FISH MIGRATION AND PASSAGE: PHYSIOLOGY AND BEHAVIOR

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International Congress on the Biology of Fish
University of British Columbia, Vancouver, CANADA

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SYMPOSIUM PROCEEDINGS

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PREFACE

In watersheds throughout the world, the environmental requirements of resident and migratory fishes conflict with society's needs for land and fresh water. Land and water development - the damming of rivers, alteration of natural flow regimes, loss of riparian and wetland habitat, and diversions of water for urban, agricultural, and industrial use - have resulted in massive changes to freshwater and estuarine habitats, threatening the fishes that depend on these environments for rearing, migration, and reproduction. Dwindling fish populations, many now at critically low levels, have heightened the sense of urgency and challenged scientists, environmental managers, and engineers to search for and develop strategies to mitigate these impacts. Successful strategies will be based on understanding the physiological capabilities and behavioral tendencies of the resident and diadromous fishes that use these waterways as essential conduits to complete their life cycles. How high can a salmon jump to ascend a fish ladder? How fast can a delta smelt swim to avoid entrainment at a water diversion? This Symposium seeks, through investigations of the physiology and behavior of affected fishes, to advance our knowledge in these areas to ensure the conservation of these fishes for wise harvest, ecosystem integrity, and perpetuation of our natural heritage.

Symposium Organizers:

Joseph J. Cech, Jr.

Christina Swanson

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I would like to extend a sincere 'thank you' to the many organizers and contributors who took the time to prepare a written submission for these proceedings. Your efforts are very much appreciated.

Don MacKinlay
Congress Chair

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MOVEMENTS, HABITAT USE AND PHYSIOLOGY OF COASTAL CUTTHROAT TROUT

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EXTENDED ABSTRACT ONLY- DO NOT CITE

Of the Pacific salmonids found in the Columbia River, USA, the migratory behavior and physiology of cutthroat trout is least understood. Cutthroat trout have extremely complex life histories with resident, fluvial and anadromous components. Coastal cutthroat trout in the Columbia River are believed to make extensive use of the main-stem and estuary (as both juveniles and adults) and are thought to be more susceptible to changes in estuarine productivity than any other Pacific salmonid. Migrant juvenile cutthroat trout are often captured in downstream traps on Columbia River tributaries. "Smolting" and rapid seaward migration are assumed. However, most evidence of life history characteristics of cutthroat trout in the Columbia River is based in historical/anecdotal information. The goal of this study was to characterize the movement and timing of migrant (fluvial or anadromous) cutthroat trout and correlate movement with physiological status within tributaries and through the main-stem of the Columbia River. The Chinook River and Mill, Abernathy and Germany Creeks (river km 6, 74,76 and 80) were studied. Methods used include long range PIT (Passive Integrated Transponder) tag technology and acoustic and radio telemetry.

From August through September of 2001, cutthroat juveniles (>10 cm, n = 473) were captured in Abernathy Creek and internally tagged with 23 mm PIT tags. In-stream movements of these fish were monitored continuously (at 50 msec intervals) at two downstream interrogation arrays 5 and 3 km from the confluence with the Columbia River. Also, migrant cutthroat trout were captured using 5ft screw traps fished within two km of the mouth of Abernathy, Mill, and Germany Creeks respectively. Captured fish greater than 43 g (n = 97) were implanted with a Lotek NTC-4-2S digitally coded radio tag and released downstream from the capture site. Movements were monitored by boat, car and stationary radio antennae arrays from the Creeks to the salt wedge.

In the Chinook River and Mill and Abernathy Creeks, migrant juveniles (n = 49) captured by screw trap were implanted with Vemco V8SC-6L-R256 coded pingers. An array of Vemco VR2 fixed acoustic receivers was maintained to monitor movements into and through the estuary and out into the ocean.

To characterize the parr-smolt transformation of cutthroat trout, hatchery fish were reared and sampled. Prior to and during the assumed period of migration (April - July) gill tissue was sampled to measure gill Na^+,K^+-ATPase activity. From April through July, cutthroat trout were also subjected to bi-weekly iso-thermal seawater transfers. After 24 h at 35 ppt, challenged fish were sacrificed and blood was taken for ion analysis. All tagged fish in the telemetry portion of this study had gill biopsies taken for the measurement of gill Na^+,K^+-ATPase activity.

Based on seawater challenges and gill Na^+,K^+-ATPase activity, cutthroat trout appear to undergo a distinct parr-smolt transformation. Juvenile hatchery fish held through the period of downstream migration demonstrated increased physiological tolerance to seawater from April to June. Observations of movements passed the fixed PIT tag interrogation arrays was directional and of greatest magnitude in May. Once in the main-stem of the Columbia River, most radio tagged cutthroat trout juveniles demonstrated directed and rapid down-stream movement. Individuals tagged with acoustic pingers were observed to travel through the estuary and into the Columbia River Plume. These characters are consistent with observations of other Columbia River salmonid smolts.

DOES SIZE MATTER: A COMPARISON OF THE BEHAVIOR OF JUVENILE SALMONIDS IN A LARGE AND SMALL ESTUARY

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We have conducted field investigations of migratory behaviour using biotelemetry on two systems on the Oregon Coast with very different physical characteristics, the Columbia River (large), and the Nehalem River (small). Juvenile salmonids (*Oncorhynchus* spp.) were implanted surgically with radio or acoustic transmitters and released into the river. Their migratory behaviour was monitored from the land and water from the point of implantation until fish had entered the nearshore ocean environment.

Our results suggest that the behavior of fish in the lower Nehalem River (steelhead trout and coho) is more variable than in the lower Columbia River (steelhead trout and chinook). In both systems river flow is an important determinant of migration rates in the river. In contrast to their behavior in the river, juvenile steelhead in both estuaries appear to behave similarly. Movement of steelhead through the estuaries corresponds to changes in the tidal cycle. There is some evidence that the tidal influence may be increasing the vulnerability of the outmigrating juveniles to both avian and mammalian predators.

Comparisons of wild/hatchery steelhead trout and hatchery coho in the Nehalem estuary suggest that average residence times for coho are significantly greater than for steelhead trout and this tends to increase the vulnerability of this species to avian predation. However, a large proportion of steelhead trout are lost at the mouth of the estuary prior to reaching the nearshore ocean.

Acknowledgements

This work was supported by grants from the US Army Corps of Engineers (Walla Walla division), the Oregon Watershed Enhancement Board, and the Oregon Department of Fish and Wildlife.

THE WAVE DRAG HYPOTHESIS: AN EXPLANATION FOR SIZE-BASED LATERAL SEGREGATION OF MIGRATORY ROUTES DURING THE UPSTREAM MIGRATIONS OF SALMONIDS

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EXTENDED ABSTRACT ONLY - DO NOT CITE

One remarkable and fascinating aspect of salmon migration is that when the adults return to spawn small fish swim upstream near the edge of the river, while larger fish swim further offshore. Perhaps the best known example of this is that sockeye salmon (Onchorhynchus nerka) are often observed swimming in well defined bands along the edge of the river, while at the same time larger chinook salmon (Oncorhynchus tshawytscha) are swimming upstream further offshore. Remarkable in another way is the fact that, although those involved in acoustical stock assessment have long been aware of this interesting behavior, it has, apparently, never been the focus of scientific study.

In this presentation I will provide documentation of this size-based lateral segregation and describe a model that I have developed which combines hydrodynamics, energetics, and 2-D flow simulation to predict the effects of body size, channel morphology and stream discharge on the migratory path and upstream swimming speed of salmon. This model is founded on the recognition that wave drag can be very significant when large fish swim upstream rapidly in shallow water. To date, the relevance of wave drag appears to have been completely overlooked by researchers interested in salmon migration. Typically, water velocity and water temperature are assumed to be the only important physical variables that affect the energy cost of upstream migration, while the effect of water depth on wave drag is neglected. This is surprising because Hertel (1966) showed that when a fish-shaped model is towed immediately below the water's surface wave drag can be as much as four times greater than the frictional drag the model experiences when submerged three or more body diameters beneath the surface. This represents a very significant additional drag force, and natural selection will undoubtedly have adapted the migratory behavior of salmon to deal with the challenges it poses.

The model I describe assumes that salmon will choose a migratory path that minimizes the total drag force they have to overcome on their journey upstream. The existence of wave drag means that the energetic benefits of swimming near the edge of rivers, where the water is relatively slow, may be offset by having to swim in shallow water, where the wave drag is high. In these circumstances a fish may select a route in deeper water, to avoid wave drag, even though this exposes it to higher water velocities and an increase in frictional drag. The fish's exposure to wave drag rises with the Froude Number, (F = u/Sqrt[g h]), where u is the fish's speed, g is the acceleration due to gravity, and h is the fish's submerged depth. Since the optimum upstream swimming speed increases with body size, large fast moving fish will have a greater incentive to avoid shallow water than smaller ones. This leads to the prediction that they will migrate further offshore than small fish. It is also possible that, for any given value of h and u, large fish have to overcome a greater wave drag because of their greater body depth.

Hertel, H. 1966. Structure, form and movement, Reinhold Publishing Corporation, New York. N.Y. 251 p.

MIGRATION AND SURVIVAL OF JUVENILE SALMONIDS IN THE LOWER COLUMBIA RIVER AND ESTUARY: RESULTS FROM RADIO-TELEMETRY

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

Over several years we have conducted radio-telemetry studies on Pacific salmonid smolts including spring and fall chinook salmon and steelhead migrating in the Columbia River and its' estuary. The principle focus of these studies has been to evaluate differences in fish migratory behavior and survival in the lower Columbia River and estuary between fish groups that have different migration histories through the Columbia/Snake river hydrosystem. This presentation will be a summary of our major findings over several years.

Methods

Paired releases were established between fish that were barged from Lower Granite Dam (Snake River) and those collected from the Bonneville Dam smolt collection facility. Fish were collected and anesthetized at the hydroelectric facilities or on barges, and then implanted either surgically or gastrically with radio tags. After recovery, both groups of fish were released 1-5 km below Bonneville Dam then tracked using a combination of fixed receiver locations and active tracking with boats and small planes. We have calculated migration speeds to the estuary from the release point, established smolt migration patterns and channel use, and identified locations of mortality in both the river and estuary.

Results/Discussion

From paired releases, comparisons between fish transported by barge from Lower Granite Dam on the Snake River and in-river fish collected at Bonneville Dam on the Columbia River have not shown large differences in migratory patterns or mortality in the lower river. Most smolts of all types and species migrate within the principle channel in the lower river, although airplane surveys have also indicted some use of side channels. River flow has some influence on migration rates to the estuary, with faster rates coinciding with greater flow, but in general migration speeds have ranged from 1.9-3.5 km/h. At these rates, most smolts take 2.5 – 5 days to migrate from the release point to the estuary. We have seen no indication of a holding pattern in the river. In most years, the majority of tagged fish successfully migrated to the estuary, with most spring chinook and steelhead releases having in-river survival rates ranging from 70-90%. Once within the estuary many smolts leave the main shipping channel on the Oregon side and cross broad shallow areas towards the Washington shore, and then follow the flow of a secondary channel into the lower estuary. Tidal cycles influence the rate of egress to the ocean, which is corroborated with our acoustic tracking of steelhead smolts. Based on tracking of individual fish by boats, smolts that reach the estuary on an outgoing tide tend to move quickly through the estuary, while those arriving at the estuary on an incoming tide reduce or arrest their downstream movement until the next outgoing tide. These behaviors may influence smolt survival rates, where arrested movement increases the time juvenile salmonids are vulnerable to avian predators. In most years, less than 20% of tagged fish that reached the estuary were found in piscivorous bird colonies. Recent tag detection data show that efforts to reduce bird predation near Rice Island in the upper estuary may have shifted predation pressure to other areas in the estuary where birds have relocated.

Acknowledgements

This multi-year study has been funded by the U. S. Army Corps of Engineers-Walla Walla District. We appreciate the cooperation and coordination with other agencies, including the Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, Pacific States Marine Fisheries Commission, and the United States Geological Survey/BRD.

MIGRATION SUCCESS OF ADULT SOCKEYE SALMON ASCENDING THE FRASER RIVER, BRITISH COLUMBIA: AN ANALYSIS BASED ON PAST, PRESENT AND EXPECTED FUTURE RIVER CONDITIONS

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EXTENDED ABSTRACT ONLY - DO NOT CITE

We evaluated the effects of long term trends in river temperature and discharge in the Fraser River on migration energetics and enroute mortality of the Early Stuart stock of sockeye salmon *Oncorhynchus nerka*. The model tracks the average individual in the stock grouping from the time of entry in the Fraser

River estuary to arrival on the spawning grounds. Fish swim 1200 km over a period of approximately one month and rely solely on energy reserves to power their migration.

Our model accounts for energy losses through discrete portions of the river. Swimming behavior and energy costs of migrants in the river have been studied through an integrated field program involving telemetered fish with EMG sensors, underwater video observations, and swimming trials of fish in flow-through respirometers and flumes. Mortality risk to the migrant is estimated in the model based on an empirical relationship between modeled energy use and a mortality estimate derived from count discrepancies of abundance measured with hydroacoustics in the lower river and fence counts near the spawning grounds.

We also provide evidence that this mortality risk falls disproportionately on the lower conditioned individuals in the spawning run, revealed through length-weight analyses conducted on this stock at a number of locations along their migration route. Using our model, we estimated energy expenditures and mortality risk for the average migrant during 1950-1999. Inputs to the model for each simulated year included daily discharge and temperature in the lower river, timing of return of adults to the river mouth, and mean body size. Model output indicates a substantial increase in migration energy use and enroute mortality risk in recent years (particularly 1999) related to unusually high discharge events.

We projected energy use and risk of mortality of the Early Stuart stock during 2010-2099 based on flow and temperature simulations driven by a global circulation model assuming a doubling in atmospheric CO_2 concentrations over this period. This simulation indicated a long term increase in power requirements for migration owing largely to increased summer water temperatures, with a concomitant increase in enroute mortality risk. This expected increase in enroute mortality may have important implications on the sustainability of this stock.

SEASONAL MOVEMENTS OF RESIDENT AND LAKE SUPERIOR ANADROMOUS FISHES IN THE BEAVER LAKES BASIN, PICTURED ROCKS NATIONAL LAKESHORE, MI, USA

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EXTENDED ABSTRACT ONLY – DO NOT CITE

The Beaver Lake drainage basin is located in Pictured Rocks National Lakeshore, Munising, MI. This drainage is composed of both lotic and lentic systems. Little is known about the movements and utilization of these dynamic systems by resident and anadromous fish species, or the response of these fishes to environmental stochasticity. The documentation of underlying environmental stimuli and patterns of movements of those fish within the drainage will provide critical insight into little known fish species life histories, behavior and ecology. This project will identify the number of anadromous adults using the drainage and characterize the timing and environmental factors that trigger their movement, as well as those of resident fishes, to spawning sites.

The Beaver Lake system is composed of two lakes (Beaver Lake and Little Beaver Lake) that are connected by a short channel, several small tributary streams, and an exit stream that connects Beaver Lake to Lake Superior. Fish resident or successfully introduced to the drainage include walleye, northern pike, bluegill, brook trout, yellow perch, burbot, slimy and mottled sculpin, a variety of cyprinids and several other common, north-temperate, cool-water species. Additionally, the system is thought to be used by anadromous steelhead, coho salmon and pink salmon. The system is under consideration for inclusion in the migratory brook trout (coaster) restoration program currently underway on the south shore of Lake Superior.

A bi-directional trap-and-weir scheme is being used in tributaries and in the channel between the lakes to identify the direction of travel of fishes. PIT-tags (passive integrated transponders) are being used to identify individual fishes for mark-recapture. To date, we have PIT-tagged 42 native brook trout (*Salvelinus fontinalis*) in the tributaries and identified 24 fish species residing in the drainage. During September 17th - October 1st of fall 2001, white suckers (*Catostomus commersoni*) were captured moving upstream in Beaver Creek (Fig. 1).

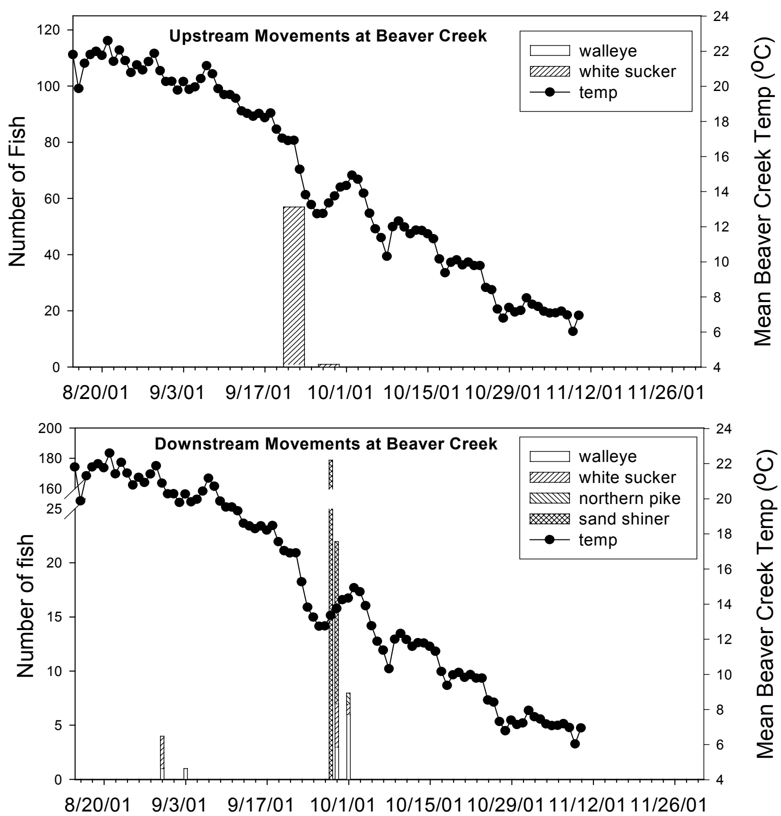

Figure 1. Passage of fish upstream (into the Beaver Lake drainage from Lake Superior) and downstream (out of the Beaver Lake drainage into Lake Superior) in Fall 2001 with respect to stream water temperature.

We captured sand shiners (*Notropis stramineus*) moving downstream during the last week of September and the first week of October. There was a drop in stream temperature of 4°C during this period. Walleye (*Stizostedion vitreum*) were captured moving from Little Beaver Lake to Big Beaver Lake during this same 2-week period (Fig 2). All the fish except the sand shiners were juvenile fish. Initial results suggest that several species are undertaking fall migrations in concert and are likely responding to similar environmental cues. This study will continue in 2002 and 2003 and will focus on the spring and fall movement patterns.

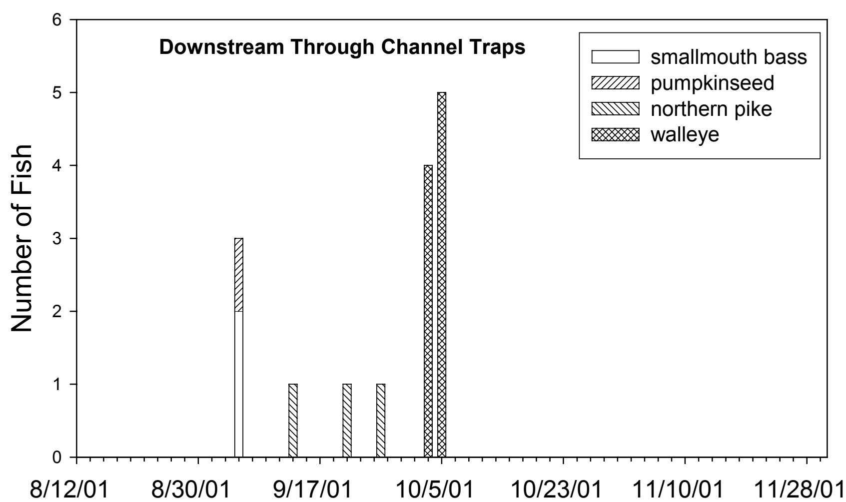

Figure 2. Passage of fish moving from Little Beaver Lake into Beaver Lake in Fall 2001.

