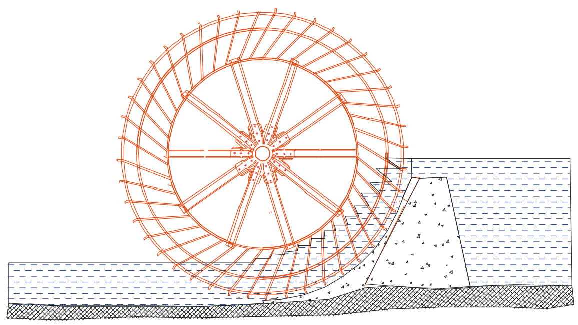
ENERGY INNOVATIONS SMALL GRANT
(EISG) PROGRAM

EISG FINAL REPORT

The Sagebien Project



EISG AWARDEE

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Acknowledgement

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Table of Contents

List of Figures

List of Tables

List of Appendices

Abstract

Original research was undertaken in the J. Amorocho Hydraulics Laboratory at UC Davis investigating possibilities of enabling fish passage through low head dams using a Sagebien waterwheel. A transparent 3' diameter wheel was constructed with the objective of testing its adaptability to pass fish up and downstream, and it was mounted in an experimental flume. The flume was 23" wide and passed .3 to almost 1.0 cfs for power and fish passage experiments, using a range of fish and internal blade configurations and speeds.

The Sagebien Wheel was tested for power at two speeds over a range of heads. The wheel developed a maximum of about 64 % mechanical efficiency. No fish would pass upstream through the wheel irrespective of speed, number of blades, or their shape. Downstream passage was effected in 3 cases. Two fish were cut by the wheel during passage.

The main impediment to fish passage was not the wheel itself, but the difficulty of interesting fish to enter the wheel. Subsequent investigations of fish herding to and into the wheel were made. Two methods of herding fish were explored: a loop bubble curtain that was slowly dragged to and from the wheel, and an array of fixed loops activated in sequential patterns. Both succeeded.

In summary, the Sagebien wheel is efficient mechanically, but unlikely to be useful for transporting fish through dams due to its unattractiveness to fish. Bubble curtains were effective at moving fish to the wheel when the curtain surrounded the fish. Bubble curtains may prove very useful in large dam applications.

Keywords: Fish dam passage, herding, bubble curtain, Sagebien waterwheel, upstream guidance

The Sagebien Project

Executive Summary

Project Objectives

The Project's primary objective was to test upstream and downstream fish passage using a modified Sagebien water wheel. A secondary derived objective was to build a Sagebien wheel in a controlled flume that had a range of fish available for testing, and see if it could be modified to pass fish. In addition to passing fish up and down stream this project had as an objective to test the wheel for power efficiency using a Prony brake as this has not been done since the 1890's. Once the wheel was constructed and tested for power output in the flume, it was exhaustively modified and test for fish passage. Finally, to get fish through the wheel, it is first necessary to get the fish to the wheel. Some fish would enter the wheel area, but this appeared to often be for the cover and protection of the wheel rather than much interest in passing. This varied from test to test. Thus, a derived final objective was to induce fish to approach the wheel.

Project Implementation

To meet these objectives, a 3-foot diameter Sagebien water wheel was built and tested for both power output and fish passage. The project was then divided into four sub-objectives. First, to construct an accurate, half-size model wheel in a flume with controlled conditions for testing and fish available for testing. Second, to study the power output of the wheel and how that was effected by modifications of the wheel to pass fish. Third, to run some long-term experiments to see if fish were physically able and willing to pass through the wheel when next to it. Finally, to explore whether fish go near or into the wheel to pass through.

Project Outcomes:

Objective 1: Build Test Facility

We built an accurate Sagebien wheel out of Plexiglas and aluminum in a flume in the J. Amorocho Hydraulics Lab at UC Davis. This facility allowed complete control of head and flow and had an abundance of freshly caught fish available for testing. Water flow and fish activity were easily monitored through the glass sides of the flume and the Plexiglas sides of the wheel. Power measurements were made using a Prony brake built coaxially but outside of the wheel. The radius of the arm was 39.9" and the force was measured with a calibrated Toledo Postal scale. The RPMs were measured by timing the wheel using a small GE PLC as a time base. We had fish available from other experiments at the facility and caught others as needed in the Central Valley. We tested salmon, trout, and hitch of specific interest to California. We focused on Chinook salmon (two cohorts) in different life stages and various indigenous trout at different life stages, and hitch on their upstream migration. We also briefly studied threadfin shad and pike minnows as models for very small fish. The selection of fish was based primarily on fish age and motivation to travel up or down stream for a particular age at this time of year.

Objective 2: Measure Power

Since the wheel was constructed and operated in a hydraulics flume at UC Davis, measuring power generation vs. flow was accomplished with instruments from Davis Hydro and calibrated instruments from the lab. The test wheel was a hydraulic and power model of the 1870's technology, and was able to produce power at about 64 % hydraulic mechanical efficiency. This was about 10 – 15 % lower than expected. The low power was due almost entirely to the modifications of the wheel to pass fish. We had only 30 blades in for the power tests, but the wheel would be normally set up for about 60. Further modifications to enhance fish habitat included very tight and rubbing seals that may have had excessive friction. Finally, small turbine models are always less efficient than larger wheels due to the high surface area to volume ratios.

Sub Objective 3: Fish Passage Tests

Fish were caught and available at the J. Amorocho Flume. There is an extensive fish handling facility available. Coho and Chinook salmon, brown and rainbow trout, and hitch were used in most tests.

Upstream and downstream passage: The wheel was put in place and its configuration was explored to see if any fish would pass upstream through the wheel. Different configurations of blades, and speeds were tested. Because we were continually unable to get fish to pass upstream, most of our modifications were to make it easier for them to pass. In the end, we removed most of the wheel blades so that only the outer ridge of the blades were used and 10 blades were left. This provided a weir of about 6-7", an easy a passage as possible for the fish. Nevertheless, no fish would pass upstream. Typically about 30 % of the salmon would pass downstream. None of the trout or hitch would pass.

Motivation: The Sagebien wheel as constructed for use in a flume, has within it a broad crested weir of about 6" formed by the breast (bottom surface) under the wheel. This is the appropriate size of the fish we were testing which varied between about 3" and 12". The 10" inch coho salmon were tested to see if they would pass upstream over this weir without the wheel in place over a wide range of flows. They showed no motivation to pass upstream. It is possible that the fish were not motivated to go upstream in the lab situation, and therefore the negative results have to be tested in the field. Due to their life history stages, the coho salmon would have the least motivation at this time of year, the trout moderately motivated, and the hitch should have been motivated to swim upstream.

Down stream passage was not tested with only the breast (no wheel) in place. It is known that the salmon have a tendency to drift downstream passively. This was observed on many occasions with them schooling at the furthest downstream end of the flume from the wheel.

Passage Summary

No fish went through the wheel going upstream, apparently because even the fish had no interest in going near the wheel over a wide range of flows. A few fish would swim up under the wheel, but would not pass through the wheel. It appeared that the fish were only interested in approaching the wheel as a hiding place or for protection from investigators moving near the test flume.

Likewise typically, 1-2 out of 6 fish would pass down stream after many hours. The results were similar for all salmon. No trout or hitch passed downstream. This is compatible with their motivation at this season of the year for their age. It appeared that the fish mostly stayed away from the large wheel thrashing in their channel.

Objective 4: Attracting fish into wheel

For fish to pass through the wheel, the fish have to be induced to go into the wheel. This is a common problem, faced at every fish passage. Because the largest problem with getting the fish to pass through the wheel was getting the fish to approach the wheel, our research expanded in this area. This is a worthy research objective, because there are many technologies to move fish over dams. Many work. However, fish locks, fish ladders, fish trucks, all are limited by getting fish to come into the technology. Thus, under this derived objective, we expanded the depth of the research significantly. We knew that fish might pass the Sagebien Wheel, if the fish would go to it. This we addressed in depth due to its wide applicability and this is discussed in the following sections.

Objective 4a Bubbles as a Fish Herding Mechanism.

We instituted an additional research topic: herding fish to fish bypass facilities. We explored the literature, and built several fish herding test apparatuses in the flume above and below the wheel as part of our ongoing experiments. The mechanisms explored were based on moving air-bubble curtains. The underlying principle is that by moving the curtain, we could move fish that were interacting with the curtain. In May, we conducted two types of relevant experiments:

We practiced with various hand-manipulated drawn air curtains, slowly dragging a single bubble curtain to and away from the wheel. This was very successful in moving various sizes and types of fish.

