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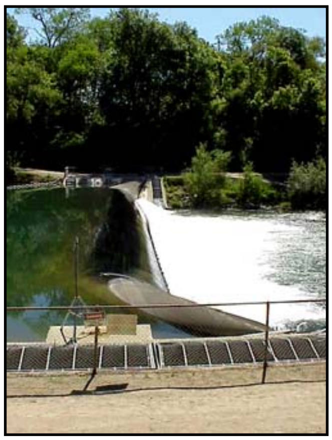
Study Years 2001-2002



Prepared By:

David J. Manning
Sean K. White
Jonathon A. Mann
Ronald C. Benkert
Ben White, and
Jennifer Michaud

July 2003

Sonoma County Water Agency
2150 West College Ave.
Santa Rosa, CA 95401

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Prepared By:

David J. Manning, Senior Environmental Specialist-Fisheries[1]
Sean K. White, Principal Environmental Specialist[1]
Jonathon A. Mann, Hydraulic Engineer[2]
Ronald C. Benkert, Senior Environmental Specialist-Fisheries[1]
Benjamin White, Natural Resources Program Assistant[1]
and Jennifer Michaud, Natural Resources Program Assistant[1]

July 2003

[1]Sonoma County Water Agency
Natural Resources
2150 West College Ave.
Santa Rosa, CA 95406

[2]NOAA Fisheries
777 Sonoma Ave.
Santa Rosa, CA 95404

Correspondence:
dmanning@scwa.ca.gov, (707) 547-1988

ABSTRACT

The Sonoma County Water Agency has been evaluating the effects of an inflatable rubber dam on steelhead smolt emigration in the mainstem Russian River. Radio tracking in spring 2000 showed the percentage of fish that passed the dam site differed substantially before and after the river was impounded. We expanded the study in 2001 and 2002 to include a free-flowing control reach and released 297 smolts 11 km above the dam. Multiple telemetry stations were used to compare travel rates and residence times in free-flowing (river) and impounded (reservoir) reaches during both years. In 2002 we compared flow characteristics and smolt responses to three dam configurations: (1) full inflation, (2) partial deflation, and (3) partial deflation to create a notched effect.

River and reservoir travel rates did not differ significantly within or among years. Residence times, however, differed between reaches, years, and dam configurations. Forebay residence time decreased by more than 50% in 2002. Median reservoir and forebay residence times were lowest when the dam was notched. In both years, most smolts passed by traveling over the dam crest as opposed to bypass pipes or fish ladders. The dam caused emigration delay but most smolts that reached the forebay passed successfully. Migratory delays in the impoundment appear directly related to conditions in the forebay. Notching the dam holds promise as a relatively simple and effective method of reducing forebay delay. We will continue to investigate spill characteristics and smolt behavior in hopes of enhancing steelhead outmigration.

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INTRODUCTION

The Sonoma County Water Agency (SCWA) Fisheries Enhancement Program has been evaluating the effects of a seasonal impoundment on fish migration, species composition, and water quality in the Mirabel-Wohler reach of the Russian River since 1999. Mirabel Dam (a 45 m long, 4.0 m high water-filled rubber bladder) creates a 5.1 km long seasonal impoundment termed Wohler Pool (Figure 1). Since 1978, the dam has been inflated annually during periods of low flow to increase recharge to the aquifer adjacent to the river. SCWA supplies water to approximately 600,000 residents by pumping from the aquifer using a series of deep collector wells.

The timing of dam operation (typically April to November) is coincident with the life histories of three salmonid populations listed as threatened under the Federal Endangered Endangered Species Act (ESA). To facilitate steelhead (*Oncorhynchus mykiss irideus*), coho salmon (*O. kisutch*), and Chinook salmon (*O. tshawytscha*) passage, the dam contains two permanent Denil-style fish ladders and screened pump intakes with bypass pipes. However, fish passage has never been evaluated in relation to these structures or the physical and biological characteristics of Wohler Pool. Questions about the effects of dam operation on listed smolts have been raised in an ongoing ESA Section 7 consultation between SCWA, the National Marine Fisheries Service (NMFS), and U.S. Army Corps of Engineers.

To address these concerns, SCWA attempted to evaluate the travel time of steelhead smolts migrating through Wohler Pool immediately before and after the dam was inflated in 1999 and 2000 (Chase et al. 2000, Manning et al. 2001). During the 1999 study, approximately 9,000 hatchery smolts were marked with flourescent dye and released 4 km above the dam. Timing was measured on three separate occasions as the difference between upstream release and recapture at a rotary-screw trap below the dam. Travel times ranged from 12 to 180 hours, however, too few fish were recaptured to ascribe confidence to the results. Low trap efficiency was likely the result of geomorphic characteristics of the river channel at the trapping location. However, it was possible that fish either delayed migration beyond the trapping period or perished in the reach between the release and recapture points.

In spring 2000, we repeated the smolt trapping study and used radio-telemetry to more closely evaluate fish passage, movement, and survival in Wohler Pool (Manning et al. 2001). Groups of 19-20 hatchery smolts, implanted with uniquely coded transmitters, were released in conjunction with 5,000 dye-marked fish on four occasions before and after the dam was inflated. Two telemetry receivers were used to track smolts in the pool and automatically record passage around the dam.

Despite the use of two additional traps, captures of dye marked fish were again insufficient to determine travel rates and overall passage success. However, radio telemetry data from 79 smolts showed that the percentage of fish that passed the dam site decreased over time and differed substantially before (85-90%) and after (42-50%) the river was impounded (Manning et al. 2001). Between 50 and 95% of the post-dam smolts spent more than 48 hours in the impoundment and some fish resided in the reach for up to 11 days before passing the dam. Smolt reluctance to pass the dam appeared to be related to depth and flow conditions in the forebay. The delay of some fish may have been exacerbated by the onset of parr reversion, stress related to surgery, and elevated water temperature.

Because changing environmental conditions partially confounded the pre and post-dam comparison in 2000, we expanded the study in spring 2001 to include a riverine control reach and released all smolts after the dam was inflated. Multiple telemetry stations and an array of antennas at the dam were used to (1) determine travel rates and residence times in free flowing and impounded reaches and (2) evaluate passage routes and fish behavior in the dam forebay. Results of the 2001 study (presented in this report) also suggested that smolt passage was retarded by shallow depth over the spillway and low velocities in the forebay. During spring 2002, we repeated the 2001 study but varied

Figure 1. Mirabel Dam and a portion of the 5.1 km long reservoir it creates above Wolher Bridge.

the level of dam inflation to increase depth and velocity. Our objective in 2002 was to compare migration rates and residence times while the dam was fully and partially inflated.

STUDY AREA

The mainstem Russian River is 177 km (110 miles) long and drains a 3,846 km^2 (1,485 square mile) watershed (Florsheim and Goodwin 1993). Originating in the Coast Ranges of Mendocino and Sonoma counties, it enters the Pacific Ocean at the town of Jenner 112 km (70 miles) north of San Francisco, CA. Mirabel Dam is located at river kilometer 37 (mile 23) near the town of Forestville (Figure 2). Extreme flows recorded at the U.S. Geological Survey (USGS) Hacienda Bridge Gauging Station (km 32) ranged from 2,887 m^3/s (102,000 cfs) to 0.02 m^3/s (0.75 cfs) between 1940 and 2001. Low flow, however, is currently regulated by releases from Warm Springs and Coyote Dams and typically ranges between 5.66 and 8.49 m^3/s (200 and 300 cfs).

We released radio tagged smolts at river kilometer 51 near the town of Healdsburg and tracked them along a 9.6 km reach. The upper 4.5 km of the reach is free flowing and consists primarily of runs, pools, and shallow glides. Mirabel Dam impounds the lower 5.1 km of the study area. Wohler Pool, the reservoir created by the dam, is approximately 70 m wide and ranges in depth from 1 to 5 m.

In addition to steelhead, recent trapping and electrofishing found 26 native and introduced fishes in the study reach (Chase et al. 2000, 2001). Chinook salmon, Sacramento sucker (*Catostomus occidentalis*), smallmouth bass (*Micropterus dolomieui*), and hardhead (*Mylopharodon conocephalus*) were the most abundant species in Wohler Pool during the study period.

METHODS

Radio Tagging

We surgically implanted transmitters in steelhead smolts from the U.S. Army Corps of Engineers / California Department of Fish Game Warm Springs Hatchery located on Dry Creek, a major Russian River tributary. In March 2001 and 2002, four to six weeks before tagging, we removed 400-500 yearling smolts from the general hatchery population and held them in two 3,785 L (1,000 gal.) rectangular fiberglass tanks supplied with flow through hatchery water. Smolts were fed Oregon Bio Moist® pellets once daily to satiation by hand in 2001. In 2002, fish received food once every four hours by automatic feeder for a total daily ration of one percent body weight.

Radio-tagged fish received small (9.2 mm diameter, 20 mm length, $weight_{air}$ 2.0 g, $weight_{water}$ 1.5 g, antenna length 30 cm), microprocessor coded transmitters designed for internal implantation (model no. MCFT-3HM, LOTEK Engineering Inc., Ontario, Canada). To minimize behavioral effects of the tag, we maintained a two percent ratio of tag to fish weight (in air) and selected fish no smaller than 100 g (Winter 1996). The tags transmitted on 5 frequencies in the 149 MHz band. Background noise was evaluated prior to selecting frequencies to minimize potential signal interference. The use of coded transmitters permitted the unique identification of all fish. Minimum transmitter battery life at a 3 second burst rate was 27 days.

Surgical procedures were performed at Warm Springs Hatchery and generally followed the methods of Moore et al. (1990), Summerfelt and Smith (1990), and Adams et al. (1998b). Prior to surgery, fish were deprived of food for 48 h and anesthetized in a bath of tricaine methanesulfonate (MS-222). During surgery, fish were held in a V-shaped aluminum surgical trough lined with foam rubber soaked in an solution of artificial mucus (Stress Coat; Aquarium Pharmaceuticals, Inc., Chalfont., PA). To

