) = \sum_{k=j+1}^{n} FO_{j\_k} \tag{28}$$

or

$$(FSC_j)(1 - P_j)(1 - T_{j,T}) = \sum_{k=j+1}^{n} FO_{j\_k} \tag{29}$$

UPSTREAM MIGRATION FOR A SYSTEM OF REFUGIA

Some adult salmonids enter the river system to spawn upstream when warm water conditions are still present. These fish must find cooler water habitat to survive the hottest parts of the day as they migrate to the spawning grounds. A linear optimization model is proposed to assess the role of refugia for upstream migration and maximize the number of fish that survive migration from the estuary (or ocean) to the spawning grounds by improving the network of available refugia.

Key Assumptions & Limitations

The system model proposed here is highly simplified, both with respect to salmonid behavior and conditions in the river system. Along with the simplifications in modeling the flow, temperature, and travel times in the river, the following additional assumptions are made:

- The model does not have a time step component, but assumed steady state conditions during the upstream migration period.
- Adult salmonids can only move upstream; no downstream movement occurs.

- Salmonids move with perfect knowledge of the system conditions ahead to maximize total population.

System Schematic

Fish begin in the ocean and move upstream to the spawning grounds. The in-migrating model assumes all fish are going to the same spawning ground. In reality, fish return to their natal tributaries. As the fish move upstream they rest in the thermal refugia during the hottest parts of the day and then continue to travel when main stem temperatures cool.

There are *n* - 2 refugia in the river system (where "0" denotes the ocean/estuary and "*n*" denotes the spawning grounds). Fish move from refuge to refuge, but do not necessarily have to remain there.

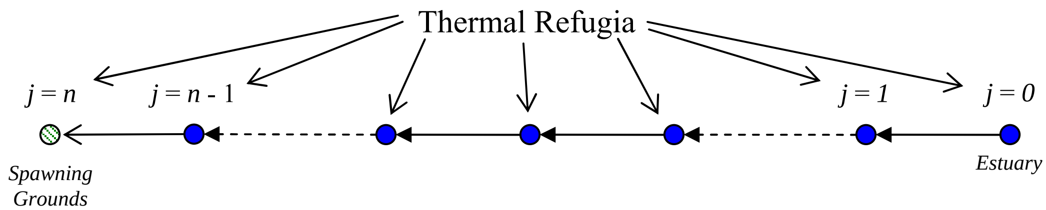

Figure 40. Example Schematic for a System of Thermal Refugia for In-Migrating Salmonids.

Fish Movement Into and Out of the Refuge

The presence of predators, food, competitors, cover and other habitat features influence fish behavior (Matthews *et al.*, 1994). In nature a fish can remain at the refuge, swim upstream, or swim downstream. For this upstream migration model, it is assumed that the fish only swim upstream. An additional major assumption is that fish have perfect knowledge of the system ahead and act to ensure the maximum number of fish reach the spawning grounds. While this assumption is not realistic, it provides an upper bound for the number of fish that could survive to the spawning grounds for a given set of conditions in the river system.

The movement of fish into refuge *j* from the downstream refugia equals the number of fish that left all of the downstream refugia with the intent of reaching refuge *j* minus the number of fish that died along the way. Death of fish along the way can be attributed to several factors; including temperature, predation (natural predation and fishing), and distance to travel, considered below (Eqn. 30).

$$FI_j = \sum_{a=0}^{j-1} \left(\left(SP_{a\_j} \right) \left(ST_{a\_j} \right) \left(SD_{a\_j} \right) \right) FO_{a\_j} \qquad (30)$$

FI_j is the total fish movement into refuge *j*, SP_{a_j} is the survival rate from refuge *a* to refuge *j* due to predation, LT_{a_j} is the survival rate from refuge *a* to refuge *j* due to water temperature, LD_{a_j} is the survival rate from refuge *a* to refuge *j* due to distance traveled, and FO_{a_j} is the flow of fish leaving refuge *a* with the intent to reach refuge *j*.

The losses due to predation and temperature are applied to each reach (Eqn. 31 and 32). In other words, if a fish travels from refuge 1 to refuge 3, it must travel through reach 1 to 2 and reach 2 to 3. Therefore the loss rates would be based on both reaches.

$$SP_{a\_j} = \prod_{k=a}^{j-1} \left(1 - LP_{k,k+1}\right) \tag{31}$$

$$ST_{a\_j} = \prod_{k=a}^{j-1} \left(1 - LT_{k,k+1}\right) \tag{32}$$

$LP_{k,k+1}$ is the loss rate due to predation in reach *k* to *k+1* and $LT_{k,k+1}$ is the loss rate due to temperature in reach *k* to *k+1*. The loss rate due to temperature depends on the temperature in the main stem ($T_{k,k+1}$). The loss due to distance is specified as a single value. This represents the likelihood that a fish could travel form refuge *a* to refuge *j* without stopping. Refugia that are close by have a lower loss rate, while refugia further apart have a higher loss rate.

Losses in the refuge due to crowding, predation, and temperature are specified as described in the earlier section Fish Survival In a Refuge.

The fish that do not die in the refuge (FS_j) leave refuge *j* for locations upstream (FO_{j_b}) (Eqn. 33). The resulting number balance on fish requires that the fish moving into refuge *j* added to the fish already there must equal the fish that die in the refuge plus the fish that leave for the downstream refugia.

$$FS_j = \sum_{b=j+1}^{n} FO_{j\_b} \tag{33}$$

Capacity Constraints

Four sets of capacity constraints must be specified. The number of fish seeking refuge in refuge *j* cannot exceed the initial capacity of the refuge ($M_{j,0}$) plus the amount of capacity expansion. If the number of fish entering refuge *j* exceeds the capacity, the excess fish die (Eqn. 34).

$$FSC_j \le TE_j \text{ or } FSC_j \le M_{j,0} + \sum_i E_{j,i} \tag{34}$$

To prevent the model from over estimating the number of fish available for passage, the number of fish that leave the “fish source” is limited. Let FI_0 denote the total number of fish available from the source (ocean/estuary). Then the flow of fish into the source (node 0) must be equal the flow of fish from the estuary to all upstream refugia (Eqn. 35).

$$FI_0 = \sum_{j=0}^{n} FO_{0\_j} \tag{35}$$

To prevent the model from being unable to converge on a solution, fish are not allowed to accumulate in the refuge (Eqn. 36).

$$FO_{j\_j} = 0 \text{ for all } j \tag{36}$$

In-Migration Optimization Model

The objective of the model is to maximize the number of fish that survive from the ocean/estuary to the spawning grounds using the series of refugia. For this purpose, let there be *n* refugia in series, where "0" denotes the ocean/estuary and "*n*" denotes the spawning grounds. The objective function is then:

$$\text{Maximize } F = \sum_{j=0}^{n-1} \left(\left(SP_{j\_n} \right) \left(ST_{j\_n} \right) \left(SD_{j\_n} \right) \right) F_{j\_n}$$

Eight sets of capacity constraints are presented below (plus three intermediate calculation equations):

Type of Constraint	Equation (n)	
Fish Inflow from Upstream	$FI_j = \sum_{a=0}^{j-1} \left(\left(SP_{a\_j} \right) \left(ST_{a\_j} \right) \left(SD_{a\_j} \right) \right) FO_{a\_j}$ for all *j*	(30)
Fish Outflow	$FS_j = \sum_{b=j+1}^{n} FO_{j\_b}$ for all *j*	(33)
Fish Surviving Crowding	$FSC_j = \left(\sum_{b=1}^{cb} \gamma_{j,b} CB_{j,b} \right) - \gamma_{j,oc} CB_{j,oc}$ for all *j*	(21)
Fish Mass Balance	$\left(FSC_j \right) \left(1 - P_j \right) \left(1 - T_{j,T} \right) = \sum_{k=j+1}^{n} FO_{j\_k}$ for all *j*	(29)
Total Cost of Expansion of Refuge *j*	$TC_j = \sum_i h_{j,i} E_{j,i}$ for all j	(10)
Expanded Capacity of Refuge *j*	$TE_j = M_{j,0} + \sum_i E_{j,i}$ for all j	(11)
Maximum Amount of Expansion Available for a Given Cost	$0 \le E_{j,i} \le M_{j,i} - M_{j,i-1}$ for all j, all i	(14)
Refuge Capacity	$FSC_j \le TE_j$ for all j	(26)

Maximum and Minimum Refuge Capacity	$M_{j,0} \leq TE_j \leq TE_{j,max}$ for all j	(15)
Total Refuge Capacity Blocks Must Equal Fish Entering Refuge *j*	$\sum_{b=1}^{cb} CB_{j,b} + CB_{j,oc} = FI_j$ for all j	(17)
Maximum Size of Each Capacity Block	$CB_{j,b} \leq \theta_{j,b} TE_j$ for all *b*	(19)
Project Budget	$B \leq \sum_{j=1}^{n} TC_j$	(16)
Fish Budget	$FI_0 = \sum_{j=0}^{n} F_{0\_j}$	(35)
Prevent Fish From Flowing Into Same Refuge It Left	$FO_{j\_j} = 0$ for all *j*	(36)

The decision variables, those terms that the model can adjust to find the maximum value of F, are the fish movement terms (FO_{a_j} and FO_{j_k}) and the amount of expansion for each refuge *j* ($E_{j,z}$). The parameters that must have values specified as inputs are the loss coefficients ($LP_{j,j+1}, LT_{j,j+1}, LD_{a\_j}$, T_j, P_j, and $\gamma_{j,b}$), the cost coefficients ($C_{j,z}$), the initial and maximum size of the refugia ($M_{j,0}$ and $TE_{j,max}$), the size of the refuge cost breakpoints ($M_{j,z}$), the total budget for the project (B), the refuge capacity terms ($\theta_{j,b}, \gamma_{j,b}, \gamma_{j,oc}$) and the size of the in-migrating fish stock (FI_0). The remaining terms are calculated internally in the model.

In-Migrating Model Example

A system of six refugia with a single spawning ground is presented in Figure 41. The refuges are arranged sequentially and for a fish to make it from the estuary to the spawning ground, it must travel through all six refugia. The loss rates, flows, temperatures, and capacity expansion variables are specified in Appendix C.

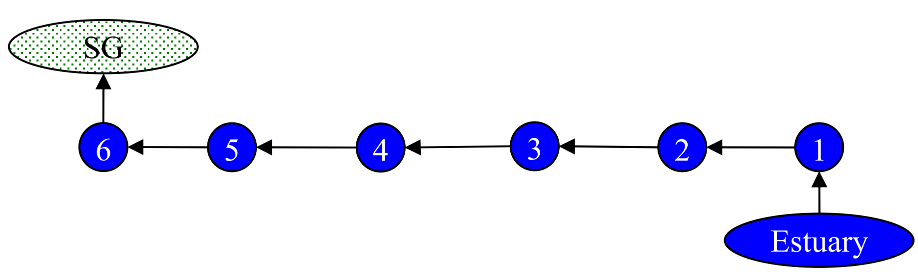

Figure 41. System Used in Upstream Migrating Model Example.

Three modeling alternatives are presented below: changing budget, changing the initial fish stock number, and changing main stem temperature.

Changing Budget

For this modeling alternative the total budget was increased to see the effects of a budget constraint. The budgets evaluated were $0, $100K, $250K, $500K, $750K, $1,000K, $1,250K, $1,500K, $1,625K, and $2,000K. Complete expansion of all refugia requires $1,625K, but other constraints limit the system. The number of fish entering the system from the estuary was 825 per time step (fish/days) (maximum refugia capacity) for all budget alternatives (recall that steady state conditions were assumed). The main stem temperature was set to 15°C to avoid losses due to temperature (the effects of main stem temperature losses are evaluated below).

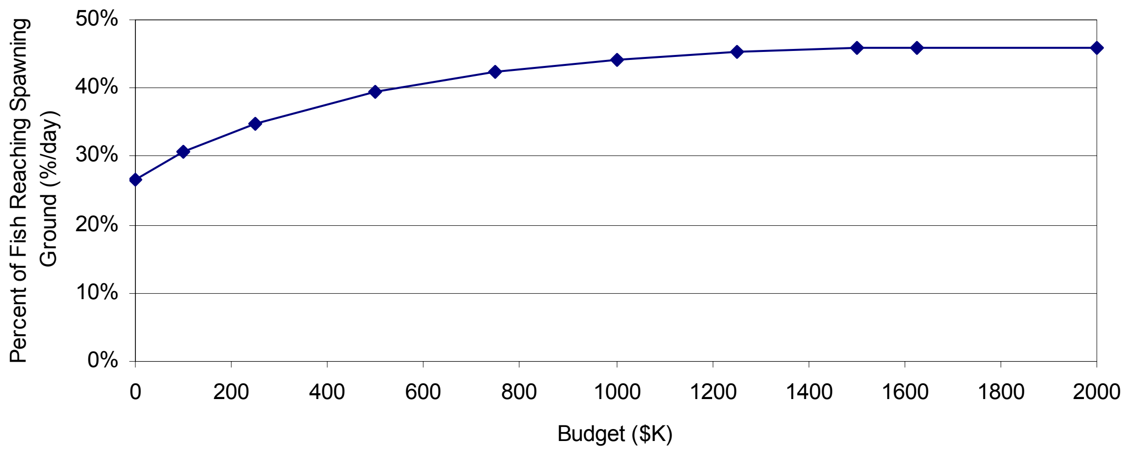

Figure 42. Percent of Fish Leaving the Estuary that Reach the Spawning Grounds for Different Budgets. (Initial fish stock rate was 825 fish/day).

As the budget increased to $2,000K, the number of fish reaching the spawning grounds increased (Figure 42). However, as the budget increases the number of fish reaching the spawning ground increases at a slower rate. Raising the budget to $100K increased the number of fish reaching the spawning ground by 34, while increasing the budget from $1,000K to $1,250K only enabled 9 more fish to reach the spawning grounds.

The initial fish stock rate in the estuary was set at 825 fish/day. (For the effects of different initial fish stocks, see below). With the loss rates in the reaches and refugia due to predation, temperature, and crowding, it is not possible for 825 fish/day to reach the spawning grounds. The migration time temperature loss rates were omitted from the budget analysis (15°C water has a temperature loss rate of 0%). Predation and crowding remained non-zero, but are the same for all refugia.

The number of fish lost due to crowding and in-refuge predation and temperature generally increased as more fish sought refuge (Figure 43). Recall that crowding losses and in-refuge predation and temperature losses are a function of the number of fish in the refuge. Higher fish populations increase loss rate. Due to capacity constraints on the refuge sizing (budget limitations) a large number of fish are lost. When budget is not limiting all six refugia are expanded to their maximum capacity. There is still a loss of 54% (446 fish/day) of the starting population. However, when the budget was zero, 73% (606 fish/day) were lost. Most fish are lost outside of the refuge (due to distance and predation loss in the main stem).

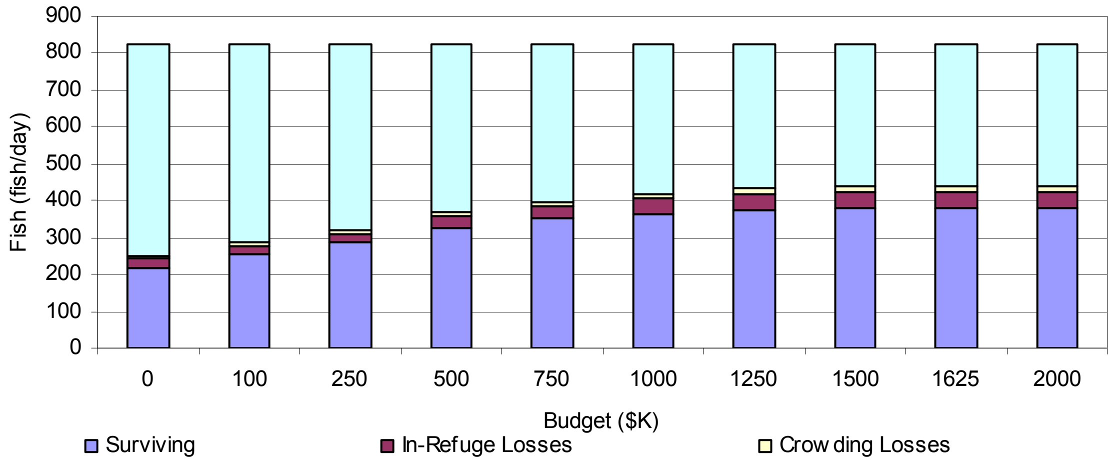

Figure 43. System-Wide Survival and Death of Fishes.

Additional funds would allow more fish to reach the spawning grounds (Figure 44), but at a decreasing marginal rate. At low budgets the size of the refugia cannot be increased and limits the number of fish that survive. As the budget increases, refugia can be expanded to the point where the capacity of the refugia no longer limit the number of fish that can make it to the spawning grounds. The value of additional capacity is relatively low for all budget cases indicating that either the budget (in low budget cases) or the initial fish stock limits the number of fish reaching the spawning grounds (Figure 46).

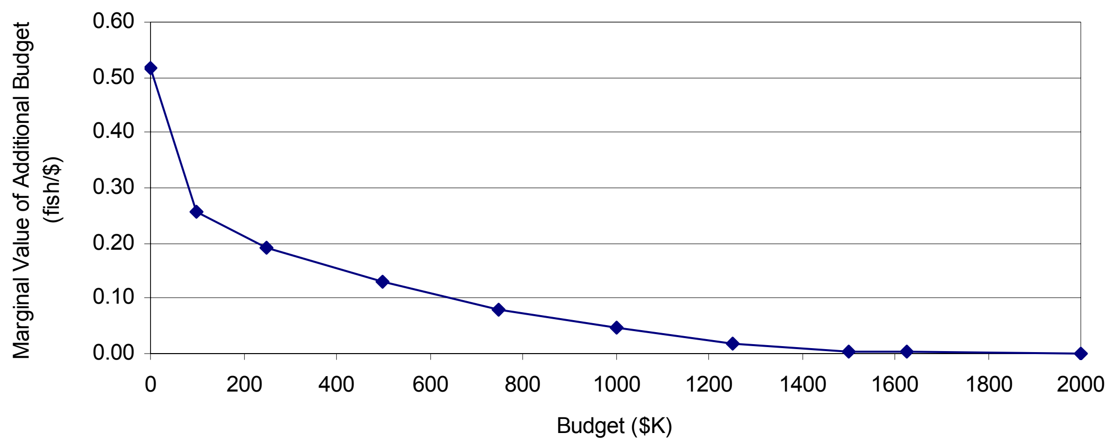

Figure 44. Marginal Value of Additional Budget for the Upstream Migrating Model Example.

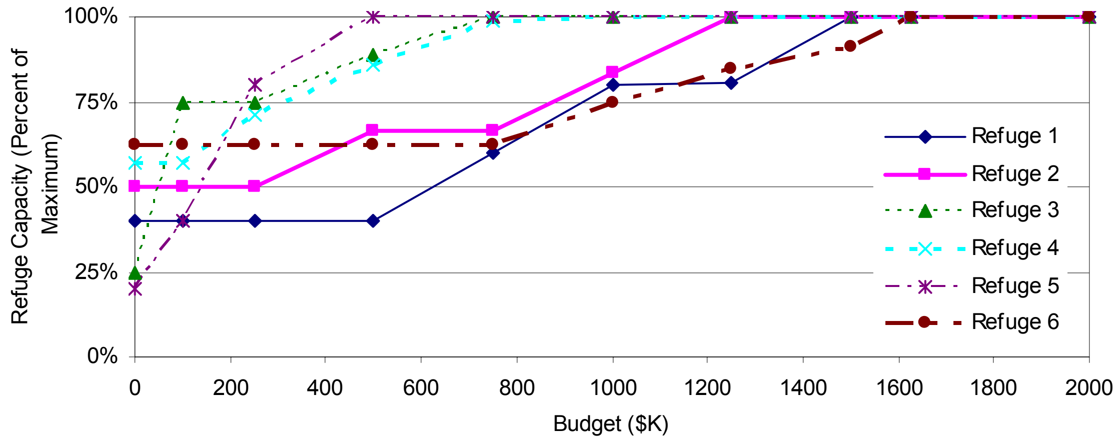

Figure 45. Refuge Capacity as a Percent of Maximum Possible.

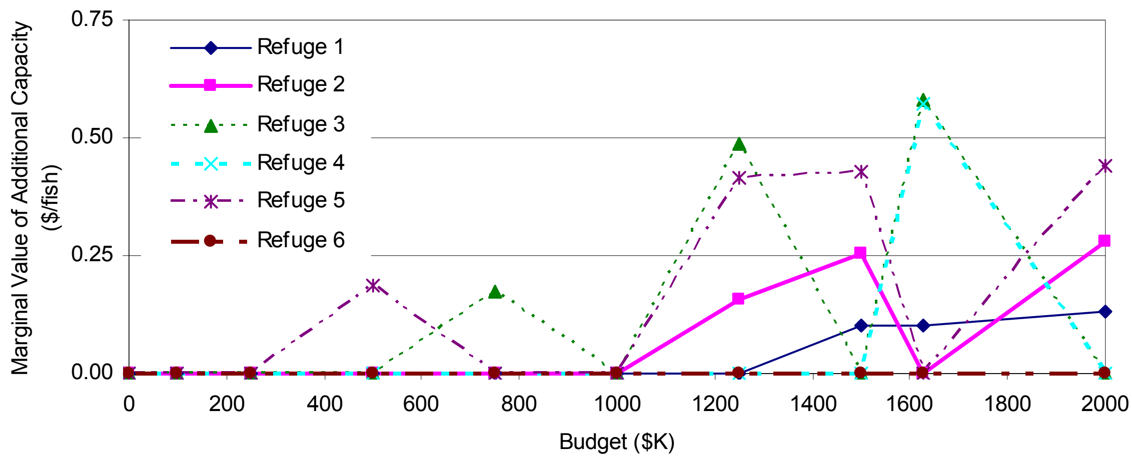

Figure 46. Marginal Value of Additional Capacity for Each Refuge.

All refugia are given the same loss rates due to predation and the same crowding block loss rates. When the budget is zero, no refuge can be expanded. Refugia 3 and 5 are the smallest, even when expanded to their maximum capacities (75 and 100, respectively). These are expanded as soon as there is budget available. The loss rates for fish movement through Refuges 3 and 5 are the lowest.

The model distributed fish so that the number of fish surviving crowding in each refuge equaled the capacity, when the budget was zero. The excess fish were lost (with many fish being lost in transit). For example, of the 448 fish that left the estuary for Refuge 6, only 58 reach the refuge. As the budget increased, the model reduced fish movement from the estuary to Refuge 6 (loss rate of over 85%) and increases fish movement to Refuge 3 and 5.

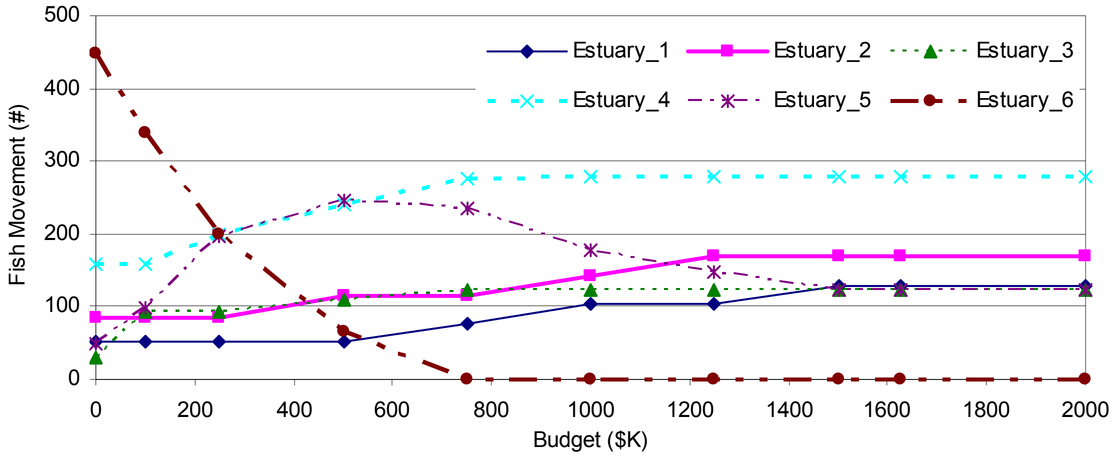

Figure 47. Number of Fish Leaving the Estuary for Each Upstream Refuge.

Changing Initial Fish Stock

The starting fish stock rate (FO_0) was increased from 100 to 2,000 fish/day. The budget was set at $2,000K so as not to limit the number of fish reaching the spawning grounds. The river temperature was set to 15°C (no losses due to temperature in the river or refuge). The starting fish stocks evaluated were 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750 and 2,000 fish/day.

Increasing the estuary fish stock raises the number of fish reaching the spawning ground (Figure 48). The most drastic increases occurred when the fish stock was small (less than 700 fish/day). The number of fish reaching the spawning grounds increased as starting stock increased, but a smaller percentage actually made it (Figure 49). If the starting stock was 100 fish/day, approximately 69% of the fish reached the spawning grounds. For a starting stock of 1,000 fish/day, approximately 40% of the fish survived; at 2,000 fish/day only 24% of the fish survived. Greater numbers make it to the spawning ground because there are more fish initially. The excess fish are lost due to distance and predation rates.

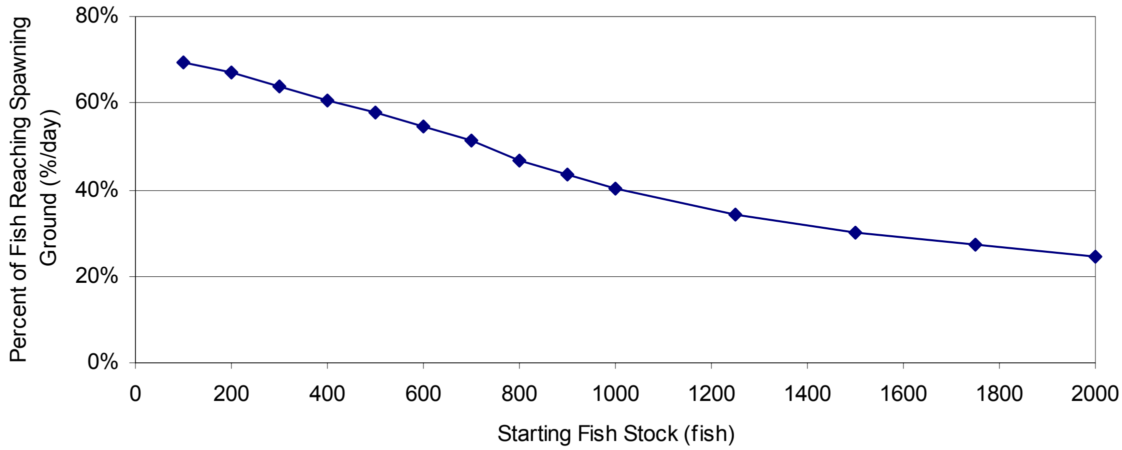

Figure 48. Percent of Fish Leaving the Estuary that Reach the Spawning Grounds for Different Number of Starting Fish Stocks.

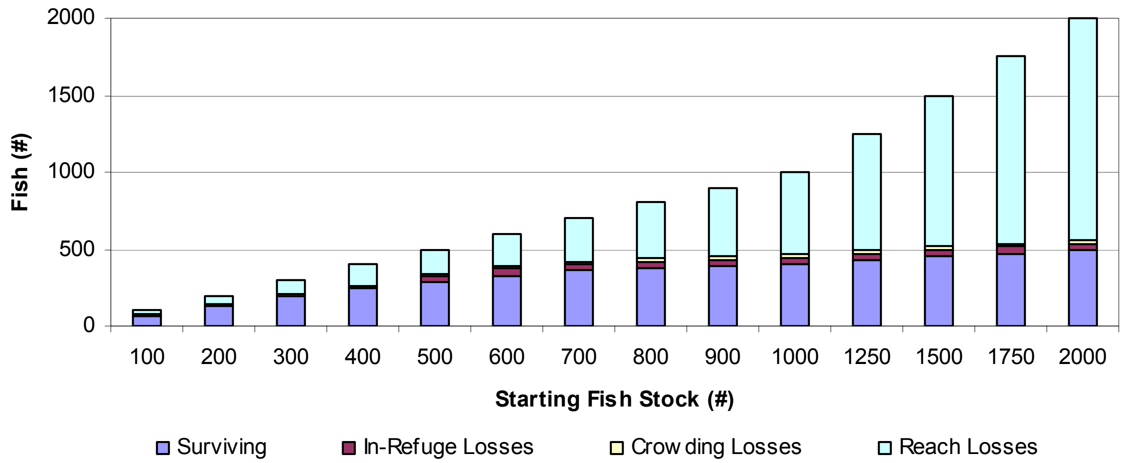

Figure 49. System-Wide Survival and Death of Fishes.

Fish mortality occurs within each refuge due to crowding, over-capacity, predation, and temperature. Likewise, in the reaches, losses occur due to predation, temperature and travel distance. Because the model seeks to maximize the number of fish reaching the spawning grounds it will want to minimize the loss of fish. Within the refuge any over capacity fish reduces the number of fish surviving crowding (Eqn. 37).

$$FSC_j = \left(\sum_{b=1}^{cb} \gamma_{j,b} CB_{j,b} \right) - \gamma_{j,oc} CB_{j,oc} \tag{37}$$

$CB_{j,oc}$ represents the number of fish over capacity in the refuge. Not only are those fish lost, but an additional $\gamma_{j,oc} CB_{j,oc}$ are also lost. To that end, the model almost never opts to allow excess fish to reach a refuge ($CB_{j,oc} = 0$ for all *j*). It would rather send fish through high loss rate reaches.

Changing River Temperature

The initial (T_{0_1}) river temperature was increased from 15°C to 30°C by increments of 1°C. The reach loss rates due to river temperature increase with water temperature. The model cannot optimize the temperature of the river or the loss rates associated with each temperature (only refuge size). Overall the number of fish reaching the spawning grounds is highly sensitive to the water temperature. Loss rates dramatically increase after 23°C, after which point few fish reach the spawning grounds. For more discussion on the loss rates, see Appendix C.

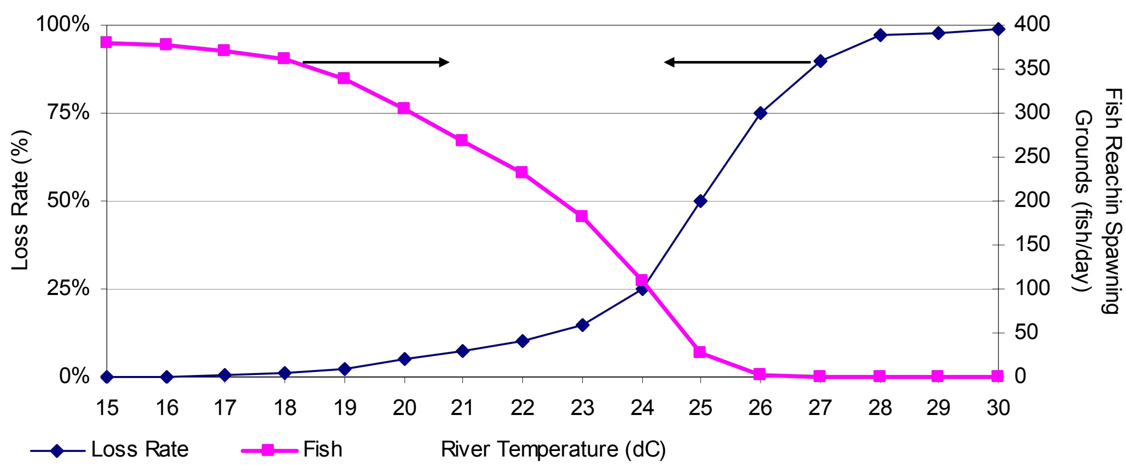

Figure 50. Fish Reaching the Spawning Ground and Loss Rates for Different River Temperatures.

The optimization model is very sensitive to water temperature. In the example, the tributary flows are relatively small and do not significantly change the main stem temperature. However, if these flows were increased then the river temperature could be changed to affect survival rates.

The model is formulated such that fish are subject to temperature losses for each reach in series. Consider a fish traveling from the Estuary to Refuge 2; skipping Refuge 1. The fish would still be subject to the temperature and predation losses between the Estuary and Refuge 1 and Refuge 1 and Refuge 2. Only one very warm reach is needed to significantly reduce the number of fish reaching the spawning grounds.

Upstream Model Summary

The model is highly sensitive to the loss rates, starting fish stock rate, and budget. The budget controls how much expansion is possible. For higher budgets more fish reach the spawning grounds because of greater refugia capacity. The starting fish stock represents how many fish are available in the estuary to spawn. Higher starting stocks mean more fish reach the spawning ground, but at a higher mortality rate (i.e., a smaller percent of the starting stock reach the spawning grounds). The loss rates represent the mortality expected due to water temperature, predation, and distance. Specification of the loss rates determines which migration paths have the lowest loss rates and which refugia are more beneficial.

Overall the model cannot adjust the loss rates or river conditions. Rather it must maximize the number of fish reaching the spawning grounds given the conditions in the river and refuges. In this model fish were assumed to have perfect knowledge of the system ahead and behave to maximize how many reach the spawning grounds. In reality, fish do not know what the system ahead looks like nor do they know what the conditions will be.

The upstream migration model indicates how a system of refugia could work to maximize the number of fish reaching the spawning ground. The model presented above is highly simplified, but could still be useful to indicate how a system of thermal refugia might function.

SYSTEM OF REFUGIA FOR OVER-SUMMERING AND OUT-MIGRATING YOUNG SALMONIDS

Young salmonids use thermal refugia as over-summering habitat in an otherwise inhospitable main stem. Coho must remain in fresh water for one year; Chinook do not have this requirement. This means that newly emerged fry (0+) and those that emerged the previous year (1+) could be present in the system at the same time. However, when the spring flows begin the older (1+) salmonids generally move downstream and out into the estuary. By early summer they have largely left the river system (based on the lack of presence during the summer monitoring regardless of year class).

