Sockeye Salmon Stock Status and Escapement Goal for Redoubt Lake in Southeast Alaska

by
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ABSTRACT

A Ricker stock-recruit model was used to analyze 20 years of catch and escapement observations. A sustained escapement of 17,400 produces the maximum sustainable catch for the estimated Ricker model. The range of consistent escapements expected to produce at least 90% of the maximum sustainable catch is approximately 10 to 25 thousand spawners. For that reason, this range is recommended as a *biological escapement goal* for the Redoubt Lake sockeye stock. The lake was intensively fertilized during most years when stock-recruit observations were made, but this program was discontinued from 1996 through 1998. A subsequent, less intense, fertilization program was started in 1999, using different delivery mechanisms and application levels. If the new fertilization program has a substantially different effect on lake productivity, or if this new program is discontinued, then the recommended escapement goal may fall far short of producing the maximum sustainable catch. Stock-recruitment data should continue to be collected for the system, and the escapement goal range should be re-examined after several years of returns under the new fertilization regime, and on a periodic basis thereafter, irrespective of the fertilization program pursued in the future.

INTRODUCTION

Redoubt Lake is a large sockeye-producing system located about 11 km south of Sitka, Alaska, just inside the southwest entrance to Sitka Sound on the west coast of Baranof Island (Figure 1). The lake has a drainage area of about 113 km^2, a volume of 2,311 hm^3, a surface area of about 16.6 km^2 (McCoy 1977) and a maximum depth of approximately 266 meters. The lake is meromictic, with an approximately 100 m deep freshwater lens that overlays a bottom layer of dense, anoxic water.

Redoubt Lake has a long history of human use. Rich and Ball (1932) stated the following:

> Redoubt Bay, into which Redoubt Lake empties, was one of the first fishery localities to be exploited in all Alaska. In the early days of Alaskan exploration and the founding of the settlement at Sitka, the Russians depended very largely upon the red salmon of Redoubt for a supply of fish. The stream was barricaded and fished unrestrictedly without the slightest regard for the preservation of the run of salmon. The inevitable result of this reckless fishing which continued and reached its height several years after Alaska was sold to the United States was the virtual destruction of the salmon runs. Even in 1889 and 1890 the supply of fish was insufficient for the profitable operation of a small cannery and as long ago as 1900 the production of salmon here had dropped almost to the vanishing point. After the approval of the act of Congress of 1906, making barricades in streams unlawful, and giving other protection to the salmon fisheries of Alaska, there was some slight improvement in the run at Redoubt, but with all the protection that was then given and has since been given to this stream, the run has not yet regained its former proportions. In 1926 all fishing in the bay within 1,000 yards of the mouth of the stream was prohibited and thus put an end to fishing in that locality as no salmon have been reported from Redoubt since 1925. In view of its history it seems possible that, under careful control and wise measures of conservation, this stream may again become an important source of red salmon.

The United States Fish Commission sent the steamer *Albatross* to Alaska to investigate the state of the salmon fisheries several times in the late 1800s and early 1900s, under the command of Jefferson F. Moser, and much of what is known about the early state of the commercial fisheries comes from the record of those cruises. Moser (1899) reported that Redoubt Lake was severely over fished: “[Redoubt] was dammed solidly for years, and from a stream out of which many thousand salmon were formerly taken each year, the catch has dwindled down to about 6,000.”

Redoubt Lake is unusual in several respects. It is a large, deep lake, and one of the largest documented meromictic lakes in North America. McCoy (1977) speculated that Redoubt Lake is a remnant fiord that became isolated from the sea by geological uplift between 650 and 800 years before the present. McCoy also reported on the unusual vertical stratification of the water within the lake, or the meromictic (Walker and Likens 1975; Moss 1988) nature of the lake. He found that 80 to 100 meters below the surface of the lake, the chemistry of the lake began to change: the water was relatively anoxic, contained high levels of hydrogen sulfide, and had a salinity of about two-thirds of that of seawater. He also found a large drop in pH at the bottom of this chemocline. Because this lake is so large and deep, it contains an enormous quantity of water. Most of this is water is locked in the region below 100 m, which does not mix with the surface layer. These findings are important for sockeye salmon management because they may have implications for the way in which marine derived nutrients from decaying salmon carcasses are trapped and stored within the lake. The nutrients within the lake affect the lake’s plankton communities, which juvenile salmon feed on for one or two years before migrating to sea, although there may or may not be ample terrestrial sources for the nutrients supporting phytoplankton. Even so, these dynamics are not understood for this lake.

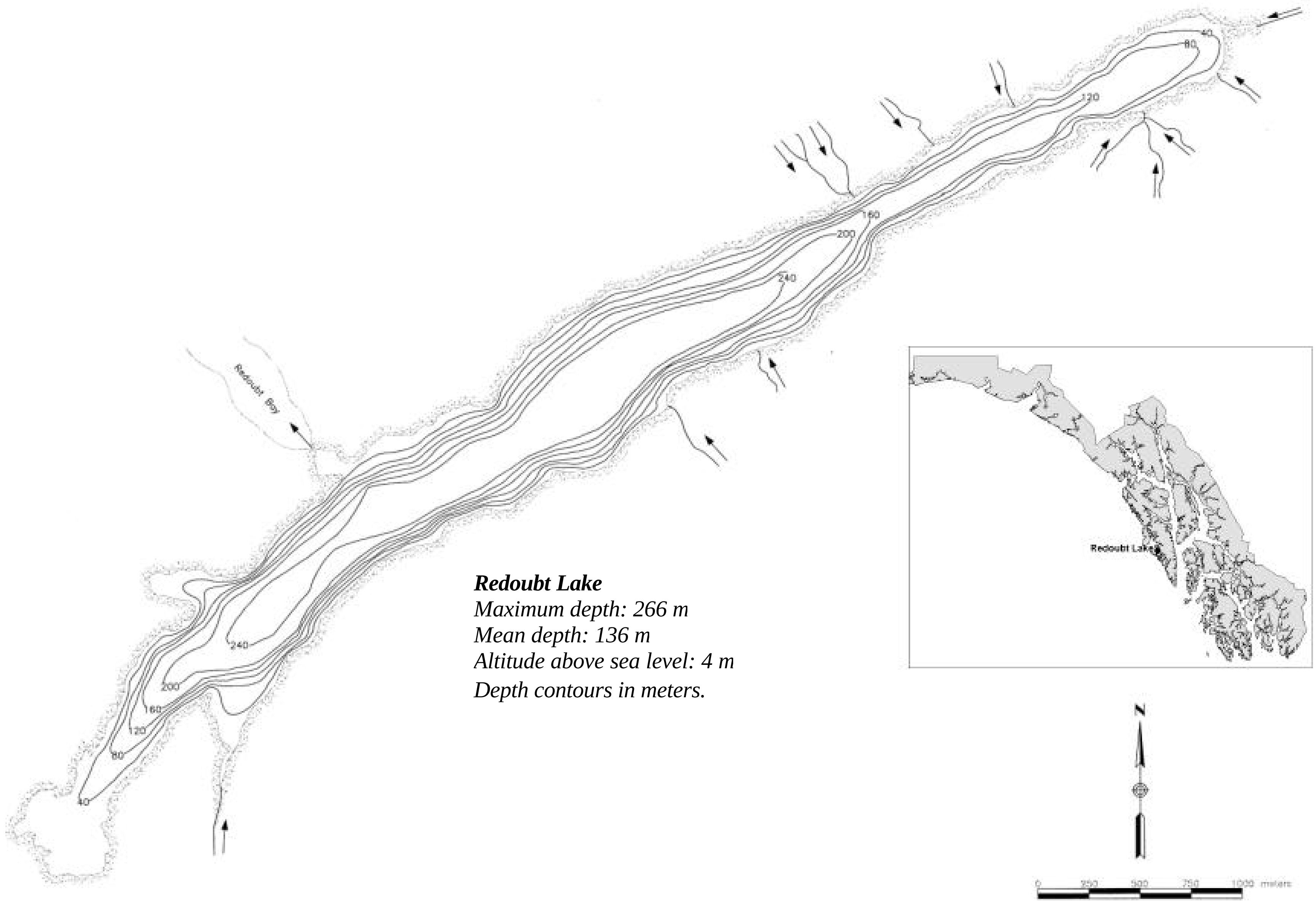

Figure 1. Map of Redoubt Lake.