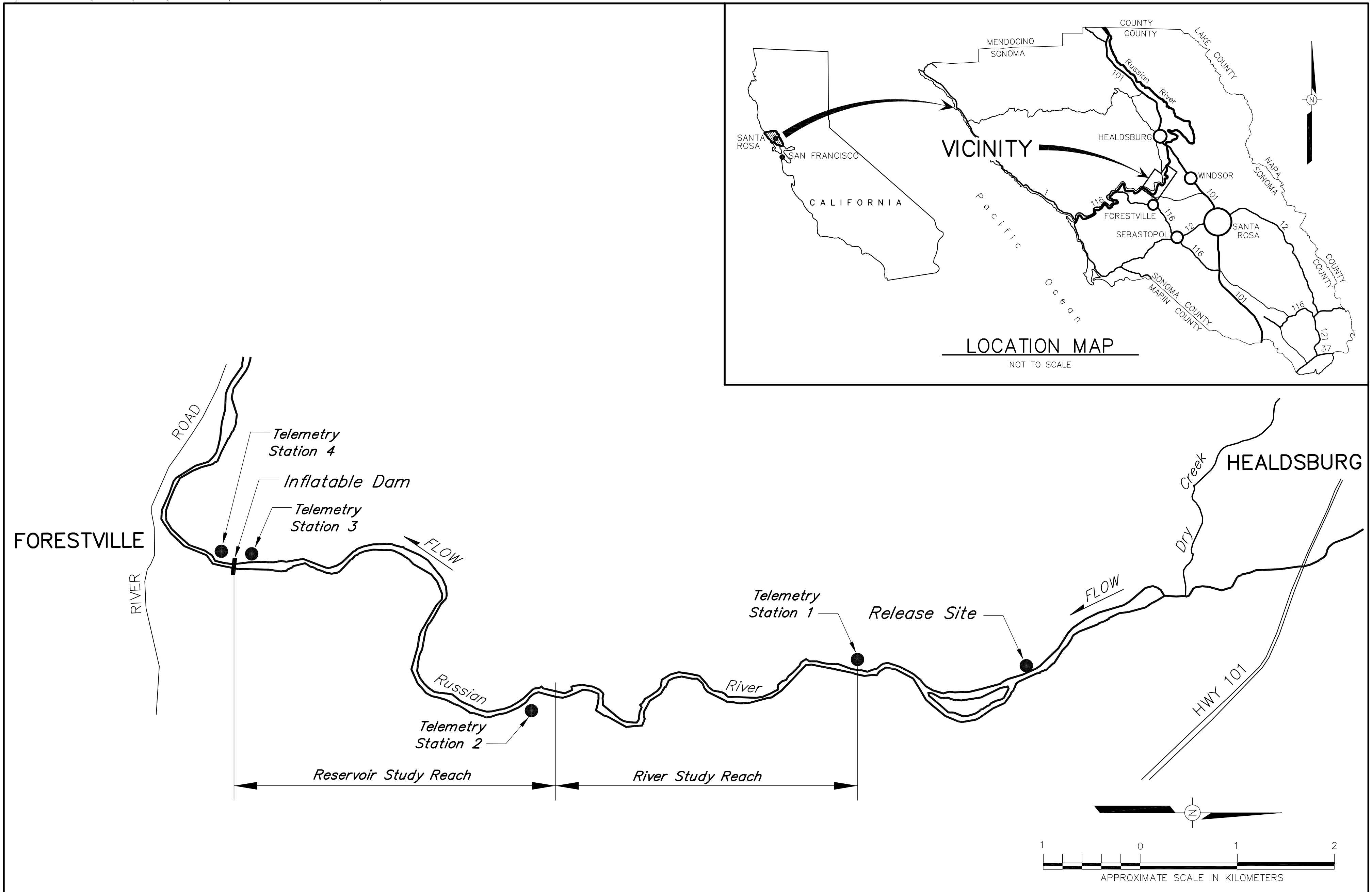

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Figure 2 Location of steelhead radio telemetry study reaches, smolt release site, and datalogging receiver stations.

maintain anesthesia during the procedure, a dilute solution of MS-222 continuously flushed the gills via a tube inserted in the mouth. To maintain aseptic conditions, we used sterile surgical gloves and disinfected all instruments with providone iodine (Swanberg et al. 1999).

Implantation was initiated by making a 10 mm incision (penetrating the peritoneum) a few millimeters away from and parallel to the midventral line anterior to the pelvic girdle (Figure 3). An outlet in the body wall (between the pelvic fins and anus) for the tag's antenna was made by passing an intravenous catheter and needle (Surflo No. 1651, 16-guage x 51 mm) through the incision (Ross and Kleiner 1982; Adams et al. 1998b). The "shielded-needle" punctured the body wall and was pulled through the catheter - leaving the catheter in place. The tag was inserted by first guiding the antenna through the incision and catheter. Once the tag was positioned below the incision, the catheter was removed and the incision was closed with a series of surgical staples (3M Precise Vista, 35W No. 3995) (Mortensen 1990; Swanberg et al. 1999). The antenna was secured to the body with a single suture (Ethicon, 4/0 coated vicryl) on the first anal fin ray posterior to the exit site (Adams et al. 1998b; Martinelli et al. 1998). To minimize infection, oxytetracycline was pipetted into the incision (Summerfelt and Smith 1990; Adams et al. 1998b).

To insure recovery after surgery, each group of 20-30 tagged fish was deprived of food and held in an aerated 946 L (250 gal) circular tank for 36-48 hours prior to release. At times when water temperature was greater in the river than the hatchery, we used submersible aquarium heaters to slowly raise the holding tank temperature by 2-3° C. Fish behavior and tag function were monitored throughout the holding period. We evaluated the longer term influence of our surgical procedures on fish behavior by conducting a growth and survival experiment at the hatchery using smolts implanted with dummy (inactive) transmitters.

The effects of intraperitoneal tag implantation on fish health and behavior have been studied extensively (Lucas 1989; Moore et al. 1990; Martinelli et al. 1998). We retained groups of dummy tagged smolts in 2001 and 2002 only to assess the proficiency of our surgical techniques. A randomly selected treatment group of 20 fish received dummy-tags identical in size, weight, and shape to active tags and second group of 20 fish served as controls. Fish from both groups were weighed, measured, and uniquely marked with alcian blue dye injected into fin rays using a Panjet® dental tool. Both treatment (tag) and control groups were held together in a 3,785 L flow-through tank for 52 days in 2001 and 25 days in 2002. Treatment and control fish were fed in the same manner as smolts held for radio tagging each year.

We weighed and measured treatment and control fish at approximately 10 day intervals in 2001 and once after 25 days in 2002. Relative growth rates (percent body weight gained or lost per day) were calculated following methods described in Busacker et al. (1990). The progress of healing and signs of infection in treatment fish were evaluated by noting the presence of mucus, abdominal bloating, and inflammation of epidermal tissue (Swanberg et al. 1999). Behavioral observations (feeding, general activity, and position in the water column) were made weekly during both years.

Seawater Challenges

Warm Springs Hatchery typically releases smolts between January and April. Our evaluation of passage at Mirabel Dam required us to hold some fish until early June. Because smolts held beyond their normal release date may begin reverting to parr, we tested physiological stage of smoltification over time by measuring blood plasma sodium concentrations after 48 hour exposure to artificial seawater.

Seawater challenge tests were conducted at the hatchery following the methods of Blackburn and Clarke (1987) and an unpublished protocol developed by the U.S. Fish and Wildlife Service California-Nevada Fish Health Center (S. Foote, pers. comm). During each test, 20 smolts were assigned to five static saltwater aquariums (four fish per aquarium). Each aquarium (a 75 L round plastic container) was filled with hatchery supply water, aerated with pumps and airstones, and partially submerged in a flow-through hatchery trough to maintain cool water temperature. Prior to

1) S rgical Table **2) Shielded needle catheter placement**

3) Radio transmitter insertion **4) Incision closed with surgical staples**

Figure 3. Major steps in the surgical implantation of radio transmitters in steelhead smolts from Warm Springs Hatchery.

adding fish, Coralife™ scientific grade marine salts were added to each aquarium to achieve salinities of 28-29 ppt. Salinity, temperature, dissolved oxygen, ammonia concentration, and pH were monitored in each aquarium. To reduce stress and organic loading, fish were not fed 24 hours prior to or during the course of each experiment. After 48 hours, all fish were euthanized in a bath of saltwater and MS-222, weighed, measured, and immediately sampled for blood using common hematological procedures.

We collected blood from the caudal artery of each fish using Vacutainer™ collection needles and tubes treated with an anticoagulant (lithium heparin) and PST™ gel to enhance plasma separation. Plasma was separated by centrifugation, pipetted from the Vacutainer tubes, and stored on ice in microcentrifuge tubes. Samples were analyzed the same day they were collected using an automated blood chemistry analyzer at a hospital laboratory (Sutter-Warrack Hospital, Santa Rosa, CA). Laboratory personnel performed all sample analyses.

Smolt Release and Radio Tracking

We released radio tagged smolts at river kilometer (rkm) 51 weekly between April 24 and June 5, 2001. This location was 1.5 km above the beginning of our riverine study reach. From April 25 to June 4, 2002, we conducted three weekly releases at rkm 51 and three releases at rkm 45 (the upstream end of the reservoir). The upstream location was selected to allow fish acclimation time before passing our first datalogging receiver station. We released fish at rkm 45 during the later half of 2002 in an attempt to increase the proportion of fish entering the forebay. Weekly release groups ranged from 20 to 30 fish in both years.

During 2001, fish were transported from the hatchery to the release site in large plastic bags filled with holding tank water and compressed oxygen. Although the bag transport method was effective, we moved fish more efficiently in 2002 using large plastic tubs with high volume aerators. Total transport times ranged from 30 to 45 min and all fish were released at dusk between 20:00 and 22:00 hours.

We recorded smolt movements with four fixed radio tracking stations that each consisted of a three or four-element Yagi antenna and datalogging receiver (model SRX_400 W9, LOTEK, Inc., Ontario, Canada). The fixed stations were located (1) at the upstream end of the riverine reach, (2) at the upstream end of the reservoir, (3) in the dam forebay, and (4) 50 m below the dam (Figure 2). To evaluate passage routes at the dam we configured Station 3 to simultaneously monitor an array of one aerial and six underwater antennas (Figure 4). To limit signal detection range in the 100 m forebay, we oriented the aerial antenna at Station 3 perpendicular to the river flow and decreased receiver gain. When the aerial antenna detected a fish in the forebay the receiver scanned each underwater antenna in a pre-determined order. We determined fish locations by comparing signal strength data from each antenna. The underwater antennas (200 mm sections of bare RG 58 coaxial cable mounted on plastic pipes) were located inside the fish ladders on either side of the dam and at the entrance of two bypass pipes associated with the screened pump intakes (Figure 4). Fish passing over the dam face were recorded by the aerial antenna in the forebay and fixed Station 4 below the dam. To verify that fish passed the dam, we oriented the antenna at Station 4 downstream and were able to detect signals up to 350 m below the facility. The battery-powered receivers at each station scanned through 5 frequencies every 15 seconds continuously and recorded date, time, frequency, code, and signal strength in non-volatile memory. Data was downloaded in the field weekly using LOTEK software and a laptop computer.

Data from the fixed stations generally showed clear patterns of increasing, peak, and decreasing signal strengths as fish moved downstream. Passage dates and times for fish that moved rapidly past each station were determined from peak signal strengths. However, a simple examination of signal strength data was insufficient to determine direction of movement for fish that remained close to receiver stations or within reaches beyond receiver range for extended periods of time. To better determine movement patterns, we augmented data from the fixed stations with mobile tracking.