The fry (both coho and Chinook) emerge in early spring. The coho must find suitable over-summering habitat; this can be either in their natal tributaries or in the main stem of the river, but they can not go to the estuary yet. Chinook also seek suitable over-summering habitat, but they can survive in the estuary as well. If conditions in the tributaries are satisfactory the salmonids remain for the summer and redistribute themselves in the early fall (to find over-wintering habitat). If conditions in the tributaries are not suitable, the salmonids move into the main stem seeking suitable habitat. In the main stem of the river, the salmonids must seek out areas of cold water with suitable habitat conditions (including low velocity, food, cover, etc.). When fall flows and cooler temperatures begin the salmonids redistribute throughout the system to survive the winter.

The model here examines downstream and over-summering of young salmonids in a series of thermal refugia, including examination of modification of individual refugia to increase the carrying capacity of the system for this life-stage.

Key Assumptions & Limitations

The system model proposed here is highly simplified, both with respect to salmonid behavior and conditions in the river system. Along with the simplifications in modeling the flow, temperature, and travel times in the river, the following additional assumptions are made:

- The total number of fry that emerge from the gravels (fry per season) is used as an initial condition, but the system model only tracks those fish that leave the spawning grounds for the main stem.

- Young salmonids can only move downstream; no upstream movement occurs.

- Only a single trigger event is modeled. The transition between acceptable temperature conditions and inhospitable conditions is instantaneous (i.e., it occurs on day *X*). At that point fish move into the next nearest *downstream* refuge. After conditions improve (on day *Y*) the fish continue to move downstream. No additional inhospitable temperature condition periods occur.

- The optimization portion of the out-migrating model is highly constrained. The optimization model only sizes the refugia given the budget and mass balance constraints. This model does not optimize fish behavior. Fish behavior is determined by flow and temperature conditions.

System Schematic

Not every tributary provides spawning habitat for salmonids. In some cases access is limited and prevents salmonids from moving upstream. In other cases conditions in the tributary are not suitable for spawning (e.g., lack of spawning gravels, too high of flows, excessive water temperature, etc.). It is also possible for a tributary to have more than one spawning ground location. Thus n (total number of refugia) does not necessarily equal m (total number of spawning grounds). Likewise, because young salmonids are assumed to move downstream only, not all refugia can be reached from all spawning grounds. In Figure 51 fish leaving spawning ground $i = 1$ can go to any refuge, whereas fish leaving spawning ground $i = m – 1$ can only over-summer in refugia $j – 1$ downstream.

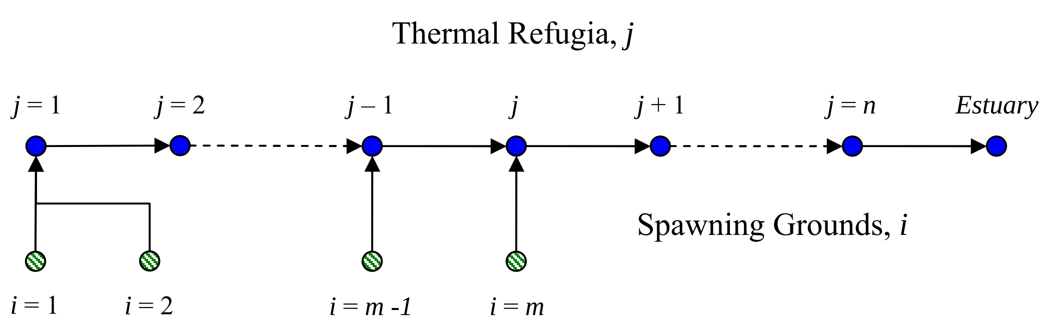

Figure 51. Example Schematic for System of Thermal Refugia for Over-Summering Habitat.

Travel Time

The time required for a salmonid to travel from refuge to refuge is needed. The flow rate in each reach can be calculated (see River Flow and Temperature Model section). The flow rates in each reach will be used to determine the average velocity ($V_{j,j+1}$) and travel time ($TTR_{j,j+1}$). River cross sections vary rapidly, but an average cross section ($A_{j,j+1}$) area will be assumed for each reach. The travel time depends on the distance ($TD_{j,j+1}$) between the refugia, the flow rate ($Q_{j,j+1}$), and a scaling factor ($\alpha_{j,j+1}$). A scaling factor is used because salmonids do not necessarily travel at the average river velocity. They can move faster (if swimming with the current) or slower (if they move in and out of the current or hold in the shallows). Movement and speed is unique to each fish, but for the purposes of this initial model it is assumed that all fish travel at the same speed between refuge *j* and *j + 1* (Eqn. 38 and 39).

$$V_{j,j+1} = \frac{Q_{j,j+1}}{A_{j,j+1}} \tag{38}$$

$$TTR_{j,j+1} = \frac{TD_{j,j+1}}{\alpha_{j,j+1} V_{j,j+1}} \tag{39}$$

With the travel time between two adjacent refugia known, the travel time from any refuge to another refuge can be determined (Table 9).

Table 9. Travel Time Between Refugia.

		Upstream Refuge, *j*				
		1	**2**	**3**	**…**	***n***
Refuge, *j*	**1**	$TTR_{1,1}$	-	-	…	-
	2	$TTR_{1,2}$	$TTR_{2,2}$	-	…	-
	3	$TTR_{1,3}$	$TTR_{2,3}$	$TTR_{3,3}$	…	-
	⋮	⋮	⋮	⋮	⋱	⋮
	n	$TTR_{1,n}$	$TTR_{2,n}$	$TTR_{3,n}$	…	$TTR_{n,n}$
	Estuary	$TTR_{1,estuary}$	$TTR_{2,estuary}$	$TTR_{3,estuary}$	…	$TTR_{n,estuary}$

Each spawning ground is located some distance upstream of the confluence with the main stem. For example in Figure 51 both spawning ground *i = 1 and i = 2* are on the tributary that forms refuge *j = 1*. These two spawning grounds are not located equal distances from the main stem, so the time it takes a fish to move from the spawning ground to the confluence will differ. While travel time varies with flow rate, distance, and other factors in the tributary, for the system model, the user specifies a travel time from the spawning ground *i* to the confluence ($TTSG_i$) (Table 10).

Table 10. Travel Time from Spawning Ground *i* to Confluence with Main Stem.

Spawning Ground, *i*

	1	2	3	…	*n*
Confluence	$TTSG_1$	$TTSG_2$	$TTSG_3$	…	$TTSG_n$

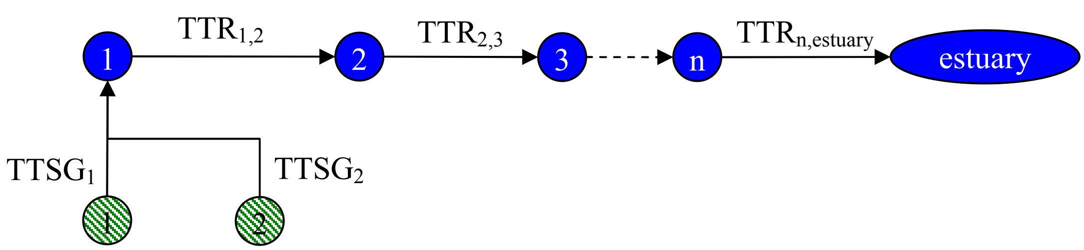

Figure 52. Example Travel Time in Each Tributary and Reach (solid-filled circles represent refugia, hash-filled circles are spawning grounds).

With the travel times from the spawning grounds to the confluence and from the confluence to downstream refugia known, the total travel time ($TT_{i,j}$) from spawning ground *i* to refuge *j* can be determined ('C' denotes the refuge formed at the confluence of the tributary with spawning ground *i*) (Figure 52) (Eqn.40 and 41).

$$TT_{i,j} = TTSG_i + TTR_{C,j} \tag{40}$$

or

$$TT_{i,j} = TTSG_i + \sum_{k=C}^{j-1} TTR_{k,k+1} \tag{41}$$

Table 11. Travel Time from Spawning Grounds to Refugia and Estuary.

		Spawning Ground, *i*			
		1	**2**	**…**	***m***
Refuge, *j*	**1**	$TT_{1,1}$	$TT_{2,1}$	…	$TT_{m,1}$
	2	$TT_{1,2}$	$TT_{2,2}$	…	$TT_{m,2}$
	3	$TT_{1,3}$	$TT_{2,3}$	…	$TT_{m,3}$
	⋮	⋮	⋮	⋱	⋮
	n	$TT_{1,n}$	$TT_{2,n}$	…	$TT_{m,n}$
	Estuary	$TT_{1,estuary}$	$TT_{2,estuary}$		$TT_{m,estuary}$

In Figure 51, the travel time from spawning ground $i = m - 1$ to refuge $j = n$ would be determined by Eqn. 42:

$$TT_{m-1,n} = TTSG_{m-1} + TTR_{j-1,n} \tag{42}$$

In Table 11 all spawning grounds have travel times to all refugia, but not all fish leaving every spawning ground can access all refuges. Recall the assumption that young fish only move downstream. All fish that enter the main stem at locations below *j* can not access refuges above *j*. For example, in Figure 51, fish coming from spawning ground $i = m - 1$, can only move to refuges downstream of (and including) $j - 1$. In this case the travel time from spawning ground $i = m - 1$ to refuge $j = 1$ and $j = 2$ would be not applicable.

Fish Movement from Spawning Grounds

An initial number of fry are present in each spawning ground (EF_i). Of these fish, some proportion ($\beta_{i,t}$) leave the spawning grounds at time *t* and some proportion will over-summer in the spawning grounds (ϕ_i). The sum of ϕ_i and all the $\beta_{i,t}$ must equal to one to account for the fish that emerge from the gravels (Eqn. 43):

$$\phi_i + \sum_{t=0}^{p} \beta_{i,t} = 1 \tag{43}$$

The fish that leave the spawning grounds ($FL_{i,t}$) move downstream as far as possible before conditions become inhospitable (Eqn. 44). In some cases the fish will manage to reach the estuary before conditions change. Fish that cannot reach the estuary will need over-summering habitat. Overall, all the fish that leave the spawning grounds must head for one of the refugia or for the estuary. (Note that *t* in this context refers to the time at which the fish leave the spawning grounds.)

$$FL_{i,t} = \beta_{i,t} EF_i \tag{44}$$

It is assumed that the salmonids enter the main stem at different times (hence the time *t* index) (Figure 53). The $\beta_{i,t}$ value indicates the percent of the emergent fry leaving the spawning ground with the intent of entering the main stem at any given time *t*. Fish can either make it all the way to the estuary or be forced into one of the refugia, depending on when critical conditions begin and the time that they left the spawning grounds.

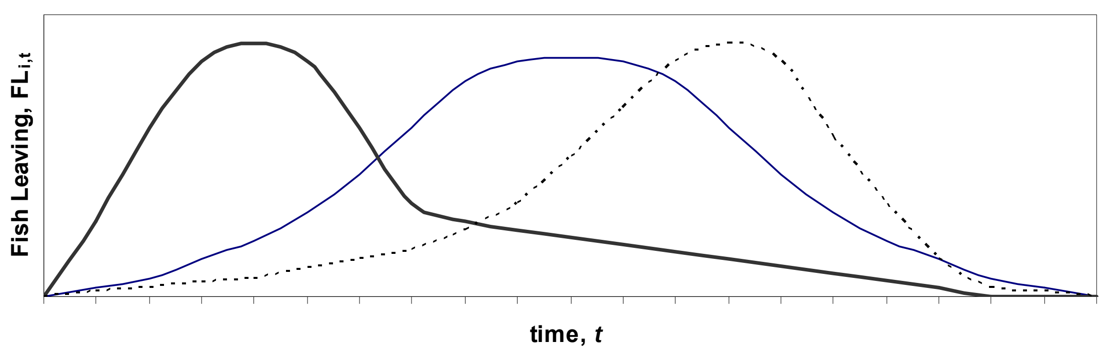

Figure 53. Example Distributions of the Number of Fish Leaving Different Spawning Grounds at Time *t*.

Fish Mortality Factors

As the fish move downstream mortality losses occur from predation in the main stem and tributary ($LP_{j,j+1}$ and $LPSG_i$, respectively), exposure time to high water temperatures ($LET_{i,t,j}$), and other factors ($LM_{j,j+1}$). Predation losses occur regardless of the conditions in the main stem, but the other two losses only affect fish survival when the river is inhospitable.

The predation rates compound to determine the total number of fish lost between spawning ground *i* and the estuary (ultimately). For example, if 100 fish leave the spawning ground, subject to 10% predation losses in the tributary, only 90 fish will reach the confluence with the main stem. If the reach of main stem downstream of the confluence has a 10% loss rate, then another 9 fish are lost moving through that reach, and so on, until the surviving fish reach the estuary or refuge.

The user specifies the loss rates due to predation for each reach ($LP_{j,j+1}$) and from the spawning ground to the confluence ($LPSG_i$), along with the loss rates due to miscellaneous reasons for each reach ($LM_{j,j+1}$) and the loss rates due to exposure time and temperature ($LET_{i,t,j}$). The systems model converts the loss rates to survival rates (survival rate equals one minus loss rate) and applies those to estimate the number of fish that reach the refugia or estuary.

Predation Loss and Survival Rate

The predation loss rates reflect the percentage of fish lost from one location to the next. The user specifies the loss rates within reaches (between refuges) and from the spawning ground to the confluence. The system model needs to know the number of fish that survive (i.e., one minus the lost rate). The survival rate from each spawning ground to refuge can be determined. For example, let $SRP_{i,j}$ represent the predation survival rate of any fish leaving spawning ground *i* for refuge *j*, passing through intermediate reaches between *i* and *j* (Eqn. 45):

$$SRP_{i,j} = (1 - LPSG_i)\left(\prod_{k=C}^{j-1}(1 - LP_{k,k+1})\right) \tag{45}$$

Where 'C' denotes the refuge formed at the confluence with the spawning ground's tributary and the main stem. In Figure 51, 'C' would equal '1' for spawning ground *i* = 2. The survival rate from predation from the spawning ground to the estuary is (assuming *n* refugia with *n + 1* being the estuary) (Eqn. 46):

$$SRP_{i,j=estuary} = (1 - LPSG_i)\left(\prod_{k=C}^{n}(1 - LP_{k,k+1})\right) \tag{46}$$

The survival rate from a refuge to the estuary ($SRPE_{j,est}$) also is needed (Eqn. 47). Again assume the system has *n* refugia. The '*n + 1*' refuge is the estuary.

$$SRPE_{j,est} = \left(\prod_{k=j}^{n} \left(1 - LP_{k,k+1} \right) \right) \tag{47}$$

The above loss rates apply regardless of the conditions in the river (i.e., apply to fish that reach the estuary prior to the onset of critical conditions and those remaining in the system when conditions change).

Exposure Time and Temperature Loss Rates

After the onset of critical conditions, the fish suffer additional losses from exposure to high water temperature over the distance to the next downstream refuge ($LET_{T,ET}$). For this loss rate, exposure time is used as a substitute for distance to the refuge. Salmonids are temperature sensitive species, with an ideal water temperature below 14°C for coho and below 16°C for Chinook (Moyle, 2002; NRC, 2004). Even short exposure to high temperature (above upper twenties) is generally considered lethal to the fish. This loss rate is independent of river reach (i.e., the loss rate is the same for reach *j* to *j + 1* as it is for *j + 1* to *j + 2*, as long as the exposure time (ET) and temperature (T) are the same).

The user specifies a matrix of loss rates due to exposure times and temperatures. If the exposure time and/or temperature that the fish experiences does not exactly match the indices in Table 12 (for example) the system model interpolates linearly between the points to determine the loss rate to apply.

Table 12. Loss Rates Due to Exposure Time and Temperature.

Exposure Time, ET	Temperature, T →	30	29	28	27	26	25	. . .	*h*
	w	$LET_{30,w}$	$LET_{29,w}$	$LET_{28,w}$	$LET_{27,w}$	$LET_{26,w}$	$LET_{25,w}$	. . .	$LET_{h,w}$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮
	8	$LET_{30,8}$	$LET_{29,8}$	$LET_{28,8}$	$LET_{27,8}$	$LET_{26,8}$	$LET_{25,8}$	. . .	$LET_{h,8}$
	7	$LET_{30,7}$	$LET_{29,7}$	$LET_{28,7}$	$LET_{27,7}$	$LET_{26,7}$	$LET_{25,7}$	. . .	$LET_{h,7}$
	6	$LET_{30,6}$	$LET_{29,6}$	$LET_{28,6}$	$LET_{27,6}$	$LET_{26,6}$	$LET_{25,6}$	. . .	$LET_{h,6}$
	5	$LET_{30,5}$	$LET_{29,5}$	$LET_{28,5}$	$LET_{27,5}$	$LET_{26,5}$	$LET_{25,5}$	. . .	$LET_{h,5}$
	4	$LET_{30,4}$	$LET_{29,4}$	$LET_{28,4}$	$LET_{27,4}$	$LET_{26,4}$	$LET_{25,4}$	. . .	$LET_{h,4}$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱	⋮
	0	$LET_{30,0}$	$LET_{29,0}$	$LET_{28,0}$	$LET_{27,0}$	$LET_{26,0}$	$LET_{25,0}$	. . .	$LET_{h,0}$

Miscellaneous Loss Rate

There is one additional loss rate that will affect the number of fish that could potentially over-summer in any given refuge. As the fish move downstream, they could be swept by the cold-water refuge or are on the wrong side of the bank and miss the refuge entirely. These fish continue downstream. In river systems there is the potential that these fish could find highly localized cold-water sources that would sustain them, but for the purposes of the system model these fish perish. The miscellaneous loss rate ($LM_{j,j+1}$) represents those fish swept by or for any other reason do not to enter refuge *j*.

Applied Survival Rate

With the three loss rates known, it is possible to determine the applied survival rate for fish that left spawning ground *i* at time *t* and must go to refuge *j* after the onset of critical conditions (Eqn. 48).

$$SR_{i,t,j} = (1 - LDT_{T,ET})(1 - LM_{j-1,j})(1 - LPSG_i)\left(\prod_{k=C}^{j-1}(1 - LP_{k,k+1})\right) \quad (48)$$

The above equation represents the applied survival rate of the fish that left spawning ground *i* in time *t* heading for refuge *j*.

Movement to the Estuary

Fish that can reach the estuary ($FR_{i,estuary,t}$) before temperature conditions become inhospitable suffer loss only due to predation enroute to the estuary ($SRP_{i,estuary}$) (Eqn. 49 and 50). For the purposes of this model it does not matter what the fish do after reaching the estuary.

$$FR_{i,estuary,t} = (FL_{i,t})(1 - LPSG_i)\left(\prod_{j=C}^{n}(1 - LP_{j,j+1})\right) \quad (49)$$

or

$$FR_{i,estuary,t} = (FL_{i,t})(SRP_{i,estuary}) \quad (50)$$

A fish can arrive at the estuary prior to the onset of critical conditions (*t* = *TC*) if they leave the spawning grounds early enough (Eqn. 51).

$$TT_{i,estuary} + t \leq TC \quad (51)$$

In Eqn. 51 *t* denotes the time that the left the spawning ground and *TC* denotes the onset of critical conditions. For example, if the onset of critical conditions occurs at time *TC* = 15, and it takes 10 days to reach the estuary from spawning ground *i*, and the fish left at time *t* = 2, then (10 + 2 = 12 < 15) that fish would reach the estuary before conditions became inhospitable. The total number of fish reaching the estuary before the onset of critical conditions ($FRPC_{estuary}$) would be (Eqn. 52 and 53):

$$MT = TC - TT_{i,estuary} \quad (52)$$

$$FRPC_{estuary} = \sum_{i=0}^{m} \sum_{t=0}^{MT} FR_{i,estuary,t} \tag{53}$$

Where *MT* denotes the maximum time at which the fish must have left the spawning ground to have reached the estuary.

Movement into Thermal Refugia

At the onset of inhospitable conditions (*t = TC*), the fish remaining in the main stem must move into the nearest *downstream* refuge. Their exposure time and the temperature of the water will determine their mortality rate. The closer they are to the next available refuge, the more likely they are to survive. The higher the water temperature in the river reach, the lower the survival rate.

The location of each group of fish must be determined at the onset of critical conditions. Each group *t* that has already left spawning ground *i* has spent some time in the system ($TTIS_{i,t}$) (Eqn. 54). This value indicates fish location in the system and their next nearest *downstream* refuge.

$$TTIS_{i,t} = TC - t \tag{54}$$

If $TT_{i,j-1} < TTIS_{i,t} \leq TT_{i,j}$ then the fish that left spawning ground *i* in time *t* are heading for refuge *j*. Another way to phrase this is that if the fish left spawning ground *i* between $TC - TT_{i,j}$ and $TC - TT_{i,j-1}$ then they are heading to refuge *j* (Eqn. 55).

$$TC - TT_{i,j} \leq t < TC - TT_{i,j-1} \tag{55}$$

With the destination known, it is possible to estimate the loss rates due to predation and miscellaneous losses. These two loss rates are independent of temperature conditions in the river and only depend on the location of the fish at the onset of critical conditions. The third loss rate depends on exposure time (distance substitute) and water temperature. Recall from the "Flow and Temperature" model, the temperature of the water is known ($T_{j,j+1}$). The exposure time ($ET_{i,t,j}$) is based on the travel time to reach refuge *j* from spawning ground *i* and the time the fish have been in the system (Eqn. 56). The loss rate is a function of the exposure time and water temperature, and is determined by interpolating Table 12 (Eqn. 57).

$$ET_{i,t,j} = TT_{i,j} - TTIS_{i,t} \tag{56}$$

$$LET_{T,ET} = f\left(T_{j,j+1}, ET_{i,t,j}\right) \tag{57}$$

Now with the three loss rates known, it is possible to calculate the total number of fish that left spawning ground *i* at time *t* that reach refuge *j* ($FRR_{i,j,t}$) (Eqn.58 and 59).

$$FRR_{i,j,t} = (1 - LPSG_i)\left(\prod_{k=C}^{j}(1 - LP_{k-1,k})\right)(1 - LM_{j-1,j})(1 - LET_{T,ET})(FL_{i,t}) \quad (58)$$

or

$$FRR_{i,j,t} = (\beta_{i,t} EF_i)(SR_{i,t,j}) \quad (59)$$

Finally the total number of fish entering refuge *j* from all spawning grounds and all departure times must be determined (Eqn. 60).

$$FI_j = \sum_{i=1}^{C} \sum_{t=TC-TT_{i,j}}^{t<TC-TT_{i,j-1}} FFR_{i,j,t} \quad (60)$$

Losses in the refuge due to crowding, predation, and temperature are specified as described in section “Fish Survival In a Refuge” (above).

Post-Critical Period Out-Migration to the Estuary

At some point, conditions within the main stem will improve and the fish in the refugia will be able to continue moving downstream. At this point they are seeking over-wintering habitat (coho) or the estuary (Chinook). The fish that survived the summer in the refuge will move downstream and are only subject to predation losses between refuge *j* and the estuary ($LP_{j,estuary}$) (Eqn. 27 and 62).

$$FS_j = (1 - T_{j,T})(1 - P_j)(FSC_j) \quad (61)$$

$$FR_{j,estuary} = (SRP_{j,est})(FS_j) \quad (62)$$

There is also the possibility that some fish had not left the spawning grounds at the onset of critical conditions. These fish remained in the spawning ground throughout the summer and after conditions improve will move downstream to the estuary. For simplicity, the in-spawning ground loss rates due to temperature (LT_T) are the same as those of the main stem, and the loss rates due to predation ($LPSG_i$) are the same as those from the spawning ground to the confluence. Then after conditions improve the fish migrate downstream and are subject to predation losses ($SRP_{i,estuary}$). The total number of fish reaching the estuary ($FR_{i,estuary}$) is determined (Eqn. 63):

$$FR_{i,estuary} = SRP_{i,estuary}(1 - LT_T)(1 - LPSG_i)\left(\sum_{t=TC}^{g} \beta_{i,t} EF_i\right) \quad (63)$$

Out-Migration Optimization Model

In the downstream movement model, the objective is to maximize the total number of fish that survive from the spawning grounds to the estuary. Some fish move directly to the estuary ($FRPC_{estuary}$), some will over-summer in the spawning grounds ($FRSG_{i,estuary}$), and others will have to over-summer in a thermal refuge ($FR_{j,estuary}$). While maximizing the total number of fish that reach the estuary from all locations is important, the focus of this model is to allow the most possible fish to survive over-summering in the main stem of the river. Therefore, the system model needs to optimize the total number of fish that reach the estuary from all refugia ($FR_{j,estuary}$). The objective function is:

$$\text{Maximize } F = \sum_{j=1}^{n} FR_{j,estuary}$$

The capacity constraints are presented below, along with intermediate calculation equations.

Type of Constraint	Equation	
Survival Rate of Fish that Left Spawning Ground *i* at Time *t* for Refuge *j*	$SR_{i,t,j} = (1 - LET_{T,ET})(1 - LM_{j-1,j})(1 - LPSG_i)\left(\prod_{k=C}^{j-1}(1 - LP_{k,k+1})\right)$	(48)
Number of Fish from Spawning Ground *i* at time *t* that Reach Refuge *j*	$FRR_{i,j,t} = (\beta_{i,t} EF_i)(SR_{i,t,j})$ for all i, t, j	(59)
Number of Fish that Reach Refuge *j* from All Upstream Spawning Grounds	$FI_j = \sum_{i=1}^{C} \sum_{t=TC-TT_{i,j}}^{t<TC-TT_{i,j-1}} FFR_{i,j,t}$ for all j	(60)
Total Refuge Capacity Blocks Must Equal Fish Entering Refuge *j*	$\sum_{b=1}^{cb} CB_{j,b} + CB_{j,oc} = FR_j$ for all j	(17)
Maximum Size of Each Capacity Block	$CB_{j,b} \le \theta_{j,b} TE_j$ for all *b*	(19)
Total Fish Surviving Crowding	$FSC_j = \left(\sum_{b=1}^{cb} \gamma_{j,b} CB_{j,b}\right) - \gamma_{j,oc} CB_{j,oc}$ for all *j*	(21)
Surviving Fish in Refuge *j* After Critical Conditions End	$FS_j = (1 - T_{j,T})(1 - P_j)(FSC_j)$ for all j	(61)
Fish Reaching the Estuary from Refuge *j* After Critical Conditions End	$FR_{j,estuary} = (SRP_{j,est})(FS_j)$ for all j	(62)
Total Cost of Expansion of Refuge *j*	$TC_j = \sum_{z} h_{j,z} E_{j,z}$ for all j	(10)

Expanded Capacity of Refuge *j*	$TE_j = M_{j,0} + \sum_z E_{j,z}$ for all j	(11)
Maximum Amount of Expansion Available for a Given Cost	$0 \le E_{j,z} \le M_{j,z} - M_{j,z-1}$ for all j, all z	(14)
Maximum and Minimum Refuge Capacity	$M_{j,0} \le TE_j \le TE_{j,max}$ for all j	(15)
Project Budget	$B \le \sum_{j=1}^{n} TC_j$	(16)

Fish movement is constrained (i.e., the optimization model does not determine fish movement). The decision variables, those terms that the model can adjust to find the maximum value of F, are the amount of expansion for each refuge *j* ($E_{j,z}$). The parameters that must have values specified as inputs are the loss coefficients ($LPSG_i$, $LMSG_i$, $LM_{j,j+1}$, $LP_{j,j+1}$, $LDT_{T,ET}$, $T_{j,T}$, P_j, $\gamma_{j,oc}$), the capacity block survival rates ($\gamma_{j,b}$), the size of each capacity block (θ_b), the distribution of fish leaving spawning ground ($\beta_{i,t}$), the number of fry that emerge from the gravels at each spawning ground (EF_i), the flow connectivity matrix (system schematic specification) and the critical time (TC). Likewise, the cost coefficients ($C_{j,z}$), the initial and maximum size of the refugia ($M_{j,0}$ and $TE_{j,max}$), the size of the refuge cost breakpoints ($M_{j,z}$), the total budget for the project (B) are inputs. Finally, the flow ($Q_{0,1}$, Q_{Mj}, and Q_{Tj}), temperature ($T_{0,1}$, T_{Mj}, and T_{Tj}), scalars ($\alpha_{j,j+1}$ and $\lambda_{j,j+1}$) and river system description parameters ($A_{j,j+1}$, $TD_{j,j+1}$, and $TTSG_i$) need to be specified. The remaining terms are calculated internally in the model.

Out-Migrating Model Example

A system of six refugia and three spawning grounds appears in Figure 54. Spawning grounds one and two are located on tributary one and enter the main stem at refuge one. The third spawning ground is on tributary three and enters the main stem at refuge three. The loss rates, flows, temperatures, fish movement, and capacity expansion variables are specified in Appendix C.

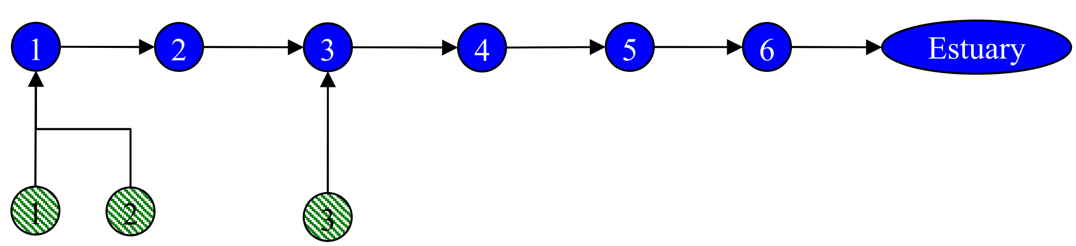

Figure 54. System Used in Downstream Migrating Model Example.

Three different fish distributions were created to represent early departure, late departure and an average departure schedule (Figure 55).

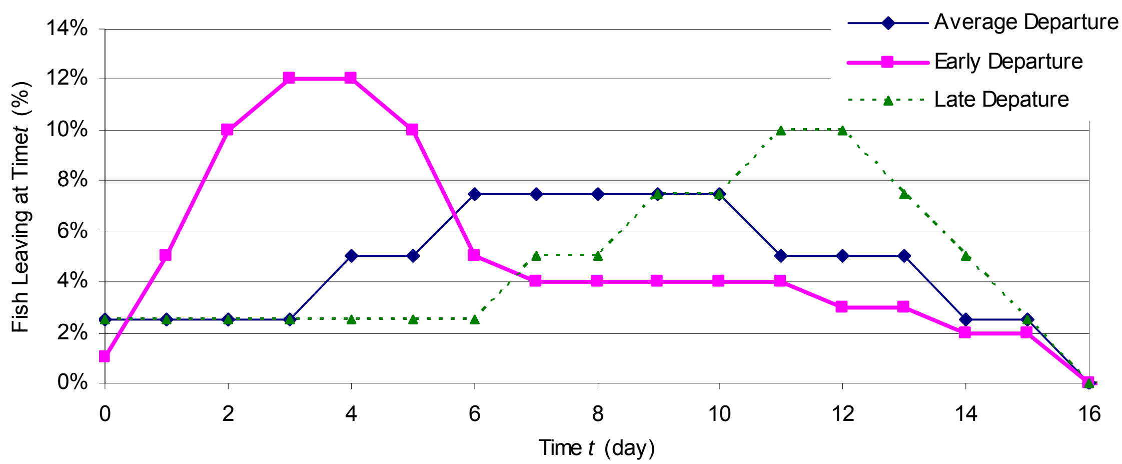

Figure 55. Example Fish Departure Distributions.

Three modeling alternatives are presented below: changing budget, changing fish distributions, and changing main stem water temperature. For all alternatives the model was run for different onset times of critical conditions.

Changing Budget

The total budget was increased to see the effects of a monetary constraint. The budgets evaluated were $100K, $250K, $350K, $500K, $750K, and $1,000K. The starting times ranged from day one to day eighteen by increments of one. The 'average' departure distribution was used for all budget values.

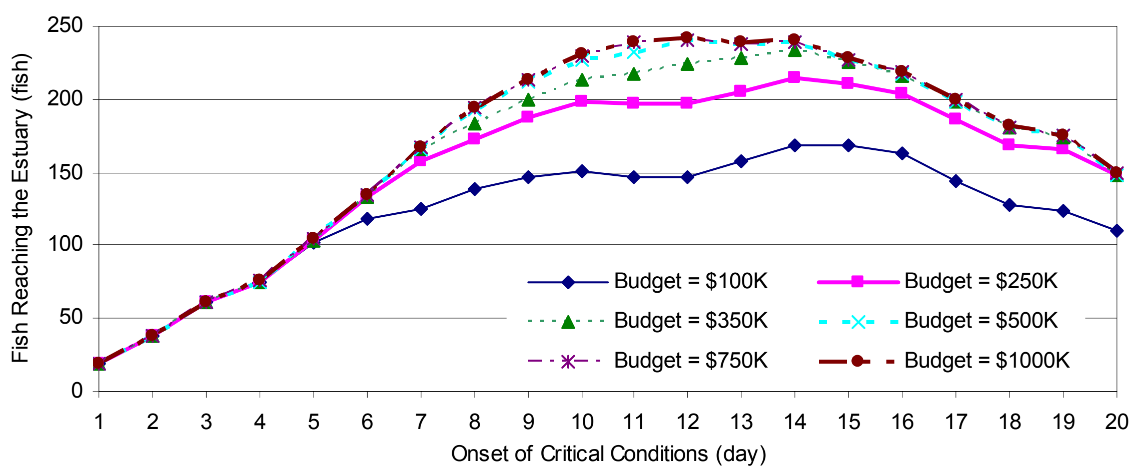

Figure 56. Fish Reaching the Estuary for Different Onset Days and Budgets.

As the budget is increased from $100K to $1,000K the number of fish reaching the estuary increases (Figure 56). However, as the budget is increased over $500K, the number of fish reaching the estuary no longer increases. This does not occur because the refuges cannot be expanded (full expansion of all six refugia would require a budget of $1,625K). Rather there is limited need for additional expansion beyond that achieved with $500K.

