

**EVALUATING FLOW MANAGEMENT STRATEGIES FOR  
THE CONSERVATION OF KOKANEE SALMON  
(*ONCORHYNCHUS NERKA*) IN THE LOWER DUNCAN  
RIVER SYSTEM, BRITISH COLUMBIA**

by

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## **ABSTRACT**

The Duncan Dam Project, British Columbia, falls under the direction of a water use plan. One provision under the current plan is to investigate the effects of facility operations on kokanee salmon (*Oncorhynchus nerka*). With the limited data set available, I developed a closed-loop simulation procedure, which uses a relationship between minimum winter flows and egg-to-fry survival to simulate kokanee population dynamics. This population is then controlled by management decisions (minimum yearly winter flows). The model acts to provide a framework to answer questions regarding flow requirements and the conservation and non-conservation consequences of flow management within a water-controlled system. Future investigations into stock distinction, flow-survival relationships, yearly escapement estimates, and biological characteristics specific to the Lower Duncan River kokanee are required if this model is to be directly applied to the Duncan System.

**Keywords:** *Oncorhynchus nerka*; kokanee salmon; management strategy evaluation; stock-recruit analysis; flow management; water use plan.

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# **CHAPTER 1: INTRODUCTION**

Artificial reservoirs and hydroelectric projects provide multiple benefits, including electricity production (Gowans, et al., 1999), flood hazard control (Quadra Planning, 2004), water storage (BC Hydro, 2007), and effluent containment (AMEC, 2002). Hydroelectric projects can be perceived as advantageous, because they provide power and water for communities, and generate employment, however, they are often associated with environmental and social costs including: changes in watershed morphology; reduction or alteration of usable habitat for fish and wildlife; changes to the irrigation system and recreation (Rosenau et.al. 2000). Public policy attempts to ensure that the construction and operation of hydroelectric projects obtain the greatest advantages while minimizing these social and environmental costs. In British Columbia, these policies are developed and applied through the *Provincial Water Use Planning (WUP) process*. Operation of the Duncan Dam in the Columbia River basin, British Columbia currently falls under the control of a WUP, which characterises the socio-economic values, and environmental priorities of local, provincial, and federal parties involved during its planning (BC Hydro, 2005). Management of dam operations under the Duncan Dam WUP considers a wide range of factors; however, one of the most critical is minimizing negative impacts of seasonal water discharge schedules on fish and fish habitat. One particular condition of the Duncan Dam WUP required that BC Hydro commit financial and human resources to exploring the effects of flow reductions and flow management on several fish species in the Duncan system. This research

project fulfils part of this need by investigating how alternative flow management procedures might affect kokanee salmon (*Oncorhynchus nerka*) production within the Lower Duncan River. Before introducing the quantitative modelling components of this study, I first provide the policy context by describing the history and operation of the water use planning process in British Columbia and specific details of the Duncan Dam Water Use Plan.

## **1.1 British Columbia's Water Use Planning Process**

In British Columbia, a Water Use Plan is a technical document that has been reviewed by agencies within the provincial and federal governments and has been accepted by the provincial Comptroller of Water Rights. The document defines detailed operating parameters that are to be used by water facility management in their day-to-day water control decisions (Province of British Columbia, 1998). The main objective of a WUP is to identify the best balance between competing uses of water including, hydroelectric production, domestic consumption, recreation, fish and wildlife, and heritage (Province of British Columbia, 1998). Plans made during the consultative process are intended to clarify how rights to water resources should be exercised, and to take account of the multiple uses for those resources. Water use plans must also recognize existing legal and constitutional rights and responsibilities, as set by provincial, federal and international legislation (Province of British Columbia, 1998).

### **1.1.1 Background**

The water use planning process was first introduced to British Columbia in 1966 by the Minister of Employment and Investment (MEI) and the Minister of Environment, Lands and Parks (MELP). The WUP was introduced as a means of ensuring that water use management decisions reflect environmental priorities and dynamic public values (BC Hydro, 2005). These priorities and values include fish and fish habitat protection, flood hazard control, beneficial use of the water (storage and power generation), and First Nations issues. Other issues, such as recreation and navigation, may also be taken into account and are project specific (Province of British Columbia, 1998).

Currently, there are several controlled watersheds in British Columbia, which either have, or are in the process of having a water use plan. Some examples include the Peace River, the Ash River, the Arrow Lakes System, the Bridge River, Lower Columbia River and the Duncan River project in the upper Columbia River Basin.

### **1.1.2 The water use planning process**

The water use planning process can be initiated by the Provincial Comptroller of Water Rights (*'Comptroller'*) when issuing a new water license (under the provincial *Water Act, R.S.B.C.1996, c 483, ('Water Act')*), reviewing an existing one, or in response to a perceived water use conflict (Province of British Columbia, 1998). After initiating the process, a public announcement is issued, and a consultative committee (*'committee'*) is assembled. The committee

comprises the licensee (e.g., B.C. hydro), regulatory agencies including the provincial and federal government, First Nations, affected municipal government representatives, and key interested parties. The degree of involvement by each party varies from project to project. Once assembled, the committee meets and compiles water resource concerns from all involved parties, as well as data relating water flows and their impacts on flood control, fish and aquatic ecosystems, and other water use issues. The data review helps to identify gaps in information and the need for further technical studies to be undertaken during the plan's development. Participants under consultation of the Comptroller define specific water use objectives including a descriptive measure to be used in assessing their achievement (Province of British Columbia, 1998).

During the WUP draft process, data is gathered with hopes to reduce information gaps on specific flow requirements for each objective. Remaining gaps are documented and accompanied by future plans to investigate these gaps. The next step is to develop and assess multiple water operation alternatives that meet the social, economic, and environment values of the water resource. Results are drafted into a technical report and areas of consensus and contention are listed. Full consensus over all issues is rarely achieved and is thus not mandatory in the WUP process (Province of British Columbia, 1998). The draft report from the committee is then sent to the Comptroller who reviews it and checks for compliance under the *Water Act*. If acceptable, the proposed WUP is authorized and a water licence is issued. The final step is a review and advice by the Federal Department of Fisheries and Oceans (DFO), which is the primary

decision making authority for the conservation of aquatic habitats. Once the WUP is deemed appropriate, the DFO provides federal authorization for the WUP. If DFO disagrees with the WUP it is free to exercise other regulatory options at its disposal (Province of British Columbia, 1998). Federal and provincial legislation relevant to the WUP process is reviewed in section 1.1.3. Water Use Plans often include a monitoring schedule that is developed to ensure that the licensee is in compliance with the terms of the water use plan. Compliance can include following predetermined water schedules, adhering to provincial and federal policy and legislation and conducting environmental and social research as described within the WUP document.

### **1.1.3 Policy, Legislation and the WUP**

Water use plans must recognize and respect existing policies at the provincial, national and international levels. Provincial policy works to address the needs and concerns of British Columbians. The *Water Act* is the principle piece of provincial legislation within the water licensing process. Through the Comptroller, the *Water Act* provides the means by which the Province authorizes the construction, operation and maintenance of water works. Under this act, and through the authority of the Comptroller, regulations on storage, diversions and other water uses are set within the provincial water license. Water use regulations are set upon approval of the WUP. Under the *Water Act*, regulations are set to protect the prior rights of other licensees, protect the environment (fish and aquatic habitat), and other provincial interests (flood hazard protection, navigation and recreational interests) (Province of British Columbia, 1998).



Additional provincial legislation exists to cover all possible concerns affected by reservoir projects including fish, wildlife, provincial parks, recreation, culture and heritage. These include the *Fish Protection Act*, S.B.C. 1997, c 21 ; the B.C. *Environmental Assessment Act*, S.B.C. 2002, c 43; the *Water Protection Act*, R.S.B.C. 1996, c484 ; the *Park Act*, R.S.B.C. 1996, c 344 ; the *Wildlife Act*, R.S.B.C. 1996, c 488 and the *Heritage Conservation Act*, R.S.B.C. 1996, c 187. Provincial policy and legislation works to represent the concerns and needs of British Columbia. Concerns and needs however, are also represented at the national and international levels. The next few paragraphs describe specific federal policies, legislation and international treaties and agreements, which are involved in British Columbia's WUP process.

At the federal level, the *Canadian Fisheries Act* represents the largest piece of federal legislation in the WUP process. Three sections of the *Canadian Fisheries Act*, R.S.C. 1985, c F-14, work to protect fish and fish habitat affected by dams. The act was introduced in 1976-77 in an attempt to neutralize negative impacts of lost habitat on fish species due to anthropogenic modification of aquatic ecosystems. Section 32 of the act, which is specifically designed to prevent the destruction of fish, states "no person shall destroy fish by any means other than fishing except as authorized by the Minister or under regulations made by the Governor in Council under this act". Incidental mortality through the operation of a dam (e.g., stranding on dried beaches or impingement in turbines) violates this section. Section 35(1) of the *Canadian Fisheries Act*, R.S.C. 1985, c F-14, states "no person shall carry on any work or undertaking that results in the

harmful alteration, disruption or destruction of fish habitat". As a follow-up, Section 35(2) states "no person contravenes subsection (1) by causing the alteration, disruption or destruction of fish habitat by any means or under any conditions authorized by the Minister under regulations made by the Governor in Council under this act". This subsection offers the opportunity for exemption assuming compensation mitigation is made under the *Canadian Fisheries Act, R.S.C. 1985, c F-14* (Department of Fisheries and Oceans, 1986). The long term policy objective of the DFO is to achieve an over-all net gain in the productive capacity of fish habitats. However, because hydroelectric projects countervail this policy a fundamental strategy used by the DFO is the no net loss (NNL) guiding principal to habitat management. The DFO works with companies such as BC Hydro so that resource development is carried out in such a way that the productive capacity of fish habitat is maintained. (Department of Fisheries and Oceans, 1998, Minns et, al, 2003). The NNL principal is flexible by definition, and is intended to guide departmental officials and other interested parties and is not to be considered as a statutory requirement to be met at all costs and in all circumstances (Department of Fisheries and Oceans, 1998). The NNL principal is part of the *federal policy for the management of fish habitat*, which was first released in 1986. The policy states the NNL principal will only be used for projects and alterations made after 1986 (Department of Fisheries and Oceans, 1986). Other federal legislation taken into account when developing a WUP includes the *Canadian Environmental Assessment Act, S.C. 1992, c 37*; the *Navigable Waters Protection Act, R.S. 1985, c N-22*; and the *International Rivers*

*Improvement Act, 1985, c I-20*. Similar to Provincial Legislation, these acts work to protect fish, wildlife, parks, recreation, culture and heritage.

In addition to competing policies at the federal and provincial levels, many hydroelectric projects span international boundaries. British Columbia and the northwestern United States share several watersheds that are important for not only hydroelectric power generation, and flood hazard control, but also for commercial fishing interests. Many Pacific salmon migration routes and spawning grounds fall in both British Columbia and Washington and/or Montana. As a result, agreements for water usage are made between the countries involved. The primary treaty between Canada and the United States is the Boundary Waters Treaty, signed in 1909 by the United States and Great Britain (on behalf of Canada). The purpose of this treaty was to provide a process for Canada and the United States to resolve disputes over shared water. Under the treaty, Canadian and American representatives are selected to make up an International Joint Commission (IJC), which is given authority to recommend solutions to water disputes between the two countries (Klein, 2006). One requirement of the Boundary Waters Treaty is that the public be given the right to 'be heard' by the IJC and thus become part of the process when dealing with international water disputes. Though the IJC has the goal of settling international water disputes, its recommendations are non-binding (Klein, 2006). The commission has been established across Canada and the United States, and includes the Kootenay Lake system. The International Joint Commission Order of Kootenay Lake (IJCOKL) operates to protect the issues and concerns of Kootenay Lake

residents. Kootenay Lake has a large recreational interest including boating and fishing. Cottage type residences surround the lake, and many of them have waterfront docks. Operations of the Duncan Dam affect the water level of Kootenay Lake, which can in turn affect these residences.

In 1967, Canada and the United States signed the Columbia River Treaty (CRT), which required that Canada provide  $1.9 \times 10^{10} \text{ m}^3$  of reservoir storage under the combined efforts of the Duncan, Arrow, Mika and Hugh-Keenleyside dams. Operations of these dams were to provide flood hazard control and water for hydroelectric production further down the Columbia River Basin. In return, Canada receives one-half of the extra power generated by the waters from the storage reservoirs (Banks, 1996). The Duncan Dam specifically is required to store  $1.7 \times 10^9 \text{ m}^3$  of water annually. Storage requirements for the Duncan Dam are outlined and updated in an Assured Operating Plan (AOP) that provides rules for control such that specific seasonal requirements are met for water use under the treaty (BC Hydro, 2005). Specific yearly schedules are developed using the rules of the AOP and are recorded in a Detailed Operating Plan (DOP). Seasonal flow release schedules are outlined in the DOP and reflect storage requirements under the treaty. Seasonal storage is influenced by the need for flood control as well as use in downstream hydroelectric production. Storage is highest, and therefore flow is lowest, during the months of July to December and lowest during the months of March, April and May (BC Hydro, 2007). Historical discharge from the Duncan Dam (since 1984) has been sporadic; however, on average discharge is highest in January, February, August and September, while

lowest in the months of May June and July (Figure 1-1). Under the treaty, discharges from the Duncan Dam are not to be less than 3 cubic-metres-per-second (cms), and not to exceed 283 cms, though in emergencies discharge is allowed to reach 566 cms. These parameters define the normal operating range of the Duncan Dam WUP.

Due to the numerous competing policy concerns (economic, environmental, and social) surrounding hydroelectric development in British Columbia, members of a WUP committee need to make tradeoffs when developing a WUP so that they can best meet the directives of the different policy and legislative concerns. Tradeoffs are made by assigning value to each water use objective; providing operational requirements for these objectives; developing alternative flow regimes; and then weighing consequences of each flow alternative on each objective.

#### **1.1.4 The Duncan Dam Water Use Plan**

The Duncan Dam was initiated in 1964 and completed in 1967. It is located 11 km north of Kootenay Lake and drains water from the Duncan River drainage basin that covers 2,400 km<sup>2</sup> (AMEC, 2003). Above the dam is the Duncan Reservoir, which is approximately 45 km long when the reservoir is at full pool (BC Hydro, 2005).

For the Duncan system, the WUP process was initiated in 2001 and was completed by April 2005. The consultative committee included 12-15 members who were representatives of federal, provincial, and municipal government, BC Hydro, First Nations and other interested parties. Committee members shared a

wealth of experience and knowledge in engineering, science, social science, culture, policy and planning. Issues addressed in the planning of the Duncan system WUP include fish habitat, flood management, industrial water usage, mosquito habitat, power generation, recreation, First Nations usage, riparian rights, water quality, and wildlife habitat (BC Hydro, 2007). Alternative operational schedules were assessed and in 2004, consensus was reached for one particular alternative that included seasonal operation schedules, physical works in lieu of operational changes, and a monitoring program (BC Hydro, 2007).