EFFECTS OF FISH SCREEN EXPOSURE ON

THREATENED DELTA SMELT

BEHAVIOR AND SURVIVAL

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In California's Sacramento-San Joaquin estuary, delta smelt *(Hypomesus transpacificus*) are exposed to thousands of water diversions located within their habitat. Entrainment losses at these diversions, most of which are unscreened, are thought to have contributed to the decline of this species and its resultant listing under the federal Endangered Species Act as threatened in 1993. However, limited information on delta smelt physiological and behavioral responses to artificial flows like those near diversions or to positive barrier fish screens has prevented development of effective fish screen designs or operational criteria for this species. In particular, planned renovations of the large state and federal water project facilities that are located along the delta smelt's migratory path require improved understanding of the responses and capabilities of this delicate fish.

To provide the information needed to develop fish screen criteria for delta smelt, we evaluated the performance and behavior of the fish near a simulated fish screen using the Fish Treadmill. This apparatus, a large annular flume equipped with a fish screen (2.3-mm vertical wedgewire, 50% porosity), is capable of producing two-vector flow regimes (i.e., approach flow, perpendicular to the screen, and sweeping flow, parallel to the screen) similar to those near screened water diversions. For groups of 20 fish (12°C, 4-8 cm SL) exposed for 2 hours to combinations of approach (range: 0-15 cm/s) and sweeping flows (range: 0-62 cm/s) during the day (lighted conditions) and night (dark conditions), we measured fish-screen contact frequency, impingement rates, stress, injury rates and severity, survival, and screen passage velocity.

For subadult and adult delta smelt, fish-screen contact rates, impingement rates, plasma cortisol, and 48-h post-exposure mortality rates all increased with increases in both approach and sweeping velocities. Injury rates were directly related to screen contact rates and strongly correlated with mortality; at high velocity flow combinations, mortality rates >50% were not uncommon. On the other hand, screen passage velocities were directly related to sweeping velocities, with the fish generally being swept downstream at flows >31 cm/s. General linear statistical models developed from these results provide guidance for developing several specific aspects of fish screen flow and operational criteria; for example, flow regimes that maximize survival from appropriate screen exposure durations and fish screen lengths. Applications of these results and models to fish screen design and operation will improve delta smelt protection during and after exposure to a screened water diversion.

This research is supported by California Department of Fish and Game, California Department of Water Resources, U.S. Bureau of Reclamation, CALFED Bay Delta Program, and the Anadromous Fish Screen Program (U.S. Fish and Wildlife Service and U.S. Bureau of Reclamation). We also thank the UC Davis Hydraulics Laboratory, Department of Civil and Environmental Engineering, for their design, construction, and operation of the Fish Treadmill; the California Department of Fish and Game, for their assistance collecting delta smelt and conducting the experiments; and our student, post-graduate, and post-doctoral research assistants from the University of California, Davis, Department of Wildlife, Fish, and Conservation Biology, M. Danley, N. West, S. Chun, T. Chen, M. Kondratieff, T. MacColl, T. Reid, S. Katzman, D. Shigematsu, J. Cervantes, J. Hsu, S. Lema, K. Day, C. Meloni, S. Gough, M. Karagosian, R. Mayfield, B. Nathaniel, M. Gonzalez, C. Lee, L. Hatton, M. Lee, S. Carlson, C. Peregrin, D. Warren, B. Begun, M. Kuoppamaki, A. Pickersgill, J. Heublein, A. Robb, M. Schoessler, T. Mussen, C. O'Grady, B. Ransom, S. Marquis, E. Zhu, F. Mo, A. Lochner, K. Tran, P. Lin, S. Somers, B. Ta, J. Roessig, without whom this work would not be possible.

COMPARATIVE PERFORMANCE OF THREE THREATENED CALIFORNIA FISHES TO REPEATED SCREEN EXPOSURE

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EXTENDED ABSTRACT ONLY - DO NOT CITE

Introduction

The threatened splittail (*Pogonichthys macrolepidotus*), threatened delta smelt (*Hypomesus transpacificus*), and endangered winter-run chinook salmon (*Oncorhynchus tshawytscha*) may be vulnerable to >2000 water diversions distributed throughout the Sacramento-San Joaquin Delta in northern California. Installation of fish screens has been identified as one means of reducing direct mortality associated with water diversions. However, exposure to multiple screened diversions could be detrimental to these native fishes. This study was conducted to quantitatively measure the performance and behavior of these species in a simulated two-screen exposure at 19°C (splittail) and 12°C (delta smelt and chinook salmon) using the Fish Treadmill apparatus.

Methods

Fish (20 per group; standard length: 4-6 cm) were exposed to a circular 3-m diameter fish screen with 2.3-mm vertical bar spacing in a 0.67-m wide test channel of the Fish Treadmill apparatus for 2 hours in a simulated two-screened diversion exposure at target flows of 10 cm/s (0.33 f/s) approach flow at different sweeping

(0, 31, 62 cm/s or 0, 1, 2 f/s) flows.

Results

Preliminary results (1-3 replicates so far) showed high survival for all three species. Mortality occurred only in one delta smelt (out of 100 experimental fish) and only at 10 cm/s approach flow with 31cm/s sweeping flow.

A general increase in total screen contact rates was observed in all fishes as water velocity was gradually increased to target flow (simulating conditions as fish approach a screened diversion), followed by either a slight decrease or maintained level as the fish were acclimated to target flow (simulating exposure to the screened diversion). Splittail screen contact rates (tail touch and body contact rates) in all flow combinations decreased at the second screen exposure indicating no detrimental effects of a second screen exposure after a 10-min rest period (no flow, simulating no screen exposure). However, delta smelt and chinook salmon screen contact rates increased at the simulated second screen exposure at the 10 cm/s approach flow with no sweeping flow, indicating that a repeated screen exposure at this flow combination may be detrimental to delta smelt and chinook salmon even after a 10-min rest period. Winter-run chinook salmon had the highest contact rates at target flows, compared with those of splittail and delta smelt.

For all species, downstream velocity past the screen was highest at the 62 cm/s sweeping velocity.

These preliminary results indicate that a second screen exposure at approach flow of 10 cm/s with no sweeping flow could be more detrimental to both delta smelt and winter-run chinook salmon than to splittail. Also, the 62 cm/s sweeping flow seems to increase fish passage past the screen, for all three species.

Acknowledgments

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Lindberg, B. Bridges, B. Nathaniel, P. Crain, K. Arkush and L. Hain (UC Davis).

A NEW TRIAL OF MONITORING SALMON MIGRATORY BEHAVIOR BY AN AUTOMATIC TRACKING ROBOT BOAT

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There are mainly three different instruments to monitor underwater fish movement. The first is ultrasonic or radio active transmitters that emit pulsed or coded sgnals detected in real time. They can directly track and monitor fish movement and do not necessarily need to be recovered, but they are very labor intensive since researchers must be constantly engaged in receiving signals, and remote detection is possible only in fixed station. The second is archival tages or micro-datalogger: that can store various data to be recovered at a later time. They can store data, including ambient temperature, swimming depth, swimming speed, hear rate, and brain waves without constant monitoring, but they must be recovered before the data can be downloaded. The third is passive integrated trasponder tags that are monitored by hand or stationary detectors. They can implanted into a great number of fish at low cost, but they never reveal fish behavior and the fish must be very close to the detector for monitoring.

Since each technique has great advantages and/or minor disadvantages in clarifying physiological mechanisms of fish behavior, ten experts in the fields of ship engineering, signal processing, acoustic engineering, and computer science have carried out a collaborative research project to develop an automatic salmon-tracking robot boat in Lake Toya since 1999. In order to monitor lacustrine salmon (sockeye salmon, masu salmon, and rainbow trout) homing migration for several days in the lake the following interrelated four equipment systems have been developing; 1) a robot boat, 2.5 m in length, 1.3 m in width, with a loading capacity of 120 kg, operating by two electric thrusters at 2 knots, 2) an ultrasonic tracking system detecting distance and direction of miniature pingers, 3) a signal processing and control system consisting of DGPS, acoustic signal, and gyroscope, 4) a telecommunication system between a land base and the boat.

Using a NTT handy-phone circuit, we have already succeeded in navigating the boat to any point in the lake using commands from shore, in having the boat cruise and stop by self-navigation, and in transmitting data from the DGPS and gyroscope from the boat to the base. And, we have just succeeded in tracking lacustrine sockeye salmon homing behavior by the robot boat at a distance of 100 m on October 2001. In the near future, we are planning to track salmon using the robot boat from the Bering Sea to Hokkaido.

Fig. A SWATH type robot boat with styrofoam twin hull constructed by pipes, operating two electric thrusters. This boat is easy to disassemble, construct, and carry to anywhere in the world.

MOVING WATER, SWIMMING FISH: USING UNDERWATER VIDEOGRAPHY TO STUDY THE EFFECTS OF HYDRAULIC CONDITION ON ENERGY USE IN UP-RIVER MIGRATING SALMON

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EXTENDED ABSTRACT ONLY - DO NOT CITE

Anadromous salmon have limited somatic reserves with which they complete their upstream migration, gamete maturation and spawning behaviours. The amount of energy used by salmon during the up-river portion of their migration may determine their spawning success. To better understand energy use in up-river salmon migration we studied the natural river swimming behaviours of Seton River sockeye salmon (*Oncorhynchus nerka*). We used underwater stereo videography to determine relationships among fish tailbeat frequency, locomotion, energy consumption and small-scale river hydraulics. Individual fish pathways and tailbeats were digitally superimposed onto measured three dimensional flow fields. Relationships between ground speed, water velocity and energy use (as determined by tailbeats and bioenergetics modeling) were compared assessing the relationship between fish activity and hydraulic

condition. It appears sockeye utilize very small scale (<0.25m2) flow fields to minimize energy use during up-river migration. Salmon are highly energetically efficient when migrating through low velocity currents (i.e. ground speeds equalled or exceeded swimming speeds). Conversely, fish tended to display faster, less energetically efficient ground speed to swimming speed ratios through sites with higher velocities. Fast swimming speeds in these areas could minimize travel time, despite high costs. Migrants may be balancing energetic costs of migration against the fitness costs of spawning delays. Within this paper we also assess the limitations of two data extraction techniques when using underwater stereo videography.

BIOENERGETIC EFFICIENCY, ADAPTIVE MORPHOLOGY, AND REPRODUCTIVE TRADE-OFFS IN UPRIVER MIGRATING, ADULT SOCKEYE SALMON: INTER-DECADAL VARIATION, AND THE INFLUENCE OF MIGRATORY DISTANCE AND ELEVATION

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EXTENDED ABSTRACT ONLY- DO NOT CITE

Adult sockeye salmon (*Oncorhynchus nerka*) depend on fixed somatic energy reserves developed during ocean residency to fuel their upriver migrations to spawning grounds and to complete sexual maturation. Depending on population, Fraser River sockeye travel distances of <100 to >1100 km, and ascend elevations ranging from near sea-level to 1200 m to reach their spawning grounds. In 1999, we collected sockeye from five major populations at various points along their migration routes up the Fraser River in British Columbia, Canada. We calculated energy content of somatic and reproductive tissues and made several morphometric measurements to examine how energetic condition and morphology of sockeye was influenced by migratory difficulty. Sockeye travelling to high and distant spawning grounds began their migration with higher levels of somatic energy and were smaller and more fusiform than those travelling to lower, less-distant grounds. The former were also less sexually developed at the start of

migration, presumably a means for conserving energy necessary for upriver migration. Migratory difficulty (a composite index of distance and elevation) was strongly associated with initial energetic state and was a stronger predictor of en-route energy-use than mean migratory degree-days, and migratory distance and elevation as individual variables. Collectively, results suggest that upriver populations of sockeye are under strong natural selection for bioenergetic efficiency. The importance of this efficiency diminishes as the difficulty of migration diminishes. Additionally, selection appears to favour an energetically efficient fusiform morphology in upriver populations, and ovarian investment is deferred for to maintain free energy stores needed for difficult upriver runs.

Principal components analysis of sockeye energetic data collected in the 1950's and 1999 show that over the past 50 years, length-corrected somatic energy reserves at the end of ocean residency (just prior to upriver migration) have declined, particularly in those populations making the most difficult upriver migrations (Chilko and Early Stuart). This reduction shows strong associations with increases in sea-surface temperature. Additionally, reproductive investment prior to upriver migration has also diminished, which may have serious consequences on reproductive fitness. Indeed, upriver energy partitioning analysis in female sockeye from the Chilko and Early Stuart populations shows that in 1956, Chilko used less energy migrating upstream than in 1999, but invested more into ovarian development, presumably because they began migration with less developed ovaries relative to 1956. The Early Stuart females did not differ significantly between 1956 and 1999. This disparity may be related to differences in river discharge rates in the tributary systems through which each population migrates.

TROUT, *SALMO TRUTTA*, MOVEMENTS IN RIVER ESTORÃOS (LIMA BASIN, NORTH PORTUGAL)

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Different patterns of fish movements have been described. Some authors consider that fish populations are relatively discrete units exhibiting restricted movement (Gerking 1959), but others consider that populations are composed by mobile and sedentary fractions (Baglinière et al., 1989; Ovidio, 1999), and that frequently switch behaviour (Ovidio, 1999; Elliot, 1994). Several factors have been pointed to explain stream fish movements and amongst them we can refer spawning needs, responses to seasonally changes, either ecological or biological factors, and even genetic differences.

Radio-telemetry was used to monitored trout, *Salmo trutta*, movements in river Estorãos, a small tributary of river Lima (North Portugal) (Figure 1), in order to establish different patterns of life cycle.

River Estorãos is the most southern catchments of the Iberian Peninsula where trout anadromous form has been described (Valente, 1993). The last 6 Km of the river are accessible to all species. However 2.2 Km further are also available, but only during flood periods as a consequence of several small artificial barriers.

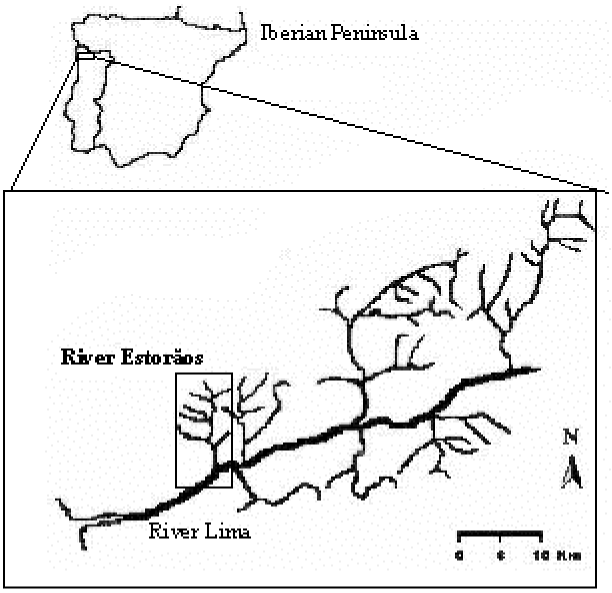

Figure 1 – Location of river Estorãos (Lima basin, North Portugal).

Fourteeen trout (fork length ranging from 24.6 to 46.6 cm; weight ranging from 161.8 to 967 g), were caught in two trap systems (placed 1.1 and 5.5 Km of the river confluence, respectively trap 2 and trap 1) or electrofishing.

An internal transmitter (Model 357 A.T.S. Inc., less than 2% of the body mass, 40 MHz) was surgically implanted in the abdominal cavity.

Trout were monitoried in two different periods, six from February to June 2000 and eight from November 2001 to April 2002. The location of each trout was registed at least once every day (February to April 2000 and November 2001 to April 2002) and three times a week during May to June 2000.

Water temperature, water velocity and flow were also registed, both periods.

Three different life cycle strategies seem to be adopted by trout population in river Estorãos (and in the Lima basin). A fraction of the population, apparently the bigger, seems to spent the hole life cycle in river Estorãos, exhibing only small movements with occasional longer displacements (Figure 2, trouts 3 and 4). Another fraction, much smaller, displays long distance movements between river Lima and river Estorãos, specially during spawning period (Figure 2, trout 5). Another small number of trout represents the third life cycle strategy, characterised by long distance migrations between river Estorãos and the Lima estuary and/or sea. This last strategy was evidencied by the capture, in trap systems, of both smolts and adult sea trout, and the capture of marked trout in the sea. Trouts 1 and 2 are example of strategies tipe II and III.

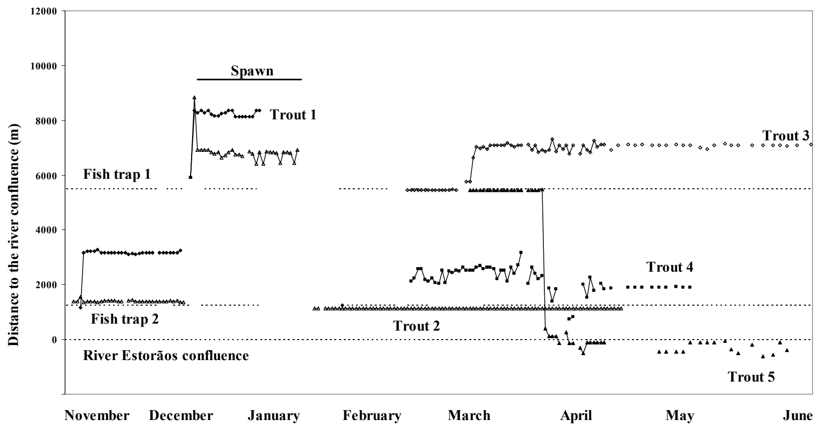

Figure 2 – Squematic movements exhibited by some tagged trout, indicating distance travelled. Trout 1 and 2 were monitoried between November 2001 and April 2002. Trout 3, 4 and 5 monitoried between February and June 2000. Empty spaces in traps locations outpoint flood periods, without trap control.

Major movements detected appeared to be associeted with spawning and post-spawning behaviour. The larger upstream displacement detected was aproximatlly of 7200 m (in 3 days) (Figure 2, trout 1). This site was reached by three monitoried individuals, and further upstream movements were limited by an untransposable dam. Most of this movements occured during night, and were associeted with rain periods followed the increase of the flow. Downstream displacements were monitoried up to the confluence with river Lima. We were unable of controling further displacements in river Lima.

From 04/01/02 to 03/02/02 we observed trout spawning, however, and dispite monitoried trout stayed in the proximity of the reads locations, we did not observed any tagged individual in spawning activity.

A preliminary statistical analysis indicates a probable relationship between movements detected and the environmental variables studied. Most of the movements (80 %) occured at temperatures between 9 and 15 ºC. At temperatures lower than 9 ºC movements of more than 500 m were not observed. For river flow values higger than 2 $m^3.s^{-1}$ the number of movements longer than 500 m duplicates.

Our results confirm the presence of three life cycle strategies as referred by other authors (Baglinière et al., Elliot, 1994; 1989; Ovidio, 1999). However the migratory fraction seems to be reduced.

Our results stress the need for the knowledge of fish life cycle variability to the development of management and conservation of fish populations, and to the need of acessible river corridors for migratory species.

