REPRINT
2171

INSTREAM TEMPERATURE MODELING AND FISHERY IMPACT ASSESSMENT FOR A PROPOSED LARGE SCALE ALASKA HYDROELECTRIC PROJECT

William J. Wilson
Michael D. Kelly
Paul R. Meyer

Arctic Environmental Information and Data Center
University of Alaska
707 A Street
Anchorage, Alaska 99501
U.S.A.
(907) 279-4523

Pages 183-206 in J.F. Craig and J.B. Kemper, eds. Regulated streams, advances in ecology. Proceedings of the 3rd International Symposium on Regulated Streams, August 4-8, 1985, Edmonton , Alberta, Canada. Plenum Press, New York, NY. 1987.

ABSTRACT

The temperature-related effects on instream fish resources due to regulating a large southcentral Alaska river system by a proposed hydroelectric development have been examined. In order to predict natural and with-project temperature regimes downstream from the proposed Watana and Devil Canyon reservoirs of the 1,620 megawatt Susitna Hydroelectric Project, a Stream Network Temperature Simulation Model (SNTEMP) has been employed. This model, developed by the U.S. Fish and Wildlife Service's Instream Flow and Aquatic Systems Group, required hydrology, meteorology, basin topography and stream geometry data as input and computed heat flux relationships and transported heat through the river system. This first application of SNTEMP in Alaska has provided an opportunity to examine the thermal effects of many potential Susitna reservoir operating schedules on instream fishery resources. Various combinations of meteorologic/hydrologic conditions were used to simulate downstream river temperatures for natural, reservoir filling, and both one- and two-dam operational scenarios. Thermal tolerance criteria were developed for five Pacific salmon species inhabiting the Susitna River. Temperature predictions from SNTEMP were then compared to these life phase temperature criteria, and a subjective prediction of effects was made.

Simulated post-project temperatures are predicted to be cooler in the river from May through August and warmer from September through April. Altered temperatures are generally within the temperature criteria established for Susitna River salmon and most operational cases should not significantly impact these species. However, two effects could result from the altered temperature regime: (1) improved mainstem salmon incubation habitat due to

warmer winter water temperatures; and (2) decreased juvenile salmon growth from colder summer water temperatures.

INTRODUCTION

The State of Alaska is proposing to construct a two dam, 1620 megawatt hydroelectric project (U.S. Federal Energy Regulatory Commission No. 7114) on the Susitna River approximately 190 km NNE of Anchorage. A study is underway to determine the effects this project may have on the indigenous aquatic resources of the Susitna drainage, and in this paper we report on studies of the expected alteration of the instream temperature regime of the Susitna River (Meyer et al. 1984). Twenty species of fish are known to inhabit the Susitna basin (table 1). This study focuses on the most numerous and economically valuable Pacific salmon species, approximately two million of which annually enter this river to spawn.

The Susitna River flows 520 km from its source at the glaciers on the southern slopes of the Alaska range to its mouth at Cook Inlet near Anchorage (figure 1). It is seasonally turbid from the glacier melt contribution with summer turbidities of 74 to 730 NTU, and winter turbidities <1 NTU (R&M Consultants, Inc. and Larry A. Peterson and Associates 1981). The river drains a basin of approximately 50,800 sq km, the sixth largest river basin in the state. Like all northern rivers, the Susitna exhibits strong seasonal variation in flow, high during the spring and summer due to breakup, snowmelt and summer rains, and low during the winter. With the project in place, high summer flows would be captured for winter release when the demand for power generation is greatest.

The project would be constructed in two stages. The first stage, Watana dam and reservoir, would be located at river kilometer (RK) 296 (296 km upriver from the mouth) and is scheduled for completion in 1996. The last year Watana dam would be operated alone is 2001. The second stage, Devil

Table 1. Common and scientific names of fish species recorded in the Susitna River basin.

Arctic lamprey	*Lampetra japonica* (Martens)
Eulachon (hooligan)	*Thaleichthys pacificus* (Richardson)
Arctic grayling	*Thymallus arcticus* (Pallas)
Bering cisco	*Coregonus laurettae* Bean
Round whitefish	*Prosopium cylindraceum* (Pallas)
Humpback whitefish	*Coregonus pidschian* (Gmelin)
Rainbow trout	*Salmo gairdneri* Richardson
Lake trout	*Salvelinus namaycush* (Walbaum)
Dolly Varden	*Salvelinus malma* (Walbaum)
Pink (humpback) salmon	*Oncorhynchus gorbuscha* (Walbaum)
Sockeye (red) salmon	*Oncorhynchus nerka* (Walbaum)
Chinook (king) salmon	*Oncorhynchus tshawytscha* (Walbaum)
Coho (silver) salmon	*Oncorhynchus kisutch* (Walbaum)
Chum (dog) salmon	*Oncorhynchus keta* (Walbaum)
Northern pike	*Esox lucius* Linnaeus
Longnose sucker	*Catostomus catostomus* (Forster)
Burbot	*Lota lota* (Linnaeus)
Threespine stickleback	*Gasterosteus aculeatus* Linnaeus
Ninespine stickleback	*Pungitius pungitius* (Linnaeus)
Slimy sculpin	*Cottus cognatus* Richardson

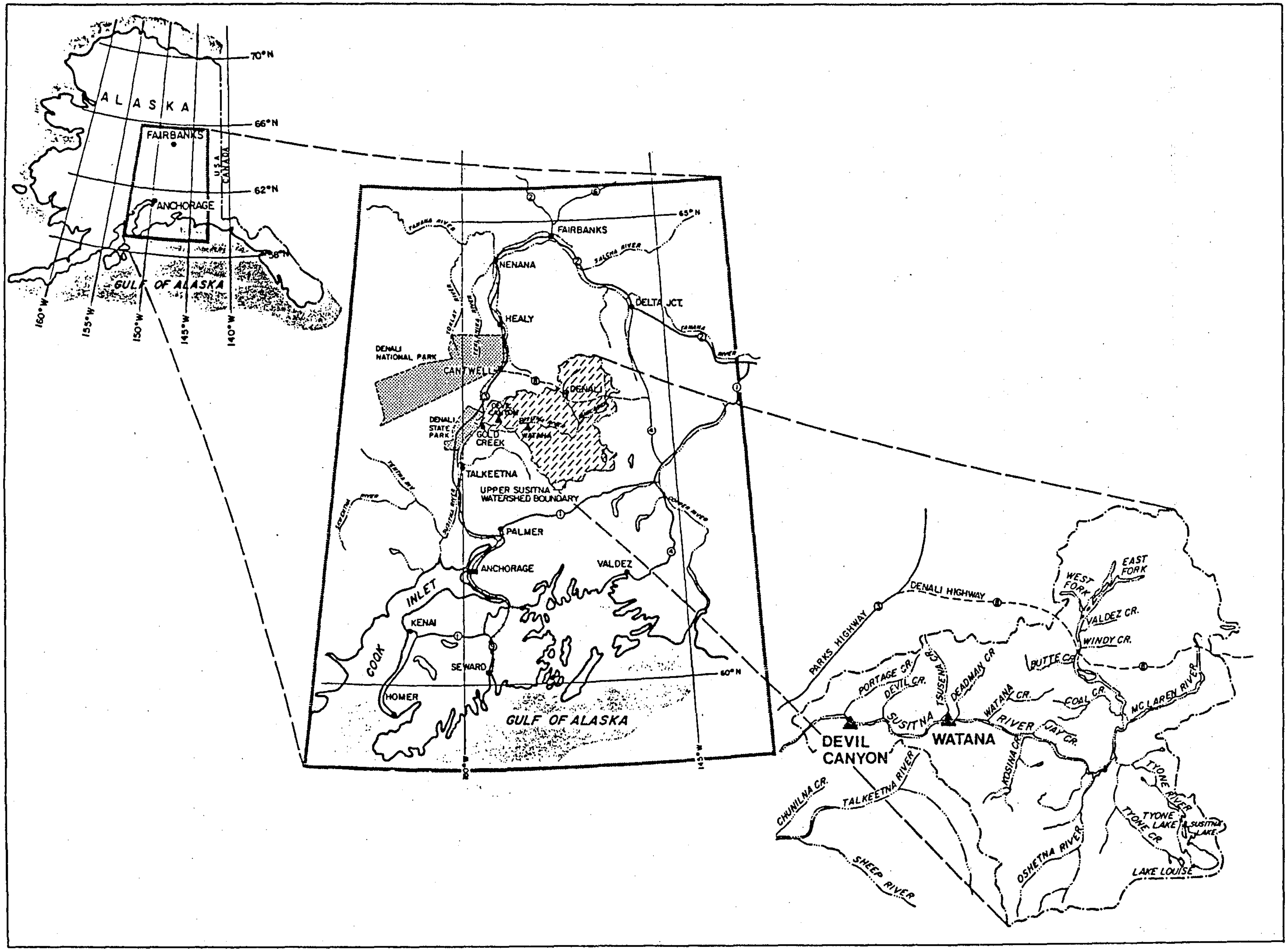


Figure 1. Susitna River Basin, Alaska, and locations of proposed hydroelectric facilities.

Canyon dam, would be located downstream at RK 243 and is scheduled to be operational in 2002. The development scenarios discussed in this paper are Watana in the year 2001 and Devil Canyon plus Watana in 2002.

The Susitna River has a mean annual flow of 275 cubic meters per second (cms) measured at an index station in the study reach. Mean monthly flows for the summer months (June through August) range from 590-740 cms, with peak flows normally occurring during June. Flows begin receding in September, reaching winter lows of 25-30 cms.

Under the regulation of the project, flow variation would be dampened considerably. With a Watana-only configuration, mean monthly flows would range from 210-340 cms, with peak flows released in August to facilitate access for salmon spawning and during winter high-demand periods. With the addition of the second dam, mean monthly flows would range from 200-320 cms, with higher flows more uniform throughout the winter and slightly lower summer flows.

Reservoirs store heat as well as storing water. The temperature of reservoir releases is expected to be cooler than natural during the summer, and warmer than natural during the winter. Since both reservoirs are expected to thermally stratify, multilevel intake structures have been incorporated into the dam design which would allow some degree of control on the release temperature.

Warmer-than-natural releases during the winter would alter the normal ice processes below the dams, delaying the formation of an ice cover and relocating the upstream end of the ice front. Cooler releases in the summer likewise would alter river temperature for a considerable distance downstream. To quantify this temperature change, an instream temperature model was used.

The model simulated effects of the hydroelectric development in an 80 km reach below the Devil Canyon dam. This is the only habitat available to salmon in the upper part of the Susitna River, as the Devil Canyon dam site blocks salmon passage further up river. Two large tributaries converge with the Susitna downstream from this study reach, the resultant flow more than double the flow upstream from this point. The dampening effect of these tributaries, both with respect to flow and temperature, creates a distinct lower boundary to the study reach. In 1984, the study reach received an escapement of 26,060 chum, 2,325 sockeye, 29,300 pink, 2,900 coho, and 13,800 chinook salmon (Barrett, Thompson and Wick 1985). The modeling system was run for a variety of power demands and hydrologic and meteorologic conditions. Downstream temperature results from these simulations were examined with respect to effects on salmon. This paper discusses the process of instream temperature modeling and our subjective assessment of effects of predicted with-project temperature regimes on salmon.

METHODS

Assessment of temperature impacts on salmon involved a three stage process. First, natural and with-project temperature regimes were predicted through use of a stream temperature simulation model for a study reach of mainstem river which extends approximately 80 km (RK 240 to RK 160) below the proposed dams. Next, fish temperature tolerance criteria were developed based on literature, laboratory, and field studies. Finally, these criteria were compared with the temperature model output and an assessment of the effects was made.

THE STREAM TEMPERATURE MODEL

The Stream Network Temperature Simulation Model, SNTEMP, was originally developed by the U.S. Fish and Wildlife Service's Instream Flow and Aquatic Systems Group in Fort Collins, Colorado (Theurer, Voos and Miller 1983). The model requires hydrology, meteorology and stream geometry data as input and computes heat flux relationships and transports heat through the system. The model is one-dimensional, producing cross-section averaged mean weekly temperatures at any mainstem location in the study reach.

A number of modifications were made to the model to better simulate northern conditions.

1. A monthly variable shade factor was incorporated to account for the stream shading from topographical features, a serious concern in northern latitudes where solar angles are very small.

2. The model was modified to accept non-constant lapse rates for air temperature and humidity. This is of special value during the winter when temperature inversions often occur.

3. An influent groundwater temperature submodel was developed and incorporated into SNTEMP. This routine considers the effects of the depth to groundwater and the cyclical temperature pattern resulting from variations in elevation and time.

4. Regression models were developed to fill discontinuous temperature records, a common problem in Alaska.

Four summers and five winters were selected from the meteorological record as representative periods of normal and extreme hydrology and meteorology. Simulations were run under these conditions for natural (i.e., without dams), single-dam (Watana) and two-dam (Watana plus Devil Canyon) project configurations. In this way, the range of downstream temperatures found naturally and predicted to occur with the project in place was identified.

DEVELOPMENT OF TEMPERATURE CRITERIA FOR FISH

To assess the effects of with-project instream temperatures on salmon, we first reviewed available information on the response of the five salmon species to different thermal conditions. Ideally, information used in an effects analysis should be specific to the water body in question and to its particular community of organisms. Little specific information exists on the effects of temperature changes on Susitna River fish stocks, necessitating the use of information from other areas and latitudes. Professional judgement was used to ascertain the applicability of each piece of information to the Susitna Basin. Generally, information proximal to the Susitna River was judged to be more pertinent than data from other areas of Alaska, which in turn was usually more useful than information from more southerly latitudes. Once the information was assembled, it was synthesized to produce thermal tolerance ranges. These criteria were the temperature ranges believed to be capable of supporting adult spawning migrations, spawning, incubation, rearing, and smolt migrations.

ASSESSMENT OF TEMPERATURE EFFECTS

Graphic techniques were used to demonstrate the relationships between simulated natural or with-project temperature regimes and the salmon thermal tolerance criteria. Illustrations were prepared showing the thermal tolerance "envelope" over a one-year time period for each salmon species. Overlays of natural and with-project temperatures were superimposed on the species-specific temperature tolerance graphics; separate illustrations were prepared for each of two representative mainstem river locations. This procedure was followed for each of the meteorological simulations.

We assumed that only in cases where the simulated temperature regimes fall outside the temperature tolerance ranges is an obvious adverse impact established. However, in cases where with-project temperatures do not exceed tolerances but yet appear to be substantially different from natural, a further subjective analysis and prediction of effects was conducted.

RESULTS AND DISCUSSION

EFFECT OF THE PROJECT ON MAINSTEM TEMPERATURES

Operation of either a single- or two-dam project would reduce mean summer river temperatures below the dam by as much as 2 C. The two-dam project would result in a greater change, primarily because the second dam would be located 53 km further downstream, reducing the length of river in which release waters would warm towards ambient air temperature.

Warmer winter release temperatures would delay the formation of an ice cover in the study reach 2 to 6 weeks with one dam and 4 to 7 weeks with both dams in place. The ice front would be located 16 to 47 km further downstream than under normal conditions (R&M Consultants, Inc., et al. 1985). A synopsis of natural and with-project mean seasonal temperatures for four summers and five winters is shown in table 2.

One of the most notable effects of project operation on temperature would be the change in the timing of seasonal warming and cooling. River temperatures would warm later in the summer than they do naturally and cool later in the fall than normal (figures 2 and 3). Figure 4 compares natural and two-dam project temperatures at RK 209 for 1981 and illustrates this delay in the normal temperature pattern.

TEMPERATURE CRITERIA FOR SALMON

Thermal tolerance ranges were established during the course of this study for the five Pacific salmon species found in the Susitna drainage. These ranges were based on literature reports of fish distribution, laboratory studies, and field studies (table 3). Observed Susitna drainage temperature data were utilized in conjunction with the literature reports to establish

Table 2. Simulated mean seasonal temperatures at RK 209 for four summer and five winter scenarios.