We constructed and used a series of 21 loops, in ladder formation, whereby sequential charging of the ladder's "rungs" with air produced apparently "moving" bubble curtain loops. This was quite successful at moving fish along the length of the flume, with the effect limited primarily by the barriers at the end of the flumes.

Conclusions

1. Efficiency: The Sagebien Wheel is a modestly efficient electric power generator from moving water. The model clearly shows the limitations of the technology. The Sagebien wheel, as in all water wheels, scales in size linearly with head. The total costs therefore vary with a multiple power of the head. This contrasts with a pressure turbine where the equipment size drops with a fractional power of head. Thus, water wheels, and this is no exception, are only useful at low heads where they can be very efficient. The Sagebien turbine turns very slowly. While this increases hydraulic efficiency through reduced turbulence, it requires a large gearbox. The maximum efficiency of 64 % was lower than that recorded in the French literature because of the modifications to the blades for fish passage.

2. In testing the Sagebien wheel, it became clear that in the entrance to the wheel, the blade drops like a guillotine cutting any fish that is only part way through the turbine on the upstream side of the upper bucket. This means that any fish that is going to pass has to be small relative to the bucket size, and/or has to pass through it quickly. There was no question from our observations that fish had the ability to move fast enough to pass through the wheel up or downstream if were they motivated. However, the mode of swimming downstream was drifting with the current, and this

proved fatal to two fish moving downstream. Thus, we conclude that this fish passage technology has inherent, limiting flaws.

3. This research addresses fish passage at dams, and a mechanism to help the fish across these barriers between habitats. We have concluded from this study that although there may be efficient mechanisms for moving fish across dams, the main problem is interesting fish to move into the various passage technologies. The Sagebien technology suffers from this problem excessively in that the fish have to enter in or under a large rotating mechanism for the technology to be effective. For this reason, we concluded this project with research on getting the fish into the wheel. This work actively continues unfunded.

4. Air bubble curtains are effective at moving some fish, some of the time. They may be effective at moving large amounts of fish to fish by-pass facilities.

5.

Recommendations

We are continuing to test bubble curtains on various species of fish and under different conditions as resources permit. It must be emphasized that all fish are different in response to various physical stimuli. Equally important is that fish respond differently at different stages in their life cycle and their conditioning at that moment. The following are recommended work items for further research.

The moving bubble curtains show considerable promise and should be researched further. This technology is interesting and needs research because if we can move fish – even certain types of fish, it will enable many fish transport and capture mechanisms. This technology may be useful in solving the problem of fish hesitancy at the entrance to fish passage devices. This entrance inhibition is a universal problem, and if it can be solved, fish can be passed by many dams, and the savings in water that is currently in use to attract fish may be significant.

Public Benefits to California

The public benefits to California of this research are both direct and indirect. The objective we addressed is to move fish past dams using less water. Using less water for fish attraction flows to bypass facilities means that more water may be available for other uses. In summary, the benefits that will flow from this includes both power savings, water savings, and fisheries enhancement as described below.

Power Savings: Less water used for fish-attraction flows. The result of this is that there will be more water for timed releases for other purposes, including fish migrations (e.g., Environmental Water Account), water quality (e.g., cool temperatures for resident and migrating salmonid fishes), hydropower, municipal uses, or irrigation. If not needed for these uses, water behind dams facilitates gravity-fed irrigation. This saves both water pumping costs for farmers on the water diversion canal, and leaves more water in the water table, reducing water pumping costs for non irrigation canal participants of all types.

Water Savings: If fish can pass using little water between habitats, then less water has to be used for this purpose. Less water used for fisheries bypass purposes implies that more water would be available for other uses.

Fisheries Enhancement: Available water could be used more creatively to expand and improve fish habitats.

In summary: In our original proposal it was thought that the Sagebien wheel could pass fish. While the wheel was found to poorly pass fish in one direction, it was not found to be useful primarily because the behavior of the fish is such that they will not approach the wheel. However, we discovered in this research that fish do respond in various ways to moving bubble curtains and that at least in the lab, moving bubble curtains can be used to move fish. The ability to move fish toward a bypass facility, which may help California fisheries management.

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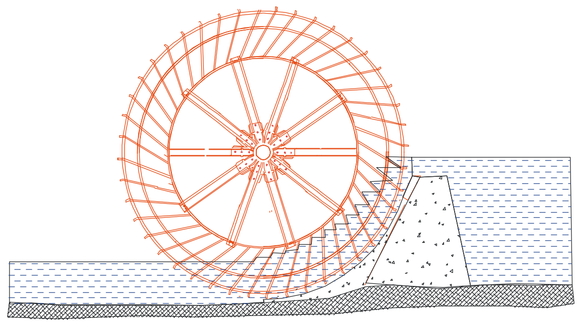

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PIER Subject Area: Renewable Energy Technologies

Introduction

This Pier subject area looks at the interaction of the environment and energy in California. The goal of fish passage through dams comes from concern for the fish that are impacted by dams which provide humans enormous benefits in hydropower, flood control, irrigation, recreation, and water supply. On the other hand, dams invariably change and destroy environments in which they are built. This work is an attempt to ameliorate that situation by looking at a method to provide passage through the dams for fish.

This study took as its mandate a systems approach to ascertain how to get fish up and down-stream in California using a modified form of a water wheel. This work is an attempt to look at undershot waterwheels in general and the Sagebien wheel in particular as possible technologies to pass fish up and down stream. The Sagebien wheel is an efficient power generator, but suffers from the problem of all water wheels: the technology scales linearly with head, or the height of the water. It takes a 6-foot water wheel to pass water down a 3-foot drop. This means that the Sagebien wheel is applicable to the small diversion dams around Northern California diverting water into rice paddies, and is applicable to low head situations where fish would benefit from passing.

Report Organization –

This report is organized as follows: First, a description of the objectives of the study. Then we describe the approach along with the individual tasks. The research was stretched in a particular direction as the result of some surprising intermediate results, so there are more outcomes and conclusions than the original research agenda. Finally, we discuss the outcomes and conclusions from this work. The outcomes and conclusions are different from what was expected because we have extended the report in the direction of solving the underlying problem, within our technology as well as many others.

Project Objectives

The Sagebien Project's primary objective was to test upstream and downstream fish passage using the Sagebien waterwheel. To accomplish this objective there were several sub or secondary objectives identified:

Build Model: A secondary derived objective was to build a test Sagebien wheel in a controlled flume and see if it could be modified to pass fish.

Measure Power: A secondary derived objective was to test the wheel for power efficiency using a Prony brake, as this has not been done since the 1890's.

Pass Fish: A secondary derived objective was to test whether fish would pass through the wheel through its modification.

Attract Fish: A secondary derived objective was to induce fish to come into the wheel. This objective is identical to a need at all fish passage technologies in the world.

Project Approach

This section discusses the procedures we undertook and how the research was extended beyond the original wheel to a newly developed technology that may be instrumental in passing fish at all dams – not just at low head dams appropriate to the Sagebien wheel.

Objective 1

The objective of this research was to test the upstream and downstream passage of fish through a Sagebien water wheel in a laboratory flume. To do this test, it was necessary to accomplish several sub objectives outlined above and the approach taken to each is discussed in the following sections. This will then be followed with an outcome section that will discuss the accomplishment of these objectives and results of the tasks.

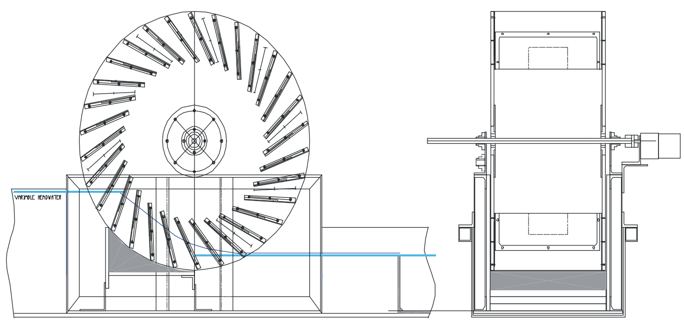

Figure 1 The Sagebien Wheel in Flume Cassette

Sub Objective 2: Build Model

To accomplish the project's main objective, a 3 foot Sagebien tur bine was constructed from Plexiglas and aluminum (Figure 1). It was sized to fit tightly into a flume that was 23.5" wide and over 50 feet long. The sides of the flume were raised 10" upstream of the wheel so that up to 9" of head could be developed with at least 6" of tail water depth. The mill had provision for 2 fixed speeds, and other speeds by varying gear ratios. Only two were used. The sides were clear to facilitate watching the fish move through the sides of the mill.

All the blades in the mill were removable so that different number of blades could be tested. All blades were modifiable so that we could test fish passage through small or large slots in combinations of blades or arbitrary heights. The mill was built and installed in the flume with some delay due to administrative problems at UC Davis.