The marginal value of additional budget (the value of one additional dollar) increases as the number of fish needing refuge in the system increases. If critical conditions begin before day 6 there is little value to additional refuge capacity regardless of the initial budget. However, for onsets occurring after or on day 6 there is some value to budget. The smallest budget case ($100K) benefits greatly from additional funds (Figure 57). As the budget increased, the value of additional funds decreased regardless of the starting day of critical conditions. After the budget exceeds $500K, there is little value from additional funds.

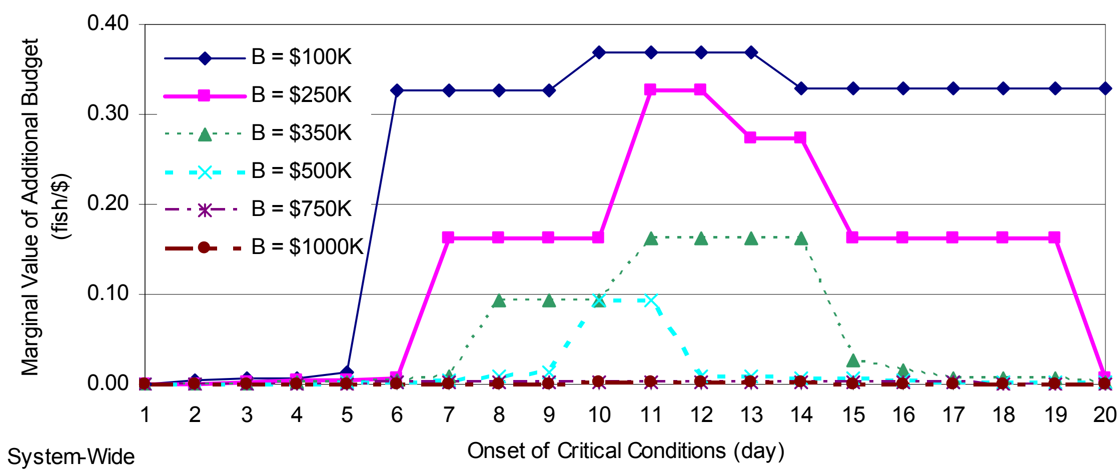

Figure 57. Marginal Value of Additional Budget.

With the expansion capacities set to the levels specified in Appendix C, many fish are lost due to crowding (Figure 58). Greater crowding losses occur when the budget is small (Figure 59 and Figure 60). From Figure 57 and Figure 58 as more fish are lost to crowding, the marginal value of additional budget increases. Greater losses occur for smaller budgets, because there is less ability to expand refugia to accommodate the fish. The decrease in fish deaths cease when the budget exceeds $500K. At this point, the refuge site conditions limit the amount of expansion that is possible.

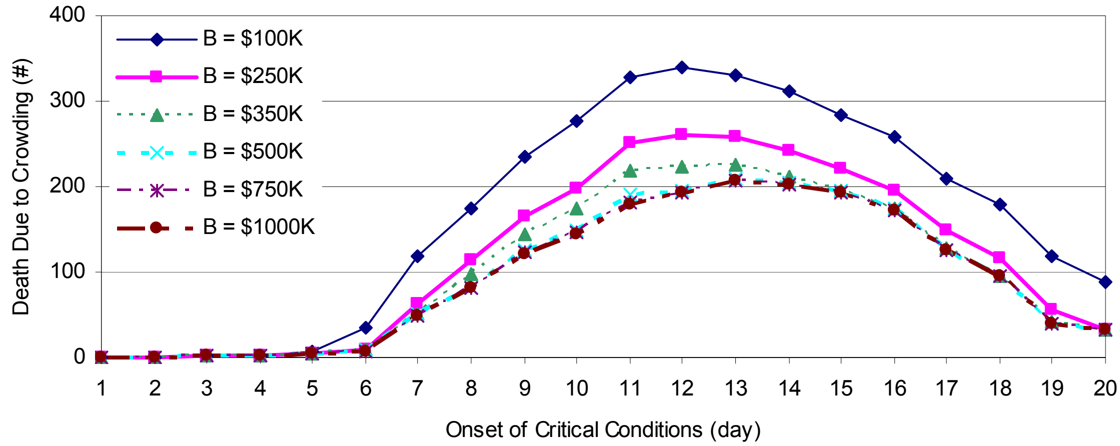

Figure 58. Number of Fish Dying in Each Refuge for Each Budget Due to Crowding.

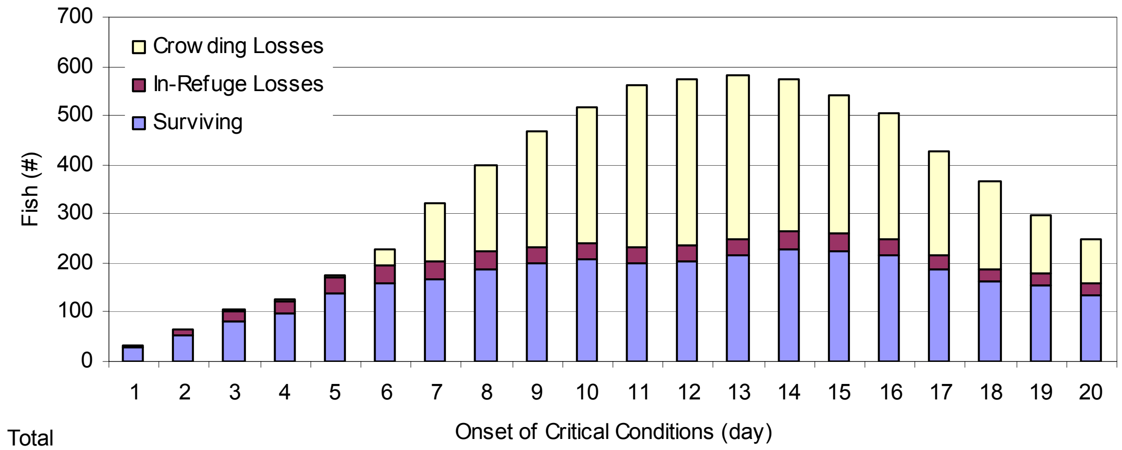

Figure 59. Fish Deaths Due to Crowding (Budget = $100K).

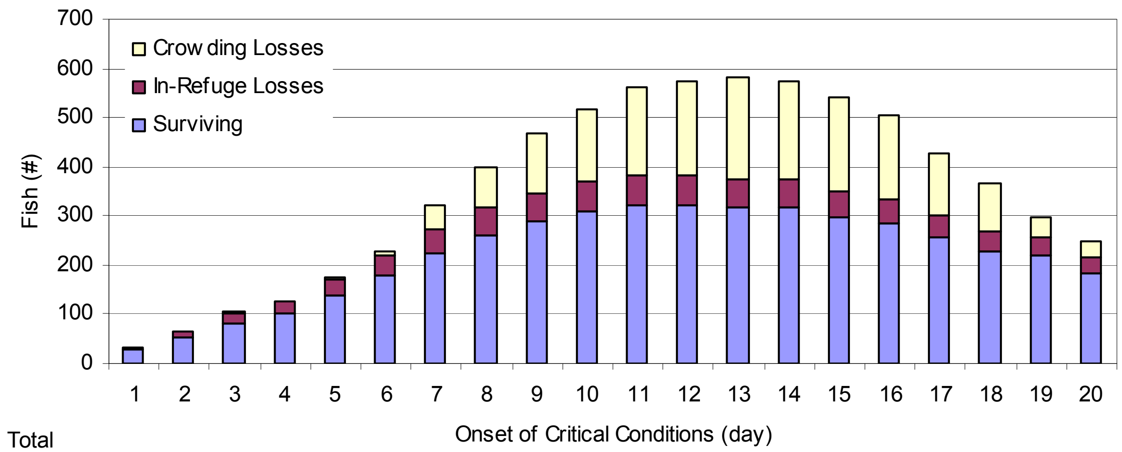

Figure 60. Fish Deaths Due to Crowding (Budget = $1,000K).

When budget no longer limits the expansion of the refugia, the highest marginal values of expansion are for Refuges 1, 3, and 5 (Figure 61). There is minor value to expanding the maximum expansion capacity limit of the other refuges. If the critical day occurs early then Refuge 1 is expanded the most (Figure 62 through Figure 64). Early in the time line not many of the fish from spawning ground 1 and 2 have had a chance to move downstream in the system and those fish that have left the spawning grounds are still heading for the first refuge. If the critical day occurs later then Refuge 3 and 5 are expanded more. Refuge 3 is in the middle of the system and is the first downstream refuge that can support fish from all three spawning grounds. As the critical day occurs later in the time line, more fish are in the system and could potentially be going to Refuge 3 and 5. Refuge 4 is not expanded until the critical day occurs late and the budget exceeds $500K. Refuge 6, located furthest downstream, is only expanded if the critical day occurs near the end and the budget is high. This happens because by a late critical day the fish are further downstream in the system and require refuge closer to the estuary.

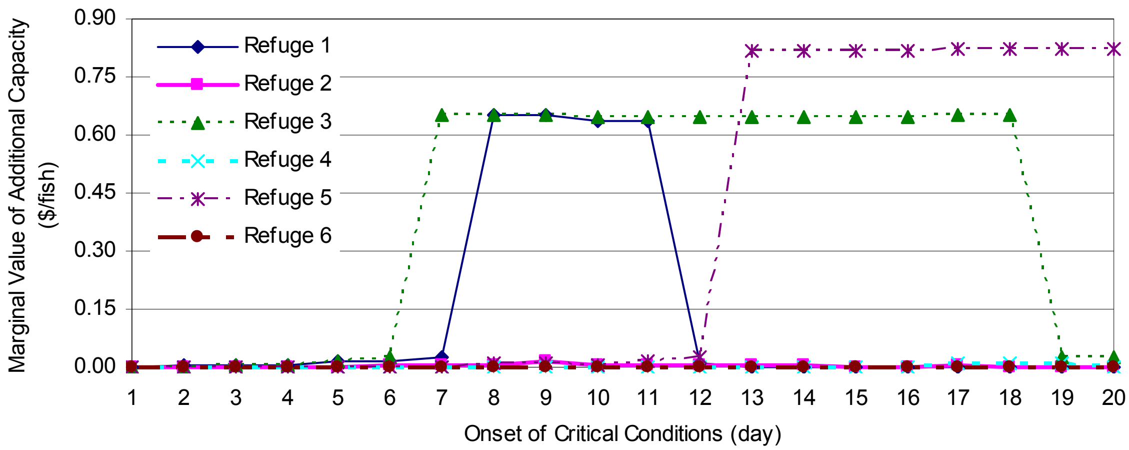

Figure 61. Marginal Value of Additional Capacity for Expansion at Each Refuge for a Budget of $1000K.

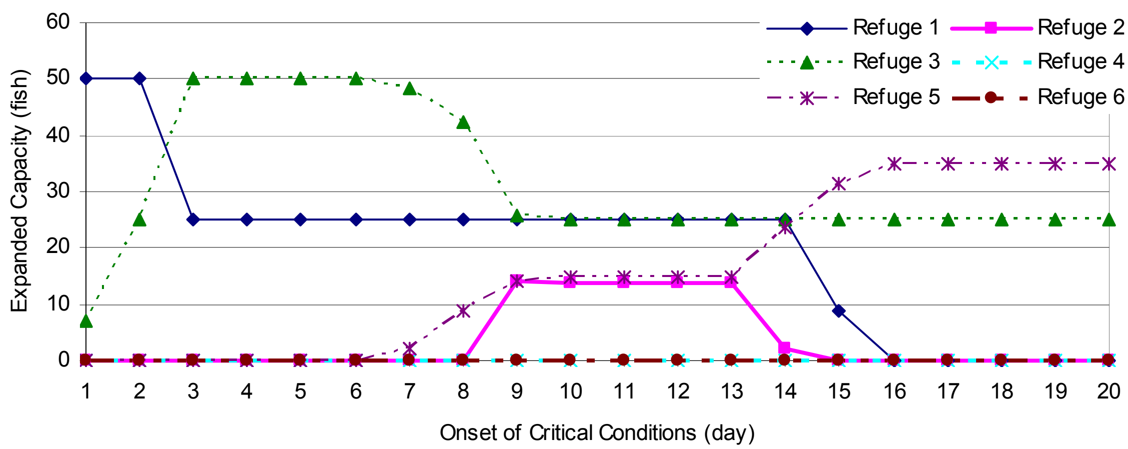

Figure 62. Amount of Expansion for a Budget of $100K.

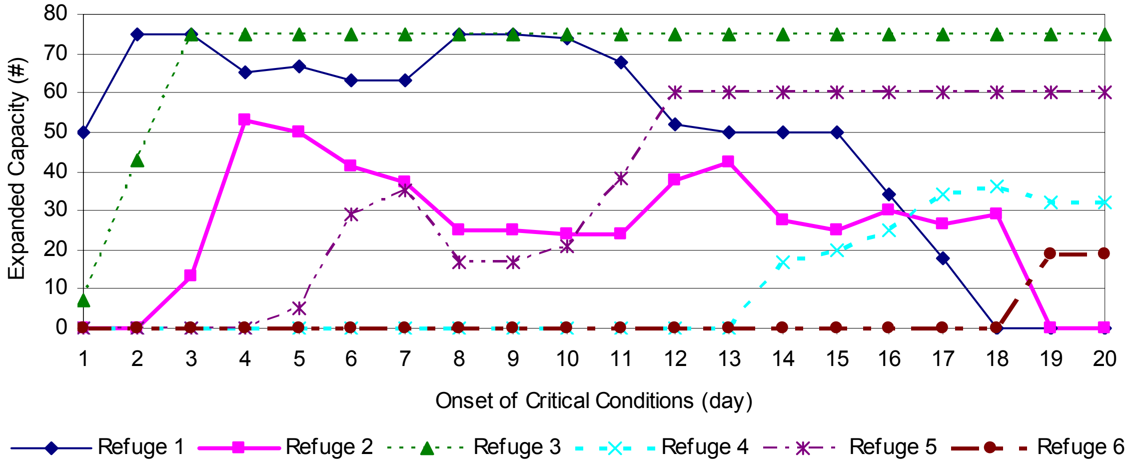

Figure 63. Amount of Expansion for a Budget of $500K.

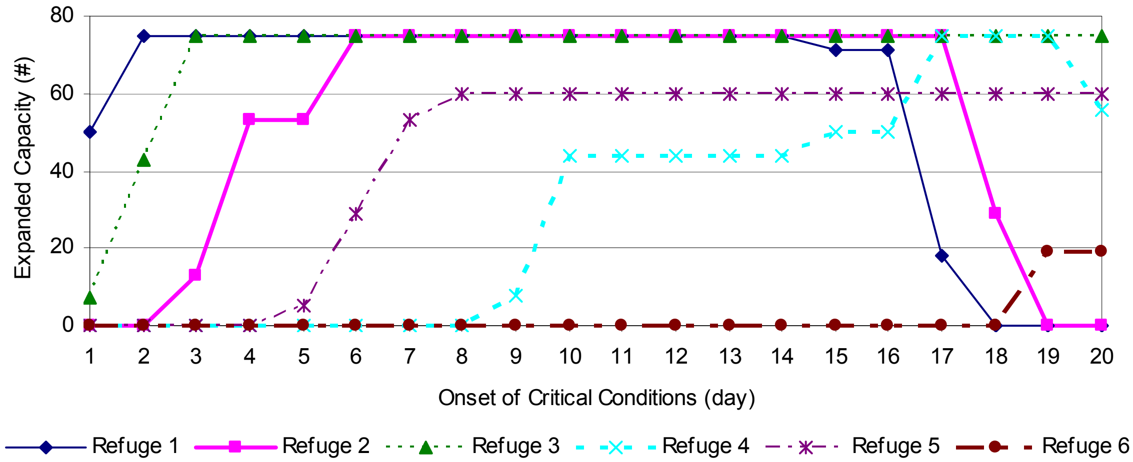

Figure 64. Amount of Expansion for a Budget of $1,000K.

Changing Distributions

These modeling alternatives changed the distributions of fish leaving each spawning ground at time *t*. The three different distributions appear in Figure 55. The same distribution is applied to all three spawning ground for each model run. The budget is set to $500K and the other variables are specified in Appendix C.

For the three different distributions considered, the number of fish making it to the estuary was greatest when critical conditions did not occur until midway through the time line (Figure 65). The 'early' distribution was affected least by the critical day, whereas the 'late' distribution was most impacted. Overall, greatest number of fish reached the estuary for the 'late' distribution and a critical day of 15. However, generally the most fish reached the estuary for the 'early' distribution.

An 'early' distribution means a lot of fish are in the system early-on and if the critical day is early, then those fish need refuge. If the critical day occurs late, most of the fish are already in the estuary or are located further downstream. Similarly, for the 'average' and 'late' distributions, most fish are in the system during the middle or later parts of the time line, so an early critical day would have less effect because the fish have not yet left the spawning grounds.

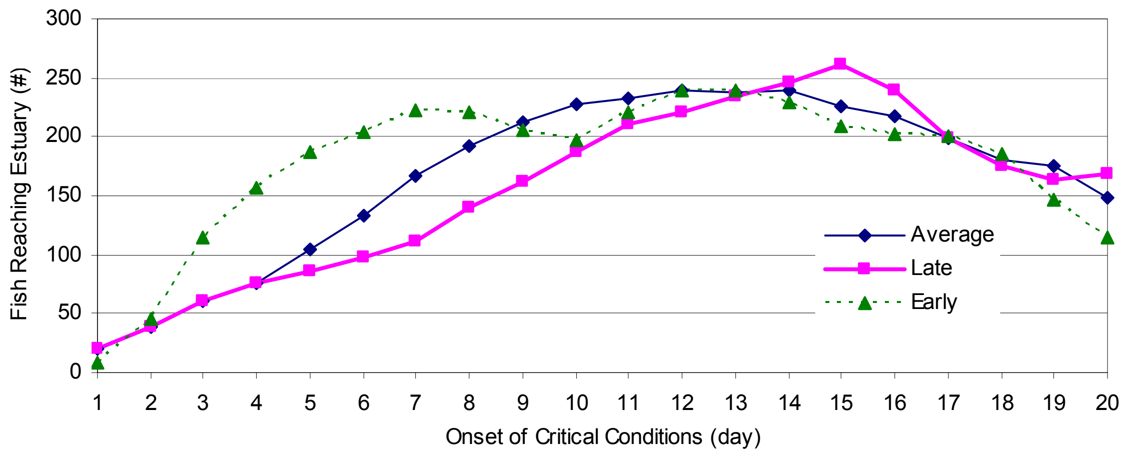

Figure 65. Number of Fish Reaching the Estuary for Each Distribution.

Consistent with the number of fish leaving the spawning grounds, the 'early' distribution suffered the greatest death due to over-crowding when the critical day was early in the time line, while the 'average' and 'late' distributions suffered the greatest losses when the critical day was in the later half of the time line (Figure 66). At the peak, the number of fish lost due to crowding, predation, and miscellaneous reasons is almost the same as the number of fish surviving (Figure 67 through Figure 69). The greatest losses occur when the critical day is similar to the peak out-migration day(s).

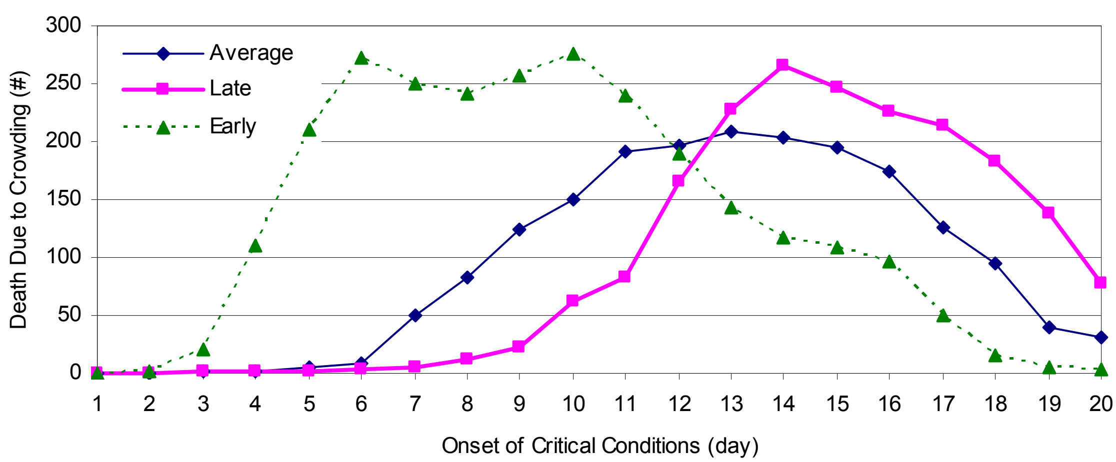

Figure 66. Fish Death Due to Over-Crowding.

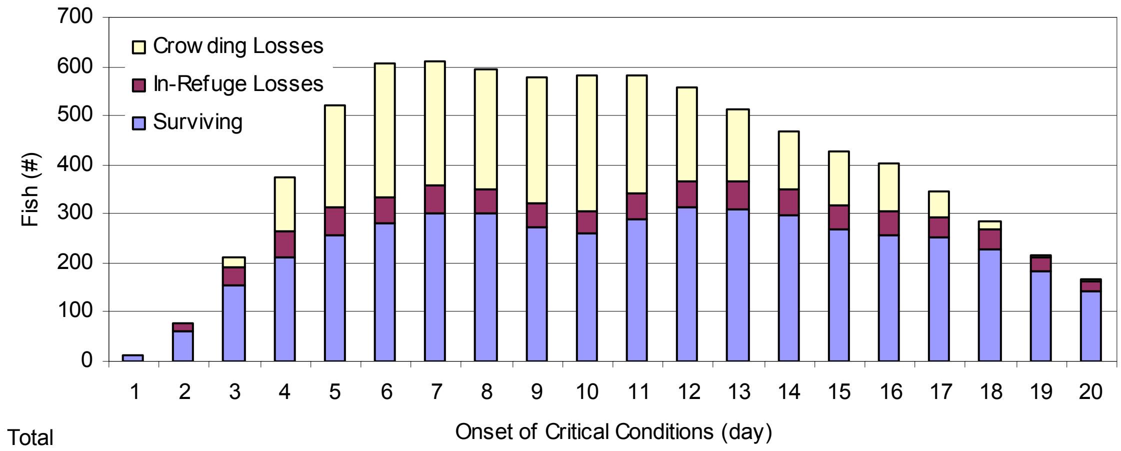

Figure 67. Number of Fish Surviving and Dying for the 'Early' Distribution.

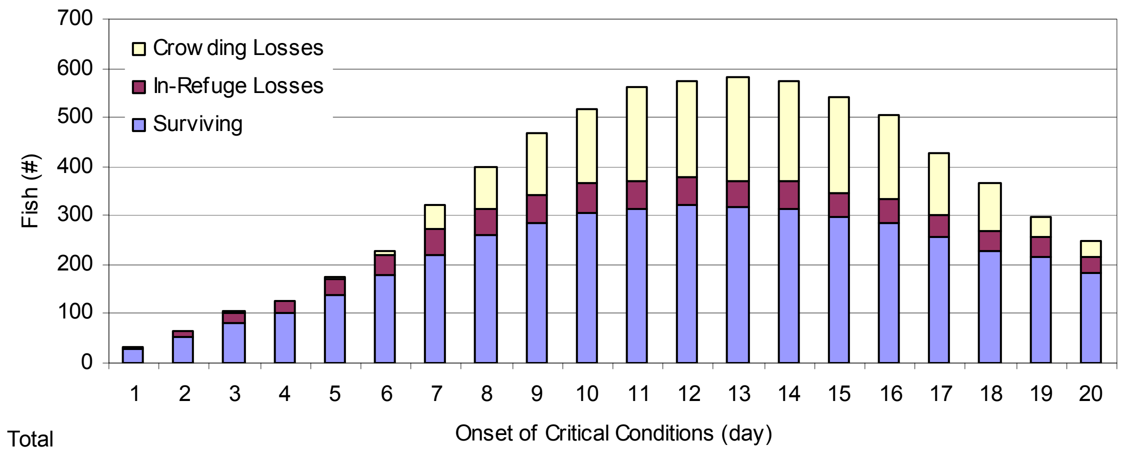

Figure 68. Number of Fish Surviving and Dying for the 'Average' Distribution.

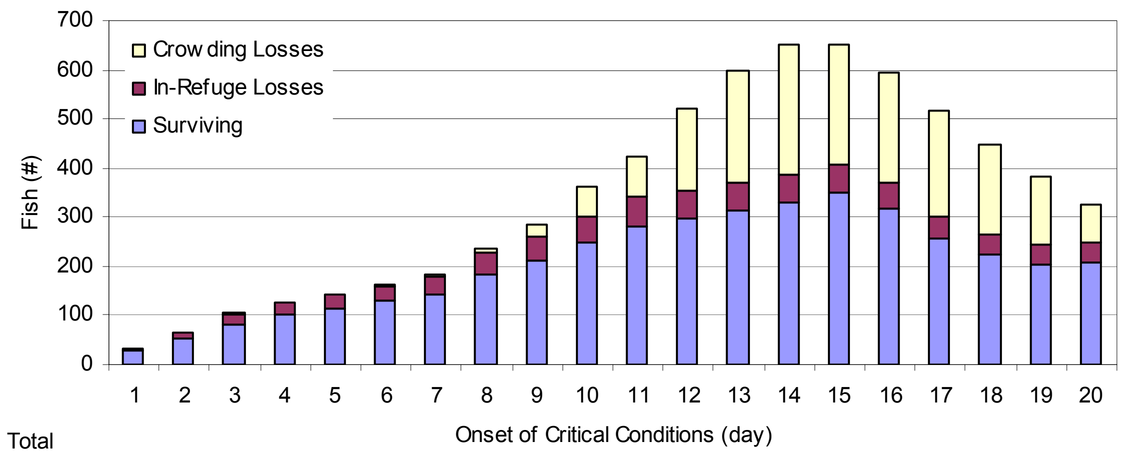

Figure 69. Number of Fish Surviving and Dying for the 'Late' Distribution.

For a constant budget of $500K, there is value to additional funds for all three distributions, but only when the critical day coincides with the peak fish out-migration (Figure 70). However, there is value to expanding Refuges 1, 3, and 5, regardless of the distribution. As with the marginal value of additional budget, the marginal value of additional capacity at the refuges is greatest when there is the greatest number of out-migrating fish. Refuge 1 would benefit from additional expansion for only a handful of critical days for each of the distribution (Figure 71). Refuge 3 would benefit from expansion for almost any critical day and all distributions (Figure 72). Refuge 5 would benefit from expansion for late critical days for all three distributions (Figure 73).

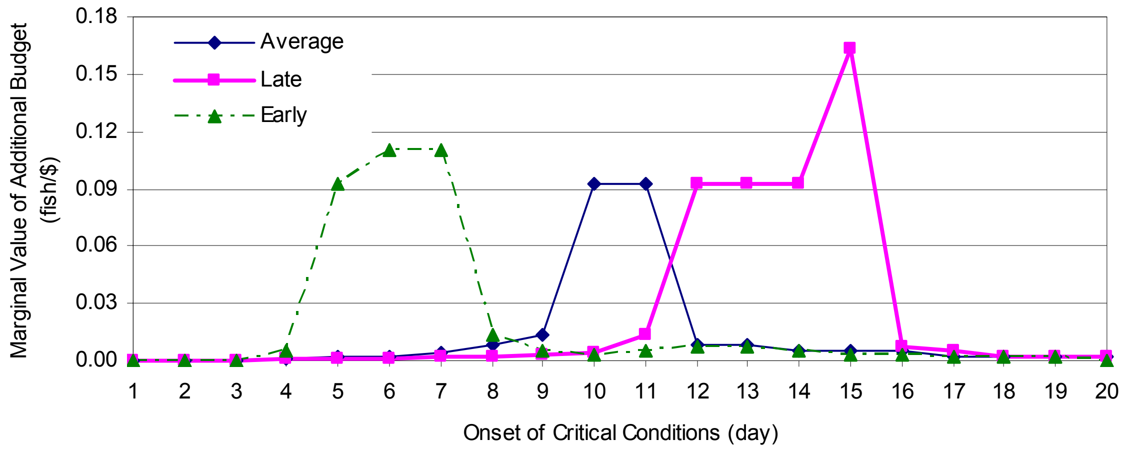

Figure 70. Marginal Value of Additional Budget.

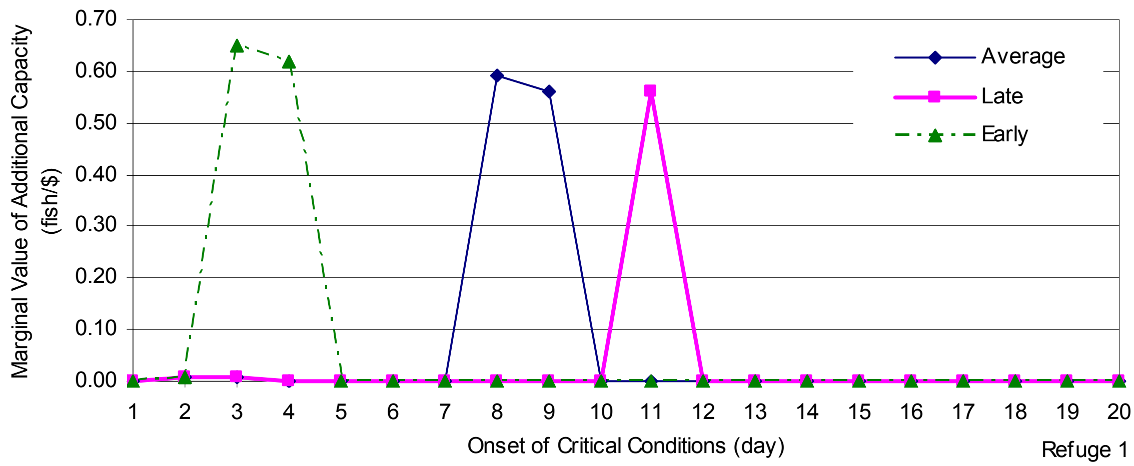

Figure 71. Marginal Value of Additional Capacity at Refuge 1.

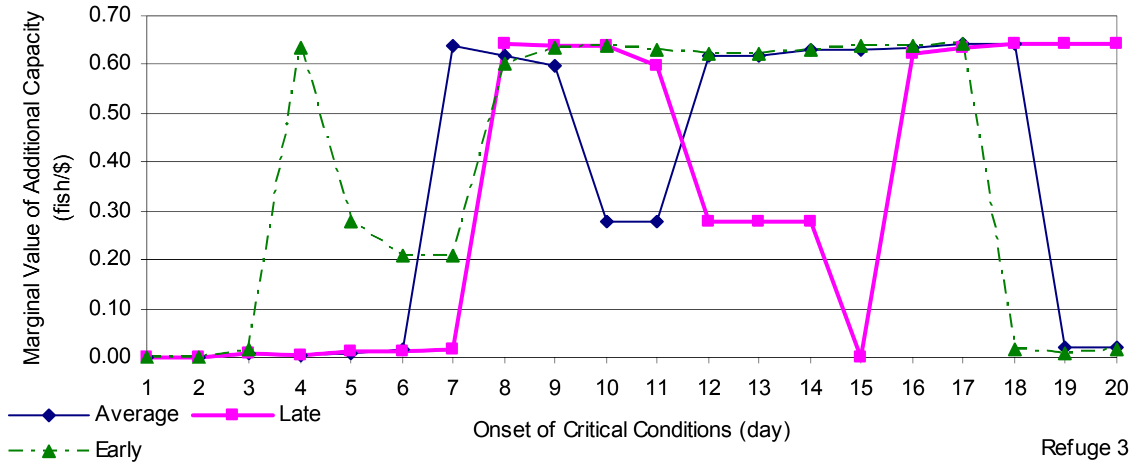

Figure 72. Marginal Value of Additional Capacity at Refuge 3.

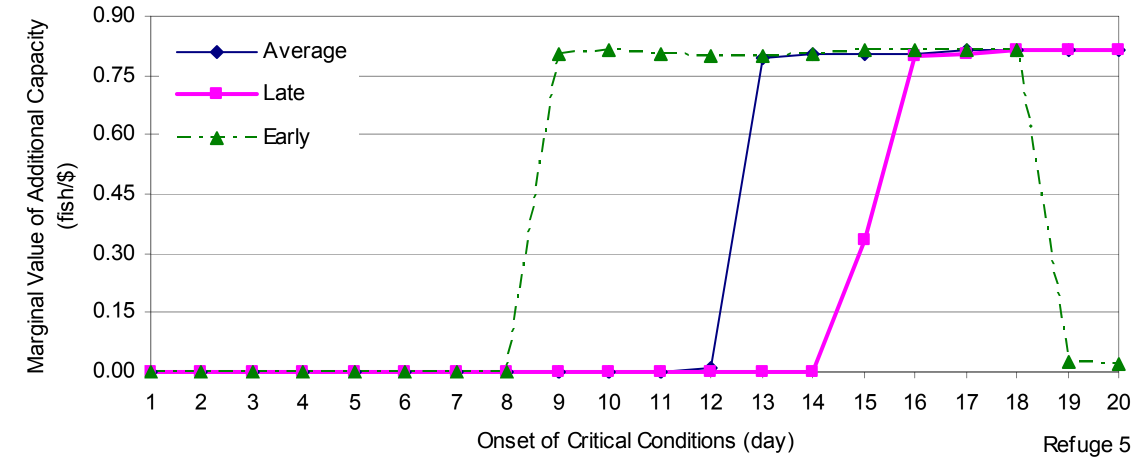

Figure 73. Marginal Value of Additional Capacity at Refuge 5.

Changing Main Stem Water Temperature

The main stem water temperature was increased from 20°C to 28°C by increments of 2°C. The starting times ranged from day one to day twenty by increments of one. The ‘average’ departure distribution was used for all budget values. A budget of $1,000K was assumed.