SUMMER (Water weeks 31-52; April 29 - September 30)					
Year	Air Temperature	Available Runoff	Natural Temperature	1-Dam Project Temperature	2-Dam Project Temperature
1971	cold	wet	7.8	6.8	6.2
1974	warm	dry	8.7	7.5	7.2
1981	average	wet	8.6	7.9	6.8
1982	average	average	8.8	7.7	7.0

WINTER (Water weeks 5-30; October 29 - April 28)					
Year	Air Temperature	Available Runoff	Natural Temperature	1-Dam Project Temperature	2-Dam Project Temperature
1971-72	cold	wet	0.0	0.1	0.2
1974-75	average	dry	0.0	0.4	0.6
1976-77	warm	dry	0.0	Not simulated	0.4
1981-82	average	wet	0.0	1.0	1.7
1982-83	average	average	0.0	1.0	1.2

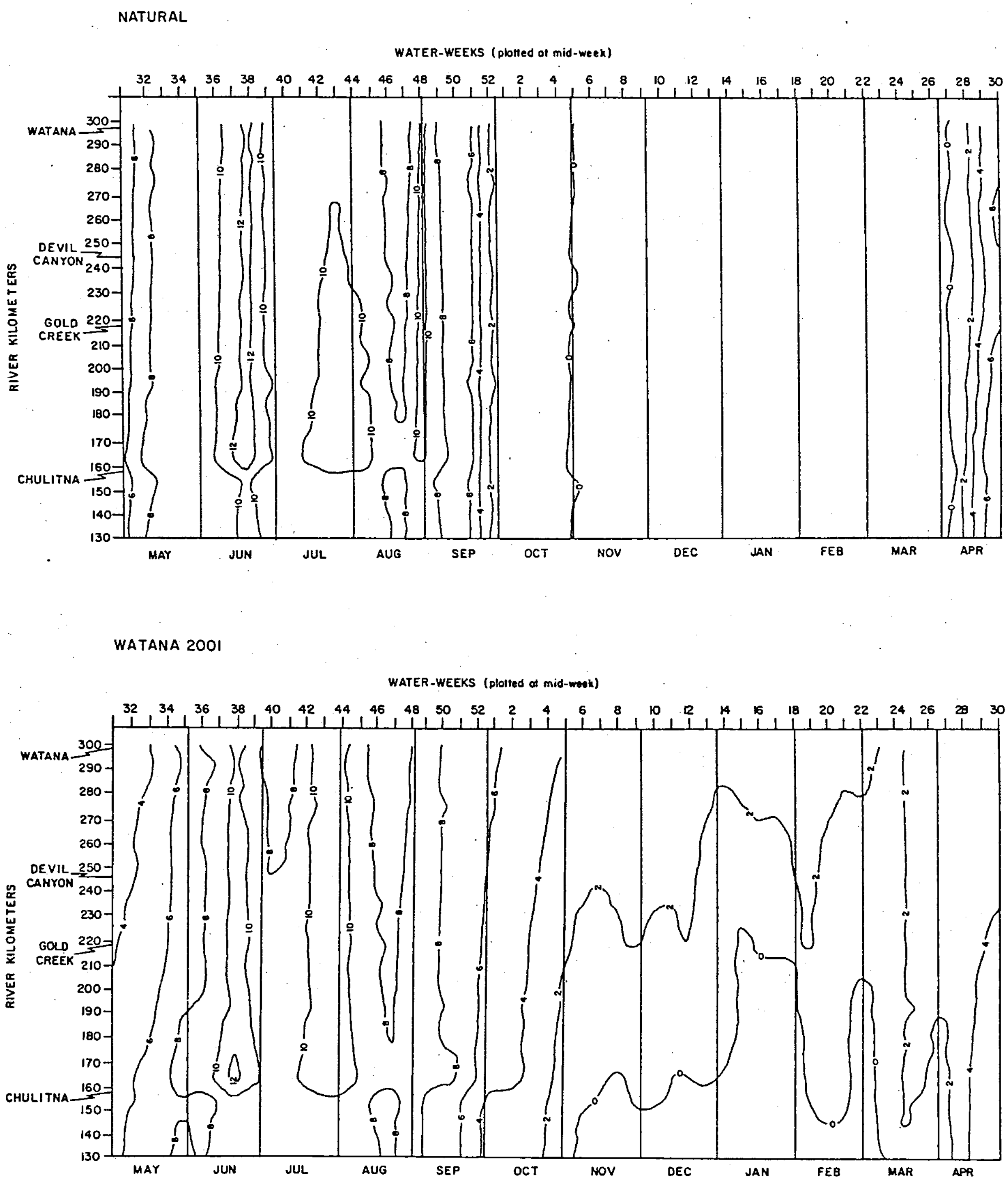


Figure 2. Isotherm plots of simulated instream temperature for natural and one-dam (Watana) conditions, May 1981 - April 1982.

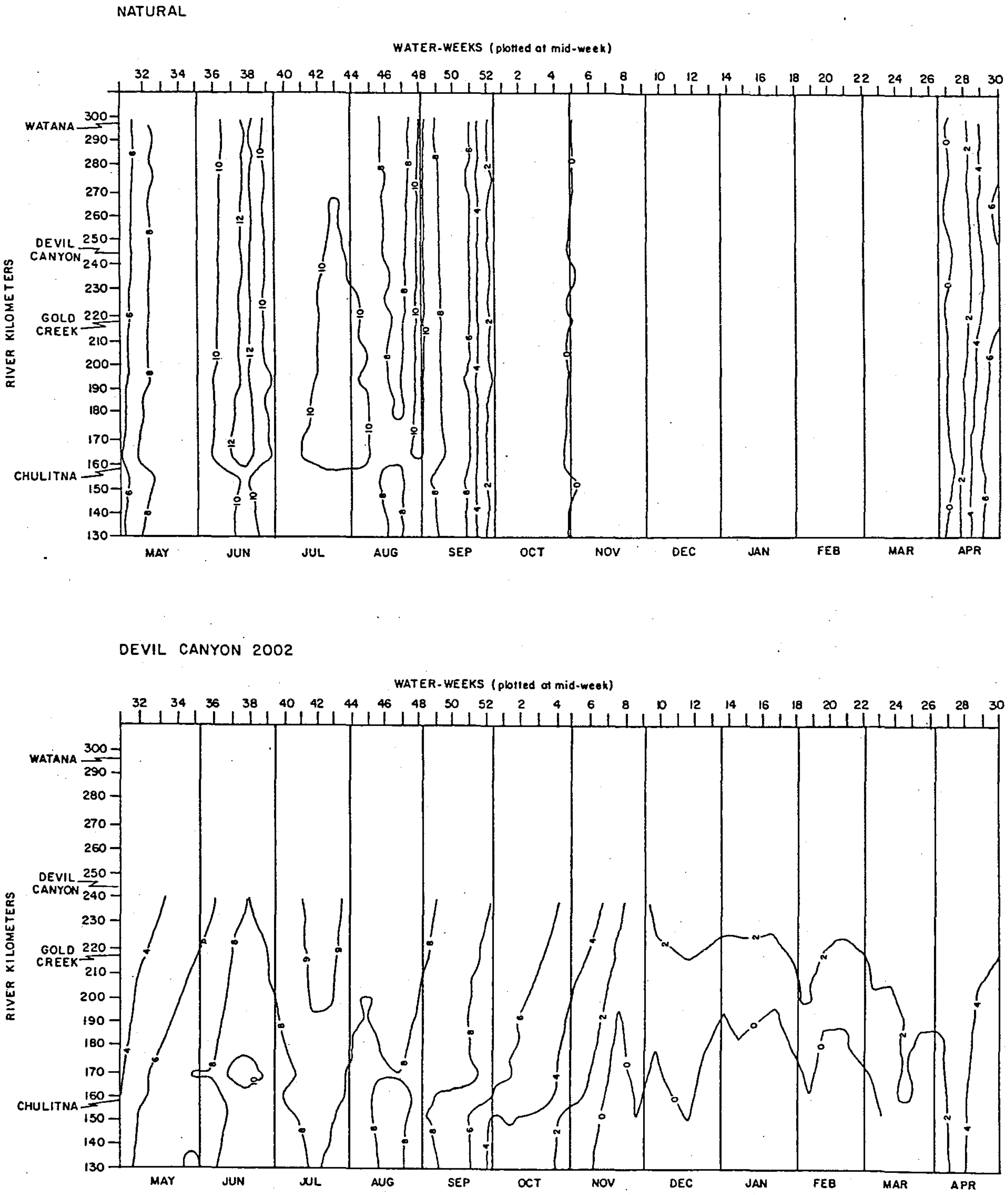


Figure 3. Isotherm plots of simulated instream temperature for natural and two-dam (Devil Canyon) conditions, May 1981-April 1982.

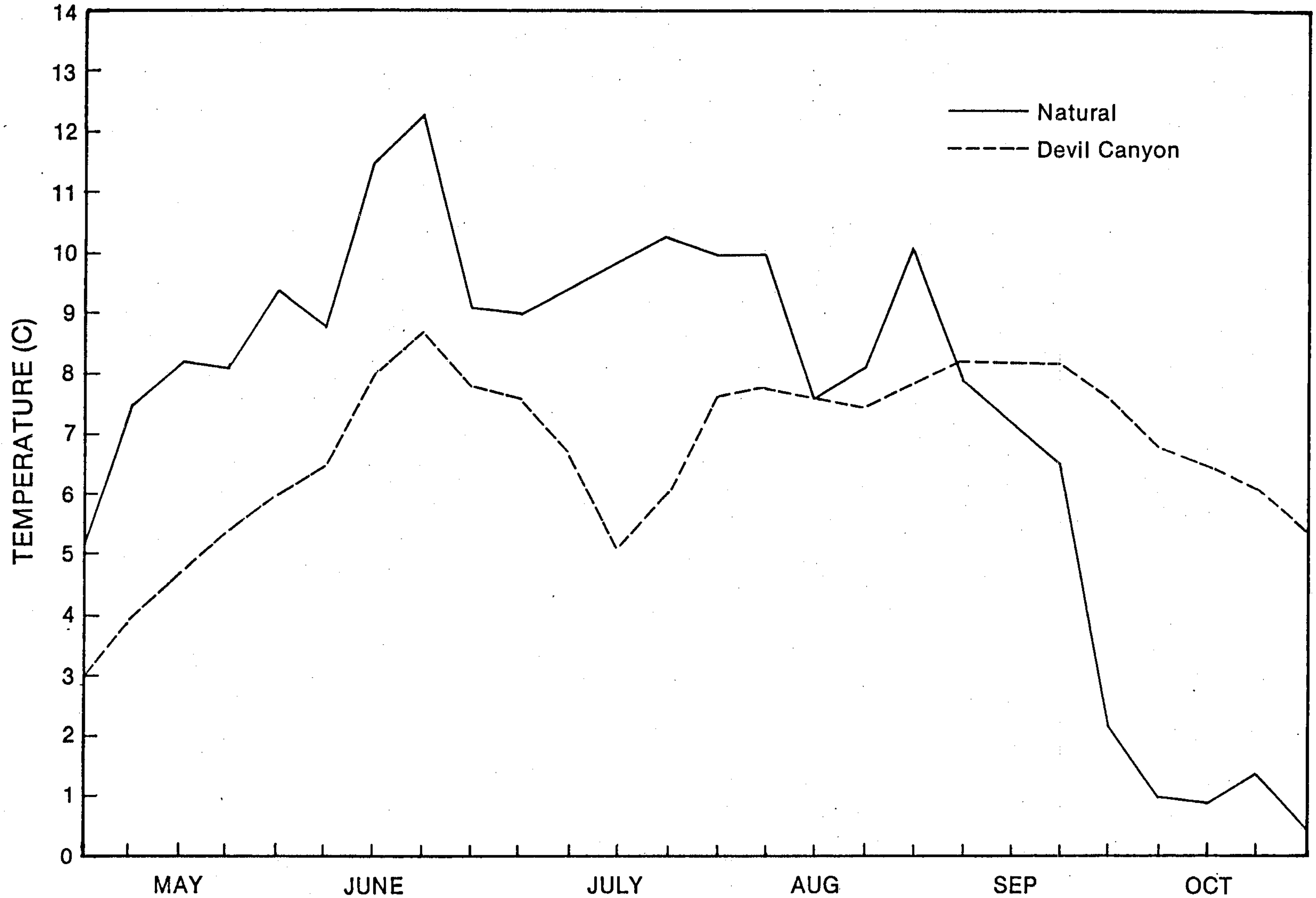


Figure 4. Natural and two-dam with-project stream temperatures at RK 209.

Table 3. Observed temperature ranges for various life stages of Pacific Salmon from literature review and laboratory investigations.

SPECIES OF SALMON	LIFE STAGE	LITERATURE SOURCE	LOCATION	TEMPERATURE RANGE C			
				MIGRATION	SPAWNING	INCUBATION	REARING
Chum	Adult	Bell 1980	General	8.3-21.0	7.2-12.8		
		Bell 1983	General	1.5			
		ADF&G 1981a	Kuskokwim Tributaries, AK	5.0-12.8			
		Mattson & Hobart 1962	Southeast, AK	4.4-19.4			
		McNeil & Bailey 1975	Southeast, AK		7.0-13.0		
		Wilson et al. 1981	Kodiak Island, AK		6.5-12.5		
		Neave 1966	British Columbia		4.0-16.0		
		Rukhlov 1969	Sakhalin, USSR		1.8-8.2		
		Merritt & Raymond 1983	Noatak R, AK		2.5		
		ADF&G 1984	Susitna R, AK	5.6-15.5	4.5-13.2		
	Juvenile	Trasky 1974	Salcha R, AK	5.0-7.0			
		Sano 1966	Bolshaia R, USSR	6.0-10.0			
		Bell 1980	General	6.7-13.5			11.2-15.7
		McNeil & Bailey 1975	Southeast, AK				4.4-15.7
		Wilson et al. 1979	Kodiak Island, AK	5.0-7.0			
		Raymond 1981	Delta R, AK	3.0-5.5			
		Merritt & Raymond 1983	Noatak R, AK	5.0-12.0			
		ADF&G 1984	Susitna R, AK	4.2-14.5			1.3-16.2
	Egg/Alevin	Bell 1980	General		4.4-13.3		
		McNeil 1969	Southeast, AK			0-15.0	
		Merritt & Raymond 1983	Noatak R, AK			0.2-9.0	
		Sano 1966	Japan			4	
		McNeil & Bailey 1975	Southeast, AK			4.4	
		Kogl 1965	Chena R, AK			0.5-4.5	
		Francisco 1977	Delta R, AK			0.4-6.7	
		Raymond 1981	Clear, AK			2.0-4.5	
		ADF&G 1983	Susitna R, AK			0-7.4	
		Wangaard & Burger 1983	Laboratory			0.5-8.0	
		ADF&G 1984	Susitna R, AK			2.0-4.3[5]	
Coho	Adult	Bell 1980	General	7.2-15.6	4.4-9.5		
		Bell 1983	General	4			
		McNeil & Bailey 1975	Southeast, AK		7.0-13.0		
		McMahon 1983	General	5-19,5-11[3]	2-17,5-13[3]		
		Wallis 1983	Anchor R, AK	2-15,7-14[4]			
		ADF&G 1984	Susitna R, AK	5.8-15.5			

Table 3. (Cont'd) Observed temperature ranges for various life stages of Pacific Salmon from literature review and laboratory investigations.

SPECIES OF SALMON	LIFE STAGE	LITERATURE SOURCE	LOCATION	TEMPERATURE RANGE C MIGRATION	SPAWNING	INCUBATION	REARI
Coho	Juvenile	Cederholm & Scarlett 1982	Washington St.	6			
		Bustard & Narver 1975	Vancouver Is., BC	7			
		Bell 1973	General	7.0-16.5			11.8-14.6
		McNeil & Bailey 1975	Southeast, AK				4.4-15.7
		McMahon 1983	General	4-16,6-12[3]			4-21,7-
		Wallis 1983	Anchor R, AK	2-15,7-14[4]			
		Whitmore 1979	Caribou L, AK	11-15.5			
			Seldovia L, AK	3.0-5.7			
		ADF&G 1984	Susitna R, AK	4.2-14.5			
	Egg/Alevin	Bell 1980	General			4.4-13.3	
		McMahon 1983	General			4-14,4-10[3]	
		Dong 1981	Washington St.			1.3-12.4,4-6.5[3]	
Pink	Adult	Bell 1980	General	7.2-15.6	7.2-12.8		
		Bell 1983	USSR	5			
		McNeil & Bailey 1975	Southeast, AK		7.0-13		
		Sheridan 1962	Southeast, AK		7.2-18.4		
		McNeil et al. 1964	Southeast, AK		10.0-13.0		
		ADF&G 1984	Susitna R, AK	7.8-15.5	8.0-11.0		
	Juvenile	Bell 1980	General				5.6-14.
		McNeil & Bailey 1975	Southeast, AK				4.4-15.
		Wilson 1979	Kodiak Island, AK	5.0-7.0			
		Wickett 1958	British Columbia	4.0-5.0			
		ADF&G 1984	Susitna R, AK	4.2-14.5			
	Egg/Alevin	Bell 1980	General			4.4-13.3	
		Bailey & Evans 1971	Southeast, AK			4.5	
		Combs & Burrows 1957	Laboratory			0.5-5.5	
		McNeil et al. 1964	Southeast, AK			1.0-8.0	
		Godin 1980	Laboratory			3.4-15.0	
Sockeye	Adult	Bell 1980	General	7.2-15.6	10.6-12.2		
		Bell 1983	General	2.5			
		McNeil & Bailey 1975	Southeast, AK		7.0-13.0		
		Nelson 1983	Southeast, AK	8.3-14.3			
		ADF&G 1984	Susitna R, AK	5.8-15.5	4.9-10.5		

Table 3. (Cont'd) Observed temperature ranges for various life stages of Pacific Salmon from literature review an laboratory investigations.