There is an extensive record of limnological data for Redoubt Lake, going back to 1980. The dominant zooplankton species found in the lake is the cladoceran, *Bosmina* (unpublished data from ADF&G Limnology Lab). In general, *Bosmina* are not the preferred sockeye salmon fry diet, although they are capable of supporting sockeye salmon growth and production, and they are preferred over copepods and calanoids, if the *Bosmina* are larger than 0.5 mm (Asit Mazumder, University of Victoria, personal communication). The limnological sampling has often recovered a few copepods, and a number of minor rotifers.

The stock was only poorly monitored during most of the twentieth century, although in the last 20 years it has been monitored more closely than most other sockeye salmon systems in Southeast Alaska. Most of the stock assessment information that is available is the result of U.S. Forest Service enhancement efforts in this system.

Run timing of the Redoubt Lake sockeye salmon run is fairly early and extended, with the first fish usually entering the lake in June, peaking at the end of July, and continuing to enter the lake well into September (Figure 2).

A comprehensive history of the harvest of Redoubt Lake sockeye salmon does not exist. Table 1 shows historical catch records Rich and Ball (1932) published for Redoubt Lake sockeye salmon. The conduct of fisheries targeting Redoubt Lake sockeye in early days of the fishery were much different than in the years since statehood. Terminal area sport and subsistence fisheries now target this stock, under much stricter regulatory control than was the case prior to statehood.

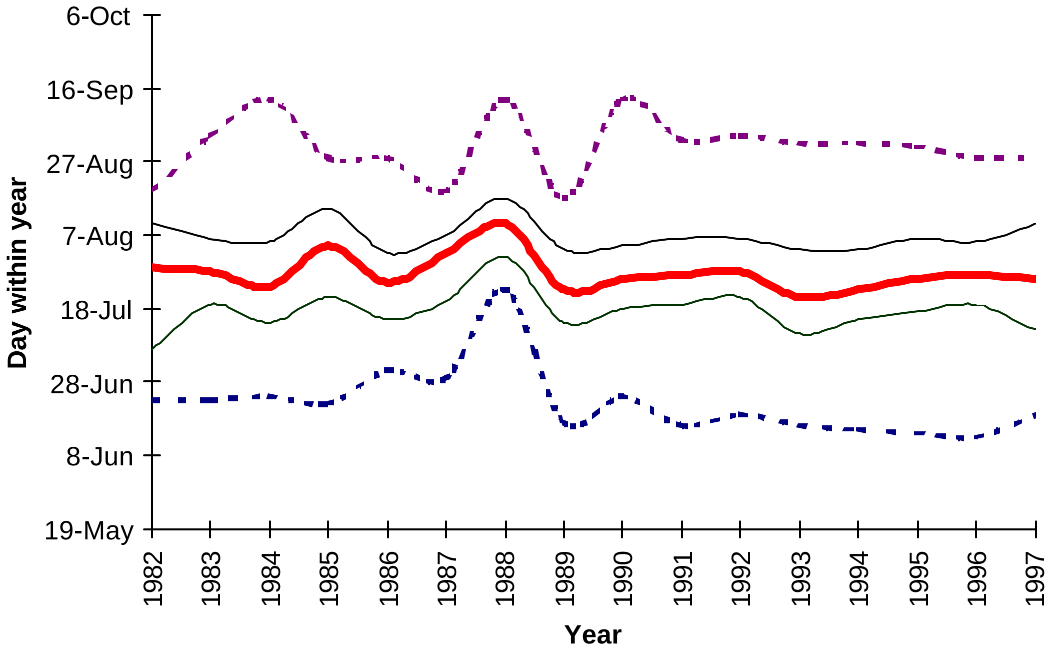

Figure 2. Run timing through the Redoubt Lake weir, by year, from 1982 to 1997. The thick centerline shows the mean passage date, for a given year. The thin solid lines show the days when 25% and 75% of the total passage were counted. The dashed lines show the date of the first and last fish counted.

Table 1. Historical catch of sockeye salmon attributed to Redoubt Lake by Rich and Ball (1932).

Year Harvest	Estimated Sockeye
1904	27,000
...	...
1911	11,375
1912	9,965
1913	13,390
1914	31,000
1915	28,628
1916	8,151
1917	1,532
1918	20,253
1919	12,780
1920	17,658
1921	6,000
1922	1,148
1923	12,141
1924	3,434
1925	2,358

There are no directed commercial fisheries on Redoubt Lake sockeye salmon. Commercial net fisheries in Sitka Sound undoubtedly harvest some Redoubt Lake sockeye salmon, although stock composition in these fisheries is unknown. The only other Sitka Sound sockeye run is from Salmon Lake, although it is likely that sockeye salmon originating from other Alaskan systems are present in the area. Apparently those fisheries harvest only a small portion of the Redoubt Lake returns, based on the low catches of sockeye salmon in the Sitka Sound net fisheries in recent years (Appendix Table 1). It is also likely that few Redoubt Lake sockeye salmon are taken in the commercial troll fishery. The troll fishery does not target sockeye salmon, and troll fishery harvests in District 113, which spans the entire western shoreline of Baranof and Chichagof Islands, have averaged only 4,600 sockeye salmon annually since 1982. There are more than a dozen sockeye salmon systems in this district and dozens if not hundreds of other Southeast Alaskan and Canadian sockeye salmon stocks that may contribute to the troll catch in this district. Therefore, although commercial harvests of Redoubt Lake sockeye salmon are unknown, the fisheries have likely harvested only small numbers in recent years.

Stock Assessment Data

Basic stock assessment statistics for Redoubt Lake are provided in Table 2. A weir was used to estimate escapement from 1982 to 2002, except in 1998 when the weir was not operated. Specific methods and descriptions of the problems associated with escapement estimation in this system have not been documented. The period the weir was operated has not been perfectly consistent each year, although the operation was similar. The U.S. Forest Service (Ben Van Alen, U.S. Forest Service, Juneau, Alaska, unpublished data) derived a series of escapement estimates from 1982 to 2001, based on interpolations of weir counts to account for unmonitored periods; an estimated regression relationship between the historical subsistence harvest estimate and historical escapement estimates was used to impute a value for the 1998 escapement in this series.

Harvests in the marine waters of Redoubt Bay and fresh waters of the Redoubt Lake drainage are assumed to be entirely of Redoubt Lake origin – although those harvest levels have been estimated in a variety of ways over the entire time series. Estimated annual subsistence harvests since 1985 were obtained from the ADF&G Southeast Region's Integrated Fisheries Database, and these estimates are based on returned subsistence questionnaires. Estimates of the sport fish harvest between 1984 and 2000 are available for those years in which at least 12 responses to ADF&G's Statewide Harvest Survey (a household-based postal survey) were received. In 2000, 2001, and 2002 there was an on-site creel survey of sport and subsistence harvest at Redoubt Lake. Estimates of total harvest are based on (1) estimates of subsistence harvest from 1982 to 1984 provided by Jan Conitz (ADF&G, personal communication), (2) the estimates of subsistence harvest in the Integrated Fisheries Database, plus the estimated sport harvest (irrespective of the number of responses to the survey), or else (3) the on-site creel survey for both subsistence and sport harvest (Robert Chadwick, ADF&G, personal communication).