Sub Objective 3: Measure Power

The wheel was constructed and operated in the J. Amorocho hydraulics flume at UC Davis. Measuring power generation vs. flow was accurately accomplished with calibrated instruments from Davis Hydro and from the lab. The test wheel was an accurate hydraulic and power model of the 1870's technology, and was able to produce power at about 64 % hydraulic mechanical efficiency.

Figure 2 Prony Brake drum on side of Sagebien Waterwheel Cassette

Figure 2 shows the Prony brake drum used for Power measurements. The drum was fitted with a fiber and wooden shoe, lever arm, and scale for power calculations. This Prony brake was constructed to measure power from the unit, and was used during all tests to help control the speed of the unit. The actual speed was regulated by a fixed gear ration of a drive motor/generator connected on the far side of the main shaft. The motor was controlled and measured by a GE series 90 Programmable logic controller.

Sub Objective 4: Pass Fish

Experimental Conditions:

Experiments were conducted using the wheel described above. The flume was connected to a variable-speed 5 Hp pump that was able to provide up to 2 cubic feet per second. The flume was modified on one end with flash boards so that the water on the up-stream side could be up to a foot higher than water on the lower side of wheel. Typical actual differential was only about 6". Many different water flows, wheel speeds, and water levels were experimented with, but eventually two protocols developed: about 0.3 cubic feet per second (slow) and about 0.5 cubic feet per second (fast). The Sagebien wheel was set at 12 feet from the upstream end of the flume. For most the work reported here, the wheel turned at 2.4 RPM. A 7" weir [1] was placed at 11 ft downstream of the wheel to adjust the tail water height. This produced about 8" of depth below the wheel in the 23" wide flume. In the experiments, the "upstream" was typically about 14" deep. The target water temperature in the flume was kept at 14 °C (+/- <2°C), and the fish that were used for the experiments were also held in fiberglass tanks with the same target water temperature. Fish were caught as needed, temperature conditioned, and made available from other experiments in the lab. The fish used included:

Coho salmon, <u>Oncorhynchus</u> <u>kisutch</u>, (mean SL[2] = 24.0 cm), in the smolt stage of their life cycle. During this life stage, they have tendency to want to swim downstream to oceans. This made them useful for downstream tests. This size and species are strong swimmers, so they have the physical ability to go either way through the wheel or over the test weirs.

Hitch, <u>Lavinia</u> <u>exilicauda</u>, (mean SL = 13.7 cm), in their upstream spawning migration stage. They have tendency to want to swim upstream during this stage. This species likewise, are strong upstream swimmers, and have the physical ability to pass up or down stream over any of the test set-ups with the wheel in place or removed.

Winter-run Chinook salmon, <u>Oncorhynchus</u> <u>tshawytscha</u>, (mean SL = 6.9 cm), in their parr stage of their life cycle. They stay in streams during this stage. These fish are smaller, and are not generally motivated to swim upstream or downstream.

Brown trout, <u>Salmo</u> <u>trutta</u>, (mean SL = 23.0 cm), which is a resident stream fish and moves around a stream for numerous reasons.

Rainbow trout, <u>Oncorhynchus</u> <u>mykiss</u>, (mean SL = 16.4 cm), which is resident stream fish. These trout species have tendency to want to stay in one place in streams but are able to swim up stream and downstream if motivated.

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[1] An 8" weir was also used in experiments to raise the tail water to encourage fish to enter the wheel.
[2] SL: Split Length measured from the center of the split in the tail fin to the nose.

Biological Motivational Setting:

At this time of year and under the laboratory conditions presented to the subject fish, winter run Chinook salmon ("parr" stage), brown trout, and rainbow trout are all found in streams in the Sacramento basin. From behavioral studies, these species were selected for applicability and because some were likely to cross the wheel both upstream and down. Coho salmon (smolt stage), which migrate down streams to oceans, were likely to cross the wheel to the downstream from the upstream. Hitch (upstream spawning migration stage) were the most likely to cross the wheel to the upstream from the downstream. The trout - being station-keepers - were expected to move either upstream or downstream when motivated.

Methods

Informal Exploratory Tests:

After some exploratory trials with several fish types, experiments settled into a pattern of continually modifying the wheel and water conditions to get any fish to pass up or downstream. The results reported below followed from these exploratory tests using the most likely conditions, including flow, wheel speed, blade configuration, direction and fish type. For example, informal exploratory work was done at higher rpm and higher flow, but the fish had little interest in approaching the wheel even when left for extended periods (6-8 hours).

Structured Tests

Fish were released in the upstream or downstream of the wheel in separate batches to examine whether these fish were able to use the Sagebien wheel to go upstream or downstream. The numbers of fish that crossed the wheel were recorded over a period of time – typically 6 hours. The typical number of fish in an experiment was 6 for small fish (<15 cm). Because putting more than 4 large (>15 cm) fish in the glass flume was too crowded, only 4 fish were used for the "large fish" experiments.

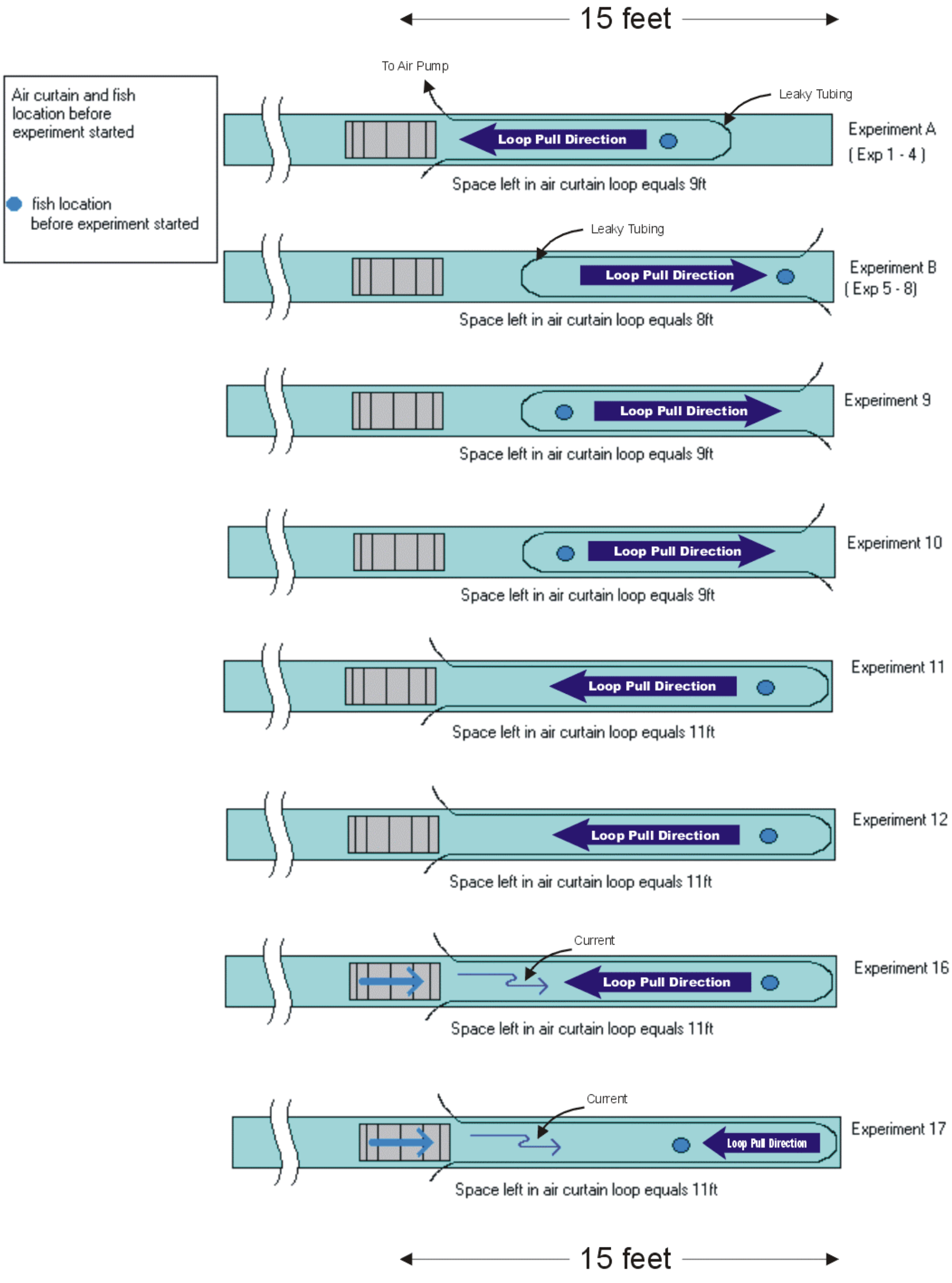
The wheel has provision for changing speed, the number and shape of vanes, as well as height above tailwater. As the result of the initial tests, the experiment fairly quickly focused on our slowest speed, the minimal number of blades, fairly high tailwater, and the minimum vane height in the hopes that fish passage would be possible. This configuration led to low power output and a fairly inefficient wheel due to internal spillage and poor bucket filling, as can be seen in the power tests. Finally, the water level and flow were varied over the testing period to find a combination of flow levels, and vane numbers most conducive to fish passage.