SPECIES OF SALMON	LIFE STAGE	LITERATURE SOURCE	LOCATION	TEMPERATURE RANGE C MIGRATION	SPAWNING	INCUBATION	REARING
Sockeye	Juvenile	McCart 1967	British Columbia	5.0-17.0			
		Raleigh 1971	Laboratory	4.5			
		Bell 1980	General				11.2-14.6
		McNeil & Bailey 1975	Southeast, AK				4.4-15.7
		Fried & Laner 1981	Bristol Bay, AK	4.0-7.0			
		Bucher 1981	Bristol Bay, AK	4.4-17.8			
		Hartman et al. 1967	Alaskawide	4.5-10.0			
		Flagg 1983	Kasilof R, AK	6.7-14.4			
		ADF&G 1984	Susitna R, AK	4.2-14.0			
	Egg/ Alevin	Bell 1980	General			4.4-13.3	
		Combs 1965	Laboratory			4.5-14.3,1.5[2]	
		ADF&G 1983	Susitna R, AK			2.9-7.4	
		Wangaard & Burger 1983	Laboratory			2.0-6.5	
		ADF&G 1984	Susitna R, AK			2.0-4.3[5]	
Chinook	Adult	Bell 1980	General	3.3-13.9	5.6-13.9		
		Bell 1983	General	4			
		McNeil & Bailey 1975	Southeast, AK		7.0-13.0		
		Wallis 1983	Anchor R, AK	2-14,5-10[4]			
		ADF&G 1984	Susitna R, AK	6.6-15.6	7.8-13.6		
	Juvenile	Raymond 1979	Columbia R, OR	7			
		Bell 1980	General				7.3-14.6
		McNeil & Bailey 1975	Southeast, AK				4.4-15.7
		AEIDC 1982	Southcentral, AK	4.5			
		Wallis 1983	Anchor R, AK	6-16,8-16[4]			
		ADF&G 1984	Susitna R, AK	4.2-14.5			
	Egg/ Alevin	Bell 1980	General			5.0-14.4	
		Combs 1965	Laboratory			1.5[2]	
		Alderdice & Velsen 1978	General			2.5-16.0	

[1] Single temperature values are lower observed thresholds
[2] After eggs had developed to the 128-cell or early blastula stage at 5.5° C
[3] Optimum range
[4] Peak migration range
[5] Mean temperature

tolerance criteria for each life phase (table 4). In cases where life phases overlap, that life phase most sensitive to temperature was chosen when preparing the tolerance criteria graphic overlays. The criteria, then, establish the narrowest temperature tolerance window for evaluation. Within these ranges Susitna salmon stocks were assumed to live and function free from the lethal effects of temperature.

Embryo incubation rates rise with increasing intragravel water temperature. Accumulated temperature units, or degree-days to hatching and emergence, were obtained from literature reports (ADF&G 1981b, 1983; Raymond 1981; Wangaard and Burger 1983) and used as criteria for incubation. Data from laboratory studies of salmon embryo development under different temperature regimes using Susitna chum salmon stocks (Wangaard and Burger 1983) were compared with other chum salmon embryo incubation time data. A regression analysis of these data illustrated a linear relationship between mean incubation temperature and development rate (the inverse of the time to emergence) for chum salmon (figure 5). A nomograph was then prepared from these data which could predict the date of emergence based upon the date of chum salmon spawning and the average temperature over the incubation period (figure 6). A nomograph was prepared only for chum salmon since this is the principal species spawning in the mainstem where project-related temperature changes are predicted. Other species spawn in tributaries or side sloughs expected to be unaffected by the temperature change.

EFFECTS OF ALTERED TEMPERATURES ON FISH

Using the graphic techniques for illustrating relationships between the natural and with-project temperature regimes and the salmon life stage

Table 4. Salmon temperature tolerance criteria for Susitna River drainage.

SPECIES	LIFE PHASE	TEMPERATURE RANGE (C) TOLERANCE	PREFERRED
Chum	Adult Migration	1.5-18.0	6.0-13.0
	Spawning	1.0-14.0	6.0-13.0
	Incubation[1]	0-12.0	2.0- 8.0
	Rearing	1.5-16.0	5.0-15.0
	Smolt Migration	3.0-13.0	5.0-12.0
Sockeye	Adult Migration	2.5-16.0	6.0-12.0
	Spawning	4.0-14.0	6.0-12.0
	Incubation[1]	0-14.0	4.5- 8.0
	Rearing	2.0-16.0	7.0-14.0
	Smolt Migration	4.0-18.0	5.0-12.0
Pink	Adult Migration	5.0-18.0	7.0-13.0
	Spawning	7.0-18.0	8.0-13.0
	Incubation[1]	0-13.0	4.0-10.0
	Smolt Migration	4.0-13.0	5.0-12.0
Chinook	Adult Migration	2.0-16.0	7.0-13.0
	Spawning	5.0-14.0	7.0-12.0
	Incubation[1]	0-16.0	4.0-12.0
	Rearing	2.0-16.0	7.0-14.0
	Smolt Migration	4.0-16.0	7.0-14.0
Coho	Adult Migration	2.0-18.0	6.0-11.0
	Spawning	2.0-17.0	6.0-13.0
	Incubation[1]	0-14.0	4.0-10.0
	Rearing	2.0-18.0	7.0-15.0
	Smolt Migration	2.0-16.0	6.0-12.0

[1] Embryo incubation or development rate increases as temperature rises. Accumulated temperature units or days to emergence was determined for each species for the incubation phase.

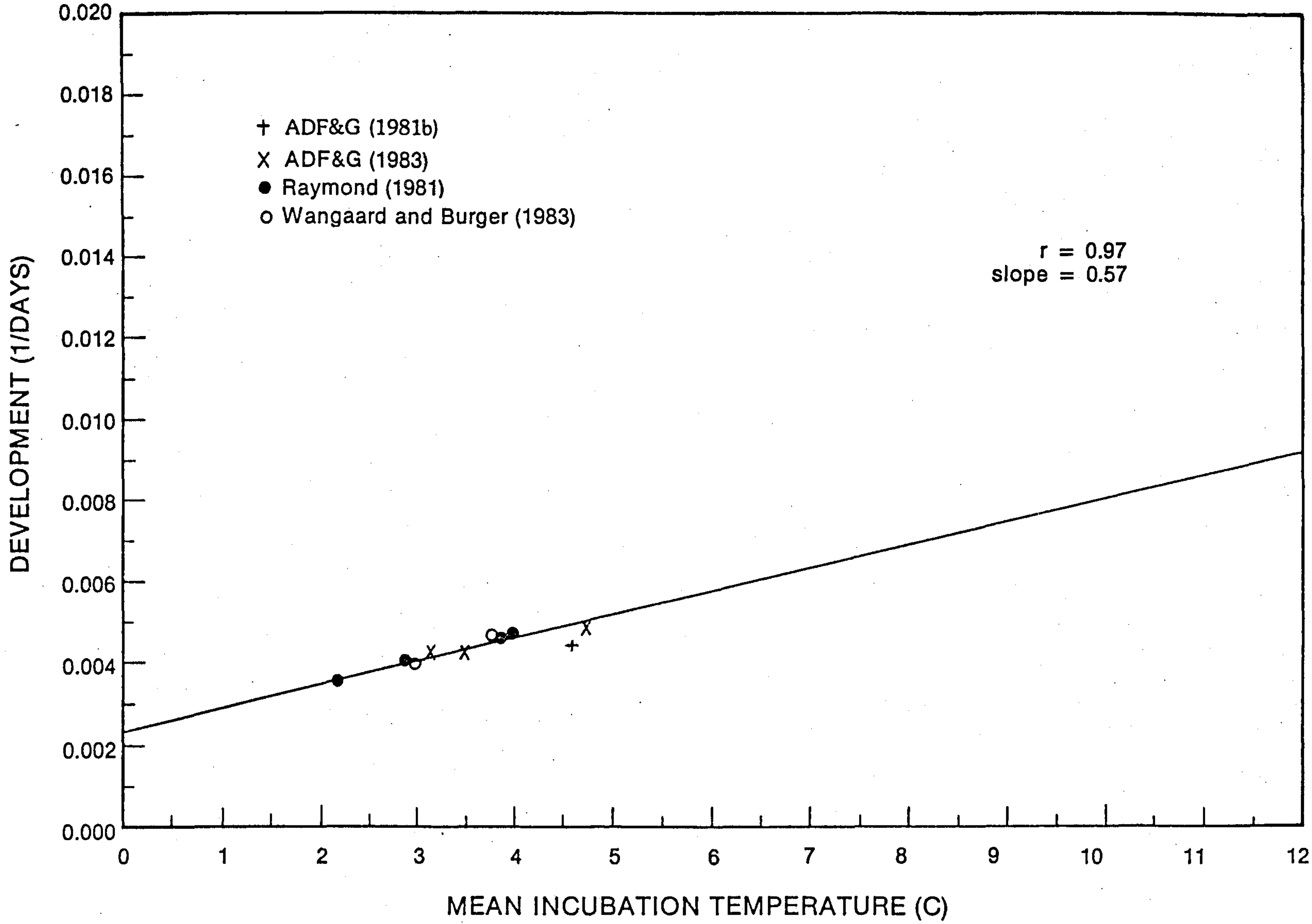


Figure 5. Relationship between mean water temperature and Alaskan chum salmon embryo development-to-emergence times.

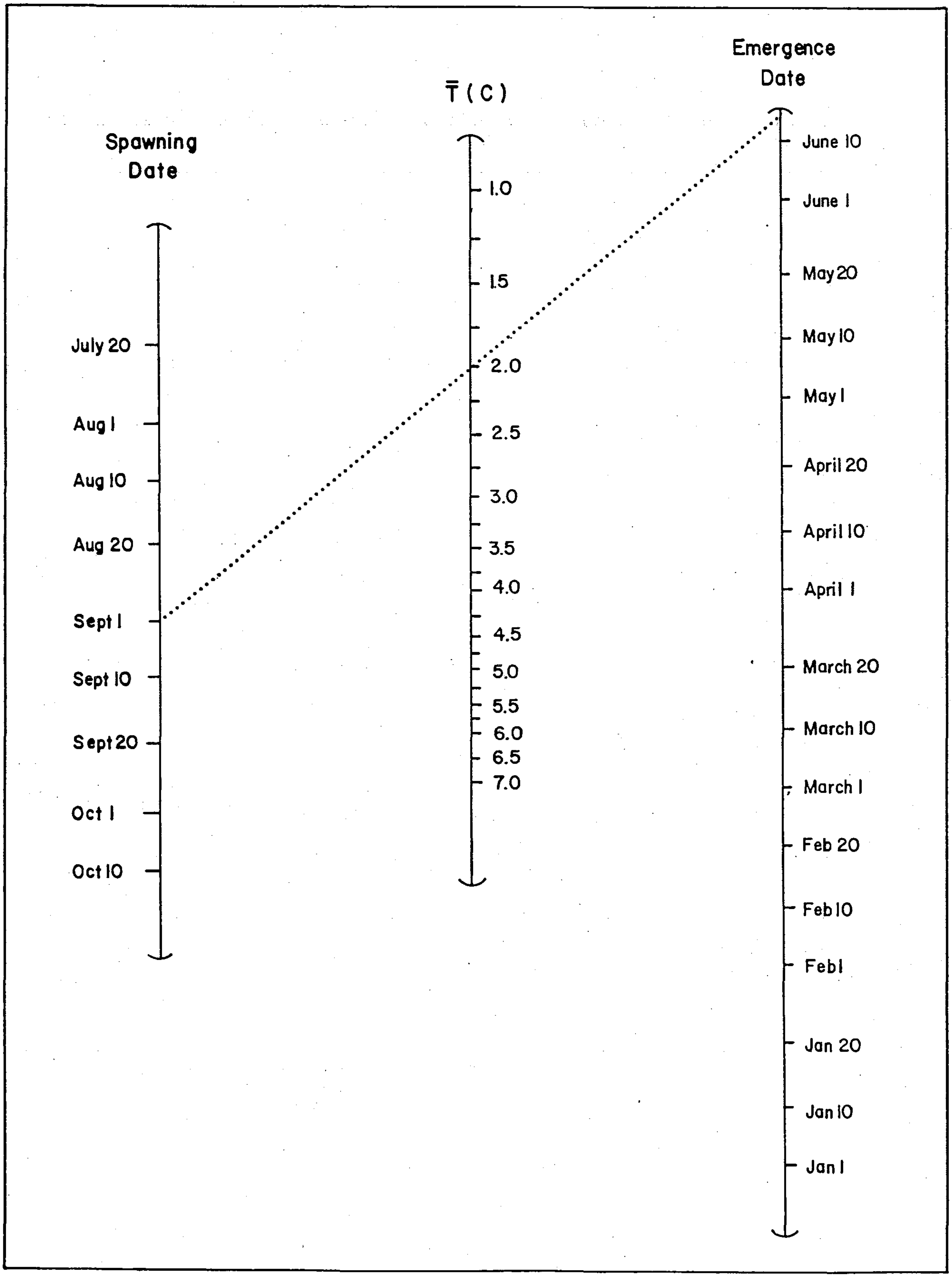
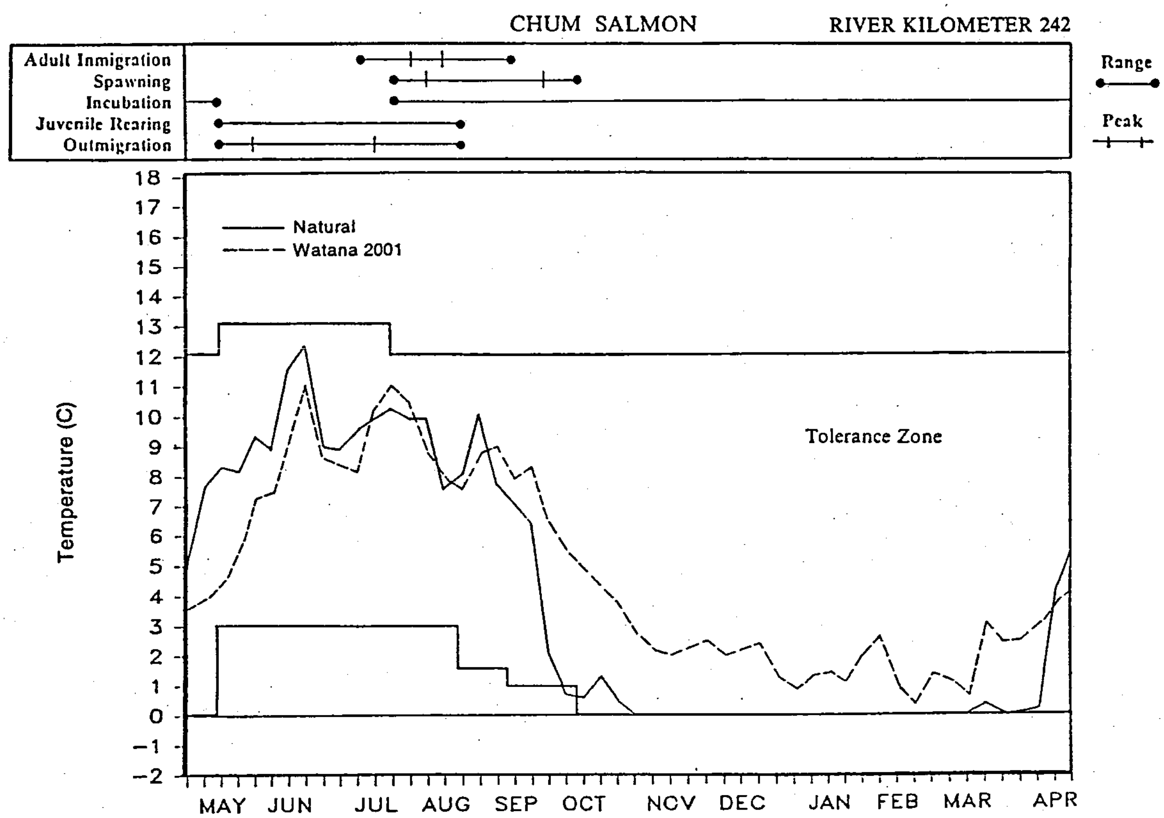


Figure 6. Nomograph for predicting Susitna River chum salmon fry emergence from spawning date and mean water temperature during the embryo incubation period. Line illustrates predicted fry emergence date from a September 1 spawning date and a mean incubation temperature of 2.0 C.

temperature tolerance criteria, we evaluated over 100 one- and two-dam development scenarios, each under different combinations of meteorologic/hydrologic conditions. These results are summarized for two representative river sites (RK 209 and 242) in figures 7-16. Two steps were taken in the interpretation of these figures. First, an examination of departures of with-project temperatures from the "tolerance window" was made. In most cases, each with-project temperature simulation fell within the temperature tolerance criteria for all life phases. For example, while with-project temperatures are different from natural, they are within the tolerance range for chum salmon (figure 7). Therefore, we assumed that no obvious adverse impacts would result from predicted with-project temperatures for this species at this location under these meteorological and hydrological conditions.