Acknowledgements

We would like to thank specially to Susana, Filipe, Hugo and Jorge for all their collaboration.

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RIVER FRAGMENTATION AND CONNECTIVITY PROBLEMS

IN SWISS RIVERS:

THE EFFECT ON THE FISH COMMUNITIES

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EXTENDED ABSTRACT ONLY- DO NOT CITE

The species composition of a local community is determined by the addition of species (colonization and establishment of breeding populations), and by the loss of species through local extinction. To colonize and respond to specific habitat requirements, a healthy population depends on an intact downstream-upstream linkage (longitudinal dimension, including tributaries). Longitudinal migrations play a major role in the ecology of riverine fish and involve movements to spawning, feeding. The impeding of the longitudinal connectivity and fragmentation (Hanski 1999) have to be considered as special habitat destructions and pose a distinct threat to the long-term survival of all fish species in streams.

The migration problem for diadromous fish is well documented and many publications exist on the swimming capability of salmonids and on fish passage facilities. For small-sized fish species and most cyprinid species no description of swimming capabilities or passage facilities exists. Despite the occurrence of extremely resident fish populations in most streams in Switzerland, brown trout *(Salmo trutta fario)* can not be regarded as independent of longitudinal connectivity.

Longitudinal connectivity implies downstream and upstream biological connectivity, that is, the active and passive displacement of organisms along longitudinal gradients of rivers. When considering the longitudinal connectivity in Swiss rivers, the influence of human interference has to be considered as the main ecological impact. For fish, several human activities and structures act as barriers and prevent most species from reaching their original spawning grounds. Any of the following objects may be a potential barrier: falls (natural or artificial), dams, weirs, culverts, river sections with monotonous transect profile, and dry sections (natural dry sections or flow diverted to another drainage).

In Switzerland, the habitat fragmentation by artificial barriers has to be considered as very high. In the Toess River, a total of 568 artificial barriers may be counted along its total length of 59.7 km, in comparison to only 35 natural barriers.

Effect on the fish communities

Fish species living in a number of Swiss rivers have been analyzed with respect of impassable barriers. Their effects on the fish fauna have been illustrated by using electrofishing above and below obstacles.

In the lower stream sections the presence of small-sized fish (e.g. *Cottus gobio*) and cyprinid fish species was extremely restricted to a few hundred metres from the confluence (up to the first barrier). The barriers strictly separate source and sink populations.

In order to show typical reactions of fishes, the fish species occurrence above and below the first barrier in two rivers, which are tributaries to Lake Constance is listed (table I). Goldach River is 17 km long and about 11 m wide at the mouth, and Steinach River 17 km long and 7.6 m wide (near the lake). In each river, two 200 m sections (one below and one above the first barrier) were sampled. In both rivers, small-sized fish species did not occur above the first barriers. The presence of lake resident brown trout in the upstream section of Goldach River indicates that the fall is passable for migrating salmonid fish.
Like showed for the Goldach and Steinach Rivers, similar patterns of fish presence/absence were found in 10 additional rivers. In general, the first impassible obstacle in a system eliminates two third of the occurring fish species.

Recognizing and mapping the existence of man-made barriers and documenting how they correlate with the occurrence of fish species should be a helpful tool in future evaluation of river corridors. Common and endangered fish species are able to disperse and find optimal habitat conditions only along open (longitudinally intact) corridors. For the next years, it will be a challenge to hasten the restoration of former longitudinal connectivity and regional biodiversity with river restoration programs.

The lack of tributary connectivity

The tributaries of whole river systems have been analyzed. Many tributaries flow abruptly over a bed drop down into the main river: longitudinal connectivity is lacking. There are no opportunities for the immigration of small-sized fish species. In addition tributaries serve as nursery habitat and are streams of high ecological value. In all cases where typical assemblages of fish above barriers are no longer possible (accidents, disturbance events), the original ecological function of the tributary is lost .

The connectivity analyses for tributaries showed that most tributaries are already impassable by small-sized fish species where tributaries flow into the main river, few tributaries are passable only along the first 100-200 m.

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Table I. Occurrence and abundance of fish species in Goldach and Steinach River below and above barriers (barrier height 60-80cm)

Fish species	Goldach River below barrier	Goldach River above barrier	Steinach River below barrier	Steinach River above barrier
Brown trout *Salmo trutta fario*	+	++	+	+
Rainbow trout *Oncorhynchus mykiss*	-	+	-	-
Grayling *Thymallus thymallus*	+	-	-	-
Eel *Anguilla anguilla*	-	-	+	-
Stone loach *Barbatula barbatula**	+	-	-	-
Burbot *Lota lota*	+	-	-	-
Gudgeon *Gobio gobio**	+	-	+	-
Chub *Leuciscus cephalus*	+	-	+	+
Dace *Leuciscus leuciscus*	+	-	++	+
Minnow *Phoxinus phoxinus**	+	-	+	-
Roach *Rutilus rutilus*	+	-	-	-
Bleak *Alburnus alburnus**	+	-	-	-
Spirlin *Alburnoides bipunctatus**.	-	-	++	-
Bream *Abramis brama*	+	-	-	-
Total species number	**11**	**2**	**7**	**3**

++ medium abundance, + low abundance, - absent, *small-sized fish species (< 150mm)

CHARACTERIZING THE MIGRATIONAL DELAY OF ADULT SALMON AT DAMS USING TIME-TO-EVENT ANALYSES

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EXTENDED ABSTRACT ONLY - DO NOT CITE

Introduction

In the Columbia River Basin in the northwestern United States, adult salmonids must pass up to 9 hydroelectric dams during their return migration. Although fish ladders are provided for upstream passage, fish are delayed at dams because the attractive flows of the ladders are interspersed among several other sources of flow. Here, I present preliminary results from some new analyses to understand the delay of adult salmon at dams. I applied "time-to-event" analyses (which are analogous to survival analyses in epidemiological studies, Hosmer and Lemeshow 1999) to data derived from radio telemetry. The main focus of the research is to relate dam delay to factors such as flow and spill level, temperature, time of day, and fish length.

Methods

In 1998, spring/summer chinook were tagged at Bonneville Dam and released several km downstream. The tagging methods are the same as those presented by Burke et al. in these proceedings. The fish were detected at fixed receivers at Bonneville, The Dalles, John Day, and McNary Dams. Dam delay was defined as time elapsed between the first time a fish was detected in front of the dam to the last time the fish was detected at the entry to a fish ladder before successfully passing up the ladder (Figure 1).

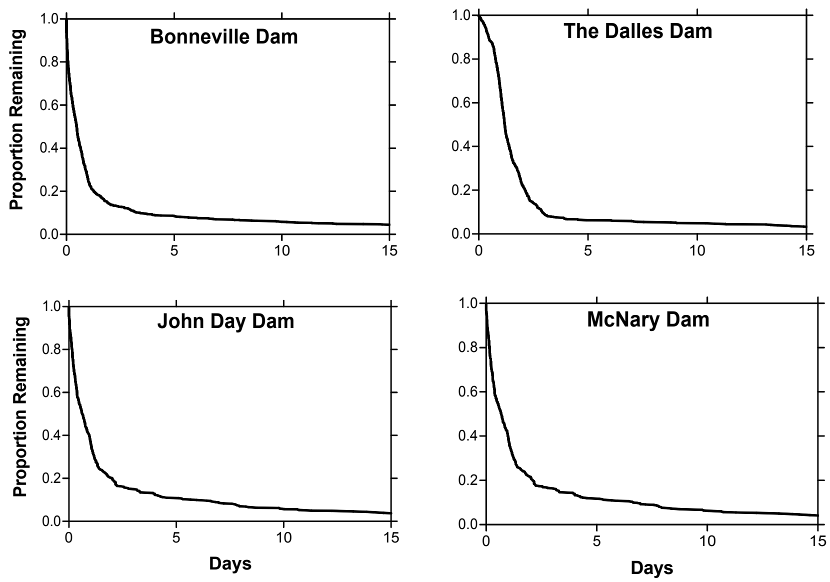

Figure 1. Proportion of adult chinook remaining versus delay time for spring (top plot) and summer (bottom plot) migrants.

Delay was modeled as a hazard function, with hazard rate, $\lambda(t)$, defined as the instantaneous rate of passage (Ross 1993). If $\lambda(t)$ is constant with respect to time, then the probability of remaining in front of a dam as a function of time is a simple exponential function:

$$\Pr(\textit{delaying t or greater days}) = \exp(-\alpha \cdot t) \qquad (1)$$

where α is the passage rate parameter. With this formulation, the mean delay time is $1/\alpha$.

The hazard rate can be elaborated as a time-varying function. In this case, the delay equation is slightly more complicated:

$$\Pr(delaying\ t\ or\ greater\ days) = \exp(\int_0^t \lambda(\tau)d\tau \qquad (2)$$

Usually the term inside the integral is a simple function and easily integrable. As an example, I developed a diel model, where passage rate varied according to the time of day:

$$\lambda(t) = \begin{cases} \alpha_N \ \ during\ nighttime\ hours \\ \alpha_D\ during\ daytime\ hours \end{cases} \qquad (3)$$

I expanded this model to relate passage rate to predictor variables. Since the majority of passage occurred during the day, the daytime passage rate in equation (3) was modified as

(4)

where X_t is a predictor variable (which may be time-varying) and α_X is a fitted coefficient. Here I present results for the factors fish length and river temperature (measured hourly). We are currently working on applying equations (3) and (4) to spill and flow measured hourly.

Model parameters were estimated by maximizing the likelihood function. The more complex models were compared to the simple model (equation (1)) using Akaike's Information Criterion (AIC). For each model, an AIC value was calculated, and the model with the highest value was selected as the "best."

Results and Discussion

The passage rate coefficient from the simple model was similar at all four dams, with mean delay ($1/\alpha$) ranging from 2.24 to 2.93 days. For all four dams, the diel model conferred a considerable improvement over the simple model. This is consistent with observations that most fish pass during the day. Temperature was always more important than fish length in predicting delay. For two dams

(The Dalles and McNary), the effect of fish length was negligible based on comparing AIC values between the length and diel models.

Little is known about the cumulative effects of upstream passage delay at dams (NRC 1996), but the duration of delay is substantial (Figure 1). The methods presented here offer a valuable approach to understanding the factors contributing to delay, and potentially this information can be used to reduce delay.

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Table 1. Results from the application of the models (equations 1 through 4) to the delay data. Parameters are maximum likelihood estimates. N is the number of fish.

	Model	α or α_N	α_0 or α_D	α_X	AIC
Bonneville Dam	Simple	0.436			
	Diel	0.085	1.506		660.16
N = 860	Fish Length	0.083	4.164	-0.035	717.99
	Temperature	0.083	0.220	0.089	723.87
The Dalles Dam	Simple	0.400			
	Diel	0.108	0.678		373.50
N = 681	Fish Length	0.108	0.164	0.007	376.33
	Temperature	0.108	0.046	0.048	423.07
John Day Dam	Simple	0.341			
	Diel	0.029	0.607		421.62
N = 547	Fish Length	0.029	1.578	-0.012	446.63
	Temperature	0.029	0.94	0.036	451.65
McNary Dam	Simple	0.447			
	Diel	0.171	0.673		182.57
N = 453	Fish Length	0.172	1.446	-0.009	189.79
	Temperature	0.172	0.022	0.048	257.56

EFFECTS OF LOW-HEAD BARRIERS
ON FISH SPECIES RICHNESS IN STREAMS
WITHIN THE LAURENTIAN GREAT LAKES BASIN

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EXTENDED ABSTRACT ONLY- DO NOT CITE

The parasitic sea lamprey, *Petromyzon, marinus*, is an exotic invader and a serious economic concern in the Laurentian Great Lakes. It causes significant economic losses by attacks on a variety of fishes, including those of commercial and recreational value. A variety of potential control procedures have been suggested or attempted to deal with this species in the Great Lakes.

Low-head barriers are being installed as an alternative to chemical control of sea lamprey in tributary streams around the lakes (Great Lakes Fishery Commission 1992). We assessed historical data from federal, provincial and state agencies to investigate whether the placement of low-head sea lamprey barriers has had an effect on stream fish communities within the Laurentian Great Lakes basin (McLaughlin et al. 2001). Previous field surveys and experimental studies on selected Great Lakes streams had suggested that sea lamprey barriers could impede instream movements of non-target fishes (Porto et al. 1999). This lead us to predict that the construction of low - head barriers would block upstream movement of nontarget fishes, and hence cause a reduction in species diversity upstream of barriers. The results of Pringle (1997) further supported our prediction of a decline in fish species diversity following the installation of low - head barriers.

Lester et al. (1996) have assessed the protocols necessary for detecting changes in nearshore fish communities, but those methods cannot be directly transferred to historical data on stream fish communities. We collated and compared historical data from a variety of sources on collections of fishes from Great Lakes tributary streams. We had data from stream before and after construction of low - head barriers ("barrier streams"), as well as from streams where no low - head barriers had been constructed ("reference streams"). We compared fish species diversity in collections before and after the placement of barriers. We also compared fish species diversity in comparable barrier and reference stream pairs to control for baseline (secular) changes in fish species diversity over time.

The lack of adequate geo-referencing of most sample locations, and inconsistencies in fish identification and collecting techniques limited our analyses of these historical data. We found no statistical differences in fish species diversity between streams with and without barriers. However, our analysis is complicated by inherent inconsistencies in the database. The major limitation is that wee had to restrict our analyses to the level of overall fish species diversity within given streams (barrier versus reference).

The value of using historical databases is limited, given the inconsistent nature of data collection over the past 100 years of sampling. The pitfalls of using historical data include variability of collection methodologies, gaps in the data time series, difficulties in pairing streams, and lack of vital georeferencing data (Underwood 1996). Given the limitations with existing data, we recommend a standardized data collection methodology in conjunction with sampling before and after construction of future barriers to assess impacts of sea lamprey barriers on fish communities. Furthermore, it is essential that identification of all species be verified by the use of voucher specimens deposited in reference collections.

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CAN FISH MORPHOLOGY PREDICT MOVEMENT OVER LOW-HEAD BARRIERS?

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EXTENDED ABSTRACT ONLY- DO NOT CITE

The parasitic sea lamprey, *Petromyzon, marinus*, is an exotic invader in the Laurentian Great Lakes. It has been a serious economic concern for the past 50 years. This situation has the status of a textbook example in many areas of ecology and management. The parasitic sea lamprey causes significant economic losses in the Laurentian Great Lakes by attacks on a variety of fishes, including those of commercial and recreational value.

A variety of potential control procedures have been suggested or attempted to deal with this species in the Great Lakes. Low-head barriers are currently being installed and assessed as an alternative to existing chemical control of sea lamprey in tributary streams around the lakes (Great Lakes Fishery Commission 1992). Low-head barriers are installed to block the seasonal spawning migration of parasitic sea lamprey, *Petromyzon, marinus*, in tributary streams around the Laurentian Great Lakes (Hunn & Youngs 1980). With increasingly numbers of these barriers being installed, there is concern as to the potential impact on nontarget fish species (e.g., Fausch & Young 1995).

We carried out a combined extensive survey and intensive experimental study of streams with and without barriers to address this concern. We followed this with an analysis of morphological characters of selected fish species to test for any predictive relationship with negative or positive impacts of barriers on fish movements. It would be a major advantage to develop a predictive relationship between morphology and impact of low - head barriers. Although this would be an indirect method, it could lead to considerable savings in time, effort and resources required for direct field studies of the responses of fishes to barriers.

We chose a number of representative streams with barriers for our studies. For each barrier stream we selected an adjacent stream without a barrier as a paired control. Our extensive surveys of barrier streams and comparable reference streams (with no barriers) show that on average there is a reduction in the number of fish species found in barrier streams. Intensive studies of selected barrier and reference streams show that upstream movement of some species is reduced by the presence of the barriers (Porto et al. 1999).

We analyzed external morphological characters ("size and shape") of the fish species affected by barriers to determine if there is a suite of characters that can predict whether a particular species will be able to pass over these barriers. We digitized lateral images of individual fishes, with a number of landmarks of features generally thought to be significant for swimming and jumping (e.g., body length, body depth, size and placement of caudal fin) (Motta et al. 1995). We applied Principal Component Analysis to these data. We categorized fish presence or absence above and below barriers, and also calculated odds ratios for each species to estimate the impact of low - head barriers on their occurrence upstream and downstream of barriers.

We could not find any evidence of a simple, predictive relationship between external morphology and whether that species could successfully move over low-head barriers. Thus we reluctantly conclude that it may not be possible to develop such an indirect method for assessing the impact of low - head barriers on non-target fishes. It appears that we will need direct observations of behavioral responses of fish to various configurations of barriers to develop a predictive relationship for fish passage.

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ABILITY OF RIO GRANDE CUTTHROAT TROUT TO ASCEND VERTICAL BARRIERS

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

We evaluated the ability of Rio Grande cutthroat trout (*Oncorhynchus clarki virginalis*) to negotiate waterfall-type barriers as part of a larger study on barriers to salmonid upstream migration. Upstream movements of fishes are an important source of population re-colonization and recruitment (Horan et al., 2000). A valid criterion for identifying potential barriers to upstream migration is needed in order to assess the suitability of candidate watersheds. We intend to develop empirical models of cutthroat trout jumping ability as a function of size (total length, TL) and waterfall dimensions, barrier height (h_1) and plunge pool depth (h_2).

Materials and Methods

All experiments were conducted within a covered raceway at the Colorado Division of Wildlife Research Hatchery, Bellvue, CO. Our artificial waterfall is a flashboard design that used a series of tongue-and-groove stacked boards to create the vertical drop structure (Figure 1). We regulated waterfall height (h_1, 10 to 50 cm, in 10 cm increments)) by installing the appropriate number of 10 cm high flashboards. The lower end of the raceway served as the plunge pool. Plunge pool depth (h_2, 10 to 50 cm in 10 cm increments) was regulated by adding the appropriate number of 10 cm high flashboards at the downstream end of the raceway. Flows were set to 570 L/min; water temperatures at the hatchery are a constant 11± 1°C.

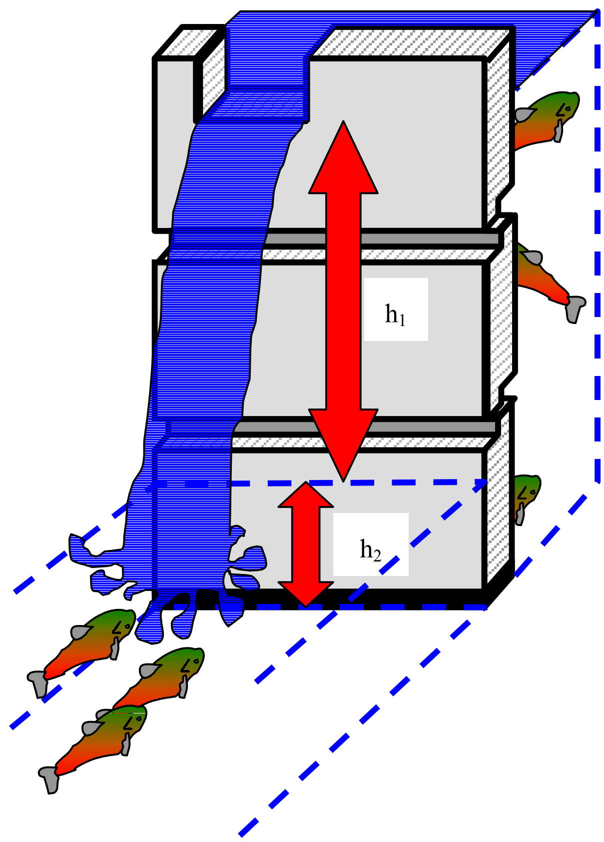

Figure 1. Schematic diagram showing flashboard-type artificial waterfall. Shown in red are h_1, barrier height and h_2, pool depth. Pool depth is manipulated by removing or adding tongue-and-groove boards to the spill at the end of the raceway.