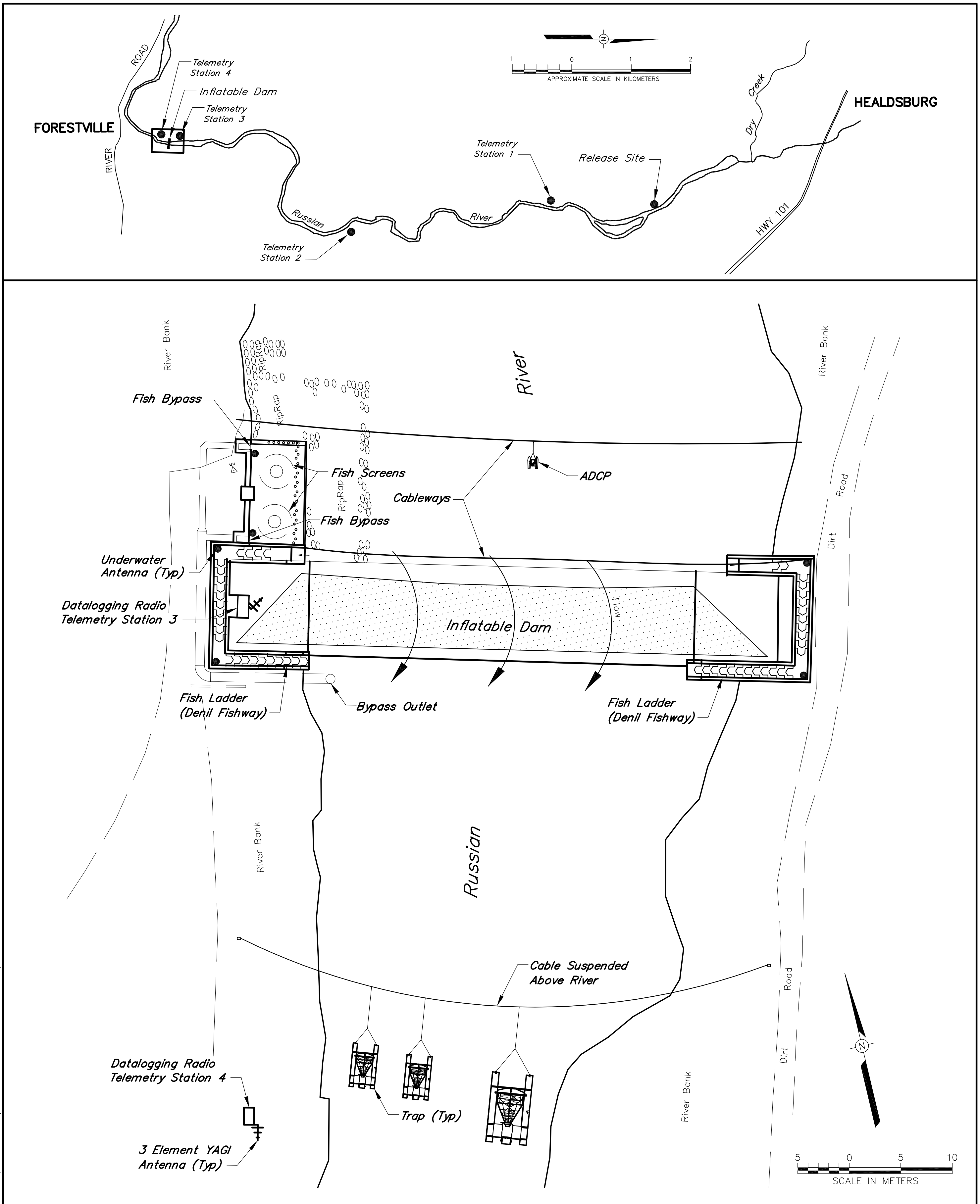

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Figure 4 Plan view of Mirabel Dam showing fish passage routes, radio telemetry antenna locations, cableways for suspending the Acoustic Doppler Current Profiles (ADCP), and locations of downstream migrant (rotary screw) traps. Underwater antennas are shown as shaded circles in the bypass pipe inlets and fish ladders.

We tracked smolts twice weekly in 2001 and once weekly in 2002 from a two-person kayak using an H-antenna and scanning receiver (SRX_400 W5, LOTEK Inc.). Kayak surveys were conducted over a 14.4 km reach from the Highway 101 bridge in Healdsburg (4.8 km above the smolt release site) to the dam (Figure 4). Tag frequencies were scanned continuously and the latitude and longitude of fish locations were recorded with a hand-held GPS receiver when signal strength was maximized. We conducted our final kayak survey 30 days after the last release of smolts each year.

Dam Operations and Hydraulic Measurements

Because Mirabel Dam is inflatable, its height and the corresponding water surface elevation of Wohler Pool can be carefully adjusted. During 2001 the dam was operated normally and water that was not diverted through the pump intakes, bypasses, or fish ladders spilled evenly across the crest of the structure (Figure 5). In 2002, we decreased the height of the dam to increase spill depth and velocity. Our goal was to concentrate spill yet maintain a water surface elevation that allowed operation of the diversion pumps. We compared flow characteristics and smolt responses to three dam configurations: (1) full inflation with a pool elevation of 11.6 m (38.0 ft), (2) partial deflation with an elevation of 11.4 m (37.5 ft), and (3) partial deflation to create a notched effect and elevation of 11.1 m (36.5 ft). Each configuration was alternated throughout the study period and maintained for a total of 2 weeks.

We measured depth and velocity in the dam forebay with a broadband Acoustic Doppler Current Profiler (ADCP; model 1200 KHz Workhorse, RD Instruments, San Diego, CA) connected to a laptop computer. The ADCP was mounted on a custom made catamaran tethered to a cabling system (Figure 6). We used two cableways, located 4 and 14 m upstream of the dam, to pull the ADCP across the channel. By adjusting the length of the tether from each cableway we established a variety of velocity profile transects.

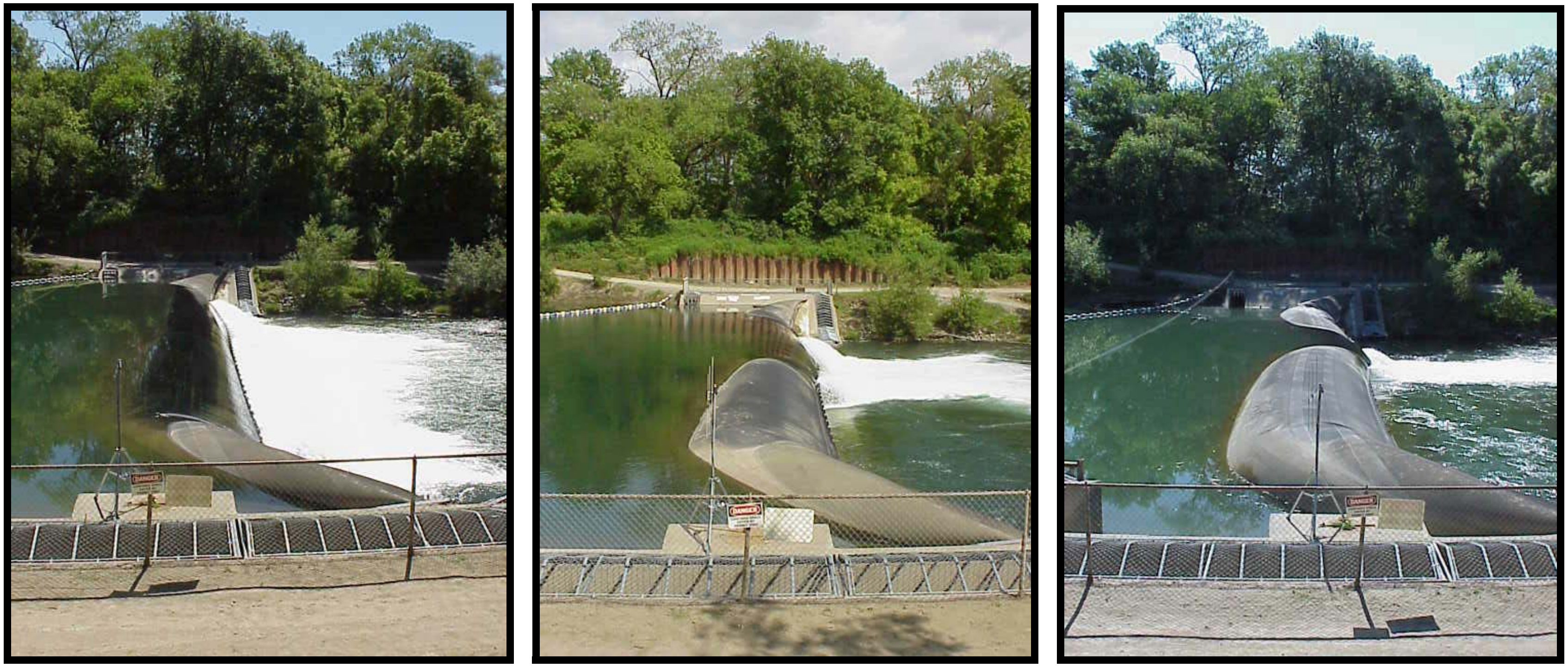
An ADCP takes velocity measurements within discrete vertical depth cells or bins. We used a bin size of 5 cm and collected velocities every 0.3 to 0.6 m along 40 to 50 m transects. Acoustic signal interference prohibits measurements at the top and bottom of the water column. This interference and the depth of the ADCP transducer below the catamaran prohibited velocity measurements within 35 cm of the water surface. The ADCP had a bottom tracking feature to determine the horizontal position of each velocity profile relative to the starting point of a transect.

Stream flow in the study area was estimated by summing daily flows from the USGS Dry Creek and Healdsburg Gauging Stations. Using the two gauges yielded an approximate flow 3.3 km above the riverine study reach. The ADCP provided direct measurements of discharge at the dam site on five occasions in 2002. Although we did not measure velocities in the river reach, the free-flowing section is characterized by alternating runs, pools, and shallow glides and contrasts sharply with the uniform low velocity conditions in the reservoir.

We measured water temperature during both years at the upstream end of the reservoir with a continuously recording datalogger (HOBO Temp, Onset Corp., Bourne, MA). Our decision to use this site was supported by data that showed the reservoir does not thermally stratify and temperatures vary by no more than 1 ˚C throughout the impoundment (Chase et al. 2002).

Data Analysis

We calculated smolt residence times, travel times, and travel rates in the river and reservoir reaches using fixed station and mobile tracking data. Residence time was defined as the total amount of time fish spent in a reach regardless of direction of movement and gaps in time. For example, if a fish moved through the river reach into the reservoir then swam back upstream - we summed the separate time periods when the fish occupied the river reach. We calculated travel time as the time elapsed from detection at an upstream station to first detection at the next station downstream in a contiguous time series. Travel time approximated time elapsed during directed downstream movement. Extending the previous example, if the fish initiated downstream movement a second time



Full Inflation | **Partial Deflation** | **Partial Deflation - Notch**

Figure 5. Three configurations of Mirabel Dam tested during the year 2001and 2002 studies. The dam was fully inflated throughout the study in 2001. Each configuration was maintained for 2 weeks during 2002.