In general, this first step in the assessment demonstrated that the Susitna Hydroelectric Project would have few adverse effects from temperature on the five salmon species. One potential impact was under the two-dam scenario where adult pink and chinook salmon inmigration may be delayed upstream of RK 209 in late June to mid-July as temperatures fall below the lower tolerance level for this life phase (figures 15 and 16). The effects on pink salmon inmigration timing are greater than those on chinook because the potential thermal block would preclude access to more habitat, would occur nearer the time of peak pink salmon inmigration, and the period of exposure to temperatures below tolerance levels would be of longer duration. While adult chinook or pink salmon migration into this river reach could be delayed, we believe inmigration would ultimately occur 5 to 15 days later as temperatures rise. This may result in a shorter period between the time pink salmon occupy spawning grounds and the occurrence of actual spawning.



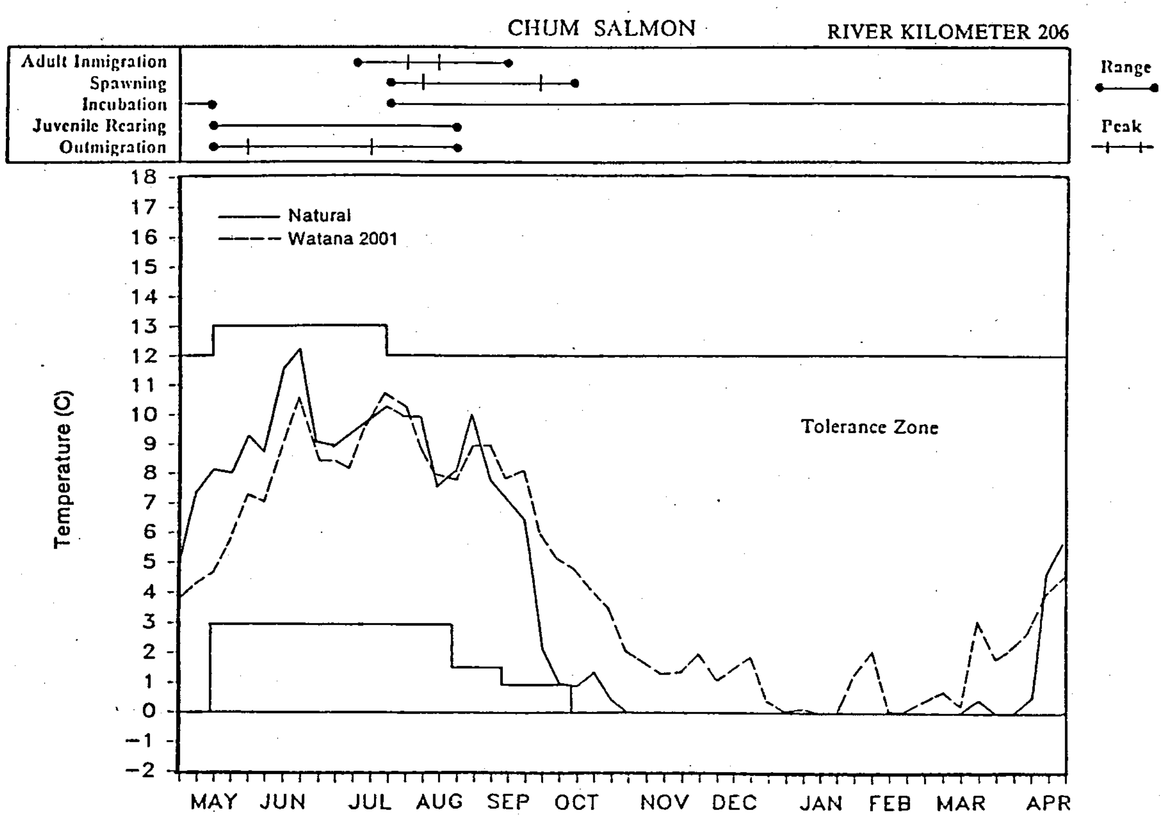
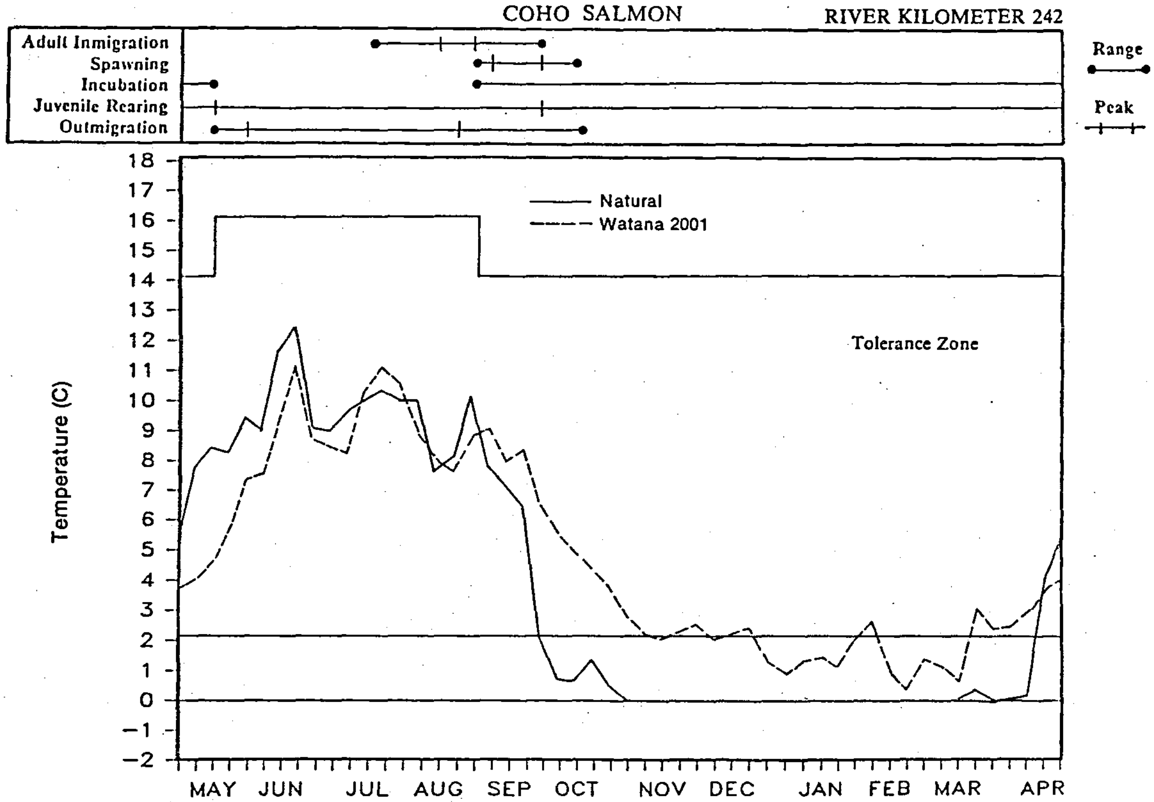


Figure 7. Natural and one-dam (Watana) with-project water temperature regimes in relation to thermal tolerance criteria for chum salmon at two locations on the Susitna River.



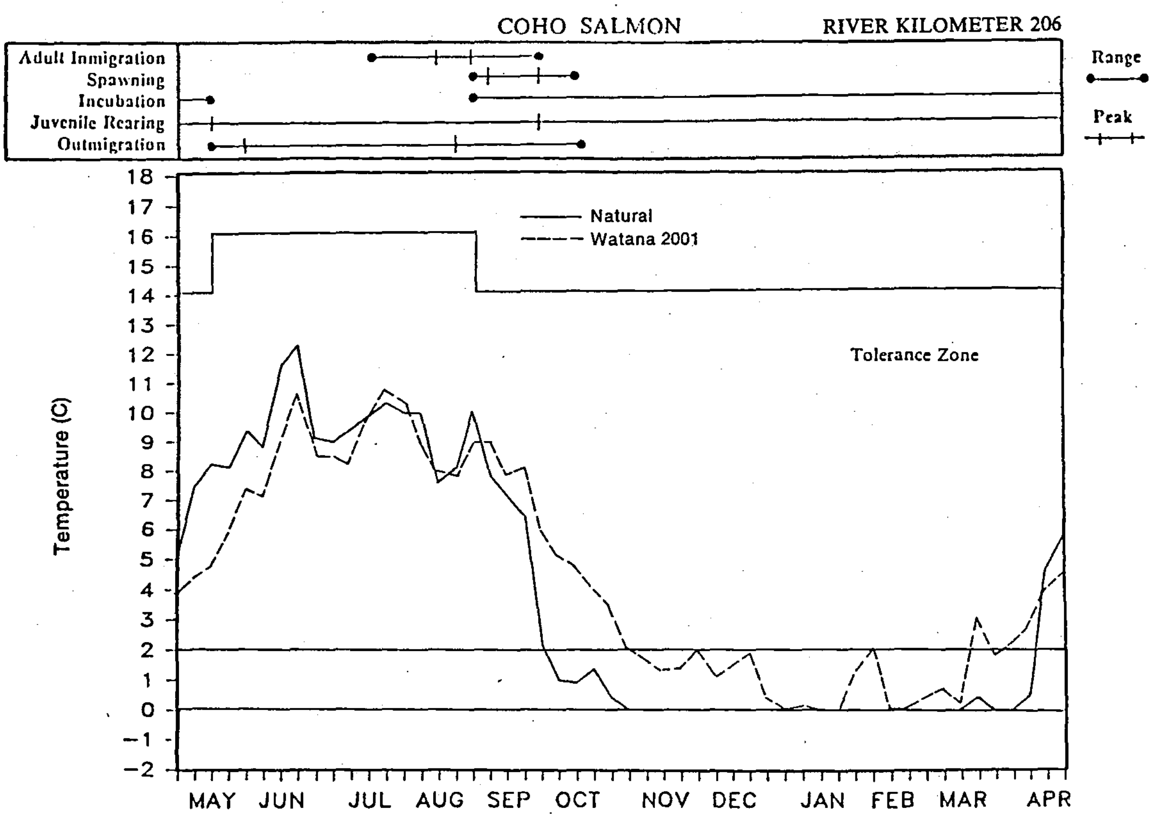
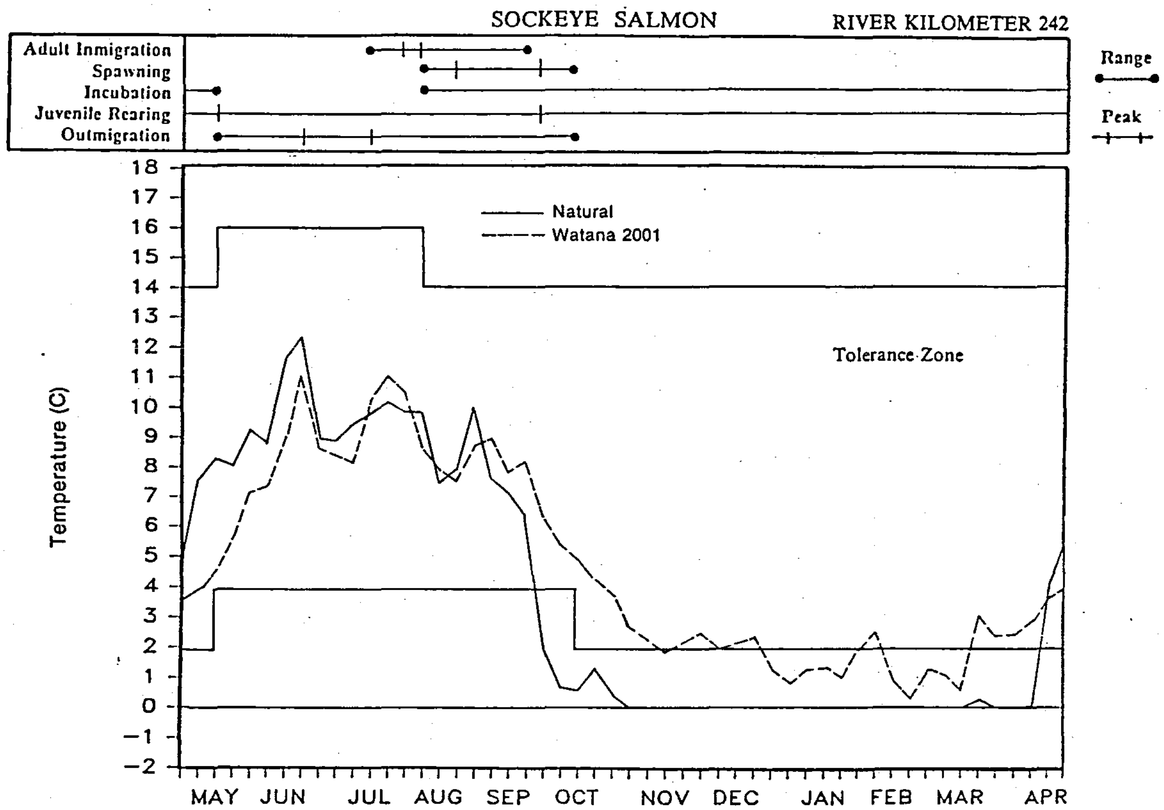


Figure 8. Natural and one-dam (Watana) with-project water temperature regimes in relation to thermal tolerance criteria for coho salmon at two locations on the Susitna River.