Jumping experiments

The artificial waterfall was set to one of 25 possible combinations of waterfall height and plunge pool depth and flow started. A random sample of 15 cutthroat trout was netted from an adjacent raceway containing 1000 individuals. Fish were placed in the plunge pool. Once fish were added, the raceway was left undisturbed for 24 hours. At the end of the experiment, we recorded the following information: fish location (upstream or downstream), length (SL, FL, TL in mm), wet weight (g), body condition, and sex (when apparent).

Model Development

Pilot study data suggested the probability of a fish successfully negotiating a barrier largely depending upon the barrier height and plunge pool depth. We chose to use logistic regression framework to model "p", the probability that a fish could jump over a barrier, based on the fish's size, the barrier height, plunge pool depth, and interactions between the three factors. We used AIC_c model selection criteria to identify the terms that would best explain the observed variation in "p" (Anderson et al., 2001).

Results and Discussion

Cutthroat trout were able to jump over barriers up to 50 cm high as long as the plunge pool was at least 20 cm deep (Table 1). Our data showed that plunge pool depths of 10 cm or less effectively prevent cutthroat trout from jumping over barriers that were 30 cm or higher. We also noted a size effect, wherein smaller fish (ca. 22 cm TL) were better able to jump over barriers when faced with a shallow plunge pool than larger fish (ca. 27.6 cm TL).

The probability of a cutthroat trout jumping the barrier was best predicted by the logistic regression model (shown below) that included h_1 and the $h_1 \times h_2$ interaction (AIC_c value: 878.08 ; AIC_c weight: 0.276; ΔAIC_c: 0.00).

$$\text{logit}(P) = -0.16 - 1.53 (h_1) + 0.91 (h_1 * h_2)$$

Table 1. Effects of waterfall height and plunge pool depth on the proportion of Rio Grande cutthroat trout that jumped the barrier.

Depth (cm)	Height (cm)	Proportion successful (95% C.I.)	N
10	10	0.47 (0.32 – 0.61)	45
	20	0.14 (0.01 – 0.27)	29
	30	0.07 (-0.02 – 0.16)	30
	40	0.00 (0.00 – 0.00)	44
	50	0.00 (0.00 – 0.00)	63
20	10	0.80 (0.60 – 0.94)	29
	20	0.70 (0.54 – 0.86)	29
	30	0.60 (0.42 – 0.78)	30
	40	0.53 (0.44 – 0.62)	117
	50	0.03 (0.03 – 0.10)	30
30	10	0.79 (0.61 – 0.97)	29
	20	0.76 (0.61 – 0.91)	30
	30	0.68 (0.56 – 0.80)	73
	40	0.17 (0.03 – 0.30)	30
	50	0.17 (0.03 – 0.30)	30
40	10	0.77 (0.62 – 0.92)	30
	20	0.82 (0.71 – 0.93)	45
50	10	0.71 (0.58 – 0.84)	59

The two other competing models (i.e., within 3 ΔAIC_c of the best model) included h_1, the $h_1 \times h_2$ interaction and either the $h_1 \times h_2 \times$ fish size or $h_1 \times$ fish size interactions. We hope to refine our model after further cutthroat trout jumping data are collected, especially at higher waterfall heights and greater plunge pool depths.

Though preliminary in nature, our results may prove useful in identifying potential barriers to migration in streams that are being considered for cutthroat trout re-introductions. This would allow managers to assess the amount of habitat available to the fish as well as determine whether any existing barriers need modification or removal. Additionally, our data could be used to design culverts and flood control structures that are negotiable by Rio Grande cutthroat trout.

Cutthroat trout restoration attempts are often thwarted by the re-invasion of upstream areas by non-native brook trout—this re-invasion can only be prevented through the use of adequate barriers to migration (Thompson and Rahel, 1998). Development of models for harmful competitors to cutthroat trout, such as brook trout (Harig and Fausch, 2000), can be used as criteria for engineering more effective in stream barriers. We are currently using the techniques developed in this pilot study to collect data on brook trout (*Salvelinus fontinalis*) jumping performance.

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Watry, N.P.S.; Robert Keith of the W.D.G.F.; and J. Preston Holloway, C.S.U.
All research was conducted in accordance with ACUC protocol #01-111A-01.

MEASURING THE ABILITY OF FINGERLING BROOK CHARR TO LEAP OVER WATERFALL BARRIERS

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

Declines and extinctions of native populations of greenback cutthroat trout (*Oncorhynchus mykiss stomias*) are partly a result of the introduction of non-native brook charr (*Salvelinus fontinalis*) (Behnke, 1992; Griffith, 1998). This is due to brook charr out-competing cutthroat trout for food and habitat in areas where both species occur (Behnke, 1992; Griffith, 1998). Management techniques that eliminate brook charr and protect cutthroat trout populations from interspecific competition have been proposed and tested. One strategy involves removing brook charr from an area and placing them downstream. However, brook charr tend to migrate upstream because of instinctive homing behavior (Belanger and Rodriguez, 2001). Another strategy is to poison sections of streams above barriers to eliminate all fish species present, and then re-introduce cutthroat trout (Stuber et al., 1988). This strategy is only successful when a barrier is present that prevents brook charr from migrating upstream. In order to construct an effective barrier to migration, the leaping abilities of brook charr must be known. This study was designed to quantitatively measure the ability of fingerling brook charr to leap over waterfall barriers.

Methods and Procedures

Design of Experimental Tank and Waterfall Barrier System
The experimental tank consisted of a raceway (the downstream section) and a flume box (the upstream section). The flume box consisted of two chambers separated by a divider. Water was pumped into the rear chamber. Water turbulence in the front chamber was reduced by the divider separating the two chambers, and by a partial divider in the front chamber. It was necessary to reduce the turbulence so that brook charr that successfully leapt over the barrier and into the front chamber had a place for refuge (Kondratieff, 2002).

The waterfall barrier system had a variable waterfall height (h_1) and plunge-pool depth (h_2) (Figure 1). Waterfall height (h_1) was changed by raising or lowering

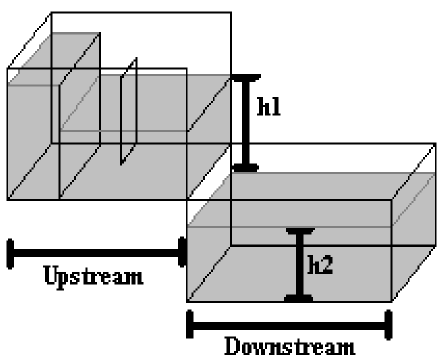

Figure 1. A waterfall barrier system. The grey color represents water. The waterfall height (h_1) is the vertical drop from the lip of the waterfall to the water surface in the plunge-pool. The plunge-pool depth (h_2) is the depth of water in the downstream section of the waterfall barrier system. The upstream section is composed of a flume box.

the flume box. Plunge-pool depth (h_2) was regulated with different sized standpipes. Flow rates were held constant at 0.47 L/min to produce a 2 cm water depth at the lip of the 10 cm wide waterfall opening. Temperature was held at 10-12°C.

Experimental Design and Procedures
All experiments were conducted indoors under a natural photoperiod. The leaping abilities of brook charr were measured following a process outlined by Kondratieff (2002) which analyzes the interactions among different waterfall heights and plunge-pool depths. Twelve waterfall heights (2 to 24 cm, in 2 cm increments) and seven plunge-pool depths (6 to 18 cm, in 2 cm increments) were

used to test the leaping abilities of fingerling (30 mm to 100 mm total length) brook charr. All possible combinations of these waterfall heights and plunge-pool depths were tested.

At the beginning of each trial, plunge-pool depth and waterfall height were adjusted. Pumps were then started and water was given the chance to level out. Once the experimental tank was ready, ten fingerlings were randomly selected from holding tanks and placed into the downstream section of the waterfall barrier system. Brook charr were given 24 hours to attempt to leap over the waterfall barrier. At the end of each 24-hour trial, each fish's position within the barrier system (upstream or downstream), weight, and length (standard length, fork length, and total length in mm) were recorded. Waterfall height and plunge-pool depth were also recorded. Data were analyzed at the end of the study using Microsoft Excel.

Results

More brook charr were able to leap over waterfall barriers that had low waterfall heights (Figure 2). No brook charr were able to leap waterfall barriers that had

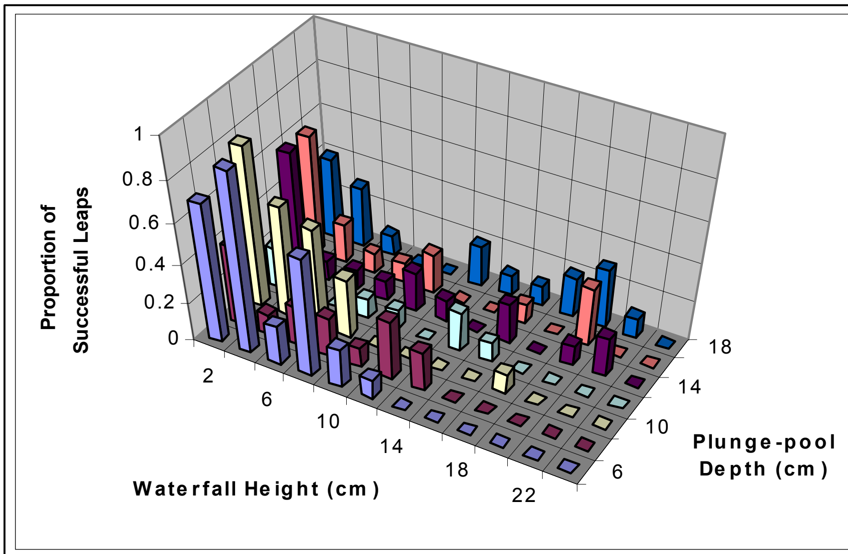

Figure 2. Proportion of successful leaps over a waterfall barrier by fingerling brook charr as a function of waterfall height (x-axis) and plunge-pool depth (z-

axis). Both waterfall height and plunge-pool depth were measured in centimeters. Proportions reflect the number of successful leaps out of 10 fish.

waterfall heights of 24 cm (Figure 2). Plunge-pool depth had no conclusive effect on leaping abilities, as fish leapt over waterfall barriers that had both shallow and deep plunge-pool depths (Figure 2).

Discussion

As expected, more brook charr were able to leap over waterfall barriers that had lower waterfall heights. It was also expected that brook charr would be less likely to leap over waterfall barriers that had shallow plunge-pool depths. However, the results on the effect of plunge-pool depth on leaping ability were inconclusive. Brook charr leapt over waterfall barriers at both shallow and deep plunge-pool depths. It is thought that these inconclusive results are a factor of small sample size.

Although some results are inconclusive, this is an ongoing preliminary study. Modifications to the waterfall barrier system and experimental procedures, for a future study on the effects of light intensity or temperature on leaping ability, will be made based on this research.

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I appreciate the help that Matt Kondratieff gave me with experimental design. I would like to give special thanks to the staff at the Colorado Division of Wildlife Research Hatchery for letting me use space at the Bellvue Research Hatchery. Funding for this project was provided by the USDA Forest Service Medicine Bow-Routt National Forest and by the Department of Fishery and Wildlife Biology at Colorado State University. All research described in this report followed guidelines set by Colorado State University's Animal Care and Use Committee protocol #01-111A-01.

OPTIMIZING CONDITIONS TO STIMULATE MIGRATORY SALMON TO JUMP UP FISHLADDERS

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

The damming of streams has been a major contributor to the decline of anadromous fish populations around the world. Fishladders have been built to help fishes overcome these obstacles, but many fishladders are inadequate in efficiently passing migrating fishes. Fishladder designs have primarily been based on engineering perspectives due to the lack of available studies on behavior and preferences of the fishes intended to use the fishladders (Clay, 1995). The few studies that have explored fish behavior in fishladders are fragmented and incomplete (McLeod and Nemenyi, 1941; Collins and Elling, 1960; Stuart, 1962; Thompson, 1970). To develop effective fishladders, one must understand the jumping preferences and abilities of the migrating fishes intended to use the fishladders. We studied a population of kokanee salmon, *Oncorhynchus nerka*, in a pool and weir fishladder simulator to experimentally determine the preferences, behaviors and biomechanics of these fish in a fishladder. The methods used in this study and the results obtained from it can serve as guides in protecting threatened and endangered migratory stream fishes hindered by stream obstacles.

Methods

Adult migrating kokanee salmon from the Tahoe Basin were used exclusively in this study. We designed and built an adjustable fishladder simulator that allowed us to expose salmon to a range of fishladder conditions by varying the water flow, weir height, weir gradient and depth of the pool below the weir. Jumping preferences were determined by counting the number of observed jumps per experimental trial for each set of conditions. Biomechanical data were obtained by analyzing video recordings of fish jumping up the weir.

Results

The fish attempted to swim up stream in nearly all spillway conditions tested but jumping was only attempted over a narrow range of conditions. Minimum water flows and steep weir gradients (>40° for more than 50% of attempts to be jumps) induced the greatest number of jumps. Pool depths and weir heights only showed an effect on the number of observed jumps when these two parameters are considered together.

Five distinct fish behaviors were observed in the pool of the fishladder simulator and were correlated with specific water flows. These behaviors involved avoiding the flow, a lack of response to the flow, station holding, swimming up the weir, and jumping up the weir. A number of kinematic parameters were calculated from the video analysis to numerically describe the jumping behavior. These parameters include takeoff velocities and angles from the surface of the water in addition to parameters describing underwater approaches to the surface of the water.

Conclusions

The salmon in this study exhibited five different behaviors in pool and weir flow conditions in a predictable manner. A narrow range of flow conditions is required to induce the salmon to advance up the weir by jumping. The kinematic data of this study suggest that salmon approach jumping in a different manner from what was previously thought. Instead of producing a rapid C-start acceleration from the surface of the water, fish use a rapid S-start from near the bottom of the pool beneath the eddy formed by water pouring over the weir. This study serves as a foundation for the improvement of fishladder designs by providing a basic understanding of the preferences, behaviors and biomechanics of salmonids jumping up weirs.

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IDENTIFYING FALL CHINOOK FISHWAY USE ON THE LOWER COLUMBIA RIVER

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EXTENDED ABSTRACT ONLY- DO NOT CITE

Fall chinook (*Oncorhynchus tshawytscha*) represent an important life history strategy in the lower Columbia River. The relatively late upstream migration of pre-spawning adults exposes them to high water temperatures concurrent with gonadal development. Therefore, the consequences of delay at dams may be more significant for these fish than for spring and summer chinook.

We used radiotelemetry to examine migration behavior and passage success of adult fall chinook at the four lower Columbia River dams: Bonneville (rkm 235.1), The Dalles (rkm 208.1), John Day (rkm 346.9), and McNary (rkm 469.8). In 1997, 1998 and 2000, fish (male and female) were captured at the adult trapping facility at Bonneville, outfitted with radio transmitters, and released 10 km downstream from the dam. We radio-tagged 51 fish in 1997, 1032 fish in 1998, and 745 fish in 2000.

Fish movement was monitored using fixed radio receivers at the dams and by tracking fish with mobile receivers. To pinpoint the areas of each dam that may be problematic for chinook, we divided the area in and around the dam into specific segments. We considered an 'Arrival' to be the time from the first detection of a fish approximately 2.8 km downstream from the dam to the first detection just outside of one of the entrances (as shown for Powerhouse 2 of Bonneville Dam in Figure 1). An 'Entrance' was from the first detection just outside of one of the entrances to detection inside the collection channel. Time spent in the 'Collection Channel' was calculated as the difference between the first record in the collection channel and the first record in the transition pools. Time spent in the 'Transition Pools' was calculated as the difference between the first record in the transition pools and the last record in the transition pools. And finally, duration in the 'Ladder and Exit' was calculated as the difference between the last record in the transition pool and the last record at the top of the ladder.

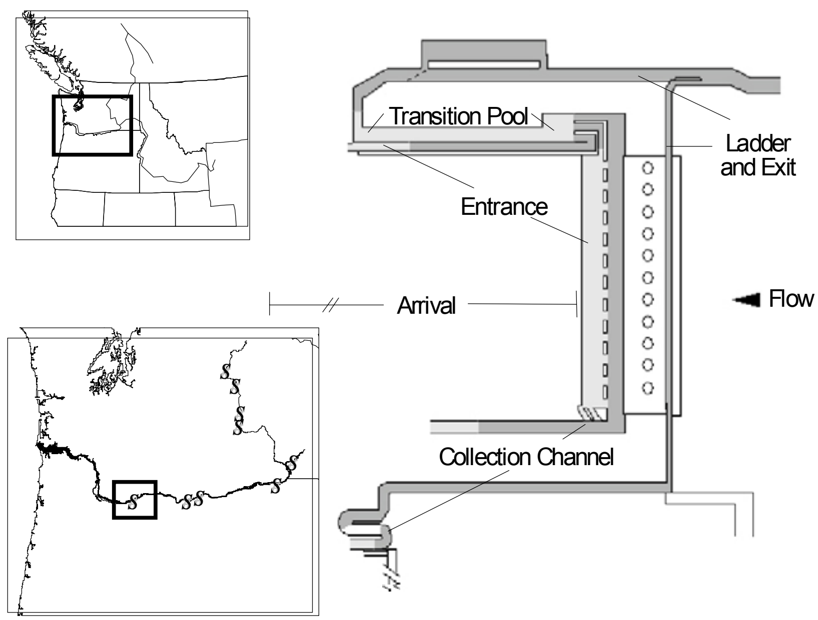

Figure 1. Powerhouse 2 at Bonneville Dam. All fishways were similarly divided.

Due to the non-normal distribution of travel durations through each of the segments, median durations are presented and non-parametric statistics were used for all comparisons. Median duration through each of the segments at all four dams was generally under 3 hours (Figure 2). However, the transition pool showed significantly higher passage times than did any other segment. This trend was consistent throughout the 3 years studied. Because of the higher passage times in the transition pool, we examined actual fish locations throughout this period to determine possible causes of delay.

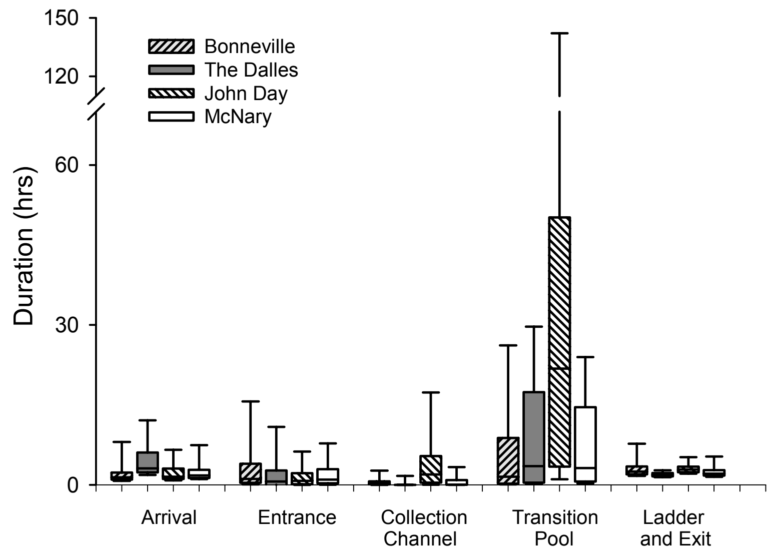

Figure 2. Passage duration through various fishway segments of the four lower Columbia River dams in 2000. Box plots show the median (bar), 25th and 75th quartile (box), and the 5th and 95th percentile (line).