Specific operational constraints were designed to satisfy as many of the issues as possible brought up during the WUP process. Specific constraints included a maximum discharge from the Duncan dam of 283 m<sup>3</sup>/s and a minimum of 3 m<sup>3</sup>/s. The minimum target flow to the Lower Duncan River was set at 73 m<sup>3</sup>/s and the maximum target flows changed seasonally (BC Hydro, 2005). These targets were designed to meet legal and policy type issues illustrated in the WUP. For example, from the period of Dec 22 to April 9, the maximum target is 250 m<sup>3</sup>/s, however, it can be raised to 300 m<sup>3</sup>/s if needed for compliance with the Columbia River Treaty (BC Hydro, 2005)

The agreed upon operational constraints came with expected positive and negative impacts on the various water use issues brought up within the WUP process. Positives included increased erosion protection within the Lower Duncan River, increased overall aquatic productivity and a decrease in the incidence of fish stranding, decrease in the occurrence of flooding within the

Lower Duncan River, decrease in the number of mosquito breeding opportunities, increase in recreational opportunities (increase in number of days that the reservoir can be accessed), and an increase in the recruitment of cottonwood vegetation within the Lower Duncan River (BC Hydro 2005). Potential negative consequences include a decrease in riparian productivity (loss of sedge grass) and loss of revenue (estimated loss of \$1.7 million annually). In compliance of a monitoring agreement, as outlined in the Duncan Dam WUP, several projects were recommended to assess uncertainty within the Lower Duncan system. These projects involved investigations into fish stranding, kokanee spawning, bull trout (*Salvelinus confluentus*) passage to the Duncan Reservoir, cottonwood production, mosquito control, fish habitat use, and erosion studies (BC Hydro, 2005). Over the 10-year life of the WUP, these projects will monitor and study the effects of facility operations on fish, wildlife, vegetation and erosion.

## **1.2 Project Objectives**

As reflected within the Duncan Dam WUP, BC Hydro is committed to studying the impacts of water control on the Lower Duncan River kokanee salmon population. Kokanee use the Lower Duncan River, and associated tributaries (Meadow Creek, and the Lardeau River) for spawning, incubation and emergence purposes. Dam operations only affect kokanee within the Lower Duncan River and can lead to fish stranding, egg stranding, and a reduction in spawning habitat.

My project investigates the impacts of flow control on long-term kokanee recruitment within the Lower Duncan River. The Lower Duncan River is one of three kokanee spawning tributaries within the Duncan System. The other two include the Lardeau River and Meadow Creek. The initial goal of this project was to evaluate alternative operational schedules to optimize kokanee recruitment within the Duncan System; however, development of specific simulation models for this system was not possible because the Lower Duncan River is data limited, having only six years of kokanee escapement, and no biological information. Larger data sets containing time series of kokanee spawners within the Lower Duncan River and biological information such as fecundity and egg-to-fry survival would be required to specifically address flow control for the Duncan dam. Other tributaries within the Duncan system have relevant information so I was able to modify the project goals and address the following two objectives:

1. To assess the impacts of various flow management procedures on conservation and non-conservation goals in a system similar to the Lower Duncan River.
2. To determine and assess the data requirements needed so the model could be set in terms of the Duncan River system.

To address the first objective, I developed a simulated system based on the biological characteristics of Meadow Creek and the hydrological information from the Duncan Dam. This approach has been used previously to determine the general properties of management systems that can subsequently be applied to real-world fisheries management scenarios (Cox et al., 2003, Sainsbury et.al.



2000). The ultimate goal of the simulation is to determine how alternate flow management strategies are likely to affect the production of kokanee in a system similar to the Duncan River. The modelling framework and background information required to develop the model are described in Chapter 2, while simulation results are provided in Chapter 3.

To address the second objective, I discuss model limitations and data gaps for the Lower Duncan River in Chapter 4. This discussion includes suggestions for data collection required to close the gaps and eventually produce a management model specific for the Duncan System.

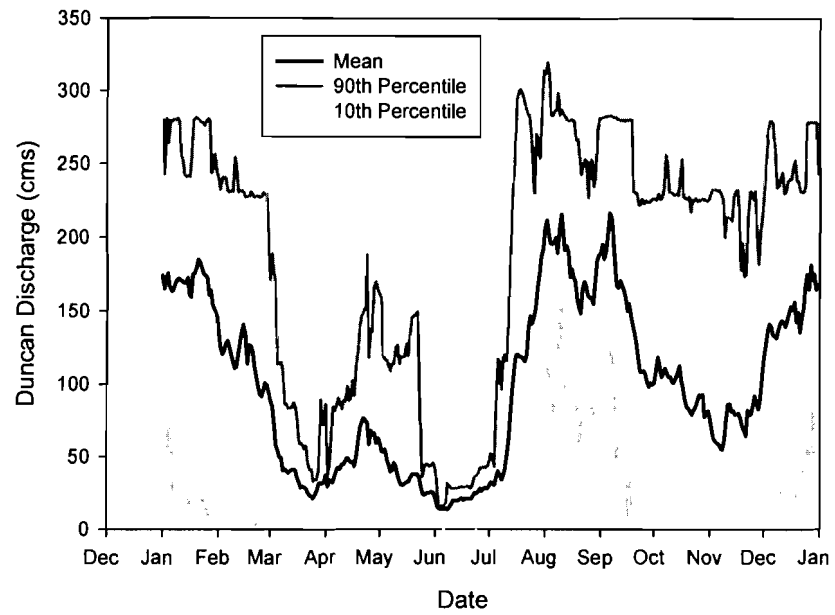


Figure 1-1. Range of historical daily flows from the Duncan Dam between 1984 and 2004. The Black line represents the mean daily flow, while the dark grey represents the upper 90th percentile and the light grey line represents the lower 10th percentile of historical values.

## **CHAPTER 2: MODELLING FRAMEWORK**

## 2.1 Background

### 2.1.1 Kokanee Biology, Life History and Distribution

Kokanee salmon (*Oncorhynchus nerka*) are a non-anadromous form of sockeye salmon that are found naturally throughout northwestern North America, and eastern Asia. It is widely maintained that present kokanee populations have diverged sympatrically from sockeye salmon over multiple independent occurrences (Ford et al., 1995; Taylor et al., 1996; Wood and Foote, 1990). Causes of divergence for many kokanee populations are a result of natural barriers such as landslides and glaciers (Ford et al., 1995). Because of living in comparatively unproductive ecosystems (as compared to an ocean ecosystem), kokanee grow slower and reach maturity at a much smaller size than anadromous sockeye. Apart from the size and the lack of an ocean phase, the kokanee and sockeye share a similar life cycle.

Kokanee return in the fall to their natal spawning areas that can be located in either beach or riverine habitat. Redds are built and the fertilized eggs are buried in the gravel to provide protection during the initial development phase. Emergence takes place in the spring and the fry immediately move to the lake shore nursery areas where they feed and grow and sometimes die. Fry, hatched from lake shore redds remain in their near shore area. This phase lasts for a variable amount of time, dependent on the system. Eventually, the fry move to the limnetic zone. During the open water phase, kokanee feed on zooplankton such as *Daphnia spp.* and aquatic insects, while they themselves act as prey for

larger fish such as rainbow and lake trout. The age of maturation ranges from 2 to 8 years depending on the system (Ford et al., 1995). Once mature the kokanee act on temperature cues and leave the limnetic zone heading to the lakeshore (beach spawners) or the up the rivers for the fall/winter spawning run (Ford et al., 1995).

Kokanee can occur as either native or introduced stocks. In many lake systems, kokanee populations contain both native and introduced stocks. Internationally, natural populations of kokanee can be found in lakes of the pacific drainages including Canada, the United States, Japan and the USSR (Ford et al., 1995; Nelson, 1968). In the United States, these native stocks are found in several states including Alaska, Washington, Oregon, and Idaho. In Canada they are found in British Columbia and the Yukon Territory. In British Columbia specifically, natural kokanee stocks are found within the Fraser, Kootenay, Okanogan, and Columbian systems as well as northern lakes such as the Williston Reservoir and Arctic Lake (Scott and Crossman 1973; Ashley et al., 1997 and Ford et al., 1995).

Since kokanee are considered to be a valuable sport and forage species, there have been numerous introductions within North America. In the United States, introductions have been made to several states including Maine, California, New York, Montana, Colorado, Connecticut, Pennsylvania, Vermont, North Dakota, Nevada, Utah and Wyoming. In Canada introductions have been made in Alberta, Saskatchewan, Manitoba, and Ontario and previously absent sections of British Columbia (Scott and Crossman, 1973). Currently, kokanee are

wide spread throughout British Columbia and as such are at risk within many controlled watersheds. Due to this risk, several mitigation strategies have been developed to help reduce the incidence of kokanee mortality.

### **2.1.2 Mitigation and Flow Management for Fish Conservation**

Mitigating the environmental impacts of hydroelectric projects can involve manipulation of flow, enhancing spawning areas, or providing additional nutrients in the form of lake fertilization. In systems where on-site electricity production is part of the dam, it has become common practice to install fish screens or guidance systems that eliminate incidental mortality from production turbines and intake systems (Stober et al., 1983). When a dam prevents fish migration, passage structures can be built to allow for above dam spawning. At the John Day Dam in the Columbia River, a passage system is used to move yearling Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*), and sockeye salmon (*Oncorhynchus nerka*) past the dam on their seaward migration (Brege et al., 1996).

Stream enhancement and the construction of spawning channels have been a commonly used strategy for habitat lost as a result of a hydroelectric project. In the Duncan system, over 35 km of spawnable river was lost when the Duncan Dam was built. As means of compensation, BC Hydro enhanced the Meadow Creek tributary and constructed the Meadow Creek spawning channel. The spawning channel allowed for an evenly distributed 5.2 kokanee/m<sup>2</sup>, which

provided some compensation for habitat lost from the construction and operation of the Duncan Dam (Acara, 1977).

Lake stocking programs have also been successful in providing compensation for impacts due hydroelectric projects. A good example comes from Lake Pend Oreille, Idaho. Eggs from the Meadow Creek spawning channel are purchased and then reared in the Cabinet Gorge Hatchery, located in the Clarke Fork River at the South-eastern end of Lake Pend Oreille. Stocking of age 0 kokanee takes place in mid to late June, and the results have shown improvements in the kokanee population, though it still falls short of historical levels (Paragamian, et al., 1995; Bowles, et al., 1989; Maiolie et al., 1998).

Flow management as a mitigation strategy has been successfully implemented as a means to reduce fish and fish habitat loss. Flow management involves the deliberate control of water released from a hydroelectric facility in order to meet management objectives such as fish and wildlife conservation, flood hazard control, and economic development.

There have been several documented cases where flow management was successful as a conservation tool for fisheries management. The following list reviews five specific cases where flow management was successfully used to reduce fish stranding and egg dewatering as well as increase salmonid recruitment.

*Banks Lake, Washington.* Banks Lake is an artificial reservoir that is used to store water for irrigation. Springtime lake drawdown gave rise to the potential for the dewatering of kokanee eggs, embryos and alevins. This not only caused

mortality but resultant changes in water temperatures delayed spring emergence of alevins. The management solution was to delay water release until the spring emergence was completed in order to conserve kokanee populations (Becker and Neitzel, 1985).

*Flathead River, Montana.* The Hungry Horse Dam, located on the Flathead River, functions to produce hydroelectric power and flood hazard control within Montana. The problem associated with the Flathead River is similar to that of the Duncan River, where high water levels in the autumn coincide with kokanee spawning. Winter drawdowns have led to redd dewatering and the subsequent mortality of kokanee eggs and alevins (Farley et al. 1986). Egg mortality was estimated to be 60% for the 1979/1980 year. The following year, water levels were dropped forcing spawning kokanee to move to deeper sections of the lake and the river, which would be safe from dewatering. As a result the dewatering mortality dropped to only 5%. (Becker and Neitzel, 1985; Farley and Decker-Hess, 1987).

*Lake Pend Oreille, Idaho.* The decline of kokanee in Lake Pend Oreille has been partly attributed to the operations of the Albern Falls Dam. Trends in population estimates and recreational catch suggested that winter drawdowns resulted in the reduction of potential lakeshore spawning habitat (Maiolie et al., 1998). The hypothesis proposed was that a lake level increase of 1.2 m would create 560 times the current gravel spawning habitat. In 1995 lake levels were increased 1.2 m and 1996 trawl surveys showed the largest kokanee population since 1977 (Maiolie et al., 1998).



*Skagit River, Washington.* Discharge in the Skagit River is controlled by the by the operation of the Gorge, Ross and Diablo dams. Fluctuations in water releases through these dams have influenced the egg-to-fry survival of pink (*Oncorhynchus gorbuscha*), chum (*Oncorhynchus keta*) and Chinook salmon as water levels were at times sufficiently low enough to cause dewatering mortality (Connor et al., 2004). The proposed solution was to reduce the annual number of drawdown events, which in turn would, increase the minimum flow. Population assessments made after implementation of the proposed flow management showed an increase in recruitment for all three salmon species.

*Ives Island, Washington.* A large chum salmon stock spawns in the Ives Island area, which is a side channel of the Columbia River, Washington. The spawning areas around the tributary are sensitive to flow changes controlled by the Bonneville Dam. Past investigations have shown that many wild chum redds have become dewatered resulting in egg mortality as a result of drawdown from the dam (Tiffan et al., 2007). A minimum flow requirement was determined for the system and as a result, egg mortality due to redd dewatering decreased.

Managers of the Lower Duncan River have successfully implemented flow control as a management tool for reducing egg mortality. Since 2002, fall flows from the Duncan Dam have been reduced to coincide with water levels that exist during the winter, when fertilized eggs are susceptible to dewatering. For the Duncan system, flow management had proven effective in reducing the incidence of redd dewatering, however, it has achieved this at a cost of a reduction in spawning habitat. The following simulation model investigates flow management

for increasing kokanee recruitment in systems similar to the Lower Duncan System.

## **2.2 Model structure**

In fisheries stock assessment, a management procedure is the process of determining an appropriate management action (such as flow control) based on stock assessment data (such as spawner escapement), biological parameters, and a decision making algorithm (such as a flow control rule) (Sainsbury et al., 2000).

In the following model, the performance of alternative flow management procedures were examined using a closed-loop simulation modelling approach that consisted of three main components (Figure 2-1). The first was the kokanee population operating model that simulated stochastic dynamics of a kokanee population in response to changes in egg-to-fry survival and adult abundance, where the former was modelled explicitly as a function of minimum winter flows (Figure 2-2). The second component was the assessment model that estimated parameters of a Ricker stock-recruitment relationship between observed kokanee fry in year  $t$  and estimated adult kokanee escapement in year  $t+4$ . Both of these observations were generated from the stochastic operating model. In the third component, the flow control rule, an optimization algorithm used the estimated population dynamics parameters from the assessment model to maximize a total utility function of minimum winter flow. These three components form a closed-loop procedure because alteration of flow forces changes egg-to-fry survival,

which then causes changes in adult abundance. Such changes then generate new fry and adult observations that are used to estimate (a) stock-recruitment parameters and (b) parameters of the relationship between minimum winter flow and egg-to-fry survival. As information about these relationships accumulates over time, the flow control rule optimization more accurately forecasts the minimum winter flow that maximizes kokanee adult abundance. Thus, the procedure, based only on observed fry, adult, and flow variables, should eventually steer the true kokanee abundance to maximum possible levels (i.e., to the maximum defined by the operating model). The equilibrium relationship between minimum winter flow and kokanee adult abundance is illustrated in Figure 2-3. The remainder of this section provides the details of each simulation model component.