Although the reported subsistence and sport harvests were no doubt collected with varying inaccuracies and biases from one year to another, they were treated as if they were essentially equivalent measures of catch, and they were all treated as if they were without error. In some years, the estimates were based on returned questionnaires, with no significant disincentive for non-reporting, while in other years these estimates were based on intensive on-site surveys that are probably very accurate. Given the relaxed harvest monitoring, the reported harvests in the early years of the time series were probably lower than the actual harvests. However, the largest reported harvest rate in the series was just over 18%, while both the mean and the median harvest rate estimates are just over 7% (Figure 3). Given the apparent very low harvest rates on this stock, even in years with very good harvest monitoring, moderate inaccuracies in the estimates of harvest should have very little effect on the estimates of total return.

The age distribution for the Redoubt Lake return was based on the estimated annual age-class distribution provided by ADF&G Southeast Region's Age Lab (Appendix Table 2). These estimates were determined by applying standard aging methods (Koo 1962) to a sample of adult fish collected at the weir. The estimated age distribution was applied to the estimates of total return (from Table 2), and are reported in Appendix Table 3.

Because of a lack of sampling in 1998, age-specific returns in 1998 for the 1991 to 1995 brood years were imputed. This was done by using the average age-class distribution for all years with complete age-class measurements. Because the 1995 and 1996 brood years had not completely returned in 2001, the last year we have complete estimates of total run size, the return of the oldest aged fish was imputed by expanding the measured brood-year return up to 2001 by the average age class distribution (e.g., the 1995 brood-year return was estimated to be 4,164 by 2001, and on average 98.2% of the return is 6-years old or younger; so the imputed total return is 4,164/0.982, or about 4,240 fish). These escapement and brood-year return estimates were combined into stock-recruit history for Redoubt Lake sockeye salmon (Figure 4).

Table 2. Stock status statistics for Redoubt Lake sockeye salmon. Weir counts, harvest and return-year adult estimates, together with enhancement statistics.

		Adult	Adult	Estimated	Sportfish	Onsite	Total	Total	Fry Stocking Activity[g]		Fertilization Activity[h]		Other Enhancement Activities		
Year	Full Limnology Survey[a]	Weir Count	Escapement Estimate[b]	Subsistence Harvest[c]	Mail Survey[d]	Creel Survey[e]	Harvest Estimate[f]	Return-year Adults	Species	Number	Fert (tons)	Total P (kg)	Activity	Species	Number
1953	no	22,988													
1954	no	21,148													
1955	no	23,648													
-															
1980	yes														
1981	yes														
1982	yes	430	456				99	555							
1983	yes	2,525	2,540				36	2,576							
1984	yes	11,558	11,579		n.e.	.	42	11,621			61	1,682			
1985	yes	10,669	10,991	97	n.e.		109	11,100			65	1,763			
1986	yes	9,414	9,798	86	n.e.		109	9,907	sockeye	28,220	78	2,163	fry stocking	chinook	900,000
1987	yes	12,990	14,251	199	n.e.		199	14,450	sockeye	28,711	75	3,045			
1988	yes	1,889	3,252	334	n.e.		425	3,677							
1989	no	28,669	31,570	2,685	n.e.		3,220	34,790	sockeye	38,800					
1990	yes	72,517	73,181	5,326	703		6,029	79,210	sockeye	59,520	107	3,045			
1991	yes	45,039	45,510	3,105	n.e.		3,337	48,847	sockeye	236,436[f]	97	2,844			
1992	yes	10,231	10,326	96	n.e.		96	10,422			95	2,003			
1993	yes	24,422	25,018	2,326	130		2,456	27,474			109	3,205			
1994	yes	39,216	39,710	4,120	721		4,841	44,551			80	1,682			
1995	yes	34,280	34,798	2,968	646		3,614	38,412			94	2,740			
1996	yes	18,076	19,209	3,337	n.e.		4,415	23,624							
1997	no	28,898	28,898	2,253	n.e.		3,822	32,720							
1998	no	n.a.	52,039	4,296	1,734		6,030	58,069							
1999	yes	57,754	57,754	6,761	3,192		9,953	67,707			9				
2000	yes	2,948	3,032	35	n.e.	95	95	3,127			10				
2001	yes	3,499	3,665	16	n.a.	50	50	3,715			10				
2002	n.a.	23,943	23,943	952	n.a.	820	820	24,763			n.a.				

[a] Full limnology survey includes water chemistry, zooplankton, and physical characteristics including light, temp and DO profiles by depth.
[b] Provided by Ben Van Alen of the U.S. Forest Service, Juneau, AK.
[c] Harvest includes sockeye salmon harvested in subsistence fisheries, from returned permits and questionnaires.
[d] Estimates are estimated annual sport fish harvest based on a mail survey. Estimates are reported only when the number of responses exceeds 12; "n.e." denotes less that 12 responses.
[e] On-site creel survey of subsistence and sport harvest conducted in 2000 to 2002.
[f] Sum of what was considered the best estimate of subsistence and sport harvests.
[g] Fry stocking involved incubation boxes for sockeye, with survival estimates to hatching only; Chinook fry were stocked also in 1986.
[h] Liquid fertilizer applied by boat 1984–1995; granular fertilizer suspended in bags and applied to beaches 1999–2001.
The weir count for 2002 is preliminary.

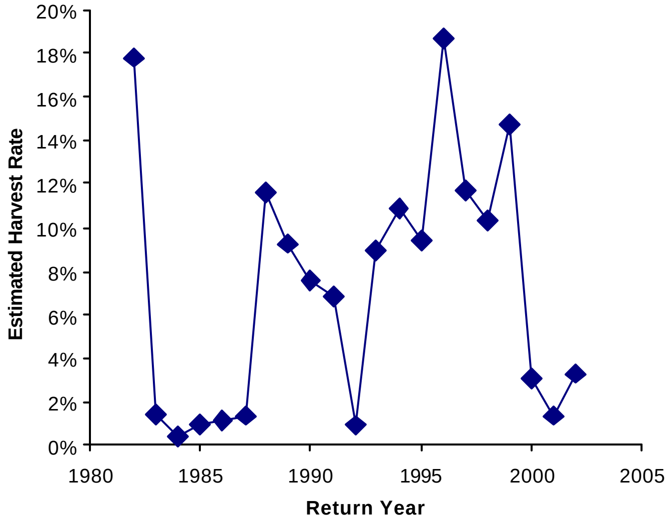

Figure 3. Estimated harvest rate on the Redoubt Lake sockeye stock.

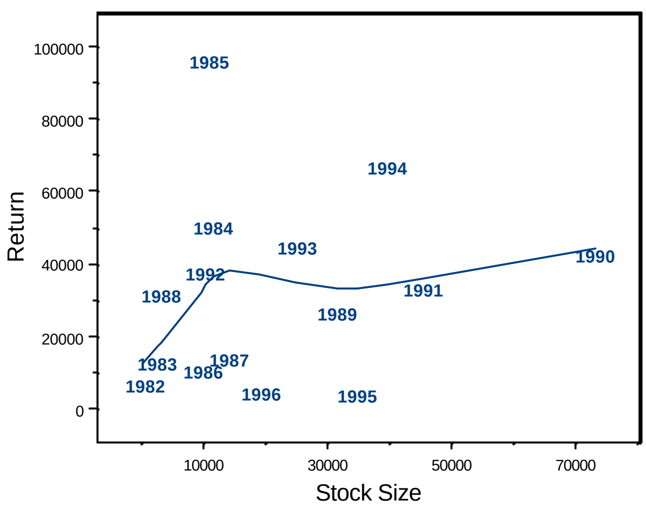

Figure 4. The estimated stock-recruit history of Redoubt Lake from the 1982 to the 1996 brood year. The thick curve is a nonparametric Friedman's smooth (Insightful Corp. 2002: Splus Version 6). The return is the number of fish caught and escaping, over all return years; the brood year is used to denote the total return at a particular stock size.