We defined passage efficiency as the ratio of the number of fish that passed the top of a dam to the number of fish that approached that dam. Passage efficiencies differed among dams, but only at The Dalles in 1997 and at John Day in 1998 and 2000 were passage efficiencies below 90%. For fish that passed a dam, total duration of passage was calculated as the time from the first record outside a fishway entrance to the last record at the top of the ladder.

Although fish had the highest median passage time at John Day dam, total passage time was generally under 24 hours at all dams.

Migrating salmon have a choice of entering a fishway via one of the main entrances at the ends of powerhouses and spillways or using one of the many orifice entrances along the base of powerhouses. We tested whether fall chinook use various entrances preferentially so that recommendations can be made regarding the state (open versus closed) of the orifice gates (if orifice gates are not used, closing them would better direct fish through the collection channel and allow greater flows from the main entrances). There was a clear difference between entrance use; main entrances were used by fall chinook more often than orifice entrances.

In 2000, gender was determined for radio-tagged fish that returned to hatcheries (N = 63). Since fall chinook develop gonadal tissue as they migrate upstream, we tested whether gender affects passage efficiency and duration. Although there seemed to be a trend for faster female passage at the first two dams (Bonneville and The Dalles) and faster male passage at the third and fourth dams (John Day and McNary), we detected no significant gender-specific patterns in passage efficiency or duration.

Acknowledgments

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USING PHYSIOLOGICAL TELEMETRY TO EXAMINE ENERGY USE, BEHAVIOUR AND SURVIVAL OF UP-RIVER MIGRATING ADULT PACIFIC SALMON

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EXTENDED ABSTRACT ONLY - DO NOT CITE

Adult Pacific salmon (*Oncorhynchus* spp.) depend on energy reserves to complete their up-river spawning migrations. Little is known about how local habitat features such as flow patterns and bank characteristics affect behaviour and consequently energy use during migration. We used electromyogram (EMG) radio telemetry to describe activity levels and estimate energy use of adult pink (*O. gorbuscha*) and sockeye (*O. nerka*) salmon during their up-river migration in the Fraser River, BC. Individuals were tracked continuously through a 7 km section of river with reaches that varied considerably in flow velocity (surface flows 0.46 m/s to 2.08 m/s) and complexity. In all reaches, pink salmon tended to migrate in paths nearshore, rarely crossed the river and their swim speeds were relatively invariant, whereas sockeye migrated further offshore, crossed the river regularly and their swim speeds were highly variable. Both seemed to use eddies and hydraulic features associated with boulders and river contours to facilitate passage. Sex and river morphology affected energy use. Females tended to have higher activity levels than males and all fish increased their activity levels when river constrictions were

encountered. Sockeye and pink salmon had similar average energy use at sites with no constrictions but at constricted sites, sockeye were more hyperactive and used more energy than pink salmon. Sockeye's hyperactivity may facilitate its passage through extremely fast and turbulent water, areas that pink salmon cannot ascend. However, extreme hyperactivity by sockeye was associated with passage failure and enroute mortality at the Hell's Gate fishways.

EVALUATION OF ENERGY EXPENDITURE IN ADULT SALMON MIGRATING UPSTREAM IN THE COLUMBIA RIVER: UNDERSTANDING THE INFLUENCE OF DELAY, FALLBACK, AND DAM OPERATIONS ON FISH PERFORMANCE

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Although radio telemetry studies of anadromous salmonids have been conducted in the Columbia River Basin for decades, little is known about the energy use of adult salmon as they migrate upstream through the hydroelectric system. To determine the energetic costs of passing a Columbia River dam, 96 adult spring chinook salmon were implanted with electromyogram (EMG) transmitters, calibrated against swim speed, and released downstream of Bonneville Dam in 2001. Using a combination of fixed and mobile tracking, EMG signals were recorded from 87 fish as they passed through the dam tailrace, fishways, and forebay. Active, aerobic metabolism was estimated for each fish using EMG-swim speed calibration data collected just prior to release, and swimming respirometry studies conducted in 2000. Median aerobic energy use was highest while fish were in the tailrace of Bonneville Dam (ca. 116 kcal), intermediate in the fishways (ca. 33 kcal), and lowest in the forebay (ca. 4 kcal). Such energy use is probably conservative because many fish showed burst swimming activity in their EMG history, indicating some degree of anaerobiosis occurs during dam passage. Energy used by individual fish to pass the dam varied greatly due to different migration behavior, passage routes, and the time it takes to pass the

dam (which ranges from few hours to over a week). Our results will be used to identify areas of difficult passage that may be modified to help decrease energy use of upstream migrating fish. Ultimately, we hope to assess the potential for depletion of energy reserves and the consequences of excessive energy use on survival and reproductive performance of adult salmonids.

Acknowledgements

This study was funded by U. S. Army Corps of Engineers, Portland District. We thank personnel at the Columbia River Research Laboratory and the Pacific Northwest National Laboratory for their excellent help in the laboratory and field.

DIEL VARIATION IN SALMON SMOLT PASSAGE AT BONNEVILLE

DAM SPILLWAY IN TWO

YEARS WITH DIFFERENT SPILLWAY OPERATIONS

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Introduction

Spillway discharge is determined by factors including the need to spill for smolt passage without either raising total dissolved gas (TDG) to physiologically harmful levels or causing fallback of up migrating adult salmon (National Marine Fisheries Service 2000). Spill discharge is usually high at night, often up to the set TDG maximum "gas cap". Since adult salmon move mostly during daylight hours, spillway discharge is usually set lower then to reduce fallback. The effects on passage of diel differences in fish behavior and distribution are confounded with the effects of spillway operations, with higher spill discharge and passage at night and lower spill discharge and passage during the day.

At Bonneville Dam on the lower Columbia River we conducted full project hydroacoustic sampling in both 2000 (Ploskey et al. 2002) and 2001 (Ploskey et al. In preparation). The year 2000 was a fairly typical water year in the Pacific Northwest but in 2001 there was a combination of very low water and high energy demand. Relatively little water was allocated to spill and so spill discharge levels were lower and the spill season was shorter than usual. In 2000 there was more spill at night than during daytime, but in 2001 the rate of spill was almost constant day and night. This provided an opportunity to separate the effects of fish distribution and behavior from spillway operations and may provide insights for more strategic use of spill for passage in low water years.

Methods

In both passage years individual spill bays were sampled 24 hours/day by down-looking transducers mounted on the upstream faces of the spill bay gates. Of the 18 spill bays the two at the ends were opened only slightly to provide adult attraction flow and were not sampled. We sampled 11 of the remaining 16 spill bays in 2000. In 2001 only eight interior spill bays operated and we sampled six of those. Samples were processed by autotracking software and resulting counts were spatially and temporally expanded to provide fish passage estimates.

Results

In 2000, when the hourly proportion of spill discharge was higher at night than during daytime, the hourly proportion of estimated fish passage was also higher at night (Figure 1).

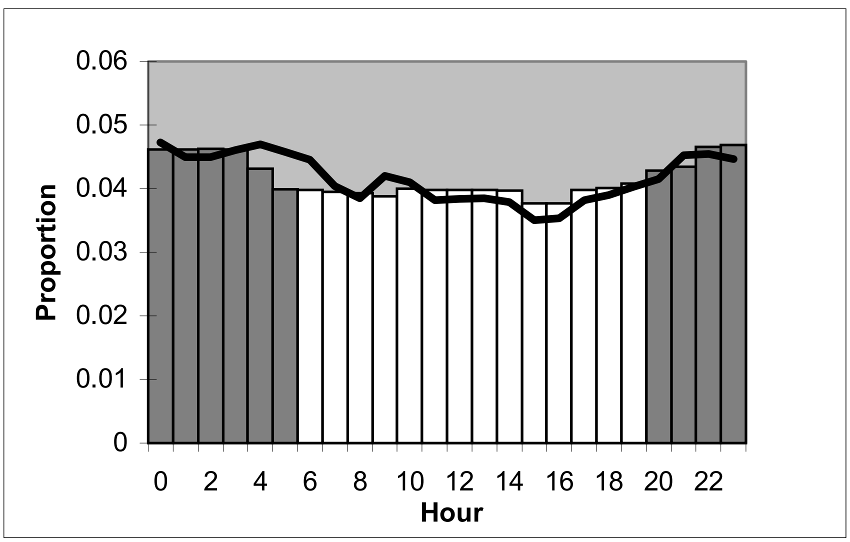

Figure 1. Hourly proportion of total spillway discharge and estimated fish passage at Bonneville Dam in 2000. Vertical bars indicate hourly proportion of total spillway discharge in 80 days of sampled spill during both spring and summer. Dark and light bars indicate approximate hours of darkness and light respectively. The black line indicates the hourly proportion of total estimated fish passage at the spillway.

In the drought year of 2001 there was an even greater diel change in hourly proportion of estimated fish passage although it was not associated with a change in hourly proportion of spillway discharge (Figure 2).

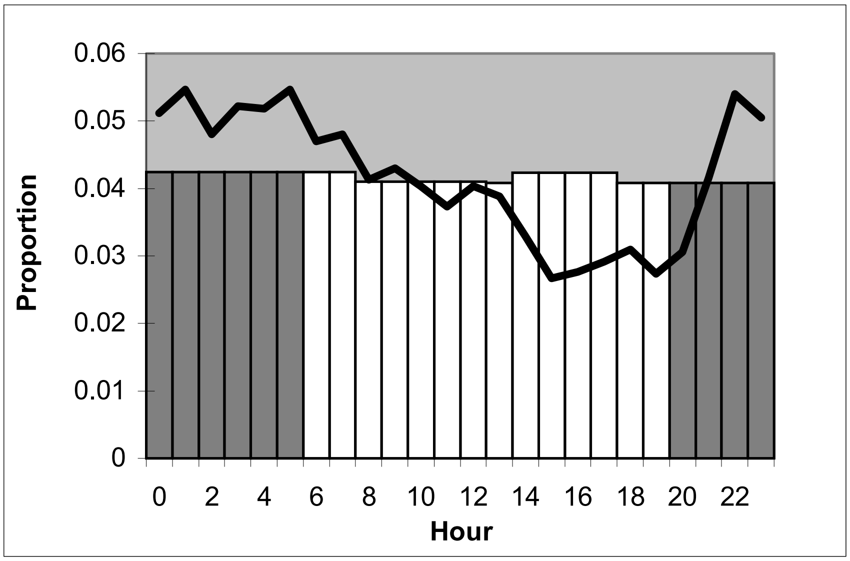

Figure 2. Hourly proportion of total spillway discharge and estimated fish passage at Bonneville Dam in 2001. Vertical bars indicate hourly proportion of total spillway discharge in 30 days of sampled spill during both spring and summer. Dark and light bars indicate approximate hours of darkness and light respectively. The black line indicates the hourly proportion of total estimated fish passage at the spillway.

The absolute values of both spillway discharge and estimated fish passage were much higher in 2000 than in 2001. In the sampling and spilling days represented here (83 days in 2000 compared to only 30 days in 2001) the Bonneville Dam spillway passed about 4.8 times more water and an estimated 17.6 times more fish in 2000 than in 2001. Normalized for number of days of sampled spill the Bonneville Dam spillway passed about 1.7 times more water and an estimated 6.4 times more fish per day in 2000 than in 2001.

Discussion

Spillway and turbine passage at Pacific Northwest dams are thought to be primarily nocturnal (Thorne and Johnson 1993) and spillway operations in normal water years usually reflect that assumption with higher spill at night. Often managers set nighttime spill to the "gas cap" for night and set lower spill levels for daytime to reduce the likelihood of adult salmon fallback. In the 2001 drought year, however, the spillway operations schedule at Bonneville Dam was very nearly constant throughout the diel cycle. In spite of that the diurnal variation in proportion of total estimated fish passage at the spillway was much greater than in a more typical spillway operations season (Compare Figures 1 and 2). This evident uncoupling of diel spillway operations and estimated fish passage suggests that, at least at low spill levels, there is a strong diel behavioral component to spillway passage, which is below the spill gates. Diel vertical migration is a common characteristic of many fishes (Helfman 1993) and of at least some juvenile salmonids (Levy 1990).

There may be fish-related reasons to spill water in a drought besides providing fish passage including the maintenance of water quality above or below the spillway, attraction of up migrating adults to fishways, maintenance of current for juvenile attraction to the spillway, and spillway tailrace egress. But if juvenile fish passage is the reason for spill in a low water year it might be well for project managers to conserve water during daytime for higher nighttime spillway discharge or to extend the spilling season.

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Acknowledgements

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MAXIMISING FISH PASSAGE THROUGH AN AUSTRALIAN FISHLOCK BY MANIPULATING VELOCITY AND EXIT PERIOD

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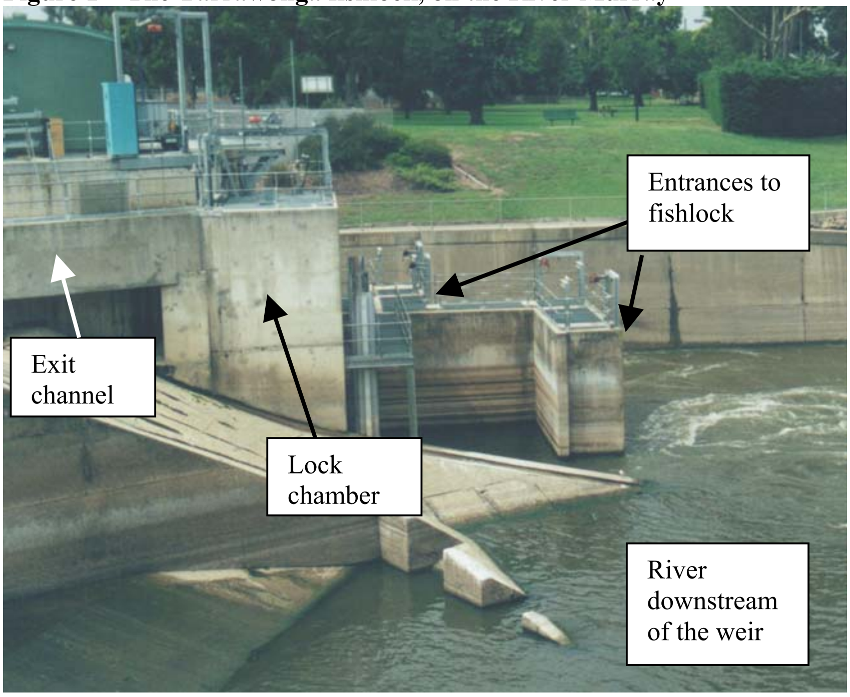
EXTENDED ABSTRACT ONLY - DO NOT CITE

Background

A fishlock is a type of fishway. Upstream migrating fish enter a lock chamber at the downstream river level. The lock chamber is then filled with water, and fish can exit (during an exit phase) from the lock chamber into the exit channel, and subsequently into the upstream storage. A photograph of a fishlock is presented in Figure 1.

Figure 1 – The Yarrawonga fishlock, on the River Murray



The efficiency of a fishlock is completely dependent on the behaviour of upstream migrating fish. The aspect of fish behaviour focussed upon in this paper is their propensity to pass from the lock chamber into the exit channel during the exit phase, for different combinations of exit period and velocity. Fish that remain in the lock chamber rather than passing into the exit channel can not successfully pass upstream of the barrier.

This paper presents selected results from a study in Yarrawonga fishlock, on the River Murray, in south eastern Australia. Following a preliminary assessment of this fishlock, Thorncraft and Harris (1997) recommended further work was required to determine the exit period so as to maximise fish passage. In that assessment, no studies were undertaken (or recommended) to relate fish exiting to the water velocity in the exit channel. It is however hypothesised that velocity in the exit channel also affects fish movement between the lock chamber and exit channel, as low velocities may be an inadequate stimuli for some fish to exit the lock chamber, and high velocities may exceed peak swimming ability.

The vast majority of the migrating fish using the fishlock were of the following potamodromous species: golden perch (*Macquaria ambigua*, [Percichthyidae]), silver perch (*Bidyanus bidyanus*, [Terapontidae]), Murray cod (*Maccullochella peeli* [Percichthyidae]), and the exotic common carp (*Cyprinus carpio* [Cyprinidae]). The length of fish trapped in the fishlock during the study ranged between 200 mm to 860 mm, with the median being 340 mm.

Method

During the exit phase, gates on the lock chamber were adjusted to create a velocity within the exit channel. Water velocity was measured using an Acoustic Doppler Velocitimeter.

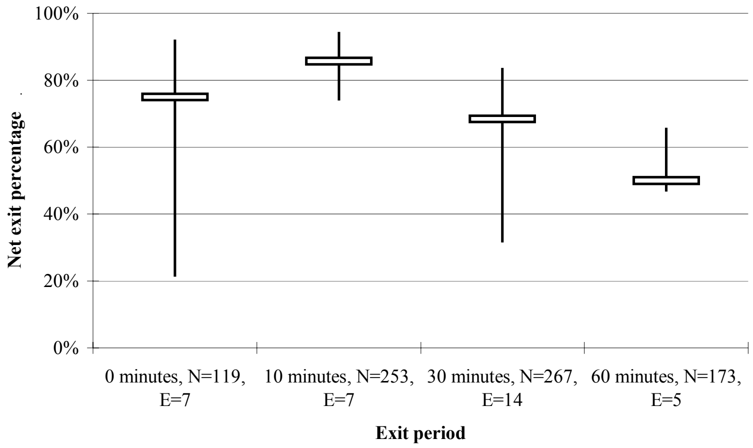
The fish were given the opportunity to exit the lock chamber and remain in the exit channel for the remainder of the exit period. At the end of the exit period, fish were trapped in the exit channel using a crowding and trapping arrangement.

The measure of success of any combination of velocity and exit period was the percentage of fish that were trapped in the exit channel divided by the total number of fish in the experiment, defined as the 'net exit percentage'. The count and species of fish in the lock chamber was determined at the end of an experiment by lowering the water level and observing the fish in shallow water above a mesh follower. The 'net' is recognition that fish had the opportunity to return from the exit channel into the lock chamber during the exit phase.

Results

For a velocity in the exit channel of 0.65 m/s, the relationship between exit period and net exit percentage is shown on Figure 2 (for all species combined).

Figure 2 – Relationship between exit period and net exit percentage. The horizontal bars represent the median, and the vertical bars represent the inter-decile range. The exit period of zero minutes corresponds to when a gate at the downstream end of the exit channel was just raised above the water surface. Any fish that exited must have swum underneath the rising gate. E is the number of experiments (there was a minimum sample size of five for inclusion) and N corresponds to the number of fish.



From Figure 2, the initial response by fish to exit the lock chamber was usually high, but can be variable, and the maximum net exit percentage (at this and other velocities) corresponded to an exit period of 10 minutes.

For exit periods of only a few minutes, some fish may have not had time to search adequately and be aware that they can swim into the exit channel. For exit periods significantly over ten minutes, the majority of fish may return to the lock chamber to hide or seek an alternative route out. It is speculated that the greater the exit period beyond 10 minutes, the more likely the fish will be evenly distributed in accordance with the water volumes in the exit channel and lock chamber.

For an exit period of 10 minutes, a similar shaped curve to that on Figure 2 was obtained for the relationship between exit velocity and net exit percentage, with a peak at 0.65 m/s.

Summary

This paper presents some of the key findings from an experimental program conducted within Yarrawonga fishlock.

Results for species are transferable to other fishlocks where the species present. The experimental method is transferable to other fishlocks.