Sub Objective 5: Attracting Fish into the Wheel

We expanded this particular research objective. That is, how to herd fish to fish bypass facilities. We explored the literature, and built several fish herding test apparatuses in the flume above and below the wheel as part of our ongoing experiments. The mechanisms explored were based on moving, air-bubble curtains. The underlying principle is that fish interact with strange air bubble

curtains, and that by moving the curtain, we could move fish that were associated with the curtain. In this work, we conducted experiments later in May:
HAND DRAWN: We practiced herding first with various hand-drawn air bubble curtains, slowly dragging a single curtain to and away from the wheel. Figure 3 shows the various configurations of loop dragging. A 15-foot test area of the glass flume (23”-width) was used to conduct the air-curtain experiments. A 25-foot long leaky air tube was placed on bottom of the flume and air was sent from an air pump into the both ends of the tube to create a uniform amount of air bubbles throughout the tube. Before each experiment, the tube was set at the initial location shown in Figure 3, and fish were placed within the loop. During the experiments, 6 fish were used at a time. The loop was slowly pulled from the initial loop location. As the loop was pulled, the number of fish escaping from the loop and the location of the loop end was recorded. For the experiments, winter-run Chinook salmon (mean SL = 6.9 cm) were used, and the results from these tests were recorded as the number of fish that crossed the loop as a function of loop position.

Figure 3 Hand-drawn Loop Arrangements
(*All figures show initial loop locations*)



FIXED ARRAY: A series of 21 loops in a ladder formation forming moving loops of bubble curtain. This was quite successful at moving fish up and down the tank with the effect limited primarily by the barriers at the end of the flumes. These are described in the following section. Figure 4 below shows the typical loop arrangements for the fixed arrays.

Figure 4 Fish-Herding, Fixed-Array Arrangement

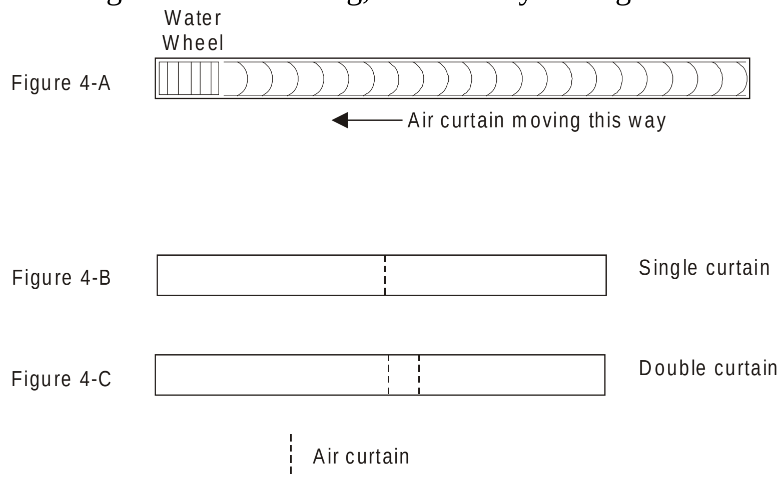


Figure 4(A) shows a 20-foot section of the 23"-long glass flume used to conduct the air curtain experiments. The sidewalls and floor of the flume were covered with a black-plastic sheet to keep the fish from locating on the flume frame hardware as the flume has glass sides. The array of 21 air tubes was fixed on the flume bottom with 10-inch inter-tube spacing. Each air tube was separately connected to a complex of ganged solenoid valves connected to an air pump. The bubble curtain loops were programmed to be activated in sequence producing what appears as either a single or multiple curtains that move up and down the flume, acting like moving walls partially surrounding the fish. The curtains move, under computer control, from one end of the flume to the other and were repeated without delay. The speed of the air curtain movement was varied in many informal experiments. Typically, it was set to move from tube to tube at 12-second intervals. As the curtain moved, the number of fish herded and curtain location were recorded. For the experiments, 6 groups of winter-run Chinook salmon (mean SL 6.9 cm) were used.

In addition to the air curtain experiments with the single-herding curtain (Figure 4.B), experiments. Double-herding curtains (Figure 4.C) were also conducted. Because a computer was used to control the valves, any combination of the loops could be used to make one or more curtains and control their movements. Typically patterns were set for a curtain every 16 or 21 or loops. When set for every 16, there would always be two curtains in the test area of the flume at the same time, which is how we expect the technology might be used in the field.

Project Outcomes

The project outcomes are presented as follows:

- power of the Sagebien wheel,
- passage of fish downstream and upstream,

- and the most promising outcome, which was unexpected,
- ways we can motivate fish movement to any fish passage technology.

Power Tests:

Measuring power generation vs. flow was easily and accurately accomplished with instruments from Davis Hydro and the lab. Other than the adjustable number of blades, the test wheel was an accurate hydraulic and power model of the 1870's technology, and was able to produce power at about 64% mechanical efficiency. Figure 2 shows the Prony brake drum that was used with the lab scale for power calculations. Its operation was smooth and repeatable. This Prony brake shown in Figure 2 was constructed to measure power from the unit, and was used during all tests to control the speed of the unit. Table 1 shows the results of the efficiency tests over a range of heads and loads.

Table 1 – Measured Efficiency

Flow	Brake	Rpm	Power out	Head	Input	Efficiency
cfs	lbs		watts	inches	watts	percent
0.230	4	2.4	3.3	5.13	8.3	40
0.243	6.75	2.4	6.4	6.58	11.3	56
0.298	7	2.4	6.7	6.99	14.7	45
0.338	7.32	2.4	7.0	7.16	17.1	41
0.384	7.55	2.4	7.3	7.11	19.2	38
0.240	5.71	2.4	5.2	5.59	9.5	55
0.298	5.79	2.4	5.3	6.09	12.8	42
0.288	5.7	2.4	5.2	5.92	12.0	43
0.305	5.07	2.4	4.5	5.06	10.9	41
0.208	6.13	1.2	2.8	6.76	9.9	29
0.277	6.56	1.2	3.1	7.31	14.3	22
0.346	7.64	1.2	3.7	7.43	18.1	20
0.145	5.2	1.2	2.3	5.16	5.3	44
0.211	6	1.2	2.8	5.60	8.3	33
0.253	6.5	1.2	3.0	6.14	11.0	28
0.295	6.95	1.2	3.3	6.40	13.3	25
0.183	4.3	2.4	3.7	4.41	5.7	64
0.240	5.4	2.4	4.9	5.09	8.6	57
0.288	6.5	2.4	6.1	5.62	11.4	53
0.313	6.5	2.4	6.1	5.74	12.6	48
0.353	7.55	2.4	7.3	7.01	17.4	42
0.302	7.3	2.4	7.0	6.88	14.6	48
0.270	5.8	2.4	5.3	6.18	11.8	45
0.217	5	2.4	4.4	5.88	9.0	49

In summary, maximum efficiency was 64 %. A complete Excel spreadsheet summary of the data measured is included as in Appendix I to this Report.

Passage of Fish Upstream:

The following is a summary of experiments with fish released downstream of the wheel and allowed, but not artificially induced, to swim upstream. In all cases the fish would orient themselves into the current, and in many cases individual batch members would have a tendency to swim upstream. However, there was no other motivation for the fish to swim upstream. In the case of the salmon, unlike the hitch or trout, it is part of their lifecycle to move downstream at this life-stage. This suggests that the motivation to cross the wheel varied between groups of fish, although no direct means were available to measure motivation.

Not one of the species crossed the wheel swimming upstream. Winter-run Chinook salmon, brown trout, coho salmon, and hitch showed some attempts to cross the wheel during the experiments, but they did not - even at the low speeds used and with large bucket settings. Intermittent tests were done with winter-run Chinook salmon at higher water speeds to see if the higher water flow would induce upstream migration. Table 1 Worksheet in Data.xls in Appendix II shows the conditions of different tests. The codes for this table are in Worksheet "codes" in the same Appendix. Notes for the runs are included within the spreadsheet as shown on sheet "notes". The following is a discussion of these tests.

