Temporal Extension of the Lake Level Record at Lake Ozette, WA and its Relationship to Sockeye Salmon (*Oncorhynchus nerka*) Population Declines

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Abstract

A threatened population of sockeye salmon has experienced a dramatic population decline of 90-98% in Lake Ozette over the last sixty years. In order to determine if hydrologic variability might have negatively impacted their spawning habitat (*i.e.* water depth), lake level data have been compared with population data. Since lake level data have only been recorded since 1981 and since the population decline began in 1949, regression modeling was successfully used to reconstruct lake levels based on precipitation data back to 1908. Recreated lake levels were adjusted to account for incremental logging in the watershed. While logging was found to have a significant impact on hydrologic variability, it appears to have not introduced enough variability (in terms of increased surface flow and increased lake level fluctuations) to cause the population decline. No large lake level fluctuations correspond with the timing of the major population decline, and correlations are not significant. In the absence of measured hydrologic data, this modeling effort suggests that factors other than logging-induced changed in hydrology are largely responsible for the population decline.

AGU Index terms: anthropogenic effects, hydroclimatology, limnology, precipitation, runoff and streamflow.

Salmon have long functioned as a symbol of the Pacific Northwest's intrinsic natural beauty and native wildlife. However, the future of this prominent icon is uncertain, as illustrated with the listing of several salmon species on the U.S. Federal Endangered Species List (Gustavson *et al.,* 1997). Throughout the nation, salmon populations have been dwindling at an alarming rate, but possibly none so disconcertingly as the population of sockeye salmon (*Oncorhynchus nerka*) in Lake Ozette, Washington. Population data from the lake indicate that over the past 60 years, the salmon have declined by an estimated 90-98% (Adkinson and Burgner, 1997). During the early to mid-1900s, the lake supported annual runs of 18,000 to 30,000 sockeye. However, recent observations suggest that a mere 300 to 2,200 adults return to spawn in the lake, with an average of less than 1,000 annually (Gustavson *et al.,* 1997; Jacobs *et al.,* 1996). An initial substantial decline in the late 1940s/early 1950s of approximately 15,000 sockeye was followed by lesser, though consistent, declines for several decades.

The National Marine Fisheries Service (NMFS) determined that Lake Ozette sockeye represent an Evolutionary Significant Unit (ESU), and the population is listed as "threatened" as defined by the Endangered Species Act (ESA 1973: Section 3). Although the population is not presently in danger of extinction, the team concluded that the population is likely to become endangered if present conditions continue into the foreseeable future (Gustafson *et al.,* 1997). Several conditions in the Ozette watershed are believed to have contributed to the population decline (Table 1). Though no single factor has been identified, logging may be a significant factor due to its suspected negative impact upon habitat (Bortleson and Dion, 1979; Dlugokenski *et al*., 1981; Blum, 1988; Adkinson and Burgner, 1996; Geiger, 1996; Jacobs *et al.,* 1996;

Lestelle, 1996). Approximately 85% of the watershed has been clear-cut logged during the past 80 years (Bortelson and Dion, 1979; Blum, 1988).

Logging-induced changes in watershed hydrology can be significant, generally resulting in greater quantities of precipitation entering the surface water system rather than the sub-surface system (Chamberlin *et al.,* 1991; Dingman, 1993). These changes in hydrology affect Lake Ozette in two significant ways. Firstly, the increased surface flow may lead to accelerated soil erosion and sedimentation rates into the lake. Secondly, volumetric and delivery rate changes result in lake level being strongly responsive to precipitation events. Frontal storms can precipitate several centimeters of rain over a few days time, resulting in the lake rising. When storms become less frequent, especially during the summer, lake levels accordingly drop. The dry season lake level is exasperated by lowered groundwater recharge. The overall impact of logging is that the lake fluctuates to a greater degree than it did prior to logging.

The hydrologic effects of logging on the Lake Ozette Basin may be significant to the salmon population because sockeye eggs extremely sensitive to water depth. Ozette sockeye selectively spawn near the gravely shores of the lake at depths between 0.3 to 2.8 m (Jacobs *et al.,* 1996). On several occasions during 1981-1996 the lake fluctuated outside of their preferred range of depth, possibly resulting in fatalities to deposited eggs and alevins. This suggests that varying lake levels might negatively impact Lake Ozette sockeye populations.

The objective of this research will be to evaluate the effects of hydraulic variability on the Lake Ozette sockeye salmon population with the hypothesis that hydraulic variability has changed historically in response to changing land use practices, and has contributed to declining sockeye populations. To assess this hypothesis this paper is organized in the following manner:

(1) A simple least-squares linear regression model relating Lake Ozette lake levels and observed precipitation data will be developed and evaluated. (2) Hydrological models will be used to evaluate the potential impacts of logging on hydrologic variability in the basin. (3) A comparison of lake level fluctuations to sockeye population trends will be made in order to establish whether a relationship exists.

<u>Ozette Basin Characteristics</u>

The 29.5 km² (2,954 ha) Lake Ozette is located on the western edge of the Olympic Peninsula, in Clallam County, WA (Figure 1). Located approximately 2 to 4 km inland of the Pacific Ocean, the lake lies on the remote coastal tip of Washington State, approximately 190 km northwest of the metropolitan hub of Seattle. Lake Ozette is classified as a large, monomictic, oligotrophic to mesotrophic lake, with an average depth of 40 m (Bortleson and Dion, 1979; Beauchamp *et al.,* 1995; Jacobs *et al.,* 1996). Lake Ozette drains an area of more than 200 km² (Figure 1). The topography of the basin is steep, with peaks rising 70 to 100 m as close as 0.3 km of the lake shore. The maximum elevation in the watershed is approximately 580 m above sea level. Three perennial tributaries along the eastern and northeastern portions of the lake account for 58% of the drainage into the lake. The 7.6 km perennial Ozette River functions as the exclusive outlet from Lake Ozette (Figure 1). Although large woody-debris jams are extremely numerous on the river, it is free of major impediments such as dams, slides, or waterfalls. As such, it is considered to be navigable for the sockeye leaving, and subsequently returning to Lake Ozette (Blum, 1988; Jacobs *et al*., 1996). Lake Ozette is home 13 species of fish, including sockeye salmon and two other species of salmon: Kokanee salmon

(*Oncorhynchus nerka kennerlyi*), the non-migrating (fresh water) variety of sockeye, and coho salmon (*Oncorhynchus kitsutch)*. Unlike the sockeye, neither species has exhibited large population declines (Jacobs *et al.,* 1996).

The geology of the Lake Ozette watershed is prone to accelerated erosion. The thin strip of land to the west of the lake is underlain by Pleistocene-age glacial drift primarily composed of unconsolidated gravel, sand, silt, and clay, while the land to the east is underlain by Pliocene- and Pleistocene-age terrace deposits, composed primarily of fluvial and unconsolidated glacio-fluvial sand and gravels (Snavely *et al.,* 1993).