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Acknowledgements

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BLOOD-CHEMISTRY INDICES OF NUTRITIONAL STATUS IN HATCHERY-REARED YEARLING CHINOOK SALMON MIGRATING THROUGH THE SNAKE-COLUMBIA RIVER FEDERAL POWER SYSTEM

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EXTENDED ABSTRACT ONLY–DO NOT CITE

Juvenile chinook salmon migrating downstream through the Snake-Columbia River Federal Power System in the Pacific Northwest, USA, must pass through eight dams and reservoirs. Lipid reserves are exhausted during the 6- to 12-week migration. The migration is slowed in years of lower river discharge, and consequently lipid reserves are depleted at points further upstream than in higher-flow years. After lipid reserves are depleted, the rate of use of body protein increases. Catabolism of body lipid and protein stores by migrating juveniles is in large part a consequence of metabolic changes associated with the parr-smolt transformation: energy stores are mobilized to provide substrates and energy for migration, for changes in cell, tissue and organ function that prepare the fish for survival in seawater, and for rapid growth in length. The rate of depletion may be modified, however, by extrinsic factors such as water temperature and food availability. In years of lower flow, rising water temperatures in late May and early June would increase the metabolic energy demand of migrating fish, but production of prey organisms also increases at this time. If food availability and intake increase during the late migration season in lower-flow years, the use of body protein might be reduced. Little is known, however, about the foraging activity of yearling chinook salmon in Snake and Columbia River reservoirs. Estimation of ration sizes by collection of fish and weighing of stomach contents is labor-intensive and impractical for the 500-km Snake-Columbia hydropower system. This study was undertaken to determine if blood-chemistry indices could be used to qualitatively evaluate the nutritional status of juvenile fish migrating through the hydropower system and, if so, if the nutritional status improves during the late migration season in lower-flow years.

Methods

Two laboratory experiments were performed to determine the effects of food deprivation on blood-chemistry indices. Fish were held in tanks at the University of Idaho without feeding (6 tanks) for up to 32-35 d; control fish (6 tanks) received a full ration of a commercial diet. Three to six fish were sampled from each tank at 7- to 11-d intervals. One experiment was done with laboratory-reared pre-smolts (March 2000), and a second experiment with migrating hatchery fish (mixed stocks) collected at Lower Granite Dam and transported to the laboratory (May 2001).

In 1999 and 2000 (higher-flow years), and in 2001 (a lower-flow year), PIT (passive interrogated transducer)-tagged yearling chinook salmon *Oncorhynchus tshawytscha* reared at three hatcheries in the Snake River Basin were sampled prior to release and while actively migrating downstream. In 2000 and 2001, migrating fish were sampled from bypass systems at Lower Granite Dam, the uppermost dam encountered on the Snake River, and 461 km downstream at Bonneville Dam, the lowermost dam on the Columbia River. In 1999, fish were sampled at Lower Granite Dam and at John Day dam, 113 km above Bonneville Dam. Plasma total protein, cholesterol, triglyceride, glucose and Ca^{++} concentrations were determined by autoanalyzer, as were also plasma activities of the enzymes alanine aminotransferase (ALT), aspartate aminotransferase (AST), lactate dehydrogenase (LDH), creatine kinase (CK), and alkaline phosphatase (AP).

Laboratory data were analyzed by multivariate analysis of variance (MANOVA) and by repeated-measures ANOVA, with sampling day as the within-subjects factor and treatment (fed and unfed) as the between-subjects factor. Field data for migrating fish were analyzed by MANOVA and by ANOVA, with site and hatchery as fixed factors. The required level for significance was $P \leq 0.05$.

Results and Discussion

For laboratory-reared pre-smolt chinook salmon, food deprivation resulted in significant changes in plasma total protein (–23% relative to fed fish after 35 d), cholesterol (–14%), AP (–72%), AST (+15%), and ALT (+4%). Declines in total protein, cholesterol, and AP were progressive over time, and these indices showed partial recovery after 10 d re-feeding at the end of the experiment. Changes in other indices were non-significant.

For migrating hatchery smolts sampled at Lower Granite Dam and transported to the laboratory, food deprivation resulted in significant changes in plasma total protein (–37% relative to fed fish at d 32), cholesterol (–42%), AP (–73%), AST (+26%), and Ca^{++} (–6.5%). Changes in other indices were non-significant.

For groups of migrating fish sampled at Lower Granite Dam and at John Day Dam (1999) or Bonneville Dam (2000 and 2001), a number of indices differed in between-site comparisons. In 2001, for example, significant Lower Granite-to-Bonneville Dam decreases were observed for plasma total protein (–32%), cholesterol (–44%), AP (–33%), triglycerides (–82%), LDH (–38%), and CK (–52%). Mean values for total protein in fish sampled at Bonneville Dam were similar to values in fish experimentally deprived of food for 22 to 32 d (Figure 1), while mean values for AP were somewhat higher (55 vs 39 U/L), and mean values for cholesterol somewhat lower (138 vs. 164 mg/dL).

The most useful indicators of nutritional state were plasma total protein, cholesterol, and AP (alkaline phosphatase). These indices declined progressively in food-deprived fish, and did not appear to be biased by stress effects or by changes in smoltification status. These indices also declined in actively migrating fish in each of the three study years. In 2001, an exceptionally low-flow year in the Snake and Columbia Rivers, values for plasma total protein, cholesterol, and AP in fish sampled at Bonneville Dam were similar to values in fish experimentally deprived of food for 3 to 4 weeks. Furthermore, the use of body protein stores was greater in 2001 (–20%) than in the two preceding average-flow years (–10, –14%). These data do not support the hypothesis that depletion of energy reserves by later-migrating fish is counteracted by increased food availability and intake.

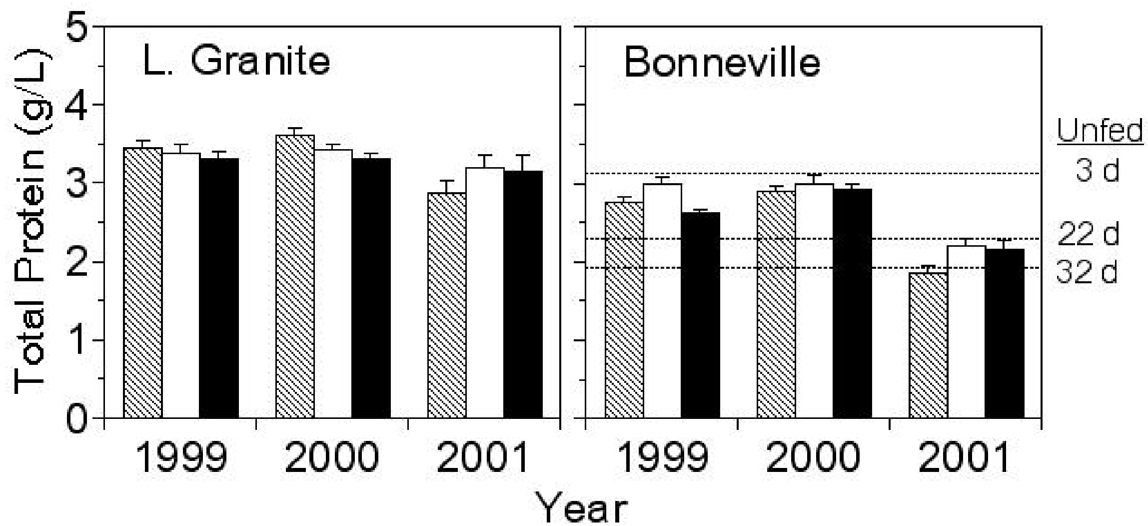

Figure 1. Plasma total protein (mean + SE) concentrations in migrating juvenile chinook salmon sampled at Lower Granite Dam (the first dam encountered on the Snake River) and at Bonneville Dam (the last dam on the Columbia River) in 1999, 2000, and 2001. The fish originated from three Idaho hatcheries: Dworshak (hatched bars), Rapid River (open bars), and McCall (solid bars). Values for migrating river-run chinook salmon sampled at Lower Granite Dam in 2001 and held in tanks without feeding for 3 to 32 d are shown for comparison.

INTERGENERATIONAL EFFECTS: FRESHWATER MIGRATION EXPERIENCE OF ADULT SOCKEYE SALMON (*ONCORHYNCHUS NERKA*) AND OFFSPRING FITNESS.

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

Semelparous sockeye salmon (*Oncorhynchus nerka*) have a single opportunity to allocate a finite supply of energy into the contrasting demands of a long stressful migration and reproduction. Our research explores the evidence, mechanisms, and implications of adult migration experience affecting offspring fitness at the individual and population level. Individual sockeye salmon from four Fraser River populations (Early Stuart Horsefly, Gates and Weaver) with different spawning migration distances were examined for physiological condition and gamete quality looking for evidence of intergenerational effects, such as interannual variation in gonad investment, and individual and population level variation in gamete viability. To elucidate some of the mechanisms responsible we correlated reproductive investment and success to migration conditions as well as directly manipulating the migration environment to recreate an intergenerational effect. The implications of these effects in regards to changes in the relative offspring survival and phenotype were explored.

Evidence

At the population level there is evidence of large interannual differences in gonadal investment as evidenced by interannual variation in both fecundity and egg sizes at the spawning grounds. There is a weak association between low gonadal investment and extreme migration difficulties in long distance migrating populations. For example, the years 1999 and 1997 had extremely high discharge levels, based on 90 years of historic data (Macdonald, 2000), during the period which Early Stuart sockeye migrated through the Fraser River and they had two of the lowest gonad masses recorded.

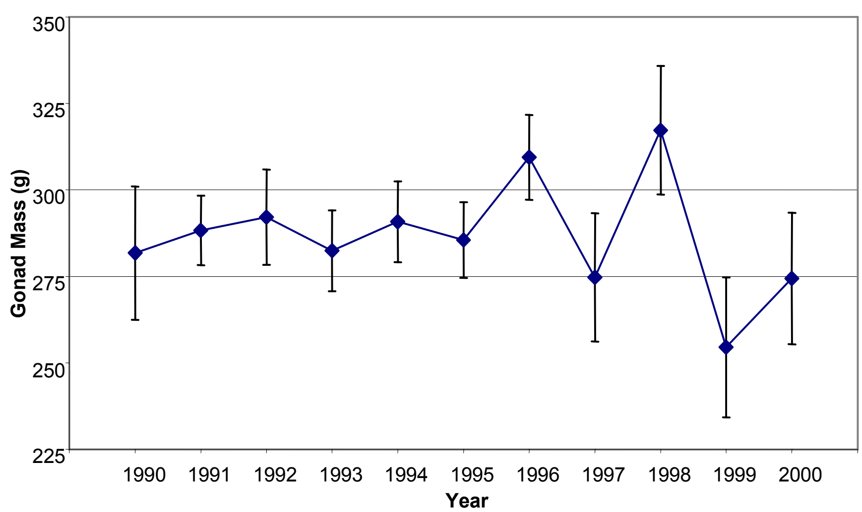

Figure 1: Interannual variation in gonad mass of Early Stuart sockeye salmon. Values represent the mean gonad mass of 50-150 females sampled at the spawning grounds, error bars +/- 95% C.I. and all values are standardize to an overall mean length.

There were significant differences in survival to eyed stage between broodlines generated from a total of 96 females and 39 males. To generate these full-sib and half-sib broodlines each female was crossed with a minimum of 3 males and each male was crossed with minimum of 5 females. There was no evidence of interaction between specific male and female combinations but there was more variability in offspring survival based on maternal rather than paternal gamete origin.

Mechanisms

The 3 longer distance migrating populations had lower survival and greater variation in offspring survival than the shortest distance migrating population (Weaver). This was more dramatic in years of harsh migration conditions. This is consistent with the hypothesis that migration experience adversely effects gamete quality. However, more long term monitoring is required to separate population effects from interannual variability in migration conditions.

Early Stuart sockeye salmon were intercepted near the beginning of their freshwater migration and forced to swim under no flow or a moderate flow environment. The manipulation of the flow environment resulted in differential reproductive success between the two groups. Contrary to our expectations exercised females achieved greater reproductive success than non-exercised females. We also explored the mechanisms behind the differential survival by correlating parental condition to gamete viability. The physiological condition of the adult female was not related to viability of eggs produced. In fact unspawned moribund or fresh dead unspawned females also produced viable offspring. A simple mechanistic link between parental condition and gamete viability remains elusive.

Implications

Previous research has already shown that adverse migration conditions are associated with high en route losses (Macdonald, 2000) and high pre-spawn mortalities on the spawning grounds (Gilhousen, 1990). We found that in years with high pre-spawn mortality the deposited egg to fry survival rates were low. The connection between harsh migration conditions, using high pre-spawning mortality as a surrogate for difficult migration experience, and egg to fry survival has consequences to future recruitment estimates that has hitherto been ignored.

When external conditions select against different adult phenotypes, such as egg size or quality, then the fitness of the individual surviving offspring may be compromised. We found that egg size was not correlated to egg embryonic survival *per se*, but was directly related to fry size at emergence. This will likely confer post emergent survival advantages. There is also an interaction between gamete quality and incubation environment. Eggs from different mothers that were fertilized and incubated under both optimal and sub-optimal (high) temperature had similar survival rates under optimal conditions but at high temperatures survival rates varied with maternal origin.

Conclusions

Parental origin has a significant influence on survival of wild sockeye salmon embryos. Migration conditions experienced by parents influences gonad investment, leads to differential reproductive success, and will shape the individual offspring phenotype. We are beginning to understand that adverse environmental conditions experienced by migrating adult sockeye salmon have implications beyond the simple reduction in the numbers of eggs successfully deposited (the current method for forecasting future returns).

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EFFECTS OF STRESS AND FATIGUE ON MIGRATION AND SPAWNING SUCCESS OF AMERICAN SHAD, *Alosa sapidissima*

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EXTENDED ABSTRACT ONLY- DO NOT CITE

The negative impacts of dams on anadromous fish populations are well documented throughout the United States. Two restoration strategies have been in operation: fish ladders or lifts have been added to facilitate upstream passage, and artificial propagation has been utilized in an attempt to improve fish numbers and re-populate upper reaches of the system. Both solutions have been confronted with difficulties and limitations. Passage of American shad, for example, has been low at many ladders (e.g., Cabot Station on the Connecticut River) and artificial propagation of captive stocks has often culminated in low and highly variable results.

Often fish ladders are designed with little knowledge of the physiological and behavioral ability of migrating fish for which they are built, thereby creating stress and fatigue effects that may be a major component resulting in low numbers of fish passing dams. Evidence from many fishes indicates that high levels of stress and fatigue may also have negative impacts on reproductive success (Contreras-Sanchez et al., 1998). The combination of stress associated with dam passage and transport, which is commonly utilized during artificial propagation, may have severe negative consequences for propagation and rearing of eggs.

Evaluations of the effects of fish ladders and other aids to upstream and downstream fish passage at dams typically focus on monitoring passage time and quantifying fishway-induced mortality in the field and laboratory (Dominy 1971). More rarely, analysis of passage success includes examining physiological indices of stress and anaerobic activity (Maule *et al.* 1988). Such physiological analyses are important because they can establish the reason(s) for poor passage success at ladders. However, when these physiological components have been considered, the focus of many studies has been on the efficacy of fishways and their physiological effect on anadromous salmonids during passage and there is very little known about physiological impacts of upstream passage on non-salmonid species. The objective of this study was to determine the impact of passage through a fish ladder on physiological measures of stress and fatigue in American shad.

Methods

Stress and Fatigue

Adult Shad were collected once during upstream migration (May-June) during 2000 and twice during the same period in 2001 at Cabot Fish ladder in Turners Falls Massachusetts. The Cabot ladder is a modified Ice Harbor fishway with 66 pools and 30 cm height between pools. Fish were sampled for the following physiological indices of stress, fatigue and osmoregulatory homeostasis: plasma cortisol, glucose, lactate, and Na^+, K^+ and Cl^- ions. To assess the effects of ladder passage these parameters were measured from fish (10 males and 10 females) from each of the following ladder components (where possible): the ladder entry, middle, and top of each ladder. Collection methods consisted of fishing (ladder entry), netting from a turn pool (middle), or netting from a mechanical trap (top). Additionally a cohort of fish returning through the downstream bypass (“fallbacks”) was sampled as above (2001 only).

Recovery

Animals from the top of Cabot ladder were collected and held for 96 hours (2000) or 48 hours (2001) in a 5-meter flow through circular tank supplied with river water at the S.O. Conte Anadromous Fish Research Center. At the end of the holding period fish were sampled as above.

Results

Plasma cortisol concentrations were three to five times higher in American shad captured at the top of Cabot ladder as compared to fish captured at the ladder entrance. Likewise, plasma glucose was 50% greater and plasma lactate concentrations three to six times greater than ladder-naïve animals (Fig. 1). Plasma lactate was also elevated in fallback American shad. Both plasma cortisol and plasma lactate were reduced following recovery for 48-96 hours.

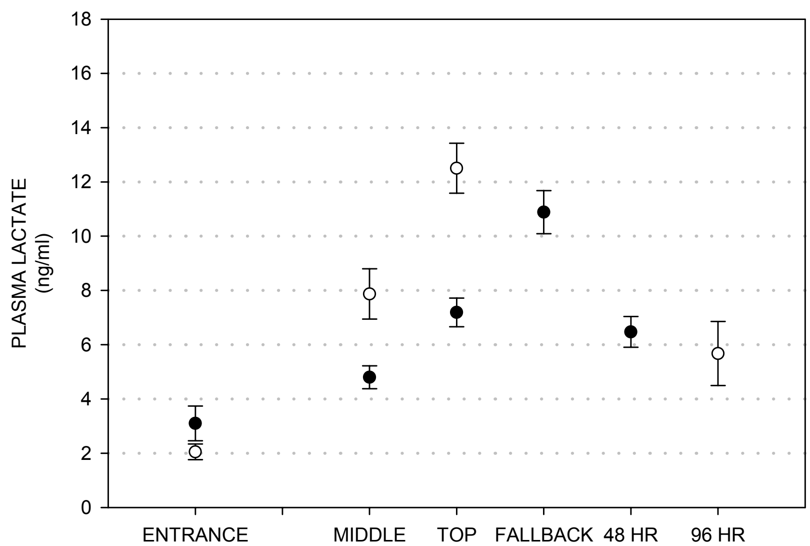

Figure 1. Mean plasma lactate (mM ± SE) sampled on 2-6 June 2000 (open circles) and 1 June 2001 (closed circles) and those held in a 5-meter circular tank for 48 or 96 hours post-capture. Each point represents 10 males and 10 females.

For plasma ions only potassium levels increased significantly as fish progressed up the ladder. Plasma chloride levels exhibited a downward trend, but were not significantly different. No changes were observed in levels of plasma Na^{+}.

Discussion

American shad exiting the top of Cabot ladder had elevated levels of plasma cortisol, indicating that upstream passage was stressful to these animals. Plasma lactate levels progressively increased as fish moved up the ladder and exhibited significant declines upon resting (Fig. 1). Increases in plasma lactate is the result of anaerobic metabolism and indicates that passage through Cabot ladder requires substantial and repeated burst swimming with only limited recovery time. Previous research indicates that extreme exercise demanding high levels of anaerobic performance can lead to mortality 6-24 hours later. However, we did not observe substantial mortality in fish held for 48 to 96 hours. We hypothesize that the high levels of stress and fatigue observed at the top of this ladder contribute to the poor passage success and large number of fallbacks observed at Cabot ladder. Future research will examine whether the stress and fatigue associated with upstream fish passage results in compromised reproductive performance.