Table 2 Fish Swimming Upstream

Run	No. of total rep	Fish species	Wheel Speed /no. floats	Upstream depth[3] (Mean)	Down - stream depth (Mean)	Flow rate	No. of fish used	No. of fish passed wheel
Wc-1	1	Winter run Chinook salmon	20	13.9 in	8.1 in	slow	6	0
	1	Winter run Chinook salmon	20	15.8 in	8.7 in	fast	6	0
	1	Coho salmon	10	13.6 in	8.4	slow	4	0
	1	Brown trout	10	13.7 in	8.3 in	slow	4	0
	1	Rainbow trout	10	13.7 in	--- *	slow	4	0
	1	Hitch	10	13.9 in	8.2 in	slow	6	0

*temporary curtain in way

[3] The upstream depth and downstream depth are taken at beginning and end of each experiment. Wheel Speed is 2.3 RPM for all tests reported here.

Detailed observations of the experiments:

Winter run Chinook salmon (mean SL = 6.9 cm), in their "parr" stage, tend to station -keep in streams, but are able to swim upstream and downstream when motivated by food, shelter, fear, or other reasons. During this season, they would normally be moving downstream. These fish were from the UC Davis Bodega Marine Laboratory and had not been used in experiments[4]. They easily had the physical ability to swim through the wheel, if so motivated. However, this was not observed. These experiments were run with a flow of about 0.3 cfs going through the wheel for the slow water velocity and 0.5 cfs for the fast water velocity.

These fish were positively rheotactic and often swam in a school, and mostly held station (physical position) during experiments. On occasion, 2-3 fish would leave the school and swim up into the wheel during the experiment with both slow and fast water flow. There was high water turbulence under the wheel. The fish that were trying to swim into the wheel were swept down by the water before they passed the floats. A few fish reached or touched the outer half of the wheel floats, but they did not proceed upstream.

Coho salmon (mean SL = 24.0 cm) in their "smolt" stage, tend to want to swim down stream to oceans. These "used" fish had been through other experiments. This experiment was run with a flow of about 0.3 cfs going through the wheel. The fish were positively rheotactic and swam mostly in a loose group. Typically, 2 out of 6 fish wandered into position to cross the wheel for the first hour of the experiment. These fish were able to reach or touched the outer half of the floats, but they appeared disinterested or were pushed back by the water coming from upstream or by the moving floats. After one hour, fish were holding in position at 3-6 ft from the wheel and did not approach it afterwards.

Motivation: Fresh fish of this type were also used is a separate set of experiments on motivation of the swim past the barrier of the Sagebien wheel. In the first of these experiments, the wheel was removed and the 12 in. weir formed by the wheel's breast was left in place. The height of the water over this weir varied with the water flow from about 0.5 inches up to about 1.5 inches. Four coho salmon fish were acclimated[5] for about 40 minutes in the flume then released to see if they would naturally pass up over the weir. Water flow was varied slowly over an hour from about 0.2 cfs all the way up to about 0.6 cfs to see if the fish would pass naturally up over the weir under conditions similar to those that the wheel is expected to address. However, they did not pass over the weir. More interesting is that they never approached it, but, rather, drifted downstream and swam in place next to the downstream grate. They would not swim upstream, even when provoked by visibly approaching them and disturbing them by manipulating the water over and just downstream of them, near the experiment's conclusion.

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[4] Fish that were fresh caught have been observed to behave differently from fish that have been used in some experiments. Tests reported here are annotated to be with "fresh" or "used." "Used" fish were also used for experimental runs testing wheel speed, water depth, sprint speed, and later for herding tests.

[5] All runs were made with "acclimated" fish. This means that they were brought slowly from their holding pen temperatures to the temperature of the flume. Typically there was some difference in the temperatures, thus the "acclimation" was to let the fish adjust to the surroundings and be slowly warmed up to the flume temperature.

A second set of motivation experiments with a different set of fish was conducted to assess the impact of weir height. The breast was removed, and a 6" board was used as a weir in about 5 inches depth of slack water. When "low" flow of about .5 cfs was used, there was about 1.5 in. between the levels with about 0.5 inches of water coming over the weir. This should have been a passable barrier for these fish, although they showed no interest in approaching the weir. Coho salmon are not good test animals in the flume to test for upstream passage, but they may suffice to indicate downstream migration.

Brown trout (mean = 23.0 cm) are resident stream fish that tend to stay in streams but have the ability to swim upstream and downstream. These trout also were not fresh fish. The experiment was run with a flow of about 0.3 cfs going through the wheel. The fish were positively rheotactic and swam mostly in a group. They swam in position at 9-10 ft away from the wheel for first 4.5 hours. They started to be active during the last 1.5 hours of the experiment, although the reason for the change in activity is unknown. It may have been hunger or an increasing familiarity with the wheel. About 5 hours from the start of the experiment, 2 fish appeared to actively cross the wheel. They swam up between floats many times, and they sometimes swam over one float. There were, however, 2-3 floats to go over in order to reach to the upstream level clear of the wheel.

Motivation: These trout were not motivated to swim over the next float. They stayed in the wheel until they were carried back into the downstream side of the wheel. There may not have been enough space in the chambers (in the wheel) to make another jump. However, the wheel spacing had been increased at this point and further increases would have negated any effective power. Only 10 floats were used in this experiment, having been reduced from the original Sagebien design of about 60, and the spacing was there for the fish was about 30 cm between the floats. Because these fish were 23.0 cm long, there was little room for acceleration.

Rainbow trout (mean SL = 16.4 cm), a resident stream fish, tend to stay in streams but are able to swim upstream and downstream. It is unclear if these fish were "fresh" or "used" (borrowed from another investigator). They were positively rheotactic, and the experiments were run with a flow of about 0.3 cfs going through the wheel. During the first 3 hours of the experiment, one fish swam under the wheel but did not try to swim through the wheel. Other fish were swimming in position at about 3-6 ft from the wheel, and showed no interest in entering the wheel. During the last 3 hours of the experiment, 4 fish were swimming in position at about 4-8 ft away from the wheel, without grouping and showed no interest in entering the wheel.

Hitch (mean SL = 13.7 cm), in their spawning migration stage, tend to swim upstream at this season of the year. We had just caught them fresh, (electrofished from the Mokelumne River). The experiment was run with a flow of about 0.3 cfs going through the wheel. Five fish went below the weir as soon as the experiment started and remained there throughout the experiment. For the first 3 hours of the experiment, they constantly swam back and forth in a tight school. They were very active and explored extensively. They sometimes tried to swim over the downstream weir out of the experimental area. For the last 3 hours of the experiment, they mostly swam in a school.

<u>Motivation</u>: The hitch swam very actively, sometimes jumping back and forth over the

downstream weir during the experiment. During the first half of the experiment, one fish often tried to swim into the wheel in the downstream area. It was able to swim up to the surface between floats, but was pushed back. During the last half of the experiment, the fish sometimes swam into the current under the wheel, but not into the wheel.

Passage Downstream:

In general, fish swam near the wheel, despite the 12 linear feet available in the flume above the wheel. The fish were not drawn into the wheel, possibly because they were in a back eddy near the bottom. There were few fish that crossed the wheel drifting downstream. These species were winter-run Chinook salmon, coho salmon, and hitch which were swimming near the surface. They seemed to be drawn into the wheel as the floats in the wheel drew the upstream water into the wheel. Table 3 shows the results of typical runs at 2.3 RPM.

Table 3 - Fish Swimming Downstream

Fish Fish	No. floats	Upstream depth	Down - stream depth	Flow rate	No. of fish in exp.	No. of fish passed wheel
Winter-run Chinook salmon	20	14.2 in	8.4 in	slow	6	4
Coho salmon	10	13.8 in	8.4 in	slow	4	0
Coho salmon	10	14.5 in	9.4 in	fast	4	1
Brown trout	10	13.5 in	9.0 in	slow	4	0
Rainbow trout	10	13.6 in	7.3 in	slow	4	0
Hitch	10	13.3 in	8.2 in	slow	6	1

Winter run Chinook salmon (mean SL = 6.9cm), in their parr stage, normally tend to stay in streams, possibly drifting down, but they are easily able to swim upstream or downstream. The experiment was run with the BML-sourced fish, with a flow of about 0.3 cfs going through the wheel. All fish were released at the far upstream end from the wheel. At the beginning of the experiment they were positively rheotactic and swimming in a school. They gradually moved toward the wheel and started to swim up and down in the water column in a school as the experiment proceeded. Three fish were drawn into the wheel at 3 - 3.5 hours from the beginning of the experiment. One of the fish was caught in the wheel and died while it was crossing the wheel. For the last 2.5 hours of the experiment, fish mostly stayed at the upstream screen. One fish crossed the wheel going downstream near the end of the experiment.