## **2.3 Model Description**

### **2.3.1 Kokanee population operating model**

The kokanee operating model is given in Table 2-1 with model notation provided in Table 2-2. The simulated kokanee population is effected exclusively by changes in the egg-to-fry survival rate, which is modelled as a function of stream flow (as measured by Duncan Dam discharge). Specifically, I assume that egg-to-fry survival is a logistic function of the minimum daily winter flow (T1.4-T1.5). The flow-survival relationship is illustrated in Figure 2-2. This is a hypothetical function because such functional relationships do not exist for this, or any other kokanee river system. I chose the logistic form and associated

parameter values such that minimum egg-to-fry survival was approximately 10% when the river went dry for at least one day, and reached approximately 30% at the maximum daily winter flows observed in the Lower Duncan River. The maximum survival rate corresponds to the average egg-to-fry survival rate in Meadow Creek kokanee ( $\bar{S} = 0.302$ ,  $\sigma = 0.155$ ). Because of the uncertainty associated with this functional relationship, I tested the sensitivity of performance measures to alternative functional relationships (Table 2-4).

For the population dynamics I assumed that all kokanee spawn at age 4, and thus the model needs to include a 4 year generation time. To accommodate this, operating model variables are initialized during the first 4 years of the simulation ( $1 < t < 4$ ). This was done by setting the flow variables  $Q_1$ - $Q_4$  to the average minimum Duncan River winter flow between 1985 and 2004 (T1.3), computing the egg-to-fry survival rates as a function of these flows (T1.4-T1.5), and then initializing the four equilibrium population sizes (T1.7,  $1 \leq t \leq 4$ ). This equilibrium and time-dynamic population model follows a Ricker function with parameters  $b_1$  (maximum fry-to-adult survival rate),  $b_2$  (density-dependence parameter), and  $\sigma_N$  (residual process error standard deviation) estimated from Meadow Creek spawning channel (Appendix A). Fry produced from the adult abundances are then calculated based on fecundity and egg-to-fry survival (T1.6). The model is then "burned-in" for 10 years to provide initial flow, fry, and adult data required for the assessment model. During the burn-in period, minimum winter flows are chosen at random from the existing Lower Duncan River data (T1.3,  $4 \leq t \leq 15$ ), while after the burn-in period, flows are determined by

the flow control procedure as described below. Note that stochastic deviations in egg-to-fry survival are included on the logit scale in T1.4 to ensure that survival rates remain in  $(0,1)$  despite the magnitude of deviations  $(\sigma_v)$ . The other source of stochasticity occurs in the relationship between fry in year  $t$  and adult kokanee escapement in year  $t+4$  with the magnitude of deviations controlled by the standard deviation  $\sigma_N$ .

At each time step, the operating model generates new observations of kokanee adult escapement and subsequent fry abundance (T1.9-T1.10), which are then appended to the existing dataset. In addition, an observation for egg-to-fry survival is generated by dividing observed fry abundance by estimated total egg deposition (T1.11).

### **2.3.2 Stock assessment model**

After the 10-year burn-in period, minimum winter flows were determined by an automated management procedure. The first step in this procedure is to conduct a stock assessment in which fry-to-adult ( $b_1$  and  $b_2$ ) and flow-survival rate function parameters are estimated from the simulated observations. Equations (T3.2 - T3.3) represent a simple linear regression estimator of the fry-to-adult function parameters, while equations (T1.11 and T3.5) provide a similar estimator for the flow-survival parameters. Both linear regression estimators are implemented using the "lm()" function in R statistical software (R Development Core Team (2008)). Figure 2-4 represents the distribution of the  $b_1$  and  $b_2$  parameter estimates over 500 simulations and is presented in boxplot form. For both parameters there appears to be a slight bias in the mean estimation. For the

$b_1$  parameter there is a slight under estimation (Figure 2-4 a), whereas there is a slight over estimation in the  $b_2$  parameter (Figure 2-4 b). There are two likely sources to the biased estimators. The first is known as 'errors in variables', where the independent variables of estimation (recruitment) are assumed to be measured without error (Hilborn and Walters, 1992, p234). When this assumed error free measurement is put into a regression, a bias can appear within the regression parameters (i.e.  $b_1$  and  $b_2$ ). The second source of bias is known as a "time series bias". Time series biases are introduced because the independent variable (fry stock) of the regression is not independent of the process errors surrounding the mean recruitment relationship (Ricker) (Hilborn and Walters, 1992, p290).

### **2.3.3 Flow-control procedure**

The flow-control procedure uses current knowledge of the fry-to-adult ( $\hat{b}$ ) and flow-survival ( $\hat{\beta}$ ) relationships to determine the "optimal" minimum winter flow  $Q_{\max}$  that meets long-term kokanee conservation and nonconservation objectives. The optimum is obtained by iterating T3.6 - T3.11 over values of  $Q$  until the utility function (equation T3.10) is maximized (Table 2-3). Total utility (Figure 2-5c) is taken to be a weighted combination of conservation utility (Figure 2-5a), represented by the adult kokanee abundance, and an exponentially declining function of flow (Figure 2-5b). The latter reflects the fact that reservoirs like the Duncan store less water as minimum winter flow increases and thus provide lower overall value. The relationship represented in Figure 2-5b assumes that all losses in storage are negative and thus a decrease in flow utility. It should

be noted that there will be instances where non-conservation type benefits can occur from a decrease in storage, such as those observed in downstream areas of increased riparian productivity. However, for the purposes of reducing the complexity of my model, I chose to use only two utility functions. Because these two components of utility are in opposition with respect to flow, and both are monotonic, the total utility function has a unique maximum. The weight placed on conservation value,  $w_N$ , will partly determine the flow level where the maximum occurs (Figure 2-5a). Finally, equation T3.10 implements the apparent optimum flow via a smoothing function between the previous year's flow and the one recommended by the above procedure. This smoothing is needed to dampen the highly variable optimum flows that typically arise in the early years of the simulations (these years have fewer observations and thus higher variance in the stock assessment estimators).

The full closed-loop simulation was performed over 500 Monte Carlo trials in which each trial included 100 simulated years. I chose 500 trials because some performance measures described below are sensitive to variations in the lower percentiles of the distribution of outcomes.

## **2.4 Performance measures**

I measured performance of alternative flow-control management procedures using conservation, 'water value', and simulation performance indicators. For a conservation indicator, I used the number of years,  $T_K$ , until the median of the distribution of adult abundance recovered to 80% of its true carrying capacity.

Economic information was not available to test in the model so I used water value a proxy measure. For this, I used a measure of inter-annual flow variability that takes the standard deviation of the year-to-year difference in flow for years  $t = \{15, 16, \dots, 100\}$ . As the inter-annual flow variability increases, the ability of a manager to plan for water use and value decreases, and thus indirectly impacts the value of water.

The third performance measure represents a measure of the success of the model over all simulations. Performance measure 1 (conservation indicator) is measured using a median result of the simulation model. The median result of the conservation indicator might achieve a successful recovery of the population, however due to the stochastic nature of the model not all simulations will represent this finding. Thus, the third performance measure calculates the number of occurrences, over all simulations that the projected population was not able to recover to the management goal of 80% of carrying capacity over 100 years of simulation.

## **2.5 Management Procedures**

Flow management is influenced by three parameters, as noted above. The weighting of the conservation ( $w_N$ ) and flow increase ( $v_1$ ) utility parameters directly affect the maximum total utility function ( $Q_{max}$ ). The effect that  $Q_{max}$  has on the next flow period is then is then determined by the weighting parameter ( $\lambda_1$ ). The management procedures are investigated by; (i) assessing the performance of four example combinations of  $w_N$  and  $v_1$ , which represent four



distinct 'management philosophies' and (ii) assessing the performance of a range of each of the two parameters (Table 2-2). The latter procedure also investigates the impact of different  $\lambda_1$  values over the parameter range.

Stochastic simulations were run under four different management procedures defined by the weighting of the conservation utility ( $w_N$ ), and flow increase utility ( $v_1$ ). The first scenario ( $w_N = 0.9$ ,  $v_1 = 0.05$ ) represents a conservation aggressive management objective placing high weight on conservation utility and minimal weight on flow increase utility. In the second scenario ( $w_N = 0.7$ ,  $v_1 = 0.05$ ) conservation utility weighting was reduced allowing for greater influence by the flow increase utility. The third ( $w_N = 0.5$ ,  $v_1 = 0.15$ ) and fourth ( $w_N = 0.5$ ,  $v_1 = 0.45$ ) scenarios further decrease the conservation utility weight as well as increasing the weighting of the flow increase utility. The latter two scenarios represent less conservation oriented management objectives.

The next step in the simulation procedure analyzed the performance of a variety of utility (both conservation and flow) weight combinations ( $w_N$  ranging from 0 to 1.0, and  $v_1$  ranging from 0 to 0.5). These combinations were then run over four alternative flow change smoothing parameters ( $\lambda_1 = 0.3$ ; 0.5; 0.7 and 0.9). The flow change smoothing parameter determines the influence of the flow decision, as the flow for the next year is a combination of the flow control decision and the flow used in the previous year (T3.10). For example, a  $\lambda_1$  value of 0.8 gives 80% influence to last year's flow, while a  $\lambda_1$  of 0.2 gives 80% influence to the optimal flow (T3.9) calculated from the control rule.

## 2.6 Sensitivity analysis

Clearly, many parameters of the simulation model are highly uncertain, particularly those related to the critical relationship between flow and egg-to-fry survival. I chose to test the performance of four alternative forms of the logistic function, by manipulating the parameters from T.1.4. (Table 2-4). Examples of function shapes are illustrated in Figure 2-6.

Sensitivity within the biological side of the simulation can be limited to the density dependant ( $b_2$ ) parameter calculated from the Ricker function. It can be assumed that the maximum fry to adult survival rate ( $b_1$ ) is similar between the Duncan River and Meadow Creek as it is not dependant on flow. By holding  $b_1$  constant, I tested the performance of varying values of  $b_2$  against the three performance measures (Table 2-2).

Because errors in data collection and environmental stochasticity can have a large impact on model performance, I chose to look at the effects of differing values of two measures of variance. These were; (i) fry-to-adult recruitment process error ( $\sigma_N$ ), and (ii) the observation error associated with spawner estimates ( $\tau_N$ ) (Table 2-2).

Table 2-1. Operating model for generating Kokanee population dynamics including abundances of adults ( $N_t$ ), fry ( $F_t$ ), egg-to-fry survival ( $S_t$ ) and corresponding observed values from hypothetical sampling programs. Model notation is provided in Table 2.

---

**Parameters**

T1.1  $\Phi = \{b_1, b_2, \beta_1, \beta_2, \beta_3, \bar{f}, \sigma, \tau, \}$

**State dynamics**

T1.2  $\omega_t \sim N(0,1), \gamma_t \sim N(0,1)$

T1.3  $Q_t = \begin{cases} \bar{Q} & t = 4 \\ Q_t^* & 5 < t < 15 \\ \tilde{Q}_t & t \geq 15 \end{cases}$

T1.4  $v_t = \beta_1 + \beta_2 Q_t + \beta_3 Q_t^2 + \sigma_v \omega_t$

T1.5  $S_t = \exp(v_t) / (1 + \exp(v_t))$

T1.6  $F_t = 0.5 \bar{f} S_t N_t$

T1.7  $N_t = \begin{cases} 2(\log 2 - b_1 - \log[\bar{f} S_t]) / b_2 \bar{f} S_t & 1 < t < 4 \\ a F_{t-1} \exp(b F_{t-1} + \sigma_N \gamma_t - \sigma_N^2 / 2) & t > 4 \end{cases}$

**Observation models**

T1.8  $\varepsilon_t \sim N(0,1)$

T1.19  $N'_t = N_t \exp(\tau_N \varepsilon_t)$

T1.10  $F'_t = F_t$

T1.11  $S'_t = 2 F'_t / \bar{f} N'_{t-1}$

---

Table 2-2. Model notation including both parameters and variables. Notation descriptions, parameter values, including values used in sensitivity analysis are also included. Base parameter values are bolded.

Symbol	Value	Description
<b>Indices</b>		
$T$	{1,2,... $T$ }	Annual time step ( $T = 100$ )
<b>Operating model</b>		
$b_1$	<b>0.072</b>	Ricker model - logarithm of maximum fry-to-adult survival rate
$b_2$	<b>-0.033</b>	Ricker model - density dependence parameter
$\beta_1$	<b>-2.32++</b>	Flow survival model - intercept
$\beta_2$	<b>0.18++</b>	Flow survival model – linear term
$\beta_3$	<b>-0.0036++</b>	Flow survival model - quadratic term
$\bar{f}$	<b>255</b>	Average female kokanee fecundity (eggs/female)
$\sigma_v$	<b>0.1</b>	Standard error in logit transformation of egg-to-fry survival rate
$\sigma_N$	<b>0.1-1++</b>	Standard error of adult recruitment process errors
$\tau_N$	<b>0.1-1++</b>	Standard error of adult kokanee escapement estimates
<b>State variables</b>		
$N_t$		Adult kokanee abundance in year $t$
$F_t$		Kokanee fry abundance in year $t$
$Q_t$		Minimum winter flow (cms) from Duncan Dam
<b>Observations</b>		
$N'_t$		Estimated adult kokanee spawning escapement in year $t$
$F'_t$		Estimated fry abundance in year $t$
$S'_t$		Estimated egg-to-fry survival rate in year $t$
<b>Flow control procedure</b>		
$\lambda_1$	<b>0.3-0.9 ++</b>	Flow change smoothing parameter
$v_1$	<b>0.05-1.0 +</b>	Rate of exponential decline in utility as flow increases
$w_N$	<b>0.2 - 0.9 +</b>	Weight placed on adult abundance in utility function

+ parameters used to calculate management procedures

++ parameters and specific range used in sensitivity analysis

Table 2-3. Assessment and flow-management models. Model notation is provided in Table 2-2.

---

**Parameters**

T3.1  $\Theta = \{\lambda_1, v_1, w_N\}$

**Stock-recruitment and flow-survival function estimators**

T3.2  $Y_t = \log(N_{t+1} / F_t)$

T3.3  $\hat{\mathbf{b}} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{F}^T \mathbf{Y}$

T3.4  $\hat{\boldsymbol{\beta}} = (\mathbf{Q}^T \mathbf{Q})^{-1} \mathbf{Q}^T \mathbf{S}'$

**Flow control procedure**

T3.5  $\hat{v} = \hat{\beta}_1 + \hat{\beta}_2 Q + \hat{\beta}_3 Q^2$

T3.6  $\hat{S} = \exp(\hat{v}) / (1 + \exp(\hat{v}))$

T3.7  $\hat{N} = 2 \left( \log 2 - \hat{b}_1 - \log \left[ \bar{f} \hat{S} \right] \right) / \hat{b}_2 \bar{f} \hat{S}$

T3.8  $U(Q) = w_N (\hat{N}) + (1 - w_N) \exp(-v_1 Q)$

T3.9  $Q_{\max} = \max_Q U(Q)$

T3.10  $\tilde{Q}_t = \lambda_1 \tilde{Q}_{t-1} + (1 - \lambda_1) Q_{\max}$

---

Table 2-4. Parameter combinations used to create alternative flow-survival relationships used in sensitivity analysis. The flow survival relationship is presented in equations T1.3-T1.5. Shape 2 (bolded) represents the base case relationship.