Recent Attempts at Redoubt Lake Salmon Enhancement

The Alaska Department of Fish and Game's Fisheries Rehabilitation, Enhancement, and Development (FRED) Division began working on this system in the late 1970s, in preparation for lake enrichment with chemical fertilizer. This work appears to be predicated on the assumption that nutrient levels in the lake were limiting in-lake productivity of juvenile sockeye salmon.

Escapement monitoring began in 1982 and fertilization began in 1984. Fertilization was not conducted in 1988 and 1989. Fertilization continued again in 1990 through 1995. Throughout this time, slightly different delivery modes were used, although the fertilizer was broadcast throughout the lake, at intervals, in liquid form. Fertilization restarted, beginning in 1999, using completely different delivery modes. The recent fertilization makes use of a dry pellet fertilizer form. The premise for this kind of enhancement was that years of low sockeye salmon escapement reduced the nutrient level in the lake to the point that carrying capacity of the lake is affected. Supporters of lake fertilization think that this process can be reversed by the addition of the nutrients (e.g., Stockner 1987). As part of this program, FRED biologists and their successors usually collected escapement estimates, measured limnological parameters (including biological and chemical features), conducted hydroacoustic surveys of sockeye fry abundance, and altered the lake ecosystem through the application of nitrogen, phosphorus, and salmon plants.

Surprisingly, there are no published reports on the progress or success of this project, and no formal reports on the results of the associated investigations. I could find no surviving written plans for this project, although there are a few surviving memoranda, letters, and draft reports that suggest the thinking of the project investigators, as the project progressed.

In the early years of the fertilization program, sampling of the smolts leaving the system was a very difficult challenge, and the number of smolts captured each year was largely a function of experimentation with different capture techniques. In other words, the number of smolts captured from year to year does *not* principally reflect the size of the smolt migration. This makes estimation of the abundance or biomass of different age-classes within a brood year impossible. While it is not clear that the age distribution shifted to younger fish after fertilization (it appears, if anything, the shift may have been to older fish; Table 3), the size at age may have increased after fertilization, beginning with the 1985 emigration year (Table 3), possibly suggesting a more favorable rearing environment within the lake. From 1984 through 1987 and again from 1990 through 1995, the level of fertilization, and the delivery mode remained similar (Table 4a). In later years, the fertilizer makeup, the delivery mode, and the overall cost changed (Table 4b). In 1999 for the first time, the U.S. Forest Service used granular fertilizer (8.52 tons of Monoammonium Phosphate). They developed a system that allowed eight 50-pound bags of fertilizer to be submerged just below the surface of the water to be dissolved by the lake's wave action. The fertilizer bags were replaced every two days to keep a continuous flow of nutrients going into the lake. In 2000 and 2001 the bags were applied in shallow water near the beach and secured with lines tied to shore.

In 1986, FRED Division stocked Redoubt Lake with approximately 0.9 million chinook salmon fry. Approximately 99 thousand of these fish were tagged with coded-wire tags (tag codes B30806, B30807, B30813, and B31305). None of these tagged fish were recovered as adults, either through the regular catch sampling of sport or commercial fisheries, or by any other means. It appears that the survival rate was essentially 0. Yet the chinook salmon fry plant corresponds to be a sharp drop in the zooplankton density, starting in 1987 and extending to 1988 (Figure 5). Following the chinook plant there appears to be a shift back to older-aged sockeye salmon smolts (Table 3), although, again, it is not possible to estimate the age distribution by brood years. The estimated return per spawner for sockeye salmon from the 1986 and 1987 cohorts were only 1.116 and 0.994 (Table 5), indicating two highly unproductive sockeye salmon brood years in a row.

Although there have been other enhancement efforts, these have probably not had any appreciable effect on the stock-recruit pattern of the naturally spawning fish. The Northern Southeast Regional Aquaculture Association (NSRAA), the U.S. Forest Service, and FRED division cooperated on an egg incubation box pilot project, beginning in 1986. Eggs from 11, 15, 0, and 13 females were used in 1986 to 1989, respectively. In 1990 and 1991, NSRAA used 124 and 82 females, respectively. It appears that mortality problems when the project moved from a pilot phase into full production may have contributed to the cessation of this project (1991 letter from Steve Reifenstuhl to ADF&G).

Table 3. Smolt size and age-class estimates for Redoubt Lake sockeye salmon from 1982 to 1995 (Source: Unpublished data, David Barto, ADF&G, Douglas, AK)

			Age I			Age II			Age III		
Emigration Year	Total Sockeye Smolt Counted	AWL Samples[a] (*N*)	Composition (%)	Length (mm)	Weight (g)	Composition (%)	Length (mm)	Weight (g)	Composition (%)	Length (mm)	Weight (g)
1982	3,329	216	8.8	68.4	2.4	89.0	75.4	3.1	2.2	86.5	4.9
1983	1,541	137	13.4	71.4	3.2	85.0	77.2	4.0	1.6	91.8	6.6
1984	540	35	79.6	75.4	3.4	16.7	90.5	5.5	3.7	94.6	6.5
1985	864	605	84.8	81.4	3.9	15.1	110.4	10.0	0.1	84.0	3.8
1986*	4,242	983	53.8	78.2	3.6	46.2	110.1	10.1	NF		
1987	71,142	1,855	27.4	80.9	3.9	71.3	100.3	7.4	1.3	107.3	10.1
1988	NS										
1989	NS										
1990	NS										
1991	211,579	1,473	64.5	72.4	2.9	34.2	94.7	6.3	1.3	110.2	9.5
1992	161,530	2,165	69.7	71.0	2.7	28.6	83.0	4.4	1.6	105.5	8.9
1993	63,577	1,890	49.3	72.6	2.9	50.3	84.7	4.6	0.4	109.0	10.4
1994	237,506	2,430	49.1	80.2	3.8	47.1	97.2	7.2	3.9	119.6	13.9
1995	105,890	2,133	32.9	74.7	3.2	67.0	82.9	4.3	0.1	112.0	11.1

[a] Age, weight, and length

Note: Age composition (%), length and weight are unweighted.

NS - not sampled

NF - none found

Table 4a. Fertilizer application summary for Redoubt Lake, 1984–1995.

Year	Fertilizer Formula	Application Dates	No. of Days	No. of Gallons	Weight (tons)	P Additions (kg)
1984	27-7-0	6/21-9/1	88	10,760	60.8	1,722
1985	27-7-0	5/20-8/20	92	11,457	64.7	1,833
1986	27-7-0	5/21-8/20	91	13,875	78.4	2,220
1987	27-7-0	6/28-8/20	53	13,210	74.6	2,114
1988	no fertilization	--	--	--	--	--
1989	no fertilization	--	--	--	--	--
1990	20-5-0	6/13-9/2	99	20,572	107.0	2,057
1991	20-5-0	6/6-9/19	106	18,702	97.3	1,870
1992	20-5-0	5/25-8/29	96	18,200	94.6	1,820
1993	20-5-0	5/21-8/30	101	21,000	109.2	2,100
1994	20-5-0	5/23-8/31	100	15,295	79.5	1,530
1995	20-5-0	5/21-8/26	98	18,050	93.9	1,805

Table 4b. Fertilizer application summary for Redoubt Lake from 1999 to 2001. In 1999, fertilizer was applied from June 22 through September 12; in 2000, fertilizer was applied from June 9 through September 9; in 2001, fertilizer was applied from June 7 through September 7.