Brown trout (mean SL = 23.0 cm) and **rainbow trout** (mean SL = 16.4 cm), resident stream fish, are reported together because they behaved similarly. They tend to stay in streams but swim upstream and downstream. The experiments were run with a flow of about 0.3 cfs going through the wheel. No fish crossed downstream through the wheel during the experiments. Fish were positively rheotactic, swimming between bottom and middle depths. They spread out between the wheel and the upstream screen, and sometimes they schooled. Few fish stayed near the wheel. However, when near it, their depth kept them from its opening.

Coho salmon (mean SL = 24.0 cm), in their smolt stage, tend to swim downstream to oceans. These fish were not fresh fish, and the experiment was run with a flow of about 0.3 cfs going through the wheel. During the experiment, no fish crossed the wheel. Fish were positively rheotactic, swimming near the bottom-middle depth throughout the experiment. During the first half of the experiment, 3 fish were in a school near the upstream screen 14 ft from the wheel and 1 fish was near the wheel. Near the end of the experiment, all fish started to be near the upstream screen in a school far from the wheel.

Some runs were made at 0.5 cfs, where the fish were mostly in a school, positively rheotactic, and swimming in position, at bottom – middle depth. They stayed within 6 ft from the wheel during most of the experiment time. Some fish occasionally swam back and forth during the experiment, and 1 fish was caught in the wheel as it crossed the wheel at 5 hrs after the start of the experiment.

Hitch (mean SL = 13.7 cm), in their upstream spawning migration stage, tend to swim upstream. These fish were fresh fish, and the experiment was run with a flow of about 0.3 cfs going through the wheel. For first 3 h, fish were in a school constantly swimming back and forth in all depths. One fish crossed the wheel during the first 30 minutes of the experiment, but its caudal fin was partially missing, probably a result from crossing the wheel. For last 3 hours, fish were mostly swimming in position, positively rheotactic and in a school. The hitch were the most illustrative of the Sagebien wheel's possibilities to operate as a "slowly rotating fish ladder" because these fish were fresh, and naturally motivated this time of year to swim upstream.

Herding

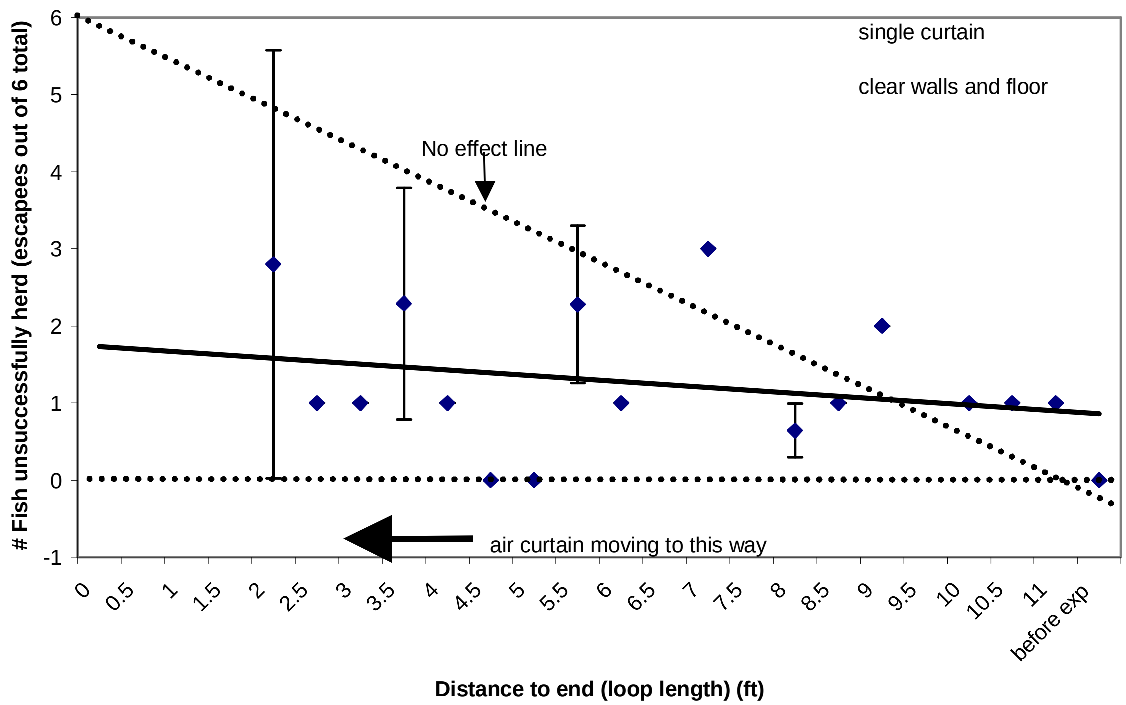
The main outcome of this research is some definition on an opportunity to herd fish. We show that we can move some fish in a direction (e.g., into a fish bypass technology as unattractive as the Sagebien Wheel appears to be). By studying the responses of many fish to moving air curtains, we have often observed a weak herding response.

Loop Dragging Results

We started fish herding experiments by very slowly dragging leaky tubing that produced an air curtain up and down a flume, watching whether the fish would be influenced by it. The loop was effective at corralling the fish and moving them up or downstream (4 experiments, Figure 5), the graph shows the relationship between the curtain position (see Figure 3) and the number of fish that were able to "escape" from the loop. The "no effect" (dotted) line shows an estimated number of fish outside of the loop, if there was no effect of the air curtain on the fish. Thus, data points from farther below the "no effect" line demonstrate increased fish herding success.

For example, if the air curtain had no effect we would expect about three out of 6 fish to be on both sides of the leaky tube when the tube is half way down the flume. This is shown by the dashed lines.

Figure 5 Pulled Loop Air Curtain Effect on Juvenile Chinook Salmon



The linear regression solid black line shows that the number of fish that escaped out of the loop remained low as the loop shortened, meaning that most of the fish were successfully herded in these experiments. During the experiment, fish were mostly in a group, swimming back and forth ½ – 1ft inside of the loop end. As the curtain was pulled through the flume, they also moved, maintaining the distance from the loop end. Although 1-2 fish sometimes swam out of the loop, they quickly swam back through the curtain joining the other fish. Complete data tables are included in Appendix III. Because these results were promising, we continued our experiments with the fixed arrays of emitting tubes on the bottom that synthesized moving the air curtains by sequentially activating adjacent tubes under computer control.

Fixed Array Results

Sequential charging rings in a fixed "ladder array" to simulate moving loops, we observed, again, that we could move fish using air bubbles. Even in the chaotic environment of a hydraulics laboratory, the effect appeared to be significant and repeatable with little difference attributable to which direction the apparent bubble curtain was moved. Typical results from 2 experiments with a single bubble curtain and 2 experiments with double herding curtains are reported. Figures 6 & 7 show the relationship between the distance of the curtain to the end and the number of fish that were not herded successfully. Both lines are located below the "no effect" line, but tend not to be as low as the result in the previous experiments with the pulled loop. Because the line for the double curtain experiments (Fig. 7) is closer to "no effect line", double curtains seemed to result in less successful herding, compared to the single curtain result.

Fish were observed to be mostly in a group and herd successfully up to about the halfway point of the flume. They mostly swam in a group, about 2 feet ahead of the herding curtain. The distance between the curtain and the fish started to decrease when the herding curtain passed the ¾ point in the flume section, and fish would turn around and bolt across the curtain(s) before they got too close to the end. These results are typical behavior of winter-run Chinook salmon with the fixed array.