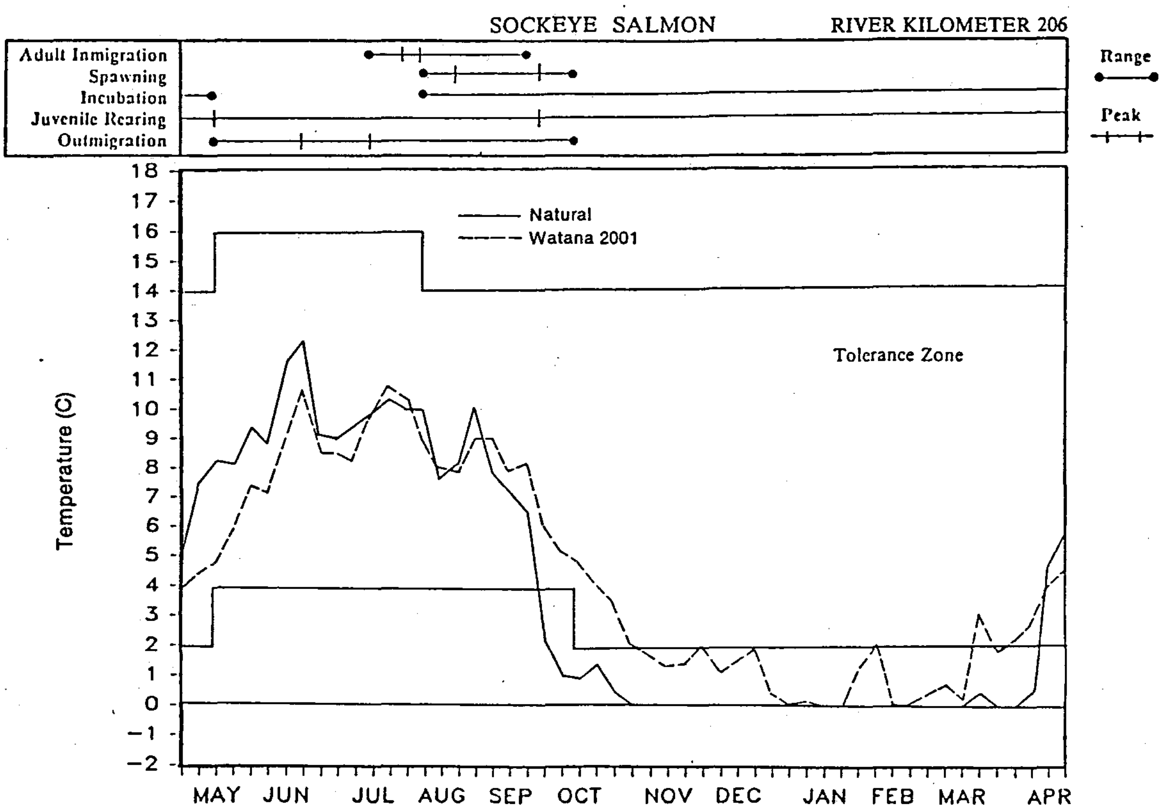
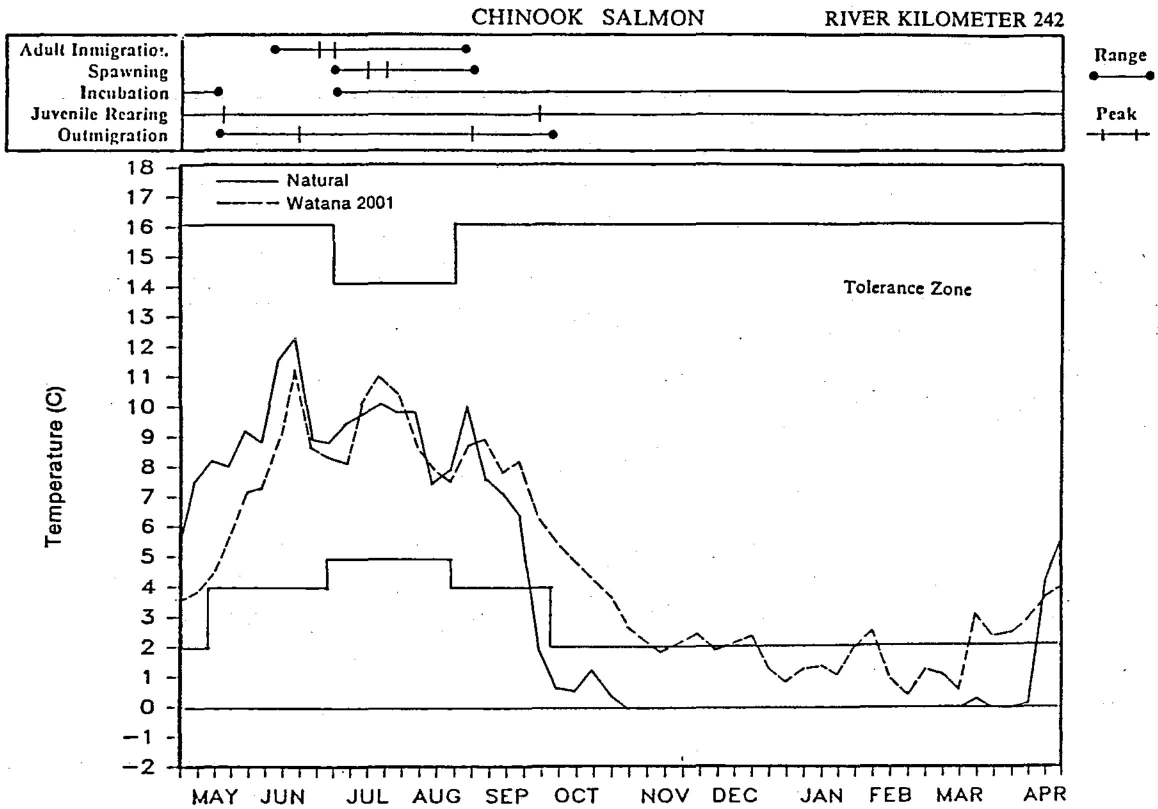


Figure 9. Natural and one-dam (Watana) with-project water temperature regimes in relation to thermal tolerance criteria for sockeye salmon at two locations on the Susitna River.



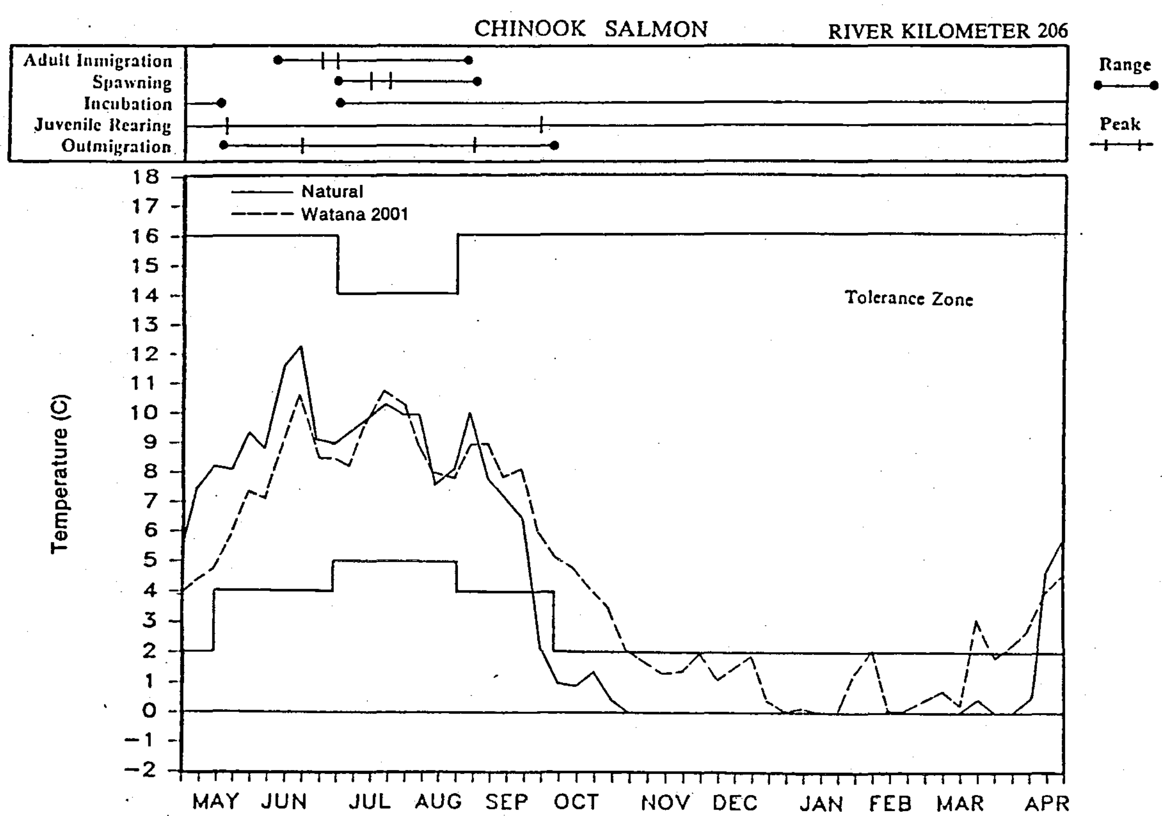
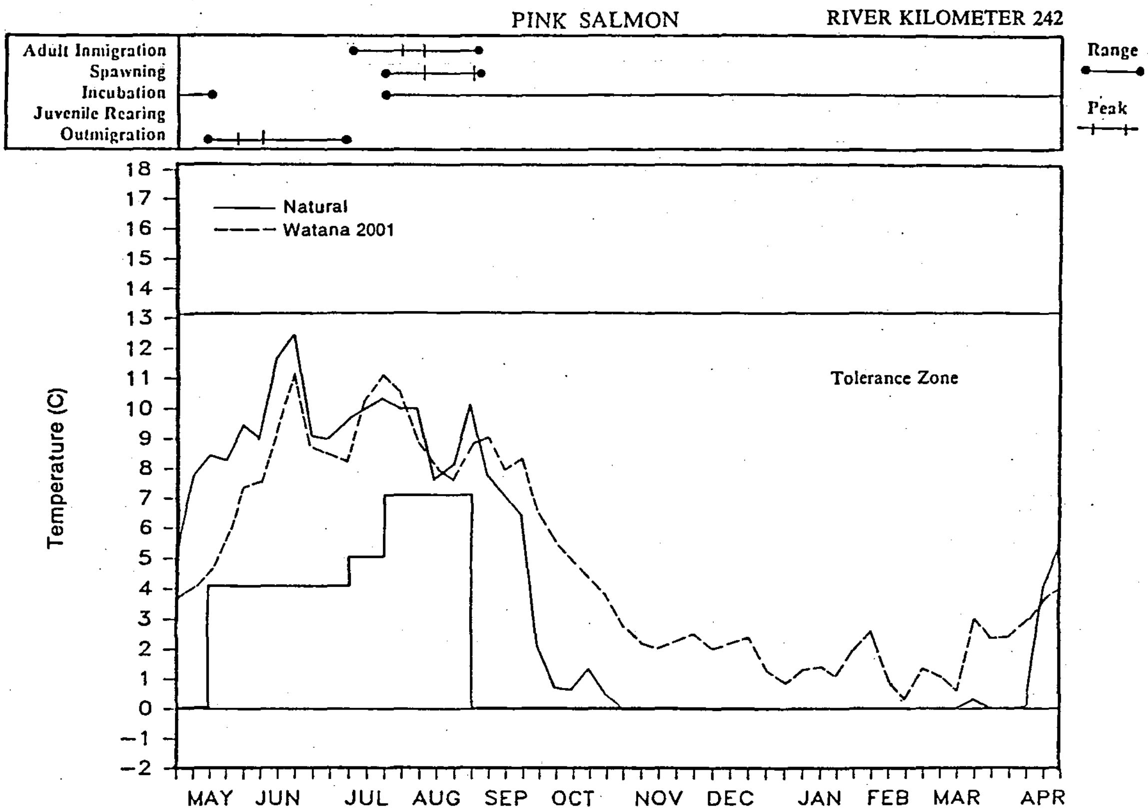


Figure 10. Natural and one-dam (Watana) with-project water temperature regimes in relation to thermal tolerance criteria for chinook salmon at two locations on the Susitna River.



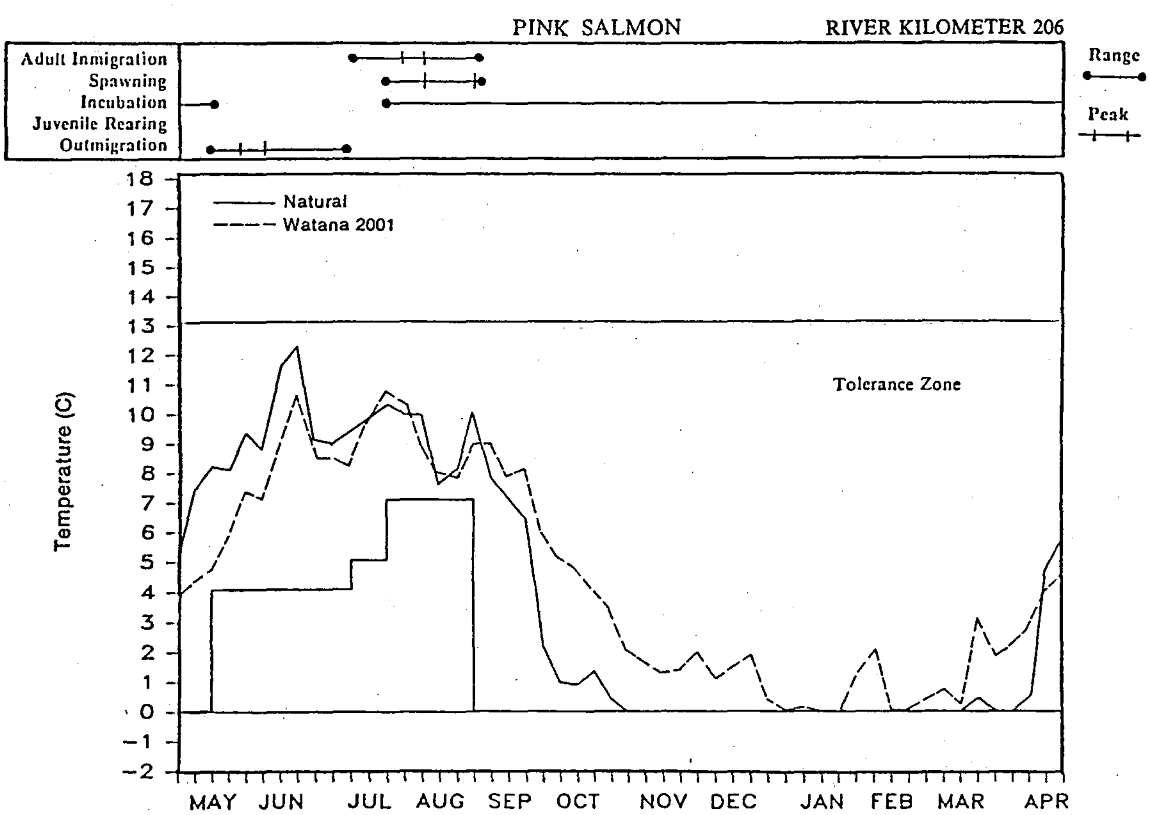
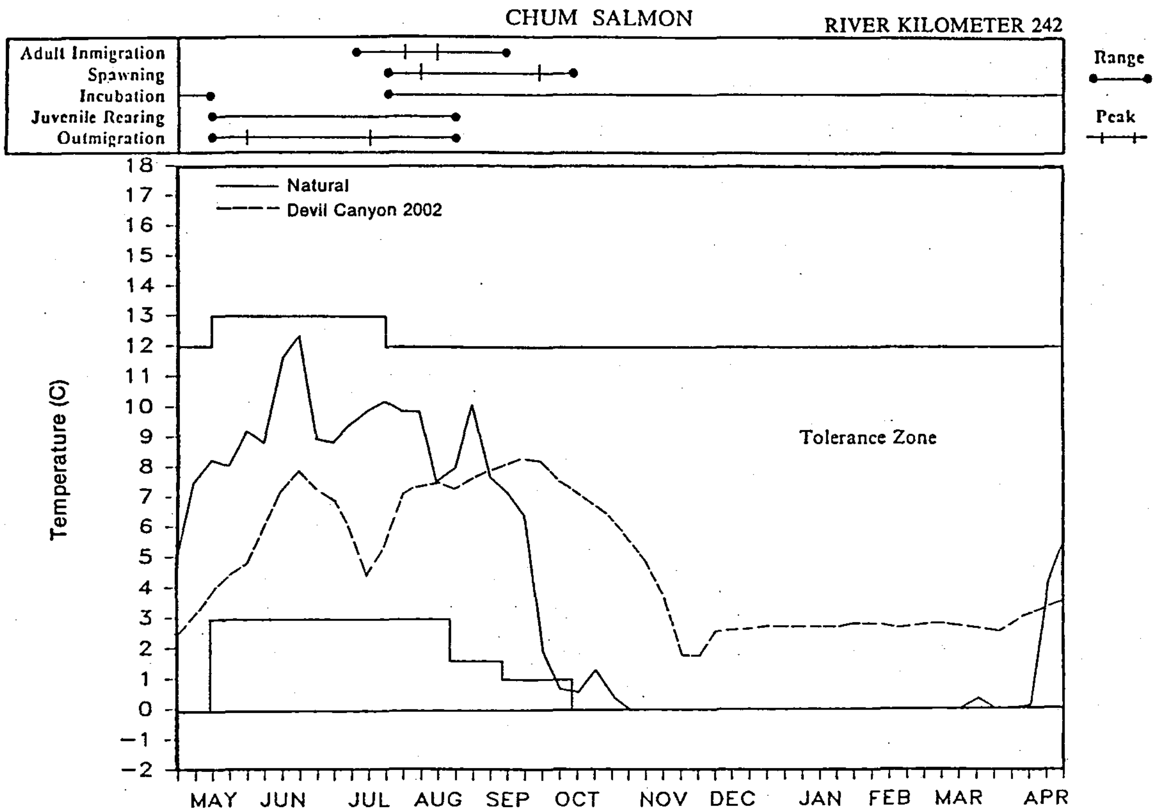


Figure 11. Natural and one-dam (Watana) with-project water temperature regimes in relation to thermal tolerance criteria for pink salmon at two locations on the Susitna River.