Shape	$\beta_1$ -parameter	$\beta_2$ -parameter	$\beta_3$ -parameter
1	-2.32	0.35	-0.02
<b>2</b>	<b>-2.32</b>	<b>0.18</b>	<b>-0.0036</b>
3	-2.32	0.05	0.009
4	-2.32	0.00055	0.014

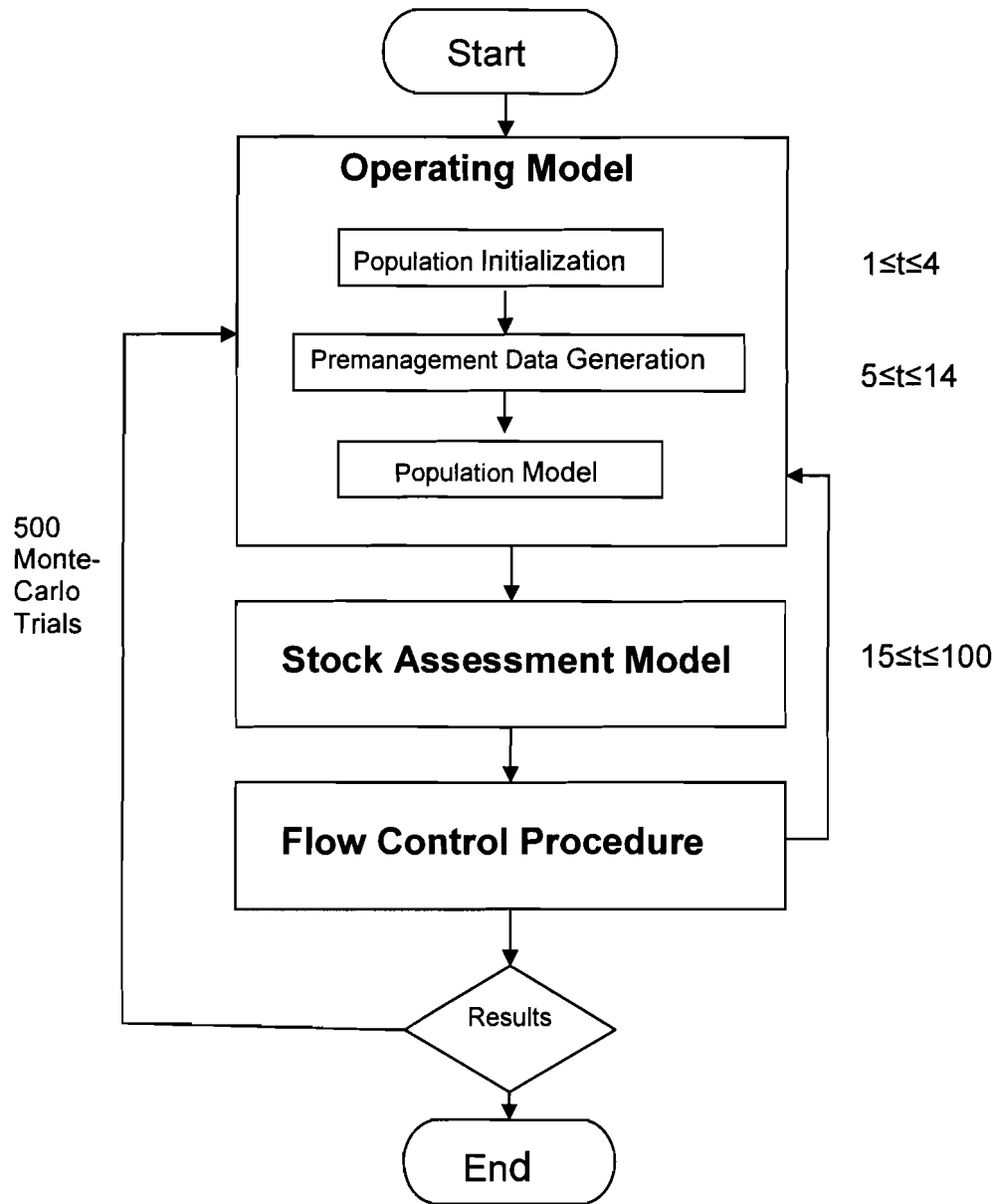


Figure 2-1. A flow diagram for the closed loop simulation model used to i) simulate population dynamics, ii) assess the impacts of flow on that population and iii) implement flow management as a means of controlling kokanee recruitment.

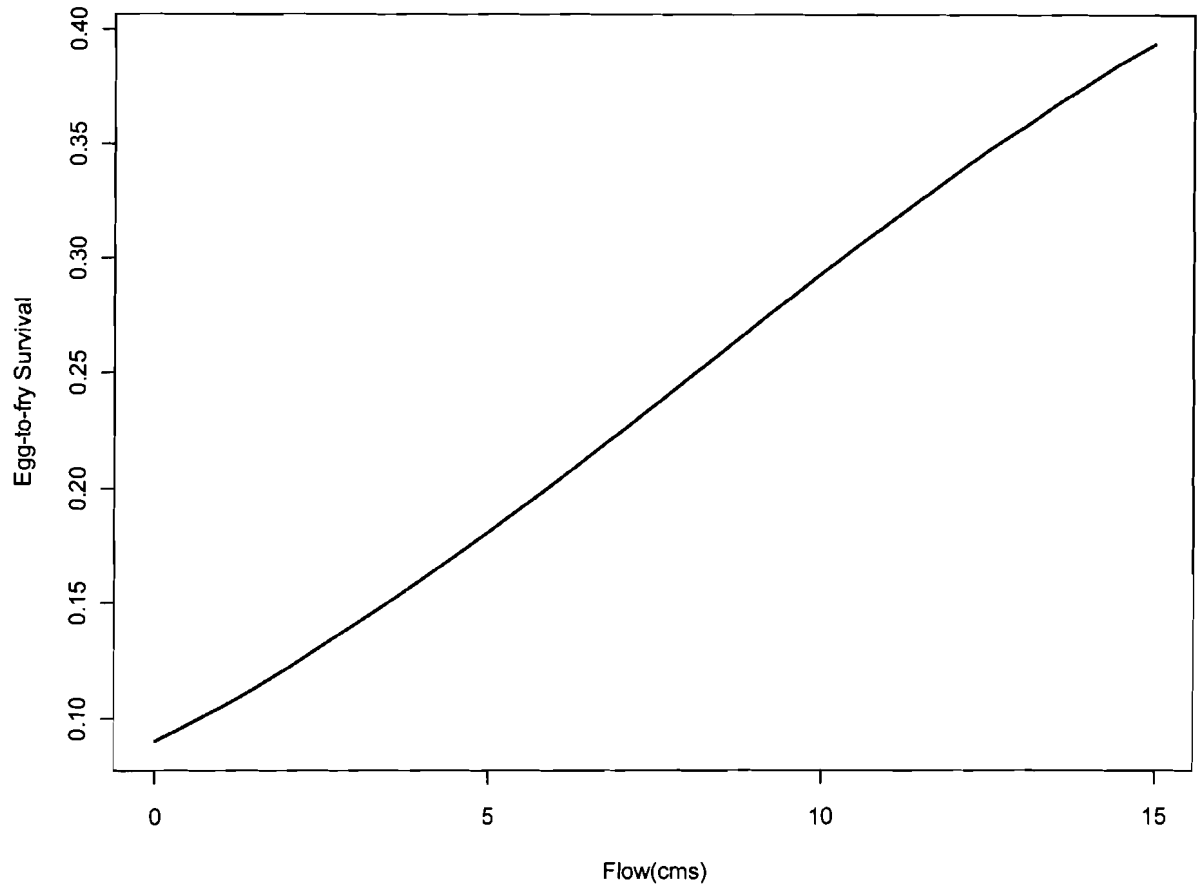


Figure 2-2. Base case relationship between minimum allowable winter flows (cms) and egg-to-fry survival. The relationship is represented by a three parameter logistic function. The base parameters are listed in Table 2-2.



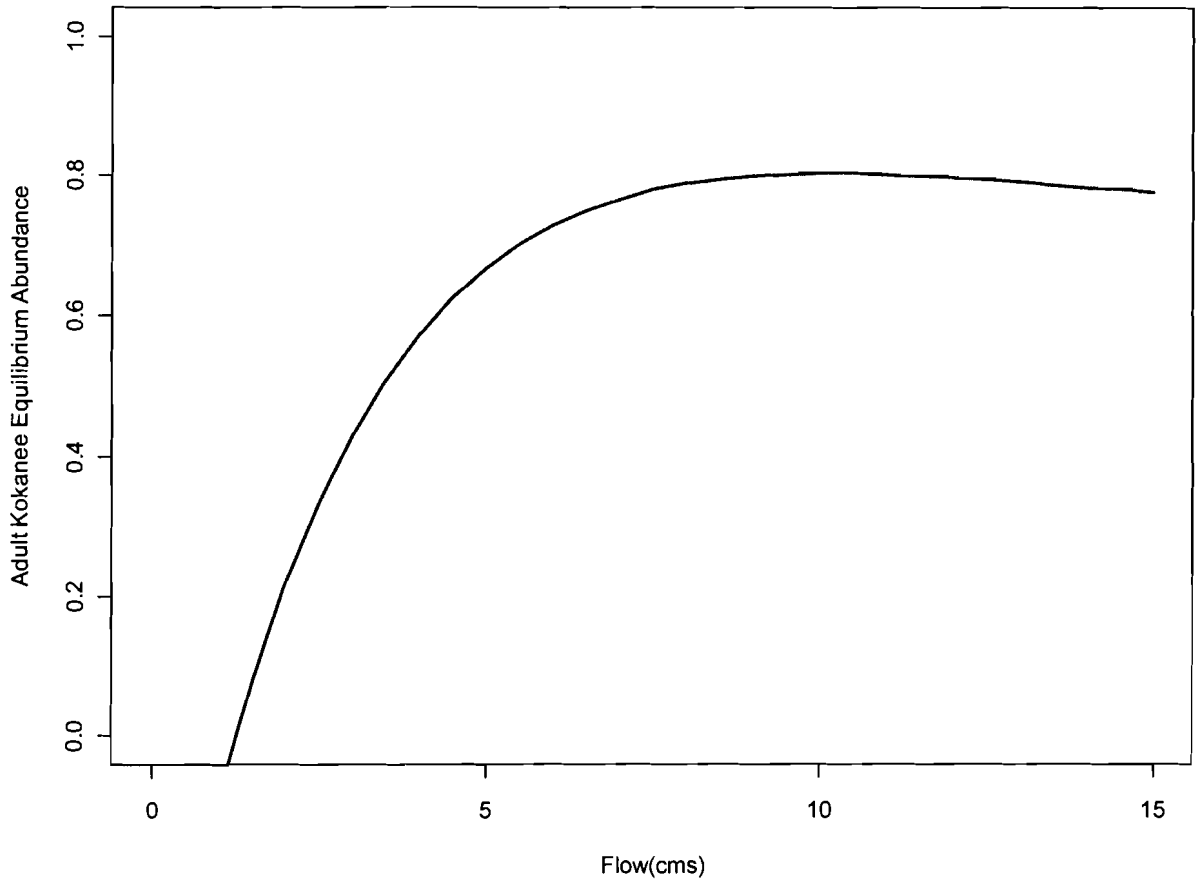


Figure 2-3. Base case relationship between equilibrium abundance (millions) of kokanee and minimum allowable winter flows (cms). Base parameters are listed in table 2-2.

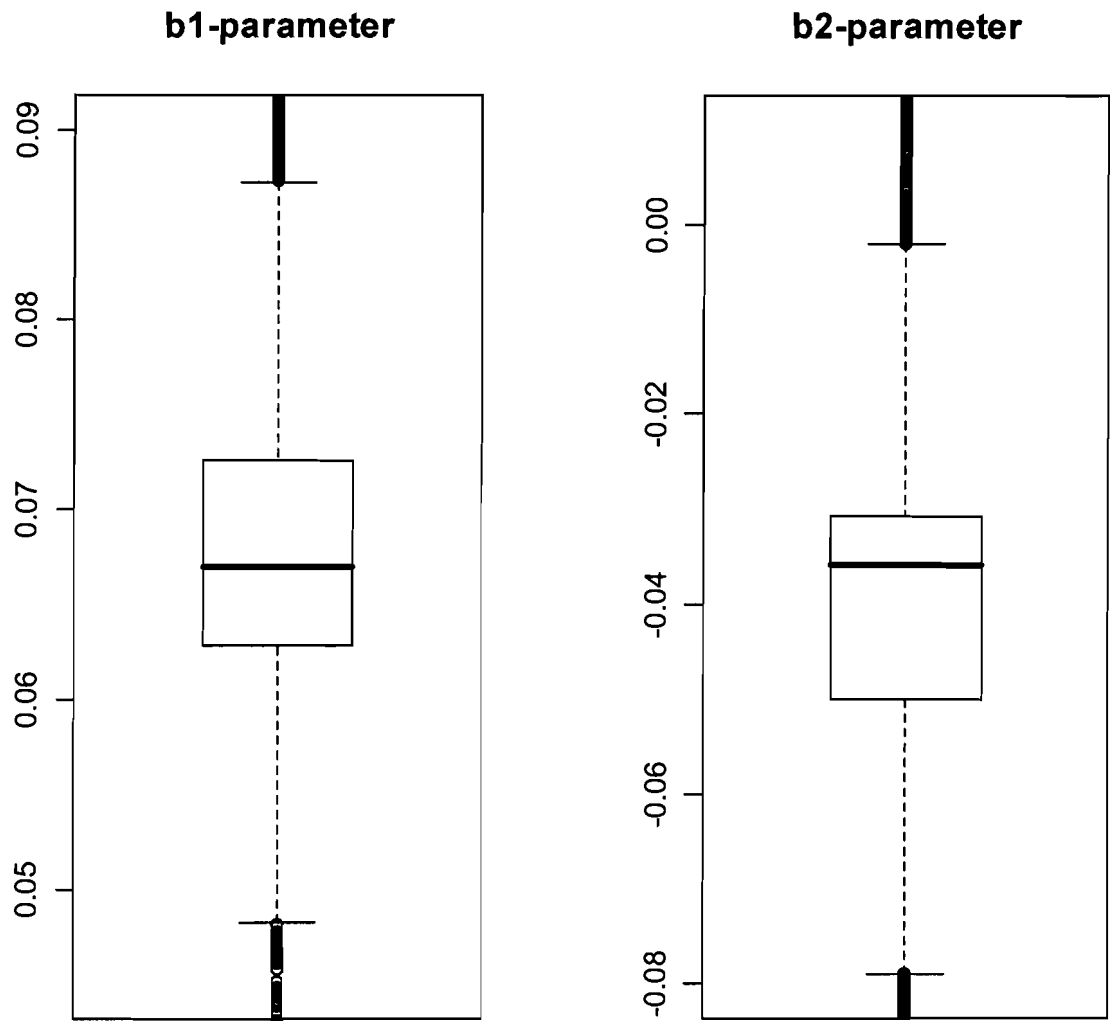


Figure 2-4. Boxplots of the distribution of the stock-recruit parameter estimates from the assessment model. (a) maximum egg-to-fry survival parameter ( $b_1$ ); and (b) the density dependant parameter ( $b_2$ ). The bold line in the middle of the box represents the median, and the top and bottom of the box represents the 25<sup>th</sup> and 75<sup>th</sup> percentile range. The boxplots were constructed using the base parameters from Table 2-2.