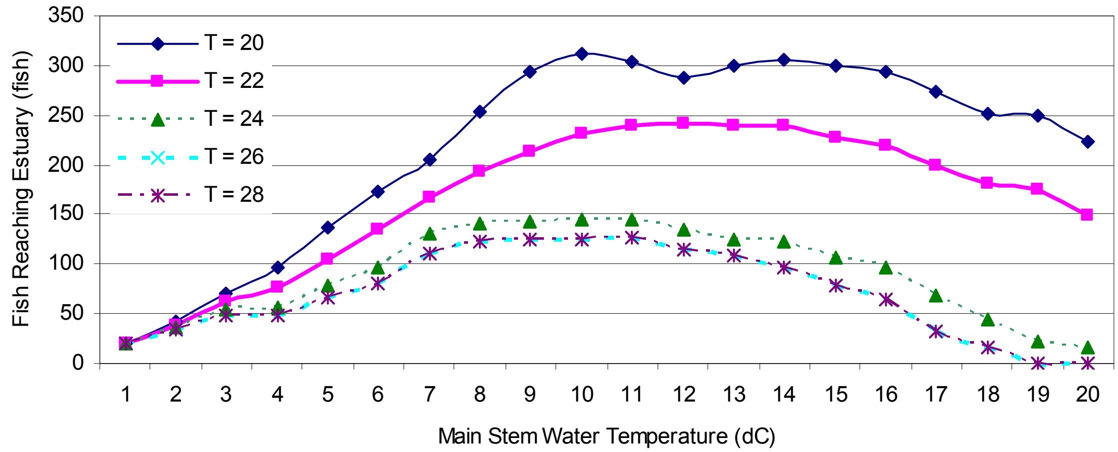

Figure 74. Fish Reaching the Estuary for Different Main Stem Water Temperatures.

As the main stem heats, increasing numbers of fish die due to exposure to warm water conditions (Figure 74). The loss rates due to temperature and exposure time increase. There was little change in the number of fish reaching the estuary above 26°C. This is because the loss rates are the same for temperature above 25°C (99%).

Warm water conditions reduce the number of fish that survive migration through the river reaches toward the refuge. As a result, the marginal value of additional budget decreases as temperature increases (Figure 75). Above main stem temperatures of 24°C there is no value to additional budget because there is insufficient fish to fill the existing refuge capacity. Overall, if main stem temperatures become to warm, whether due to climate change or operational changes, the number of fish that survive the out-migration decreases.

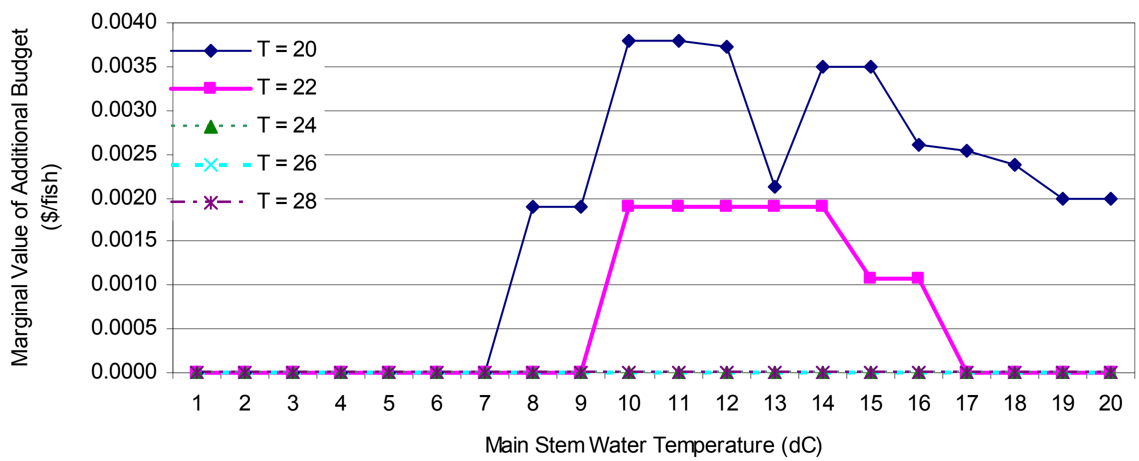

Figure 75. Marginal Value of Additional Budget with Changing Water Temperatures.

Summary

For the system configuration presented above, the greatest value of expansion came from expanding Refuges 1, 3, and 5, with most of the benefit coming from expanding Refuges 3 and 5. Refuge 1 benefits from expansion when the critical day occurs early. Refuge 3 and 5, being downstream and initially small provides the greatest benefits when expanded, regardless of the distribution or critical day. These two refuges, along with Refuge 4 and 6, can be used by fish from all three spawning grounds, whereas Refuge 1 and 2 can only be used by fish from two of the spawning grounds. Refuge 4 and 6 does not need additional expansion because their large initial capacity (starting capacities of 100 and 125, respectively).

Changing budgets or distributions result in different number of fish reaching the estuary, but the general pattern is similar. The greatest losses occur when the peak out-migration occurs just before the critical day. Greater budget reduces over-crowding deaths as refugia are expanded. Expansion of the refugia that could be used by the most fish seems to have the greatest benefits regardless of the critical day, out-migration pattern, or budget.

Future Work

Both the in-migrating and out-migrating models are in the preliminary development stages. Future work should include better estimation of the loss rates. For the current examples the loss rates were specified to create a curve that "looked right" but do not contain any scientific basis. The loss rates should be based on observed field data which requires monitoring of representative sites.

The in-migrating model routes fish to maximize the number reaching the refuge. Over-crowding in refugia can occur in the field, but the current formulation of the model does not result in that happening. A means a better representing fish movement and behavior should. The out-migrating model deterministically specified fish behavior. All fish behavior in the same manner and no variability for individual fish are allowed.

Fish behavior models have been developed to predict the response of a fish or group of fishes to a wide variety of stimuli for variety of scales. Some models focus on the behavior of a population of fish (Halls and Welcomme, 2004), while others focus on individual fish behavior (Goodwin *et al.*, 2006). Fish growth, movement, competition with other species, predator-prey interactions, and mortality can be estimated (Clark and Rose, 1997; Railsback *et al.*, 1999; Anderson *et al.*, 2005), allowing managers to evaluate the impacts alternatives will have without making potentially costly and harmful changes to the system (Goodwin *et al.*, 2006). Future work should include a means of allowing for more random fish behavior through the addition of uncertainty in the fish movement or incorporation of a fish behavior model.

The model could be used to identify critical reaches if the fish behavior model is improved. Another future modification would be to make a 2-stage linear program to reflect the uncertainty in the start of critical conditions. Decision would be made to expand some refugia prior to the onset and then emergency modifications could be made in the next stage.

In-migrating salmonids use the refugia as they migrate upstream and do not need them for rearing. Out-migrating salmonids, especially coho and Chinook, need to rear in thermal refugia if they are in the main stem. Work has focused on quantifying the use of thermal refugia in the main stem by salmonids, but temperature in the main stem and within the refugial area are often excessive (Deas *et al.*, 2004; Deas *et al.*, 2006). It would also be beneficial to improve representation of the tributaries where fry and parr could also rear. Addition of the tributaries into the model could identify promising tributary reaches for over-summering salmonid habitat, as well as identifying inhospitable reaches.

The in-migrating and out-migrating models are separate, but future development should focus on merging the models. A combined model will enable managers to determine how to manage the system for both life-cycle stages. While rare, it is possible that out-migrating and in-migrating salmonids (not necessarily the same species) could be in the system at the same time, in which case management for both would be beneficial. A dual model would help to identify which refugia are the most critical and which are used by multiple life cycles. This could be done as a 2-stage linear program where each stage represents a different stage in the life cycle.

CONCLUSIONS

The upstream migration model is a pure optimization model. The model was able to prescribe fish behavior to maximize the number reaching the spawning grounds. While this is an over-estimate because fish do not have perfect knowledge of the system ahead it did illustrate that the smallest refugia have the greatest benefit to expansion.

The downstream migration model was a mixture of simulation and optimization. A simulation model was developed to represent fish movement out of the spawning grounds. The optimization model was then used to size the refugia. The simulation model essentially ‘scheduled’ fish movement because movement out of the spawning grounds was specified as a percentage of the total emergent population. In reality the emergent fry would leave the spawning ground due to changes in conditions and not necessarily in a uniform manner. However, despite this, the model did illustrate that refugial areas downstream of the most spawning grounds were the most used because the greatest numbers of fish were in the system seeking refuge.

The two models were sensitive to the predation and temperature loss rates, as well as the budget and starting fish stock. Improvements in the estimations of predation and temperature loss rates (as well as miscellaneous loss rates for the downstream migration model) are necessary to better represent the system.

Both the upstream and downstream migration models are highly simplified and subject to limitations. Despite those limitations they can indicate the usefulness of a systems model for fish migration during periods of warm water. Both models could be use to highlight which refugia are the most robust for a variety of water conditions. Overall, the models indicated that even if abundant fish ready to enter the system, insufficient high-quality refugial capacity results in very few fish surviving to their intended destination.

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CHAPTER 6: MODELING AT A STATEWIDE LEVEL - ECONOMIC-ENGINEERING EVALUATION OF POSSIBLE SACRAMENTO-SAN JOAQUIN DELTA MANAGEMENT OPTIONS

INTRODUCTION

In the previous chapters a local model of a refuge and a model of a system of refugia were presented. Now a statewide model is presented. This chapter explores potential economic and operational effects of eliminating South Delta exports, increasing Delta export pumping capacities, and increasing required Delta outflows for 2050 levels of development and population. These results illustrate the physical and economic adaptability of complex water resource systems and the economic and operational importance of the institutional forms of environmental regulations.

THE SACRAMENTO-SAN JOAQUIN DELTA

Water is a scarce resource in California, with increasing competition among growing agricultural, urban, and environmental water uses (Hundley, 2001). The Sacramento-San Joaquin Delta (the Delta), part of the San Francisco Estuary, is the hub of the State's water resource system, with most of California relying on it, either directly or indirectly, for water. The State Water Project (SWP) and Central Valley Project (CVP) directly export water from the Delta for Southern California and Bay Area cities and San Joaquin and Tulare basin irrigation (CALFED, 2000; USDA, 1999). Local urban water districts and in-Delta agriculture also rely on withdrawals from the Delta for their water needs. Upstream of the Delta, irrigation and urban users withdraw water from the major rivers and tributaries that would have otherwise flowed into the Delta.

Along with being the major hub of California's water supply system, the Delta is also one of California's most important environmental habitats. Over 750 species of plants and animals, including some that the Endangered Species Act protects, live in or pass through the Delta (CALFED, 2001). Environmental degradation within the Delta (and upstream) remains a key concern for all Delta users. New ideas and solutions are needed to better manage and operate the system. Alternatives to restore the Delta include increasing and decreasing exports to south of Delta users, decreasing north of Delta consumptive use, implementing various types of water market and cooperative water operations both north and south of the Delta (CALFED, 2000), and changing Delta flow requirements to improve local habitat and salinity regimes.

WATER MARKETS AND INSTITUTIONAL FLEXIBILITY

Many management options are being considered by California water managers, including several means to more flexibly operate the water system. Water markets enhance flexibility by allowing willing sellers and buyers to re-allocate water to theoretically higher valued crops, which provide incentives for more efficient water operations as well as economic water allocations. However, there are problems with water markets, including ill defined water rights, the potential for externalities, and difficulties in communication between willing sellers and buyers (Howe *et al.*, 1986; Brajer *et al.*, 1989; Lund and Israel, 1995; Hill, 1999). Despite these limitations, water markets are now common in California on local, regional, and inter-regional scales.

In this chapter, the statewide water market is assumed to be ideal (i.e., there are no transaction costs or risks). Each buyer and seller has perfect knowledge of each other and of the future hydrology (referred to as perfect foresight). These two assumptions lead to idealized results, which can be interpreted to represent the minimum (or lower bound) on costs (i.e., scarcity and operating costs) that can be obtained from more flexible operations.

Much of this study centers on economic scarcity of water and scarcity costs. Scarcity here is the difference between the volume of water at which users' willingness to pay for additional water becomes zero and the volume of water actually received (Figure 76). Scarcity cost is the dollar valued economic loss associated with a scarcity volume, as might arise from reduced deliveries. These terms provide economic definitions for what is colloquially referred to as "shortage."

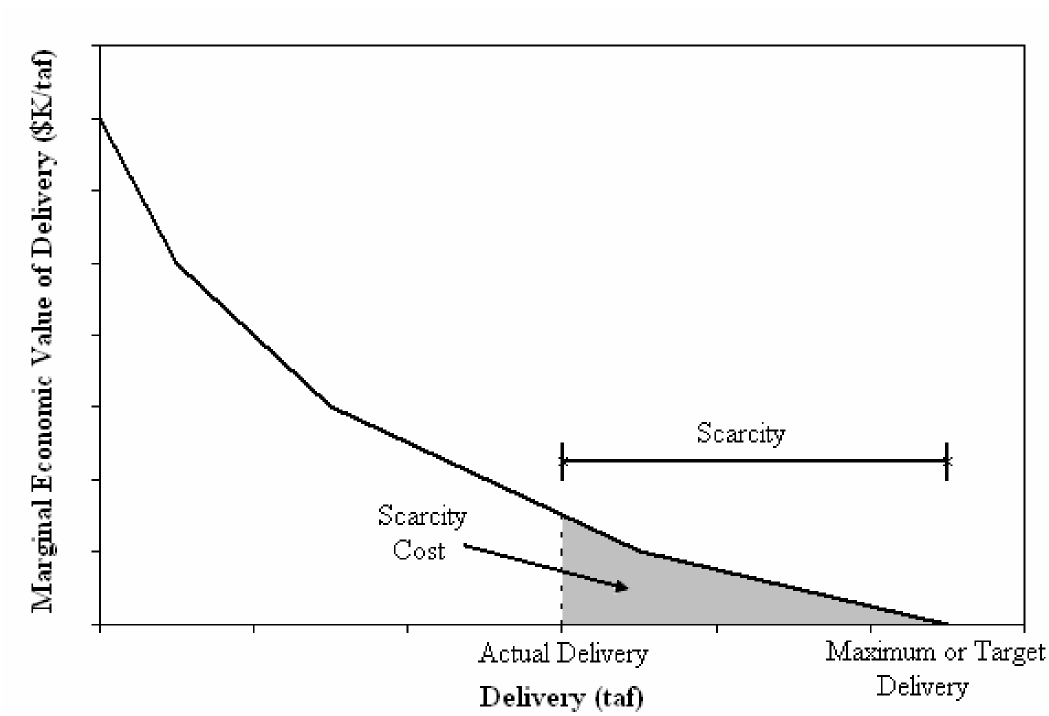

Figure 76. Scarcity Curve.

MODELING APPROACH AND LIMITATIONS

CALVIN (CALifornia Value Integrated Network) is a generalized network flow-based economic-engineering optimization model of California's inter-tied water supply system applied here for the year 2050 level of development (Jenkins *et al.,* 2001; Draper *et al.,* 2003; Medellin *et al.*, 2005). It has been previously applied to various water management problems in California (Jenkins *et al.,* 2001; Newlin *et al.,* 2002; Draper *et al.*, 2003; Tanaka *et al.*, 2003; Jenkins *et al.,* 2004; Pulido-Velázquez *et al.*, 2004; Null and Lund, 2006; Tanaka *et al.*, 2006).

Optimization models are well suited to exploring alternatives and identify alternatives with more promising performance. CALVIN seeks to minimize operating costs and economic losses for urban and agricultural users throughout California's water system over the range of water conditions seen in the historical hydrology or a climate change hydrology. Constraints on operations and allocations represent the physical and institutional bounds on the solution, including water losses:

$$\text{Minimize:} \quad Z = \sum_i \sum_j c_{ij} X_{ij}$$

$$\text{Subject to:} \quad \sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j \quad \text{for all nodes } j$$

$$X_{ij} \le u_{ij} \;\&\; X_{ij} \ge l_{ij} \quad \text{for all arcs}$$

Z is the total cost of flows throughout the network, X_{ij} is flow leaving node i towards node j, c_{ij} = unit economic costs (agricultural, urban, or operating), b_j = external inflows to node j, a_{ij} = gains/losses on flows in arc ij, u_{ij} = upper bound on arc ij, and l_{ij} = lower bound on arc ij. Costs are piece-wise convex with over a million decision variables statewide.

CALVIN uses a generalized water resources network flow optimization solver HEC-PRM (Hydrological Engineering Center – Prescriptive Reservoir Model) to find the least cost solution to specified constraints (HEC, 1991). Urban water demands are scaled for 2050 population growth (Medellin *et al.*, 2006). The original urban water demands were based on the year 2020 per capita demands by county and population estimated by the California Department of Water Resources Bulletin 160-98 (Jenkins, 2000; Jenkins *et al.*, 2003) and by estimates from Metropolitan Water District data for Southern California urban areas. Urban water prices were developed from a California survey of residential water prices (Black and Vetch, 1995). The 2050 agricultural water demands and values were developed from results from the Statewide Agricultural Production Model (SWAP) (Howitt *et al.*, 1999), which extends the Central Valley Production Model (CVPM) model commonly used in California (USBR, 1997).

California's water managers can implement many actions to improve the system. There are the traditional activities to improve reliability and increase water supplies (expanding surface water storage, conveyance facilities, and water treatment facilities) along with newer ideas (such as improving water use efficiencies, groundwater banking (conjunctive use), wastewater reuse, desalination, and water marketing) that water managers can consider. Table 13 summarizes the water supply management options commonly available to water managers. These include demand and supply-side options. CALVIN cannot represent all actions available to water managers, but many of the most commonly used ones are included the model (denoted with an asterisk in Table 13).

Table 13. Water Supply System Management Options.

Demand and Allocation Options
General
Pricing*
Subsidies, Taxes
Regulations (Water Management, Water Quality, Contract Authority, Rationing, etc.)
Water Transfers and Exchanges (Within and/or Between Regions/Sectors)*
Insurance (Drought Insurance)
Demand Sector Options
Water Use Efficiency (Urban*, Agricultural*, Ecosystem, Recreation)
Water Scarcity (Urban*, Agricultural*, Environmental, Recreation)
Ecosystem Restoration/Improvements (Dedicated Flow and Non-Flow Options)
Recreation Improvements
Supply Management Options
Operations Options (Water Quantity and/or Quality)
New or Expanded Facilities (Surface Storage, Conveyance)*
Conveyance and Distribution Facility Operations*
Cooperative Operation of Surface Facilities*
Conjunctive Use of Surface and Ground Waters*
Groundwater Storage, Recharge, and Pumping Facilities*
Supply Expansion Options (Water Quantity and/or Quality)
Supply Expansions Through Operations Options (Reduced Losses and Spills)
Agricultural Drainage Management
Urban Water Reuse (Treated)*
Water Treatment (Surface and Ground Water, Sea and Brackish Water, Contaminated Waters)*
Desalting (Brackish and Seawater)*
Urban Runoff/Stormwater Collection and Reuse (In Some Areas)

* Options represented in the CALVIN model
Table modified from Lund *et al.* (2007).

CALVIN requires many physical and economic input parameters to characterize California's water system. Physical parameters include infrastructure capacity (such as canals and pumping plants), environmental requirements (such as minimum instream flows and wildlife refuge requirements), operating requirements (such as flood pools on reservoirs), and inflows into ground and surface reservoirs. Economic parameters include the urban and agricultural water delivery penalties/demand functions and operating costs for water treatment and conveyance facilities. More detailed information on the required CALVIN inputs can be found in Jenkins *et al.* (2001) and appendices.

Results from a CALVIN model run include the time series of deliveries to agricultural and urban users, stream, channel, and aqueduct flows, storage quantities, annual average scarcity costs for each demand area, the marginal economic values of additional water at every node in the system, the economic shadow values on the binding constraints, and storage volumes in reservoirs and groundwater basins.

All computer models have limitations. In this case, data are problematic for some areas and perfect hydrologic foresight somewhat reduces scarcity and scarcity costs by dampening the effects of droughts (Draper, 2001). CALVIN has fixed monthly urban and agricultural economic water demands, water use efficiencies, and environmental requirements. Hydropower representation is limited to a few major facilities. Reservoir and river recreation values are not included in CALVIN. Groundwater basins are highly simplified. And significant uncertainties exist regarding inflows and return flows in some important parts of the system. Nevertheless, despite these and other documented limitations (Jenkins *et al*., 2001), CALVIN is the most comprehensive technical attempt yet to assess management possibilities for California's water supply system and, despite its limitations, can provide insights into the management of California's water system and its regional sub-systems.

STUDY AREA AND ALTERNATIVES

The CALVIN model includes 92% of the California's population and 88% of the State's irrigated lands (Figure 77 and Figure 78). It includes the SWP and CVP and the major facilities associated the projects, along with many smaller more regional or local facilities. CALVIN economically represents 24 agricultural areas and 30 urban areas. There are 53 surface water reservoirs and 31 groundwater basins. The statewide model combines four regional models: Upper and Lower Sacramento Valley and Bay-Delta, San Joaquin and South Bay, Tulare, and Southern California. A detailed description of the region is available in Jenkins *et al.* (2001) and appendices. The full, statewide, CALVIN schematic can be found at http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

Current facilities are included in the CALVIN model, along with some additional intertie conveyance capacity, reflecting projects which are planned or currently underway. These facilities are assumed to be completed by 2050. These new interties include: capacity to divert water from the Sacramento River at Freeport to the Mokelumne River Aqueduct, a diversion from the Mokelumne River Aqueduct to the Contra Costa Canal, and an intertie between San Francisco PUC and EBMUD at Hayward. These interties allow the Contra Costa Water District, which currently is served exclusively by Delta pumping, access to alternative supplies, and they provide the Santa Clara Valley, San Francisco PUC, EBMUD, and others with additional water purchase, sale, and management opportunities.

Urban coastal areas were assumed to have access to desalted seawater at a cost of $1,400/acre-foot and all urban areas were assumed to have access to reused wastewater of up to 50 percent of their allowable wastewater flows at a cost of $1,000/acre-foot. Household and industrial water conservation is also available at a variable cost represented by a constant-elasticity of demand curve for residential users and survey-based cost functions for industrial users (Jenkins *et al.*, 2003). Traditional water supplies from surface and ground waters incur operating costs for pumping, recharge, water treatment, and some relatively saline urban supplies also incur costs to customers due to their salinity (Jenkins *et al.*, 2001).

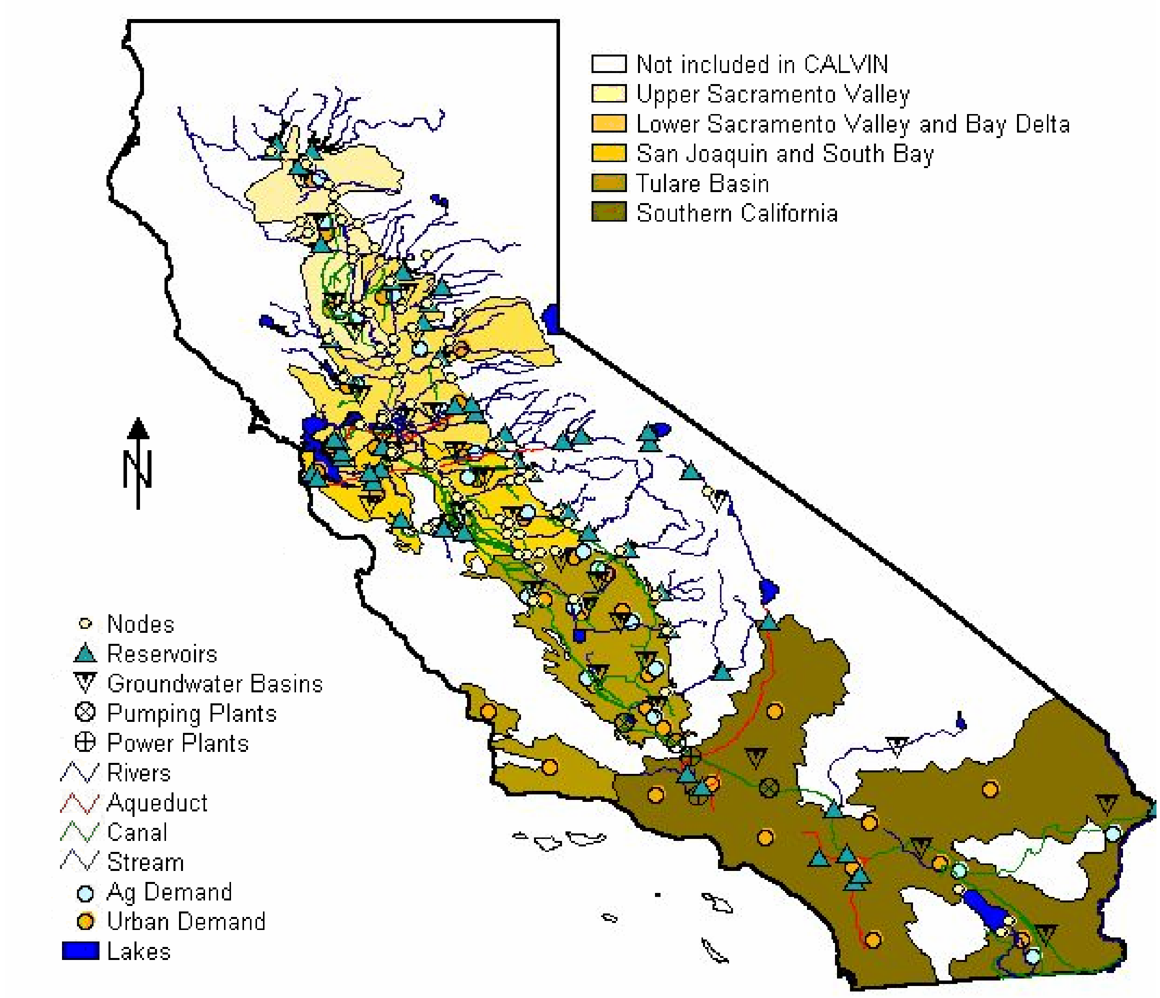

Figure 77. Demand Areas and Major Inflows and Facilities Represented in CALVIN.

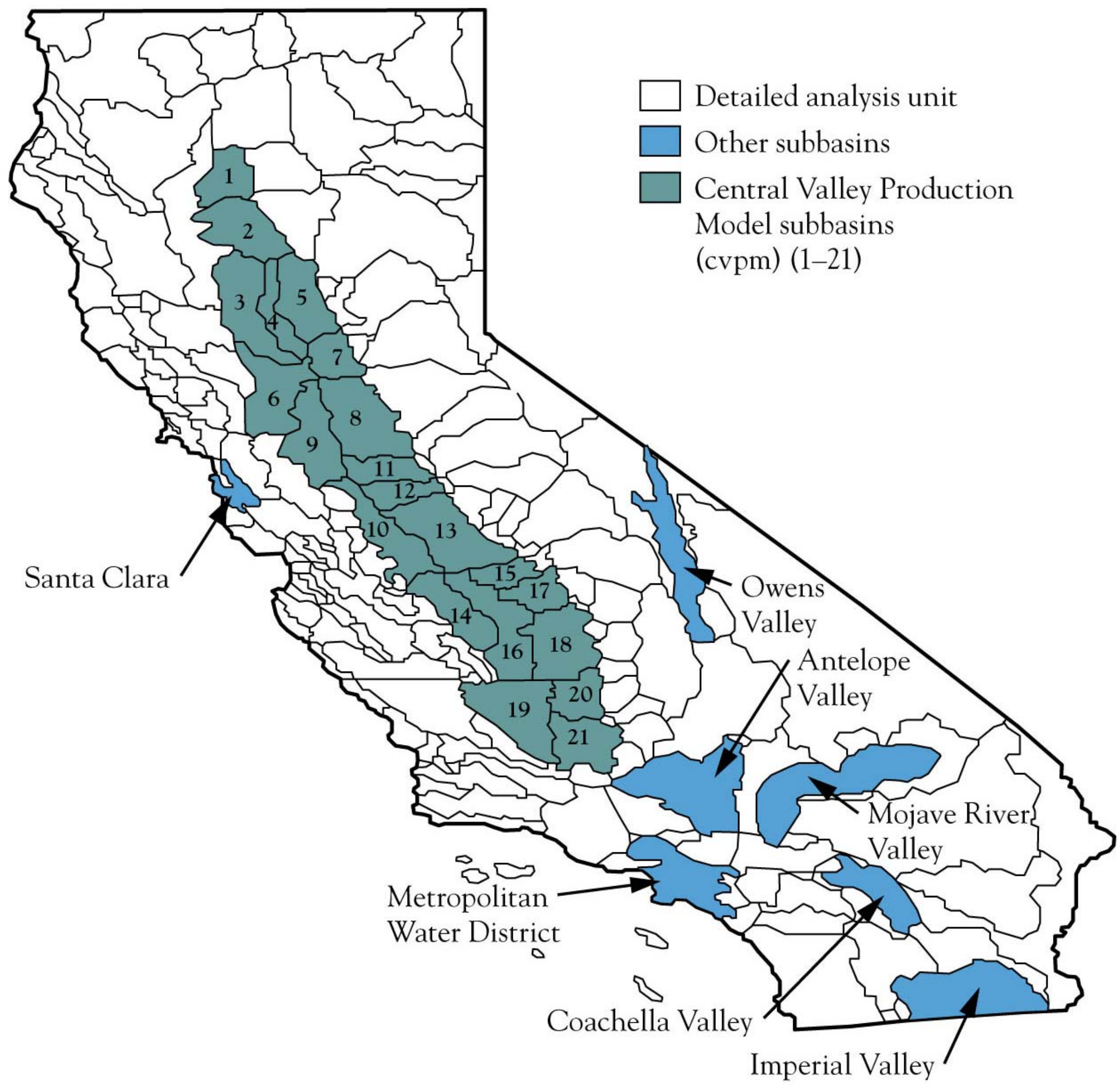

Figure 78. CVPM Regions Included in CALVIN (from Lund *et al.*, 2007).

Four modeling alternatives were considered for this study:

- An optimized current conditions case with 2050 water demands (base case), where Delta export limits and required Delta outflow are set to match the current operational levels,

- No Delta exports, where pumping was not allowed at Tracy, Banks, Rock Slough, Old River, or Contra Costa pumping plants,

- Increased pumping capacity, where pumping capacities at Banks pumping plant were systematically increased, and

- Increased Delta outflow requirement, where outflows requirements were systematically increased.

A brief summary of each case is presented in Table 14 highlighting the differences in pumping plant capacities at Banks and the required Delta outflow.

Table 14. Modeling Alternatives.

Model Alternative	Pumping Capacity at Banks (cfs)	(taf/mon)[a]	Required Delta Outflow Minimum (taf/mon)	Annual Average (taf/yr)
Base Case				
Current Conditions[c] (CC)	6,600[b]	430	179	5,593
No Export Case				
No Export (NE)	0	0	179	5,593
Increased Pumping Plant Capacity				
Hydraulic Capacity (HC)	8,500	513	179	5,593
Infrastructure Capacity (IC)	11,300	622	179	5,593
Unlimited Capacity (UC)	Unlimited	Unlimited	179	5,593
Increased Minimum Delta Outflow (MDO)				
250MDO	8,500	513	250	5,699
500MDO	8,500	513	500	7,285
700MDO	8,500	513	700	9,130
1,000MDO	8,500	513	1,000	12,271
1,200MDO	8,500	513	1,200	14,500
1,400MDO	8,500	513	1,400	16,828
1,500MDO	8,500	513	1,500	18,013
1,600MDO	8,500	513	1,600	19,205

[a] Monthly average pumping equivalents of the cubic-feet per second.
[b] Monthly average; current conditions have varying Banks pumping plant capacities depending on the month.
[c] Current conditions with 2050 level of development water demands.

For the optimized current conditions (base case) the pumping plant capacities for the State Water Project (Banks), Central Valley Project (Tracy) and Contra Costs Water District (Rock Slough, Old River, and Contra Costa) were set at their current operating levels. The required outflows from the Delta were also set to match the levels specified in DWRSIM model run DWRSIM_2020D09B-Calfed-514-output (DWR, 1998b). This alternative serves as a base line for comparison when the export capacities are changed.

In the no exports (NE) case the pumping plant capacities for the State Water Project (Banks), Central Valley Project (Tracy) and Contra Costs Water District (Rock Slough, Old River, and Contra Costa) were set to zero. This alternative represented the situation that would occur if pumping from the Delta was no longer possible. Required Delta outflow remained at current levels.

The increased pumping capacity alternative increased pumping at Banks from the current levels (approximately 6,600 cfs). The capacity was increased to the hydraulic capacity (HC) (8,500 cfs), the infrastructure capacity (IC) (10,300 cfs), and ultimately unlimited capacity (UC). The current capacity is below the physical capacity of the plant due to operational constraints. As part of the South Delta Improvements Project the pumping plant capacity would be increased to the hydraulic capacity (8,500 cfs) (DWR, 2007). For all of these alternatives the required Delta outflows were at current levels.

Finally, the increased Delta outflow requirement alternative systematically increased the required Delta outflows from the current levels (5,593 taf/year) by raising the minimum Delta outflow (MDO) values. The increased Delta outflows could represent the situation where the Delta was kept fresher (high outflows would push the saline gradient toward the Bay or increasing water needs to retain existing Delta freshness with sea level rise). For this modeling alternative the Banks pumping plant capacity was set to the hydraulic limit (8,500 cfs).

The purpose of the last three modeling alternatives was to assess the effects of changes in operations on the economic water users of California. The use of new facilities, new technologies, and new operations would also be identified in terms of volumes and economic benefits.

MODEL RESULTS

No South Delta Exports

An extreme policy alternative for the Delta would be to completely abandon all exports from the Delta by the CVP, SWP, and Contra Costa Water District (CCWD) (diversions for in-Delta agriculture and the North Bay Aqueduct would continue). The abandonment of exports examined here is not the sudden unavailability of water exports due to levee collapse (Illingworth *et al.*, 2005) or other catastrophic events, but a planned and prepared abandonment of direct water exports from the Delta.