Year	Fertilizer Formula	Application Mode	Weight (tons)
1999	12-61-0	Dry granular	8.5
2000	12-61-0	Dry granular	10
2001	12-61-0	Dry granular	10

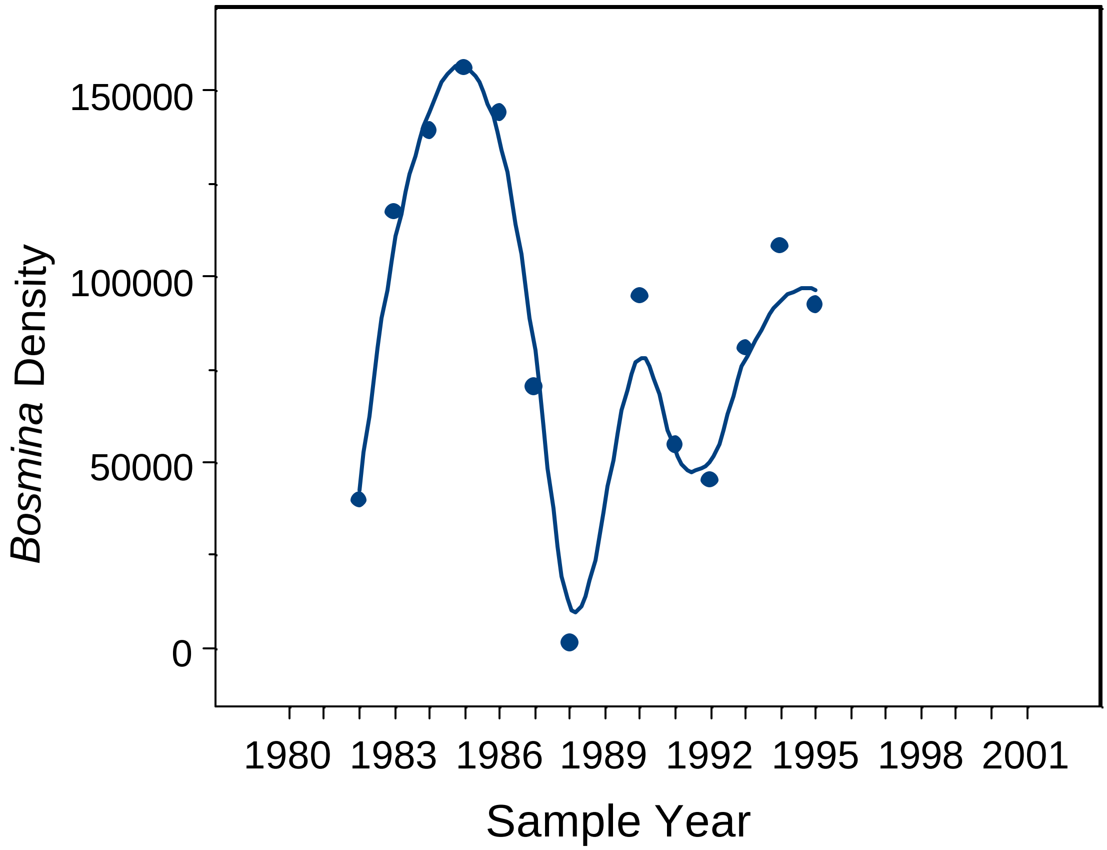

Figure 5. Mean *Bosmina* density (number per m^2 of lake surface) in Redoubt Lake (*y*-axis), plotted against year (*x*-axis). *Bosmina* are both the dominant Caldocerian species and the dominant zooplankton species in this lake system. The large drop in abundance in 1987 follows a fish-stocking event involving almost 1 million chinook salmon fry. The drop in 1991 follows an escapement of over 71 thousand sockeye salmon in 1990. The thick black line is a lowes smooth (Splus Version 6). Note the absence of a sample in 1989.

TRENDS IN ESCAPEMENT

The method of Geiger and Zhang (2002) was used to analyze the trend in escapement. Following their recommendation, a 15-year data series was examined because 15 (years) divides evenly into three five-year periods, and the dominant age of Redoubt Lake sockeye is five-year olds (in most years). So, 15 years approximates an examination of three generations. The Redoubt Lake data set contains a total of 19 estimates from 1982 to 2002, with a missing value for 1998. I truncated the escapement series to the most recent 15 years of data, excluding the missing value for 1998, by simply appending the post-1998 data to the pre-1998 data.

Denote the median escapement value in the first third as m_1, and denote median in the last third as m_3. Because there are five years in the first third, five years in the second third, and five years in the last third, there are 5/2 +5 +5/2 = 10 years between the middle year in the first third and the middle year in the last third of a 15-year series. A robust estimate of the underlying decline (or increase) is found by calculating the slope through this data as, *slope* = (m_1-m_3)/(years between middle of first and last periods). Geiger and Zhang suggest looking at a benchmark value they call the *year zero escapement reference point*, y_0, which they calculate by averaging the three possible estimates of the y-axis intercept.

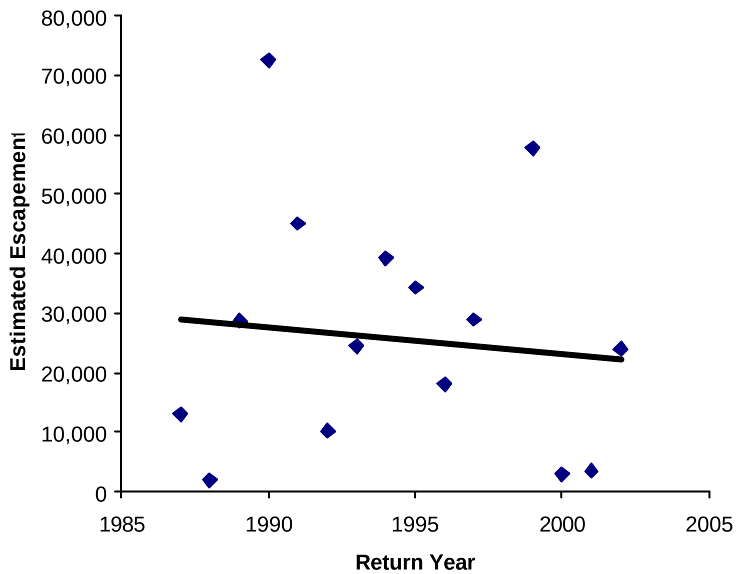

Figure 6. The escapement history of Redoubt Lake for the 15-year period of 1987 to 2002, excluding the missing value for 1998. The slope of the thick line shows the robust estimate of stock decline of 473 fish per year, with an intercept, or year-zero escapement reference point of approximately 29,500 fish.

The escapement was measured at less than 500 fish in 1982, and the escapement level rose to over 70,000 1990, and subsequently fluctuated between very high, moderate sizes and even low stock sizes in 2000 and 2001. The escapement history for this system has been highly variable, with fishing effort appearing to contribute very little to the variability. Overall, this series does not show a substantial trend, up or down, in escapement level (Figure 6) – although the recruitment into this system is highly variable. The estimated downward trend of a loss of 473 spawners per year, which is 1.6% of the year-zero reference point, is not considered biologically meaningful.

ESCAPEMENT GOAL ANALYSIS

Over the last 20 years there has not been a formal escapement goal established for Redoubt Lake. A range of 7.5 to 12 thousand sockeye salmon spawners was established in 2002 as a management goal, until an escapement goal could be established. The following analysis is intended to supersede this management goal and establish a formal *biological escapement goal* for Redoubt Lake sockeye salmon.