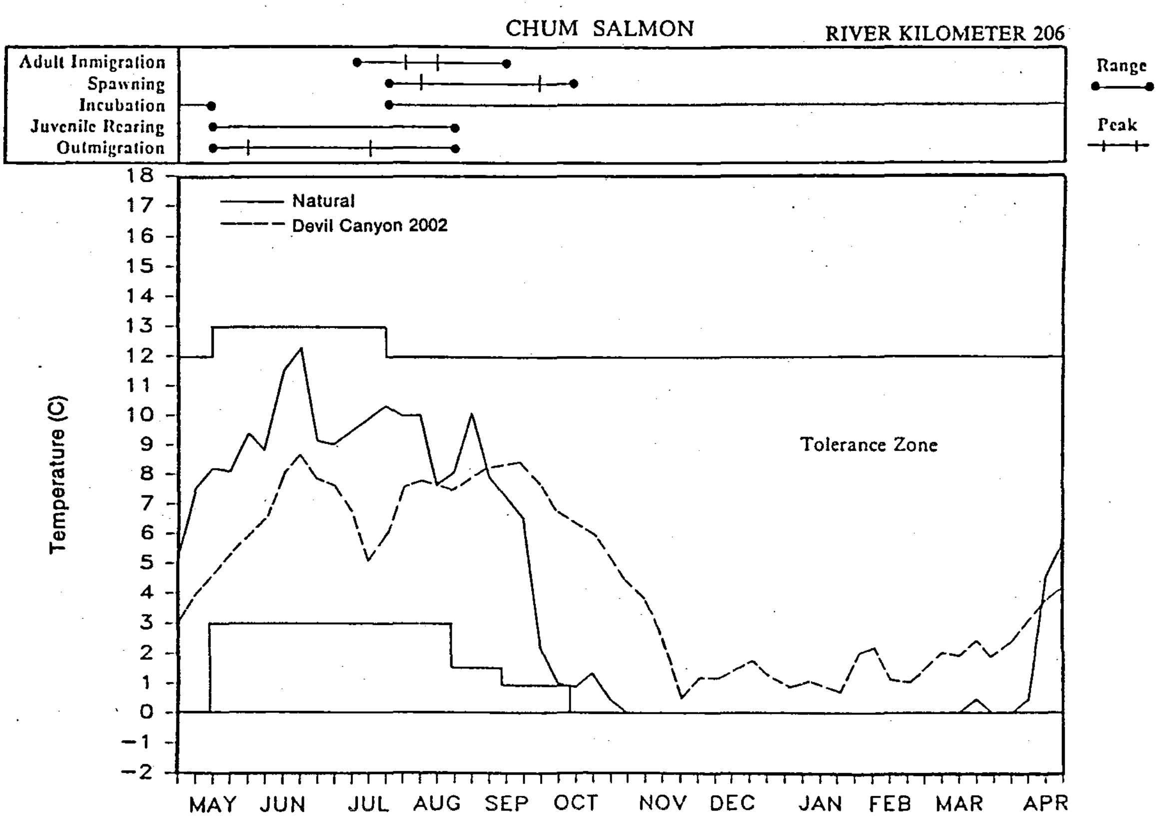
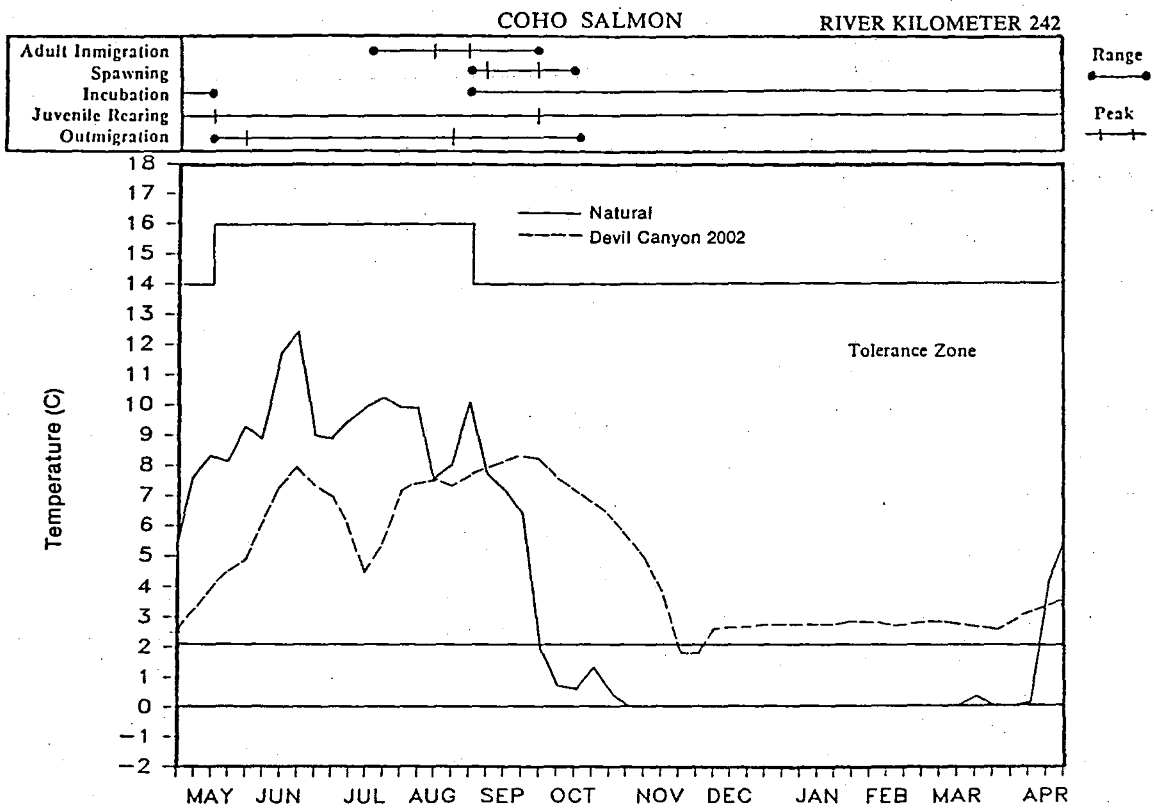


Figure 12. Natural and two-dam (Devil Canyon) with-project water temperature regimes in relation to thermal tolerance criteria for chum salmon at two locations on the Susitna River.



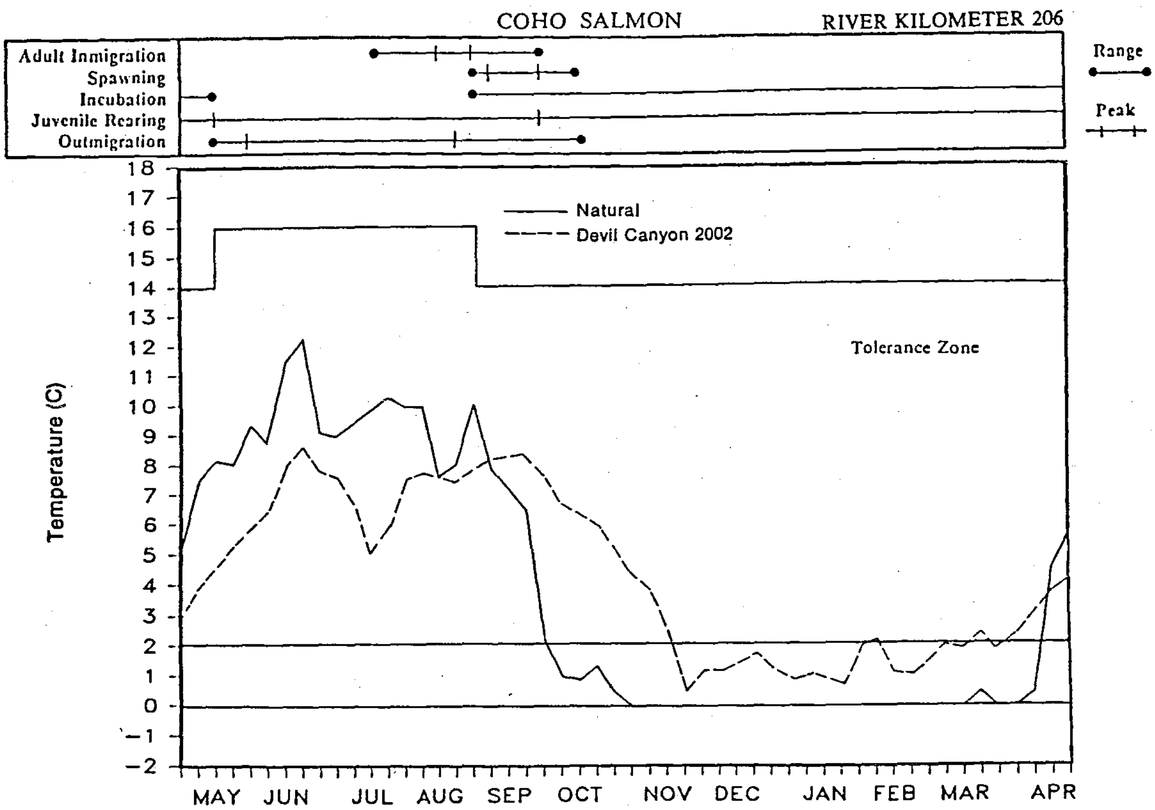
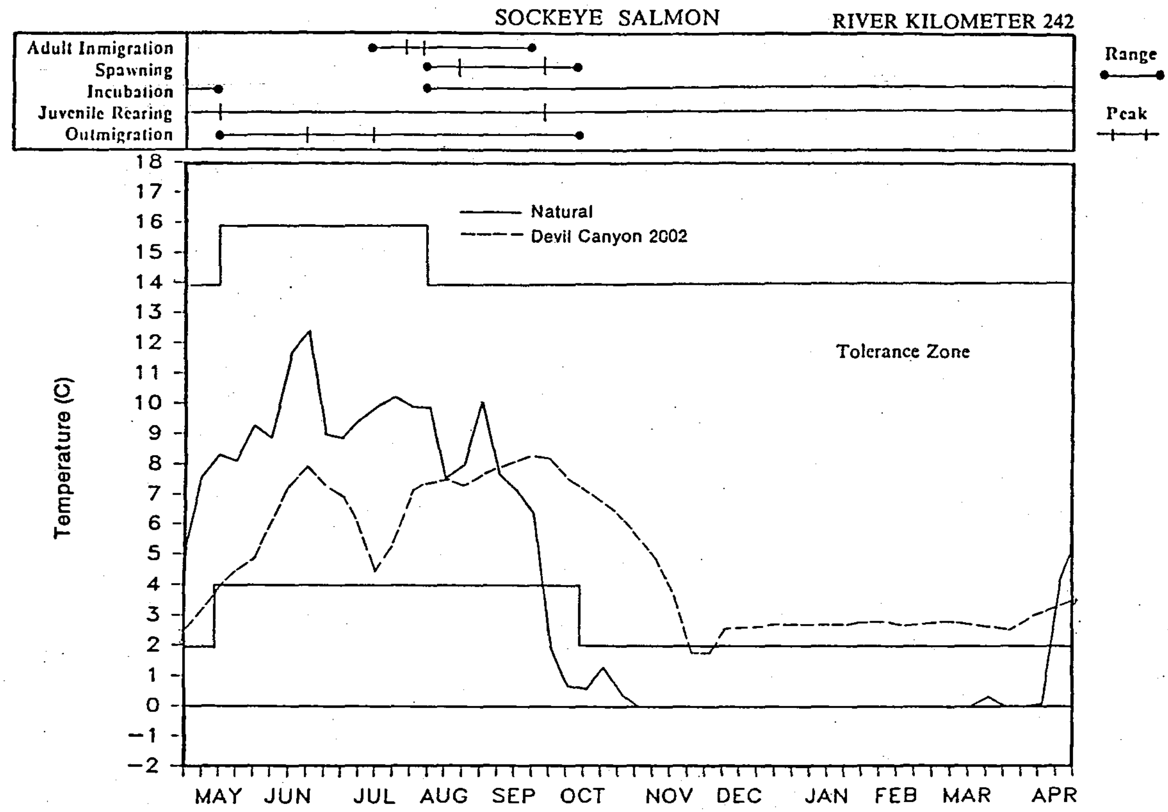


Figure 13. Natural and two-dam (Devil Canyon) with-project water temperature regimes in relation to thermal tolerance criteria for coho salmon at two locations on the Susitna River.



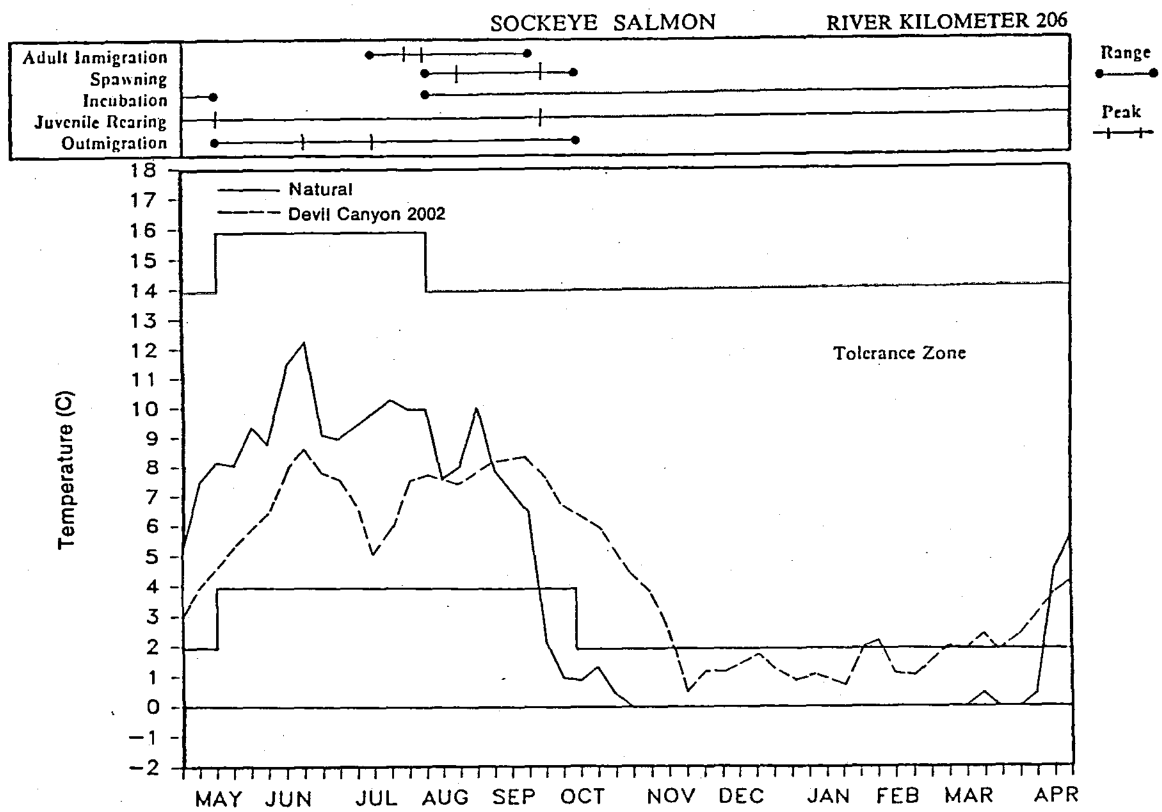


Figure 14. Natural and two-dam (Devil Canyon) with-project water temperature regimes in relation to thermal tolerance criteria for sockeye salmon at two locations on the Susitna River.