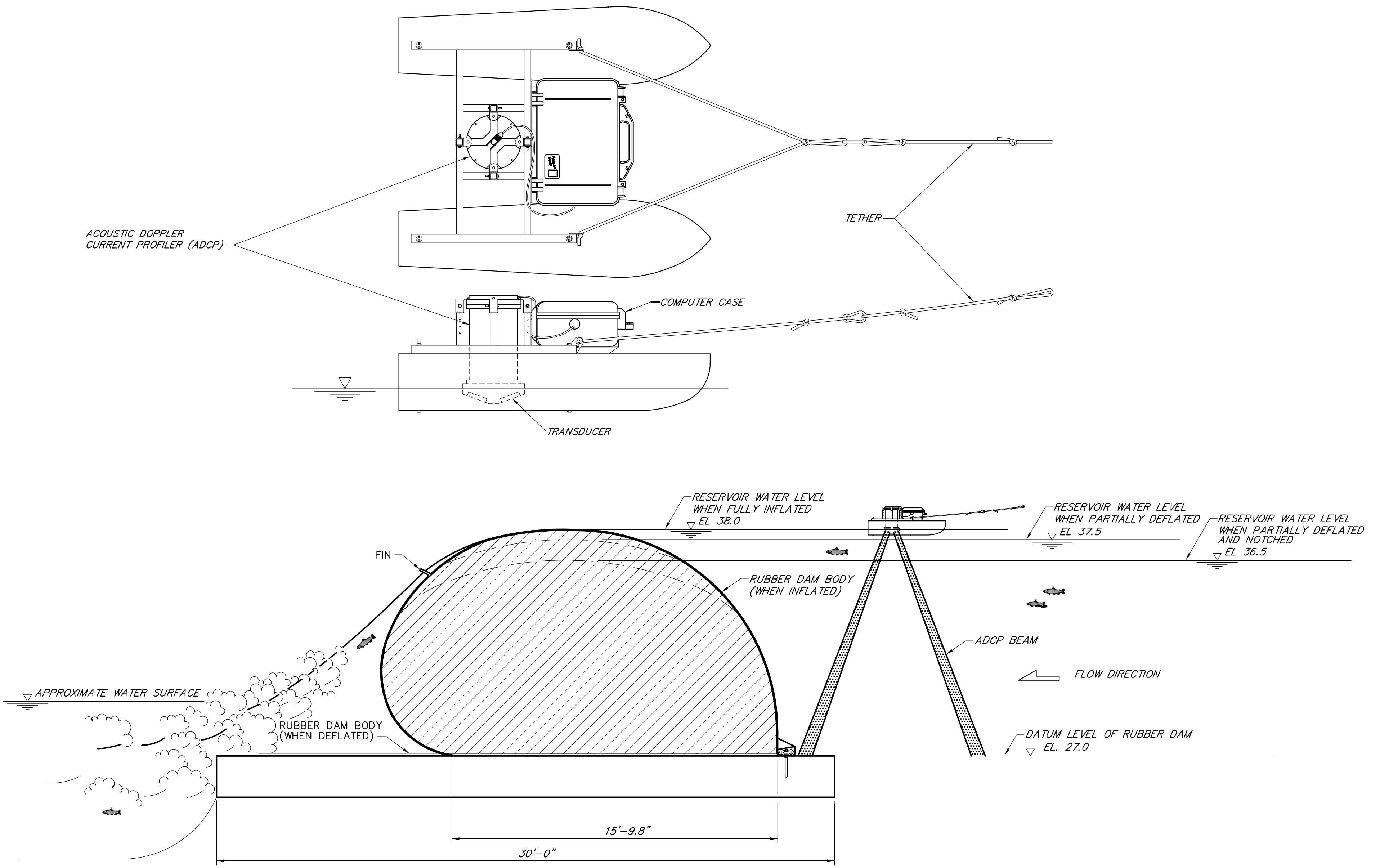


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Figure 6 Detail of Acoustic Doppler Current Profiler (ADCP) mounted on a custom made catamaran and profile of Mirabel Dam with water surface elevations for different levels of dam inflation.

and passed through the reservoir to the forebay - we used only the data from its second entry into the reservoir to calculate reservoir travel time. Travel rates were determined by dividing reach length by travel time. Our travel rate is not analogous to a total migration rate (i.e., reach length divided by total residence time). We calculated travel rate to help determine if migratory delays were associated with low water velocities through the impoundment or conditions in the forebay. If low velocities through the reservoir slowed migration we would see differences between river and reservoir travel rates. Were we only to analyze total migration rates we might not detect delays associated with passage routes in the forebay. We limited our analysis to fish that moved steadily downstream and ultimately passed the dam. In most instances, river residence and travel time were equivalent. Because reservoir travel time was based on first detection at the dam, not passage, it always differed from reservoir residence time. Forebay residence time, a portion of total reservoir residence time, was calculated as time elapsed from first detection 100 m above the dam to passage. Our decision not to analyze total migration rates might have biased our comparison of the two reaches had their lengths not been similar.

Nearly half the fish in 2002 were released at the upstream end of the reservoir near Station 2. To compare the behavior of these fish to smolts released above Station 1, we discounted individuals released at Station 2 that (1) failed to move from the release site, (2) disappeared within 24 hours, or (3) moved upstream.

Because residence times and travel rates were not normally distributed, nonparametric procedures were used to compare reaches and dam configurations within and between years. We used the Wilcoxon-Mann-Whitney test and Kruskall-Wallis one-way analysis of variance (ANOVA) for two and three sample comparisons respectively (Siegel and Castellan 1988). Significance was assumed at $P < 0.05$. We also used nonparametric techniques to compare plasma sodium concentrations from the seawater challenges. Plasma sodium concentrations were compared with Kruskal-Wallis ANOVA and the Kruskal-Wallis multiple comparison procedure ($\alpha = 0.05$).

Growth rate data from the dummy tag experiments was normally distributed with homogeneous variances. Differences in growth between time periods within treatment and control groups were compared with repeated measures ANOVA with $\alpha = 0.05$ (Hicks 1993). We tested differences between the dummy tag and control groups at each time interval with equal variance *t*-tests with $\alpha = 0.05$ (Zar 1984). Statistical analyses were performed using NCSS 2001 (Hintze 2001).

RESULTS

Smolt Release, Dummy Tag Experiment, and Seawater Challenge

We released 297 radio tagged steelhead smolts between April 24 and June 5, 2001 and 2002 (Table 1). Our initial study design called for the release of 300 fish, yet three tags malfunctioned prior to implantation. In 2001, the mean fork length and weight of 139 fish was 230 mm and 136 g. In 2002, 158 smolts averaged 239 mm fork length and 144 g. Smolts were significantly larger in 2002 than 2001 (*t*-tests, $P < 0.01$). Mean condition factor was higher in 2001 than 2002 (*t*-test, $P < 0.001$).

Survival of dummy tagged fish was 95% in 2001 and 100% in 2002. The single mortality in 2001 resulted from mishandling during a growth evaluation 20 days after surgery. The survival rate of 297 radio tagged smolts was 99% during the 36-48 hour pre-release holding period. Two fish in 2001 and 2 fish in 2002 died 24 hours after surgery. Another 4 radio tagged fish that displayed abnormal swimming behavior were sacrificed prior to release in 2002. Active transmitters were removed from all mortalities, sterilized, and re-implanted in healthy fish.

Growth rates varied over the course of the dummy tag experiment in 2001 (ANOVA; $P < 0.001$) but treatment and control groups did not differ significantly at each time interval (*t*-tests; $P > 0.05$; Figure 7). In 2002, mean relative growth rate was significantly higher in control fish after 25 days (t-test; *P* <

0.001). Growth rate at 25 days for both tag and control groups was lower in 2002 than 2001 (Figure 7).

Table 1. Release date, number (N), mean fork length, weight, and Fulton condition factor of radio-tagged steelhead smolts released 11km above Mirabel Dam in 2001 and 2002. Standard deviation is indicated in parenthesis.

Release Date	N	Fork Length (mm)	Weight (g)	Condition
			2001	
April 24	20	235.4 (8.3)	145.1 (17.0)	1.11 (0.09)
May 1	20	230.5 (11.8)	136.0 (20.3)	1.11 (0.10)
May 8	20	230.1 (10.0)	135.3 (17.9)	1.11 (0.07)
May 15	19	228.4 (12.3)	139.8 (20.3)	1.17 (0.10)
May 22	20	225.2 (9.6)	128.7 (12.5)	1.13 (0.09)
May 30	20	223.7 (8.8)	125.2 (14.2)	1.12 (0.08)
June 5	20	233.8 (12.2)	142.0 (26.9)	1.10 (0.08)
All	139	229.6 (11.0)	136.0 (19.7)	1.12 (0.09)
			2002	
April 25	30	233.7 (8.5)	134.6 (17.7)	1.05 (0.09)
May 1	30	240.1 (11.3)	145.4 (21.2)	1.05 (0.08)
May 7	20	236.2 (8.8)	135.9 (19.1)	1.03 (0.10)
May 14	30	240.1 (9.8)	142.2 (17.4)	1.03 (0.07)
May 22	30	239.2 (13.1)	142.5 (20.7)	1.04 (0.09)
June 4	18	246.4 (10.2)	167.2 (20.6)	1.11 (0.06)
All	158	238.9 (11.0)	143.5 (21.3)	1.05 (0.08)

We conducted 12 seawater challenges from April 25 to September 10, 2001 and 3 tests between April 30 and June 11, 2002 (Table 2). Median plasma Na^+ levels ranged from 173 to 195 mmol/L and differed significantly over the course of the study in 2001 (Kruskal-Wallis; $P < 0.001$). Only the challenges with the two lowest Na^+ levels, April 25 and June 5, differed from other test dates in 2001 (Kruskal-Wallis multiple comparison; $Z > 3.37$). Plasma Na^+ concentrations were higher in 2002, ranging from 202 to 205 mmol/L, and did not differ significantly between dates (Kruskal-Wallis; P = 0.53). Despite elevated Na^+ levels during both years, survival after 48 hour challenge was 99.6% in 2001 and 100% in 2002. In addition to the one mortality, 3 of the 240 fish were moribund after 48 hours in 2001 and 5 of the 60 fish in 2002 were lethargic and likely close to death. Variability (interquartile range) within test groups was similar in both years (Figure 8). When data from three challenges conducted during the year 2000 study are included, Na^+ levels appear to increase sharply from March to early June (Figure 8).

The dam was fully inflated throughout the study in 2001 and for a total of 12 days during May 7-13 and May 21-28, 2002. Flow was concentrated for 12 days when the dam was partially deflated between April 25 and May 6, 2002. We maintained maximum depth at the dam crest for 14 days after partially deflating the structure to create a notched effect on May 14-20 and June 4-10, 2002. When the dam was fully inflated, partially deflated, and notched we released 50, 60, and 48 smolts respectively. We released 78 of the total 158 fish in 2002 near Station 2 at the upstream end of the reservoir between May 14 and June 4.

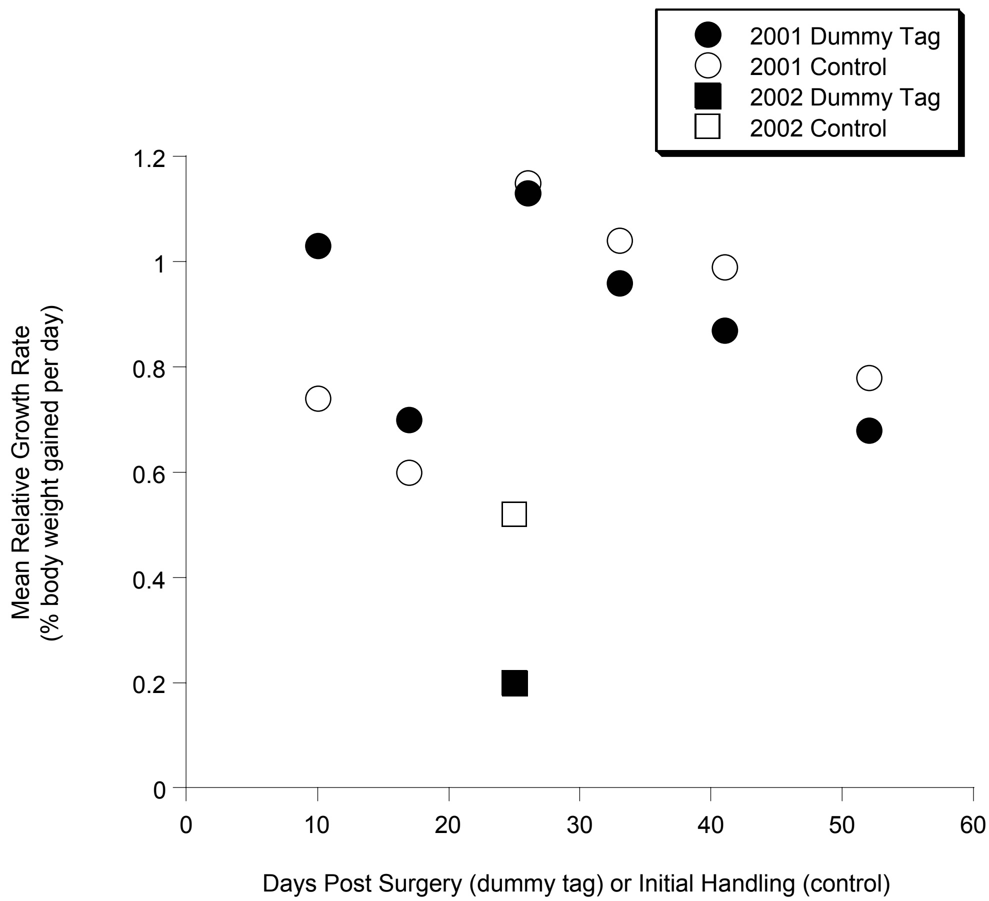

Figure 7. Mean relative growth rates for steelhead smolts implanted with inactive (dummy) transmitters and control fish in 2001 and 2002.