Ricker Analysis

A standard fisheries procedure, the "Ricker analysis" (Ricker 1975, Quinn and Deriso 1999) is often used to estimate the underlying relationship – assuming a random, uncorrelated error around the stock-recruit curve – in order to forecast the effect escapement has on the return and catch. This "curve fitting" approach requires at least a moderately large sample size. Because the Ricker model is essentially a forecasting tool used to forecast catch, the most basic assumption underlying this kind of analysis is that the observed returns are all drawn from the same statistical universe. Equally important is the assumption that the returns in the future are following the same random processes as were at work in the past – that is, the future is part of the same statistical universe. These may be important unmet assumptions in the Redoubt Lake analysis, given the changes in the fertilization regime.

The Ricker Law of stock and recruitment relates the escapement, or stock, at a particular time, to subsequent return (or recruitment) of adults, using a normally distributed random shock to the system (represented with e), and two parameters: a (productivity parameter) and b (the carrying capacity parameter). Formally, the model is written:

$$R_t = aS_t \exp(-bS_t + e_t) \,. \tag{1}$$

This model can be rearranged so that the usual statistical regression techniques can be used to estimate the parameters (Quinn and Deriso 1999). That is, the model can be rewritten as follows:

$$\begin{aligned} R_t / S_t &= a \exp(-bS_t + e_t) \\ \ln(R_t / S_t) &= \ln(a) - bS_t + e_t \\ y &= a + bx + e_t. \end{aligned} \tag{2}$$

Once estimates of a and b are developed, Ricker's a parameter will be estimated by taking the anti-log of the estimate of a. Ricker's b parameter will be estimated by taking the additive inverse of the estimate of b. Because b is a very small number in units of inverse fish, and because $1/b$ is the size of the escapement that will produce the largest underlying return, estimates of $1/b$ will be reported below.

If z is a log-normally distributed random variable (i.e., $\ln(z)$ follows a normal distribution with a mean of m and variance of s^2), then the mean and variance of z are given by $\exp(m+s^2/2)$ and $\exp(2(m+s^2))$-$\exp(2m+s^2)$ (e.g., Casella and Berger 1990). The random shock in equation (1) is usually assumed to follow a log-normal probability distribution with parameters 0 and s^2 (i.e., a mean of zero and a variance of s^2). The practical effect of this result is that error is not symmetric around the stock-recruit curve; the greater the variance in the error, the more the average return tends to be above the stock-recruit curve. In other words, the practical result is that a large error parameter, s^2, has the effect of increasing the apparent productivity of the stock. Some analysts multiply the estimated a by exp($\hat{s}^2$ /2), and refer to this as a "bias adjustment." Here the estimates of a, 1/b, and s^2 will be reported separately, and without this adjustment, but when we refer to the "estimated expected return" at a stock size *S*, that will refer to,

$$R = \hat{a}S \exp(-\hat{b}S + \hat{s}^2 / 2),$$

with $\hat{s}^2$ denoting the residual mean-squared error from the regression analysis to estimate *a* and *b* and with $\hat{a}$ and $\hat{b}$ denoting the estimated Ricker parameters. Note that this is algebraically equivalent to the "bias adjustment." The escapement goal recommendation is based on the range of escapements that are estimated to maximize the "estimated expected return."

The model fit was judged by the significance level of the parameters, the lack of a trend or autocorrelation in the residuals, and Cook's distance (Neter et al. 1996).

An Estimated Ricker Model

The logarithm of the return per spawner was regressed on brood year escapement, for the 1982 to 1996 brood years (Table 5), resulting in an estimated Ricker model of recruitment for Redoubt Lake. Parameter estimates were 4.496 for a, 23,250 for 1/b, and 1.293 for s^2. (The "bias adjusted" estimate of a would be given by 4.496 times exp(1.293/2), or about 8.581; the estimated value of b is 0.0000430). These parameter estimates correspond to an estimate of the escapement that will maximize sustained catch near 17,400 spawners, although escapements between 11,040 and 25,200 produce similar (at least 90% of) expected catches (Figure 7).

Both stock-recruitment parameters were considered statistically significant (largest *P*-value < 0.01). A trend in residuals was noted (Figure 8), but this apparent trend is largely caused by two low recruitment events in a row at the end of the series. The residuals do not show a statistically significant autocorrelation at any lag (largest correlation coefficient just over 0.25 at lag 9). Recall that the 1986 brood year was strongly affected by the chinook salmon plant, but the estimated sockeye Ricker curve is very insensitive to the observed return-per-spawner value in that region (Figure 9; the 1986 escapement was 9,798 and the return per spawner was 1.11). The brood year with the largest escapement disproportionately affected the shape of the fitted regression line (Figure 9), and this single point largely determined the shape of the estimated curve.

Table 5. Stock-recruitment statistics for Redoubt Lake sockeye salmon. "Spawners" denotes brood year stock size. "Return" denotes the estimated catch and escapement at return, of the cohort that originated in the brood year. Logarithm denotes the natural logarithm.

Brood Year	Spawners (Escapement)	Return (Catch+Escapement)	Return per Spawner	Logarithm of Return/Spawner
1982	456	6,870	15.066	2.712
1983	2,540	12,928	5.090	1.627
1984	11,579	50,507	4.362	1.473
1985	10,991	96,544	8.784	2.173
1986	9,798	10,935	1.116	0.110
1987	14,251	14,167	0.994	-0.006
1988	3,252	31,862	9.798	2.282
1989	31,570	26,851	0.851	-0.162
1990	73,181	42,987	0.587	-0.532
1991	45,510	33,250	0.731	-0.314
1992	10,326	38,798	3.757	1.324
1993	25,018	46,784	1.870	0.626
1994	39,710	67,592	1.702	0.532
1995	34,798	4,242	0.122	-2.105
1996	19,209	4,362	0.227	-1.483

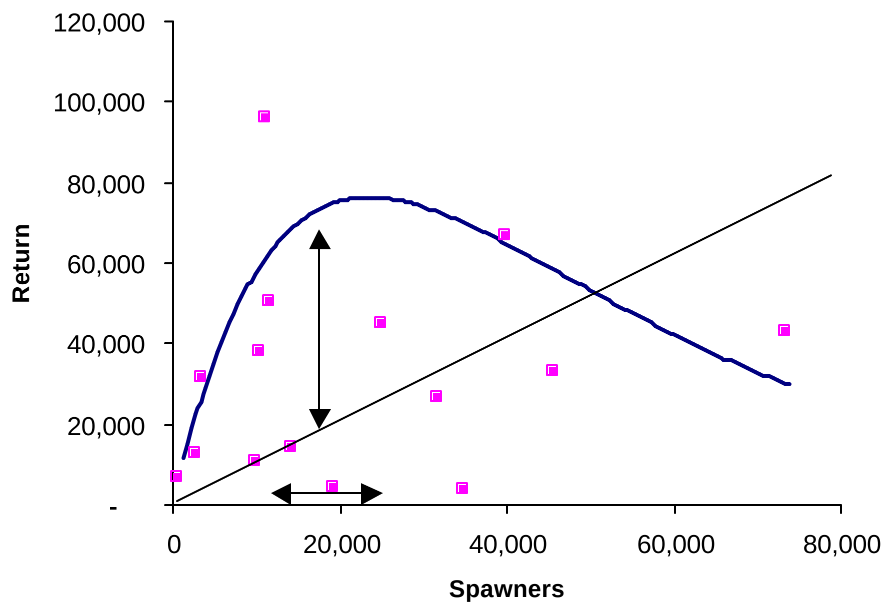

Figure 7. The estimated Ricker curve (thick curve) for Redoubt Lake sockeye salmon. The curve shows the "expected return." The diagonal line shows the partitioning of expected return into yield (above the line, shown by the vertical arrow) and escapement (below the line). The horizontal arrow shows the region of escapement levels expected to produce at least 90% of the maximum sustainable yields.