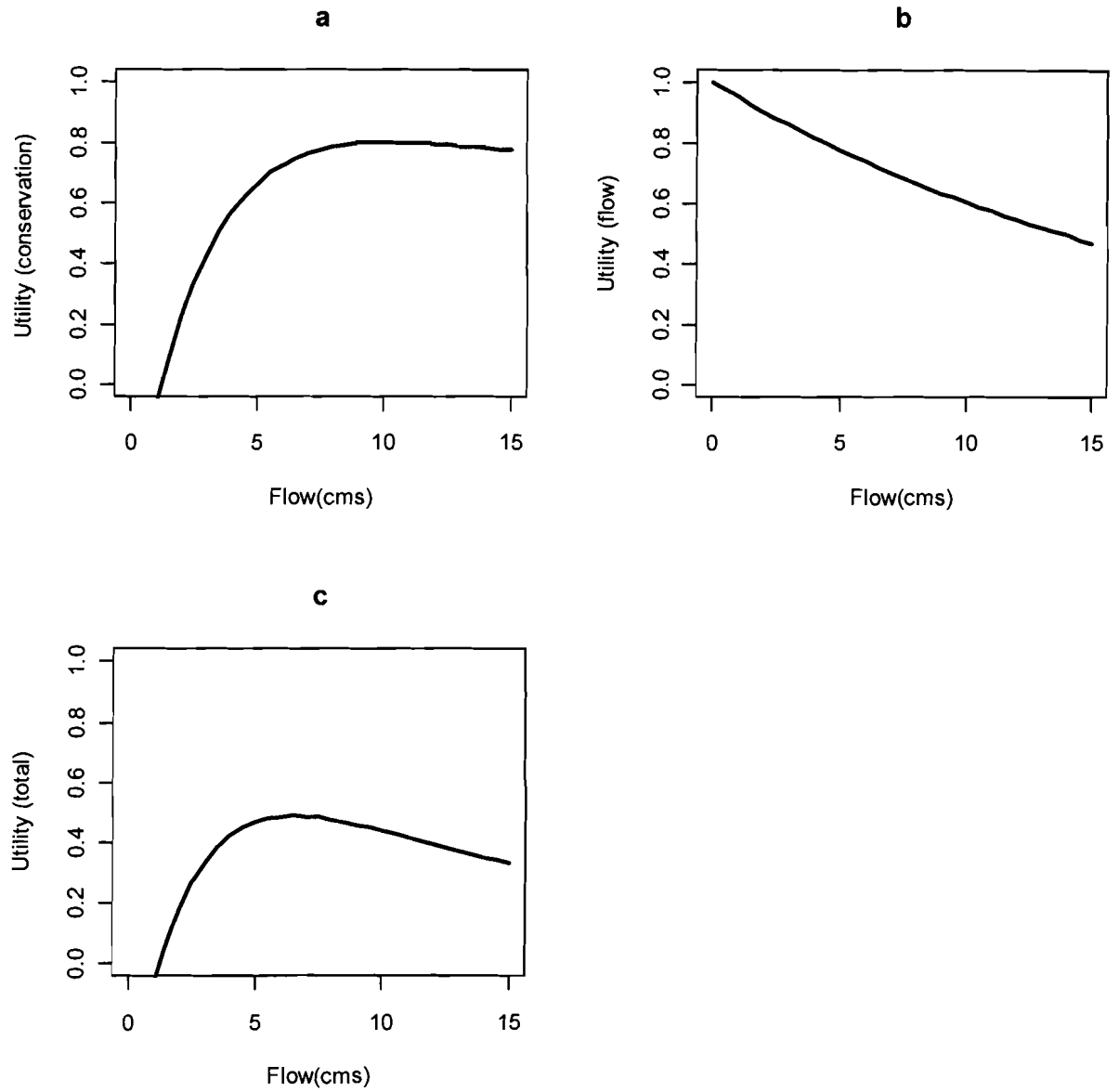


Figure 2-5. The utility functions used in the management model. Figure a) represents the conservation utility over minimum allowable winter flows (cms); b) represents the flow increase utility over minimum winter flows (cms) and c) total utility is represented by the weighted combination of conservation and flow utilities over minimum winter flows (cms).

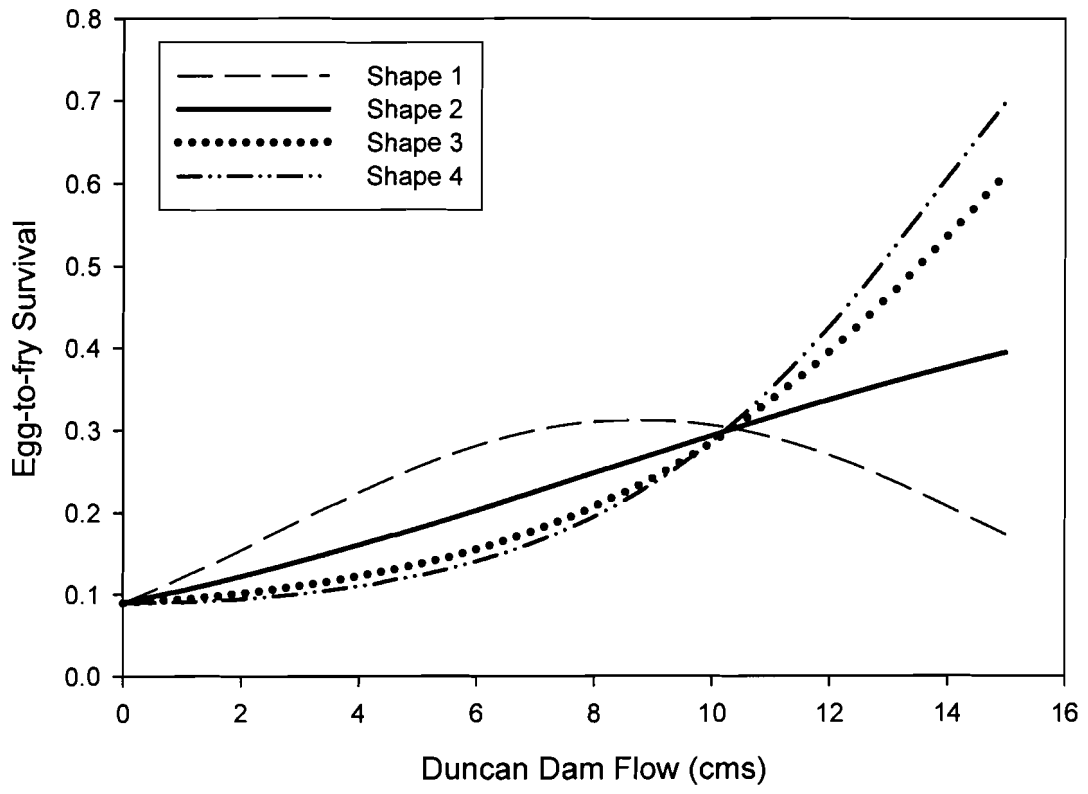


Figure 2-6. Example shapes of different egg-to-survival relationships used in sensitivity analysis. Shapes correspond to parameters listed in Table 2-4. Shape 2 represents the base flow survival function.

## **CHAPTER 3: RESULTS**

### **3.1 Deterministic Results**

Deterministic simulations were run and time series projections were plotted for adult abundance, egg-to-fry survival, minimum winter flow and total utility over 100 years (Figure 3-1). Years 1 to 4 represent the initial four generations of kokanee, while years 5-14 represent the pre-management burn-in period. The management model starts at year 15 and runs to the 100<sup>th</sup> year.

With a lack of stochasticity after initialization, each projection immediately jumps to its optimal solution at year 15. For adult abundance, the optimal solution is the system's true carrying capacity of 800,000 kokanee (as defined by the operating model). The egg-to-fry survival jumps to the maximum value of 0.30, also defined by the operating model. The trajectories show optimal yearly flows, which level off near 10 cms. This eventually leads to a yearly total utility of 0.55. These results represent the behaviour of the model in a best-case scenario and are based on the base case parameters from Table 2-2.

### **3.2 Stochastic Results**

A summary of 500 stochastic Monte-Carlo trials is shown in Figure 3-2. Parameter values were the same as those used in the deterministic model run; however, process error (in the Ricker stock-recruit) and observation error (escapement estimates) were included. The results of this particular example show that the median population recovers to 80% of carrying capacity within 35 years after initialization, however it generally takes longer to reach this objective

than in the deterministic case. Upper and lower 90% envelopes (upper and lower 90% of simulation results) are also shown on each trajectory. In many cases individual simulations fail to return the population to within 80% of  $K$ . This is captured by the lower bound of the 90% envelope.

The four management procedures were evaluated based on three performance measures, and the results are displayed in Table 3-1. Management procedure 1 showed the quickest recovery time (performance measure 1), bringing the population to within 80% of its true carrying capacity in 41.73 years (median result over all simulations), however it also had the highest inter annual flow variability (performance measure 2), a flow of 37.42 (median value over all simulations). This management procedure also proved to be the most successful (performance measure 3) having all simulations reaching the conservation objective of 80% of true carrying capacity within the 100 simulated years.

Management procedure 4 had the longest recovery time (75.84) and the lowest inter-annual flow variability (18.48). This procedure proved unreliable having met the conservation goal only 50% of the time (Table 3-1).

Figure 3-3 provides four contour plots of stock recovery time under different utility weighting combinations, and using four different flow change smoothing parameters. The results suggest that recovery time is minimized for high conservation weights ( $w_N = 0.6 - 1.0$ ), despite the rate of flow increase utility ( $v_1$ ). Below a  $w_N$  of 0.6, the  $v_1$  parameter becomes more influential and drives the recovery time up quickly, in many cases preventing the stock from recovery after 100 years of management. The effect of using different flow smoothing

parameters showed that high  $\lambda_1$  values (such as  $\lambda_1 = 0.9$ ) produced longer recovery times than lower ones (such as  $\lambda_1 = 0.3$ ).

The opposite affect was observed for inter-annual flow variability. High weighting on conservation utility ( $w_N$ ) generated large flow variability (Figure 3-4). This variability decreased as  $w_N$  decreased, especially with an increase in the flow utility parameter ( $v_f$ ). Large differences were observed among differing flow smoothing parameters ( $\lambda_1$ ). At high levels, such as those seen in the example of  $\lambda_1 = 0.9$ , the variability was relatively low having a maximum flow rate variability of approximately 20. At the opposite end, a flow smoothing weight of  $\lambda_1 = 0.3$  produced a maximum inter-annual flow variability of greater than 140.

Figure 3.5 assess the effect of weighting combinations on the number of failed simulations. The results were similar to those observed with the first performance measure. Low numbers of failures were observed at high  $w_N$  weightings, and as these values dropped below 0.6, the number of failures grew until eventually none of the simulated management procedures were recovering the kokanee population to at least 80% of  $K$ . The changing of the  $\lambda_1$  parameter affected performance for conservation utility weightings of  $w_N$  0.6 to 1.0. Within this range, a decrease in  $\lambda_1$  resulted in a decrease in the proportion of failures. Below this range ( $w_N < 0.6$ ), the model was unaffected by changes in the flow smoothing parameter.

### 3.3 Sensitivity Analysis

Model sensitivity for the flow survival relationship was determined by analyzing four alternative logistic functions. Shape 1 represented a convex



representation of the logistic function while shapes 3 and 4 represented more of a concave shape (Figure 2-6.). The model was sensitive to change in function shape. As the shape moved towards the convex maximum, the flow has less influence on the egg-to-fry survival rate. Shape 1 recovered quickly (21 years to recovery) and did so without producing any failed simulations. The opposite was reported for shapes 3 and 4, which were not able to recover the population over any of the simulations, and failed over every simulation.

Biological sensitivity focused on changing the  $b_2$  parameter from the Ricker fry-to-adult relationship. The results showed that the stock recovery time increased with a decrease in the density dependent parameter (Table 3-3). Inter-annual flow variability did not appear to be sensitive to this parameter.

Stochastic sensitivity analysis was performed for the process error standard deviation ( $\sigma_N$ ) and the observation error standard deviation in the operating model ( $T_N$ ). For both parameters, the time to stock recovery increased with an increase in stochasticity (Figure 6). Observation error seemed to have the greater effect on recovery time. Inter-annual flow variability was not sensitive to changes in either error parameter. While the number of unsuccessful simulations were not affected by lower values of  $\sigma_N$  or  $T_N$ , changes were observed at high levels of error (Table 3-3).

Table 3-1. Simulation results for four example management procedures (first column). The management procedures tested include; i) recovery time (years), ii) inter annual flow variation, and iii) proportions of failed simulations. The simulations were run under the base parameters (Table 2-2). Parameters varied include the conservation utility weight ( $w_N$ ) and flow utility weight ( $v_f$ ).

<b>Parameter Values</b>	<b>Recovery Time (years)</b>	<b>Inter-annual Flow Variation</b>	<b>Proportion of failed simulations</b>
$w_N = 0.9$ $v_f = 0.05$	41.73	37.42	0
$w_N = 0.7$ $v_f = 0.05$	48.76	30.82	0.01
$w_N = 0.5$ $v_f = 0.45$	74.14	19.45	0.45
$w_N = 0.5$ $v_f = 0.45$	75.84	18.48	0.50

Table 3-2. Parameter combinations used to create alternative flow-survival relationships used in sensitivity analysis. The flow survival relationship is calculated in Table 2-1. The sensitivity was run under the base parameters from Table 2-2.

<b>Shape</b>	<b>Recovery Time (years)</b>	<b>Inter-annual. Flow Variation</b>	<b>Proportion of failed simulations</b>
1	21.19	21.6	0.0
2	40.27	35.45	0.32
3	>100	2.14	1.0
4	>100	2.01	1.0

Table 3-3. Results of the sensitivity analysis performed on the density dependant stock-recruit parameter ( $b_2$ ) sensitivity analysis. Performance measures tested include; i) recovery time (years); ii) inter-annual flow variation; and iii) proportions of failed simulations.

Parameter	Value	Recovery Time (years)	Inter-annual. Flow Variation	Proportion of failed simulations
$b_2$	-0.2	30.85	38.63	0
	-0.25	36.21	38.15	0
	-0.3	39.58	37.69	0
	-0.35	43.13	37.23	0
	-0.4	47.30	36.8	0
	-0.45	51.60	36.38	0
	-0.5	57.23	35.96	0.026
	-0.55	64.52	35.53	0.026
	-0.6	73.13	35.09	0.08
	-0.65	84.05	34.61	0.28

Table 3-4. Results of sensitivity analysis on model stochasticity. Performance measures tested include; i) recovery time (years); ii) inter-annual flow variation; and iii) proportions of failed simulations. Parameters tested included i) process error standard deviation ( $\sigma_N$ ); and ii) observation error standard deviation in the operating model ( $T_N$ ).