The vegetation in the watershed is classified as Olympic rainforest (Franklin and Dyrness, 1973). The forest is predominantly comprised of sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*), and to a lesser extent, western red cedar (*Thuja plicata*), red alder (*Alnus rubra*) and other mixed strands of alder. Douglas-fir (*Pseudotsuga menziesii*) occurs in the higher elevations, and shore pine (*Pinus contorta*) near the ocean (Buckingham *et al.,* 1996). The understory is rich in shrubs, grasses, and other types of foliage. Due to intense logging during the past six decades, a large majority of the basin’s forests are in early stages of succession, rather than the mature, or climax conditions that dominated the region prior to the 1940s (Blum, 1988).

The land use surrounding Lake Ozette is indicative of land use throughout the Olympic Peninsula. The Makah Tribe and other native peoples practiced a hunter-gatherer type of subsistence lifestyle in the region for thousands of years (McMillan, 1999). European homesteaders first began to locally clear forests in the late-1800s. Wide-scale commercial logging did not begin until the 1940s. Sixty-seven percent of the land surrounding Ozette is privately owned, largely utilized for intensive timber production (Jacobs *et al.,* 1996). Approximately 23% of the watershed—in addition to the lake and the lake's shores—is managed as part of Olympic National Park (Figure 1). The remaining 10% is State owned, and is also managed primarily for timber production. Only about a hundred people occupy the watershed year-round.

The marine climate of the Lake Ozette region is moderated by the neighboring Pacific Ocean and is marked by cool, though mild, winters, and warmer, though still mild, summers. The region experiences a maximum mean of approximately 16°C during the July to August period, and a minimum mean of approximately 4°C during the December to January period, (Figure 2). Lake Ozette is located on the windward side of the Olympic Mountains, receiving an immense amount of rain due to its position as the first land surface to introduce uplift to air masses arriving from the Pacific. Annual precipitation averages 305 cm (120 in), 80% of which falls between the months of October and March (Figure 2). Heavy rains— exceeding more than 5 cm per day—are regularly experienced, often times resulting in the flooding of the lake and its tributaries (Jacobs *et al.,* 1996).

The steep slopes, short drainage length, and high soil moisture content (due to high precipitation totals nearly year-round) throughout most of the watershed means that the lake level is extremely responsive to precipitation. Due to mild winter temperatures and low elevation, the basin does not typically support a snowpack. During rain events the steep slopes and high soil moisture leads to overland flow, a process that is exacerbated by clear-cut logging. Since all points within the drainage are within approximately 8 km of the lake, overland flow is delivered to the lake virtually simultaneously by all drainages within a few hours of the onset of precipitation. Because of the single outlet, the lake can rise and fall a meter or more during a single precipitation event. Consequently, Lake Ozette behaves during a precipitation event in much the same way as a river behaves during a flood event.

The Sockeye Salmon of Lake Ozette

Though Lake Ozette sockeye's spawning practices and life cycle do, in general, follow the typical behavior of sockeye salmon, they do exhibit some unique adaptations (Gustafson *et al.,* 1997). Similar to most sockeye, Ozette sockeye choose spawning sites based on water flow and gravel size. Spawning is concentrated along shores at a 0.3 to 2.8 m range of depth, with a majority of redds placed between 1.0 to 2.8 m in depth. The eggs (and alevins) are extremely sensitive to water depth: in too low of levels of water the eggs are desiccated, and in too high of levels the eggs receive too little aeration to survive (Bortleson and Dion, 1979). The spawning routine occurs between November and March (Figure 3). The eggs incubate for 68 to 82 days, a period less than the average incubation period for sockeye (Jacobs *et al.,* 1996). During April to June, the juveniles emerge and migrate to the pelagic zone of the lake where they rear for approximately one year before undergoing smoltification and emigration to the ocean in April and May.

After two years in the ocean, the adult salmon return during the May to September period (Figure 3). However, unlike most sockeye, which spawn immediately upon return to their natal waters, Lake Ozette sockeye hold in the lake for approximately 3 months prior to spawning. Though the reason for this holding period is not known, it may be that the sockeye strengthen and refortify for the upcoming spawning (M. Haggerty, Makah Fisheries Management, personal communication, 2000). After spawning on the lake shore, Ozette sockeye die, having lived an average of four years.

Research Framework

The hypothesis for this study is that hydraulic variability in the Ozette Basin has historically changed in response to land use practices, contributing to the sockeye population decline. To evaluate this issue it is necessary to compare lake levels with sockeye population data to determine whether or not a relationship between the two variables exists. For a comparison to be made, some of the historical lake level data for Lake Ozette must be reconstructed.

Reconstruction of Lake Level Data Using Regression Analysis

A linear regression model is used to describe the relationship between lake level and precipitation, with the intent of using the model and historic precipitation data to recreate lake level data (Jones *et al*., 1987; Bengtsson and Malm, 1997). The statistics program SPSS 10.0 is employed for all statistical calculations. Although the National Climatic Data Center maintains data from several different precipitation gauges in the Lake Ozette vicinity, the Forks, WA record was selected for analysis since it has the longest and most complete record of the all the proximal precipitation gauges. No attempts were made to fill minor gaps of missing data in the January 1908 through December 1997 record.

Lake Ozette lake level data are the dependent variable in the regression analysis. The National Park Service (NPS) maintains a daily record of Lake Ozette lake levels that extends from November 1981 through December 1999. The stream gauge is located on the Ozette River (WRIA20.0046 USGS HVC) at the NPS Ozette Ranger Station, approximately 100 m downstream from the lake outlet (Figure 1). The record contains a 39-month long block of missing data from October 1994 through December 1998. Due to temporal discrepancies between the two variables, the daily lake level measurements were averaged to produce mean monthly lake levels. The averaging of lake levels was considered beneficial to the analysis because it removed the effects of the basin runoff time delay (of precipitation events on lake level) that are inherent in daily measurements. During the mid-1990s the stream gauge was relocated; however, the lake level measurements were corrected for this change (M. Haggerty, Makah Fisheries Management, personal communication, 2000).

A 14-year common period of data was split into two euqual sub-periods, 1981-1987, and 1988-1994. Half the data were used to calibrate and calculate the regression model, then the model was verified with data from the second sub-period to ensure model accuracy (Jones *et al.,* 1987; Velero *et al.,* 1996). The 1988-1994 sub-period was chosen as the calibration period for the regression analysis because it represents the most current hydrological situation. The 1988-1994 data set meets all the prerequisite assumptions of linear regression (Cykler-Ignac, 2001). The model has an R^2 value of 0.530, and has a significance level of 0.000. Figure 4 shows a scatterplot and line of best fit, along with both prediction and confidence intervals.

To determine the validity of the regression equation, the model is used to calculate lake levels for the 1981-1987 sub-period (Velero *et al.,* 1996). These modeled lake levels are then compared to the observed 1981-1987 lake levels (Figure 5). The model is clearly sensitive to the seasonal fluctuations in lake level. Of the 72 observations during the 1981-1987 sub-period, the model overestimates 37 times and underestimates 37 times. The largest model overestimate is 0.62 m above the observed level in February 1982, and the largest underestimate is 0.91 m below the observed level in October 1982. The two data sets have a paired samples correlation of 0.797 ($p=0.000$, $n = 74$). A paired samples t-test indicates that the observed and modeled data sets are not statistically different from one another (two-tailed, 95% confidence level, df=73).