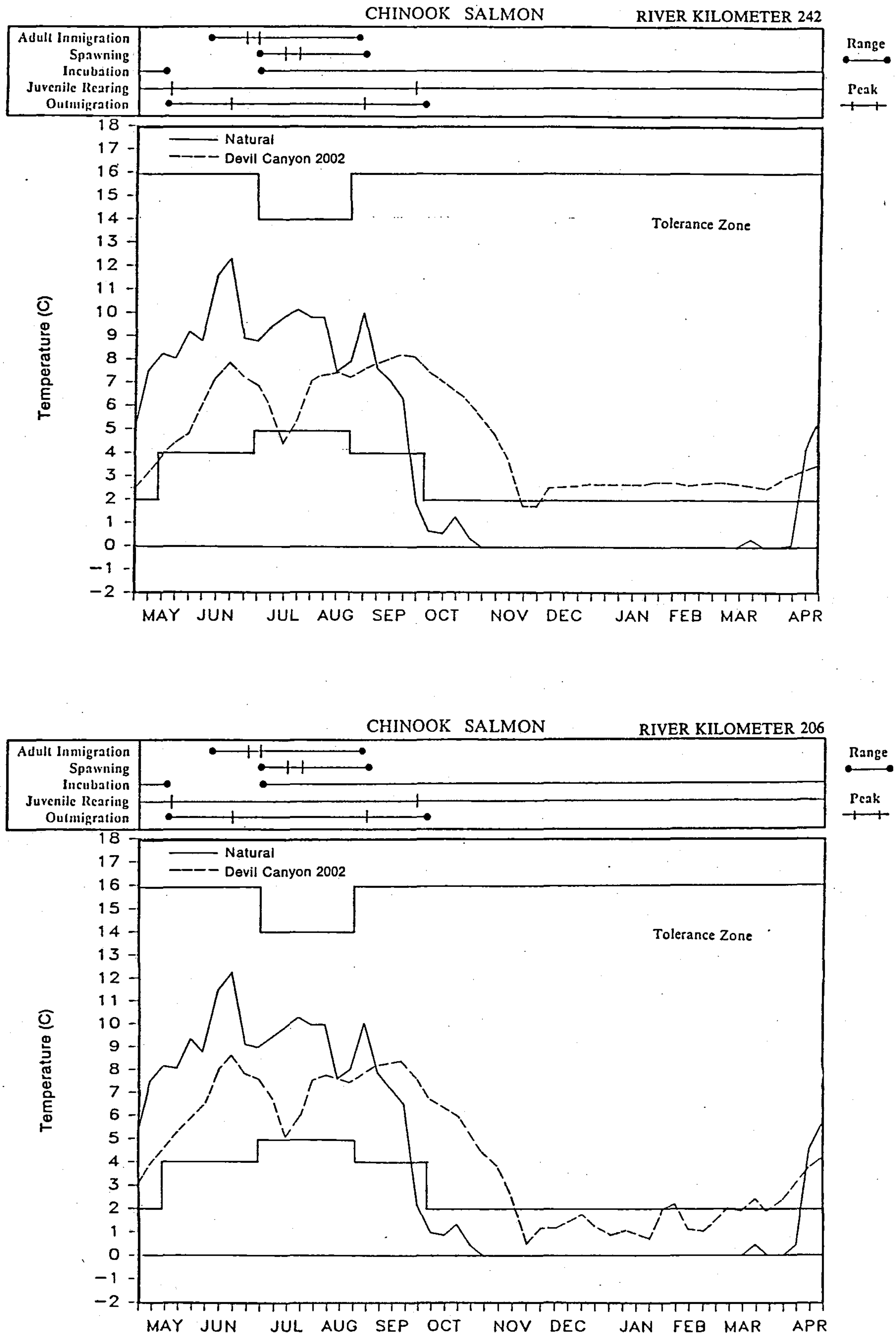
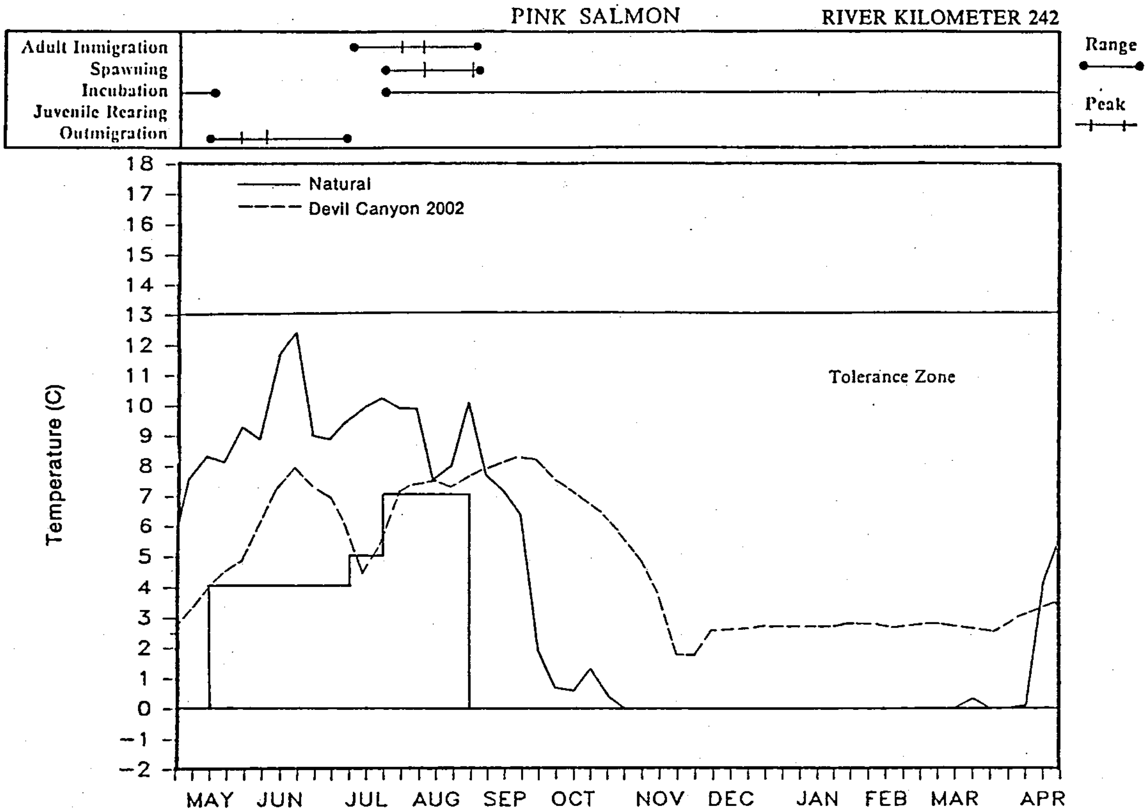


Figure 15. Natural and two-dam (Devil Canyon) with-project water temperature regimes in relation to thermal tolerance criteria for chinook salmon at two locations on the Susitna River.



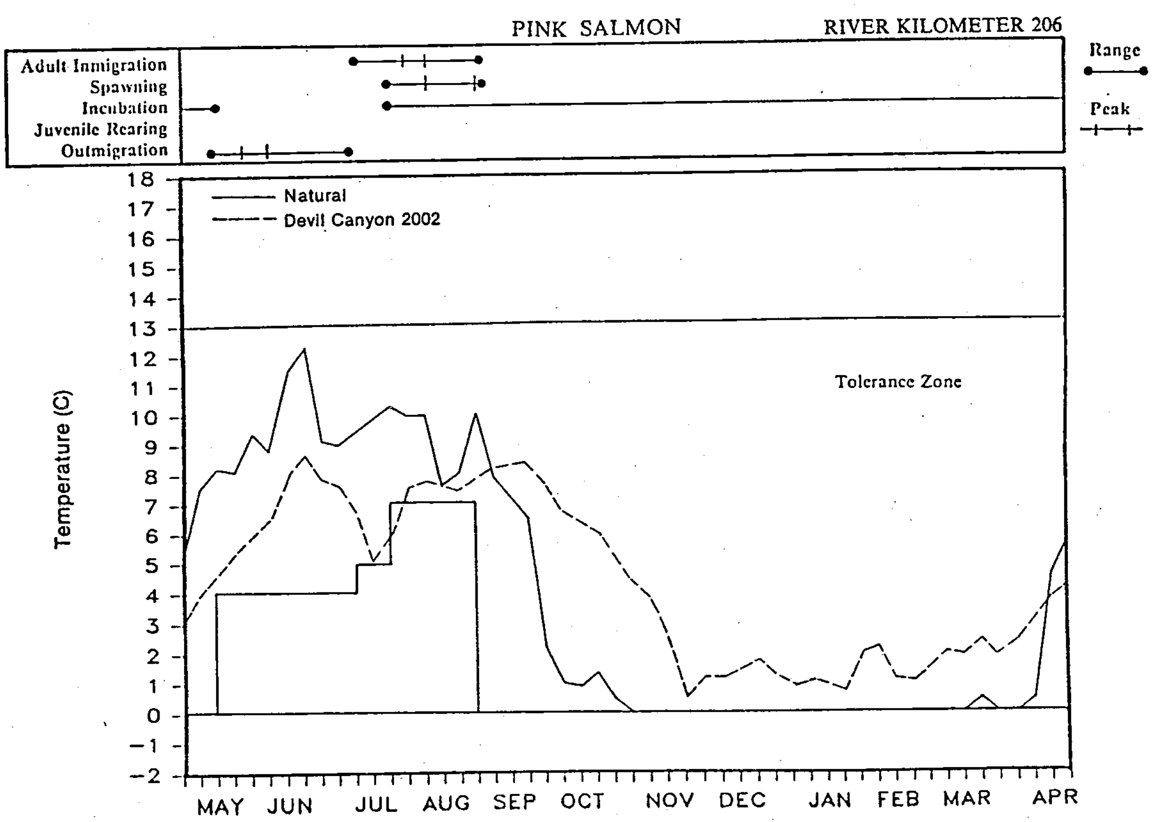


Figure 16. Natural and two-dam (Devil Canyon) with-project water temperature regimes in relation to thermal tolerance criteria for pink salmon at two locations on the Susitna River.

Another situation was found where temperatures upstream of RK 209 in July also fall outside pink and chinook salmon spawning tolerance zones (figures 15 and 16). Since this only occurs for about one week, we believe that this would temporarily delay this species' spawning migration but would pose no long-term impediment to the spawning act. Neither pink nor chinook salmon are presently known to use this habitat for spawning, and thus this is not a present concern. Mitigation studies are currently focusing on the potential increased suitability of mainstem habitats for chinook spawning after the project is operating due to improved hydraulic, turbidity, and winter ice conditions.

The second step in our analysis was a more in-depth examination of effects of temperature change on juvenile fish growth and on embryonic development. Even though the with-project temperature scenarios are largely within the established thermal tolerance ranges for salmon (figures 7-16), some reduction in juvenile salmon growth could occur due to cooler summer temperatures under with-project scenarios. Although unquantifiable, we believe effects on rearing chinook salmon could be the most severe as juveniles of this species are the most numerous in habitats directly under mainstem temperature influence. In spring through fall, juvenile chinook move from overwintering clearwater tributaries and side sloughs into turbid water side channels and mainstem habitats (Schmidt et al. 1984), presumably to forage on drift and benthic invertebrates and to utilize cover provided by the turbid conditions in these areas.

We made estimates of juvenile chinook salmon growth under natural and with-project temperature regimes using a growth table presented in Brett (1974). Our growth assessment indicates that, depending on climate and the temperature of reservoir-released waters, growth (measured by weight gain) of juveniles rearing in affected mainstem areas (above RK 209) could be substantially reduced (figure 17). These estimates of growth reduction are based on the sum of increased growth during the warmer fall temperatures and decreased growth during cooler spring and summer temperature. They are also based in part on the assumption that affected juvenile fish would feed to satiation. Since we believe this may not occur in the wild, these estimates should be viewed as worst case scenarios.

Embryonic development time also is affected by changes in stream temperature, and was used as an estimator of project effect instead of tolerance criteria. With-project water temperatures are expected to be warmer during the salmon embryo incubation period of September through April. Simulated natural mainstem average water temperatures near RK 209 for the September to April period range from 0.8 to 1.2 C depending on meteorological conditions. Watana-only operational average water temperatures would be about 0.7 to 1.2 C warmer and Devil Canyon operational temperatures would be about 0.8 to 2.0 C warmer than natural (table 5).

Our assessment of these elevated winter incubation temperatures was based on the chum salmon nomograph previously described. Under natural conditions, only chum salmon have been found to spawn in mainstem habitats. In 1984 approximately 3,800 chum salmon used the mainstem for spawning; 14,600 spawned in side sloughs (Barrett et al. 1985) at a nearly constant 3 to 4 C where groundwater upwelling maintained elevated temperatures throughout the winter (ADF&G 1983). In the mainstem spawning areas, upwelling groundwater also maintains warm temperatures in the intragravel environment (ADF&G 1983). However, to illustrate effects of natural winter temperature regimes (approximately 1 C) on chum salmon incubation if warm groundwater is absent, our nomograph (figure 6) shows chum fry emergence well into the summer from a

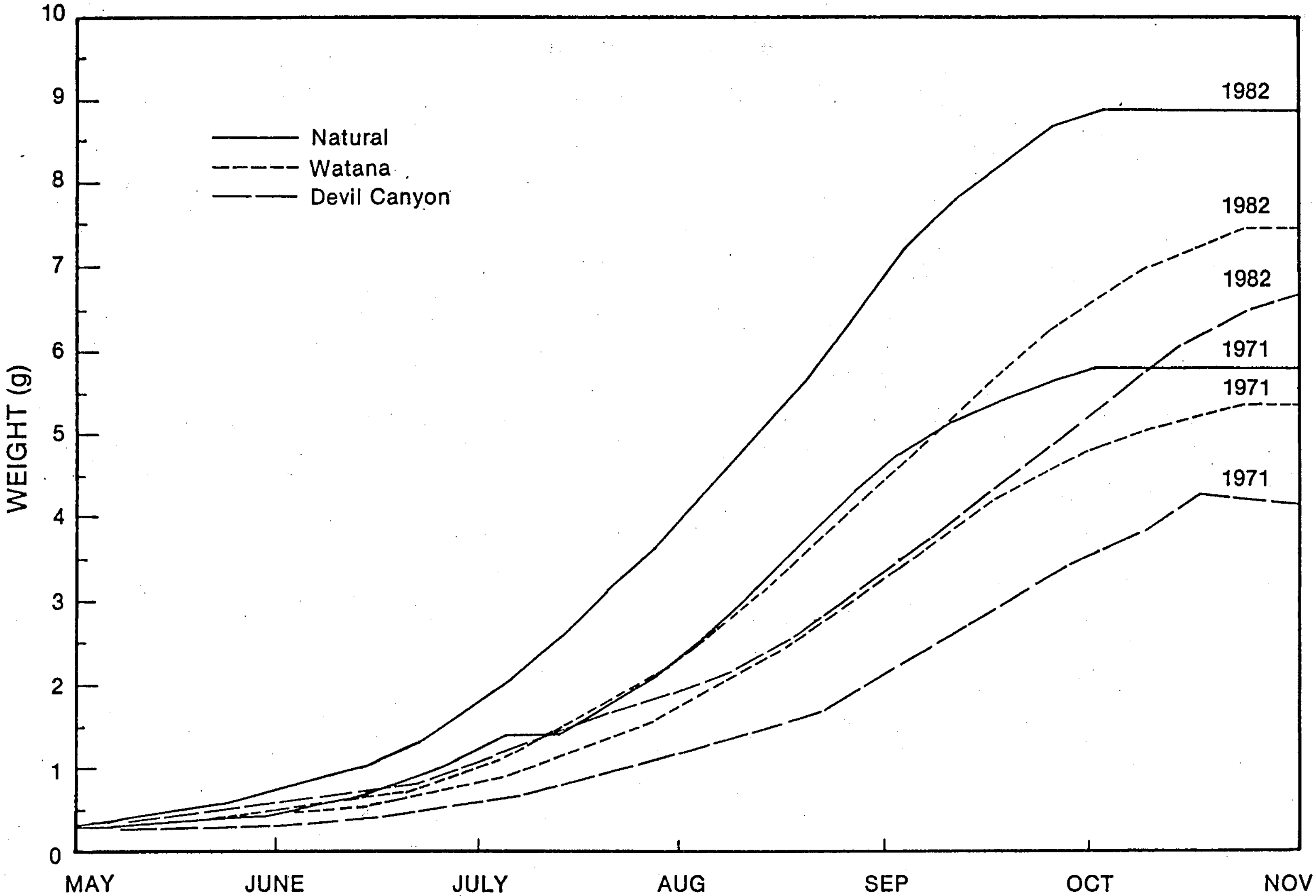


Figure 17. Estimates of juvenile salmon growth in the Susitna River near RK 209 under natural and with-project water temperature regimes comparing 1971 (cold) and 1982 (average) meteorological conditions.

Table 5. Natural and with-project Susitna River temperature ranges (C) under four meteorological scenarios for the period September through April.