Table 2. Mean length, weight, Fulton condition factor, and median plasma sodium concentrations of saltwater challenge fish in 2001 and 2002. Standard deviations are indicated in parenthesis.

Test Date	N	Fork Length (mm)	Weight (g)	Condition Factor	Na^+ (mmol/L)
			2001		
Apr 25	20	224 (13)	112.9 (18.1)	1.00 (0.07)	173
May 2	20	209 (11)	88.9 (13.9)	0.98 (0.09)	181
May 7	20	206 (13)	87.8 (16.4)	1.00 (0.09)	190
May 14	20	213 (15)	98.7 (24.7)	1.00 (0.05)	187
May 21	19	205 (9)	87.7 (14.7)	1.01 (0.07)	195
May 29	19	206 (9)	87.5 (10.1)	1.00 (0.06)	194
Jun 5	20	220 (9)	110.2 (14.9)	1.04 (0.07)	179
Jun 18	20	209 (15)	97.1 (21.3)	1.05 (0.07)	194
Jul 1	19	216 (12)	108.8 (18.5)	1.07 (0.05)	187
Jul 16	20	216 (17)	109.8 (27.7)	1.07 (0.06)	188
Jul 30	20	231 (14)	123.8 (24.0)	1.00 (0.04)	194
Sep 10	20	235 (16)	133.6 (30.3)	1.01 (0.05)	184
			2002		
Apr 30	20	236 (11)	129.9 (22.3)	0.99 (0.11)	205
May 13	20	238 (15)	130.8 (23.3)	0.96 (0.07)	202
Jun 11	20	251 (9)	161.5 (17.2)	1.02 (0.06)	204

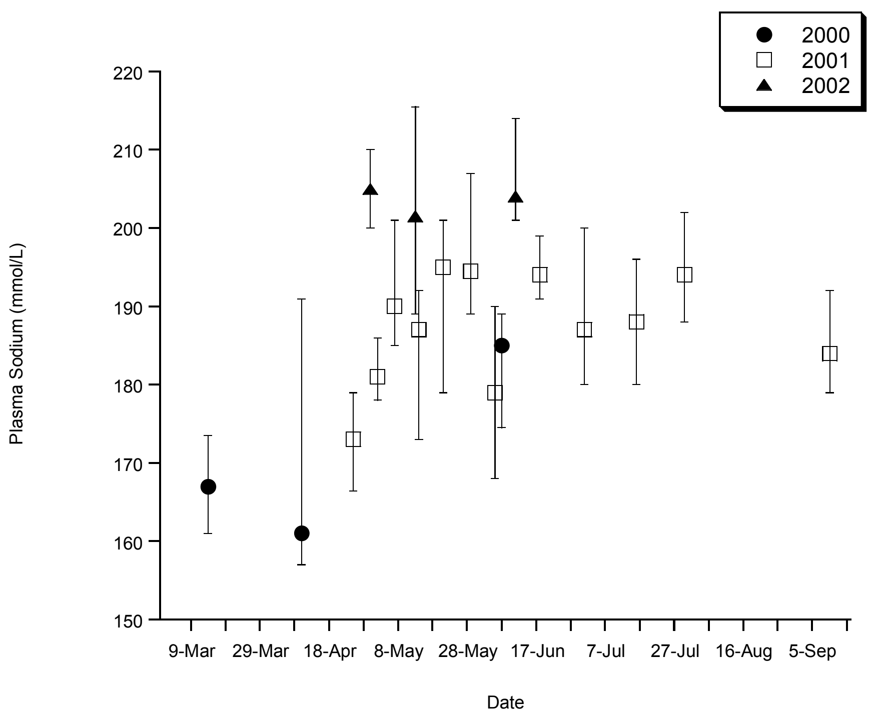

Figure 8. Median plasma Na^+ levels in steelhead smolts after 48 hr seawater challenges in 2000, 2001, and 2002. N = 19-21 fish. Error bars depict interquartile range.

Smolt Passage

The percentage of smolts detected entering the reservoir at Station 2 was similar in 2001 (49%) and 2002 (44%) (Table 3). Of the 68 fish that entered the reservoir in 2001, 65% passed the dam, 15% were detected in the forebay but failed to pass, and 21% were never detected in the forebay (Figure 9). In 2002, 47% of the 70 fish that entered the reservoir passed the dam, 6% were detected but failed to pass, and 47% were not detected. Of the smolts that reached the forebay, 76% successfully passed in 2001 and 89% passed in 2002 (Table 3). In 2002, passage success was greater than 80% for all three dam configurations. The number of passing fish declined over time in 2001 but was variable in 2002. Most smolts that successfully passed in 2001 (84%) and 2002 (94%) traveled over the crest of the dam (Figure 10). Bypass pipes near the pump intakes received the second highest use.

Table 3. Numbers of radio tagged steelhead smolts that were released, detected in the reservoir, detected in the forebay, and passed the dam in 2001 and 2002.

Year	Total Released	Detected in Reservoir	Detected in Forebay	Passed Dam
2001	139	68	58	44
2002	158	70	37	33

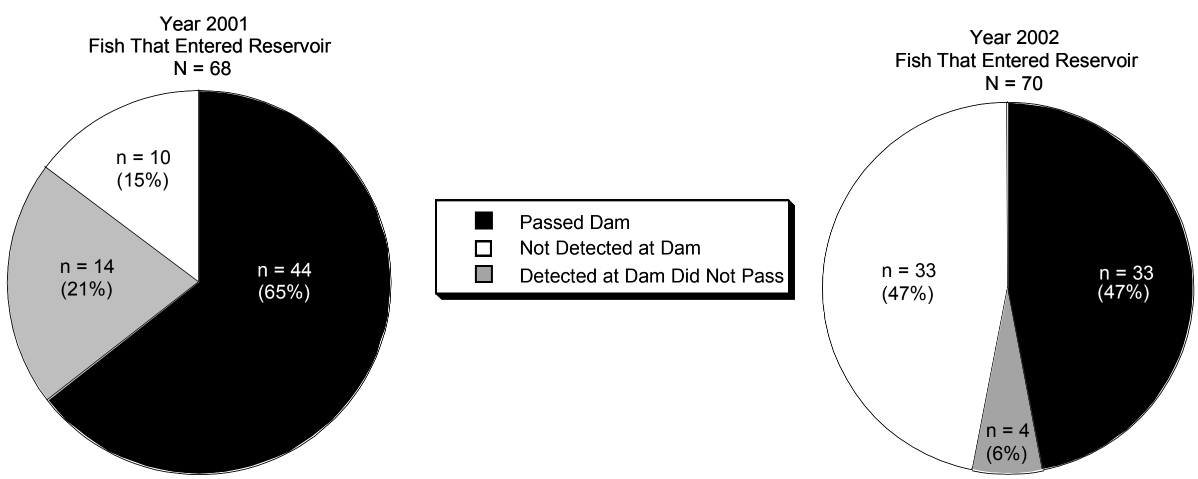

Figure 9. Percentages of radio tagged steelhead smolts that passed Mirabel Dam, were detected at the dam but did not pass, and were not detected at the dam. Percentages were based only on fish that entered the reservoir (not the total number released) each year.

Figure 10. The percentage of radio tagged steelhead smolts that used four passage routes in the forebay of Mirabel Dam during 2001 and 2002.

Most released fish failed to reach the dam forebay in both years. Of the 139 fish released in 2001, 37 were last detected upstream of Station 1, 39 remained in the river reach, 19 stayed in the reservoir, and 44 passed the dam (Table 4). In 2002, 29 fish were found above Station 1, 34 stayed in the river reach, 52 remained in the reservoir, and 33 passed. Most fish initially migrated downstream then stopped moving for the duration of the study in both years. We lost signals from a substantial proportion of fish (25% in 2001, 36% in 2002) before the end of their transmitter's 27 day minimum battery life (Table 4). Loss rates above Station 1 were similar in both years (8% in 2001, 6% in 2002). The percentage of fish that disappeared in the river reach was also similar in 2001 (12%) and 2002 (10%). A higher proportion of fish were lost in the reservoir reach in 2002 (14%) than in 2001 (5%). The average length of time before signal loss was 9.4 days in 2001 and 9.2 days in 2002 (Table 4).

Table 4. Final recorded locations of all radio tagged steelhead smolts released in 2001 and 2002.

Final Recorded Location	Total Fish Remaining in Reach		Fish Not Accounted For in Reach: Number		Fish Not Accounted For in Reach: Percent		Mean Days to Signal Loss (SD)	
	2001	2002	2001	2002	2001	2002	2001	2002
Above Reaches	37	29	11	10	8%	6%	12.5 (6.3)	11.0 (7.9)
River Reach	39	34	16	16	12%	10%	8.5 (6.5)	9.0 (8.2)
Reservoir Reach	19	52	7	22	5%	14%	6.2 (3.7)	7.5 (7.2)
Unknown		10		10		6%		
Below Dam*	44	33						
All	139	158	34	58	25%	37%	9.4 (6.4)	9.2 (7.4)

*passing fish

Travel Rate and Residence Time

Travel rates did not differ significantly within (Wilcoxon test; 2001, P = 0.425; 2002, P = 0.955) or between (Wilcoxon test; river, P = 0.700; reservoir, P = 0.396) years (Table 5). In 2001, median river and reservoir travel rates for 44 passing fish were 0.78 and 1.2 km/h respectively (Table 6). Median river and reservoir travel rates in 2002 were 0.70 and 0.99 km/h (Table 7). With the exception of the river rate in 2002, variability (interquartile range) was also similar among years (Figure 11). Dam configuration had no apparent influence on reservoir travel rate in 2002.

Table 5. Wilcoxon signed ranks (two-sample) and Kruskal-Wallis ANOVA (three sample) test results for median travel rates and residence times of radio tagged steelhead smolts that passed Mirabel Dam in 2001 and 2002. Sample size (n) and probability level (P) are shown for each comparison. Significance was assumed at P< 0.05.