Scarcity and Scarcity Costs

In the optimized base case, about 6.0 million acre feet (maf) per year are pumped via the SWP, CVP and CCWD. The majority of that came from the SWP (4.7 maf/yr) and CVP (1.2 maf/yr). When direct exports are eliminated the scarcity for users south of the Delta and in the Bay Area increase by about 5.2 maf/yr on average (see Table 15) and resulted in an increase of $831 million per year in scarcity costs (Table 16). Of that increase in scarcity, 4.9 maf/yr was to agricultural users, while the remaining 0.3 maf/yr was to urban users (Figure 79). Of the scarcity costs $554M/yr was to agricultural users and $276M/yr was to urban users (Figure 80 – only those urban users with scarcities were included).

The agricultural areas of the San Joaquin Valley and Tulare Basin saw the highest increases in scarcity (4.9 maf/yr). Users that rely on the SWP and CVP see the greatest increase in scarcity when exports to those projects are eliminated. Those agricultural areas that depend directly on stream flowing from the Sierra Nevada Mountains (primarily on the East Side of the San Joaquin Valley: CVPM regions 11, 12, 16, and 17) are much less affected by elimination of Delta exports, as their water supplies do not depend on the Delta and they cannot connect to other agricultural regions further south and west without going through the Delta. Water districts which depend more on Delta pumping (CVPM regions 10, 14, 19, and 21) are more severely affected.

Likewise, there was also an increase in the urban scarcity in the San Joaquin Valley and Tulare Basin. While small compared to the increase in agricultural scarcity, urban scarcity is very costly. The 29 thousand acre-feet (taf) per year increase in scarcity translated to a $35M/yr increase in scarcity cost. The 4.9 maf/yr increase in agricultural scarcity only increased scarcity costs by $94M/yr.

When Delta export pumping is eliminated, approximately 930 taf/yr less water is exported over the Tehachapi Mountains into Southern California. The main periods of reduction are in the winter months. About 1.3 maf/yr of exports still occur from the Tulare and San Joaquin basins to Southern California. This reduction in imports over the Tehachapis translated to a substantial increase in urban scarcity (259 taf/yr). Southern California urban users make up some of the lost imports via increased wastewater reuse. Wastewater reuse increased by 696 taf/yr, while desalination rates remained unchanged. Southern California agriculture remained unaffected. The Colorado River Aqueduct is at capacity, thus Southern California agriculture (Palo Verde, Coachella, and Imperial) is unable to transfer any more water to the urban communities. The 259 taf/yr increase in scarcity resulted in a $242M/yr on average increase in the scarcity costs.

North of the Delta (Upper and Lower Sacramento Valley and in Delta agriculture) actually saw a reduction in scarcity of about 181 taf/yr because economic competition with south of Delta users for the water was absent. Along with a reduction in scarcity, north of Delta water users saw a modest decrease in scarcity cost ($2M/yr). Despite having lost the ability to pump water from the Delta, CCWD did not experience any scarcity. They were able to make up for lost supplies via increased wastewater reuse and purchases from East Bay Municipal District (EBMUD).

In addition to increased scarcity for economically represented users south of the Delta, there were also non-economically represented users that had their deliveries reduced or eliminated. These users relied on the State Water Project and Central Valley Project to meet some or all of their demands. Without pumping, the Projects were unable to or had to significantly reduce deliveries to central coast agricultural users and the cities of Huron and Coalinga.

Operating costs are substantial in both the base case and no exports alternatives (Table 17). There is approximately $3 billion per year in operating costs statewide, with most of those costs in Southern California. With exports at current levels, there is approximately $2B/yr in operating costs in Southern California, primarily due to pumping and treatment costs. When Delta exports are eliminated, the costs increase slightly ($169K/yr) due primarily to increased urban wastewater recycling and desalination in the Bay Area and Santa Barbara-San Luis Obispo.

For north of Delta users operating costs increase. CCWD cannot pump water and must rely on more expensive sources, such as EBMUD and urban water recycling. Overall operating costs increase for urban areas that rely on the Delta because reduced pumping requires use of more expensive alternatives (such as desalination and recycling) to meet demands.

Table 15. Annual Average Scarcity by Region.

Region	Annual Average Scarcity (taf/yr)			
	Agriculture		Urban	
	Base Case	No Exports	Base Case	No Exports
North of Delta	318	137	0	0
San Joaquin and South Bay	619	1,866	0	29
Tulare Basin	1,012	4,669	0	0
Southern California	941	941	60	318
South of Delta	**2,573**	**7477**	**60**	**347**

Table 16. Annual Average Cost by Region.

Region	Annual Average Scarcity Cost ($M/yr)			
	Agriculture		Urban	
	Base Case	No Exports	Base Case	No Exports
North of Delta	2.7	1.2	0.0	0.0
San Joaquin and South Bay	10.1	103.5	0.0	34.5
Tulare Basin	24.7	485.5	0.0	0.0
Southern California	129.2	129.2	44.4	286.3
South of Delta	**164.0**	**718.3**	**44.4**	**320.8**

Table 17. Annual Average Operating Cost by Region.

Region	Annual Average Operating Cost ($M/yr)	
	Base Case	No Exports
North of Delta	190	201
San Joaquin and South Bay	339	409
Tulare Basin	659	565
Southern California	1,966	2,136
South of Delta	**2,964**	**3,110**

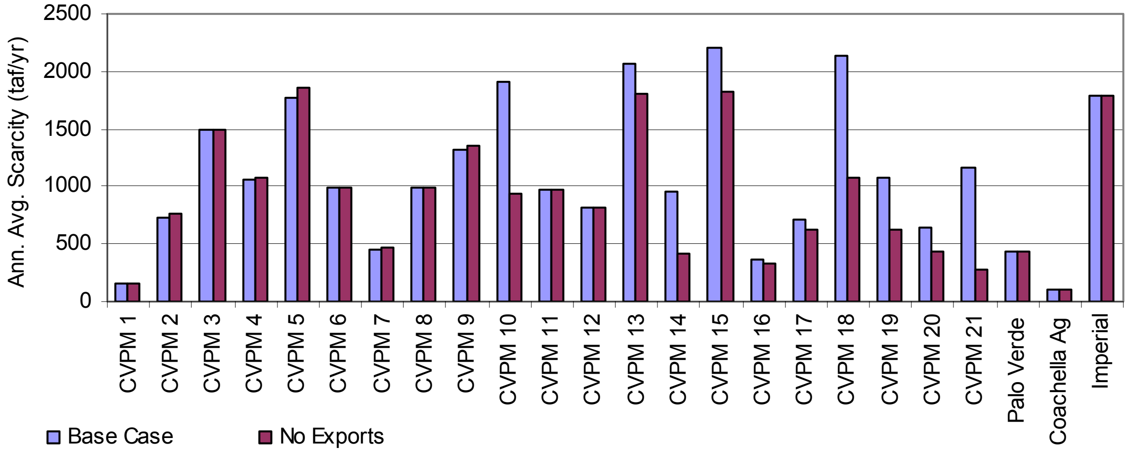

Figure 79. Annual Average Agricultural Water Scarcity User.

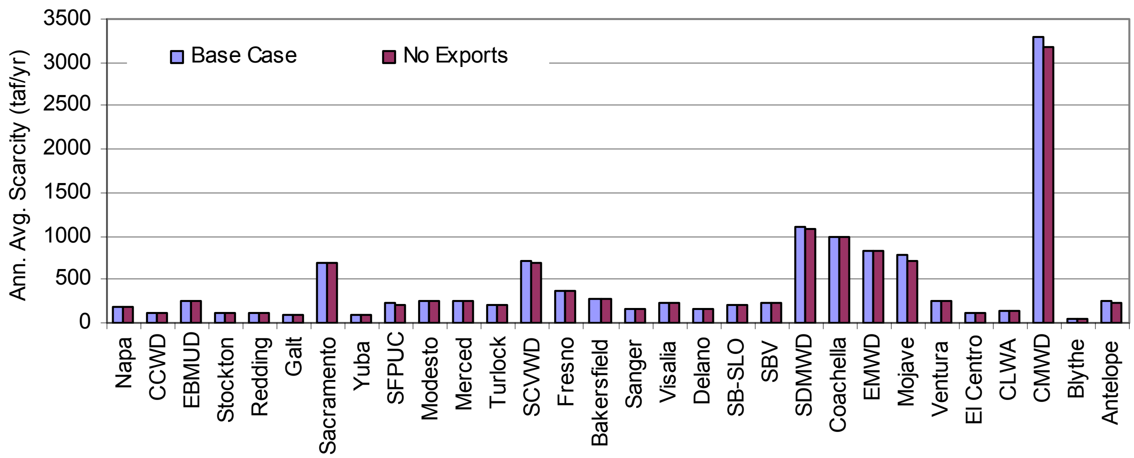

Figure 80. Annual Average Urban Scarcity For Areas with Scarcity.

Delta Outflows

Current average required Delta outflow is about 5.6 maf/yr. The monthly average required outflows range from 179 taf/mon in September to 871 taf/mon in March. The highest flows are required in the early spring and the lowest are required in the early fall. Required outflows did not change between the no export and base cases; however, the surplus outflows did (Figure 81 – 'BC' denotes base case (optimized current conditions with 2050 level of development water demands) and 'NE' denotes no exports). Surplus outflows occur because releases upstream of Delta are in excess of those needed to meet the required flows. Under base case conditions there is approximately 7.7 maf/yr of average surplus outflows. When exports are eliminated, surplus outflows increase to approximately 13 maf/yr on average.

For both alternatives the greatest volumes of surplus outflows occurred in the winter months, with a peak occurring in January. By summer the surplus outflows are nearly zero, with only modest increases without exports. The increased surplus outflows under the no export alternative results from increased flows into the Delta from the Sacramento and San Joaquin Rivers. On average there is less flow into the Delta from the San Joaquin River under the no export alternative, but without pumping from the South Delta (for the SWP, CVP, and CCWD) a greater volume reaches the outflow location.

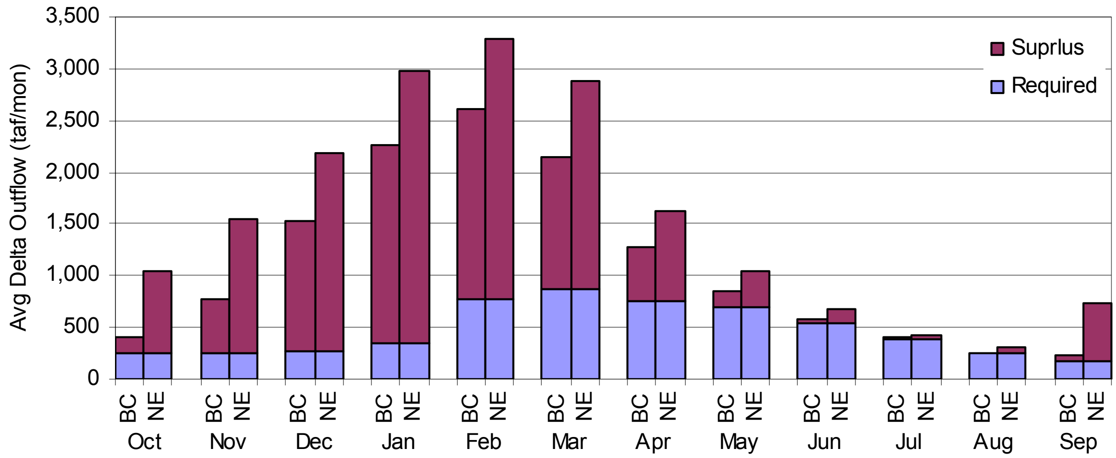

Figure 81. Monthly Average Required and Surplus Delta Outflows (taf/mon).

Environmental Marginal Costs

CALVIN represents environmental flow requirements as fixed constraints (i.e., deliveries or flows that must be met). In general the environmental requirements represented in CALVIN are minimum instream flows and fixed deliveries to wildlife refuges. Under base case conditions, the costs of environmental flows range from $38 per acre-feet (af) to less than a dollar (Table 18). Generally, the marginal costs are the highest for consumptive use requirements (those requirements for which the water cannot be reused downstream for economic benefits). Examples of the consumptive use requirements are the Trinity River minimum instream flows and flows needed by the wildlife refuges.

When Delta exports are eliminated the marginal costs of environmental flows north of the Delta decrease slightly, while marginal costs of the south of Delta environmental flows increase. Without exports, the marginal costs of environmental flows range from $511/af to less than $1/af. The greatest increases in the marginal costs are for the required flows into the Kern and San Joaquin Wildlife Refuges. These refuges rely on San Joaquin River flows and directly reduce available supplies for agricultural and urban users south of the Delta. The increased marginal cost of environmental flows south of the Delta reflects the increased scarcity and operating costs.

Table 18. Marginal Opportunity Cost of Environmental Requirements.

Environmental Flow Requirement	Region	Average Marginal Cost ($/af)	
		Base Case	No Exports
Instream Flow Requirements			
Trinity River*	Sac Valley	34.8	31.7
Sacramento River	Sac Valley	1.8	1.5

Feather River	Sac Valley	0.3	0.3
American River	Sac Valley	0.6	0.8
Mokelumne River	Sac Valley	2.2	2.5
Stanislaus River	San Joaquin	2.3	2.7
Tuolumne River	San Joaquin	1.4	1.6
Merced River	San Joaquin	11.6	24.7
San Joaquin River	San Joaquin	8.8	90.0
Refuges			
Sacramento East Refuges	Sac Valley	2.4	0.3
Sacramento West Refuges	Sac Valley	2.7	0.4
San Joaquin Wildlife Refuge	San Joaquin	24.0	406.3
Pixley National Wildlife Refuge	Tulare	34.2	114.0
Kern National Wildlife Refuge	Tulare	38.3	511.1
Other			
Required Delta Outflow	Sac Valley	2.6	0.3
Mendota Pool	Tulare	21.4	88.7

* Trinity River minimum instream flows are consumptive in CALVIN and may include the lost hydropower benefits on Trinity Reservoir.

Reservoirs and Conveyance Facilities Marginal Benefits

The marginal value of reservoirs and conveyance facilities indicates the per acre-foot economic value of additional capacity for the statewide system. In general there is greater value to increasing capacity for key conveyance facilities, rather than reservoirs under the no-export alternative (Table 19). In most locations the marginal value of additional reservoir capacity decreases without exports because there is less need to store water north of the Delta and there is less water to store south of the Delta. Reservoirs that would benefit from expansion tend to be in the Tulare Basin, where water can be exported to urban areas of Southern California. The maximum benefit of reservoir expansion would come from Lake Kaweah, but it would average only about $92/af per year. North of the Delta the value to increasing reservoir storage is generally less than $10/af per year and generally decreases in value when Delta exports are eliminated. Overall the changes in marginal values of expanding south of Delta reservoirs only increased a small amount from the base case to the no-export alternative (Lake Skinner was an exception, with a large decrease in value due to limited supplies to store).

In aggregate, statewide storage is higher without exports, primarily due to reservoirs north of the Delta. North of the Delta storage is significantly higher because there is less demands for the water and higher storage levels generate greater hydraulic head for hydropower (Figure 82). South of the Delta the storage levels are slightly higher without exports overall (Figure 83), but individual reservoirs may be emptier or fuller. Reservoirs with the greatest benefits to expansion are generally at capacity in the winter months. If expanded, these reservoirs would be able to store more winter flows for use in the summer.

Expanding key conveyance facilities, on the other hand, would provide great benefits. Facilities like the Hayward inter-tie, the Hetch Hetchy Aqueduct, the New Don Pedro Inter-tie, Mokelumne Aqueduct, Colorado River Aqueduct, and Tijuana Canal could provide additional benefits if expanded. These facilities would allow urban areas in the Bay Area and Southern California to access more water, which becomes increasingly scarce without Delta exports. Facilities that provide water to the Bay Area (such as the Hetch Hetchy Aqueduct and Hayward Inter-tie) are especially valuable because of larger scarcities in the urban areas without Delta exports.

Both the Colorado River Aqueduct and the Hayward Inter-tie (EBMUD to San Francisco Public Utilities Commission (SFPUC)) are at capacity in all months with and without Delta exports. The Mokelumne Aqueduct and CCWD/EBMUD inter-tie have value to expansion when no Delta exports are allowed because CCWD relies on EBMUD transfers (along with wastewater recycling) to meet their demands. The Friant-Kern Canal and Cross Valley Canal allow San Joaquin River water to be transferred to Southern California. Like the CCWD/EBMUD Inter-tie, there is value to expanding the Friant-Kern Canal and Cross Valley Canal only when there are no Delta exports.

Other facilities, such as the Coastal Aqueduct would no longer benefit from expansion. When exports are allowed, SB-SLO diverts up to the aqueduct's capacity and must still use desalination and recycling to meet their demands. If they could pump additional water from the California Aqueduct via the Coastal Aqueduct, it would reduce their need to use most costly sources. However, when exports are eliminated, additional water is not available for pumping.

Finally some of the artificial recharge facilities would provide benefits if expanded (Table 19). Santa Clara Valley would benefit from being able to recharge more of their wastewater, as would Antelope Valley. There is also some benefit to both urban areas if they could divert more fresh water into their aquifers for storage. However, not all artificial recharge facilities would benefit from expansion when Delta exports are eliminated. Some recharge facilities are unchanged or show small decreases in benefits (such as Mojave that goes from $265/af to $241/af when exports are eliminated).

Table 19. Average Monthly Marginal Values of Expanded Capacity at Key Conveyance Facilities and Reservoirs.

	Average Marginal Value of Expansion ($/af)		
	Base Case	**No Exports**	**Difference**
Conveyance Facilities			
Freeport Project*	0	4	4
Mokelumne River Aqueduct	0	112	112
New Don Pedro Inter-tie	170	583	413
Hetch Hetchy Aqueduct	193	608	415
EBMUD/CCWD*	0	14	14
Hayward Inter-Tie*	109	518	409
Cross Valley Canal	0	151	151
Friant Kern Canal	0	2	2
Coastal Aqueduct	926	0	-926

Colorado River Aqueduct	169	488	319
Tijuana Canal	306	906	603
Reservoirs			
Clair Engle Lake	0.2	0.2	0.0
Shasta Lake	0.5	0.4	0.0
Lake Oroville	0.8	0.6	-0.2
Folsom Lake	0.7	0.6	-0.1
New Melones Reservoir	0.5	0.5	0.0
San Luis Reservoir	0.0	0.0	0.0
Hetch-Hetchy Reservoir	0.3	0.3	0.0
New Don Pedro	0.5	0.4	0.1
Millerton Lake	0.3	1.6	1.3
Lake Isabella	0.2	0.9	0.7
Lake Kaweah	2.9	9.3	6.4
Lake Success	2.6	8.3	5.7
Lake Skinner	29.4	1.5	-27.9
Artificial Recharge Facilities			
Santa Clara Valley	313	1315	1002
Antelope Valley	710	1159	449

* New inter-ties in this model.

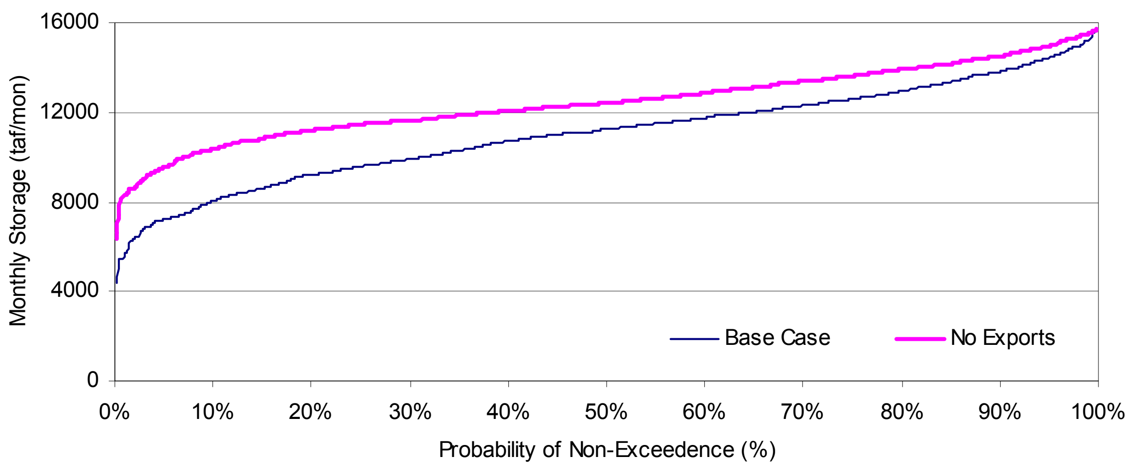

Figure 82. North of the Delta Surface Storage Non-Exceedence.

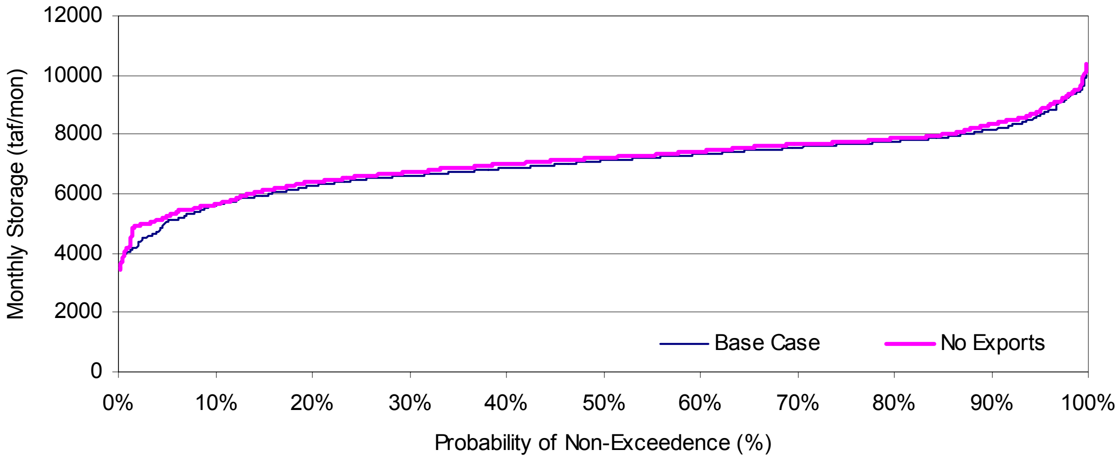

Figure 83. South of the Delta Surface Storage Non-Exceedence.

New Technologies

As additional supplies of available freshwater become increasingly costly and difficult to locate, urban water users turn toward new technologies and techniques, such as increasing wastewater reuse and desalination, to stretch their existing supplies. For the 2050 level of demands, it was assumed that all urban areas could reuse up to half of their wastewater at a cost of $1,000/af. Coastal urban areas were given access to unlimited desalination at a cost of $1,400/af.

In total, 11 of the 30 urban users represented in CALVIN rely on wastewater reuse when Delta exports are eliminated (Table 20). This is an increase of five from the base case. Under optimized current conditions for 2050 (with exports), the Bay Area and South Central Valley relied on wastewater reuse the most, while north of the Delta urban communities relied on it the least. On average Bay Area and South Central Valley users relied on wastewater recycling to meet 2.2% of their average demand, while north of the Delta and Southern California communities on relied on wastewater recycling to meet 0.5% and 1.7% of their demands, respectively. Volumetrically, Southern California had greatest around of urban wastewater recycling (on average about 145 taf/yr), followed by Bay Area and South Central Valley (65 taf/yr), and then North of the Delta (8 taf/yr).

When Delta exports are eliminated, all regions increase wastewater reuse, with the largest increases occurring in Southern California. Without Delta exports Southern California communities relied on wastewater recycling to meet 10.1% of their demand (approximately 841 taf/yr). South Bay and South Central Valley relied on wastewater recycling to meet 3.5% of their demand (104 taf/yr) and north of Delta urban areas used wastewater recycling to meet 1.8% of their demand (28 taf/yr). Overall when Delta exports are eliminated there is a consistent increase in the use of wastewater recycling. The inter-annual and inter-monthly variability in wastewater reuse is reduced (Figure 84).

Table 20. Annual Average Wastewater Reuse by Area (taf/yr).

	Average Wastewater Reuse (taf/yr)

Urban Area	Base Case	No Exports
East Bay MUD	0.0	7.9
Contra Costa Water District	7.6	20.4
Santa Clara Valley	15.6	15.6
San Francisco	0.0	34.0
Santa Barbara-San Luis Obispo	49.6	54.0
Central MWD	0.0	422.4
Eastern MWD	41.2	114.0
Antelope Valley	6.0	50.2
Ventura	27.2	27.2
Castaic Lake Water Authority	0.0	28.8
San Diego	58.5	186.0

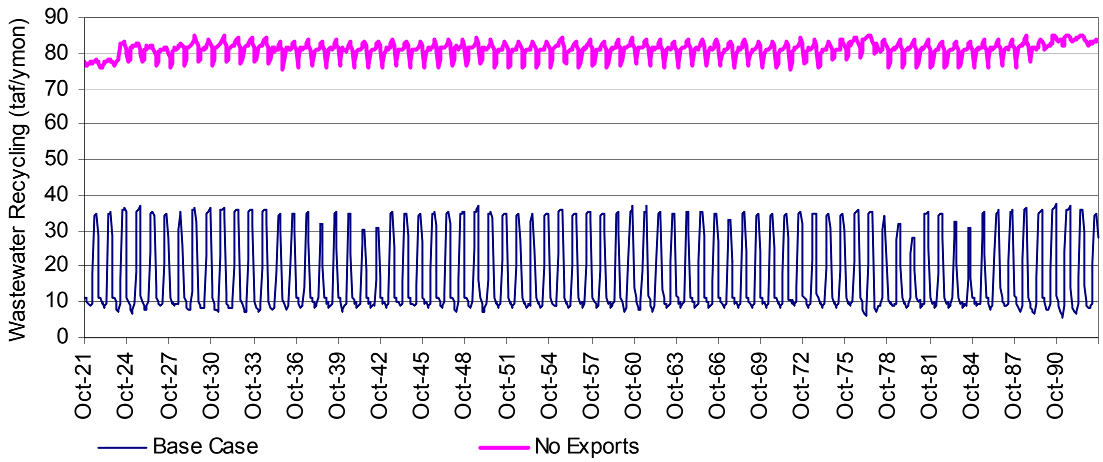

Figure 84. Monthly Urban Wastewater Recycling (taf/mon).

Only eight urban areas had access to unlimited ocean desalination (Table 21). Of these, only three opt to use this source under base case conditions for 2050 (Santa Barbara-San Luis Obispo, San Diego, and Eastern MWD). When Delta exports are eliminated two more urban areas begin to use desalination (San Francisco and Santa Clara Valley). In general desalination is used less than wastewater recycling (Figure 85). Because of the cost difference, urban areas would rather use wastewater recycling before turning to desalination if possible. The largest user of desalination under optimized current conditions for 2050 is Santa Barbara-San Luis Obispo (21 taf/yr). When exports are eliminated, Santa Barbara-San Luis Obispo increases their use to 68 taf/yr, but the largest user is Santa Clara Valley (187 taf/yr). Overall desalination is used much more inconsistently than wastewater recycling. Santa Barbara-San Luis Obispo is the most consistent user of desalination with and without Delta exports. Without Delta exports Santa Clara Valley also uses desalination fairly consistently (about half of the time). Most other users only use desalination occasionally (ex., less than 15% of the time).

It should be noted that representation of desalination is problematic in CALVIN. Urban areas have unlimited access to desalination plants without having to invest in construction (capital) costs or pay maintenance costs for existing facilities. They can call upon desalination for infrequent, but large volumes of water at the same cost as if they used it frequently for small volumes. For example, San Francisco only uses desalination for three months out of the 72-years, but uses about 14 taf/mon each time. In practice, it would not be economically feasible for San Francisco to build a 14 taf/mon (235 cfs) desalination plant to be used only three times. For all the urban areas, except Santa Barbara-San Luis Obispo, desalination is used sporadically during the 72-years.

Table 21. Average Urban Desalination (taf/yr).

	Average Desalination (taf/yr)	
Urban Area	**Base Case**	**No Exports**
East Bay MUD	0.0	0.0
San Francisco	0.0	0.5
Santa Clara Valley	0.0	186.9
Santa Barbara-San Luis Obispo	20.6	67.6
Central MWD	0.0	0.0
Eastern MWD	5.9	5.9
Ventura	0.0	0.0
San Diego	>0.1	>0.1

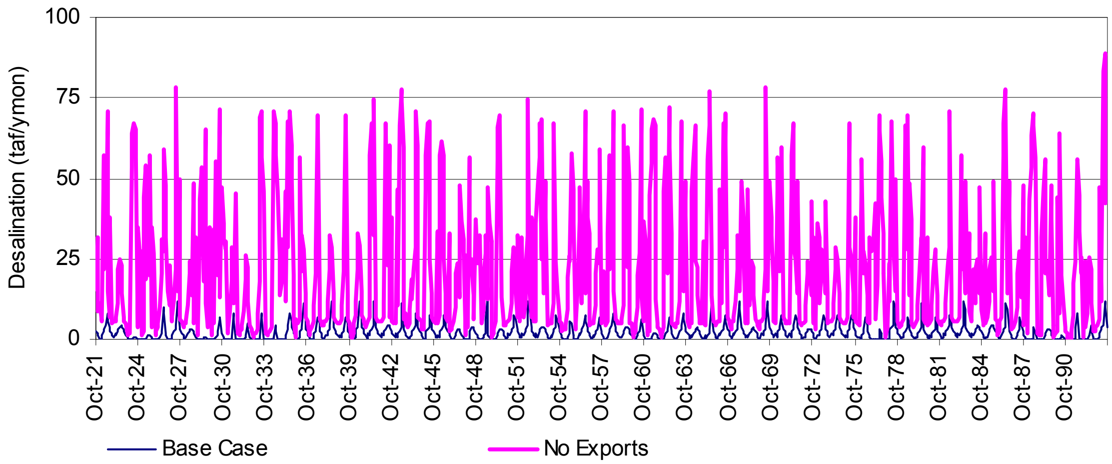

Figure 85. Monthly Desalination (taf/mon).

Summary

Currently there is about 6 maf/yr of pumping from the South Delta by Contra Costa Water District, the State Water Project, and Central Valley Project. When exports are eliminated, the agricultural areas in the San Joaquin and Tulare Basins experiences significant increases in water scarcity. Southern California also saw increased scarcity, but some of the potential scarcities were avoided because of their ability to transfer water from the San Joaquin and Tulare Basins and their access to alternative (though costly) supplies. Construction of key facilities in the Bay Area enables those urban areas to reduce the potential magnitude of the scarcities, but not avoid it all together. Overall, the elimination of Delta exports would be costly for all sectors and, unless caused by a catastrophe, would probably be an unacceptable means of managing the Delta from both an urban and agricultural perspective.

Capacity Expansion

Banks pumping plant is currently operated below its physical capacity due to operational and regulatory constraints. The current pumping rate (approximately 6,600 cfs) was systematically increased to investigate the effects that increased pumping capacity would have on water supplies and availability. Three rates were selected: the hydraulic capacity (8,500 cfs), the infrastructure capacity (10,300 cfs) and no capacity (unlimited).

Increasing the capacity at Banks Pumping Plant in the CALVIN model provided some insights into how the system would operate. However, CALVIN's representation of the Delta is coarse. CALVIN cannot represent non-linear constraints and as such some important requirements, such as the carriage water requirements, could not be included. The representation of those in-Delta and through-Delta requirements are limited to those that can be represented by minimum instream flows and required Delta outflows, both of which are pre-specified. CALVIN does not include water quality constraints and changes in flows that might result in different salinity regimes within the Delta. Different salinity regimes would normally affect the in-Delta agricultural pumping and the cost of treatment for urban areas that withdraw from the Delta. Also many of the Delta requirements are based on sub-monthly events that a monthly model like CALVIN cannot explicitly represent.

Despite the limitations, some general conclusions about operations with increasing pumping capacity can be identified. Generally, increased capacity at Banks had limited effects on operations because of capacity constraints elsewhere in the system, such as those on the California Aqueduct. There were modest reductions in scarcities and scarcity costs outside of Southern California. Overall, increasing Banks pumping plant capacity had minimal impacts and as such only limited discussion is provided here.

Scarcity and Scarcity Costs

Changing the Banks pumping plant capacity has very little effect on the scarcity in any of the regions. With increasing capacity agricultural users north of the Delta and in the San Joaquin and Tulare Regions experience a minor decrease in their scarcities (Figure 86). Southern California agricultural users are unaffected by the change in pumping plant capacity. The urban scarcities remain unaffected; as there are very little urban scarcities with current pumping capacity. The decrease in scarcities resulted in a slight decrease in the scarcity costs (approximately $1.6M/yr). The increased capacity had minimal effect on statewide operating costs.

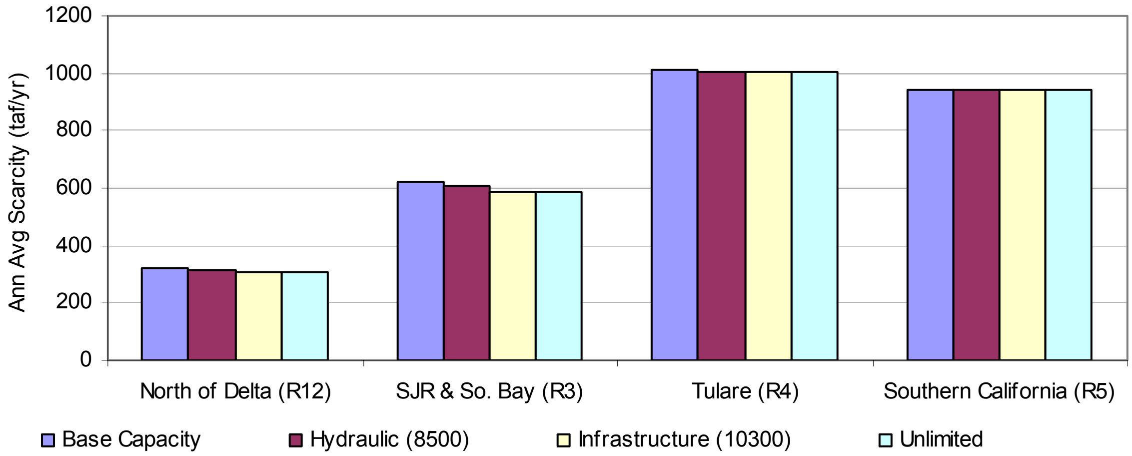

Figure 86. Annual Average Agricultural Scarcity by Region.