Having verified the model accuracy using independent testing for the 1981-1987 sub-period, the model is considered sufficient to reconstruct lake levels at Lake Ozette (Velero *et al.*, 1996). Precipitation data from Forks are used to recreate lake level data for the periods of January 1908 through December 1981, and October 1994 through December 1997 (Figure 6). When combined with the measured lake level data, a nearly continuous--except for those periods in which precipitation data are missing--lake level record for Lake Ozette for the years 1908-1999 has been constructed (Cykler-Ignac, 2001).

Accounting for Hydrological Effects of Logging

Although a nearly complete record of Lake Ozette lake levels for the 20th century has been established, it is a record based on the current hydrologic relationship between precipitation and lake level. Effectively, the model is reflective of hydrology in a basin that was approximately 24% logged during the 1988-1994 regression period, coupled with cumulative effects of historical logging in the watershed. In order to more accurately model lake levels it is necessary to account for the effects of logging on hydrology during the last century.

Though a study of the hydrological impacts of logging and road building has not been undertaken at Ozette, a multitude of studies examining the effects of logging on hydrology in similar Pacific Northwest watersheds have been undertaken. The findings of these studies have been extremely disparate. Studies examining the changes in water yield due to logging and road-building on lower elevation lands (*i.e.* no snow-on-rain events) have found no appreciable change in peak flows (Rothacher, 1970; Harr, 1986; Duncan, 1986) and, contrastingly, significantly higher peak flows (Harr *et al.,* 1975; Lyons and Beschta, 1983; Berris and Harr, 1987; Potter, 1991).

The amplitude of peak flow discharge increases have been shown to increase 5-100% (Jones and Grant, 1996; Thomas and Megahan, 1998; Bowling *et al.,* 2000). Annual volumetric discharge has been reported to increase by a similar range of values (Rothacher, 1970; Harr *et al.,* 1975; Berris and Harr, 1987; Bowling *et al.,* 2000). The timing of the greatest relative increases varies between studies as well. Some studies have found that summertime shows the greatest increase (Keppler and Ziemer, 1990; Bowling *et al.,* 2000), others have found wintertime (Harr *et al.,* 1975; Jones and Grant, 1996), and yet others the beginning of fall (Rothacher, 1970). While some studies have found small precipitation events to have the largest response (Bowling *et al.,* 2000), others found that large events have the largest response (Jones and Grant, 1996), while yet others suggest no relative difference between small and large events (Rothacher, 1970). Since a hydrologic study of the Ozette Basin is lacking and previous studies of similar watersheds are incongruous, one can only surmise the effects of logging upon water yield in the basin.

Three different models, representing varying degrees of impacts, are applied to the Ozette lake level data: (1) Logging and related road building has no effect upon water yield in the basin. (2) Logging results in a 20% increase in water yield in the basin. (3) Logging results in an increase in annual water yield proportional to the area logged. By no means are these three models the only impacts logging may impose upon the basin hydrology. Rather, the selected models are meant to allow the reader to gain an impression of how the hydrology in the Ozette Basin may have changed during the 20th century due to logging, and, consequently, the degree to which sockeye habitat may have been affected.

The first scenario is that logging has not impacted the hydrology of Ozette Basin (Rothacher, 1970; Harr and McCorison, 1986; Duncan, 1986). Under this scenario the modeled lake level data are not adjusted. Under the second scenario, lake levels are adjusted to represent a 20% increase relative to the percentage of the basin that is logged (Berris and Harr, 1987). For example, if 25% of the basin is logged, then lake levels will be adjusted for a 5.0% (20% of 25%) overall hydrologic increase. This scenario is intended to represent moderate effects that logging might have on the runoff. The third scenario is that annual water yield increases proportionally to the area logged (Rothacher, 1970). Thus, if 15% of the basin is logged then the annual water yield increases by 15%, etc. This scenario represents an upper-extreme of the effects that logging could have on basin hydrology.

Approximately 85% of the Ozette Basin has been incrementally logged since the 1940s. Accordingly, it is necessary to account for the timing of logging in the second and third scenarios. The temporal adjustments for the rate of logging are based on unpublished data by the Makah tribe and the Olympic National Park (Table 2) which describe the age classes of forest communities in the basin (Jacobs *et al.,* 1996). The data are interpreted from 1990 aerial photographs and therefore reflect the approximate acreage logged. It should be noted that approximately 38% of the 135 km^2 area of watershed forest evaluated was of unknown age and therefore could not be categorized (Jacobs *et al*., 1996). Most studies have shown that the effects of logging on runoff decrease over time, returning to pre-harvest hydrological conditions in 6 to 22 years (Rothacher, 1970; Harr *et al.,* 1975; Jones and Grant, 1996; Bowling *et al.,* 2000). Given the poor temporal resolution of our logging data, we assume that logging impacts are confined within each time period (Table 2).

Relationship Between Salmon Population Data and Lake Level Changes

To evaluate the potential effects of lake level upon the sockeye population, it is necessary to examine the portion of each year in which the sockeye are susceptible to fluctuations. This includes the months from November until June, when spawning begins until when the fry emerge (Figure 3). For each year, and under each of the three hydrological models, during the critical November to June period, the maximum and minimum lake levels are recorded, and the range calculated. If the lake fluctuates are larger than the survivable range of depth, the eggs may perish.

These fluctuations are plotted on bar graphs, with the height of each bar representing the lake level fluctuation during the spawning and incubation period (Figure 7). For facilitation in interpreting the data, three reference lines are plotted, each demarcate a critical lake level fluctuation for sockeye habitat. Ozette sockeye concentrate the deposition of their eggs in a general range of 0.3 to 2.8 m in depth. The reference line labeled 'General Range' represents the level of fluctuation that would place all eggs outside of their habitat requirements. If the lake level fluctuates outside of this range, then all or nearly all of the deposited eggs are disposed to death. A majority of eggs are concentrated in the 1.0 to 2.8 m depth. The line labeled 'Preferred Range' represents the level of fluctuation that would place all eggs deposited within this range of depth outside of their habitat requirements. If the lake level fluctuates outside of this range, a large majority of the deposited eggs are likely to be disposed to death. The third reference line labeled 'Half Preferred Range' represents the level of fluctuation that would place approximately half of all eggs outside of the preferred range. Although a lake level fluctuation equal of greater than 0.9 m does not guarantee the death of eggs, a fluctuation of this height might place a significant portion of deposited eggs in jeopardy.

Discussion of Findings

Lake Level Fluctuations During the 1908-1999 Record

The linear regression analysis comparing 1988-1994 Forks precipitation and Ozette lake levels produced a model with an R^2 value of 0.530 ($\rho = 0.000$), suggesting that it explains a substantial proportion of the variability in lake levels. The model was found to be not significantly different from the 1981-1987 measured lake level using a paired t-test (Figure 5). A 1908-1999 lake level record was constructed for Lake Ozette using the regression model which portrays the seasonal fluctuation of the lake and inter-annual variability (Figure 6).