Figure 6 Fish Herding Results with a Single, Fixed Air-curtain Array:
Effects on Juvenile Winter-run Chinook salmon

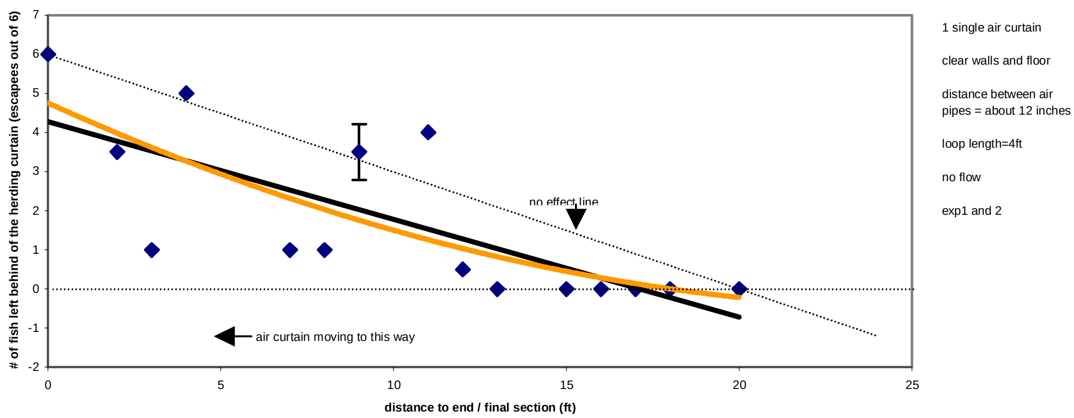
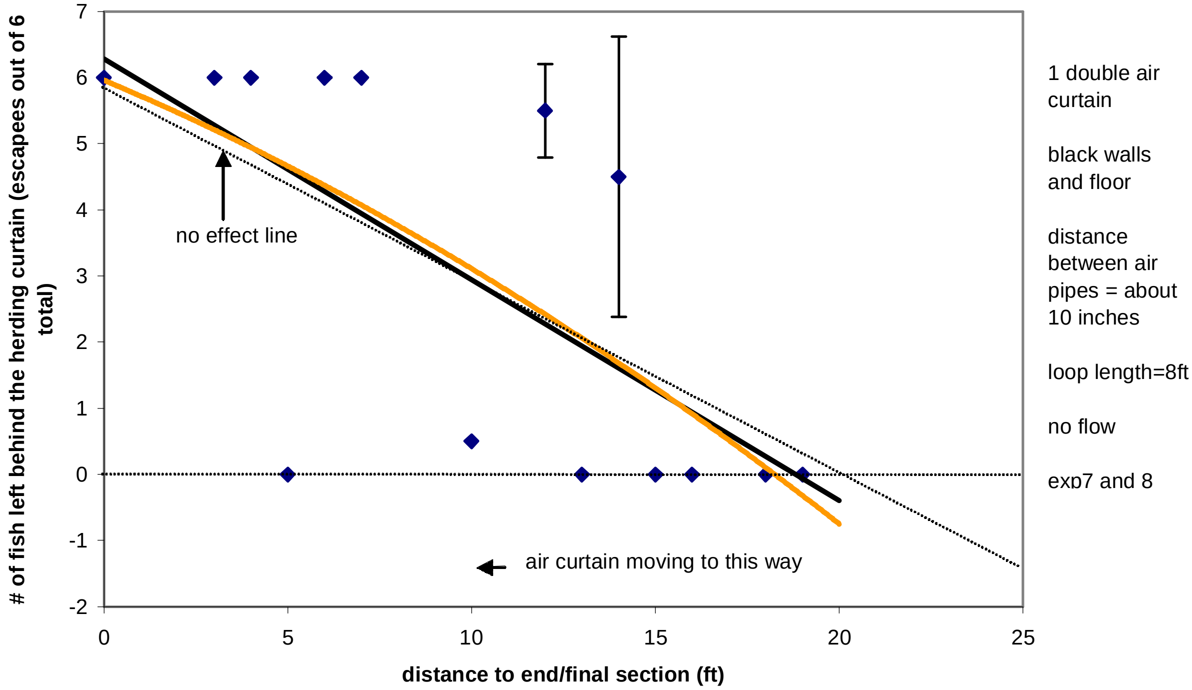


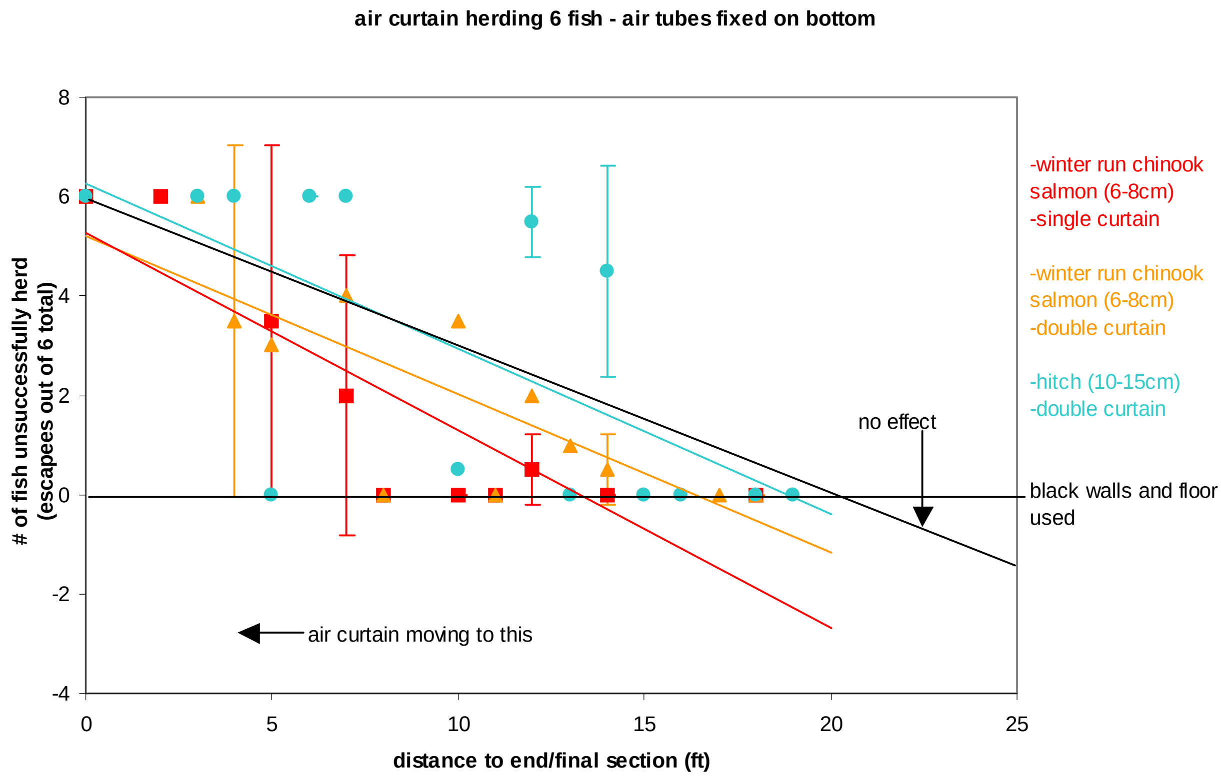
Figure 7 Fish Herding Results with a Double, Fixed Air-curtain Array: Effects on Hitch



As the double air curtain moved from 20 to 10 ft, almost no fish crossed the curtain. During the experiments, hitch swam in a tight group back and forth from one end from the other end of the flume to the other end, often through the air curtains. Typically, the hitch moved ahead of the advancing curtains of air until they swam in tight circles, appearing trapped, near the end of the flume. Then, as a group, they would bolt through the air curtain (e.g. distance to flume end < 10 ft., Fig. 7). Two more sets of experiments were conducted with Chinook salmon, and the results shown along with the hitch in Figure 8.

Figure 8 shows the aggregate response that is clear when observing the fish. They generally move in front of the curtain until they get near the looming barrier at the end then they bolt as a group. This shown in the figure a sigmoidal curve starting in the lower left and moving to the left where suddenly there is a bolt point.

Figure 8: Summary of Herding with Fixed Arrays



Factors that inhibited the herding behavior were external movements of the observers and crowding near any "end" of the flume. Specifically, when the fish were herded in a direction, they would be observed to stay at a fixed position relative to a moving air curtain until the end of the flume loomed, then the fish would bolt back, through the air curtain, toward the middle of the test area in the flume.

Summary of Observations

Upstream Passage

Small fish were observed to have a hard time to swim against the fast flow and turbulence underneath the wheel. We produced no evidence that lower flows would be sufficient to motivate fish to pass upstream. This was true whether or not the wheel was in place.

Larger fish, notably the hitch and the trout, were able to come up beneath the wheel to hide. Some fish swam up in between the floats, but they didn't seem to jump over the floats and reach to the upstream, although they were capable of it physically. Exceptions included only 2 brown trout which repeatedly swam over one float, but never went over the two floats necessary to get upstream. Thus, in some cases, spawning fish might be motivated enough to jump over few floats, but the motivation has to be there. Our primary target fish, the coho salmon simply were not motivated to go upstream over any weir. The question of motivation can be broken down into:

- a question of motivation to move at all, and
- a question of overcoming repulsion from the potentially threatening wheel.

The trout and hitch, were interested and willing to relocate (A), but not approach the wheel (B). The salmon, at this phase of their lives, were not willing to relocate at all - and only drift downstream.