Delta Outflows and Pumping

Modest changes occurred in Delta pumping when pumping capacity was increased. The average monthly pumping increased for seven months and decreased for five months. Overall pumping from Banks and Tracy increased from 5,789 taf/yr to 5,920 taf/yr on average. Most of the decreased pumping occurred in winter (November through February). Overall, there was slightly more pumping during the wet periods and less pumping during the drought periods (Figure 87). On an annual basis the most significant changes in pumping occurred in February (reduction) and March, April and May (increase). Large changes in Delta pumping did not occur because of capacity constraints downstream of the Delta.

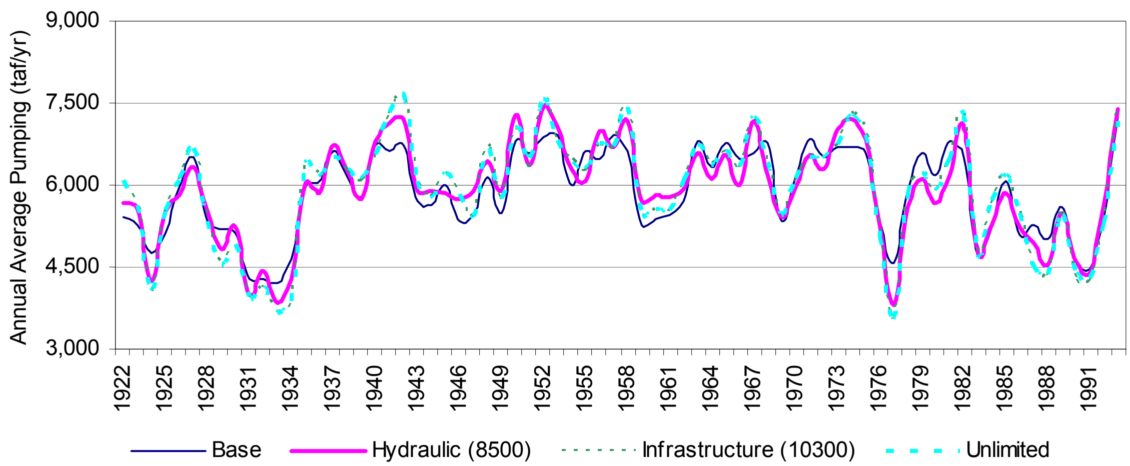

Figure 87. Annual Delta Pumping (taf/yr).

Increasing the Banks pumping plant capacity has very little effect on the Delta outflows. The required outflows were the same regardless of the plant capacity, thus only the surplus outflows could be affected by the change in pumping. Under current pumping rates, there was 7,721 taf/yr of surplus outflows. This drops to 7,678 taf/yr when unlimited pumping is allowed. The largest monthly changes in surplus outflows coincided with the most significant changes in Delta pumping. The surplus in February was higher than it was with current capacities and it was lower in March through May.

Summary

Increasing the Banks pumping plant capacity from the proposed hydraulic capacity of 8,500 cfs had very limited impacts on the statewide scarcity and operating costs. Local effects were more variable, with some areas benefiting more from expansion than others, though all reduction in scarcity was limited to agricultural areas in the Sacramento, San Joaquin, and Tulare areas. Southern California urban and agriculture was not affected. Capacity on the aqueduct systems downstream of the Delta limit the volumes of water that can be withdrawn from the Delta, thus it would not make sense to increase pumping rates beyond those that could be accommodated downstream.

Increasing Minimum Net Delta Outflows

Outflows from the Delta directly affect the salinity of the waters within the Delta. Increased Delta outflows could represent the situation where the Delta was kept fresher because higher outflows would push the saline gradient further toward the Bay or to reflect additional outflows needed to counteract the effects of sea level rise. For this modeling alternative the Banks pumping plant capacity was set to the hydraulic limit (8,500 cfs).

Delta Outflows

The current (base) minimum net Delta outflows (NDO) range from 179 taf/mon to 374 taf/mon, depending on the month and year. The maximum NDO was 1,713 taf/mon. For each of the nine alternatives chosen the minimum required net Delta outflows was raised. For example, if the new minimum monthly NDO was 250 taf/mon, then all months that had flows less than 250 taf/mon would be changed to the new value. All months with required outflows greater or equal to 250 taf/mon would be unchanged. As the minimum NDO increased, the number of months affected also increased. In Figure 88 non-exceedence probability plot is presented. Each dashed line represents one of the alternatives where the monthly net Delta outflow was raised from its current value to the new minimum value.

On an annual average basis, the required NDO went from 5,593 taf/yr (approximately 7,725 cfs) to 19,205 taf/yr (26,527 cfs) when the minimum was raised to 1,600 taf/mon (Table 22). For these cases, the surplus Delta outflow fell from 7,700 taf/yr to 2,027 taf/yr and average annual Delta outflows increased from 13,293 taf/yr to 21,232 taf/yr.

Table 22. Annual Average Required, Surplus, and Total Delta Outflows (taf/yr).

	Annual Average Delta Outflows (taf/yr)		
Minimum NDO	**Required**	**Surplus**	**Total**
Base (179)	5,593	7,700	13,293
250	5,699	7,600	13,299

500	7,285	6,157	13,442
700	9,130	4,817	13,947
1,000	12,271	3,341	15,612
1,200	14,500	2,848	17,349
1,400	16,828	2,392	19,220
1,500	18,013	2,213	20,226
1,600	19,205	2,027	21,232

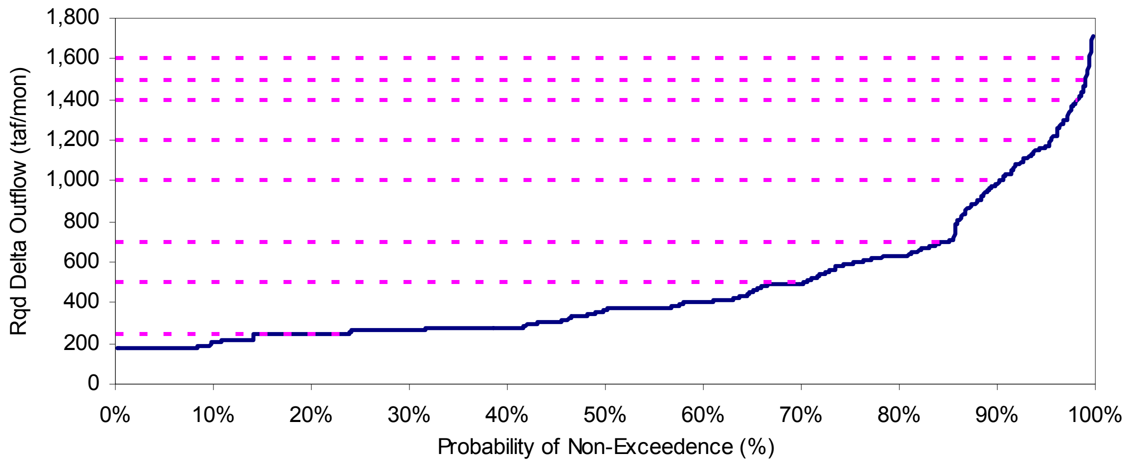

Figure 88. Average Monthly Required Delta Outflow Probability of Non-Exceedence.

As the minimum NDO increased the surplus Delta outflows (those flows above the required amount) decreased (Figure 89). In Figure 89 the nine alternatives are presented for each month (in order from left to right, starting with base conditions and ending with the 1,600 minimum NDO). Regardless of the alternative, the greatest Delta outflows occurred in the winter (December through March) and the lowest outflows occurred in the summer (June though September). Under current conditions there were surplus outflows in all months except for July and August. When the minimum NDO was raised to 1,600 taf/mon there was still surplus in November through June, but the volumes had significantly decreased.

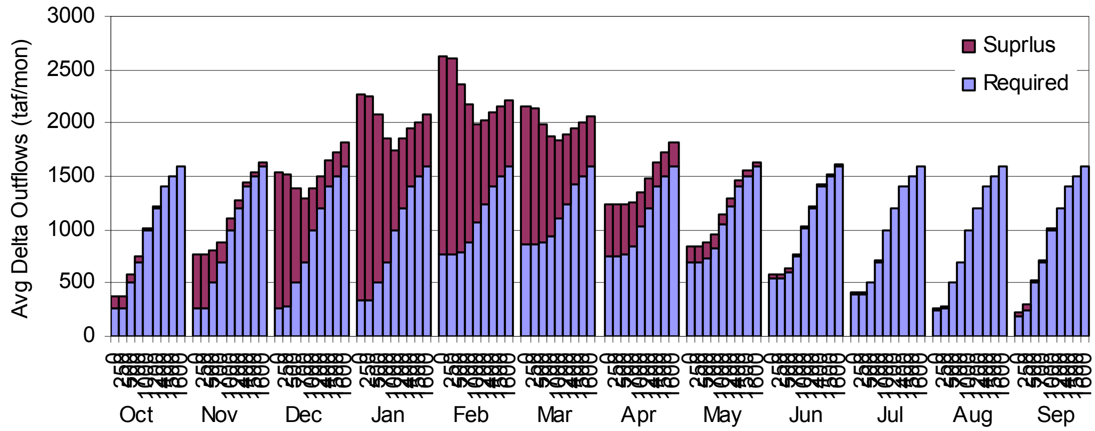

Figure 89. Average Monthly Required and Surplus Delta Outflows (taf/mon), In Order From Left to Right, Starting with Base Conditions and Ending With the 1,600 Minimum NDO.

Scarcity and Scarcity Costs

As the minimum NDO was increased, Delta surplus outflows were reduced. Along with the reduction in surplus outflows there was also a reduction in deliveries. Agricultural regions experienced increased scarcity (over those with current NDO requirements) almost as soon as the minimum NDO was raised (Table 23). Generally, these increases were modest until the minimum NDO reached about 1,000 taf/mon (12,271 taf/yr) (Figure 90). When minimum NDO were raised to 1,600 taf/mon almost all agricultural regions saw an increase in their scarcity and scarcity costs.

Primarily, it was those agriculture users that directly compete with urban users for water or those users that share supply sources with required environmental flows that experienced the largest increases in scarcity. Unlike the No Export alternative, the San Joaquin and Eastside stream agricultural users were not isolated from the impacts of changing Delta outflow requirements. As the minimum NDO was raised additional water from both the Sacramento and San Joaquin River systems were needed. Overall, an additional 2.0 maf/yr was used from the Sacramento River and an additional 6.0 maf/yr was used from the San Joaquin River system. These large increases in water for Delta outflow requirements resulted in large increases in the scarcity and scarcity costs.

Agricultural users in the San Joaquin and South Bay saw a 6-fold increase in their annual average scarcity and a 22-fold increase in their scarcity costs. Tulare basin agriculture saw a smaller increase in both their scarcity (3-fold) and scarcity cost (9-fold). However, it was north of the Delta agriculture was impacted the most by the increased minimum NDO. Initially having the least regional scarcity, north of Delta scarcity increased 16-fold and the associated scarcity cost increased 97-fold. The only agricultural regions that remained unaffected by changes in the minimum NDO were located in Southern California. Their scarcity remained constant at 942 taf/yr for all alternatives.

Table 23. Annual Average Agricultural Scarcity (taf/yr).

Minimum NDO	Annual Average Scarcity (taf/yr)

	North of the Delta	San Joaquin & South Bay	Tulare Basin	Southern California
Base (179)	317	604	1,004	941
250	322	606	1,005	941
500	415	666	1,025	941
700	661	841	1,237	941
1,000	1,723	1,274	1,788	941
1,200	2,801	2,022	2,160	941
1,400	4,171	2,472	2,671	941
1,500	4,805	2,921	2,894	941
1,600	5,105	3,467	3,193	941

Table 24. Annual Average Agricultural Scarcity Cost ($M/yr).

Minimum NDO	Annual Average Scarcity Cost ($M/yr)			
	North of the Delta	San Joaquin & South Bay	Tulare Basin	Southern California
Base (179)	2.6	9.5	24.4	129.2
250	2.7	9.6	24.5	129.2
500	3.5	10.9	25.2	129.2
700	6.5	16.0	35.6	129.2
1,000	35.5	32.5	74.2	129.2
1,200	85.4	79.0	104.5	129.2
1,400	172.4	110.9	159.6	129.2
1,500	220.1	153.2	186.2	129.2
1,600	256.9	213.3	224.5	129.2

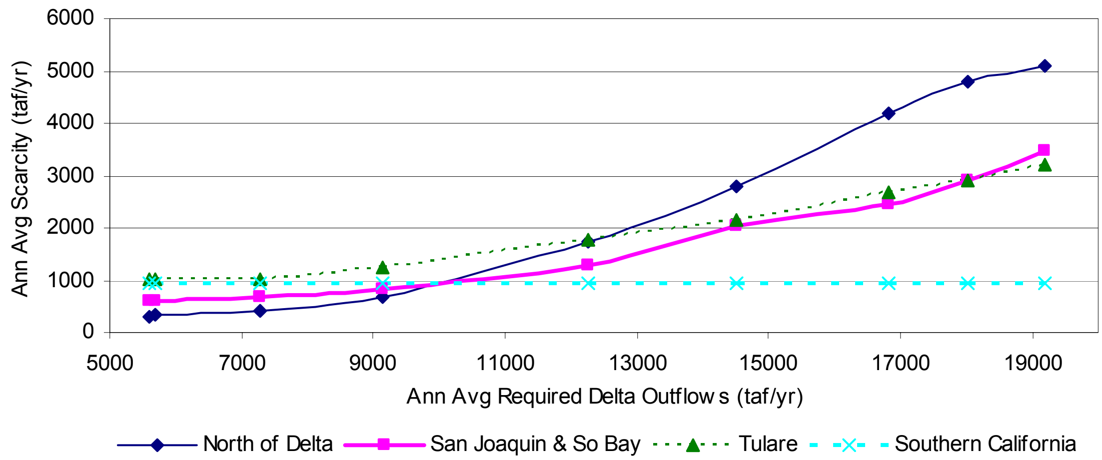

Figure 90. Annual Average Agricultural Scarcity Versus Required Delta Outflow.

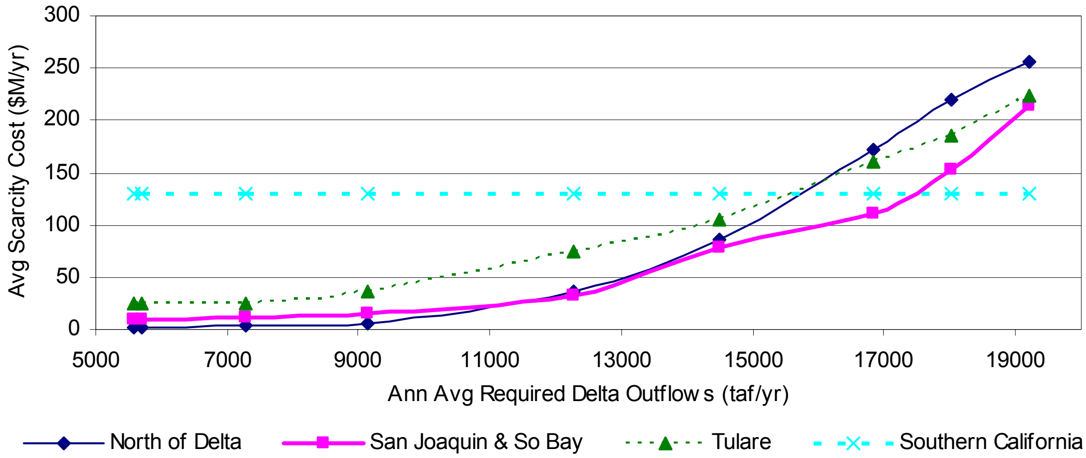

Figure 91. Annual Average Agricultural Scarcity Costs Versus Required Delta Outflow.

Urban users, except those in Southern California, were not affected by increased Delta outflows until the most extreme requirements (Table 25). Under current outflow conditions there would be 59.5 taf/yr of urban scarcity in Southern California. This remained unchanged until minimum NDO were set to 1,000 taf/mon, at which point Southern California urban users saw scarcity increase by 16.4 taf/yr. At the highest minimum NDO level urban Southern California had 88.3 taf/yr of scarcity on average. Overall Southern California remained relatively isolated from changes in Delta outflow requirements because of their ability to purchase and transfer San Joaquin and Tulare basin water over the Tehachapi Mountains. Annual average Delta pumping decreased by 2.3 maf/yr, but flow over the Tehachapis only decreased by 18.7 taf/yr. This was mainly due to reduced transfers from the California Aqueduct to the Delta Mendota Canal and increased use of the Semitropic Water Bank and transfers via the Cross Valley Canal.

Likewise at the highest level of minimum NDO urban scarcities had occurred north of the Delta (3.4 taf/yr) and San Joaquin and South Bay (9.1 taf/yr). Tulare Basin urban users were the only ones not affected by the increased minimum NDO. Most of the urban scarcity (outside of Southern California) occurred in the Bay Area (EBMUD, SFPUC, SCVWD) where alternative supplies are limited. Until the minimum NDO was at 1,600 taf/mon, they were able to meet demands through use of Freeport project and the Hayward Inter-tie. While much smaller in volume, urban scarcities result in significantly higher scarcity costs (Table 26). A 3.4 taf/yr scarcity increase resulted in a $2.5M/yr increased in annual average scarcity cost for urban north of the Delta.

Table 25. Annual Average Urban Scarcity (taf/yr).

Minimum NDO	Annual Average Scarcity (taf/yr)			
	North of the Delta	San Joaquin & South Bay	Tulare Basin	Southern California
Base (179)	0.0	0.0	0.0	59.5
250	0.0	0.0	0.0	59.5
500	0.0	0.0	0.0	59.5
700	0.0	0.0	0.0	59.5

1,000	0.0	0.0	0.0	76.0
1,200	0.0	0.0	0.0	77.6
1,400	0.0	0.0	0.0	83.5
1,500	0.0	0.0	0.0	86.1
1,600	3.4	9.1	0.0	88.3

Table 26. Annual Average Urban Scarcity Cost ($M/yr).

Minimum NDO	Annual Average Scarcity Cost ($M/yr)			
	North of the Delta	San Joaquin & South Bay	Tulare Basin	Southern California
Base (179)	0.0	0.0	0.0	44.4
250	0.0	0.0	0.0	44.4
500	0.0	0.0	0.0	44.4
700	0.0	0.0	0.0	44.4
1,000	0.0	0.0	0.0	53.1
1,200	0.0	0.0	0.0	54.2
1,400	0.0	0.0	0.0	58.1
1,500	0.0	0.0	0.0	60.2
1,600	2.5	10.8	0.0	61.9

Operating costs were relatively unaffected by changes in the minimum NDO (Table 27). North of the Delta and San Joaquin and South Bay see increased operating costs, while Tulare Basin and Southern California see decreases. Statewide operating costs increased from $3.15B/yr to $3.17B/yr. Reduction in pumping costs at Banks and Tracy were offset by increases in more expensive alternative water supplies (such as desalination and recycling).

Table 27. Annual Average Operating Costs ($M/yr).

Minimum NDO	Annual Average Operating Cost ($M/yr)				
	North of the Delta	San Joaquin & South Bay	Tulare Basin	Southern California	Statewide
Base (179)	190	338	659	1,966	3,153
250	190	338	659	1,966	3,153
500	190	337	658	1,966	3,152
700	190	331	655	1,966	3,143
1,000	191	318	649	1,960	3,117
1,200	189	306	644	1,959	3,098
1,400	180	304	647	1,956	3,087
1,500	178	303	644	1,955	3,080
1,600	208	358	650	1,954	3,170

Environmental Marginal Costs

As deliveries are reduced to meet increasing Delta outflow requirements, the marginal cost of all environmental flows (consumptive and non-consumptive) increased (Table

28). The highest cost instream flows were on the Sacramento and Mokelumne Rivers. These costs reflect the scarcities associated with Sacramento River agricultural users and Bay Area urban users. The cost of the minimum instream flow requirements increased, but not as much as consumptive use marginal costs. The greatest costs are for the consumptive environmental requirements, such as the Trinity River and the National Wildlife Refuges. Unlike the No Export alternative where the north of the Delta refuges had smaller marginal costs than the refuges located in the San Joaquin and Tulare Basin, as the Delta outflows increased the marginal cost of all refuges increased to over $100/af. The highest cost refuges were still located south of the Delta. Similar in magnitude to south of Delta refuges, the marginal cost of the Trinity River requirements increases from $34.6/af to $412.9/af. Likewise the marginal cost of the Delta outflow requirements also increases from $2.5/af to $339.3/af.

Table 28. Marginal Cost of Environmental Flows with Increasing Minimum Net Delta Outflow ($/af).

Environmental Flow Requirement	Average Marginal Cost ($/af)								
	Base (179)	250	500	700	1000	1200	1400	1500	1600
Instream Flow Requirements									
Trinity River*	34.6	34.8	37.3	42.4	75.3	98.1	127.5	146.2	412.9
Sacramento River	1.7	1.7	2.1	2.4	4.6	6.0	7.5	8.6	33.7
Feather River	0.3	0.3	0.6	1.0	2.3	2.9	3.8	4.2	5.4
American River	0.6	0.6	0.9	1.3	2.7	2.9	3.0	3.3	10.6
Mokelumne River	2.3	2.3	2.7	3.3	7.1	8.7	10.3	10.8	25.8
Stanislaus River	2.2	2.3	2.6	3.4	7.5	10.4	12.8	13.9	18.2
Tuolumne River	1.4	1.4	1.5	1.9	3.7	4.6	5.5	5.5	6.8
Merced River	11.4	11.4	11.2	9.9	9.0	8.0	7.5	6.9	7.2
San Joaquin River	8.1	8.2	9.3	10.9	14.5	12.9	14.7	15.7	14.5
Refuges									
Sacramento East	34.6	34.8	37.3	42.4	75.3	98.1	127.5	146.2	412.9
Sacramento West	2.3	2.4	4.2	8.1	33.3	50.8	68.3	75.3	173.4
San Joaquin Wildlife	37.4	37.5	39.8	44.6	77.3	98.4	125.8	138.9	151.7
Pixley National Wildlife	2.6	2.7	4.6	8.7	36.0	55.1	78.6	88.8	131.1
Kern National Wildlife	33.2	33.3	35.6	39.5	67.6	82.2	103.7	111.5	113.0
Other									
Required Delta Outflow	20.6	20.7	22.8	26.8	50.7	65.2	82.2	93.7	277.0
Mendota Pool	23.2	23.3	25.8	30.9	62.4	83.2	110.0	126.3	361.7

* Trinity River minimum instream flows are consumptive in CALVIN.

Reservoirs and Conveyance Facilities Marginal Benefits

As Delta outflow requirements increase, economic users are forced to rely more on water transfers. There would be modest benefit to expanding the Delta pumping plant capacities. This would allow more transfers of water south during the wet periods for use in the drier periods. San Joaquin, Tulare, and Southern California users would benefit from expansion of the Friant-Kern Canal. This would allow more water to be transferred from the San Joaquin River Basin to users in the south. Because of capacity constraints and limited supplies, there is little benefit to urban users in Southern California to expand the Cross Valley Canal. The Colorado River Aqueduct would provide some benefit if it were expanded. Also the proposed Tijuana canal would benefit from expansion as exports are reduced because it would provide greater flexibility for San Diego and Southern California.

Urban users in the Bay Area would benefit from additional inter-tie capacity among themselves. EBMUD transfers water to CCWD and SFPUC (except in the highest outflow requirements instance) and expansion of the Freeport Project Pipeline would enable EBMUD to import more Sacramento River water. Likewise expansion of the Hetch Hetchy Aqueduct and New Don Pedro inter-tie into the Hetch Hetchy Aqueduct would enable SFPUC to import more water that could be used to meet their demands, plus those of SCVWD, both of whom experience scarcity when minimum outflows are at 1,600 taf/mon. The Hayward Inter-tie, which allows bi-directional transfers between EBMUD and SFPUC, is almost always full when the minimums are at 1,600 taf/mon. In most periods EBMUD is transferring water to SFPUC, but during the drought periods (late-1920's through early 1930's, mid-1970's, and early 1990's) water flows from the Hetch Hetchy Aqueduct to EBMUD.

Another facility that would yield benefit from expansion is the SB-SLO pipeline to the California Aqueduct. Currently the capacity of the aqueduct plus local supplies is insufficient to meet 2050 demands. SB-SLO uses desalination and wastewater reuse to augment their local and imported supplies and additional aqueduct capacity would allow them to reduce desalination and wastewater reuse. However the benefit to expansion decreases as less water is available via the California Aqueduct due to reduced exports.

As with the No Exports alternative, expanding some of the artificial recharge facilities associated with urban areas would create benefits (Table 29). Santa Clara Valley would benefit from expanding their ability to recharge their groundwater basin using wastewater, as would Antelope Valley. Other recharge facilities see small decreases in benefit to expanding as less exports are available for recharge.

Table 29. Marginal Benefit of Expanding Key Conveyance Facilities and Reservoirs.

	Average Marginal Benefit of Expansion ($/af)								
	Base (179)	**250**	**500**	**700**	**1000**	**1200**	**1400**	**1500**	**1600**
Conveyance Facility									
Banks Pumping Plant	1	1	1	2	5	6	8	8	9
Tracy Pumping Plant	0	0	0	0	1	2	2	3	3
Freeport Project*	0	0	0	0	2	4	5	6	18
Mokelumne River Aqueduct	0	0	0	0	0	1	1	1	1
Hetch Hetchy Aqueduct	255	210	184	237	201	200	200	209	183
New Don Pedro Inter-tie	225	186	163	209	177	176	176	185	173
CCWD/EBMUD Inter-tie*	0	0	0	0	0	0	0	0	0
Hayward Inter-tie*	109	109	107	106	106	107	106	105	102
Cross Valley Canal	0	0	0	0	0	1	1	1	1
Friant-Kern Canal	0	0	0	0	1	1	1	1	1

Coastal Aqueduct	927	927	924	920	887	865	836	820	820
Colorado River Aqueduct	137	142	172	139	169	165	174	192	208
Tijuana Canal	306	306	307	309	329	342	357	365	372
Reservoir									
Lake Skinner	29.4	29.4	29.3	29.0	26.2	24.3	22.0	20.9	19.9
Englebright Lake	2.5	2.5	2.5	2.7	4.3	4.9	5.5	5.8	9.5
Lake Kaweah	2.8	2.8	3.0	3.3	5.5	6.4	8.3	8.9	8.9
Lake Success	2.5	2.5	2.7	2.9	4.8	5.8	7.3	7.9	8.0
Black Butte Lake	0.4	0.4	0.6	0.8	2.1	2.9	3.7	4.1	7.9
Camp Far West Reservoir	0.3	0.3	0.5	0.7	1.7	2.4	3.1	3.5	7.7
New Bullards Bar Res	1.0	1.0	1.1	1.2	2.0	2.5	3.2	3.5	7.5
Folsom Lake	0.7	0.7	0.8	0.9	1.7	2.3	2.9	3.2	7.2
Thermalito Afterbay	0.5	0.5	0.7	0.8	1.4	1.7	2.1	2.4	6.8
Clear Lake & Indian Valley Reservoir	0.1	0.1	0.2	0.3	0.8	1.1	1.4	1.7	6.6
Lake Oroville	0.8	0.8	0.9	0.9	1.6	1.9	2.1	2.3	6.3
Shasta Lake	0.5	0.5	0.5	0.6	1.0	1.1	1.3	1.5	5.2
Clair Engle Lake	0.2	0.2	0.2	0.2	0.4	0.5	0.7	0.8	4.5
Millerton Lake	0.3	0.3	0.4	0.4	0.7	0.8	0.9	1.0	4.4
New Melones Reservoir	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	4.3
New Don Pedro Reservoir	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.7	4.2
Hetch-Hetchy Reservoir	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.7	4.2
San Luis Reservoir	0.0	0.0	0.0	0.0	0.2	0.3	0.3	0.4	3.8
Artificial Recharge									
Santa Clara Valley	313	313	314	317	351	374	403	418	623
Antelope Valley	709	709	712	718	757	780	812	828	847

* New inter-ties in this model.

As with the No Export alternative the value of additional surface water storage is less than the value of expanding key conveyance facilities. Even when minimum NDO is raised to 1,600 taf/mon, the highest value of expansion is only $19.9/af on average (Lake Skinner). However, there are short periods when expanded storage has significantly higher values (exceeds $1,000/af). Overall, as the minimum NDO was increased, value of additional surface water storage increased. The largest increases in average value came for the north of Delta reservoirs, followed by the San Joaquin and South Bay and Tulare basins. Southern California had the reservoir that would provide the greatest benefit if expanded (Lake Skinner), but its value decreased as minimum NDO increased. This was due to the reduced availabilities of supplies. Table 29 presents the average marginal value of increased surface water storage capacity at those facilities with values greater than $6/af plus a few other key reservoirs of interest.

As the minimum NDO is increased, the system must manage its ground and surface waters more aggressively. Surface water reservoirs are drawn down further and the range of storages are greater (Figure 92). When minimum NDOs are high, reservoirs are filled higher when there is available water, but drawn down further to meet demands. The greatest variability occurs outside of Southern California. Southern California surface water storage is relatively unaffected by the minimum NDOs. North of the Delta, the surface storage is kept lower when minimum NDOs are high (average storage was 9.4 maf/mon when minimum NDO was 1,600 taf/mon and 11.0 maf/mon at current minimum NDOs). South of the Delta, but north of the Tehachapis, the surface water storage was more variable. It was drawn down further, but all filled higher indicating a much larger refill-draw down cycle.

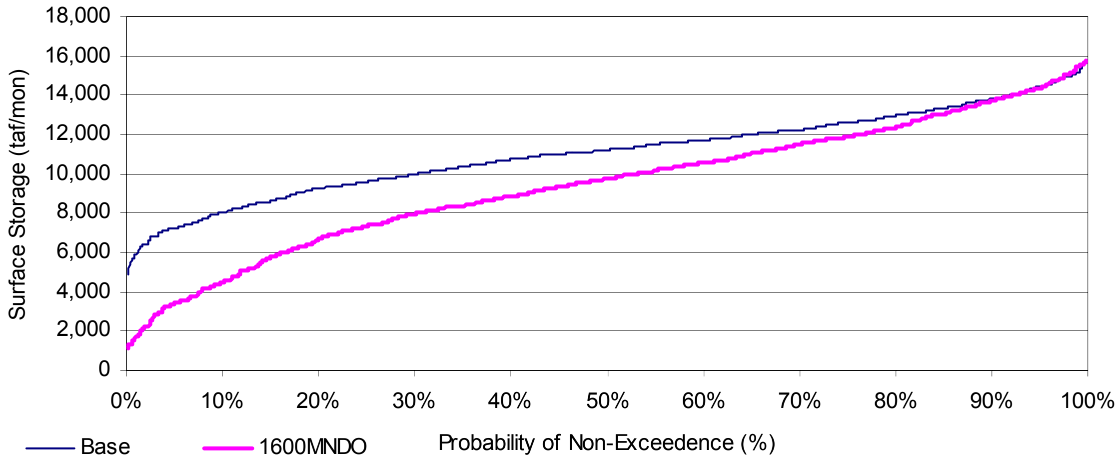

Figure 92. Monthly Statewide Surface Water Storage Probabilities of Non-Exceedence.

Like that of surface water storage, groundwater storage also has a larger draw down-refill cycle as minimum NDOs increase (Figure 93). North of the Delta the groundwater storage did not vary much when minimum NDOs changed. South of the Delta in the San Joaquin and Tulare basins the groundwater storages were much more variable. In general the basins were drawn down further and refilled higher as minimum NDOs increased. Southern California groundwater storage had a pattern similar to the San Joaquin and Tulare basins, but the magnitude of the differences was much smaller.

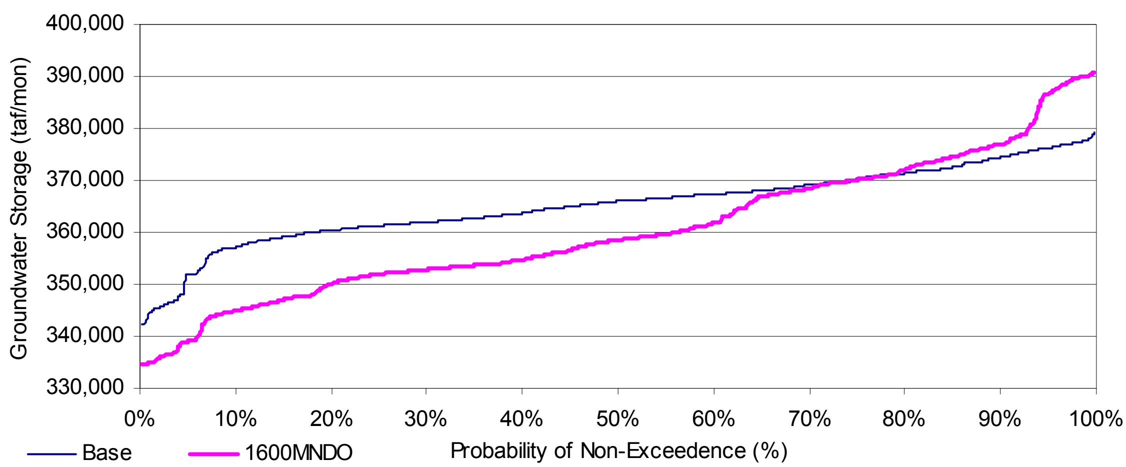

Figure 93. Monthly Statewide Groundwater Storage Probabilities of Non- Exceedence.