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STOCK SPECIFIC DIFFERENCES IN THE SWIMMING ABILITY, METABOLIC RATES AND POST-EXERCISE METABOLIC RECOVERIES OF FRASER RIVER SOCKEYE (*ONCORHYNCHUS NERKA*), PINK (*O. GORBUSCHA*) AND COHO SALMON (*O. KISUTCH*) IN RELATION TO MIGRATION DISTANCE ANDTEMPERATURE

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Pacific salmon do not feed during spawning migration and rely on body reserves for all the energy requirements associated with locomotion, gamete maturation and spawning behaviours. Inappropriate allocation of energy due to inefficient migration limits the amount available for gamete production and could significantly reduce reproductive fitness. Evidence suggests that selection imposed by migration distance and difficulty results in improved swimming performance and energetic efficiency of longer distance migrators versus their shorter distance migrating counterparts.

To assess the swimming abilities of different populations of Fraser River salmon, the prolonged swimming performance and energetics of several stocks of sockeye *(O. nerka)*, pink *(Oncorhynchus gorbuscha*), and coho salmon (*O. kisutch*) were examined over two field seasons. Sockeye have traditionally been considered the strongest swimmers of all the Pacific salmon species, while pink are assumed the weakest and coho of intermediate ability. Selected stocks included early Stuart sockeye, Seton/Thompson pink, Seton sockeye, Weaver sockeye and Chehalis coho. The respective spawning grounds are located in tributaries of the Fraser, at distances from the ocean ranging from 150 to 1200 km.

Two large mobile Brett-type swim tunnel respirometers were used to evaluate critical swimming speed (Ucrit), routine and active oxygen consumption (MO_2), and recovery ability of sexually mature salmon on their spawning migration. Fish performed modified ramp, repeat Ucrit tests at temperatures in the range of ambient river temperature ± 5°C. Video analyses of swim trials by early Stuart sockeye and Seton/Thompson pink salmon allowed the determination of tail beat frequency (TBF) and stride length at various temperatures and swimming speeds.

We found that stocks migrating at warmer temperatures or those which traverse longer or more difficult migration routes may be better adapted for aerobic swimming. Each stock shows a distinct temperature optimum where performance is maximized. Pink salmon performed better than expected and demonstrated Ucrits similar to sockeye and higher than coho. Results indicate that routine Mo2 is dependent on temperature and is independent of stock or species. The rate of recovery is driven by temperature and metabolic scope.

Management of fishes has commonly been based on the physiology or behaviour of a given species. We show that swimming abilities and energetics are as variable between stocks as they are between species of Pacific salmon. The effects of changing temperature are also differential with respect to stock. Therefore management plans should be customized for each stock of interest in order to reflect these differences.

FIELD-BASED MEASUREMENTS OF OXYGEN UPTAKE AND SWIMMING PERFORMANCE WITH ADULT PACIFIC SALMON (*Oncorhynchus* sp.) USING A LARGE MOBILE BRETT-TYPE RESPIROMETER SWIM TUNNEL

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

Studies examining swimming performance have continued to hold the interest of fish researchers since the pioneer work of Brett and co-workers began over 40 years ago (Brett, 1965). However, the majority of such studies have focused on immature cultured fish. The swimming performance of adult wild salmon are limited and have been conducted primarily in a laboratory setting (Brett & Glass, 1973; Jones *et al.,* 1974; Farrell *et al.,* 1998). Only three field-based swimming performance studies involving large salmon have been performed to date (Jones *et al.,* 1974; Williams *et al.,* 1986; Farrell *et al.,* 2001), none of which have measured oxygen uptake (Mo_2) during swimming. Respirometry experiments are restricted either to wild adult salmon after they have been transported long distances to laboratories (e.g., Jones *et al.,* 1974; Williams *et al.,* 1986; Randall *et al.,* 1987; Jain *et al.,* 1998; Farrell *et al.,* 1998) or to adult fish that were hatchery-reared (e.g., Kiceniuk & Jones, 1977).

The paucity of data on both swimming performance and related energetics for adult migratory salmon is clearly a handicap for fisheries managers who make annual predictions of migration success for salmon stocks returning to natal streams. In this regard, a particular problem for fisheries managers is the annual fluctuations in both river water velocity and water temperature that occur during salmon migrations and which create barriers to successful fish passage.

For this situation to be resolved, a respirometer swim tunnel that can be used in the field will be required. Here we outlined the successful development and implementation of a robust Brett-type respirometer swim tunnel that permits field-based measurements of critical swimming performance (U_{crit}) and Mo_2 with adult Pacific salmon up to 3.5 kg in mass. Because the swim tunnel is mobile, it is possible to: perform the measurements at various geographic locations without transporting fish large distances, use different species, and use natal river water at ambient temperature for the tests.

Description of Swim Tunnel

The swim tunnel was constructed to be mobile. It consists of three PVC sections, a PVC expansion chamber (Steffensen *et al.,* 1984) and a Plexiglas swim chamber. When assembled, it holds a water volume of 471.2 L. The swim chamber has a diameter of 25.4 cm (10") and is approximately 185.5 cm (73") long. When assembled the trailer is approximately 7 m long and 2.7 m high. Water flow is driven by a 29 cm diameter fiberglass centrifugal impellor pump that is coupled to a 7.5 hp, 208 V, 3-phase, 1200-rpm motor and controlled by a Siemens Midimaster Vector frequency drive (PLAD, Coquitlam, BC). The control unit can be operated manually by varying the frequency of the motor or can be controlled remotely via computer (RS-485 interface). When in operation for long periods of time, the controller assembly and tunnel itself was covered in tarps to minimize unnecessary weathering.

The swim tunnel assembly is housed on a single axle 1,000 kg boat trailer, reinforced with a 7 cm galvanized steel frame. The controller, pump and motor are mounted to an aluminum base plate that is attached to the trailer. During transit, the center of mass of the motor and pump assembly is relocated directly over the rear axle of the trailer by means of a track mounted on to the trailer and 9 cm ball bearing wheels on the base plate. The control unit is removed from the motor-pump assembly during transportation. By using a fiberglass impellor, PVC tubing, galvanized steel framework, and stainless steel and aluminum fittings, it is possible to routinely use seawater in the swim tunnel.

The swim tunnel can be moved in one trip using a full-size three-quarter tonne pick-up truck. Complete assembly requires two people and takes approximately four hours. The main design features the swim tunnel can be found at the following website:

www.sfu.ca/biology/faculty/farrell/swimtunnel/swimtunnel.html

Calibration

Routine calibrations are made whenever the swim tunnel is reassembled. Typically the relationship between water velocity (U) and motor frequency (Hz) is linear up to a maximum U of approximately 160 cm s^{-1}. Water flow is uniform across approximately 85% of the diameter of the swim chamber. At lower velocities variability between the extreme top and bottom of the swim chamber is largest (18% at 40 cm s^{-1}). This variability decreases as velocity increases (5% at 160 cm s^{-1}). The variability between calibrations on different occasions and locations is small (< 1%).

Swimming Performance and Mo_2

Data is shown for Early Stuart sockeye salmon (*Oncorhynchus nerka*), Somass River sockeye salmon, Chehalis River coho salmon (*Oncorhynchus kitsuch*) and transgenic coho salmon. The data illustrates that (a) U_{crit} values for Early Stuart sockeye salmon and Somass River sockeye salmon are comparable to earlier values for Stamp River sockeye salmon (Brett, 1965) (b) Maximum Mo_2 for Early Stuart sockeye salmon is higher than Stamp River sockeye salmon tested by the Brett (1965) at a comparable temperature, and (c) transgenic coho salmon swam more poorly than ocean-ranged coho salmon at a comparable temperature.

TABLE I. Mean temperature, U_{crit} and Max. Mo_2 of adult Pacific salmon species measured at various field locations with a portable swim tunnel.

	Early Stuart sockeye salmon	Somass River sockeye salmon	Stamp River sockeye salmon (Brett, 1965)	Chehalis River coho salmon	Transgenic coho salmon
Temp. (^oC)	13.0 ± 0.2	21.0 ± 0.2	15.0	7.9 ± 0.6	8.6 ± 0.1
N	6	7	9	13	5
U_{crit} (cm s^{-1})	136.8 ± 3.4	123.4 ± 5.1	107.0	96.5 ± 1.9	66.2 ± 5.2
Maximum Mo_2 (mg O_2 kg^{-1} min^{-1})	13.6 ± 0.3	n/a	12.0	8.8 ± 0.3	8.8 ± 0.2

Mean values are presented with S.E.M.

Discussion

These results and comparisons clearly show that reliable respirometry can be performed on wild exercising adult salmon in field locations using a mobile swim tunnel. Thus, by foregoing long transportation times and retaining ambient water quality and temperature when performing field-based measurements, it may be possible to reliably replicate swimming performance and energetics of wild fish *in situ*, and this may be especially valuable for fish that are too fragile for transportation.

The tools are now available to make reliable field measurements of swimming performance and Mo_2 without having to move large adult salmon long distances to laboratories. Implementation of a mobile respirometer swim tunnel should enable future studies to carefully dissect the influences of fish stocks and species, water temperature, reproductive status and sex on swimming performance and migration energetics. In doing so, it may also be possible to assess the effect migration distance may have on salmonids energetics and swimming performance.

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THE LIMITATIONS OF TRADITIONAL SWIM TUNNEL RESPIROMETERY EXPERIMENTS IN PREDICTING

POST-EXERCISE PHYSIOLOGY AND PERFORMANCE

OF FREE-SWIMMING SMALLMOUTH BASS,

***MICROPTERUS DOLOMIEU*, IN AN EXPERIMENTAL CULVERT**

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction and Rationale

Much of what is currently known about locomotory capacity and exercise physiology of fish has been learned by studying fish forced to swim in a respirometer. These devices allow quantitative measurements of the relationship between swimming speed and endurance, energetics, muscle dynamics, and metabolic processes. However, the unnatural and confining conditions in respirometers may inhibit natural behaviors associated with energy conserving strategies. As behavior is generally suppressed or ignored during swim trials, the extent to which these data can be extrapolated to free-swimming fish under natural conditions is, at best, uncertain. The primary purpose of this study was to measure post-exercise physiology of smallmouth bass in a swim tunnel respirometer and compare the results with physiological and behavioral parameters generated from free-swimming fish moving through a 25 m experimental culvert. The working hypothesis was that swimming failure in a respirometer might not result from muscular exhaustion, but a behavioral disinclination to continue swimming at speeds close to maximum sustained.

Methods

Wild smallmouth bass were placed in a respirometer and forced to swim at 30-75 cm/s for 30 min, after which muscle and blood samples were removed. Hematocrit was measured and plasma was analyzed for lactate and glucose content, while lactate and glycogen levels were measured in muscle samples. Critical speed was determined for smallmouth bass using traditional methods, and blood and tissue samples were taken immediately following swimming failure to assess the degree to which fish were exhausted by the protocol.

Smallmouth bass were similarly sampled after voluntarily ascending a 25 m raceway against water velocities ranging from 40 to120 cm/s. Swimming speed and behavior was monitored using light-gate sensors placed along the longitudinal length of the structure. In some tests, bass were allowed to move freely throughout the system and ascent rate, success rate, and time between ascents were monitored to determine the degree to which behavior reflects physiology. Post-fatigue physiological measurements were performed on bass chased to fatigue, to provide a basis for comparison with Ucrit-fatigued fish.

Results and Discussion

Mean critical swimming speed was 86 cm/s. Post-exercise physiological measurements gave little indication of anaerobic activity below 87% of Ucrit, supporting the commonly held belief that Ucrit is an estimate of maximum sustained speed, and that all but the highest sub-Ucrit speeds are maintained aerobically (Figure 1). However, physiological data from free-swimming bass in the raceway suggested that maximum sustainable speed and maximum aerobic speed (the highest maintainable using only oxidative metabolism) are quite different and that Ucrit is a poor

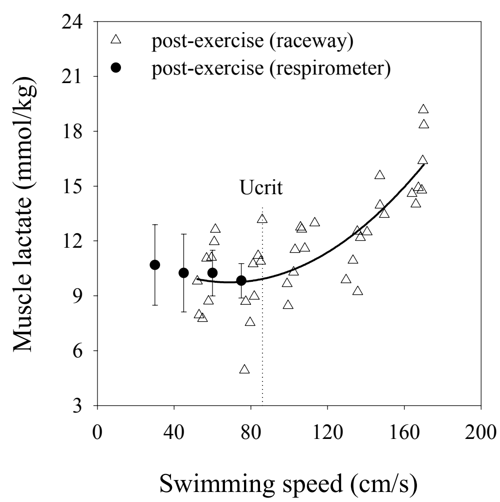

Figure 1. Muscle lactate dynamics for free-swimming and confined bass.

estimator of both. There was little evidence that (1) speeds less than 100 cm/s (115% of Ucrit) were maintained by anything other than aerobic processes, and (2) speeds less than 115 cm/s (134% of Ucrit) were not maintainable for extended, if not indefinite, periods. It is hypothesized that speeds greater than maximum aerobic but less than maximum sustainable have no measurable effect on performance because anaerobic metabolites are removed as they are produced. Maximum speeds demonstrated by smallmouth bass were well over 2 m/s, and these speeds were maintained for at least 50-70 s, which argues against theories stating that burst swimming results in fatigue within a few seconds.

Results of this study clearly indicate that the true relationship between swimming speed and endurance of a free-swimming fish cannot be elicited from a swim trial performed in a respirometer. This has serious implications for models that have used these data to predict allowable flows in fishways and culverts. In addition, it is clear that swimming failure in respirometers has a large behavioral component for bass, and likely other species, as the physiological response of Ucrit-fatigued bass was muted compared to that of fish chased to exhaustion (Figure 2). This implies that current knowledge related to physiological dynamics of fatigue and recovery may need to be re-examined in a more behavior-oriented manner.

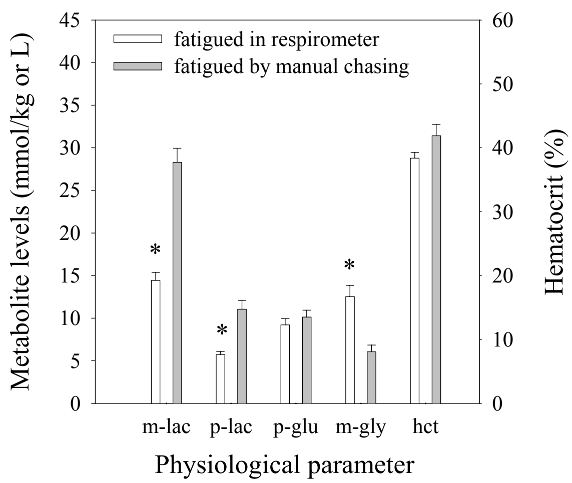

Figure 2. Post-fatigue physiological parameters for Ucrit-fatigued and chased bass.

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THYROXINE OR GNRH ANALOGUE EFFECTS ON THYROID HORMONE DEIODINATION IN THE OLFACTORY EPITHELIUM AND RETINA OF RAINBOW TROUT AND SOCKEYE SALMON: IMPLICATIONS FOR BEHAVIOURS RELATED TO HOMING

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EXTENDED ABSTRACT ONLY-DO NOT CITE

Introduction

Thyroxine (T4) is a prohormone with modest biological activity. It undergoes inner-ring deiodination (T4IRD) to form inactive 3,3',5'-triiodothyronine (reverse T3), or outer-ring deiodination (T4ORD) to form biologically active 3,5,3'-triiodothyronine (T3), which in turn can be inactivated by inner-ring deiodination (T3IRD) to form 3,3'-diiodothyronine (T2) (Eales and Brown, 1993). In this study we determined the levels of T4 and T3 deiodination in the olfactory epithelium (OLF) and retina (RET) of immature rainbow trout, *Oncorhynchus mykiss*, and sockeye salmon, *O. nerka*. We also determined the extent to which these deiodination pathways may be regulated due to administration of either T4 or a gonadotropin releasing hormone analogue (GnRHa), which can affect the visual (Browman and Hawryshyn, 1992) and olfactory systems (Morin et al., 1995) of salmonids at parr-smolt-transformation and maturation, respectively. Additionally we tested whether GnRH has a motivational effect on jumping behaviour in sockeye salmon.

Methodologies

T4 treatment of rainbow trout

Experimental rainbow trout were individually held for six weeks in 40-L aquaria in water (14°C) containing 100 ppm T4. Control trout were treated identically but were not exposed to T4.

GnRHa treatment of sockeye salmon

Two-and-a-half-year-old immature sockeye salmon were injected with GnRHa (GnRHa; D-Ala-6, des Gly 10 ethylamide) at a dose of 20 $\mu g \cdot kg$ body $weight^{-1}$ in 0.9% saline into epiaxial muscle 12 and 36 h before sampling or behavioural testing.

Behavioural Testing

The behavioural response of 20 fish was recorded for 2 h each in a waterfall set-up. Ten fish were subsequently injected with GnRHa while the other ten were injected with a physiological saline solution (controls). Three days after the first test, all fish were re-tested and behavioural performance was compared.

Assays

Total plasma T3 and T4 concentrations were determined by radioimmunoassays (RIA). Determination of deiodination activity followed procedures taken from Eales *et al.*, (1999).

Results

T4 treatment of rainbow trout

T4 treatment elevated plasma T4 levels 3-fold to 25 $ng \cdot ml^{-1}$ and increased plasma T3 levels by 50% to 3 $ng \cdot ml^{-1}$. T4 treatment depressed liver T4ORD activity but increased T4IRD and T3IRD activities in brain, liver and RET. In control trout the tissue rankings for each deiodination pathway were as follows: T4ORD, liver>OLF=RET=brain; T4IRD, liver=RET=OLF=brain; T3IRD, liver=RET=OLF=brain. In control trout T4ORD predominated in liver but IRD pathways predominated in RET (Table 1) .

GnRHa treatment of sockeye salmon

GnRHa caused significant elevation (37%) in plasma T3 levels with no significant change in plasma T4 levels. GnRHa treatment depressed RET T4IRD and T3IRD activities but caused no other changes in deiodination. In control sockeye tissue rankings for deiodination pathways were: T4ORD, liver>OLF=brain=RET; T4IRD, RET=OLF>liver=brain; T3IRD, RET>liver>brain=OLF. In control trout T3IRD activity was especially evident in liver and RET (Table 1).

Table 1: Deiodinase activity rankings in control fish

TISSUE	RAINBOW TROUT	SOCKEYE SALMON
Brain	$T_4ORD=T_4IRD=T_3IRD$	$T_4IRD=T_4ORD=T_3IRD$
Liver	$T_4ORD>T_4IRD=T_3IRD$	$T_3IRD>T_4ORD=T_4IRD$
OLF	$T_4ORD=T_4IRD=T_3IRD$	$T_4IRD=T_4ORD=T_3IRD$
RET	$T_3IRD>T_4IRD=T_4ORD$	$T_3IRD>T_4IRD>T_4ORD$

Behavioural tests

Time to move in test2 increased significantly in control fish (t-test, P = 0.021, test1: 4.9 ± 1.7 min, test2: 24.9 ± 8.4 min) while it stayed constant in GnRH injected fish (t-test, P = 0.922, test1: 10 ± 2.1 min., test2: 9.3 ± 5.6 min.). The number of passes through the waterfall increased significantly (t-test, P = 0.01) in GnRH injected fish (test1: 29.9 ± 5.8, test2: 85.9 ± 16.9) but stayed nearly unchanged for control fish (test1: 44.3 ± 7, test2: 42.8 ± 13.2). Jumping activity, did not change significantly in control fish (t-test, P = 0.296, test1: 0.7 ± 0.5 jumps, test2: 2.2 ± 1.4 jumps) but increased significantly for GnRH injected sockeye (t-test, P = 0.007, test1: 0.5 ± 0.5, test2: 10.5 ± 2.7)(Figure 1).