	Travel Rate (km/h)					Residence Time (h)				
Reach	Year 2001		Year 2002			Year 2001		Year 2002		
	n	median	n	median	P	n	median	n	median	P
River	44	0.78	19	0.70	0.700	44	5.75	19	6.41	0.530
Reservoir	44	1.20	33	0.99	0.396	44	21.50	33	10.47	0.063
Forebay						43	6.25	33	0.81	0.033
P		0.425		0.955			0.001		0.002	

Unlike travel rates, residence times differed between reaches, years, and dam configurations. In 2001, river, reservoir, and forebay median residence times were 5.75, 21.50, and 6.25 hours respectively (Table 5). River residence time in 2002 (6.41 hours) did not differ significantly from 2001 (Wilcoxon test; P = 0.530) but reservoir and forebay times dropped to 10.47 and 0.81 hour (Figure 12). Residence times within each year were also significantly different (Kruskal-Wallis; 2001, P = 0.001; 2002, P = 0.002). We found river and reservoir times differed in 2001 (Kruskal-Wallis multiple comparison; Z > 3.09) but could not detect differences in 2002 (Kruskal-Wallis multiple comparison; Z > 1.51). Forebay time was significantly lower in 2002 than 2001 (Wilcoxon test; P = 0.033). Forebay time averaged 49% of reservoir residence time in 2001 and 33% in 2002 but was highly variable in both years (coefficient of variation; 2001, 76%; 2002, 100%). When the dam was fully inflated, partially deflated, and notched forebay time was 28, 55, and 10% of reservoir residence time respectively.

Median reservoir (5 h 30 min) and forebay (3 min) residence times were lowest when the dam was notched (Table 8). However, reservoir times did not differ significantly among configurations (Kruskal-Wallis; P = 0.122). Forebay times were different (Kruskal-Wallis; P = 0.006) but the notched was only significantly lower than the partially deflated configuration (Kruskal-Wallis multiple comparison; Z > 3.19). Total reservoir and forebay residence times were lower in 2002 than 2001. When fish that passed the dam in the notched configuration were removed, however, residence times in both years were similar (Figure 13).

Table 6. Travel rates (km/h) and residence times (h) for radio-tagged steelhead smolts that successfully passed Mirabel Dam between April and June 2001. The river and reservoir reaches were 4.5 and 5.1 km long respectively. Residence time is the total amount of time fish spent in each reach and was calculated using data from automated stations and mobile tracking. Forebay residence time is a portion of total reservoir time and was calculated as time elapsed from first detection 100 m above the dam to passage. No fish passed the dam from the May 22 release.

Year 2001 Release Date	Dam Status	Passing Fish	Statistic	Travel Rate (km/h) River	Travel Rate (km/h) Reservoir	Residence Time (h) River	Residence Time (h) Reservoir	Residence Time (h) Forebay
April 24	Full Inflation	13	Minimum	0.22	0.03	1.75	3.00	0.03
			1st Quartile	0.82	0.56	2.00	9.50	0.57
			Median	**1.29**	**0.99**	**3.50**	**23.50**	**13.25**
			3rd Quartile	2.25	1.72	5.50	48.75	26.00
			Maximum	61.71	78.97	20.25	192.00	82.00
May 1	Full Inflation	12	Minimum	0.03	0.08	1.25	3.25	0.03
			1st Quartile	0.52	0.94	2.44	4.69	1.05
			Median	**0.79**	**1.74**	**5.75**	**18.38**	**2.50**
			3rd Quartile	1.85	1.91	8.69	43.06	27.88
			Maximum	3.60	3.29	171.75	76.75	72.25
May 8	Full Inflation	7	Minimum	0.02	0.21	4.50	1.75	0.05
			1st Quartile	0.10	0.46	4.50	12.63	4.41
			Median	**0.67**	**1.49**	**6.75**	**19.25**	**11.50**
			3rd Quartile	1.00	1.94	46.13	39.63	32.50
			Maximum	1.00	3.25	225.75	127.75	104.25
May 15	Full Inflation	5	Minimum	0.03	0.34	20.50	9.00	0.78
			1st Quartile	0.03	0.55	39.25	19.75	4.50
			Median	**0.11**	**0.55**	**41.50**	**23.50**	**14.00**
			3rd Quartile	0.11	0.63	133.25	42.75	33.25
			Maximum	0.22	1.82	135.25	47.50	44.75
May 22	Full Inflation	0						
May 30	Full Inflation	5	Minimum	0.62	0.02	1.25	4.75	0.17
			1st Quartile	0.67	0.50	3.00	5.50	0.43
			Median	**0.75**	**1.02**	**6.00**	**33.50**	**1.25**
			3rd Quartile	1.50	1.53	6.75	150.25	23.25
			Maximum	3.60	1.74	7.25	337.00	147.50
June 5	Full Inflation	2	Minimum	0.22	1.28	3.25	5.00	0.90
			1st Quartile	0.51	1.31	7.63	5.75	1.74
			Median	**0.80**	**1.34**	**12.00**	**6.50**	**2.58**
			3rd Quartile	1.09	1.36	16.38	7.25	3.41
			Maximum	1.38	1.39	20.75	8.00	4.25
All		44	Minimum	0.02	0.02	1.25	1.75	0.03
			1st Quartile	0.24	0.55	2.93	7.75	0.81
			Median	**0.78**	**1.20**	**5.75**	**21.50**	**6.25**
			3rd Quartile	1.53	1.75	19.13	47.80	27.00
			Maximum	3.60	3.29	225.75	337.00	147.50
			Mean	**1.05**	**1.24**	**24.1**	**41.00**	**20.3**
			SD	0.92	0.88	48.5	61.00	30.9

Table 7. Travel rates (km/h) and residence times (h) for radio-tagged steelhead smolts that successfully passed Mirabel Dam between April and June 2002. The river and reservoir reaches were 4.5 and 5.1 km long respectively. Residence time is the total amount of time fish spent in each reach and was calculated using data from automated stations and mobile tracking. Forebay residence time is a portion of total reservoir time and was calculated as time elapsed from first detection 100 m above the dam to passage. Because smolts were released at the upstream end of the reservoir beginning May 14, river travel rates and residence times were not available after that date. None of the fish released on June 4 were detected in the dam forebay.

Year 2002 Release Date	Dam Status	Passing Fish	Statistic	Travel Rate (km/h)		Residence Time (h)		
				River	Reservoir	River	Reservoir	Forebay
April 25	Partial Deflation	4	Minimum	0.13	1.02	1.25	2.17	0.05
			1st Quartile	2.25	1.92	1.36	2.58	0.37
			Median	**3.09**	**2.24**	**1.46**	**12.18**	**9.90**
			3rd Quartile	3.31	2.31	9.71	48.87	45.89
			Maximum	3.60	2.43	34.28	130.58	125.58
May 1	Partial Deflation	9	Minimum	0.03	0.07	1.25	2.70	0.45
			1st Quartile	0.51	0.22	6.41	23.00	13.13
			Median	**0.60**	**0.52**	**7.53**	**26.00**	**16.30**
			3rd Quartile	0.70	1.02	8.90	40.68	22.00
			Maximum	3.60	2.27	168.43	87.00	31.25
May 7	Full Inflation	6	Minimum	0.10	0.68	1.32	3.00	0.05
			1st Quartile	0.38	1.02	2.37	4.61	0.25
			Median	**0.96**	**1.20**	**4.69**	**9.35**	**4.76**
			3rd Quartile	2.35	1.41	19.34	19.45	12.49
			Maximum	3.41	1.70	47.08	66.12	62.62
May 14	Partial Deflation Notch	9	Minimum		0.19		3.83	0.02
			1st Quartile		0.89		4.05	0.05
			Median		**0.97**		**5.5**	**0.05**
			3rd Quartile		1.28		7.15	0.81
			Maximum		1.79		27.47	4.00
May 22	Full Inflation	5	Minimum		0.09		5.16	0.20
			1st Quartile		0.50		9.90	0.50
			Median		**0.53**		**10.47**	**0.50**
			3rd Quartile		0.55		18.85	0.57
			Maximum		1.09		55.67	9.16
June 4	Partial Deflation Notch	0						
All		33	Minimum	0.03	0.07	1.25	2.17	0.02
			1st Quartile	0.50	0.53	1.56	4.8	0.20
			Median	**0.70**	**0.99**	**6.41**	**10.47**	**0.81**
			3rd Quartile	2.89	1.29	9.16	26.0	14.68
			Maximum	3.60	2.43	168.43	130.58	125.58
			Mean	**1.40**	**1.05**	**18.06**	**23.02**	**12.26**
			SD	1.35	0.67	38.44	28.31	24.38

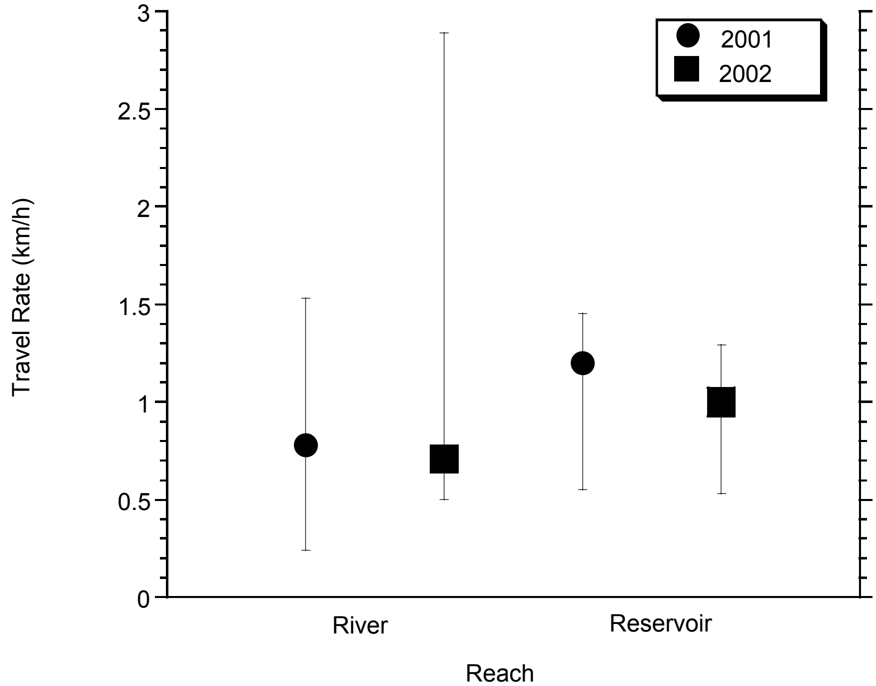

Figure 11. Median travel rates (km/h) for radio tagged steelhead smolts that passed Mirabel Dam from April to June, 2001 and 2002. Rates in the river and reservoir reaches are indicated. Bars depict the first and third quartiles.