Overall, water storage, be it in surface water reservoirs or groundwater basins, becomes more variable as minimum NDOs increased. The reservoirs and basins were drawn down further to meet demands and refilled higher when there was water to store. In general the greatest changes occurred in the San Joaquin and Tulare basins, especially in terms of groundwater storage. Southern California's storage was relatively unaffected by changes in minimum NDOs, through there was some response to increasing outflow requirements.

New Technologies

Urban areas turned to alternative supplies of water to meet their demands when deliveries were reduced due to increased minimum NDO. For users south of the Delta (including SFPUC and SCVWD) the increasing minimum NDO did not significantly affect use of recycling and desalination until the minimum outflow was 1,600 taf/mon. At this point both recycling and desalination increase for some urban users. Urban users north of the Delta were more likely to use recycled water as minimum outflows increased. Overall, wastewater recycling levels were fairly constant regardless of the state of the Delta, except during the drought periods (Table 30 and Figure 94). High minimum NDO coupled with a drought increased wastewater recycling.

Santa Clara Valley Water District does not increase their wastewater recycling, despite experiencing increased scarcities primarily because their facility is already at maximum capacity during the critical periods. SFPUC only uses recycling when minimums were the highest. Santa Barbara-San Luis Obispo increased their wastewater recycling from 49.6 taf/yr to 51.97 taf/yr when outflows are the highest. In Southern California, of five areas that use recycled water (Eastern Metropolitan Water District (EMWD), Antelope Valley (AV), Ventura, San Diego, and San Bernardino Valley (SBV)), only San Diego increases their wastewater recycling when minimum outflows are raised. Initially using 58.4 taf/yr, they increase their use to 59.32 taf/yr, a relatively minor increase.

On the other hand, north of the Delta urban users significantly increase their wastewater reuse when outflow requirements increase. East Bay MUD does not use wastewater recycling until minimum outflows are 1,500 taf//mon. Contra Costa Water District almost immediately begins to increase there use. Initially they rely on recycled water for 7.6 taf/yr (about 6.7%). When minimum outflows are at the highest, Contra Costa is using 18.7 taf/yr of recycled water (about 16.5% of their demand).

Table 30. Annual Average Urban Wastewater Recycling (taf/yr).

	Annual Average Wastewater Recycling (taf/yr)								
	Base (179)	**250**	**500**	**700**	**1000**	**1200**	**1400**	**1500**	**1600**
EBMUD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	5.4
CCWD	7.6	7.6	8.1	8.4	16.9	18.1	18.6	18.6	18.7
SCVWD	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
SFPUC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.3
SB-SLO	49.6	49.6	49.6	49.6	49.6	49.6	49.6	49.6	52.0
AV	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
EMWD	41.2	41.7	41.5	41.8	41.1	41.0	41.1	40.9	40.3

Ventura	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2
San Diego	58.4	58.0	58.1	57.9	58.5	58.7	58.6	58.7	59.3
SBV	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
STATEWIDE	**217.6**	**217.6**	**218.2**	**218.4**	**227.0**	**228.1**	**228.6**	**229.3**	**246.8**

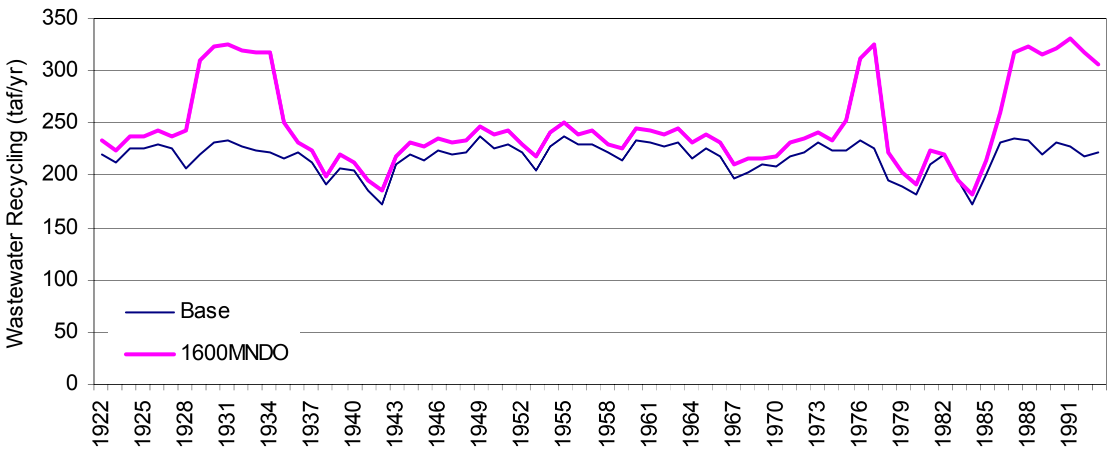

Figure 94. Statewide Annual Urban Wastewater Recycling (taf/yr).

Six urban areas use desalination to augment their water supplies (Table 31) when minimum NDO are at 1,600 taf/mon. Only three urban areas, Eastern MWD, Santa Barbara-San Luis Obispo, and San Diego, use desalination regardless of the Delta outflow requirements. Eastern MWD relies on about 5.8 taf/yr of desalination, primarily concentrated in July and August, when competition with agricultural users is highest and natural inflows are the lowest. Santa Barbara-San Luis Obispo completely depends on flows in the Coastal Aqueduct (along with local supplies) and they use desalination approximately 75% of the time, mostly in summer and fall. Their annual average use is the highest (about 21 taf/yr). San Diego does not use desalination consistently (either annually or monthly) and their use is limited to only a handful of periods (three or four times in 72 years). EBMUD, SCVWD, and SFPUC only use desalination when the minimum NDO were at 1,600 taf/mon. All three urban areas used desalination during droughts (Figure 95).

Table 31. Annual Average Urban Desalination (taf/yr).

	Annual Average Desalination (taf/yr)								
	Base (179)	**250**	**500**	**700**	**1000**	**1200**	**1400**	**1500**	**1600**
EBMUD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.5
SCV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.1
SFPUC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.7
SB-SLO	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	28.7
EMWD	5.8	5.7	5.8	5.8	5.8	5.9	5.8	5.8	5.8
SDMWD	0.2	0.3	0.1	0.2	0.1	>0.1	0.1	0.1	0.1
STATEWIDE	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	103.0

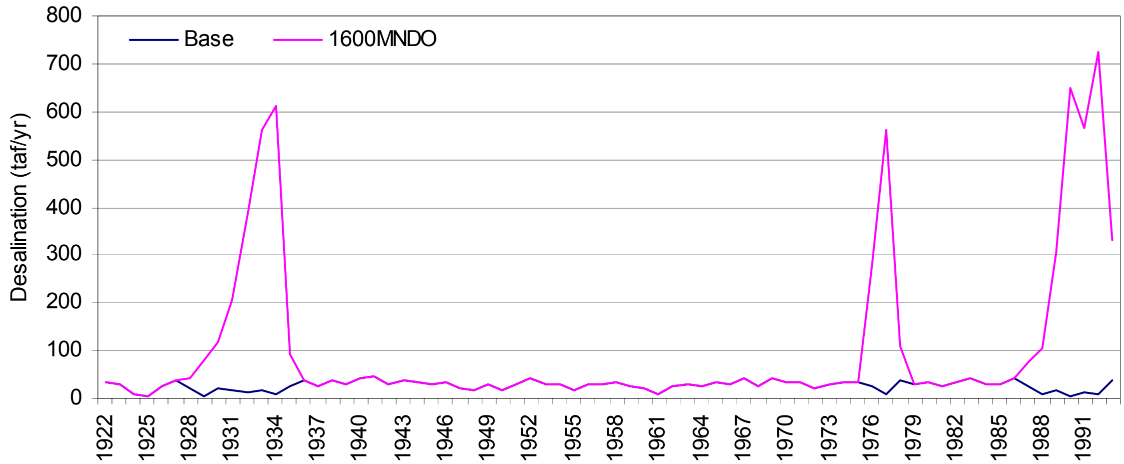

Figure 95. Statewide Annual Urban Desalination (taf/yr).

The same limitation with regards to desalination is present in the case of increasing minimum NDO as was present in the No Export alterative. Urban areas are able to call upon desalination facilities for unlimited volumes without having to invest the capital cost of expanding the facility or pay maintenance costs for existing facilities.

Summary

When minimum NDO was increased from the base level of 179 taf/mon to 1,600 taf/mon there is increased scarcity and the associated costs throughout the state, but with the use of water transfers, changes operations, and increased use of recycling and desalination many users are able to adapt, albeit at some cost. Agricultural areas take the greatest scarcity, especially those north of the Delta (they are presumably selling water south). Urban areas are relatively protected from changes in Delta outflows until they are at the highest. Use of new facilities, such as the Freeport Project and inter-ties to the California Aqueduct, allow urban users to replace Delta water with other sources. Overall, the state does not see major changes in scarcity until minimum NDOs are at 1,000 taf/mon. Raising the minimum NDO to 1,000 taf/mon affected the outflow requirements approximately 90% of the time. This would indicate that the state could adapt to changes in the outflow requirements in most periods without significant impacts if flexibility in operations and transfers already existed and certain key facilities were constructed.

CONCLUSIONS

As Delta exports decreased agricultural users south of the Delta experienced increased scarcity. Some of these costs would be offset by revenues from sales of water to urban areas. Urban areas are not significantly affected until exports are severely reduced. At this point there is no additional water available for purchase from lower value users (due to hydrologic constraints and conveyance capacity constraints). The significant increase in Central Valley and Southern California scarcity and its associated costs if exports are curtailed highlights their dependence upon the Delta as a water supply source.

Economic valuation of environmental services is controversial (Shabman and Stephenson, 2000), but the shadow values on the required environmental flows provide by CALVIN are a means by which to estimate the cost of these requirements. As exports decreased the cost of the environmental flows, especially those in the Central Valley, increased. The highest costs were associated with the consumptive use requirements, such as the wildlife refuges.

Additional storage, while having some benefit when exports are reduced, is not as economically beneficial as expanding key conveyance and recharge facilities. Those aqueducts, canals, and inter-ties that allow users to buy and sell water, especially between agricultural and urban users, are the most valuable.

As exports are decreased, the volume of water that flows out of the Delta increases. Some months see a larger increase, especially the summer and fall months when raising the NDO impacts them. Depending on the management goals, having more (or less) water flow through the Delta may be desirable.

Overall, management of the Delta requires a balancing of the interests that rely on it; this includes in-Delta users, water exporters, and environmental concerns. Results from large system models, like CALVIN, enable decision makers to see the impacts that changes in management of one part will have on the rest of the system. While not perfect such results produce reasonable insights. Overall, there is a fair bit of economical adaptability in the water supply system to changes in Delta water policies. While such adaptation incurs cost, it need not incur catastrophe.

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CHAPTER 7: FUTURE WORK AND CONCLUSIONS

INTRODUCTION

With the public's concern about environmental protection and enhancement, water managers must consider many impacts of proposed operations. Through monitoring and studies, agencies can gather the information needed to develop computer models that integrate understanding of a basin and provide insights for decision-making. Computer models are useful in managing environmentally sensitive systems because it is not often feasible or prudent to directly change the physical system to assess the impacts of management options. Models also can help highlight where additional information is needed.

This dissertation has two parts: information/data gathering and modeling. Both are necessary for successful management of water systems. Prior to developing a model, the basic theories and concepts underlying the phenomena being modeled should be understood. That understanding will help in developing data collection. Model development can begin while data collection occurs. With the model developed (and tested) and the necessary data gathered, it is then possible to begin using the model for management and adaptive management purposes.

Two environmentally sensitive areas were selected for study and modeling in California: the Klamath River and the Sacramento-San Joaquin Bay Delta (the Delta). Both the Klamath and the Delta are environmentally sensitive areas that provide habitat for threatened or endangered species. Management of these systems must consider both environmental needs and economic consequences of various options.

THERMAL REFUGIA IN THE KLAMATH RIVER

The Klamath River provides habitat for temperature sensitive coho salmon (NRC, 2004). Hydraulically, thermal refugia are areas of cool water produced by inflowing tributaries, springs, seeps, or through upwelling hyporheic flow or groundwater, in and otherwise warm water body. Fish use these refugia when river temperatures become excessive. These refugia are physically and biologically complex areas. The refuge's ultimate size is a function of flow, temperature, geomorphology, and meteorology.

Conceptually, a thermal refuge is a form of a mixing zone. At the inflow point the water has the characteristics of the inflow. At some distance downstream the water has the characteristics of the receiving waters. In between it is a mixture of both. The area between the inflow location and where it is fully mixed is important to water managers in the Klamath River. Maximizing the area of cold water available to the fish at the refugia can help expand survival of salmonids in the Klamath River.

Intensive monitoring occurred at two thermal refugia in the Klamath River. The Beaver Creek (RM 162) and Red Cap Creek refugia (RM 53) were monitored for stage, water temperature, air temperature, and relative humidity for two summer periods (warmest periods of the year in the Klamath River basin). Remote water temperature loggers were deployed at both sites, along with one air and one relative humidity loggers. Detailed site surveys were completed for both sites, delineating the locations of the water temperature devices and the associated elevation of the riverbed, location and elevation of the shoreline, the location and elevation of other instrumentation, as well as the selected markers that identified the fish counting grids. Fish counts were conducted to identify the types and numbers of fish that were present in each grid of the refuge.

The intensive monitoring that occurred at the two sites captured the detail and complexity of the thermal refugia. The Beaver Creek refuge provided habitat for coho, Chinook, and Steelhead, while the Red Cap Creek refuge did not contain coho. Both refugia experienced expansion of the cold-water pool during the night and early morning hours, and a contraction during the afternoon and evening hours. As river and tributary water temperature increased, the lateral (bank-to-bank) size of the refuge decreased as did the difference in water temperature between the river and tributary. Local meteorological conditions influenced water temperatures near the water surface more than they did for water at the bed. However, strong vertical stratification did not occur at either site. Local features, such the backwater pool at the Beaver Creek site, are important to the usefulness of the refuge. Finally, the fish counts were overlain with the recorded temperatures. When river temperatures exceeded 23ºC, the number of fish in each refuge increased.

Future work should include an investigation of tributaries (both the refuge formed at the confluence and upstream in the tributary proper) likely to provide over-summering habitat for coho, as well as other species of salmonids. After identifying those tributaries that form thermal refugia, several temperature devices should be deployed along the longitudinal axis of the stream to identify temperature gradients that may be important to over summering salmonid populations. A means of categorizing and identifying thermal refugia should be identified. This matrix would allow for quick identification of functioning refugia. Some criteria to consider include main stem and tributary flow and temperature, geomorphic conditions, and presence or absence of fish.

MODELING AT A LOCAL LEVEL: A SINGLE THERMAL REFUGE

The water temperature and stage data were used to create a model of the Beaver Creek refuge between the two summer monitoring periods. UnTRIM, an unstructured grid, three-dimensional, semi-implicit, finite-difference hydrodynamic model, was selected (Cheng and Casulli, 2001). The bathymetric survey of the site was converted into an UnTrim grid and the water temperature and stage measurements were used as inputs to the model.

The initial model results showed a drying of the left bank and backwater area. At the time of the model development the stage and channel roughness were altered to avoid drying out the backwater. The backwater area was over-estimated, resulting in to large a volume of water being necessary to keep it wet. A comparison of nine locations in the UnTRIM model grid and the monitoring data indicated that the model was generally within 0.5ºC of the recorded data. The modeled velocity field agreed with observations made at the site (a quantitative comparison was not possible).

Despite the preliminary nature of the model, it did indicate that a more detailed model could be developed (with updated data) to assist in management of the Beaver Creek refuge. However, more detailed bathymetry of the site is needed. An improved grid might reduce the need to modify stage and channel roughness. Also, velocity measurements should be made so a comparison with the model is possible. Only nine locations were selected for comparison; future modeling efforts will need more comparison points.

MODELING AT A REGIONAL LEVEL: A SYSTEM OF THERMAL REFUGIA

If a model of the site, like the preliminary one developed for Beaver Creek, were available managers would be able to determine what the size of the refuge would be for each configuration (geomorphology and flow). If this information were available for all (major) refugia in the system it would be possible to develop an optimization model to assist managers in identifying which refugia are the most critical for migrating salmon populations.

Systems, or optimization, models are used to identify the "best" alternative given the constraints on the system. The most common form of optimization models are linear optimization models where the objective function and constraints are all represented by linear functions (Ford *et al.*, 1962). Water systems can be modeled using network flow with gains, where the system is represented with nodes (representing diversion, return flow points, confluences, various facilities, etc.) and links (canals, pipelines, rivers, etc). Optimization models are being used, but not to the degree of simulation models (Friedman *et al.*, 1984; Rogers and Fiering, 1986; Loucks, 1992; Simonovic, 1992; Labadie, 1997). However, optimization models have the potential to identify promising management options.

While it is important to maximize the benefits of each thermal refuge, it is also important to consider their interactions as a system of refugia. A set of simple system models were developed to represent out-migrating salmons and in-migrating salmons. The models sought to maximize the number of fish reaching the destination (either the estuary or the spawning grounds). Losses due to predations, temperature and other miscellaneous reasons reduced the number of fish reaching the destination. Within each refuge the fish also died due to crowding and over-crowding. To reduce the effects of crowding and over-crowding the model was able to expand the size of the refugia at fixed incremental prices. Expansion was limited by a budget.

Both models are highly simplified representations of a river system and refugia. Upstream migrating fish are assumed to have prefect knowledge of the system and move in a manner that maximizes the number that reaches the destination. The temperature of the thermal refuge is assumed to be that of the tributary, but in reality the thermal refuge is a mixture of the tributary and main stem temperatures. Every fish is assumed to behave in exactly the same manner, and individual fish behavior is not modeled. Users must specify the loss rates and travel parameters (distance, speed, etc.). Finally, fish are assumed to be able to move in one direction (upstream or downstream depending on the model).

Both models share the same representations for flow and temperature, refuge expansion, and crowding losses. Flow and temperature are modeled as simply. The river between the refugia is not modeled. Gains and losses in flow within the reach are modeled as a lumped delivery at each refuge. Temperature is modeled as a fully mixed conservative substance. A delta is used to increase or decrease the water temperature; a substitute for meteorological conditions. For the downstream model, the uniform channel is assumed within each reach and fish are assumed to move at a speed that is some fixed fraction of the water velocity. Expansion of the refugia is assumed to be possible for a pre-specified cost. Each incremental increase in capacity comes at an increasing cost. The over-crowding and crowding losses are represented by 'blocks'. For each capacity block a percentage (increasing) of that block was lost. All fish over the refuge's capacity were lost, plus an additional percentage.

The in-migrating model sought to maximize the number of fish reaching the spawning grounds. Steady state conditions were assumed. Three alternatives were explored: increasing budget, increasing the starting fish stock number, and increasing main stem temperature. The budget controls the amount of expansion that is possible. Unsurprisingly, as the budget increased, more fish were able to make it to the spawning grounds. Likewise, as the starting fish stock number increases, more fish make it to he spawning ground, but at a higher mortality rate. As water temperature increased, mortality increased and fewer fish made it to the spawning grounds.

The out-migrating model sought to maximize the number of fish reaching the estuary. Fish movement was highly constrained and the optimization model was not able to optimize fish movement. Two alternatives were explored: increasing budget and different fish departure schedules with different critical days. Like the in-migrating model, as the budget increased the number of fish reaching the estuary increased. For the different fish distributions, the different critical days impacted the number of fish reaching the estuary. In general, when the peak migration coincided with the critical day, high losses occurred.

Both the in-migrating and out-migrating models are in the preliminary development stages. Future work should include better estimation of the loss rates. For the current examples the loss rates were specified to create a curve that "looked right" but do not contain any scientific basis. Also, a means of modeling the system for all life stages could benefit decision makers. The critical refugia for both life stages could be identified and focused on for enhancement. While rare, it is possible that out-migrating fish and in-migrating could be in the system at the same time, in which case management for both would be necessary.

The out-migrating model deterministically specified fish behavior. All fish behavior in the same manner and no variability for individual fish are allowed. Future work should include a means of allowing for more random fish behavior through the addition of uncertainty in the fish movement. Fish would no longer travel in blocks. Another future modification would be to make a 2-stage linear program to reflect the uncertainty in the start of critical conditions. Decisions would be made to expand some refugia prior to the onset and then emergency modifications could be made in the next stage.

MODELING AT A STATEWIDE LEVEL: ECONOMIC-ENGINEERING EVALUATION OF POSSIBLE SACRAMENTO-SAN JOAQUIN DELTA MANAGEMENT OPTIONS

A system model, like the one created for the state of California, can be used to evaluate how different management options will affect nearby and distant areas. Managers of large projects must consider the impacts that their decision will have on many users. Statewide modeling is less detailed than local modeling.

CALVIN model is a network flow with gains optimization model of California's inter-tied water system. It uses a generalized network flow optimization solver, HEC-PRM to find the least cost solution to specified constraints (HEC, 1991). It includes most of the major reservoirs, facilities, and river, ranging from Shasta reservoir in the north to San Diego in the south. There are 54 economical areas (agricultural and urban), 53 reservoirs, and 31 groundwater basins included in CALVIN.

The Sacramento-San Joaquin Delta is the hub of the State's water resource system, with most of California relying on it, either directly or indirectly, for water. Two of the largest projects (the CVP and SWP) pump water from the Delta for users in the Central Valley and Southern California. Along with being a major hub of California' water supply system, the Delta is also one of the State's most important environmental habitats. Numerous species rely on the Delta to provide habitat and passage. Current management practices in the Delta are not sufficient to balance the demands on and the needs of the Delta (Lund *et al*., 2007).

Three alternatives were evaluated using the CALVIN model: no exports, increased pumping plant capacity, and increased minimum net Delta outflow. When no exports were allows from the Delta for users in the Central Valley, Southern California, and CCWD there were significant increases in scarcity and the associated costs. Outflows from the Delta increased, as did the demand for alternative water technologies (recycling and desalination). Areas that depend on the Delta for water were the hardest hit because they were unable to transfer enough water to meet their demands.

The opposite of eliminating exports is to increase the pumping plant capacities of the State and Federal water projects. When pumping was increase there was a slight reduction in scarcity south of the Delta. Pumping from the Delta did not increase much due to downstream conveyance capacity limitations. Likewise there was a minor decrease in Delta outflows due to increased pumping.

As a means of representing opportunistic pumping the minimum net Delta outflows were systematically increased from the current 5.6 maf/yr to 19.2 maf/yr. As the minimum outflow requirements increased, so did scarcity throughout the State. Unlike when no exports were allowed, when the minimums are increased north of the Delta users also experienced increasing scarcity. Agricultural users saw increased scarcity almost as soon as minimum outflows were increased. Urban users experienced increased scarcity only when the minimums were significantly higher. Those agricultural areas that directly competed with urban users saw the greatest scarcities.

The Delta outflow increased with minimum outflows, through surplus Delta outflows (those above the requirement) decreased. The cost of environmental flows increased as more water was needed for the Delta outflows. There was not much value for expanding reservoirs, but key conveyance facilities showed benefit. Primarily those conveyance facilities that allow additional transfers of water from lower valued to higher valued users would provide the greatest benefit. As in the no export case, urban areas increased their usage of alternative technologies to supplement their water supplies.

CALVIN is useful to highlight those management alternatives that provide the greatest benefit to the State as a whole. However, it cannot model the Delta in great detail. Many of the Delta requirements are complex and ill-suited to network flow optimization. Requirements such as the X2 standard and carriage water are non-linear processes, and cannot be represented in CALVIN. Likewise, the uses of water within the Delta are presented by a single aggregate demand. Future work for modeling Delta alternatives in CALVIN would be to create a finer resolution representation of Delta users and improve representation of key environmental requirements.

CLOSING

The theoretical background for thermal refugia, a form of a mixing zone, was presented, followed by the results from a detailed monitoring study at two sites in the Klamath River. The data from the monitoring was then used to develop a local model of the Beaver Creek refuge using UnTRIM. Then the framework for a system of refugia model that could be used to manage a system of refugia was presented. Finally a statewide model was used to evaluate the effects that different Delta management options would have on water users throughout California.

Westervelt (2001) describes three approaches to modeling: use a theory based-model, use a management model for the specific region, or use a management model with an embedded theory model. UnTRIM, used to model the Beaver Creek refuge, is an example of the theory based-model. It is based on the principles of hydrodynamics and can provide very detailed analysis of the site. It is not, however, designed for the average user. It has significant data requirements and requires use of additional pre- and post-processors to interpret the results.

The system model developed for the Klamath River refugia is an example of the watershed management model that could have an embedded theory model. Fish movement, water flow, and temperature could be molded use theories of fish behavior and hydrodynamics. If these were added then the optimization solver could be wrapped around the theory/simulation and a more robust model would be available.

CALVIN is a generalized network flow optimization model and as such there is no detailed hydrodynamics, water use, environmental response, etc. models within it. The theory could be applied anywhere, but the current application is for California. Like the system model it can be used by decision makers to help manage the California water system.

The type of model selected must be based on the question(s) that need to be answered and the system that is being modeled. Managers should be familiar and comfortable with both simulation and optimization. This will allow them to use a wide range of models, and to use the model that is the most applicable to the situation and conditions being modeled.

As environmental concerns continue to be important to the public, water managers must consider the long- and short-term effects of their decisions. In California, the Klamath River and Sacramento San-Joaquin Delta are examples of environmentally important areas that must balance the needs of water users with the needs of the environment. Managers of these systems need tools to enable them to manage the system in ways that will provide improved benefit at the least costs. Computer models enable managers to evaluate and explore the impacts of changes, both large and small, on their system prior to implementing changes in the field, identify those changes with the most promise, and integrate knowledge of a problem in a way that promotes practical understandings and potential management insights.

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APPENDIX A: ACRONYMS

af – Acre-Feet
AV – Antelope Valley
CALVIN – California Value Integrated Network
CCWD – Contra Costa Water District
CEAM – Center for Exposure Assessment Modeling
cfs – Cubic Feet Per Second
CORMIX – Cornell Mixing Zone Expert System CVP – Central Valley Project
CVPM – Central Valley Production Model
CWR-ELCOM – Centre for Water Research Estuary and Lake Computer Model
DHI – Danish Heritage Institute
DKHW – Davis, Kannberg, Hirst model for Windows
DO – Dissolved Oxygen
EBMUD – East Bay Municipal District
EDFC – Environmental Fluid Dynamics Code
EMWD – Eastern Metropolitan Water District
HEC-PRM – Hydrological Engineering Center – Prescriptive Reservoir Model
HSCTM-2D – Hydrodynamic, Sediment and Contaminant Transport Model
HSPF – Hydrological Simulation Program
LP – Linear Program
maf – Million Acre-Feet
MWD – Metropolitan Water District
NDO – Net Delta Outflows
NPDES – National Pollutant Discharge Elimination System
NRC – Natural Resource Council
PDE – Partial Differential Equations
PDSW – Prych, Davis, Shirazi Model for Windows
RH – Relative Humidity
RMA – Resource Management Associates
RSB – Roberts, Snyder, and Baumgartner Model
SB-SLO – Santa Barbara-San Luis Obispo
SBV – San Bernardino Valley
SCVWD – Santa Clara Valley Water District
SFPUC – San Francisco Public Utilities Commission
Si3D – Semi-Implicit 3D
SMS – Surface Water Modeling System
SWAP – Statewide Agricultural Production Model

SWP – State Water Project
taf – Thousand Acre-Feet
UM – Updated Merge Model
UnTRIM – Unstructured Grid Tidal, Residual, Inter-Tidal Mudflat
USGS – United States Geological Survey
VP – Visual Plumes
VSW – Very Shallow Water Model
WASP – Water Quality Analysis Simulation Program

APPENDIX B: MIXING ZONE MODELS

The available and applicable models can be generally broken down into two categories: dilution models and hydrodynamic models. Sprinkled throughout the literature discussing mixing zone modeling are references to a number of models. The majority of the models discussed for mixing zone analysis tend to be dilution models, through there a few hydrodynamic models that have mixing zone modeling capabilities or sub-models. The main focus of this investigation is on the mixing zone models (dilution models); thus only a brief mention of the more complex hydrodynamic models will be included.

A total of 9 models or modeling suites were reviewed. Five other models were preliminarily reviewed, but dismissed before a detailed review occurred. CE-RIV1, HSPF (Hydrological Simulation Program), and QUAL2E/QUAL2K are one-dimensional models, meaning that only linear variability is accounted for. A minimum of two-dimensions (linear (x) and lateral (y)) is necessary to represent the mixing zone. Likewise, CE-QUAL-W2 despite being a two-dimensional model (depth (z) and linear (x)) is laterally averaged. Additionally, SWMS (Surface Water Modeling System) is an entire modeling environment and the hydrodynamic and water quality models within it are RMA 2, 10, and 11. Therefore it is not discussed separately.

3-Dimensional Hydrodynamic Models

There are a number of 3-dimensional hydrodynamic models available that are capable of modeling the mixing zone. Eight models (or modeling suites) were briefly investigated to determine their applicability to modeling mixing zones. Table 1 presents a list of the model (or suite), where they are available from (or if distributed by multiple vendors, who is developing the model), and if the model is actively supported.

Model Name	Number[1] of Dimensions	Open Source Code[2]	Cost[3]	Support	Available From or Developed By
CWR-ELCOM	X,Y,Z	Yes	Yes	Yes	University of Western Australia[4]
EDFC/WASP	X,Y,Z	-	No	Limited	EPA[6]
HSCTM-2D[7]	X,Y	-	No	Limited	EPA[6]
MIKE3/MIKE11	X,Y,Z	No	Yes	Yes	DHI Software[4]
RMA2/RMA10/RMA11	X,Y,Z	Yes	Yes	Yes	Boss International[6]
Si3D	-	-	-	-	Dr. Peter Smith, USGS[4]
UnTRIM	X,Y,Z	No	Yes	Yes	Prof. Vincenzo Casulli, Trento University[4]

[1] X,Y,Z represent longitudinal, lateral, and vertical dimensions, respectively.
[2] Open source code refers to non-proprietary model codes.
[3] License fee. Current costs must be requested from the model owner.
[4] Developed by, Maintained by, and Distributed by
[5] Developed by, Maintained by
[6] Distributed by
[7] The model is capable of representing the fate of contaminants in a water body, but representation of the mixing zone (or zones of dilution) is not a primary function of the model.

Three-dimensional models also tend to be more complex than dilution models and require some dedication to learn to properly implement. The eight models in Table 1 are discussed briefly below.

CWR-ELCOM

CWR-ELCOM (Centre for Water Research Estuary and Lake Computer Model) "solves the unsteady shallow water equations with modules for heat and momentum transfer across the water surface due to wind and atmospheric thermodynamics" (CWR, 2005a). It is a three-dimensional model. It can be coupled with another model to estimate biological and chemical processes. It is capable of handling wetting and drying of cells during a model run, using the principles developed for the UnTRIM model (Hodges, 2000).

CWR-ELCOM is a proprietary model, distributed by the Centre for Water Research at the University of Western Australia for an unspecified fee. There are pre- and post-processors are available to assist users in setting up and analyzing a model run. A user's manual and technical documentation is available for download prior to purchase of the model.

Applications of CWR-ELCOM appear to be limited. The authors of the model present a few applications, mainly focusing on lakes (and internal processes associated with changes in ambient conditions). In general it appears that CWR-ELCOM has been applied for academic research opposed to regulatory decision making. Applications have been primarily limited to peer-reviewed research articles and conference papers (CWR, 2005b).

EDFC/WASP

EFDC (Environmental Fluid Dynamics Code) is a "hydrodynamic model that can be used to simulate aquatic systems in one, two, and three dimensions. ... It solves three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable-density fluid. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The EFDC model allows for drying and wetting in shallow areas by a mass conservation scheme" (EPA, 2005a).

EDFC is a hydrodynamic model and by itself it does not have the capability to model water quality. Water quality can be modeled in two methods: by coupling EDFC with 1) EPA's WASP (Water Quality Analysis Simulation Program) model or EPA's JPEDFC. WASP (or WASP6, the updated version) "predict[s] water quality responses to natural phenomena and manmade pollution for various pollution management decisions. . . The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model" (EPA, 2005b). JPEDFC is a sub-model directly incorporated into EDFC and is capable of modeling buoyant jets in the near-field (EPA, 1999).

EDFC and WASP6 are available from the EPA for free via their website. However, at present, there is no graphical user interface (GUI) for EDFC, pre- or post-processors are available to assist users in setting up and analyzing a model run from EDFC. There are pre- and post-processors available for WASP to assist in setting up the data and comparing model results with field data. There are user manuals available for download for both models.

EDFC/WASP can be used for National Pollutant Discharge Elimination System (NPDES) permits. Generally WASP is used to model conventional pollutants (nitrogen, phosphorus, dissolved oxygen, BOD, sediment oxygen demand, algae and periphyton), organic chemicals, metals, mercury, pathogens, and temperature is lakes, rivers, streams and estuaries. WASP can be coupled with EDFC to dynamically model velocity and flow depths. WASP has been used to model eutrophication, phosphorus loading, and PCB, volatile organic, heavy metal, and mercury pollution in water bodies. The majority of the applications have been on the East coast (EPA, 2005c). Published literature on applications is limited to earlier versions of WASP (primarily used in the 1980's). EDFC has been applied to rivers, lakes, estuaries, and lagoons throughout the Eastern U.S. and in a few instances on the West Coast (Los Angeles and Lower Duwamish Waterway) (EPA, 2005c).

HSCTM-2D

HSCTM-2D (Hydrodynamic, Sediment and Contaminant Transport Model) "is a finite element modeling system for simulating two-dimensional, vertically-integrated, surface water flow (typically riverine or estuarine hydrodynamics), sediment transport, and contaminant transport. The modeling system consists of two modules, one for hydrodynamic modeling (HYDRO2D) and the other for sediment and contaminant transport modeling (CS2D). . . . HYDRO2D solves the equations of motion and continuity for nodal depth-averaged horizontal velocity components and flow depths. . . . CS2D solves the advection-dispersion equation for nodal vertically-integrated concentrations of suspended sediment, dissolved and sorbed contaminants, and bed surface elevations" (Hayter *et al.*, 1995, pg. iv).