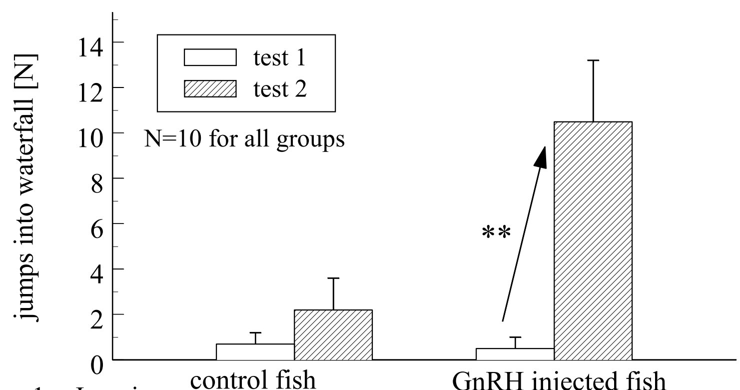

Figure 1: Jumping motivation in GnRH and saline (control) injected sockeye salmon

Conclusions

To our knowledge there have been no previous reports of IRD activity in teleost RET or ORD or IRD activities in OLF. In both species RET T3IRD activity predominated over RET T4ORD activity. Therefore, RET may depend to a greater extent than OLF on a plasma source of T3. In both species, OLF and RET T4ORD activities were lower than those for liver but comparable to those for whole brain. However, RET T4IRD and T3IRD activities exceeded those of whole brain for both species and exceeded that of liver for sockeye. Overall our data indicate a role for deiodination in the salmonid OLF and a particularly important role for IRD activities in the salmonid RET (Plate et al., in press).
The GnRH-triggered increase of jumping behaviour and overall activity may indicate a motivational role of GnRH for migration-related behaviour in anadromous salmonids also found by Sato et al. (1997).

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NEUROSTEROID BIOSYNTHESIS IN THE BRAIN AND PITUITARY GLAND OF SALMONID FISHES

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Abstract

The present study was conducted to investigate the relations between neurosteroid biosynthesis and their possible roles on migratory mechanisms of salmonid fishes, using sockeye salmon (*Oncorhynchus nerka*). First, the ability of brain to produce sex steroid hormones was examined with exogenous steroid substrates during smoltification. It was demonstrated that the brain had the ability to produce sex steroid hormones during smoltification, and the ability tended to be higher in the anterior brain than in the posterior brain. Secondly, the ability of salmon brain and pituitary to synthesize and metabolize cholesterol was examined by *in vitro* thin-layer chromatography method during sexual maturation. It was revealed that pregnenolone was identified as one of cholesterol metabolites in the brain and pituitary gland. These results suggest that neurosteroids are produced in the brain and pituitary gland of sockeye salmon, and might be involved in smoltification and sexual maturation of salmonid fishes.

Introduction

It is well established that peripheral sex steroid hormones regulate reproduction and migratory behaviors of salmon by acting on the central nervous system (CNS). Recently, it has been reported that steroid hormones accumulate in the

CNS of many vertebrates through mechanisms independent of peripheral sources (Robel and Baulieu, 1985, Le Goascogne et al., 1987, Tsutsui et al., 1995, 2000), and these molecules have been called "neurosteroid" or "neuroactive steroid".

Neuroreactive steroid, 3α-hydroxy-4-pregnen-20-one, which is a metabolite of progesterone, was discovered in rat pituitary and suggested that they selectively suppressed pituitary follicle stimulating hormone secretion by rapid non-genomic interaction with the Ca^{2+}-driven cell signaling mechanism (Wiebe et al., 1997). Seasonal profiles of neurosteroid have also been investigated in *Rana nigromaculata*, and the concentrations of pregnenolone and its sulfate ester in the brain were high during the active season and low during the quiescent season, whereas plasma pregnenolone concentrations were virtually constant through the year (Takase et al., 1999).

However, little is known about the production of these steroids in the brain of salmonid fishes. In this study, we examine the ability of sockeye salmon (*Oncorhynchus nerka*) brain and pituitary gland to produce steroid hormone by biochemical analyses in order to investigate the mechanism of neurosteroid biosynthesis during smoltification and sexual maturation.

Methods

Yearling (1+) sockeye salmon and 3-year-old (3+) lacustrine sockeye salmon were used in this study. After brain and pituitary were removed, brain was cut into small regions by dissection in ice-cold rainbow trout ringer. In 1+ fish, anterior or posterior brain was incubated with exogenous steroid substrates, 17α-hydroxyprogesterone (OHP_4) or testosterone (T) for 18 hrs at 15 ^oC. After incubation, various steroid hormone, such as T, estradiol-17β (E_2), 11-ketotestosterone (11-KT), and 17α,20β-dihydroxy-4-pregnen-3-one (DHP) levels in the incubation medium were measured by time-resolved fluoroimmunoassay. In 3+ fish, each sample of brain regions (7 sections including pituitary) was incubated with ^{14}C-labeled cholesterol for 18 hrs. After incubation, steroid metabolites in the medium were separated by thin-layer chromatography (TLC) and were identified using recrystallization method.

Results and Discussion

T, E_2, 11-KT, and DHP productions in the anterior and posterior brain in the presence of OHP_4 or T was higher than in the absence of these substrates in both sexes. DHP production in the female brain was higher in May, but T, E_2, and 11-KT productions increased in June (Fig. 1). On the other hand, T and DHP

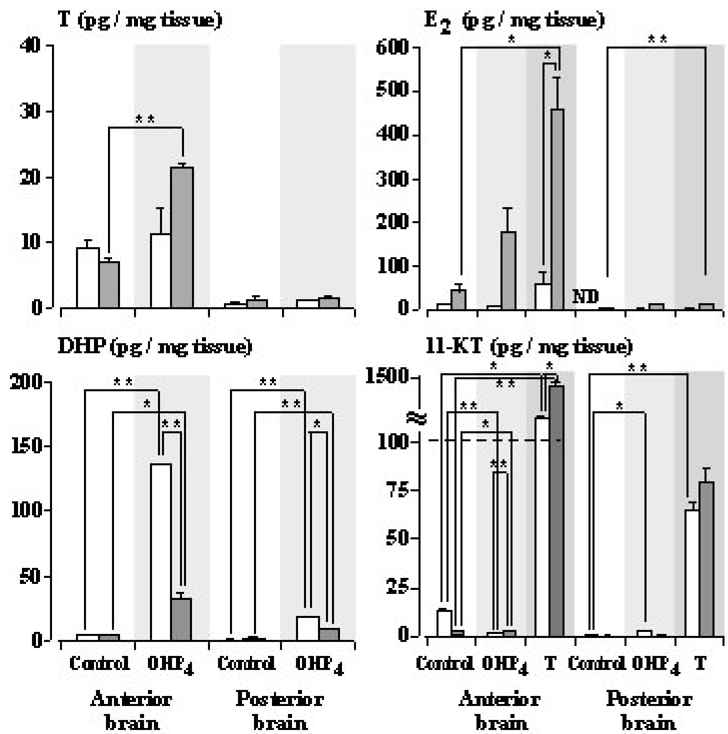

Figure 1. Changes in T, E_2, 11-KT, and DHP production in the anterior and posterior brain of female sockeye salmon during smoltification in May (open column) and June (closed column) 2001. Each tissue was incubated with 0.1 μg/ml OHP_4 (light shadow phase), T (dark shadow phase), or Ringer only (control). Each values represent the means±SEM of three replicates from three fishes. Significant differences at 5% (*) and 1% (**) levels are indicated.

production in the male brain was higher in May than in June, but E_2 production increased in June (Fig. 2). Moreover, the ability to produce sex steroids tended to be higher in the anterior brain compared with the posterior brain of both sexes. These data reveal the evidence of the ability of sex steroid hormone production in the brain suggesting the existence of steroid hormone converting enzymes in the brain of sockeye salmon.

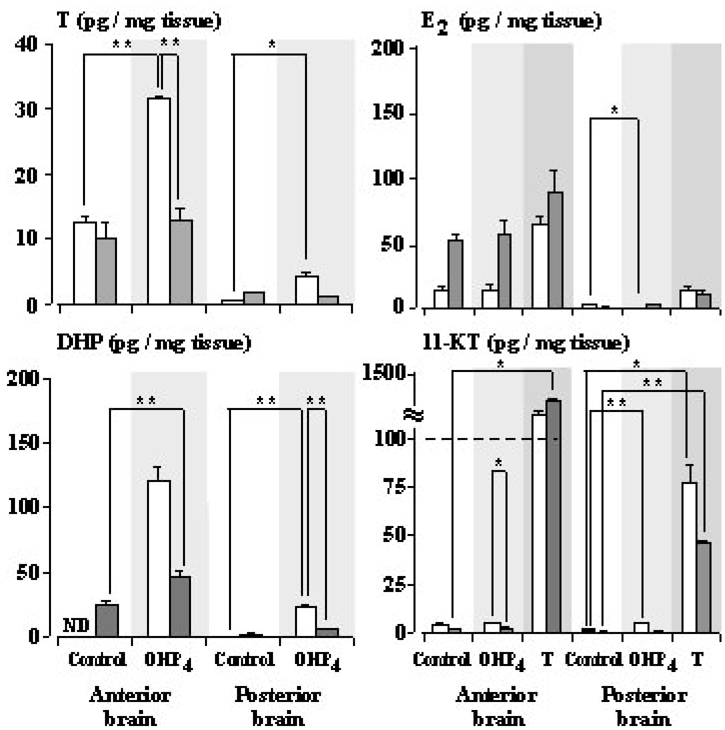

Figure 2. Changes in T, E_2, 11-KT, and DHP production in the anterior and posterior brain of male sockeye salmon during smoltification from May (open column) to June (closed column) 2001. Each tissue were incubated with 0.1 ?g/ml OHP_4 (light shadow phase), T (dark shadow phase), or Ringer only (control). Each values represent the means±SEM of three replicates from three fishes. Significant differences at 5% (*) and 1% (**) levels are indicated.

In 3+ fish, pregnenolone was identified as one of cholesterol metabolites in the brain and pituitary on August. The ability of olfactory bulb to convert cholesterol is shown in Fig. 4. However, major metabolite band was not identified in this study, and further studies are in progress to examine the detail pathway of neurosteroid biosyntheses from pregnenolone.

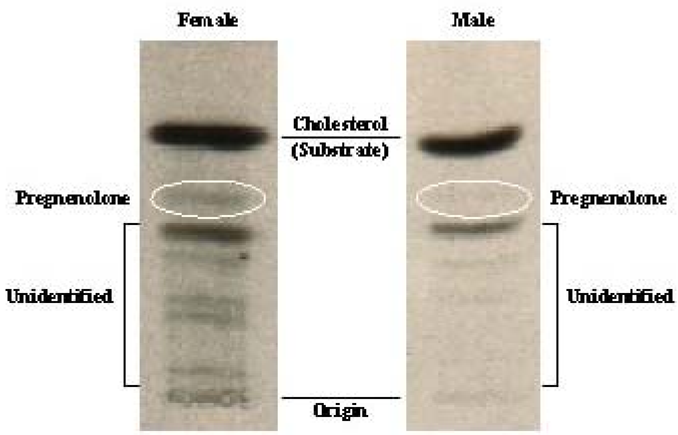

Figure 4. Autoradiographs of TLC plates showing the metabolites by incubating with ^{14}C-labeled cholesterol in the olfactory bulb of lacustrine sockeye salmon in August.

From these results, it is clearly demonstrated that neurosteroids are produced in the brain and pituitary gland of salmonid fishes. Since smoltification and sexual maturation are believed to correspond with imprinting and homing phenomena of salmonid fishes, roles of neurosteroids are highly interesting to investigate during these critical period of salmon migration. Several intensive biochemical analyses are under investigation to clarify the neurosteroids biosynthesis and their important roles on migratory behavior of salmonid fishes.

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SWIMMING ENERGETICS AND EPOC IN ADULT SOCKEYE (*Oncorhynchus nerka*) AND COHO (*O. kisutch*) SALMON

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EXTENDED ABSTRACT ONLY – DO NOT CITE

Introduction

In some salmon-bearing streams, water temperatures may fluctuate by more than 13°C in a single day (Mochan and Mrazik, 2000). Thus, when adult salmon return to their natal rivers, they may have to tolerate non-optimal temperatures to reach their spawning grounds (Macdonald *et al.,* 2000), and in some river systems such as the Fraser River, BC, salmon repeatedly swim at velocities that can exceed their maximum aerobic capacity (Hinch & Rand, 1998; Rand & Hinch, 1998). Thus, information on how temperature influences swimming speeds (U_{crit}) and rates of oxygen uptake (Mo_2) provides important integrative information on the fish's physiology, as well as being extremely valuable for fisheries managers who are required to predict the temperature and hydraulic barriers for adult migratory salmon. In this regard and of broader interest, is whether or not different stocks of the same species and in the same river system have evolved different optimal temperatures for U_{crit} and maximum Mo_2 (Mo_{2max}) to exploit different niches within a watershed. The Fraser River is an interesting watershed in which to examine this issue because stocks of salmon in the lower river face relatively short in-river migration distances (~100 km) and colder temperatures. In contrast, stocks of salmon in the upper river face substantially longer in-river migration distances (up to 1,000 km), including particularly challenging sections of white water such as Hell's Gate and Saddle Rock, as well as warmer temperatures.

We are not aware of any study that has examined the swimming energetics of salmon stocks from the same watershed. A few studies have measured U_{crit} in salmonids under field conditions (e.g., Jones *et al*., 1974, Williams et al., 1986; Farrell *et al*., 2002), but only one has measured Mo_2 under field conditions (Lee *et al*., sub). Berst & Simon (1981) suggest that field-based rather than lab-based studies are more likely to reveal any differences among species or stocks, because animal transportation is minimized and natal river water can be used. The effects of temperature on swimming energetics have not been tackled under field conditions. In view of these important data gaps for swimming energetics in adult salmon, the present study took advantage of a newly developed mobile Brett-type respirometer swim tunnel (Lee *et al.* sub.) to perform field-based measurements of U_{crit} and Mo_2 with adult sockeye salmon (*Oncorhynchus nerka*) and adult coho salmon (*O. kisutch*) at various temperatures. Three important questions were addressed: (1) What are the temperature optima for maximum Mo_2 in different Pacific sockeye and coho salmon stocks? (2) How does temperature affect excess post-exercise oxygen consumption (EPOC) and routine Mo_2? (3) Are field-based measurements comparable with more controlled laboratory measurements?

Materials and Methods

Fraser River, B.C. adult salmon were obtained during their in-river migration between May 2000 and September 2001 (Table I).

The majority of salmon were tested on-site in a portable 471.2 L Brett-type respirometer. Water temperatures reflected those that the fish were experiencing at the field location. Some fish were transported to the Cultus Lake Research Facility (Chilliwack, B.C.) and were tested at either their acclimation temperature or at one adjusted no more than 5^{o}C over 5 days. Salmon were swum to exhaustion using a ramp-U_{crit} protocol after a 24-hr habituation period in the tunnel. Two swim trials, ~3 h in duration, were conducted with a 45-min recovery in-between. Oxygen consumption was measured during each swim trial and during the recovery period to assess EPOC. Refer to our website for full details: http://www.sfu.ca/biology/faculty/farrell/swimtunnel/swimtunnel.html

Table 1: Stock information, migration distance and migratory difficulty.

	Stock	Migration Distance	Hydrological Challenge
Long-distance			
Sockeye salmon	Early Stuart (ES)	~1,100 km	Hell's Gate / Saddle Rock
Sockeye salmon	Seton (STN)	~400 km	Hell's Gate / Saddle Rock
Short-distance			
Sockeye salmon	Weaver (WVR)	~100 km	none
Coho salmon	Chehalis (CHE)	~120 km	none

Results and Discussion

Temperature

53% of the variance seen in routine Mo_2 was explained by temperature. Stock-specific temperature optima existed for Mo_{2max} and U_{crit} (Fig. 1).

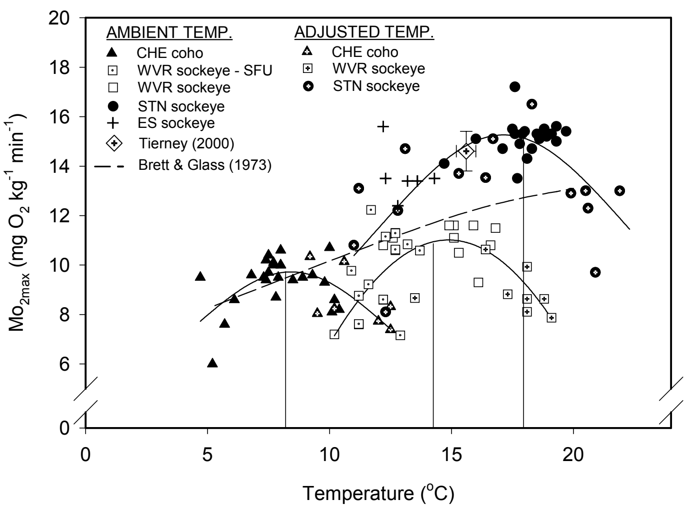

Figure 1: Oxygen uptake at U_{crit} (Mo_{2max}) as a function of temperature for all stocks tested at ambient and adjusted temperatures. Values are shown in relation to Brett & Glass (1973) data on adult sockeye salmon. Distinct peak optimums correspond closely to average ambient water temperature.

EPOC and swimming economy were higher at warmer temperatures (Fig. 2).

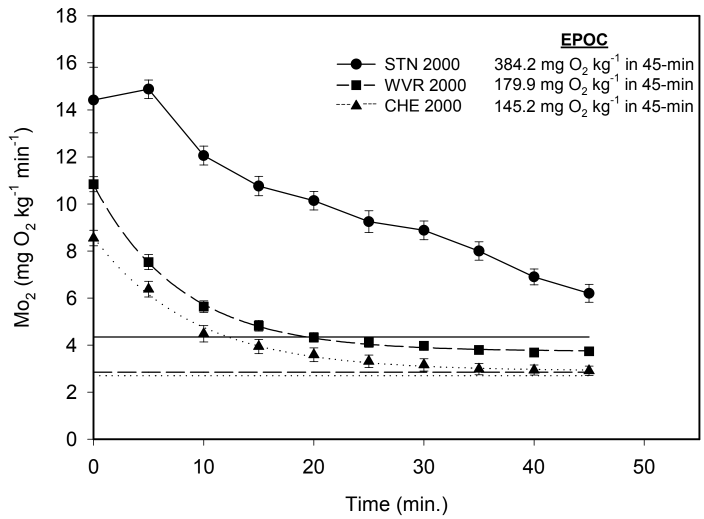

Figure 2: Excess post-exercise oxygen consumption (EPOC) relative to routine Mo_2.

Stocks

At comparable temperatures, Mo_{2max}, U_{crit}, metabolic scope and routine Mo_2 were all higher for long-distance versus short-distance migratory sockeye salmon. The temperature optima in Mo_{2max} for each stock corresponded closely to ambient river temperature.

Field data

Mo_{2max} and U_{crit} field data were equivalent to or better than previously published laboratory data for sockeye and pink salmon (Brett & Glass, 1973; Williams et al., 1986). Results of tests performed at Cultus lake lab were comparable to field data at a comparable temperature. Therefore, we conclude that good quality field testing of salmonid energetics is possible and a short transport with Marinil anaesthetic and ice and a 5-day acclimation period did not impede swimming performance.

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