Downstream Passage

Because the entrance to the wheel was through a weir formed by the top of the breast 12" above the flume bottom, fish near the wheel, were not drawn into it because they were at bottom-middle depth below the weir. Placing a slope in front of the wheel might help bring the fish up toward the surface, at the level of the wheel and allow for easier passage. Several of the fish would pass through the wheel, and this might be improved in the field with a larger wheel in all dimensions. However, the utility of a wheel for transporting fish downstream is limited, as fish will naturally pass over a weir. Thus, to the extent that the "B" effect exists, the wheel will inhibit passage. The "A" problem exists at all fish passage facilities.

In general, fish mostly stayed away from the wheel during experiments. Some fish did not appear to be motivated to move in the test direction. Some of the fish were clearly afraid of the wheel to an extent that it inhibited any passage, and others were motivated to simply hide under or within the wheel making it appear that they are trying to go through the wheel when they are simply hiding.

Conclusions

This study comes to two conclusions, the first derived directly from the research objectives, and a second derived from experiments undertaken to overcome fish avoidance behavior observed during the study of the wheel.

First, from within the original study protocol, we have concluded that moving fish through low head dams using a large water wheel is probably not useful. It does not appear to be kinetically or technologically difficult to pass them through provided they move quickly. The major problem is the behavior of the fish. They are simply not interested in moving into this water wheel, no matter how proficient it is in passing them upstream. Thus, we conclude that the fish passage problems are directly related to motivating the fish to enter it.

Lack of motivation for the fish to enter mechanical bypass facilities is identical to what is observed at every fish passage facility on real dams around the world. The fish elevators, fish locks, fish trucks, fish ladders all work – provided you can get fish to go to and into them. Because fish will not approach the particular technology, "entrance" becomes the path -critical technology rather than the internal mechanical bypass mechanism. To meet this problem, an increased effort was made to address it, using moving air curtains to herd fish. The herding effect can be initiated by using numerous curtains following each other in regular patterns. This technology may prove very valuable when applied to fish at full-sized dams. Important characteristics of the technology that needed to be addressed include:

- The amount of air creating a fear/attraction on response,
- The length and shape of the air curtains,
- The spacing of tubes that generate the curtains,
- The speed of movement of the curtains,
- The number of parallel tubes that make one curtain, and
- The pattern repetition rate of the curtains.

These factors interact with relevant fish characteristics, such as:

- Type of fish,
- Age and season of the year,
- Conditioning & Experience, and
- Familiarity with air curtains.

"One size does not fit all," and the flexibility of the bubble curtain technology has to be matched with the target fish at all times. Fortunately, this is relatively easy, with computer control.

Recommendations

The ability to move fish to the wheel, and more generally to move fish in general to any fish passage technology is becoming a focus of research. The need for fish herding is a pervasive problem that permeates all fish passage technologies, research on this problem is paramount. Our data suggest that fish herding is possible. Further, the discovered technology of moving air curtains may scale well to field situations. Much work remains. Motivating fish to move probably depends on fish type, life stage, location, time of day, water conditions, season, and the proximity of prey and predators. There is a large amount of field experimentation needed to find out how to herd specific fish in specific locations at specific days. Because what will work in one place on one species will not necessarily work on another, this work will be extensive. However, because we have blocked rivers and streams, we have a responsibility to mitigate the resultant effect and one method is to help fish move around the dams. Research could help show them the way.

Public Benefits to California

Background

Currently, California is faced with removing dams because fish passage is being inhibited. For example, at Red Bluff dam on the Sacramento River, the gates have to be open for fish passage from October to May. The water from Red Bluff was used to supply irrigation water to a large number of farmers in the Sacramento Valley who now have to pump water. Currently, plans for complete dam removal are being considered along with alternative plans for having the dam remain open year around if no efficient passage is found for salmon. This will put a large burden on Central Valley farmers and will increase electricity usage in the state significantly.

If fish could successfully (i.e., without increased vulnerability to predation or other mortality sources) pass this dam, which is only about 30 ft. high, it would not have to be removed and considerable energy would be saved. We studied using a series of smaller Sagebien wheels to pass fish around the dam. What was discovered is the problem of interesting the fish to enter "fish passage" facilities.

Benefits Already Received From Study

A major benefit of this study is the realization that fish can be herded to some extent like cattle (or perhaps more accurately – cats) with air curtains. The effect of the curtain is incremental, only some of the fish are moved by any one curtain. The key to this technology is that the curtains can be made to appear to move past a point repeatedly, thereby potentially herding a large percentage of the fish over time as the result of repeated curtain movement.

Future Benefits

The preliminary results that fish can be herded will be very valuable to California and the world in the future. Besides being potentially useful for helping fish around dams, the technology might also be useful at larger dams and will save water, power, and fish. Perhaps fish herding also will become part of fish capture or a quasi-open fish farming/ranching practice where the fish are not constrained by fences, but by migratory patterns that can be used with herding for efficient fish harvesting and resource management.

Public Benefits / Costs

This was an experimental, environmental technology study. To evaluate the economic impact, amount of power saved, water supplied or redirected, and fisheries enhanced, is far beyond the scope of this work. The indirect effects of fisheries improvements and better water use clearly swamp the direct economic effects of increased fish availability.

For this report, Table 4 lists some of the potential benefits of this technology if it is developed successfully. There are no significant costs other than the air-pumping costs.

Table 4 Potential Benefits and Costs of Fish Herding

Benefits at Dams • Increase in fish for a given amount of attraction and spill flows at dams. • Increase in gravity-irrigation water availability. • Increase in hydropower due to reduction in attraction flow usage at hydropower dams.
Other Benefits

- Possible use in open-water capture.
- Possible use in helping guide fish past false outfalls.
- Assistance in aquaculture and fish farming.

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Fish Herding Marketing and Development

Marketing & Development

This technology is very easy to market in that there is a pressing need for a technology to work. Presently, the FERC is requiring dams to be removed because they do not pass fish. The "marketing" of this technology will be after research. It needs to be tried at a full -size dam. The problems we ran into in the laboratory flumes of people moving around, strange overhanging ends and the artificiality of a flume would be removed. As the technology of fish herding is developed, we will be using it at any interested dams and publishing our results.

We have been just issued a US provisional patent on the use of air curtains as primary fish movement devices. The patent has been accepted for filing and is pending. A full utility patent is being applied for. We now intend, as stated above to study the range of applicability of the air curtain herding technology with real fish in real rivers. The research has been discussed with some professionals in the field, and a proposal is being prepared based on this preliminary work. We have discussed the idea with the Bureau of Reclamation and USFWS people at the Red Bluff dam and they have expressed an interest in some tests there if we can find funding. An attractive asset of this technology is that it is economical, portable – does not require concrete, and can be reconfigured easily, both for testing and later for different fish.

One of the work products developed here is a research protocol for further work in the Sacramento River. While there is some intellectual property being developed under this research, the main aspects of this work will be in the public interest. We intend to eventually apply it to the Red Bluff dam to assist the salmon of various age classes, the trout and, if possible, other species passing this dam as a test site.

Other Energy Commission Issues

Significant engineering, technical, and (most important) behavioral issues remain. If the next test were to take place at a research site (e.g., a tributary to the Sacramento River), the following questions should be addressed first:

- What materials will work and be reliable, yet benign in the open stream?
- What fixed tubing spacing and shape patterns timing, should be used?
- What types of fish does this work on, and how can it be modified to work on other types?

Herding fish, like cats, or catching fish, is an art as well as a science. Because we are at the beginning of developing this art, the best parameters may not be obvious. These should evolve from field observations.

Production Readiness: The simplicity of the technology allows it to be built from readily available materials with field assembly and modification. This is an assembly and computer driven technology, not one that requires much special equipment. Thus, the only inhibition to production is understanding how to use the technology most effectively, then set up the arrays and do the programming of the bubbles for the specific fish at a particular point in their life cycle. The optimal patterns and speed of movement are not to be underestimated. Their solution is entirely a field research problem.

References

Akiyama S., Arimoto T., Inoue M. 1992. *Fish herding effect by air bubble curtain in a large circular tank.* Nippon Suisan Gakkaishi 58(1): 45-48.

Appendices

The following first three Appendices are available as Excel Files. For the online version, these files, like the Final Report, are available separately unzipped and are included in the zipped complete report file.

Appendix I – Prony Brake Results.
Appendix 1 - Efficiency-data.xls

Appendix II – Fish Passage Data and Results:
Appendix 2 Number of fish passed wheel.xls

Appendix III – Herding Results
Appendix IIIa - Dragging loop herding.xls
Appendix IIIb - Fixed loop array herding.xls

Appendix IV –Photographs & Movie Loop

Appendix IV contains a series of pictures to show the wheel, and its operation in the lab with students. They are mostly "JPG" files about 100-500 k in size. There is a small "gif" of the fixed ***herding*** *array in action, and one very short (500k) "avi" movie clip showing the wheel in action.*