An inspection of the record (n=1036) finds that the lake drops to a minimum level around 10 m on a routine basis, falling below 9.8 m 17 times (1.6% of the record) (Figure 6). This suggests that groundwater recharge enables the lake to maintain minimum levels of no lower than approximately 9.8 m. The maximum levels, however, show more temporal irregularity than the minimum levels. The lake level reaches or exceeds a height of 12 m only three times (0.1% of the record), and reaches or exceeds levels of 11.5 m 16 times (1.5% of the record). Throughout the 92 year record the peak levels are irregularly spaced and extremely varied in size, as compared to the regularly occurring minimum lake levels of 9.79-10.0 m (Figure 6).

The three hydrologic scenarios are statistically different from one another, confirming our hypothesis that logging has a significant impact on discharge. An ANOVA test indicates that the unadjusted data (Scenario 1) demonstrates the greatest degree of fluctuation, and the proportional fluctuations (Scenario 3) demonstrate the smallest degree of fluctuation during the 1908-1999 period. The maximum difference between the three scenarios occurs during 1970 with a difference of 0.47 m between Scenario 1's fluctuation (0.86 m) and Scenario 3's fluctuation (1.33 m). Not including measured data (i.e. 1981-1994 & 1998-1999), the maximum difference between the scenarios averages 0.15 m with a standard deviation of 0.085 m.

Implications of the Results of the Hydrologic Scenarios

The three hydrologic scenarios concur that during 1908-1999 at no point during the November to June critical period did the lake level fluctuate beyond the 2.5 m habitat range (Table 3). Thus, at no time during the 92 year record does it appear that the lake level fluctuations were large enough to dispose the entire population of eggs and alevins to death. The conformity between the three scenarios suggests that even if logging significantly increases runoff, such extreme lake level fluctuations rarely, if ever, occur in Lake Ozette.

The modeling scenarios indicate that during the 92 year period, the lake level fluctuated beyond the 1.8 m preferred range of depth 6.6-8.7% of the time (Table 3). This implies that in a given 100 critical periods (years), the lake level fluctuates enough to dispose to death a majority of the deposited eggs and alevins during 6 to 9 of the periods (years). Thus, once out of every 11 to 15 years a significant proportion of the deposited sockeye population might be lost due to lake level fluctuations.

The modeled scenarios indicate that the lake levels commonly fluctuated beyond the mid-point of the preferred range of depth, exceeding a 0.9 m fluctuation approximately 75.0-80.4% of the time. Based on these data, one would expect Lake Ozette to experience, on average, a 0.9 to 1.79 m fluctuation approximately every 1.2 to 1.3 years. This suggests that on a regular basis Ozette's lake level fluctuates enough to potentially dispose to death a portion of the deposited redds. Given the common occurrence of lake level fluctuations of this magnitude, it is likely that the Ozette sockeye have adapted, and that spawning and incubation habits have been accommodated to survive this variable system.

While the climate and fish populations in the Pacific Northwest have been found to have relationships with the Pacific Decadal Oscillation and other oceanic phenomenon (Beamish and Bouillon, 1993; Mantua *et al.,* 1997), no temporal trends were detected in this data set (Figure 6). The regular occurrences of 0.9 to 1.79 m and semi-regular occurrences 1.8 to 2.49 m lake level fluctuations appear consistent throughout the record. This implies that it is likely that the sockeye population has adapted in some form to survive these events. One such adaptation may be the short (83 day) incubation period in order to leave the nest before the lake level radically fluctuates. More substantiation is needed to verify this conjecture.

It is also important to point out that large fluctuations (greater than 1.8 m) have never occurred in sequential years (Figure 7). This indicates that although a single brood cycle may be impacted by lake fluctuations, the rest of the population remains intact. In other words, while non-frequent larger fluctuations may dispose to a portion of the deposited redds, the rest of the population—the 1, 2, and 3 year-old sockeye—remain unimpaired.

Fluctuations During the 1940s and 1950s

Of particular interest are lake level fluctuations that occur during and prior to the significant decline between 1949 and 1950. To allow for cause and effect time delays the 1940-1959 period is further scrutinized. During this 20 year period, lake level fluctuations are, on average, smaller than the entire 92 year record (Table 4). The average fluctuation for the 1940 to 1959 period is lower in each scenario than the 92 year average, as are the standard deviations and maximum fluctuations (Table 4). A t-test comparing the 1940-1959 lake level fluctuations to the entire record suggests no significant differences (2-tailed, $p=0.05$, $n=101$). Thus, one can conclude that the 1940-1959 fluctuations were not significantly different then 20th century fluctuations. The data suggest that lake level fluctuations were likely not the instigating factor in the sockeye declines in the late 1940s and early 1950s.

The Role of Fluctuations in Sockeye Declines

In an attempt to better understand the potential impacts of the logging practices on basin hydrology, three scenarios have been employed to assess changes in land use. Although each of the scenarios adjusts the data using different hydrological assumptions, none of the hydrologic scenarios indicate that lake level fluctuations have significantly contributed to sockeye declines. Scatterplots of estimated adult escapements plotted against lake level fluctuations for each of the scenarios show similarly disassociated patterns (not included). Moreover, Pearson correlation comparing sockeye population numbers and lake level fluctuations for each of the three scenarios for the 1948-1995 period are similar. Non-significant correlation coefficients range between -0.014 and 0.022, indicating that there is no relationship between lake level fluctuations and sockeye population.

Were lake level fluctuations a factor in the sockeye decline, one would expect to observe either an increase in fluctuations, a series of large fluctuations over a short period, or a few extremely high fluctuations during or immediately preceding the period of declines (Figure 7). However, the lake level record does not indicate that the fluctuations were any different during the 1940-1959 period than during the entire 92 year record. Indeed, the average fluctuations are slightly lower during this period than during the overall 20th century record (Tables 4 and 5). This suggests that some factor, other than lake level fluctuations is responsible for the dramatic decrease in sockeye during the late 1940s and early 1950s (*i.e.* Table 1).

The five largest fluctuations which occurred in 1935, 1953, 1980, 1982, and 1999 do not appear to correspond to the initial or subsequent reduction in the sockeye salmon in Lake Ozette (Figure 7). Since there are no population data for 1935, it is unknown if the lake level fluctuation occurring that year had an impact on the sockeye population. However, since it occurs more than 15 years prior to the 1949-1950 reduction, it is unlikely to have played a role in the population reduction.

The large 1953 fluctuation occurs just after the immense population reduction. While this large fluctuation did not instigate the decline, it may have further suppressed an already-diminished population. Occurring approximately 3 years after the initial decline, the population, already reduced by ~85%, may have been more susceptible to a large fluctuation than it would be during more typical times. Though this supposition cannot be supported by the data, it is conceivable that these poor hydrologic conditions furthered the population declines during the mid-1950s.