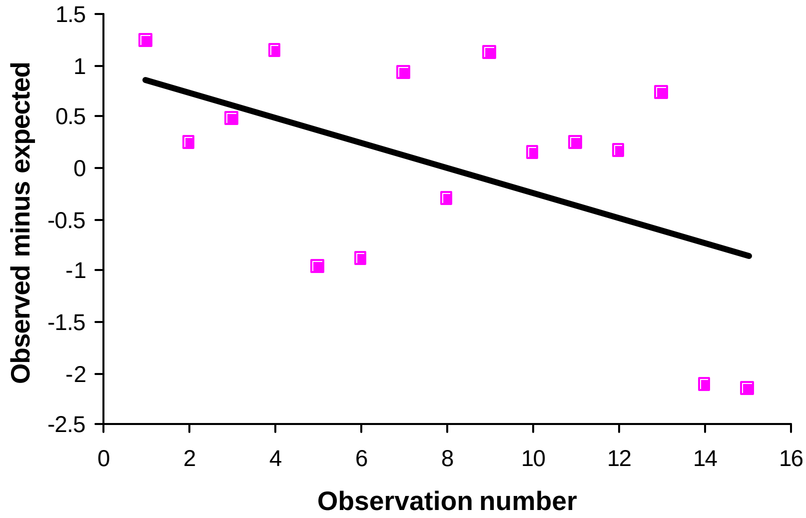

Figure 8. A plot of the residuals (observed minus expected ln(return/spawner)) in the regression to estimate a Ricker curve for Redoubt Lake. Most of the appearance of a downward trend (indicating a loss of productivity over time) is the result of two low recruitment events in a row, from the 1995 and 1996 brood years.

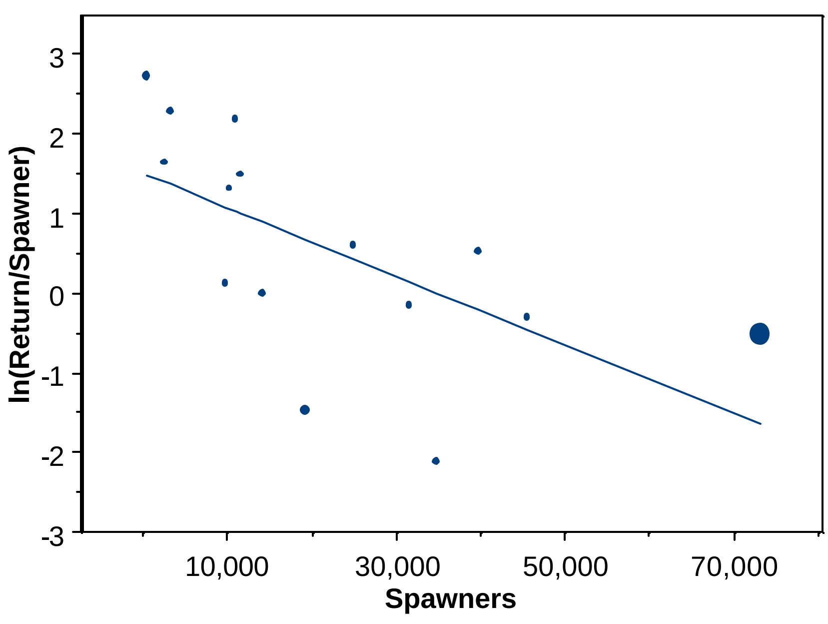

Figure 9. The logarithm of return per spawner for brood years 1982 to 1996 at Redoubt Lake. The size of the plotting point is Cook's distance, a measure of the influence each point had on the fitted line. Note that the 1990 brood year, with an escapement of over 70,000, had a very large influence on the fitted line.

RECOMMENDATIONS

The stock-recruitment analysis was sufficient to develop and recommend a *biological escapement goal* for Redoubt Lake sockeye salmon. Rounding to the nearest 2,500 fish, I recommend an escapement goal range of 10 to 25 thousand spawners for this system. This recommendation is based on the Ricker analysis and estimated range of escapements that appear to have been near the maximum sustainable catch level for this system in the 1980s and 1990s.

In addition to formally recommending a biological escapement goal range of 10 to 25 thousand sockeye salmon for Redoubt Lake, I wish to make the following additional recommendations with regard to this sockeye salmon stock. The most important recommendation is that the counting weir be continued. Similarly, the biological sampling to estimate the age, sex, and size of the Redoubt Lake sockeye salmon escapement should be continued, as should the harvest monitoring programs in the terminal Redoubt Bay area and Redoubt Lake drainage. The information from the weir and the biological and fisheries sampling is the basis for understanding Redoubt Lake, and without this information rational recommendations about escapement goals or enhancement will be impossible. I also recommend that the fertilization efforts continue in a consistent, stable manner, and that those directing the enhancement efforts should try and understand the fate of nutrient additions as they pass through various trophic levels within the lake ecosystem. Finally, I recommend that the biological escapement goal be reviewed in 2005, prior to the next Southeast Board of Fisheries meeting.

DISCUSSION

Although substantial resources were spent fertilizing this lake under the assumption that it was depressed in the latter part of the twentieth century, and under the assumption that the system's productivity would be restored by the addition of artificial fertilizer, essentially no resources have been directed at understanding the fundamental effect of this fertilization, or spent to develop principles that could be applied to other systems. There is very little, if any, evidence that this system is producing below its inherent capacity. Also, there is little, if any, evidence that the fertilization affected sockeye salmon productivity in Redoubt Lake. If the productivity of the 1990s might be representative of what this system is capable of in the near future, irrespective of the fertilization routine – that is assuming that the system was *not* depressed and that the fertilization *did not* increase productivity – then the estimated Ricker model, presented above, provides a logical way to forecast the effects of future escapement levels, and therefore to recommend an escapement goal.

However, if for the sake of argument, we assume the fertilization did have an effect on the lake's productivity, then the recommended escapement goal may not lead to escapements that will maximize catch — even though the recommended goal of 10 to 25 thousand spawners still may be preferred for other reasons. While the long-term goal may be to maximize catch, to reach that goal requires improved understanding of what level of productivity is consistently achievable in the future and definition of the stock-recruit relationship with respect to the fertilization regime. The recommendation for an escapement between 10 and 25 thousand is essentially a recommendation for large stock sizes. Density dependence may have partially limited recruitment between 10 and 25 thousand spawners (Figure 4 and Figure 7), and that is the region of the stock-recruitment relationship that appears to be the most informative for the b

parameter of the Ricker model. Additionally, if the fertilization did greatly affect the productivity of the Redoubt Lake stock, then that implies that marine-derived nutrients are an important factor in the system's productivity. If a lack of nutrients coming into this system does partially limit sockeye salmon production in this system in some years, then larger stock sizes may help mitigate the need for artificial fertilizers. To help understand these dynamics of the populations, the most important objective should be to develop a reliable and consistent series of estimates of catch and escapement — without simultaneous shocks from large-scale enhancement, such as the chinook salmon plant of 1986.

Similarly, if fertilization is continued, it should be carried out in a consistent manner for an extended period of time (i.e. 10 years or longer). That way the effect of the fertilization can be partially separated from background fluctuations. Similarly, if lake fertilization is to be continued, those responsible for it should identify which nutrients are potentially important, and make some attempt to predict and describe the fate of those nutrients as they pass though the various trophic levels within the lake ecosystem. Just as importantly, they should demonstrate that these nutrients either are, or are not, affecting the sockeye salmon population.