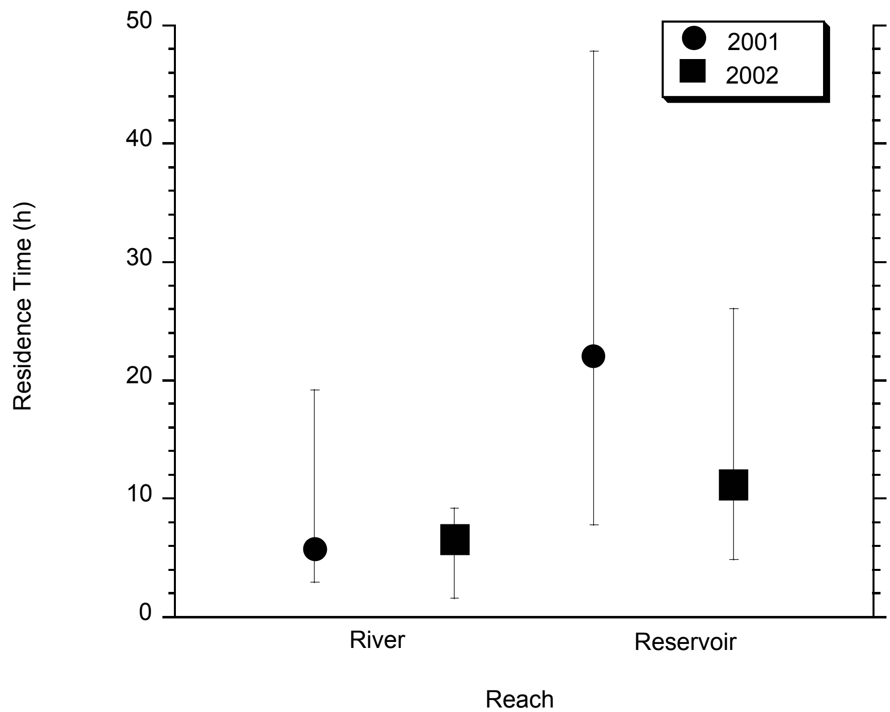

Figure 12. Median residence times (h) for radio tagged steelhead smolts that passed Mirabel Dam from April to June, 2001 and 2002. Times in the river and reservoir reaches are indicated. Bars depict the first and third quartiles.

Table 8. Reservoir and forebay residence times for radio tagged steelhead smolts that passed Mirabel Dam while it was fully inflated, partially deflated, and notched. Dam configurations were alternated throughout the study period and maintained for two weeks. Residence times for each configuration were compared using Kruskal-Wallis ANOVA. Significance was assumed at $P < 0.05$.

Year 2002 Release Dates	Dam Status	Fish Released	Passing Fish	Residence Time (h)		
				Statistic	Reservoir	Dam Forebay
May 7 May 22	Full Inflation	50	11	Minimum	3.0	0.05
				1st Quartile	4.98	0.35
				Median	*10.47*	*0.57*
				3rd Quartile	20.08	8.94
				Maximum	66.12	62.62
April 25 May 1	Partial Deflation	60	13	Minimum	2.12	0.05
				1st Quartile	21.10	6.0
				Median	*24.42*	*16.3*
				3rd Quartile	40.68	22.0
				Maximum	130.58	125.58
May 14 June 4	Notch	48	9	Minimum	3.83	0.02
				1st Quartile	4.05	0.05
				Median	*5.5*	*0.05*
				3rd Quartile	7.15	0.81
				Maximum	27.47	4.00
P					0.122	0.006

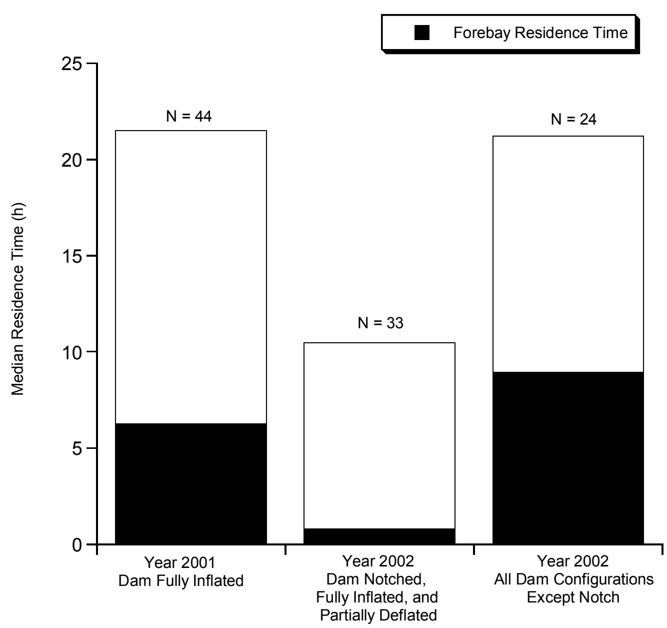

Figure 13. Residence times for smolts that passed Mirabel Dam when it was fully inflated, partially deflated, and notched. Forebay time (shaded area) is a portion of total reservoir residence time.

Hydraulic Measurements

River flow (estimated from USGS Dry Creek and Healdsburg gauge data) decreased and water temperature increased over the course of the study in both years (Figure 14). In 2001, mean flow ranged from 10.3 m^3/s (364 cfs) on April 24-30 (one week after the first smolt release) to 5.4 m^3/s (191 cfs) on June 5-11. On average, mean flow during the week following each release was 1.6 times higher in 2002 than 2001. Flows in 2002 ranged from 14.3 m^3/s (505 cfs) on April 25-30 to 7.1 m^3/s (251 cfs) on June 4-10. Water temperature averaged 1.4 ˚C lower in 2002 than 2001. In 2001, mean temperatures ranged from 18.1 ˚C (64.6 ˚F) on April 24-30 to 20.9 ˚C (69.6 ˚F) on June 5-11. Mean temperatures in 2002 increased from 15.8 ˚C (60.4 ˚F) on April 25-30 to 20.6 ˚C (69.1 ˚F) on June 4-10.

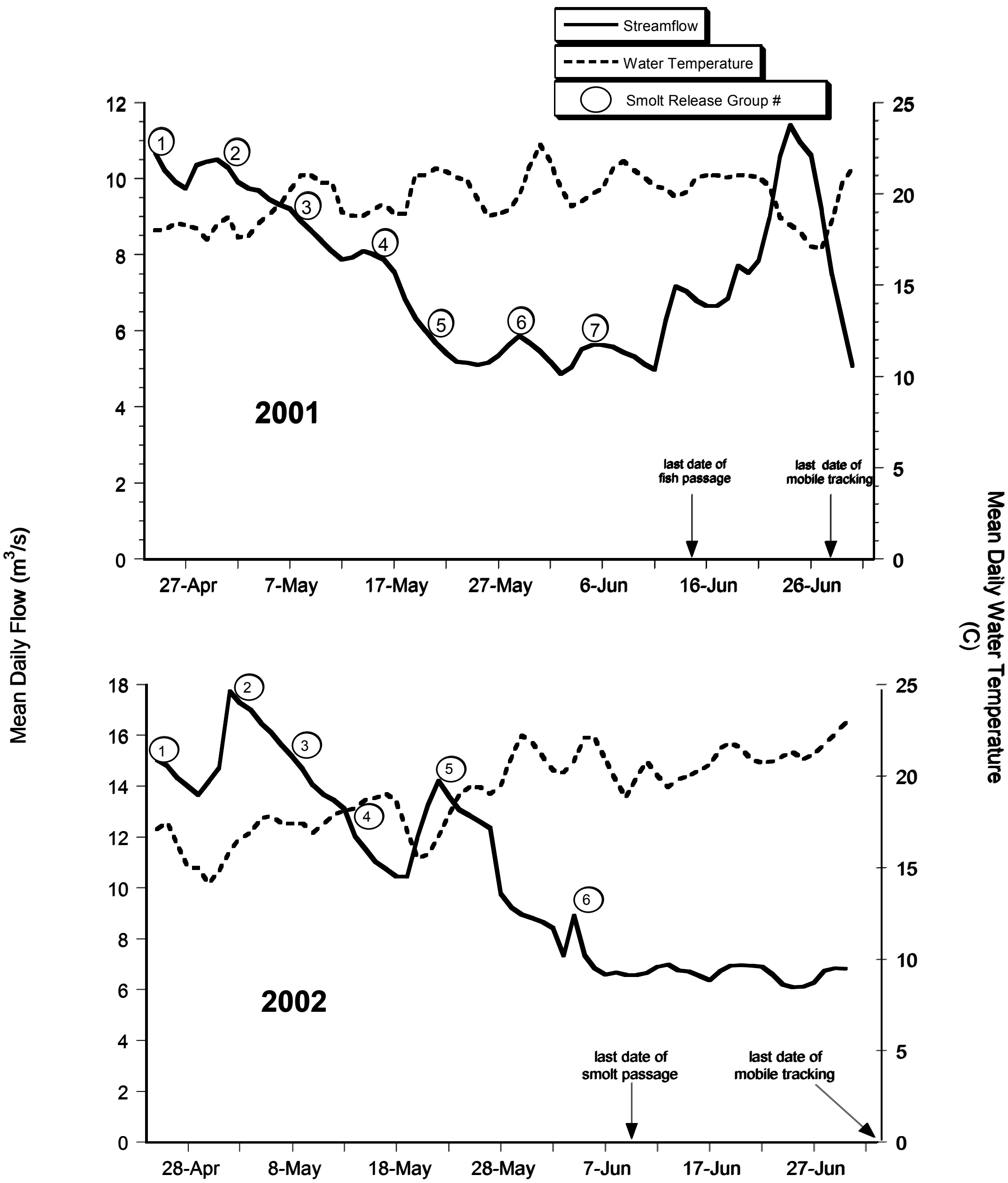

Figure 14. Mean daily flow and water temperature for the Healdsburg to Mirabel reach of the Russian River from April 24 to June 30, 2001 and 2002.

We collected velocity data along 3 transects in the dam forebay using the ADCP on April 30, May 3, 8, 16, and June 4, 2002. The data from May 3, 8, and 16 corresponded best to the 3 dam configurations. Direct river discharge measurements at the upstream transect agreed poorly with our estimated flows derived from combining USGS Dry Creek and Healdsburg gauge data (Table 9). Discharge calculated by the ADCP at the upper forebay transect was 2.2 (78 cfs) to 4.4 m^3/s (155 cfs) lower than our estimated flows from the USGS gauges 13 km above the dam. Flows at the upper forebay transect were 13 m^3/s (459 cfs), 11.5 m^3/s (406 cfs), and 8.8 m^3/s (311 cfs) when the dam was partially deflated on May 3, fully inflated on May 8, and notched on May 16 respectively.

Table 9. Dam configuration, water surface elevation, and river flow in the forebay of Mirabel Dam on ADCP measurement dates. River Flow is the summation of USGS gage data at Healdsburg and Dry Creek. Flow data from the acoustic Doppler current profiler (ADCP Flow) was collected at the same horizontal transect in the upper forebay on each date during May 2002.

Dam Configuration	Date	Water Surface Elevation in Forebay	River Flow (13 km above dam)	ADCP River Flow (upper forebay)
Full Inflation	May 8	11.6 m (38.1 ft)	15.2 m^3/s (536 cfs)	11.5 m^3/s (405 cfs)
Partial Deflation	May 3	11.5 m (37.6 ft)	17.4 m^3/s (615 cfs)	13.0 m^3/s (460 cfs)
Notched	May 16	11.2 m (36.7 ft)	11.0 m^3/s (390 cfs)	8.8 m^3/s (312 cfs)

The extent of flow concentration for each configuration was apparent from ADCP measurements at the transect closest to the dam (Figure 15). Flow was not concentrated when the dam was fully inflated. Areas of increased average water column velocity extended over approximately 15 and 11 m of the transect when the dam was partially deflated and notched.