Parameter	Value	Recovery Time (years)	Inter-annual. Flow Variation	Proportion of failed simulations
$\sigma_N$	0.0	36.62	35.09	0
	0.1	38.4	34.37	0
	0.2	39.88	35.10	0
	0.3	36.5	30.67	0
	0.4	41.07	36.38	0
	0.5	42.01	33.66	0
	0.6	43.19	31.58	0
	0.7	45.58	30.84	0.026
	0.8	47.85	31.15	0.026
	0.9	53.29	32.81	0.04
	1.0	58.34	32.08	0.09
$T_N$	0.0	39.92	32.16	0
	0.1	41.73	37.41	0
	0.2	44.76	34.10	0.04
	0.3	48.17	35.96	0.04
	0.4	50.36	33.82	0.04
	0.5	52.99	32.21	0.085
	0.6	54.07	21.68	0.09
	0.7	56.26	23.89	0.11
	0.8	59.33	22.85	0.16
	0.9	61.63	22.96	0.20
	1.0	62.89	22.67	0.23

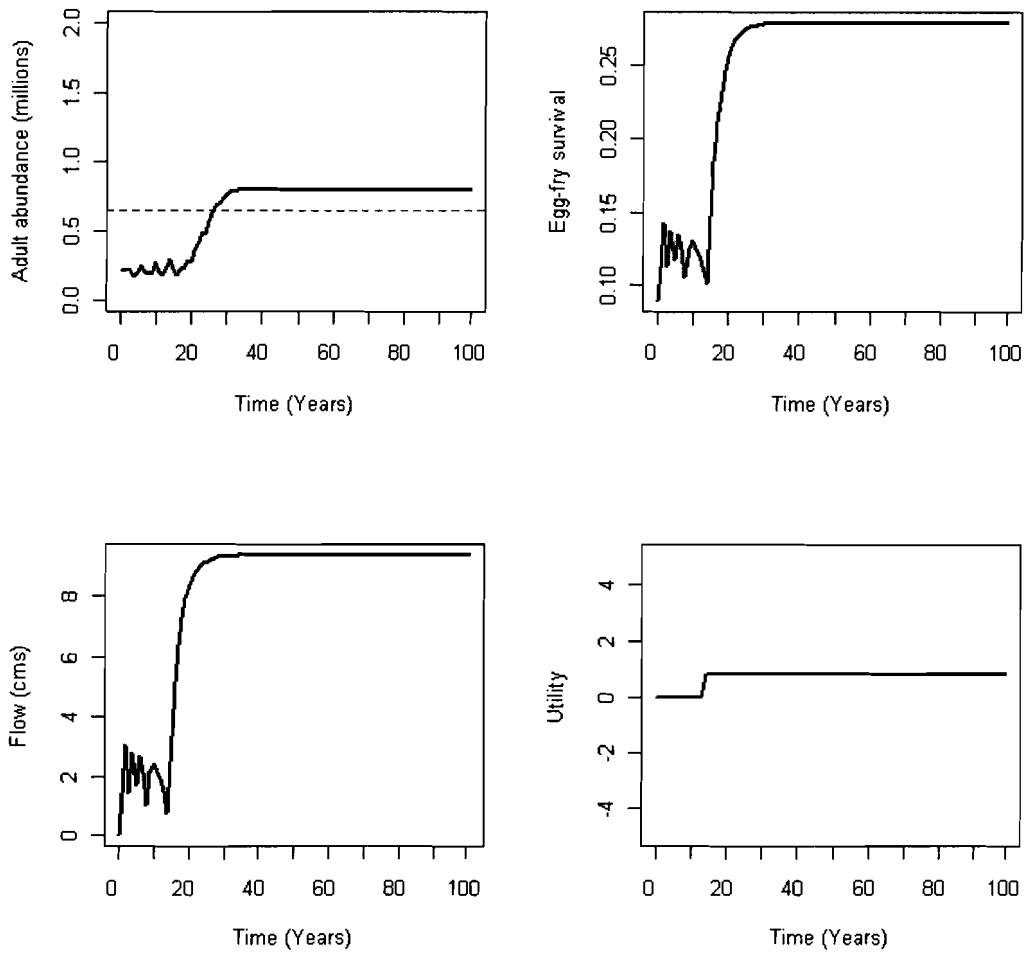


Figure 3-1. Time series plots of adult abundance over time (top left), egg-to-fry-survival over time (top right), minimum winter flow over time (bottom left), and yearly utility (bottom right) for a deterministic scenario. The model was run under base parameters with the exception of the stochastic terms, which have been set to zero, thus representing an errorless system once the management model is initialized. This scenario was run under a conservation weight of  $w_N = 0.9$ , a flow increase utility of  $v_f = 0.05$  and a flow change smoothing parameter of  $\lambda_1 = 0.8$ .

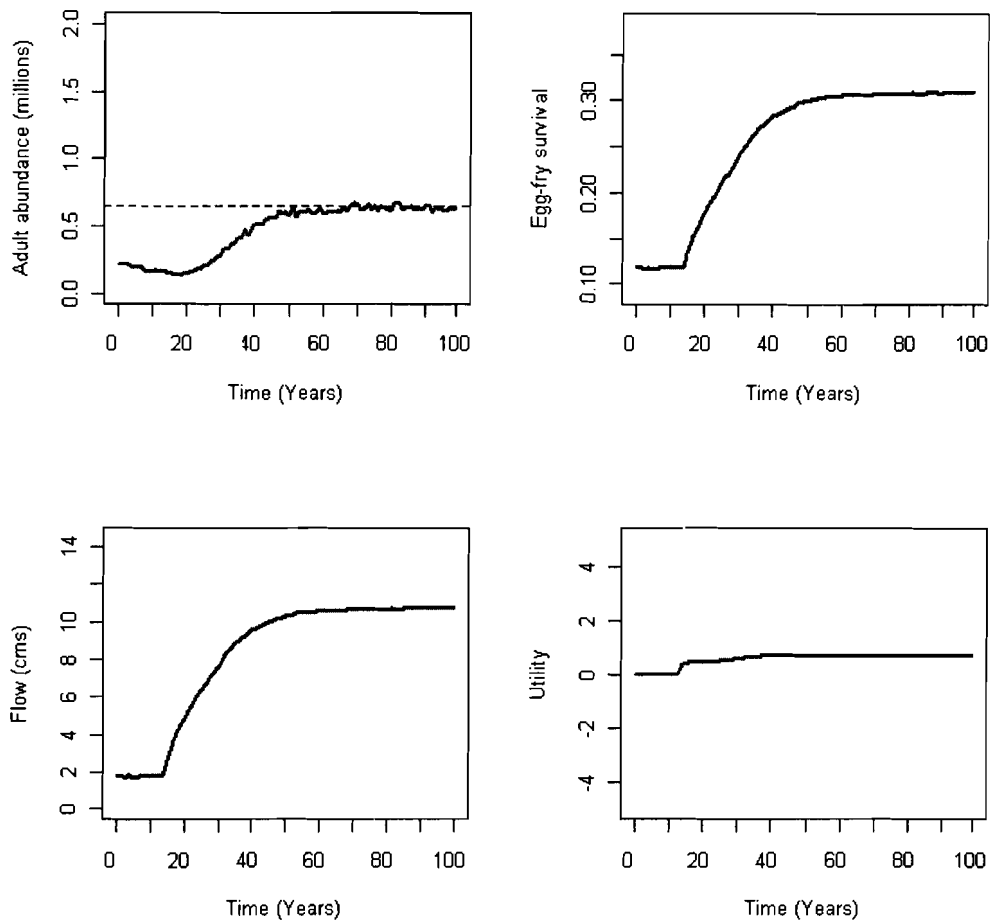


Figure 3-2. Model projections using base parameters. Time series plots of adult abundance over time (top left), egg-to-fry-survival over time (top right), minimum winter flow over time (bottom left), and yearly utility (bottom right) for a stochastic scenario. The solid dark line represents the mean result of the Monte-Carlo trials and the grey shaded area represents the 90% envelope. The blue dashed line in the adult abundance plot represents 80% of the true carrying capacity. This scenario was run under a conservation weight of  $w_N = 0.9$ , a flow increase utility of  $v_f = 0.05$  and a flow change smoothing parameter of  $\lambda_1 = 0.8$ .

Time to Recovery (years)

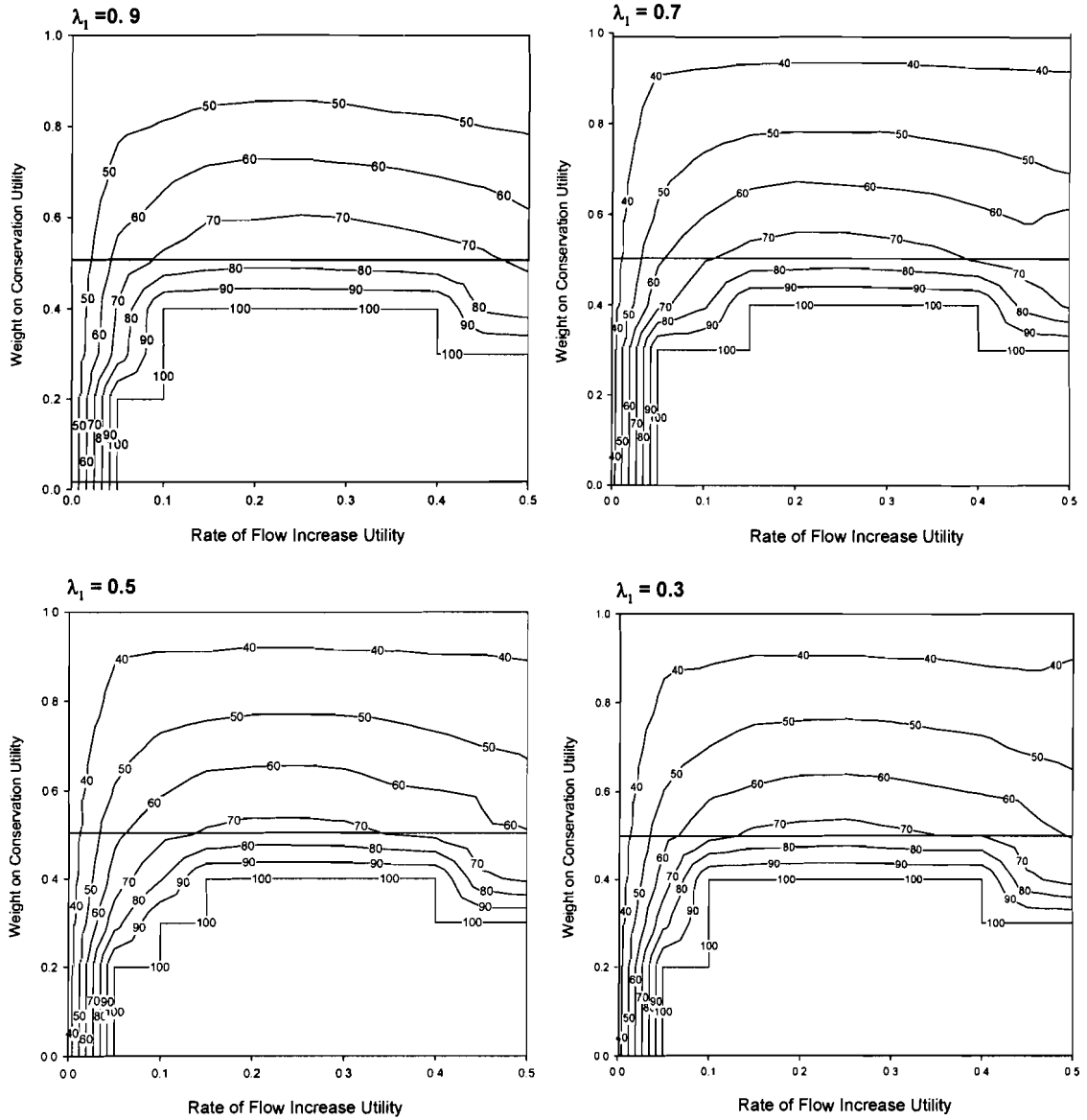


Figure 3-3. Contour plots of years to recovery plotted against flow increase rate and conservation utility weight. Each plot represents a different flow change smoothing parameter ( $\lambda_1$ ). The labelled contours represent the years it takes to recover the kokanee stock to 80% of its true carrying capacity. Horizontal black line represents a 50% weighting on conservation and flow increase utility.



Inter annual flow variability

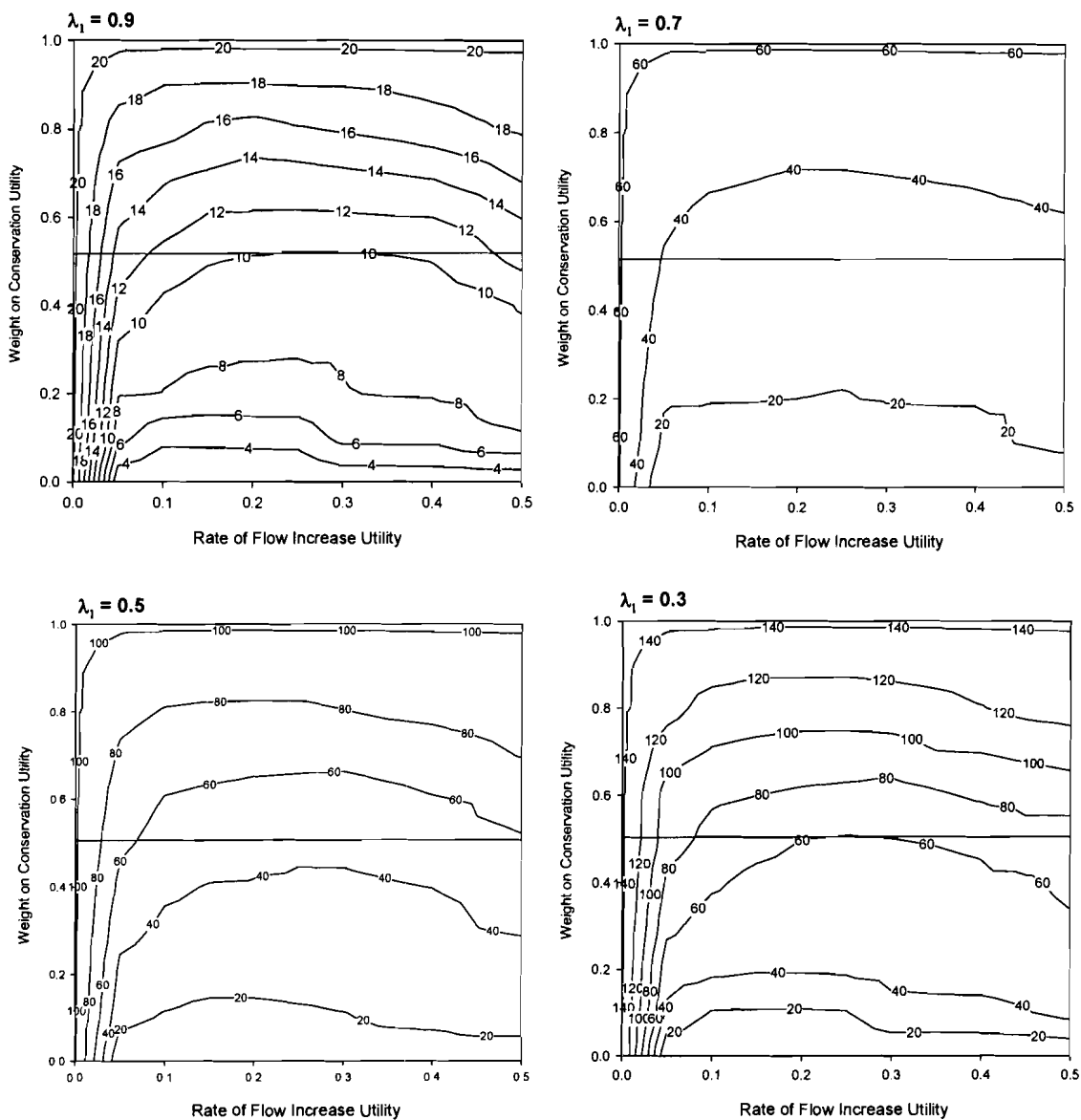


Figure 3-4. Contour plots of inter-annual flow variability against flow increase rate and conservation utility weight. Each plot represents a different flow change smoothing parameter ( $\lambda_1$ ). Horizontal black line represents a 50% weighting on conservation and flow increase utility.