	1971 - 1972 Meteorology (Cold, Wet)					
	Natural		Watana 2001		Devil Canyon 2002	
RK	Range	Mean	Range	Mean	Range	Mean
242	0-6.8	0.7	0-8.4	1.7	0.7-8.4	2.3
209	0-6.9	0.8	0-8.3	1.5	0-8.4	1.6
161	0-7.1	0.8	0-8.5	1.3	0-8.5	1.4

	1974 - 1975 Meteorology (Average, Dry)					
	Natural		Watana 2001		Devil Canyon 2002	
RK	Range	Mean	Range	Mean	Range	Mean
242	0-8.5	0.9	0-9.8	2.2	1.2-9.4	3.0
209	0-8.6	1.0	0-9.6	1.8	0-9.4	1.9
161	0-9.1	1.1	0-10.0	1.6	0-9.9	1.9

	1981 - 1982 Meteorology (Average, Wet)					
	Natural		Watana 2001		Devil Canyon 2002	
RK	Range	Mean	Range	Mean	Range	Mean
242	0-7.7	1.1	0.4-9.0	3.0	1.8-8.3	4.0
209	0-7.9	1.1	0-9.0	2.5	0.7-8.2	3.2
161	0-8.4	1.3	0-9.4	2.1	0-8.6	2.4

	1982 - 1983 Meteorology (Average, Average)					
	Natural		Watana 2001		Devil Canyon 2002	
RK	Range	Mean	Range	Mean	Range	Mean
242	0-7.9	1.1	0-9.0	2.9	0.9-8.6	3.5
209	0-8.0	1.2	0-8.8	2.4	0-8.6	2.8
161	0-8.4	1.3	0-9.1	2.1	0-8.9	2.2

spawning date of September 1, the period of peak spawning in Susitna River habitats. Under natural conditions, chum fry emerge in early May (ADF&G 1983). This illustrates that temperature may be a factor limiting successful production of chum salmon in mainstem habitats.

With either one or two dams in place, however, eggs deposited on September 1 at an average incubation temperature greater than 2.0 or 3.0 C should emerge in time to produce viable fry (table 5 and figure 6). Average mainstem temperatures under the Watana-only scenario are above 2.0 C in two of the four different meteorological scenarios and for three of the four Devil Canyon scenarios (table 5). Mainstem temperatures near RK 209 in all but the coldest years average above 2.0 C for the incubation period and any eggs deposited under these warmer temperatures should produce viable fry. It appears, therefore, that better mainstem incubating habitat could exist under with-project scenarios due to the warmer temperatures.

CONCLUSIONS

Our analysis of expected effects on salmon from altered water temperatures due to operation of the Susitna Hydroelectric Project is based on a comparison of available predictions from the SNTEMP model with fish thermal tolerance criteria. While the SNTEMP model served this analysis well, there are limitations in the available water temperature data and in the modeling system that affect the reliability of the absolute temperatures predicted. The temperature data to which the model was calibrated was available for only a few years and numerous discontinuities in these data exist. Additionally, water temperatures are taken at single points in the river, and assumed representative of entire cross sections. The SNTEMP model itself, as used in this study for predicting with-project temperatures, relies on the results from a reservoir temperature model for upstream boundary conditions which also has inherent error. Consequently, simulated temperatures include the possibility of a variety of combined errors.

While the ability of SNTEMP to predict absolute temperatures is uncertain, much greater reliance may be placed on the relative temperature differences resulting between different simulation scenarios. Thus, the ability to assess the temperature changes resulting from operation of the project remains good. We conclude that our analytical procedure, albeit largely nonquantitative, permitted a reasonable analysis of effects on salmon from temperature changes predicted to occur from operation of the Susitna Hydroelectric Project.

The available fish thermal tolerance information, while of sufficient scope for use in gauging effects on salmon generally, is biased to lower latitudes of North America, necessitating professional interpretation for use in Alaska. Also, salmon are poikilotherms, and thus their body functions are very influenced by environmental temperature. Yet salmon exhibit a degree of thermal plasticity, and are often able to maintain some degree of independence of environmental temperature through homeostatic mechanisms (Warren 1971). We believe the Susitna stocks are adapted to a temperature range of 0 to 18 C. Certainly, narrower tolerance ranges apply to each life phase, and ranges differ slightly among species. Due to the wide temperature range in which salmon can live and function, any project-induced change that remains within their tolerance range requires a subjective analysis.

Based on the SNTEMP model results, salmon thermal tolerance criteria, Susitna stock life history information, and professional judgement, we conclude that no direct mortality is anticipated to occur from with-project temperatures. Although unquantifiable, indirect mortality to some species may occur.

Foremost among these effects is our concern with rearing chinook salmon (in an 80 km mainstem reach downstream from the Devil Canyon dam). Regardless of operating scenario, we believe juvenile chinook salmon growth would be retarded; effects would be more acute under the two-dam configuration than with one. This may result in smaller than normal smolts and/or a delay in outmigration, both of which are known to result in reduced survival (Groot 1982, Wedemeyer et al. 1982). The extent of this effect is unquantifiable without more specific information on Susitna salmon stock temperature versus growth relationships.

With-project water temperatures (for the two-dam scenario only) could also delay adult pink and chinook salmon inmigration (and hence, spawning) above RK 209. This could offset the normal timing of embryonic incubation, emergence, and outmigration of the progeny of these species. Of lesser concern, with-project water temperatures (for the two-dam coldest climate scenarios only) could delay pink and chinook salmon outmigration from rearing habitats near RK 242.

ACKNOWLEDGEMENTS

Financial support for this work was provided by the Alaska Power Authority through its subcontractor Harza-Ebasco Susitna Joint Venture. Support also was provided for the authors' participation in this symposium by the Andrew W. Mellon Foundation and by the Arctic Environmental Information and Data Center, University of Alaska-Fairbanks.

REFERENCES

AEIDC (Alaska, Univ., Arctic Environmental Information and Data Center). 1982. Summary of environmental knowledge of the proposed Grant Lake hydroelectric project area. Alaska Power Authority, Anchorage, AK. Report for Ebasco Services. 212 pp.

Alaska Dept. of Fish & Game. 1981a. Annual Salmon Management Report, 1980, Kuskokwim area. Commercial Fisheries Division, Anchorage, AK. 56 pp.

__________. 1981b. Freshwater habitat relationships. Unpublished report by Habitat Division for U.S. Fish and Wildlife Service, Anchorage, AK. 1 vol.

__________. 1983. Susitna hydro aquatic studies, phase 2 data report. Winter aquatic studies (October 1982 - May 1983). Final report for Alaska Power Authority. 137 pp.

__________. 1984. Observed water temperatures for salmon species life stages in the Susitna River drainage. Personal communication with Arctic Environmental Information and Data Center, University of Alaska, Anchorage, AK. April 18, 1984.

Alderdice, D.F., and F.P.J. Velsen. 1978. Relation between temperature and incubation time for eggs of chinook salmon (Oncorhynchus tshawytscha). Journal of the Fisheries Research Board of Canada 35(1):69-75.

Bailey, J.E., and D.R. Evans. 1971. The low-temperature threshold for pink salmon eggs in relation to a proposed hydroelectric installation. Fishery Bulletin 69(3):587-593.

Barrett, B.M., F.M. Thompson, and S.N. Wick. 1985. Adult adadromous fish investigations (May - October 1984). Alaska Dept. of Fish & Game, Anchorage. Report for Alaska Power Authority. 1 vol.

Bell, M.C. 1980. Fisheries handbook of engineering requirements and biological criteria. Revised. Prepared for Fisheries Engineering Research Program, U.S. Army, Corps of Engineers, Portland, OR.

__________. 1983. Lower temperatures at which species of salmon move within river systems. Personal communication with Woodward-Clyde Consultants, Inc., Anchorage, AK. January 8, 1983.

Bucher, W. 1981. 1980 Wood River sockeye salmon smolt studies. Pages 28-34 in C.P. Meacham, ed. 1980 Bristol Bay sockeye studies. Div. of Commercial Fisheries, Alaska Dept. of Fish & Game, Anchorage, AK.

Bustard, D.R., and D.W. Narver. 1975. Aspects of winter ecology of juvenile coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri). Journal of the Fisheries Research Board of Canada 32(5):667-680.

Cederholm, C.J., and W.J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington 1977-1981. Pages 98-100 in E.L. Brannon and E.O. Salo, eds. Proceedings of the Salmon and Trout Migratory Behavior Symposium. School of Fisheries, Univ. of Washington, Seattle, WA.

Combs, B.D. 1965. Effects of temperature on the development of salmon eggs. Progressive Fish-Culturist 27:134-137.

Combs, B.D., and R.E. Burrows. 1957. Threshold temperatures for the normal development of chinook salmon eggs. Progressive Fish-Culturist 19(1):3-6.

Dong, J.N. 1981. Thermal tolerance and rate of development of coho salmon embryos. M.S. Thesis. University of Washington, Seattle, WA. 51 pp.

Flagg, L.B. 1983. Sockeye salmon smolt studies, Kasilof River, Alaska 1981. FRED Div., Alaska Dept. of Fish & Game, Juneau, AK. Technical Data Report 11. 31 pp.

Francisco, K. 1977. Second interim report of the Commercial Fish-Technical Evaluation Study. Joint State/Federal Fish and Wildlife Advisory Team, Anchorage, AK. Special Report 9. 46 pp.

Fried, S.M., and J.J. Laner. 1981. 1980 Snake River sockeye salmon smolt studies. Pages 34-45 in C.P. Meacham, ed. 1980 Bristol Bay sockeye studies. Div. of Commercial Fisheries, Alaska Dept. of Fish & Game, Anchorage, AK.

Godin, J.G. 1980. Temporal aspects of juvenile pink salmon (Oncorhynchus gorbuscha) emergence from a simulated gravel redd. Canadian Journal of Zoology 58(5):735-744.

Groot, C. 1981. Modification on a theme--a perspective on migratory behavior of Pacific salmon. Pages 1-21 in E.L. Brannon and E.O. Salo, eds. Proceedings of the salmon and trout migratory behavior symposium, 1st, University of Washington, Seattle, June 3-5.

Hartman, W.L., W.R. Heard, and B. Drucker. 1967. Migratory behavior of sockeye salmon fry and smolt. Journal of the Fisheries Research Board of Canada 24(10):2069-2099.

Kogl, D.R. 1965. Springs and groundwater as factors affecting survival of chum salmon spawn in a subarctic stream. M.S. Thesis. Univ. of Alaska, Fairbanks, AK. 59 pp.

McCart, P. 1967. Behavior and ecology of sockeye salmon fry in the Babine River. Journal of the Fisheries Research Board of Canada 24:375-428.

McMahon, T.E. 1983. Habitat suitability index models: coho salmon. U.S. Fish & Wildlife Service. FWS/OBS-82/10.49. 29 pp.

McNeil, W.J. 1969. Survival of pink and chum salmon eggs and alevins. Pages 101-117 in T.G. Northcote, ed. Symposium on Salmon and Trout in Streams. Univ. of British Columbia, Vancouver, B.C. H.R. MacMillan Lectures in Fisheries.

McNeil, W.J., and J.E. Bailey. 1975. Salmon rancher's manual. U.S. National Marine Fisheries Service, Auke Bay, AK. 95 pp.

McNeil, W.J., R.A. Wells, and D.C. Brickell. 1964. Disappearance of dead pink salmon eggs and larvae from Sashin Creek, Baranof Island, AK. U.S. Fish & Wildlife Service. Special Scientific Report--Fisheries 485. 13 pp.

Mattson, C.R., and R.A. Hobart. 1962. Chum salmon studies in southeastern Alaska, 1961. Bureau of Commercial Fisheries, U.S. Fish & Wildlife Service, Auke Bay, AK. Manuscript Report 62-5. 32 pp.

Merritt, M.F., and J.A. Raymond. 1983. Early life history of chum salmon in the Noatak River and Kotzebue Sound. FRED Div., Alaska Dept. of Fish & Game, Juneau, AK. Technical Bulletin 1. 56 pp.

Meyer, P.R., M.D. Kelly, K.A. Voos, and W.J. Wilson. 1984. Assessment of the effects of the proposed Susitna Hydroelectric Project on instream temperature and fishery resources in the Watana to Talkeetna reach. Vol. 1. Arctic Environmental Information and Data Center, University of Alaska, Anchorage. Report for Alaska Power Authority. 130 pp.

Neave, F. 1966. Salmon of the North Pacific Ocean - Part III. A review of the life history of North Pacific salmon. 6. Chum salmon in British Columbia. International North Pacific Fisheries Commission Bulletin 18. Vancouver, B.C.

Nelson, D.C. 1983. Russian River sockeye salmon. Sport Fish Div., Alaska Dept. of Fish & Game, Juneau, AK. Federal Aid in Fish Restoration. Vol. 24. Project AFS-44. Annual Report. 50 pp.

R&M Consultants, Inc. and Larry A. Peterson & Associates. 1981. Review of existing Susitna River basin water quality data. Report for Acres American, Inc. 1 vol.

R&M Consultants, Inc., Harza-Ebasco Susitna Joint Venture, Arctic Environmental Information and Data Center, University of Alaska, LGL Alaska Research Associates, Inc., and Agriculture and Forestry Experiment Station, University of Alaska. 1985. Susitna River ice processes: natural conditions and projected effects of hydroelectric development. Unpublished report. Vol. 1. Alaska Power Authority, Anchorage, AK. 305 pp.

Raleigh, R.F. 1971. Innate control of migration of salmon and trout fry from natal gravels to rearing areas. Ecology 52:291-297.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. Transactions of the American Fish Society 108(6):505-529.

Raymond, J.A. 1981. Incubation of fall chum salmon (Oncorhynchus keta) at Clear Air Force Station, AK. FRED Div., Alaska Dept. of Fish & Game, Juneau, AK. 25 pp.

Rukhlov, F.N. 1969. The natural reproduction of the autumn chum salmon (Oncorhynchus keta) on Sakahlin. Problems of Ichthyology 9(2):217-223.

Sano, S. 1966. Salmon of the North Pacific Ocean - Part III. A review of the life history of North Pacific salmon. Chum salmon in the Far East. Pages 41-57 in International North Pacific Fisheries Commission Bulletin 18.

Schmidt, D.C., S.S. Hale, D.L. Crawford, and P.M. Suchanek. 1984. Resident and juvenile anadromous fish investigations (May-October 1983). Alaska Dept. of Fish & Game, Anchorage, AK. Susitna hydro aquatic studies. Report 2 for the Alaska Power Authority. Document 1784. 1 vol.

Sheridan, W.L. 1962. Relation of stream temperatures to timing of pink salmon escapements in southeast Alaska. Pages 87-102 in N.J. Wilimovsky, ed. Symposium on Pink Salmon. University of British Columbia, Vancouver, B.D., 1960. H.R. MacMillan Lectures in Fisheries.

Theurer, F., K. Voos, and W. Miller. 1983. Instream water temperature model. Draft report. Instream Flow and Aquatic Systems Group, U.S. Fish & Wildlife Service, Fort Collins, CO. Instream Flow Information Paper No. 16. 263 pp.

Trasky, L.L. 1974. Yukon River anadromous fish investigations, July 1973 - June 1974. Div. of Commercial Fisheries, Alaska Dept. of Fish & Game, Anchorage, AK.

Wallis, J., and D.T. Balland. 1983. Anchor River steelhead investigations. Sport Fish Div., Alaska Dept. of Fish & Game, Juneau, AK. Federal Aid in Fish Restoration. Vol. 24. Project AFS-48. Annual Report. 44 pp.

Wangaard, D.B., and C.V. Burger. 1983. Effects of various water temperature regimes on the egg and alevin incubation of Susitna River chum and sockeye salmon. Final Report. National Fishery Research Center, U.S. Fish & Wildlife Service, Anchorage, AK. 43 pp.

Warren, C.E. 1971. Biology and water pollution control. W.B. Saunders Company, Philadelphia. 434 pp.

Wedemeyer, G.A., R.L. Saunders, and W.C. Clarke. 1982. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Marine Fisheries Review June:1-14.

Whitmore, D.C., N.C. Dudiak, and J.W. Testor. 1979. Coho enhancement on the Kenai Peninsula. FRED Div., Alaska Dept. of Fish & Game, Juneau, AK. Completion Report AFS-45-1. 54 pp.

Wickett, W.P. 1958. Review of certain environmental factors affecting the production of pink and chum salmon. Journal of the Fisheries Research Board of Canada 15:1103-1123.

Wilson, W.J., E.W. Trihey, J.E. Baldridge, C.D. Evans, J.G. Thiele, and D.E. Trudgen. 1981. An assessment of environmental effects of construction and operation of the proposed Terror Lake hydroelectric facility, Kodiak Island, AK. Instream flow studies. Final Report. Arctic Environmental Information and Data Center, University of Alaska, Anchorage, AK. Prepared for Kodiak Electric Association. 419 pp.

Wilson, W.J., L.S. Underwood, J.E. Baldridge, C.F. Bowden, E.H. Buck, J.M. Colonell, S. Cuccarese, M. Floyd, J.C. LaBelle, D. Spencer, P. Spencer, and D.E. Trudgen. 1979. An assessment of environmental effects of construction and operation of the proposed Terror Lake hydroelectric facility, Kodiak, AK. Arctic Environmental Information and Data Center, University of Alaska, Anchorage, AK. Report for Kodiak Electric Association. 334 pp.