Summary, Conclusion, & Recommendations

The hypothesis of this study is that hydraulic variability in the Ozette Basin has changed in response to land use practices, and that this variability has contributed to decreasing sockeye populations during the past 60 years. To examine the impacts of fluctuations it was necessary to develop historical lake level data from proxy records. Since changes in lake level is strongly correlated with precipitation levels, a linear regression model was developed between the two variables, in order to recreate lake level data.

The linear relationship is statistically significant and was therefore used to develop historical lake level data. These data were then adjusted using three models, which assume a range of potential hydrological impacts due to logging in the Ozette Basin. Under each of the three scenarios, the maximum lake level fluctuation that occurred during the November to June period, critical to salmon redd survival, was calculated. These data illustrate the maximum range the lake level may have fluctuated during the time in which the sockeye eggs were deposited and when the fry emerged. Subsequently, correlation values were calculated comparing the lake level fluctuations of each scenario to the sockeye population declines in Ozette.

Although each of the scenarios suggest that five substantial lake level fluctuations occurred during the 20th century, their occurrences appear to not correspond with the timing of the population decline. More importantly, however, the fluctuations do not statistically relate to decreases in the Lake Ozette sockeye population. It is probable that lake level fluctuations have resulted in eggs being deposited outside of their habitable range during extreme fluctuations, potentially resulting in some sockeye deaths. However, it appears unlikely that lake level fluctuations have been the determining factor in the historical declines. During the 1908-1999 record, large fluctuations did not occur in consecutive years, suggesting that while a single occurrence of a large fluctuation may have impacted deposited redds, the brood cycle would protect the overall population.

While logging in the basin has likely resulted in increased fluctuations in Lake Ozette, this study fails to find an association between lake level fluctuations and sockeye decreases. This certainly does not suggest that lake level fluctuations are completely faultless in the declines in Lake Ozette. The 1953 fluctuation likely contributed to the decline which had begun 3 years earlier. The effects of the fluctuations may be masked behind more forceful factors, such as sedimentation from logging, historical over-fishing, log jam removal, or other factors yet to be determined.

The results of this study should be interpreted as suggestive due to limitations of the statistical methods and of the data employed. The monthly averaging of daily precipitation and lake level data conceals short-term fluctuations, which can significantly impact the population. Additionally, the logging data were interpreted from a limited temporal series of air photos, which might have masked true spatial-temporal relationships in the Ozette Basin.

Although the reason for the sockeye declines in Lake Ozette is still unknown, the results of this study are helpful because they discount the likelihood that hydrologic variability is one of many potential factors that are considered suspect in the declines. Thus, future research can concentrate on other remaining potential factors, with the goal of determining the true factor(s). Here, as with Geiger (1996), we find that though we could bring some closure to some issues about the sockeye population, we did not have the information to precisely diagnose problems and recommend solutions.

Thus, research examining other potential factors must continue (Table 1). The effects of land use, specifically logging, in the Ozette Basin are worthy of further scrutiny, as are seal, bird, and other sea mammal predation, non-native introduced diseases and parasites, and the combined effects of several factors. Future work in the basin might include: (1) a pre- and post-logging hydrological study so as to more fully determine the effects of clear-cutting on the basin's hydrology, (2) further investigations of the effects of logging on sedimentation rates on the lake's shores, (3) developing more specific logging data, in terms of both the date of occurrence and the percentage of area logged in the basin, (4) continued under-water surveillance during spawning periods to more accurately gauge sockeye population numbers, and (5) continued investigations into other (non-logging related) potential factors, including, but not limited to log jam removal, historic overfishing, and predation by seals and river otters.

This is clearly a complex problem that can only be answered with continued research. One hopes that not only will future research find an answer to why the declines are occurring, but it will also find a solution for preventing the extinction of the sockeye population in Lake Ozette. The loss of this population would truly be a loss to us all. The best way to conserve genetic diversity in sockeye salmon is to preserve populations in as many unique habitats as possible. From an evolutionary perspective, it is prudent to save the genetically diverse, anadromous sockeye salmon because they are adapted to a variety of habitats and conditions (Wood, 1995). With salmon populations diminishing every day, it is necessary to preserve as diverse a genetic population of salmon as possible. Since Ozette sockeye salmon are a genetically distinct population, their preservation is important in maintaining the genetic diversity of the species. It is essential that the causes of their demise be understood so that remediation can occur, and so that this Evolutionary Significant Unit can be sustained.

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Figure Captions

Figure 1. Map of study area. Source: U.S. Geol. Surv. Cape Flattery, Wash.-B.C., 1:100,000 topographic series, 1981.

Figure 2. Climograph for Forks, WA. (Data from National Climatic Data Center).

Figure 3. Timing of use of the Lake Ozette Basin by sockeye salmon (adapted from: Jacobs *et al.* 1996).

Figure 4. 1988-1994 Regression. Shown with 95% Confidence and Prediction intervals. Least-squares regression line: *Lake Level t (m)* = 2.345e-2 * *Precipitation t (cm)* + 9.79. $R^2 = 0.530$.

Figure 5. Comparison of modeled to observed values, 1981-1987. Modeled values based on least-squares regression line *Lake Level t (m)* = 2.345e-2 * *Precipitation t (cm)* + 9.79; observed values based on lake level measurements.

Figure 6. Historical record of lake levels at Lake Ozette. Lake levels reconstructed with regression modeling 1908-1980 and 1995-1997, and measured 1981-1994 and 1998-1999.

Figure 7a. Lake level fluctuations assuming no change to the hydrology (Scenario 1). Note that the year given represents the year that the period ended in, i.e. the November 1907 to June 1908 period is recorded as "1908."

Figure 7b. Lake level fluctuations assuming a 20% change to the hydrology relative to the percentage of basin logged (Scenario 2).

Figure 7c. Lake level fluctuations assuming increases in hydrology relative to the percentage of basin logged (Scenario 3).

Table 1: Potential causes leading to the Ozette sockeye decline

Potential Cause	Potentiality
Ozette sockeye physical characteristics	Unlikely contributing factor [a b d]
Water quality/characteristics	Unlikely contributing factor [a]
Intra- and interspecies competition	Unlikely contributing factor [a b]
Climatic/Oceanic variability	Potentially contributing factor [b]
Predation	Potentially contributing factor [b f g]
Non-native disease or parasite	Potentially contributing factor [a]
Log jam removal	Likely contributing factor [f]
Historic overfishing	Likely contributing factor [a b d]
Land use* (logging) in the watershed	Likely contributing factor [a b c d]

[a] Jacobs *et al*. 1996, [b]Adkinson and Burgner 1996, Beamish and Bouillon, 1993, [c] Geiger 1996, [d] Lestelle 1996, [f] M. Haggerty, Makah Fisheries Management, personal communication, 2000, [g] Beauchamp *et al.*1995

* Dams, urban development, agriculture, and industry are not present in the watershed.

Table 2. Rate of logging in the Ozette Basin[a] (Jacobs *et al.* 1996).

Period of Logging	km^2 Logged	Percent Basin Logged
<1910	0.46	0.34
1910-1949	7.90	5.83
1950-1969	13.46	9.94
1970-1979	28.30	20.90
1980-1990	32.08	23.69
1990-1999 [b]	32.08	23.69

[a] Based on logging in Umbrella Crk., Big Crk., Siwash Crk., and South Crk. watersheds. This accounts for approximately 135 km^2 of the basin, approximately 80% of the land in the Ozette Basin.