It is hard to know what effect these lake enrichment activities have had. These fertilization activities almost certainly increased phytoplankton abundance, which subsequently may have increased the size of the zooplankton. Because the initiators of the lake fertilization project did not study the lake for a significant period of time prior to enrichment, it is impossible to distinguish the effects of the enrichments from background fluctuation, or to distinguish the variation in recruitment from variation explainable by other hypotheses. Note that the shift to younger sockeye salmon smolt (Table 3) corresponded to not only the fertilization, but this shift also corresponded to what may have been an increase in marine derived nutrients associated with increased escapements in 1983 and 1984. Even though 1983 was a year of relatively low escapement, the escapement in 1983 was much higher than in 1982. Indeed, the zooplankton density and the shift in age began to increase before fertilization started in 1984 (Table 4; Figure 5).

Overall, the most striking feature of the Redoubt Lake data is that when fertilization ended in 1995, recruitment five and six years later failed to replace parent-year escapements. The main scientific question about this system remains: Why would this system have such a variable recruitment, with only minimal harvest? The unexplained variability of recruitment in this system may be an inherent feature of the meromictic structure of the lake. Unfortunately, the zooplankton-density series ended at the same time as the first round of lake enrichment, so it is impossible to conclude that the reduction in productivity was due to the end of fertilization, or to even infer that the freshwater life stage contributed to the low survival in these years – although that certainly seems very likely.

The escapement of over 70,000 in 1990 corresponded to a sharp drop in zooplankton levels in 1991; escapements near 30,000 were not obviously related to a drop in zooplankton the next year. However, there may be some suggestion that the escapement of 40,000 in 1991 was related to a slight decline in zooplankton in 1992 (Figure 5). Escapement near or above 40,000 may have potential consequences for catch, especially if these high escapement events were allowed to occur on a consistent basis, there is some justification for using harvest management to prevent very large escapement events.

At this stage, the effect of fertilization has been essentially ignored in the escapement-goal analysis. When the Redoubt Lake escapement goal is re-evaluated in the future, it will be important not to just mechanically re-estimate a new Ricker curve, but to try and draw some conclusions about the interaction between stock size, fertilization, and the appropriate harvest level in Redoubt Lake. The estimated Ricker model presented here is essentially a forecasting tool. Because this system is so well monitored, this tool is helping to create an opportunity to learn some general lessons about fertilization and meromictic lakes.

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APPENDIX

Appendix Table 1. Commercial net harvest of sockeye salmon in the Sitka Sound area.

Catches are of mixed stock origin; the Redoubt Lake contribution is unknown.

Year	Traditional Purse Seine (113-41)	Terminal Harvest Area Purse Seine (113-38)	Terminal Harvest Area Drift Gillnet (113-38)	Total
1982	3	-	-	3
1983	77	-	-	77
1984	10	-	-	10
1985	141	-	-	141
1986	9	-	-	9
1987	84	-	-	84
1988	4	-	-	4
1989	-	-	-	-
1990	-	-	-	-
1991	-	-	-	-
1992	-	5	-	5
1993	-	425	261	686
1994	100	887	203	1,190
1995	-	1,485	401	1,886
1996	476	758	34	1,268
1997	3,038	1,750	640	5,428
1998	483	1,881	505	2,869
1999	867	1,221	649	2,737
2000	99	476	96	671
2001	155	408	726	1,289
2002	116	164	331	611
Average	270	450	183	903

Subdistrict 113-41 is Sitka Sound.
Subdistrict 113-38 is the Deep Inlet Terminal Harvest Area.

Appendix Table 2. Estimated age distribution of Redoubt Lake sockeye salmon, together with sample size (bottom row, denoted as “*n*”), based on a sample of adult salmon captured at the Redoubt Lake weir.

	Return Year																			
AGE	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
0.2	1	2	0	0	0	0	0	0	0	0	0	0	0	1	1	0	n.a	0	1	0
0.3	2	3	0	0	1	0	0	0	1	0	0	1	0	0	1	0	n.a	0	3	2
1.1	0	1	0	6	9	7	0	8	16	5	95	25	25	210	47	65	n.a	6	35	46
1.2	55	189	46	10	208	252	48	93	130	168	137	723	693	250	374	252	n.a	40	367	285
1.3	139	380	168	80	131	205	73	386	226	74	402	179	784	1521	399	968	n.a	2,201	869	825
1.4	6	0	0	2	1	0	0	0	2	1	2	3	2	7	12	4	n.a	0	80	2
2.1	0	30	1	1	26	185	0	46	3	28	85	52	18	71	26	30	n.a	0	2	30
2.2	46	218	321	187	283	131	214	940	1,466	74	188	982	85	138	543	64	n.a	4	13	18
2.3	24	63	190	551	594	276	35	187	656	1,837	374	162	933	111	179	904	n.a	397	4	22
2.4	11	0	0	3	2	2	0	0	0	4	23	1	2	6	1	0	n.a	0	0	0
3.1	1	0	1	1	0	0	0	1	0	2	8	0	1	0	0	0	n.a	0	0	1
3.2	8	6	3	16	21	0	0	9	10	3	11	178	1	0	4	0	n.a	1	0	0
3.3	3	2	7	17	9	1	0	1	0	53	3	21	40	0	0	0	n.a	0	0	0
3.4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	n.a	0	0	0
4.2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	n.a	0	0	0
n	296	894	738	874	1,285	1,059	370	1671	2,510	2,250	1,328	2,327	2,584	2,315	1,587	2,287	n.a.	2,649	1,374	1,231

Appendix Table 3. Estimated brood-year specific return of Redoubt Lake sockeye salmon. Columns denote brood years, and rows denote return year. Column totals denote estimated return for the brood year, based on the estimated age classes.

Return	Estimated	Estimated	Total	Brood Year																	
Year	Escape-ment	Harvest	Run	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995[a]	1996[a]
1982	456	99	555	2																	
1983	2,540	36	2,576	640	8																
1984	11,579	42	11,621	7,716	732																
1985	10,991	109	11,100	7,226	3,408	133	78														
1986	9,798	109	9,907	85	4,750	3,190	1,813	69													
1987	14,251	199	14,450		43	3,771	4,596	5,939	101												
1988	3252	425	3,677			0	349	2,850	478	0											
1989	31,570	3,220	34,790				35	4,070	27,589	2,922	174										
1990	73,181	6,029	79,210					0	21,070	53,467	4,198	475									
1991	45,510	3,337	48,847						1,270	39,956	3,273	4,250	98								
1992	10,326	96	10,422							198	3,043	4,691	1,740	750							
1993	25,018	2,456	27,474								247	4,039	13,737	9,149	302						
1994	39,710	4,841	44,551									713	16,172	14,968	12,252	446					
1995	34,798	3,614	38,412										115	1,959	27,504	5,339	3,495				
1996	19,209	4,415	23,624											24	2,929	13,962	5,977	732			
1997	28,898	3,822	32,720												0	12,990	14,789	4,025	916		
1998	52,039	6,030	58,069													514	14,536	31,870	10,085	1,064	
1999	57,754	9,953	67,707														0	10,156	56,400	1,016	135
2000	3,032	95	3,127															0	191	2,010	844
2001	3,665	50	3,715																0	74	2,544
2002	23,943	820	24,763																		
		Estimated Return:		15,669	8,940	7,095	6,870	12,928	50,507	96,544	10,935	14,167	31,862	26,851	42,987	33,250	38,798	46,784	67,592	*4,242*	*4,362*

Age composition of total adult return extrapolated from scale sampling of escapement.
[a] Total return for 1995 and 1996 brood years was based on statistically expanding the return up to 2001. The expansion was based on the average rage class at return for the 1982 to 1994 brood years.
Note the 1982 to 1985, and the 2000 and 2001 return year's total return do not sum to row totals because these include brood years not in this table.

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