HSCTM-2D is available from the EPA Center for Exposure Assessment Modeling (CEAM) for free via their website. There is a user manual available for download as well.

HSCTM-2D is capable of modeling contaminant distribution and fate in a water column, but the primary application of the model appears to be in modeling sediment transport. The user's manual includes an example problem concerning the tidal flow and sediment transport in Winyah Bay, South Carolina (Hayter *et al.*, 1995). HSCTM-2D has not been used in the regulatory NPDES permitting process.

MIKE3/MIKE11

The MIKE models are a family of water resources models created and distributed by DHI. "MIKE 3 simulates unsteady flow taking into account density variations, bathymetry and external forcing such as meteorology, tidal elevations, currents and other hydrographic conditions" (DHI, 2005a). It is capable of three-dimensional representation of rivers, lakes, and estuaries. Like other DHI models it is able to model wetting and drying of cells during a model run (DHI, 2005b).

MIKE 11 is can be used to model conditions (such as water quality) in lakes, rivers, canals, and other water systems. It "contains an implicit, finite difference computation of unsteady flows in rivers and estuaries" (DHI, 2005c). Both MIKE 3 and MIKE 11 are proprietary, closed-source code models available from DHI for a fee. Both models have graphical user interfaces (GUI), and pre- and post-processors available to assist users in setting up and analyzing a model run. User's manuals and technical documentation is available.

MIKE 3 is applicable for situations where three-dimensional representation are important, these include tidal areas, stratified flows, water pollution studies, and environmental impact assessment studies (DHI, 2005a). MIKE 11 is primarily used for flood modeling, but it can be used to model water quality in rivers as well (DHI, 2006).

RMA2/RMA10/RMA11

RMA (Resource Management Associates) 2, RMA 10, and RMA 11 are a set of hydrodynamic (RMA 2 and RMA 10) and water quality models (RMA 11). "RMA2 is a two dimensional depth averaged finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two dimensional flow fields. RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed" (Boss Int., 2005a).

"RMA10 is a multi-dimensional (combining 1-D, 2-D either depth or laterally averaged, and 3-D elements) finite element numerical model written in FORTRAN-77. It is capable of steady or dynamic simulation of three dimensional hydrodynamics, salinity, and sediment transport. It utilizes an unstructured grid and uses a Galerkin based finite element numerical scheme" (Boss Int., 2005b).

"RMA11 is a finite element water quality model for simulation of three-dimensional estuaries, bays, lakes and rivers. It is also capable of simulating one and two-dimensional approximations to systems either separately or in combined form. It is designed to accept input of velocities and depths, either from an ASCII data file or from binary results files produced by the two-dimensional hydrodynamic model, RMA2, or the three-dimensional stratified flow model, RMA10. Results in the form of velocities and depth from the hydrodynamic models are used in the solution of the advection diffusion constituent transport equations" (Boss Int., 2005c).

All three RMA models are proprietary software, available from Boss International or the original model developer. From Boss International a single user license for RMA 2 costs

$1,500, for RMA 10 costs $3,000, and for RMA 11 costs $2,500 (before tax). All three models have graphical user interfaces (GUI), and pre- and post-processors are available to assist users in setting up and analyzing a model run. User's manuals and technical documentation is available.

SI3D

Si3D (Semi-Implicit 3D) is a three-dimensional model developed by Dr. Peter Smith at the USGS.

UnTRIM

UnTRIM (Unstructured Grid Tidal, Residual, Inter-Tidal Mudflat) model is an "semi-implicit finite difference (-volume) model based on the three-dimensional shallow water equations as well as on the three-dimensional transport equation for salt, heat, dissolved matter and suspended sediments" (BAW, 2005) developed by Casulli at the Trento University in Italy.

It is a proprietary, closed source code model, available from the developer for a fee. Additional tools are needed to create the input files for a model run, and it not clear if these are included as part of the UnTRIM package or must be developed by each. User's manuals and technical documentation is available and the theoretical background of the model was been presented in numerous journal articles.

UnTRIM is typically used to model flow and circulation in shallow water bodies, such as estuaries, lakes and river systems. UnTRIM has been applied in studies of the San Francisco Bay (Cheng *et al.*, 1993; Cheng and Casulli, 2001), Big Lost River in Illinois (Casulli and Walters, 2000) and the Klamath River (Cheng, 2004).

Dilution Models

In many cases where mixing zone modeling studies have occurred for the purposes of obtaining a NPDES permit, a dilution model has been employed. Currently there are two dilution model suites in wide spread use: CORMIX and Visual Plumes. There are others, such as JETLAG and RIVPLUM5, but their use is not as common, and as such discussion of them will be limited. Table 2 presents a list of the modeling suites, where they are available from (or if distributed by multiple vendors, who is developing the model), and if the model is actively supported.

Model Name	Number[1] of Dimensions	Open Source Code[2]	Cost[3]	Support	Available From or Developed By
CORMIX	X,Y	No	Yes	Yes	MixZon Inc.[4]
PLUMES/Visual Plumes	X,Y	No	No	Limited	EPA[5]

[1] X,Y,Z represent longitudinal, lateral, and vertical dimensions, respectively.
[2] Open source code refers to non-proprietary model codes.
[3] License fee. Current costs must be requested from the model owner.
[4] Developed by, Maintained by, and Distributed by

[5] Developed by, Maintained by

CORMIX and Visual Plumes are both considered modeling suites and have multiple sub-models within their framework to model a variety of conditions. Dilution models are generally simpler then 3-dimensional hydrodynamic models, both in terms of ease of use and data requirements. However, their representation of the hydrodynamic processes is also significantly simpler and the output is much less detailed than it would be if a fully 3-dimensional model were used. Both models are essentially length scale models.

CORMIX

CORMIX (Cornell Mixing Zone Expert System) is a plume modeling suite, composed of five sub-models (sub-modules): CORMIX1, CORMIX2, CORMIX3, CORJET, and FFLOCATR. There is also a graphical utility (CMXGRAPH). The original version of CORMIX did not contain all the sub-modules, but over time the sub-models have been developed to increase the flexibility and capabilities of the modeling suite.

- CORMIX1 – Steady-state, buoyant discharges from a submerged single port discharge location into flowing, density-stratified waters.
- CORMIX2 – Steady-state, buoyant discharges from a submerged multi-port discharge location into flowing, density-stratified waters.
- CORMIX3 – Steady-state discharges from a surface single port discharge location into flowing, homogeneous, density-stratified waters.
- CORJET – Near-field model of a single port buoyant jet.
- FFLOCATR – Far-field locator model.

The CORMIX1, CORMIX2, and CORMIX3 use the "hydrodynamic equations governing the conservation of mass and momentum" (CORMIX, 2005a) to estimate the mixing zone effects of a point source wastewater discharge into lakes, rivers, and estuaries. CORMIX is a two-dimensional (linear (x) and lateral (y)) model, with some capabilities to model buoyancy driven vertical processes. The model is capable of modeling dilution and decay of various constituents in wastewater discharges.

Built into CORMIX is a discharge classification system to determine the behavior of the plume. Based on user input, a variety of length scales are computed (Donekar, 2005). With the known length scales, the flow classification is selected. From that, the modeling suite can provide the user with some basic qualitative information about the behavior of that type of plume as well as the quantitative results.

CORMIX is a proprietary model. There is a graphical user interface (GUI), and pre- and post-processors are available to assist users in setting up and analyzing a model run. A user's manual and technical documentation is available for download prior to purchase of the model. A single computer license of CORMIX is approximately $4,000 (before tax) (as of March 2005).

PLUMES/Visual Plumes

Visual Plumes (VP), the successor to the DOS based PLUMES model, "is a mixing zone modeling system . . . that simulates single and merging submerged plumes in arbitrarily stratified ambient flow and buoyant surface discharges" (Frick *et al*., 2001, pg. iii). VP contains five different models within its framework: DKHW, UM3, PDSW FRFIELD/NRFIELD, and DOS PLUMES.

DOS PLUMES was essentially an interface that enabled a user to create and run the RSB (Roberts, Snyder, and Baumgartner) and UM (Updated Merge) models. It has been retained so that users familiar with DOS PLUMES can import existing studies into the new framework.

A history of the UM3 model is provided in Frick *et al*. (2001). Briefly, in 1976 a cooling tower plume model was developed for the EPA. It was later modified to be applicable to marine waters (OUTPLM). The marine model was further refined to become the MERGE model in 1980. Five years later, MERGE was replaced by UMERGE and UOUTPLM. The UMERGE was the freshwater version of MERGE, while UOUTPLM was the marine application. In 1994 the UM model (the updated form of the MERGE model) was included in the DOS PLUMES modeling suite. UM uses a Lagarian formulation and the projected area entrainment hypothesis (Frick, 1984) to solve for plume conditions in the near-field (EPA, 1999). The UM model is capable of representing single and multi-port discharges. VSW (Very Shallow Water) is a special configuration of the UM model designed for discharges into shallow waters. For Visual Plumes, the UM model was extended to be able to represent three dimensions and the name was changed to UM3. UM3 uses a Lagrangian approach with time as the independent variable to determine the size, shape and trajectory of the plume.

Originally developed as part of a trio of models, ULINE the immediate predecessor to RSB, was only capable of modeling a single port discharge into un-stratified waters (Frick *et al*., 2001). In 1994, the RSB model (the updated form of ULINE) was included with DOS PLUMES. RSB "is a semi-empirical model based on the principles of dynamic similitude and dimensional analysis applied to an extensive set of laboratory and field observations of multi-port discharge behavior" (EPA, 1999, pg. I.3-16). For Visual Plumes, RSB was split into two models: FRFIELD and NRFIELD. FRFIELD and NRFIELD are used to create estimates of the "distribution of pollutants in the vicinity of the outfall" (Frick *et al*., 2001, pg. 1.5). The NRFIELD (Near Field) component is used for modeling the "near-field" or "short-term" effects, while the FRFIELD (Far Field) component is used for modeling the "far-field" or "long-term" effects.

DKHW (Davis, Kannberg, Hirst model for Windows) model, the most recent version of the UDKHDEN model, is another three-dimensional flow model (like UM3). Both models can be used to simulate single and multi-port submerged discharges. DKHW uses an Eulerian approach which uses distance as the independent variable to determine the size, shape, and trajectory of the plume.

PDSW (Prych, Davis, Shirazi model for Windows) "is a three-dimensional plume model that applies to discharges to water bodies from tributary channels . . . [and] provides simulations for temperature and dilution over a wide range of discharge conditions . . . [PDSW] calculates plume trajectory, average and centerline dilution, plume width and depth and centerline excess temperature." (Frick *et al.*, 2001, pg. 1.4-1.5).

VP is available from the EPA Center for Exposure Assessment Modeling (CEAM) for free via their website. There is a user manual available for download as well.

JetLag and RivPLUM5

JetLag and RivPLUM5 are two other dilution models. RivPLUM5 is a spreadsheet application that "is a one-dimensional model that calculates dilution at a specified point of interest downstream in a river" (DOE, 2000, pg. 24). As it is one dimensional (longitudinal), RivPLUM5 is only applicable for conditions where the discharge is thoroughly mixed throughout the vertical and lateral water column.

JetLag, like UM3, uses a Langarian formulation to predict the mixing of buoyant jets in three-dimensions. The model "does not . . . solve the usual Eulerian governing differential equations of fluid motion and mass transport. Instead, the model simulates the key physical processes expressed by the governing equations" (Lee *et al.*, 2006, pg. 2). Like UM3, JetLag uses the projected-area-entrainment hypothesis. While it does appear that JetLag could be used to model mixing zones for NPDES permits, it has not been used before nor has it been identified by the EPA as a recommended model.

Summary of Mixing Zone Models

Seven hydrodynamic models and two dilutions model were presented above. The hydrodynamic models were two- or three-dimensional, while the dilution models were generally mixing length models. For most mixing zone problems, the EPA generally recommends the use of dilution models such as CORMIX and VP. These models are relatively use-friendly, with limited input data requirements. However, for highly complex systems the assumptions made for dilution modeling can significantly impact the results. When selecting a model it must be decided how much detail (spatial, temporal, and accuracy) is required in the output, what the input data limits are, and how easy is it to use the model. Dilution models general have the least data input requirements and are the most user-friendly, but they also have a low-level of detail. Hydrodynamic models generally have significant input data requirements and are not user-friendly, but the results are much more detailed.

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APPENDIX C: SYSTEM MODELS DETAILS

LOSS RATES

The user needs to specify the reach predation, temperature and miscellaneous loss rates, as well as the refuge predation, temperature, and crowding loss rates.

- The predation loss rates should be based on the number of fish that are eaten (including those eaten by other fish) and caught (by fisher-people). It is the same for both in the main stem and the refuge.

- The temperature loss rates should be based on the relative tolerance the fish has for different water temperatures. There is no time component to either model, so long-term or average temperature tolerances would be the most applicable. It is the same for both in the main stem and the refuge.

- Miscellaneous loss rates represent those fish that are swept by or for any other reason do not enter the current refuge. These fish die and as such this loss rate should be based on the number of fish that are observed downstream of the refugia.

- Crowding loss rates are based on the number of fish that die due to fish density in the refuge. As the refuge because more crowded the loss rate increases due to the increased likelihood of disease, parasites, stress, degradation of habitat, competition for food, etc.

In general the loss rate should be based on field observation and the published literature. The loss rates used in the example (Chapter 5) were fictitious and used for example purposes only.

VARIABLE DEFINITIONS

This section contains a list of the variables used in the system models presented in Chapter 5: Modeling at a Regional Level: A System of Thermal Refugia.

$A_{j,j+1}$ = average cross sectional area between refuge *j* and refuge *j + 1*

B = total budget

C = refuge formed at confluence of tributary with spawning ground *i*

$C_{j,z}$ = cost of expanding capacity of refuge *j* to the *z*-th segment

$CB_{j,b}$ = number of fish in crowding block *b* of refuge *j*

$CB_{j,oc}$ = number of fish in over-capacity block *b* of refuge *j*

$E_{j,z}$ = maximum expansion capacity of refuge *j* in the *z*-th segment

EF_i = total number of fish that emerge from the gravels of spawning ground *i*

FI_j = total fish moving into refuge *j*

$FL_{i,t}$ = fish leaving spawning ground *i* in time *t*

FO_{j_k} = fish moving from refuge *j* to refuge *k*

$FR_{i,estuary}$ = fish reaching the estuary from spawning ground *i*.

$FRPC_{estuary}$ = number of fish reaching the estuary before critical condition

$FRR_{i,j,t}$ = fish reaching refuge *j* from spawning ground *i* in time *t*

FS_j = total number of fish leaving refuge *j*

FSC_j = fish surviving crowding in refuge *j*

$h_{j,z}$ = cost slope of expanding refuge *j* in the *z*-th segment

LC_j = capacity/crowding loss rate in refuge *j*

$LDT_{T,ET}$ = water temperature and exposure time loss rate

$LM_{j,j+1}$ = miscellaneous loss rate from refuge *j* to refuge $j + 1$

$LMSG_i$ = miscellaneous loss rate from spawning ground *i* to the confluence *C*

$LP_{j,j+1}$ = predation loss rate from refuge *j* to refuge $j + 1$

LP_j = predation loss rate in refuge *j*

$LPSG_i$ = predation loss rate from spawning ground *i* to the confluence *C*

LT_j = water temperature loss rate in refuge *j*

$M_{j,z}$ = fish capacity of refuge *j* at the *z*-th segment

$M_{j,0}$ = initial capacity of refuge *j*

OC_j = number of fish over-capacity in refuge *j*

P_j = predation loss rate in refuge *j*

$Q_{j-1,j}$ = flow from refuge *j – 1* to refuge *j*

$Q_{j,j+1}$ = flow from refuge *j* to refuge *j + 1*

Q_{Mj} = flow from miscellaneous gains/losses into refuge *j*

Q_{Tj} = flow from tributary into refuge *j*

SD_{a_j} = survival rate from travel distance between refuge *a* and refuge *j*

SP_{a_j} = survival rate from predation between refuge *a* and refuge *j*

$SR_{i,t,j}$ = survival rate of fish leaving spawning ground *i* in time *t* to refuge *j*

$SRP_{i,j}$ = survival rate from spawning ground *i* to refuge *j*

$SRPE_{j,est}$ = survival rate from refuge *j* to the estuary

ST_{a_j} = survival rate from temperature between refuge *a* and refuge *j*

$T_{j-1,j}$ = temperature of water entering refuge *j* from refuge *j - 1*

$T_{j,j+1}$ = temperature of water leaving refuge *j* for refuge *j + 1*

T_j = temperature loss rate in refuge *j*

TC = time step when conditions become critical

$TC_{j,max}$ = maximum capacity of refuge *j*

TC_j = total cost of expanding refuge *j*

$TD_{j,j+1}$ = distance between refuge *j* and refuge *j + 1*

TE_j = total capacity of refuge *j* after expansion

T_{Mj} = temperature of miscellaneous gains/losses flow into refuge *j*

T_{Tj} = temperature of tributary flow into refuge *j*

$TT_{i,j}$ = travel time from spawning ground *i* to refuge *j*

$TTR_{j,j+1}$ = travel time between refuge *j* and refuge *j + 1*

$TTSG_{i}$ = travel time from spawning ground *i* to the confluence *C*

$V_{j,j+1}$ = velocity of flow from refuge *j* to refuge *j + 1*

$\alpha_{j,j+1}$ = fish velocity scaling factor between refuge *j* and refuge *j + 1*

$\beta_{i,t}$ = percent of emergent fish leaving spawning ground *i* at time step *t*

$\gamma_{j,b}$ = survival rate associated with crowding block *b* of refuge *j*

$\gamma_{j,oc}$ = loss rate associated with over-crowding in refuge *j*

$\theta_{j,b}$ = percent of total capacity of crowding block *b* for refuge *j*

$\lambda_{j,j+1}$ = water temperature scaling factor between refuge *j* and refuge *j + 1*

ϕ_{i} = percent of emergent fish remaining in spawning ground *i*

DATA USED FOR SYSTEM MODEL EXAMPLES

This section contains the data used to create the examples discussed in Chapter 5: Modeling at a Regional Level: A System of Thermal Refugia.

Common Variables

The flow and temperature values and the capacity expansion (economic) variables are the same between both models. These common variables/values are presented below.

Flow and Temperature

The values needed for the flow and temperature model are presented in Table 32. The values in italics represent user specified numbers, while the non-italic numbers are calculated by the model.

Table 32. Tributary and Miscellaneous Flow and Temperature Values.

			Refuge					
			j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
Tributary Flow	cfs	Q_{Tj}	50	25	30	15	15	15
Tributary Temperature	°C	T_{Tj}	21	15	23	15	15	15
Miscellaneous Flow	cfs	Q_{Mj}	5	0	10	15	15	15
Miscellaneous Temperature	°C	T_{Mj}	20	20	20	20	20	20
Heat Scalar	-	$\lambda_{j,j+1}$	1.020	1.050	1.025	1.020	1.000	1.000

In addition the initial flow and temperature into the first refuge from upstream must be specified by the user (Table 33). The heat scalars used for each reach must also be specified.

Table 33. Initial Flow Conditions.

Main Stem Flow	cfs	$Q_{0,1}$	800
Main Stem Temperature	°C	$T_{0,1}$	22

With these values known the flow and temperature in each reach of the main stem can be determined (Table 34).

Table 34. Main Stem Flow and Temperature.

			Refuge						
			j = 0	j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
Flow	cfs	$Q_{j,j+1}$	800	855	880	920	950	980	1010
Temp	°C	$T_{j,j+1}$	22	21.9	22.2	23.2	23.6	23.9	23.7

Refuge Capacity Expansion and Associated Costs

Each refuge has a starting capacity and a maximum possible expanded capacity limit (Table 35). For each refuge there are expansion intervals, each assigned an upper and lower bound and an associated cost (Table 36). From that the unit cost of expansion can be determined (Table 37).

Table 35. Starting and Maximum Capacity for Each Refuge.

			Refuge					
			j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
Starting Capacity	#	$M_{j,0}$	50	75	25	100	15	125
Maximum Expanded Capacity	#	$TC_{j,max}$	125	150	100	175	75	200

Table 36. Capacity and Cost of Expansion for Each Refuge.

	Refuge 1		Refuge 2		Refuge 2		Refuge 4		Refuge 5		Refuge 6	
	Size	Cost	Size	Cost	Size	Cost	Size	Cost	Size	Cost	Size	Cost
Interval	$M_{1,z}$	$C_{1,z}$	$M_{2,z}$	$C_{2,z}$	$M_{3,z}$	$C_{3,z}$	$M_{4,z}$	$C_{4,z}$	$M_{5,z}$	$C_{5,z}$	$M_{6,z}$	$C_{6,z}$
z = 1	50	0	75	0	25	0	100	0	15	0	125	0
z = 2	75	2500	100	4500	50	2500	125	7000	30	2500	150	10000
z = 3	100	7500	125	12500	75	7500	150	17500	50	7500	175	22500
z = 4	125	25000	150	27500	100	17500	175	37500	75	15000	200	40000

Table 37. Unit Cost of Expansion for Each Interval and Refuge.

	Refuge					
	j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
$h_{j,1}$	100	180	1.0	280	170	400
$h_{j,2}$	200	320	2.0	420	250	500
$h_{j,3}$	700	600	4.0	800	300	700

The total budget for expansion is B = $1,000K. (Note that for the alternatives where the budget changes, the value B changes.)

In-Migrating Model Example

The values presented in this section were used for the example model presented in the In-Migrating Section of Chapter 5.

Flow and Temperature Model

The in-migrating model uses the data in Table 32 and Table 33 to determine the temperature in each reach of the river. Table 38 contains the flow and river temperatures when the initial temperature was 20°C (note that the river temperatures change as the starting temperature changes).

Table 38. Main Stem Flow and Temperature.

	Temperature	Flow
Reach	°C	cfs
j = 7 (sg)	800	20.0
j = 6	830	19.9
j = 5	860	19.8
j = 4	890	19.7
j = 3	920	19.7
j = 2	960	19.8
j = 1	985	19.7

Loss Rates

There are loss rates associated with the water temperature (Table 39), predation (Table 40), and distance (Table 41) for the river. There are also loss rates associated with water temperature (Table 42), predation (Table 43), and crowding (Table 44).

Table 39. Reach Water Temperature Loss Rates.

Water Temperature (°C)	Loss Rate (LT_T)
30	*0.99*
29	*0.98*
28	*0.97*
27	*0.9*
26	*0.75*
25	*0.5*

24	*0.25*
23	*0.15*
22	*0.1*
21	*0.075*
20	*0.05*
19	*0.025*
18	*0.01*
17	*0.005*
16	*0*
15	*0*

Table 40. Reach Predation Loss Rates.

Reach	Loss Rate ($LP_{j,j+1}$)
j = 0	*0.025*
j = 1	*0.05*
j = 2	*0.025*
j = 3	*0.01*
j = 4	*0.025*
j = 5	*0.01*
j = 6	*0.01*

Table 41. Loss Rate Due to Distance.

	Starting Location							
	E (0)	**1**	**2**	**3**	**4**	**5**	**6**	**SG (7)**
E (0)	-	*1*	*1*	*1*	*1*	*1*	*1*	*1*
1	*0.01*	-	*1*	*1*	*1*	*1*	*1*	*1*
2	*0.05*	*0.01*	-	*1*	*1*	*1*	*1*	*1*
3	*0.1*	*0.05*	*0.01*	-	*1*	*1*	*1*	*1*
4	*0.3*	*0.1*	*0.05*	*0.01*	-	*1*	*1*	*1*
5	*0.65*	*0.3*	*0.1*	*0.05*	*0.01*	-	*1*	*1*
6	*0.85*	*0.65*	*0.3*	*0.1*	*0.05*	*0.01*	-	*1*
SG (7)	*1*	*0.85*	*0.65*	*0.3*	*0.1*	*0.05*	*0.01*	-

Table 42. In Refuge Water Temperature Loss Rates.

Water Temperature (°C)	Loss Rate (LT_T)
30	*0.99*
29	*0.98*
28	*0.97*
27	*0.95*
26	*0.9*
25	*0.75*
24	*0.5*
23	*0.25*
22	*0.15*
21	*0.125*
20	*0.1*
19	*0.075*

18	*0.05*
17	*0.025*
16	*0.01*
15	*0.005*
14	*0.001*
13	*0*

Table 43. In Refuge Predation Loss Rates.

Refuge	Loss Rate (LP_j)
j = 1	*0.05*
j = 2	*0.1*
j = 3	*0.05*
j = 4	*0.15*
j = 5	*0.05*
j = 6	*0.025*

Table 44. Survival Rates Due to Crowding.

% Capacity		Survival Rate
< 25%	γ_1	*1.000*
25% ≤ X < 50%	γ_2	*0.990*
50% ≤ X < 75%	γ_3	*0.980*
75% ≤ X ≤ 100%	γ_4	*0.950*
100% < X	γ_{oc}	*0.150**

* Loss Rate

Out-Migrating Model Example

The values presented in this section were used for the example model presented in the Out-Migrating Section of Chapter 5.

Flow and Temperature Model

In addition to the values in Table 32 and Table 33 the out-migrating model needs additional information (i.e., the average channel cross-sectional area, distance between refuges, and velocity scalars) (Table 45). With this information the velocity, travel times and conditions in each reach can be determined.

Table 45. Main Stem Flow, Temperature, and Other Values.

			Refuge						
			j = 0	j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
Area	ft^2	$A_{j,j+1}$	-	*500*	*400*	*475*	*500*	*500*	*500*
Distance	mi	$TD_{j,j+1}$	-	*20*	*30*	*15*	*25*	*15*	*10*
Flow	cfs	$Q_{j,j+1}$	*800*	855	880	920	950	980	1010
Velocity	ft/s	$V_{j,j+1}$	-	1.71	2.20	1.94	1.90	1.96	2.02
Velocity Scalar	–	$\alpha_{j,j+1}$	-	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*	*0.25*
Travel Time	day	$TTR_{j,j+1}$	-	2.9	3.3	1.9	3.2	1.9	1.2
Temp	°C	$T_{j,j+1}$	*22*	21.9	22.2	23.2	23.6	23.9	23.7

Travel Times

Likewise the travel times from the spawning grounds to the confluence with the main stem must be specified (Table 46).

Table 46. Travel Time and Confluence for Each Spawning Ground.

			Spawning Ground		
			i = 1	I = 2	i = 3
Travel Time	Day	$TTSG_i$	*1*	*2*	*3*
Confluence	-	C	*1*	*1*	*3*

With the flow rates and velocities known, the travel time in each reach can be determined (Table 47).

Table 47. Travel Time from Spawning Ground to Each Refuge.

		Spawning Ground		
		i = 1	I = 2	i = 3
Refuge	j = 1	1.0	2.0	0.0
	j = 2	3.9	4.9	0.0
	j = 3	7.2	8.2	3.0
	j = 4	9.1	10.1	4.9
	j = 5	12.3	13.3	8.1
	j = 6	14.2	15.2	10.0
	estuary	15.4	16.4	11.2

Emergent Fish and Distributions

Table 48 present the emergent fish and fish distribution information.

Table 48. Number of Emergent Fish and Percent Leaving and Staying.

		Spawning Ground		
		i = 1	i = 2	i = 3
Number of Emergent Fish	EF_i	*500*	*800*	*1000*
Sum of Percents of Fish Leaving	$\Sigma\beta_i$	0.78	0.78	0.78
Percent of Fish Remaining	φ_i	0.23	0.23	0.23

The percent of emergent fish that leaving each spawning ground at time *t* is presented in Table 49 and Table 50, number of emergent fish that leave is presented in Table 51 and Table 52.

Table 49. Percent of Emergent Fish that Leave at Time *t* from Each Spawning Ground (time 0 through 9).

t	0	1	2	3	4	5	6	7	8	9
$\beta_{1,t}$	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.050*	*0.050*	*0.075*
$\beta_{2,t}$	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.050*	*0.050*	*0.075*
$\beta_{3,t}$	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.025*	*0.050*	*0.050*	*0.075*

Table 50. Percent of Emergent Fish that Leave at Time *t* from Each Spawning Ground (time 10 through 16).

t	10	11	12	13	14	15	16
$\beta_{1,t}$	*0.075*	*0.100*	*0.100*	*0.075*	*0.050*	*0.025*	*0.000*
$\beta_{2,t}$	*0.075*	*0.100*	*0.100*	*0.075*	*0.050*	*0.025*	*0.000*
$\beta_{3,t}$	*0.075*	*0.100*	*0.100*	*0.075*	*0.050*	*0.025*	*0.000*

Table 51. Number of Emergent Fish that Leave at Time t from Each Spawning Ground (time 0 through 9).

t	0	1	2	3	4	5	6	7	8	9
$FL_{1,t}$	12.5	12.5	12.5	12.5	12.5	12.5	12.5	25	25	37.5
$FL_{2,t}$	20	20	20	20	20	20	20	40	40	60
$FL_{3,t}$	25	25	25	25	25	25	25	50	50	75

Table 52. Number of Emergent Fish that Leave at Time t from Each Spawning Ground (time 0 through 9).

t	10	11	12	13	14	15	16
$FL_{1,t}$	37.5	50	50	37.5	25	12.5	0
$FL_{2,t}$	60	80	80	60	40	20	0
$FL_{3,t}$	75	100	100	75	50	25	0

Loss Rates

Loss rates need to be specified. Table 53 presents the loss rates from the spawning ground to the confluence due to predation and miscellaneous other reasons.

Table 53. Spawning Ground Loss Rates.

		Spawning Ground		
		i = 1	i = 2	i = 3
Predation	$LPSG_i$	*0.050*	*0.100*	*0.025*
Other	$LMSG_i$	*0.050*	*0.050*	*0.050*

Table 54 presents the loss rates associated with each main stem reach that are independent of the conditions in the river (i.e., not temperature dependent).

Table 54. Main Stem Loss Rates.

		Reach j to j + 1					
		j = 1	j = 2	j = 3	j = 4	j = 5	j = 6
Predation	$LP_{j,j+1}$	*0.050*	*0.075*	*0.050*	*0.025*	*0.050*	*0.025*
Other	$LM_{j,j+1}$	*0.025*	*0.050*	*0.025*	*0.050*	*0.001*	*0.050*

In the main stem fish are subject to losses due to exposure time to water of a certain temperature (Table 55).

Table 55. Loss Rates Due to Exposure Time and Water Temperature.

Exposure Time (day)	Water Temperature (°C)													
	25	24	23	22	21	20	19	18	17	16	15	14	13	12
10	*0.99*	*0.99*	*0.99*	*0.95*	*0.9*	*0.8*	*0.65*	*0.4*	*0.2*	*0*	*0*	*0*	*0*	*0*

9.5	0.99	0.98	0.97	0.92	0.86	0.75	0.59	0.33	0.12	0	0	0	0	0
9	0.99	0.97	0.95	0.89	0.82	0.7	0.53	0.26	0.04	0	0	0	0	0
8.5	0.99	0.96	0.93	0.86	0.78	0.65	0.47	0.19	0	0	0	0	0	0
8	0.99	0.95	0.91	0.83	0.74	0.6	0.41	0.12	0	0	0	0	0	0
7.5	0.99	0.94	0.89	0.8	0.7	0.55	0.35	0.05	0	0	0	0	0	0
7	0.99	0.93	0.87	0.77	0.66	0.5	0.29	0	0	0	0	0	0	0
6.5	0.99	0.92	0.85	0.74	0.62	0.45	0.23	0	0	0	0	0	0	0
6	0.99	0.91	0.83	0.71	0.58	0.4	0.17	0	0	0	0	0	0	0
5.5	0.99	0.9	0.81	0.68	0.54	0.35	0.11	0	0	0	0	0	0	0
5	0.99	0.89	0.79	0.65	0.5	0.3	0.05	0	0	0	0	0	0	0
4.5	0.99	0.88	0.77	0.62	0.46	0.25	0	0	0	0	0	0	0	0
4	0.99	0.87	0.75	0.59	0.42	0.2	0	0	0	0	0	0	0	0
3.5	0.99	0.86	0.73	0.56	0.38	0.15	0	0	0	0	0	0	0	0
3	0.99	0.85	0.71	0.53	0.34	0.1	0	0	0	0	0	0	0	0
2.5	0.99	0.84	0.69	0.5	0.3	0.05	0	0	0	0	0	0	0	0
2	0.99	0.83	0.67	0.47	0.26	0	0	0	0	0	0	0	0	0
1.5	0.99	0.82	0.65	0.44	0.22	0	0	0	0	0	0	0	0	0
1	0.99	0.81	0.63	0.41	0.18	0	0	0	0	0	0	0	0	0
0.5	0.99	0.8	0.61	0.38	0.14	0	0	0	0	0	0	0	0	0
0	0.99	0.79	0.59	0.35	0.1	0	0	0	0	0	0	0	0	0

In each refuge there are losses associated with predation (Table 56), refuge temperature (Table 57), and crowding (Table 58).

Table 56. In Refuge Predation Loss Rates.

Refuge	Loss Rate (LP_j)
j = 1	0.05
j = 2	0.1
j = 3	0.05
j = 4	0.15
j = 5	0.05
j = 6	0.025

Table 57. In Refuge Water Temperature Loss Rates.

Water Temperature (°C)	Loss Rate (LT_T)
30	0.99
29	0.98
28	0.97
27	0.95
26	0.9
25	0.75
24	0.5
23	0.25
22	0.15
21	0.125
20	0.1
19	0.075

18	*0.05*
17	*0.025*
16	*0.01*
15	*0.005*
14	*0.001*
13	*0*

Table 58. Survival Rates Due to Crowding.

% Capacity		Survival Rate
< 25%	γ_1	*1.000*
25% ≤ X < 50%	γ_2	*0.950*
50% ≤ X < 75%	γ_3	*0.925*
75% ≤ X ≤ 100%	γ_4	*0.900*
100% < X	γ_{oc}	*0.150**

* Loss Rate