[b] Estimated using 1980-1990 data since data not available.

Table 3. Comparison of modeled fluctuations, 1908-1999. All measurements are in meters (m). Calculations based on n = 91.

	mean	std. dev.	min. fluc.	max. fluc.	Number of Fluctuations >= 2.5	>=1.8	>=0.9
Scenario 1	1.27	0.41	0.47	2.39	0	8	74
Scenario 2	1.24	0.40	0.47	2.3	0	7	74
Scenario 3	1.16	0.39	0.47	2.19	0	6	69

Table 4. Comparison of modeled fluctuations, 1940-1959. All measurements are in meters (m). Calculations based on n = 20.

	mean	std. dev.	min. fluc.	max. fluc.	Number of Fluctuations >= 2.5	>=1.8	>=0.9
Scenario 1	1.26	0.37	0.70	2.31	0	1	17
Scenario 2	1.21	0.35	0.68	2.25	0	1	16
Scenario 3	1.10	0.32	0.61	2.06	0	1	14

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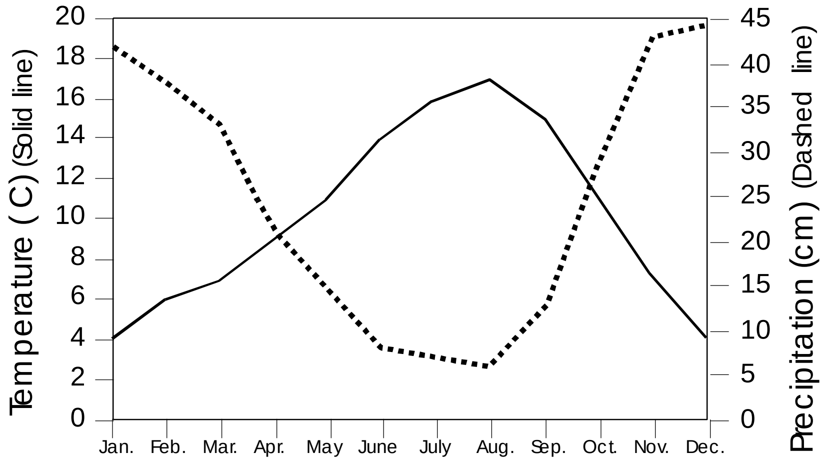

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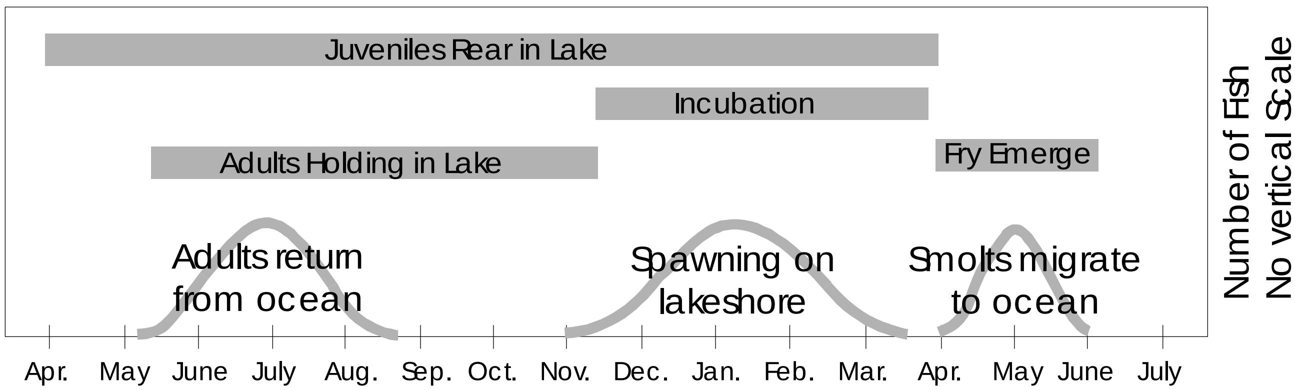

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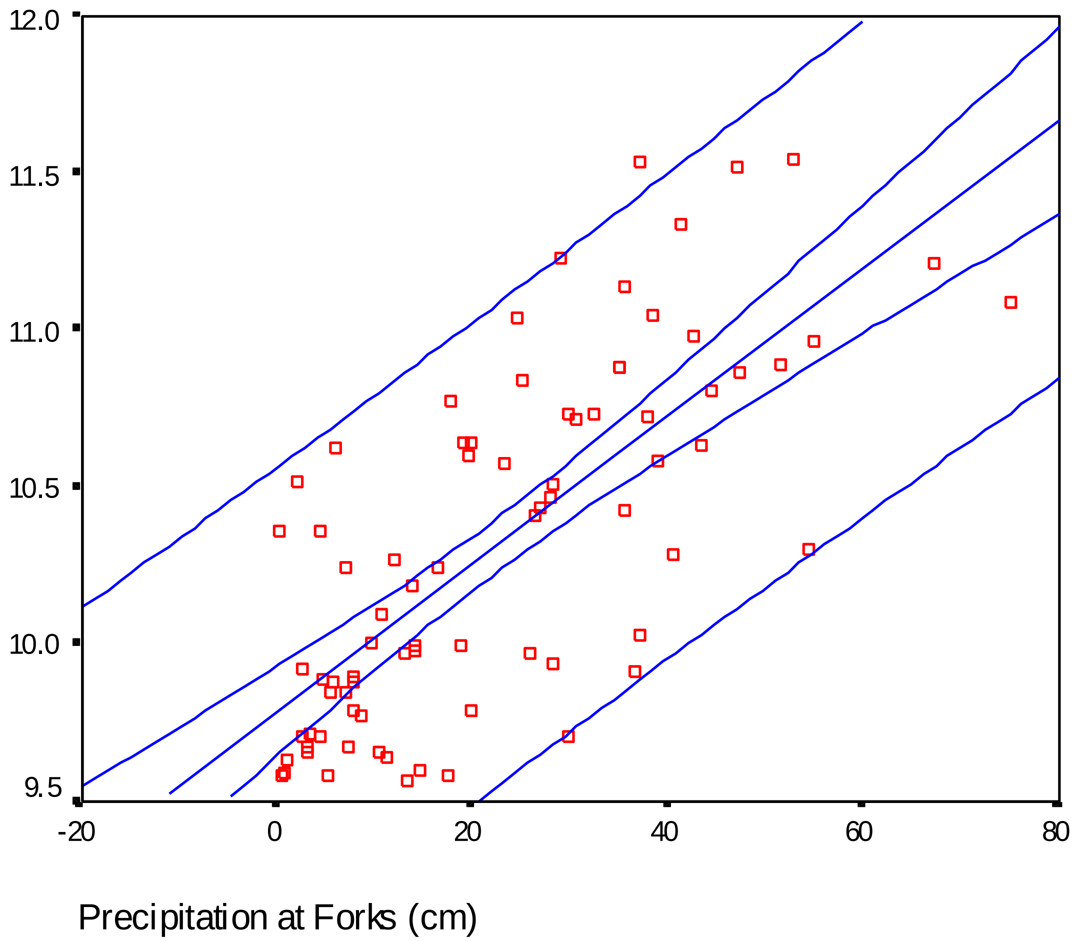