Proportion of unsuccessful simulations

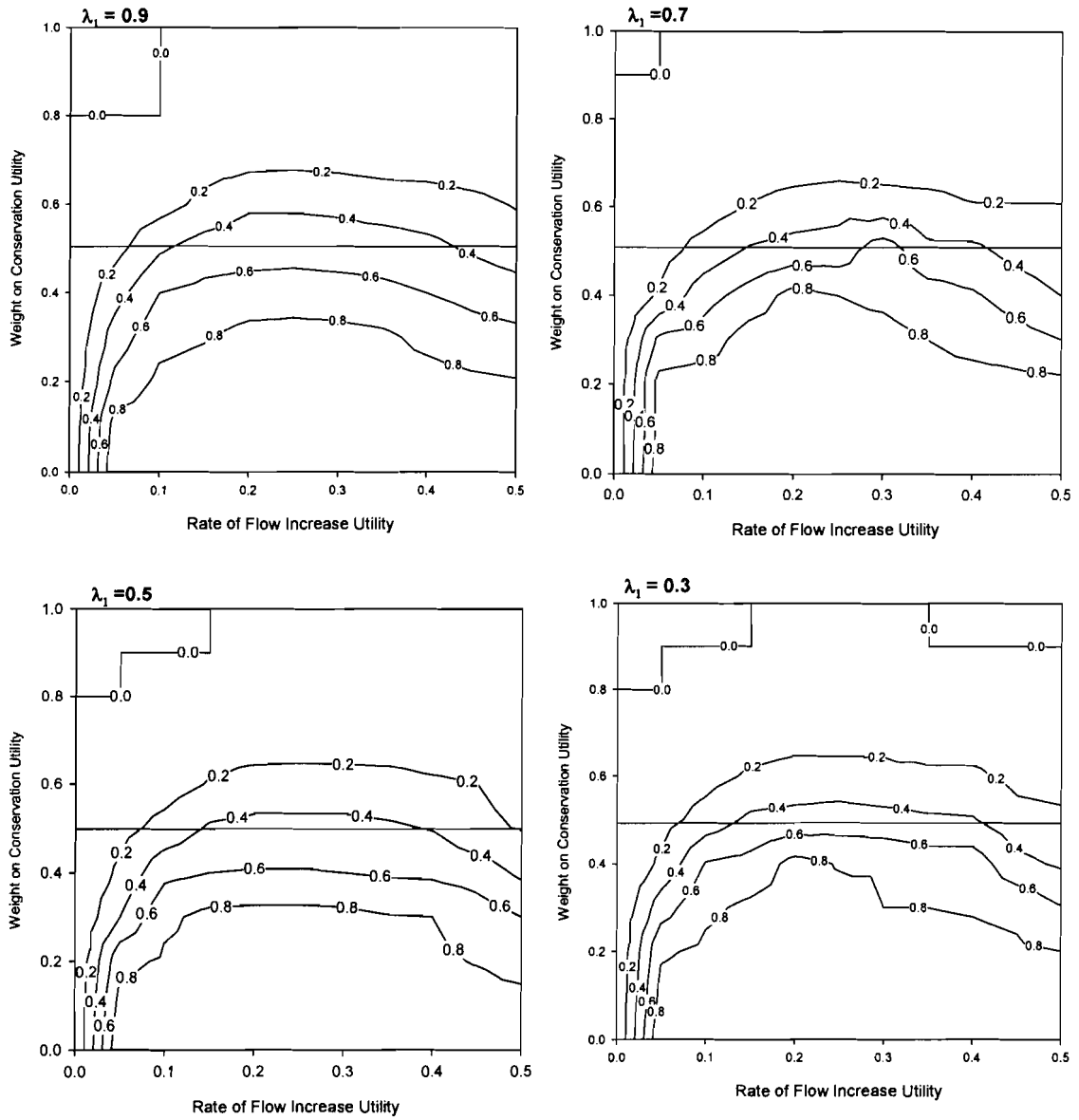


Figure 3-5. Contour plots of proportion of unsuccessful simulations against flow increase rate and conservation utility weight. Each plot represents a different flow change smoothing parameter ( $\lambda_1$ ). The labelled contours represent the proportion of simulations that fail to meet the conservation objective of bringing the kokanee abundance to or above 80% of the true carrying capacity. Horizontal black line represents a 50% weighting on conservation and flow increase utility.

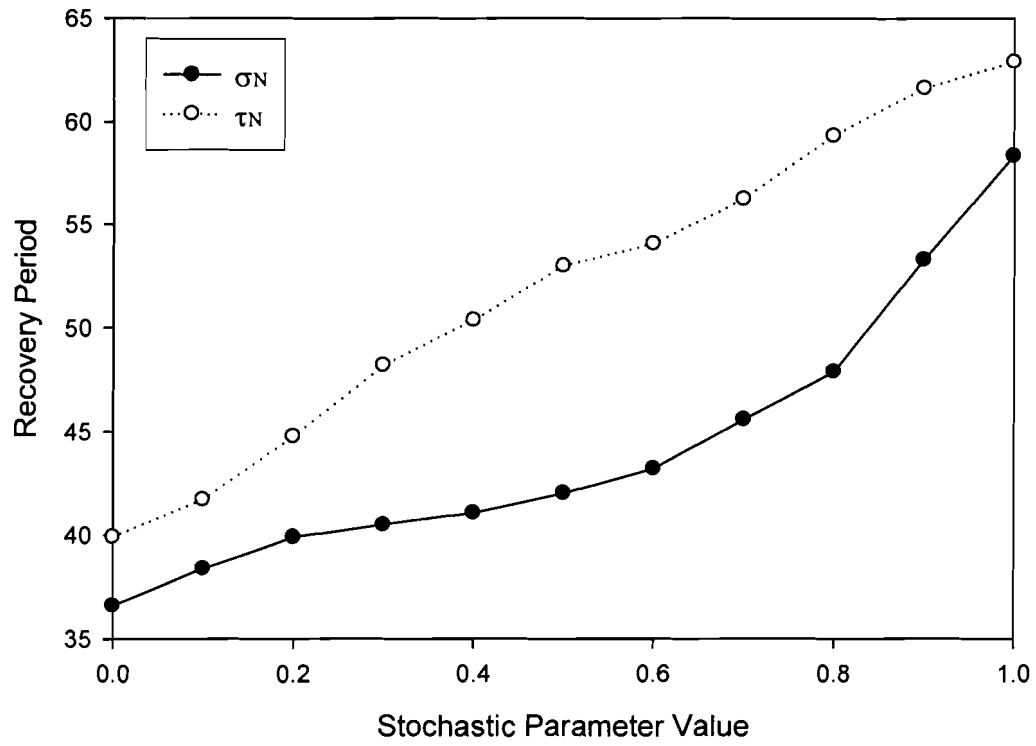


Figure 3-6. Sensitivity analysis results for different levels of model stochasticity. Plot is of error term (process- $\tau_N$ , and observation- $\sigma_N$ ) vs time to stock recovery. Recovery time is measured in years.

## **CHAPTER 4: DISCUSSION**

## **4.1 Model Results**

### **4.1.1 General Results**

Since 2002, flow management within the Lower Duncan River has been used to reduce fall flows and decrease over-winter egg dewatering. This has been done at a cost of reductions in available spawning habitat. A likely result of this reduction is an overall decrease in kokanee recruitment. Flow management that increases the minimum winter flows from the Duncan Dam would be needed to optimize kokanee recruitment within the north arm of Kootenay Lake. The model developed for this project acts to provide a framework to answer questions about flow requirements and the conservation and nonconservation consequences of flow management within a dam operated system such as the Lower Duncan River.

The concept of increasing flows to enhance kokanee recruitment is not new. In Lake Pend Oreille, for example, mean flow was increased to create more spawning habitat, which led to an increase in the kokanee population (Maiolie et al., 1998). Managers of the Lake Pend Oreille system made the decision to raise the lake levels based on a theory that more spawning habitat would provide greater adult returns. The model developed in this project attempts to provide a tool for which a manager can take biological and hydrological information and project the expected outcomes under various management actions, like those attempted in Lake Pend Oreille. By using a simulation approach, a manager would be better equipped to make flow control decisions for the system.

The simulation procedure started with a pre-management kokanee population that was in a depleted state due to historical low minimum winter flow levels. The true carrying capacity as defined in the operating model represented the ultimate goal in the recovery of the kokanee stock. The assessment model component used yearly monitoring information on spawning abundance, egg-fry survival, and recruitment to optimize flow such that conservation (i.e., recruitment levels) and flow utility goals are most likely to be met. In deterministic simulations minimum winter flows increased soon after the management system was initiated and an optimal flow value was reached that corresponded to the maximum egg-to-fry survival as defined by the operating model. The novel aspect of this behaviour is that the simulated management control system (i.e., monitoring-assessment-management) was able to find these "optimal" flow levels corresponding based on accumulated monitoring data alone. In this case, the population approached the true carrying capacity rapidly because the management system was based on perfect monitoring data (i.e., egg-fry survival and spawner abundance) and the assessment model used an identical (Ricker) model structure as the operating model.

An important test of "robustness" of the management system is to examine the range of performance when stochasticity is introduced to several components of the simulation including monitoring data and population dynamics. In most of these stochastic simulations, mean recovery times were considerably longer and in some cases the populations did not recover to the management goal of 80% of carrying capacity within the 100-year simulation time

horizon. In other cases, simulated populations over-shot the true carrying capacity. Large variation among the trajectories was mainly due to the large process error standard deviation derived from the original stock recruit analysis for Meadow Creek kokanee. However, my original stock-recruit analysis assumed that all deviations from the expected Ricker relationship were due to process errors only; thus, the standard deviation from original model fits probably over-estimated the range of variation in the population dynamics. That is, some of the variation in the original data was due to observation errors that should have no impact on projected kokanee population variability. Alternative estimation methods such as an errors-in-variable approach would allow for separating process and observation errors. Such analyses would ultimately provide lower process error variances and a smaller range of variation in the simulated outcomes.

Simulated management strategies showed the expected trade-offs between conservation and non-conservation outcomes. However, under the simulated management control system, a manager could choose where to operate along these trade-offs by altering the weightings placed on conservation and non-conservation objectives. When assessing time to stock recovery, the obvious choice is to place a conservation weighting as close to 1.0 as possible because it minimizes time to recovery (to 80% of  $K$ ). This is then traded-off against the results of the inter-annual flow variability. A quick recovery can satisfy conservation goals; however, it can come at a cost of a reduction in water use controllability. This would not be ideal for non-conservation oriented water use

concerns. From here, it is up to the WUP committee members to make these trade-offs.

#### **4.1.2 Sensitivity**

Performance of management strategies were most sensitive to changes in the shape of the egg-to-fry survival relationship. As the logistic function moved away from the base case towards a convex shape, the time to stock recovery decreased. For the convex shape, the recovery time was just over 20 years. This was because egg-to-fry survival was higher for low flow rates than it was in the base and concave versions of the logistic shape. The model then initiated at a low flow, which produced a large survival rate, making stock recovery easy, as the population was never at low abundances to begin with. As the flow-survival relationship moved towards a concave shape the opposite effect was observed where egg-to-fry survival was low for more minimum flow values, and thus recovery time was longer. For both of the concave shapes the egg-to-fry survival was sufficiently low which kept the stock from recovering.

The density dependent parameter ( $b_2$ ) was used to test for biological sensitivity. This was done while holding the maximum fry-to-adult survival ( $b_1$ ) constant. I chose to run the sensitivity analysis under the assumption that the maximum fry-to-adult survival was similar for both Meadow Creek and the Lower Duncan River. Since the fry-to-adult portion of the life stage is spent in open water, we can suggest that kokanee from both tributaries would be spending their time in the northern section of Kootenay Lake, and thus be subjected to similar conditions that affect survival.



I choose two stochastic parameters for my sensitivity analysis, both being errors within the stock-recruit relationship. The reason for choosing these was to compare their effects on time to recovery. The results suggest that time to recovery was more sensitive to observation error ( $\tau_N$ ) than process error ( $\sigma_N$ ). This suggests that implementing programs to collect better spawner data would be beneficial as this could help to reduce observation error, which happens to have the bigger impact of the model performance. However, future analyses should not apply such a double accounting for stochasticity because the process error term likely contains some observation error as noted above.

## **4.2 Management Actions and the WUP**

My simulation analysis cannot provide specific results to be used within a specific WUP, because the data used to run the model was not from any specific system. However, my results do suggest how simulation modelling can be used within a WUP context. Four types of results are emergent from the model including proportions of failures, time to recovery, inter-annual flow variability, and the flow requirements from the management decisions. Proportion of failed simulations provides a measure of confidence in a proposed strategy where, if a strategy provides a high proportion of failures, then its potential value would be decreased. The time to recovery and the flow requirements would likely provide the most useful information for the WUP committee. Clear expectations for how long a recovery will take, and the flow requirements for that recovery, can be directly introduced into the process when making trade-offs with other issues.

However, it is important to note that in addressing trade-offs with non-conservation issues there would likely be the need for other sub-models that present seasonal flow requirements for other water uses. For example, such sub-models could include storage requirements (for example, as directed by the Columbia River Treaty), flow requirements for flood and mosquito control, flow requirements for erosion control, and seasonal flow requirements for First Nations issues. Once these sub-models were included direct conflicts for water uses would be revealed, and tradeoffs could be made.

### **4.3 Relevance to the Duncan System and the WUP**

The second objective of my project was to assess the data requirements to set this model framework in terms of the Duncan System. To address this, I will discuss model assumptions and limitations, and suggest data collection that will help make the model relevant to the Lower Duncan system. As is generally the case with simulation models, several assumptions were made during model development. Some of these can be investigated, modified, and eventually implemented into the model to create a more realistic representation of the Lower Duncan system.