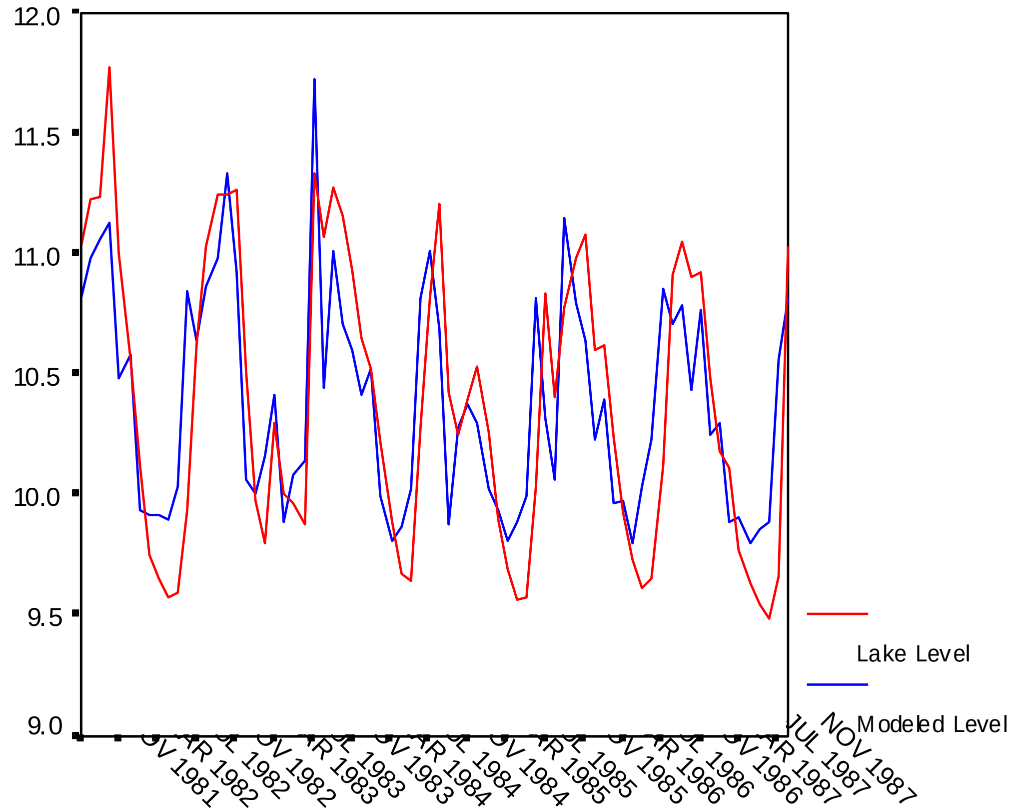

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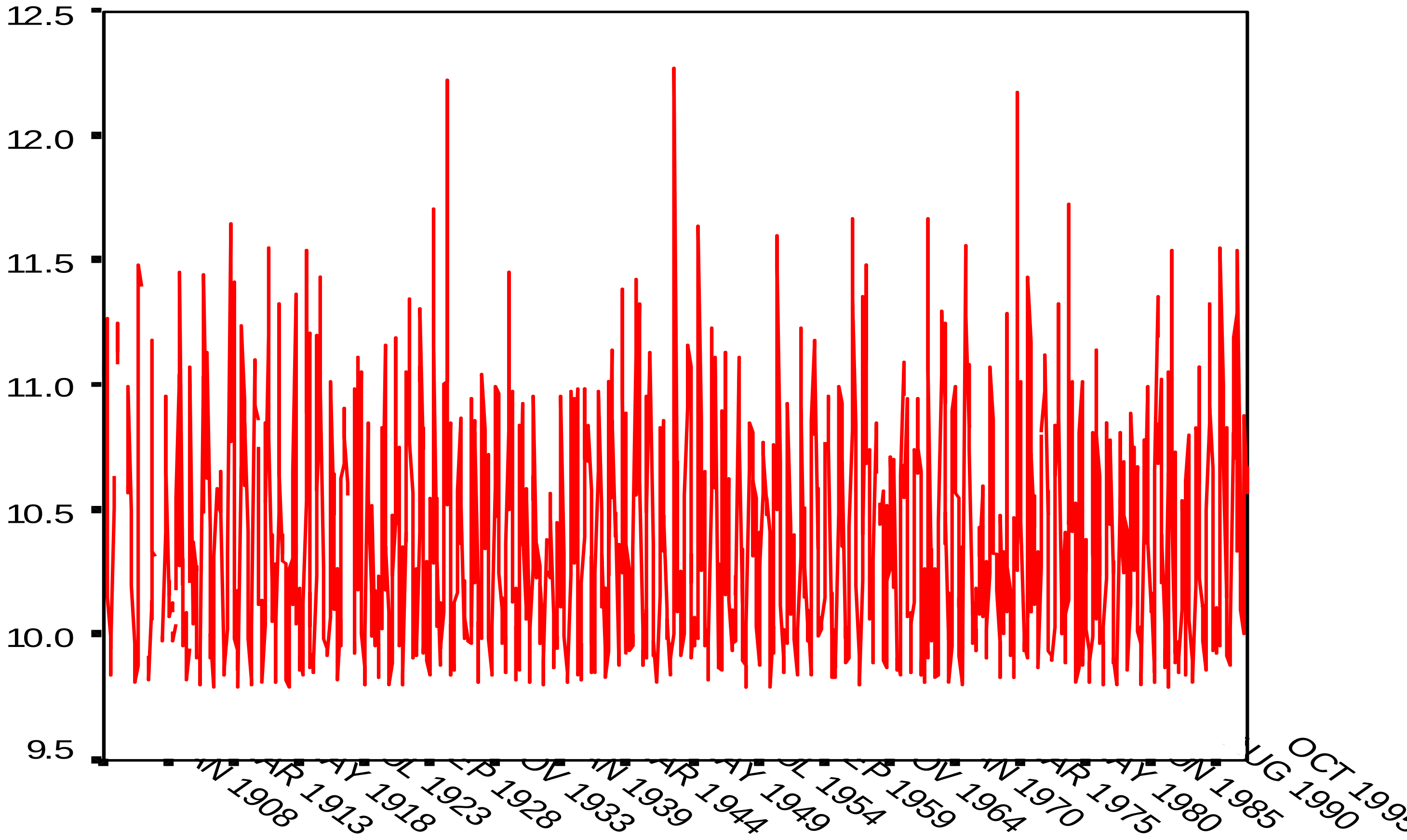