First, I assumed that kokanee within the Lower Duncan River are of a different genetic stock than kokanee spawning within the Lardeau River and Meadow Creek. Using this assumption, I was able to implement flow management exclusively within the Lower Duncan River. Vernon (1957) used morphometric features to suggest that kokanee in the north arm of Kootenay Lake are likely from one distinct stock, and that there was likely mixing among

those spawning in the Duncan River tributaries (i.e., without the dam, the Lower Duncan River was just the Duncan River). A follow-up study confirming stock structure and identity needs to be done. Testing to determine genetically distinct stocks have been successfully conducted on other systems within British Columbia, including Okanagan Lake (Taylor et al., 1996). If sufficient evidence is provided to suggest that kokanee from Meadow Creek, Lardeau River, and the Lower Duncan River are from the same genetic stock then there would be no need for flow management since only a small fraction of the "Duncan System" population would be affected by flows from Duncan Dam. Since 2002, escapement data suggests that less than 1% (mean=0.96%,  $\sigma=0.99\%$ ) of the total yearly spawners for Meadow Creek, the Lower Duncan River, and the Lardeau River come from the Lower Duncan River, and thus less than 1% of the population is affected by dam operations. Until such an investigation is complete, the assumption must be made that the three tributaries are distinct, and thus should be managed that way.

The second model assumption is that of the total utility function. Total utility is calculated by weighting and combining the conservation and flow increase utilities. The flow increase utility assumes that as minimum winter flow increases, there is a decrease in utility. This was done to imply that any change in facility control (e.g., increasing minimum winter flow) would decrease flexibility in how the dam could be operated, and in turn could lead to economic and social costs. This simplifies the model. It should be noted that there can also be positive consequences to increasing minimum allowable winter flows. Ideally, during the

WUP process, more precise utility functions can be created that will allow for a more accurate trade off between competing water uses.

The third model assumption is the flow-survival relationship, which is a vital part of the simulation because it plays an important role in determining the number of eggs that will survive to become fry. This indirectly affects the number of adults that make it back to spawn. This relationship is somewhat arbitrary; the maximum egg-to-fry survival was estimated from Meadow Creek data and the alternative shapes of the function were chosen subjectively. Future work would involve field investigations designed to produce a more representative relationship. Alternatively, one could use further simulation analyses to determine whether the assumed asymptotic relationship in the assessment model is "good enough". This would require examining other management procedures that are not as seriously affected by the "true" underlying functional relationship.

A fourth limitation to this model is an assumption that there were no age class interactions. Once fry become juveniles, they head out to a pelagic environment and do not compete for food and habitat with kokanee of other age classes (or at least to the extent where other cohorts affect survival in the lake). With these interactions comes varying degrees of mortality since they often lead to less food and reduced residence habitat. To account for this variable mortality, future model work may include age class interactions during the fry to adult stage.

A fifth influential limitation within this model was the assumption that all kokanee spawn at year 4. In the case of the data used in the simulation model,

the average age of recruitment was 4; however, some kokanee mature one year early and some one year later. The proportions of non-4 year old kokanee should be taken into account when running population trajectories.

Apart from the above mentioned model assumptions, data collection is needed to add strength to the biological parameters used within the model. Continued escapement estimation is needed to decrease observation errors in spawner data and thus the estimated stock-recruit relationship. Data used for maximum egg-to-fry survival and fecundity were estimates derived from the Meadow Creek spawning channel. These need to be collected specifically for the Lower Duncan system, although they would likely be similar.

With additional data collection and the further development of ideal utility functions, this Lower Duncan River kokanee flow management model can provide a useful tool in the planning of the next Duncan Dam water use plan.

## APPENDICES

### Appendix A

Parameters used in calculation of adult abundance (T1.7) within the operating model were derived from a typical Ricker type stock-recruit relationship. This was done under the assumption that there exists a biological relationship between kokanee stock at time  $t$  and the subsequent recruitment at time  $t+4$ . For equation T1.7 I was interested in the relationship between fry abundance (stock) at time  $t$  and the adult spawner abundance (recruitment) at time  $t+4$ .

Plotting fry abundance against adult recruitment we can fit an average relationship that describes the stock-recruit relationship (Myers and Barrowman, 1996). Several stock recruitment models exist including the Ricker (Ricker, 1954), Beverton-Holt (Beverton and Holt, 1957) and Deriso (Deriso, 1980) model. Each model has its own biological interpretation of the relationship and have been used to describe the behaviour of various fish stocks including pacific salmon, halibut and herring (Hilborn and Walters, 1992, pp 253-256). The Ricker model is generally used to describe the stock recruit relationship for sockeye salmon, and thus I chose that function for my kokanee model.

The Ricker relationship uses stock recruit data to determine the maximum fry-to-adult survival ( $b_1$ ), density dependence ( $b_2$ ), variability within this relationship ( $\sigma_N$ ), and a measure of the stock's carrying capacity ( $K$ ). The data used in parameter calculations came from the Meadow Creek spawning channel.

Fry abundance was determined using yearly counts of eggs deposited and an estimate of egg-to-fry survival. The egg-to-fry survival was estimated using emergence trap experiments. Adult spawning stock was directly measured at the Meadow Creek counting fence. The fry and adult data used in the stock recruit analysis is presented in table A-1.

The data was plotted and the average relationship was inserted using the Ricker Model, as described in equation A.1. The relationship is illustrated in figure A-1.

$$R = b_1 S * \exp(b_2 S) \quad (\text{Equation A.1})$$

where  $R$  represents adults at  $t+4$ ,  $S$  represents the fry stock at time  $t$ ,  $b_1$  is the maximum fry-to-adult survival rate parameter and  $b_2$  is the density dependence parameter. In order to estimate the values of  $b_1$ ,  $b_2$ ,  $K$  and  $\sigma_N$ , I took the natural logarithm of equation A.1 and calculated the log of recruits per spawner, as described in Equation A.2. This form of the stock recruit relationship is linear and the parameters can be estimated using a simple linear regression. The relationship between fry abundance and log adults / fry is illustrated in figure A-2.

$$\ln\left(\frac{R}{S}\right) = \ln b_1 + b_2 S \quad (\text{Equation A-2})$$

The results of the linear regression provide parameter estimates for  $\ln b_1$ ,  $b_2$  and  $\sigma_N$ . To calculate the carrying for the kokanee stock, I used the estimates of  $b_1$  and  $b_2$ , as well as the average egg-to-fry survival (0.302) and fecundity  $\bar{f}$  (255 eggs/female) as measured for the Meadow Creek spawning channel. These values were then placed in equation A-3 to obtain the estimate of  $K$ .

$$2\left(\log 2 - b_1 - \log[\bar{f}\bar{S}]\right) / b_2 \bar{f}\bar{S} \quad (\text{Equation A-3})$$

By using a bootstrap method I resampled the fry and subsequent adult recruitment data sets 100 times, each time running through Equations A-1 to A-3 and produced distributions for all four parameters. From these distributions I was able to calculate upper and lower confidence limits for each parameter. The results are displayed in table A-2.



Table A-1. Kokanee fry and spawner abundance estimates used in the calculation of the stock-recruit parameters used within the operating model.

Year	Fry Abundance (millions)	Spawner Abundance (millions)
1985	35.5	9.2
1986	7.3	9.9
1987	3.7	7.6
1988	4.6	18.9
1989	9.2	46.4
1990	9.9	55.9
1991	7.6	37.6
1992	18.9	35.6
1993	46.4	15.5
1994	55.9	43.5
1995	37.6	38.4
1996	35.6	32.9
1997	15.5	29
1998	43.5	20.8
1999	38.4	24.1

Table A-2. Estimated Ricker stock-recruit parameters for the Meadow Creek Spawning Channel. Parameters were estimated using the log transformed Ricker function, and the upper and lower 95% confidence intervals were obtained using a boot strap resampling method. The  $b_1$  parameter represents the maximum fry-to-adult survival rate,  $b_2$  represents the density dependence parameter,  $\sigma_N$  represents the variability within the model fit, and  $K$  is the carrying capacity in millions.

Parameter	Estimate	Upper 95 % Confidence Limit	Lower 95 % Confidence Limit
$b_1$	0.072	0.08	0.064
$b_2$	-0.033	-0.038	-0.029
$K$	0.801	0.779	0.826
$\sigma_N$	0.469	0.479	0.390

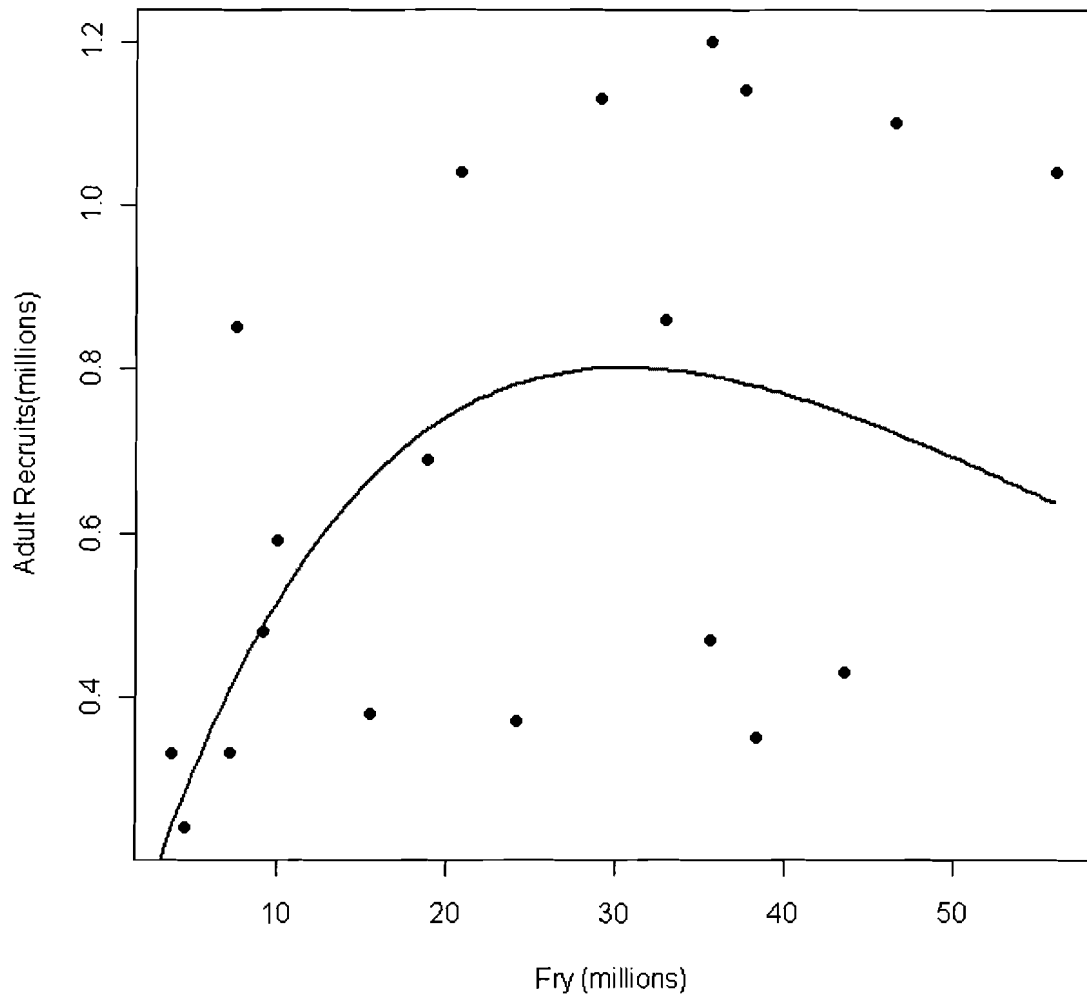


Figure A-1. The Ricker type stock-recruit function for the Meadow Creek spawning channel data. The function describes the relationship between spawning stock and subsequent recruitment at time  $t+4$ .

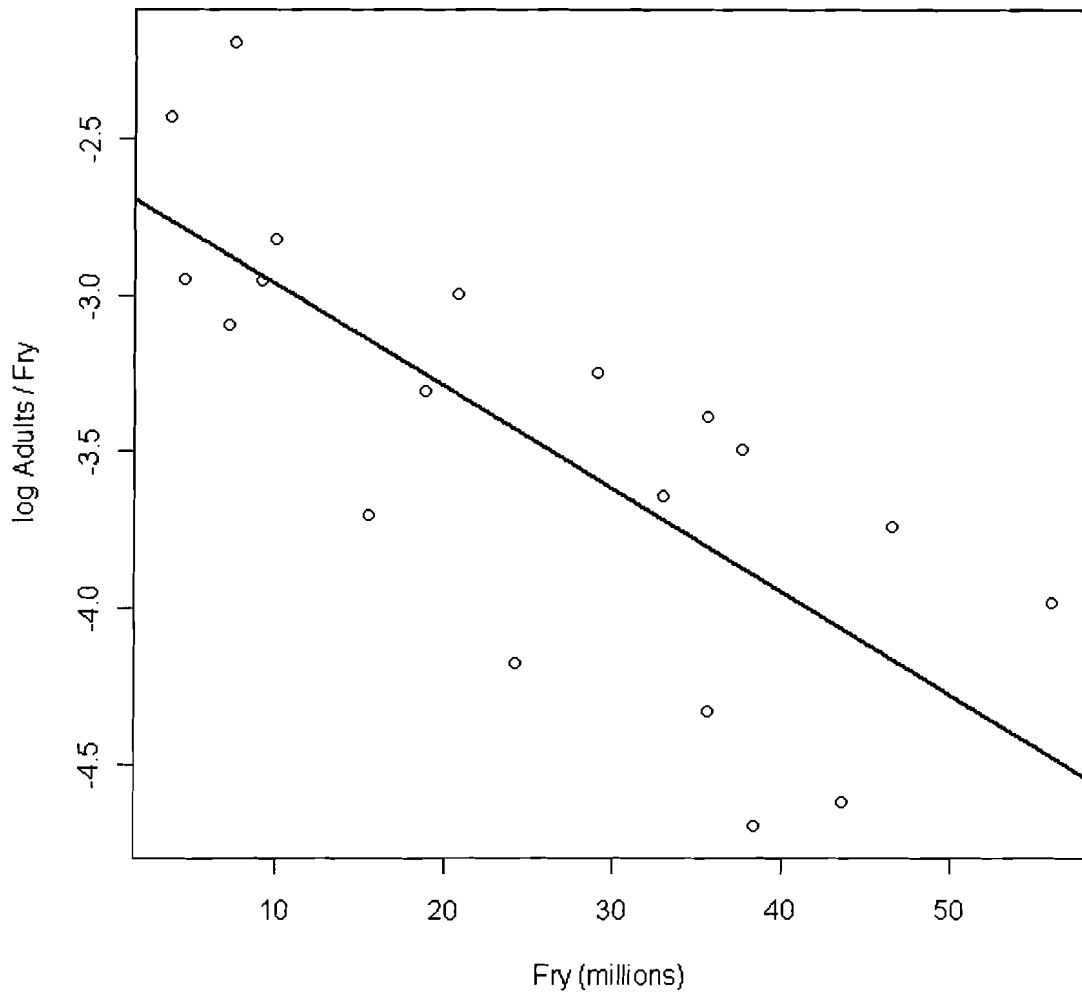


Figure A-2. Ricker type stock recruit relationship using log transformed data. The average relationship (blue line) is now a linear function and a simple regression analysis can be used to determine estimates of  $b_1$ ,  $b_2$ , and  $K$ .

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