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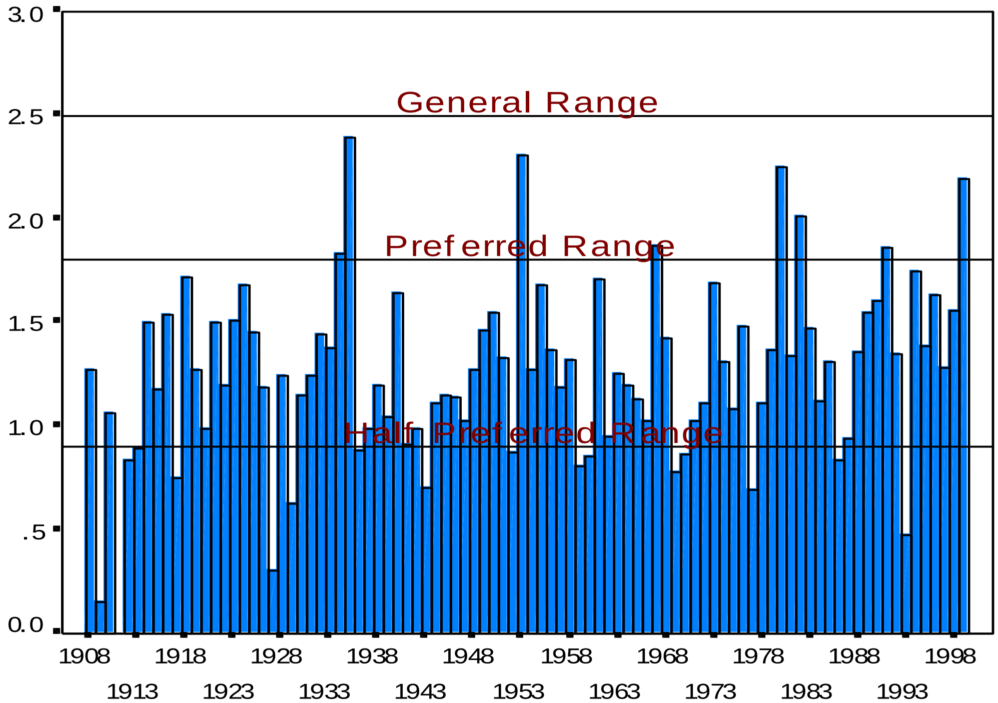

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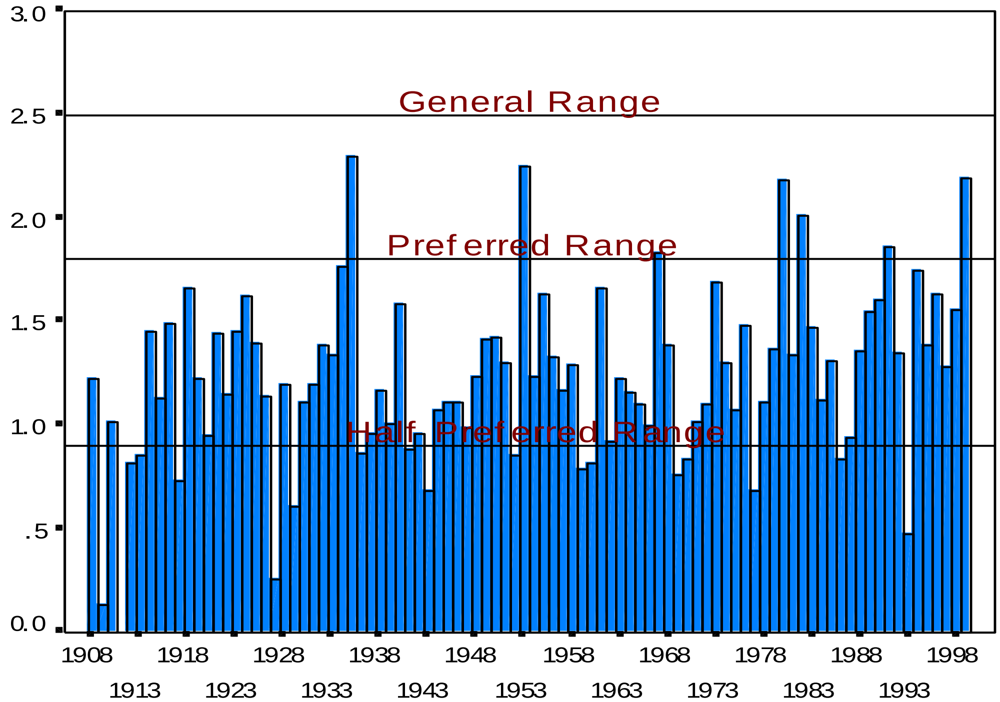

Figure 7b. Lake level fluctuations assuming a 20% change to the hydrology relative to the percentage of basin logged (Scenario 2).

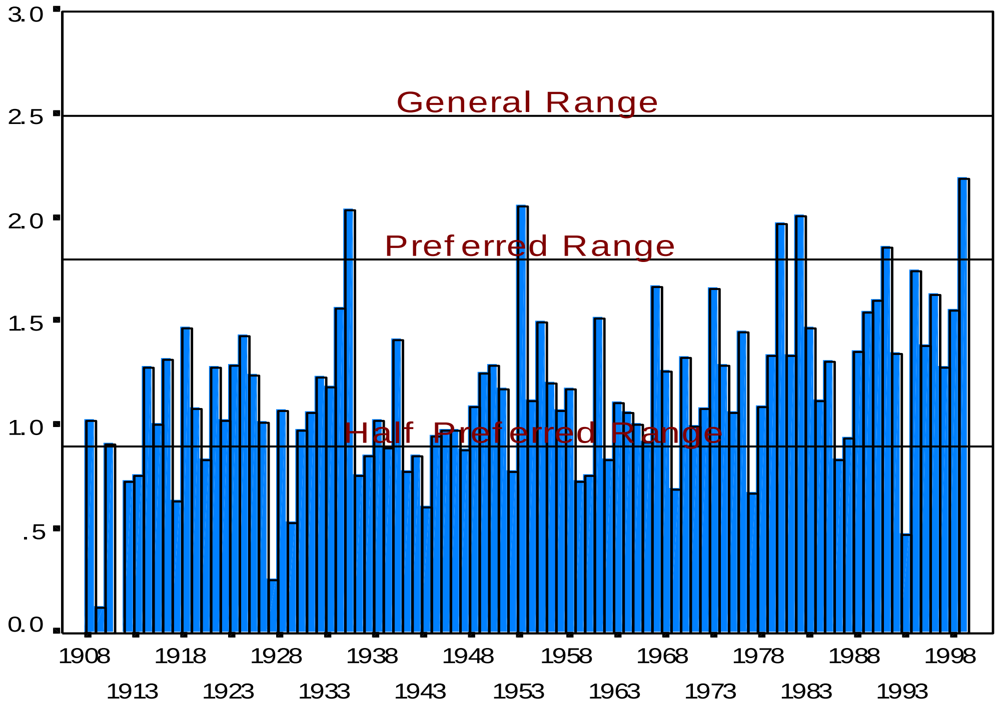

Figure 7c. Lake level fluctuations assuming increases in hydrology relative to the percentage of basin logged (Scenario 3).