Because flow differed among measurement dates, the magnitude of velocities at each transect could not be directly compared between configurations (Figure 15). To standardize the velocity measurements and compare configurations we related flows to the highest measured discharge (13 m^3/s) at the upper transect. The upper transect was above the influence of the water diversion pump intakes and provided the best approximation of flow entering the forebay. To standardize velocity measurements, we divided the flow on May 3 (13 m^3/s) by flows on May 8 and 16 to produce flow equivalent coefficients. We then multiplied these coefficients by the measured velocities at each transect on each date to generate estimated velocities equivalent to velocities at the highest flow (Table 10). Following Table 10, flow at the upper transect was 1.5 times higher on May 3 (partially deflated configuration) than May 16 (notched configuration).

The observed maximum average water column velocity at the lower transect on May 16 was 23.2 cm/s and 34.7 cm/s on May 3. Applying the flow equivalent coefficient to the lower transect velocity on May 16 produced a standardized velocity of 34.8 cm/s. Had river flow on May 16 been 1.5 times higher, maximum water column velocities over the dam crest would have been the same as the velocity observed on May 3. At full inflation, however, standardized maximum water column velocity at the lower transect (13.8 cm/s) was less than 50% of the velocities at the partially deflated and notched configurations. Standardized velocity increased from the upstream to downstream forebay transects when the dam was partially deflated and notched yet decreased from 17.8 cm/s to 13.8 cm/s when the dam was fully inflated (Table 10).

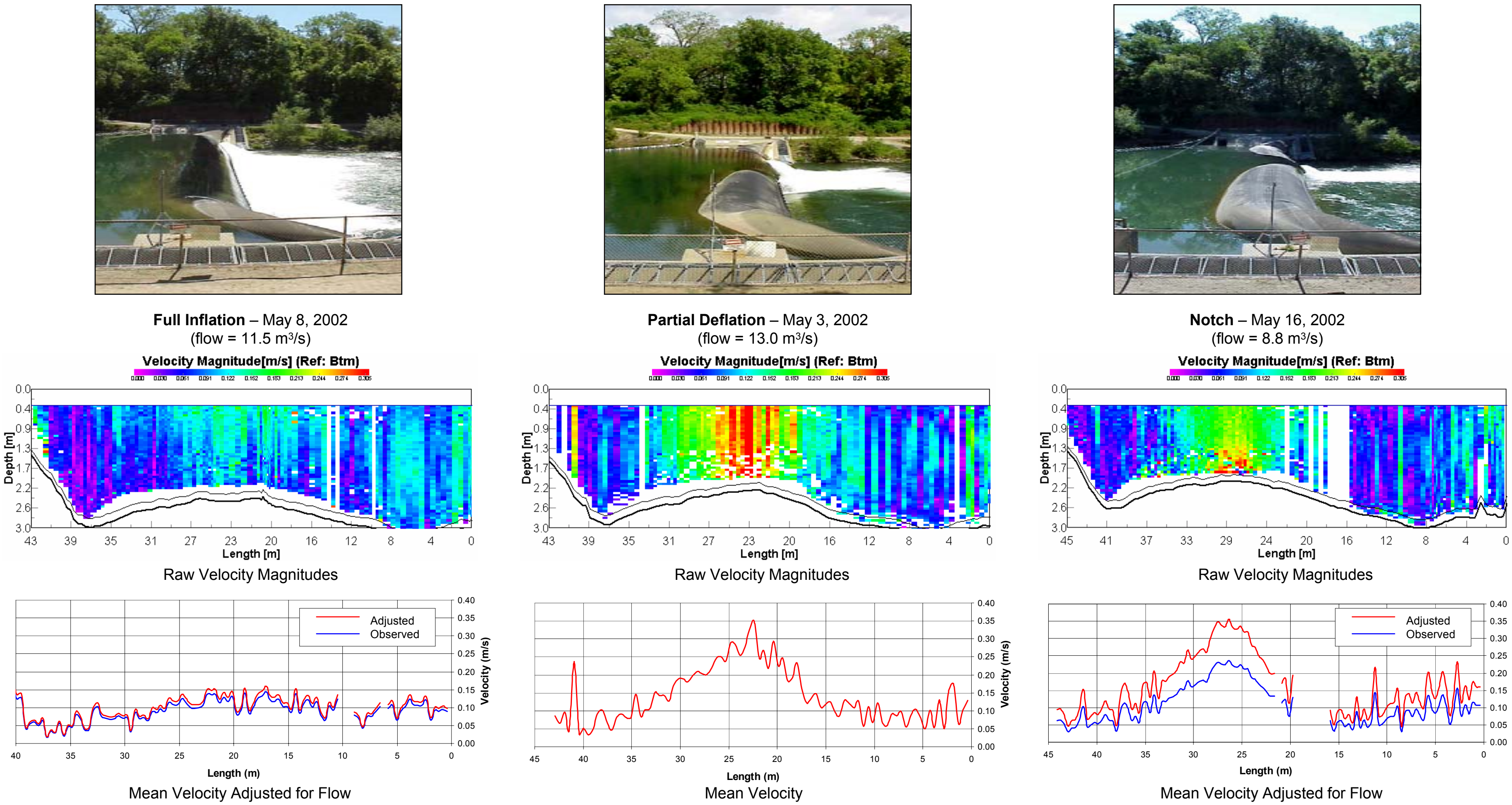

Figure 15. Raw velocity magnitudes and mean velocities adjusted for flow at the lower transect in the forebay of Mirabel Dam when the dam was fully inflated, partially deflated, and notched. Plots are oriented downstream and length indicates horizontal position along each transect. Hydraulic data was collected using an Acoustic Doppler Current Profiler.

Table 10. Observed and standardized maximum average water column velocities for 3 transects in the forebay of Mirabel Dam when the dam was fully inflated, partially deflated, and notched in May 2002. Velocity was standardized by applying a flow equivalent coefficient to measured velocities. Flow equivalent coefficients were derived by divided the highest flow observed at the upper transect on May 3 by upper transect flows on May 8 and 16. The upper transect was above the influence of forebay diversion pumps and the lower transect was closest to the dam.

Dam Configuration	Flow at Upper Transect (m^3/s)	Flow Ratio		Flow Equivalent Coefficient		Maximum Ave. Velocity (cm/s) Observed		Standardized
						Upper Transect		
Full (May 8)	11.5	13/11.5	=	1.1	x	16.2	=	17.8
Partial (May 3)	13.0	13/13	=	1.0	x	21.0	=	21.0
Notch (May 16)	8.8	13/8.8	=	1.5	x	11.3	=	17.0
						Middle Transect		
Full (May 8)	11.5	13/11.5	=	1.1	x	12.2	=	13.4
Partial (May 3)	13.0	13/13	=	1.0	x	18.3	=	18.3
Notch (May 16)	8.8	13/8.8	=	1.5	x	11.0	=	16.5
						Lower Transect		
Full (May 8)	11.5	13/11.5	=	1.1	x	12.5	=	13.8
Partial (May 3)	13.0	13/13	=	1.0	x	34.7	=	34.7
Notch (May 16)	8.8	13/8.8	=	1.5	x	23.2	=	34.8

DISCUSSION

Migratory Behavior and Dam Passage

Water velocity affects smolt migratory behavior and studies on Chinook salmon, Atlantic salmon, and brown trout have reported decreased migration rates in impoundments (Aarestrup et al. 1998; Venditti et al. 2000; Olsson et al. 2001). In 2001 and 2002, however, we found smolts traveled through the river and reservoir reaches at approximately the same rate despite lower velocity in the reservoir. Olsson et al. (2001) reported that low current speed in a small artificial pond retarded smolt outmigration and high discharge accelerated migration rates in a free flowing control reach. In contrast, average flow during our study was 1.6 times higher in 2002 than 2001 yet median travel rate did not increase in 2002. Declining flows over the course of the study in both years also had no apparent influence on river or reservoir travel rates. Our inability to detect differences in travel rates among reaches and years suggests the magnitude of velocities during the study did not alter migratory behavior.

The rapid movement of smolts may also be related to the short 5.1 km length of Wohler pool. Studies in larger impoundments have shown migration rates decrease downstream (Aarestrup et al. 1998; Venditti et al. 2000). Because smolt movements are guided by current direction, fish may become disoriented in low velocity environments. Venditti et al. (2000) hypothesized that juvenile Chinook were disoriented emigrating through a 60 km long impoundment and displayed “searching” behavior to relocated current. Smolts in Wohler pool either detected slow currents or encountered the dam before the low velocity environment triggered searching behavior.

The similarity in river and reservoir travel rates can be partially explained by our method of calculating travel times. Our travel rate is not analogous to a total migration rate. We calculated travel rate based on time elapsed from detection at an upstream station to the first detection at the next station downstream. Comparing travel rates helped determine if current speed through the reservoir or forebay conditions affected total migration rate. Studies that compare total migration rates (i.e., total time elapsed from reach entry to passage) may not detect the influence of obstacles on migratory behavior.

Greater residence time in the reservoir coupled with similarities in travel rates suggests the dam, not current speed through the impoundment, slowed outmigration. While we found travel rates similar among years and reaches, in 2001 average residence time was 60% higher in the reservoir. During both years most smolts traveled through the reservoir at rates greater than average current speed then slowed when they encountered the dam. Aarestrup et al. (1999) reported that radio-tagged Atlantic salmon smolts migrating through a 12 km reservoir were delayed an average of 18 h in the vicinity of a narrow culvert. Venditti et al. (2000) showed that juvenile salmon had difficulty locating passage routes in the forebay of a large reservoir and were delayed 14 to 19 hours. During our 2001 study, mean residence time in the short 0.1 km long forebay (20 h) was half the total reservoir residence time and nearly equivalent to time (24 h) in the longer 4.5 km river reach.

Our manipulation of dam configurations in 2002, although not conclusive, presents additional evidence that emigration delay was related to forebay conditions. In 2002, forebay residence time was 50% lower than 2001. The reduced forebay time in 2002 was driven by releases on May 14 (notch configuration) and May 22 (full inflation). Median forebay residence time for the notched configuration was an order of magnitude lower than full inflation. After removing fish that passed under the notched configuration from the 2002 data set, reservoir and forebay residence times were similar to 2001. Although forebay residence time was reduced when the dam was notched, small sample size (number of passing fish) did not yield enough statistical power to detect a significant difference between the notched and full configurations. The similarity between the 2001 and 2002 data (after removing the notched configuration) nonetheless suggests that emigration delay was reduced when the dam crest passage route was improved.

Although delayed, more than 80% of the fish that entered the forebay successfully passed the dam. However, most released fish in both years failed to reach the forebay. Of the smolts that reached the reservoir, more were detected in the forebay in 2001 (86%) than 2002 (53%). Our release strategy in 2002 partially explains this discrepancy. We anticipated that environmental factors such as higher stream flow and lower water temperature would favor greater downstream smolt movement in 2002. After the first three weekly releases in 2002, however, fewer fish reached the forebay. Because we were primarily interested in testing the effects of dam manipulations on forebay residence time, we moved the release site to the upstream end of the reservoir in the later half of 2002. Moving the release site downstream did not increase the proportion of fish that entered the forebay and partially confounded our ability to compare smolt movements between years. As in 2001, more than half the released fish in 2002 initially moved downstream then stopped migrating for the duration of the study. Although we tried to remove these non-migrant fish from the 2002 data, it was impossible to fully account for fish that would have stayed in the river reach had they been released upstream.

The failure of environmental conditions and release location to accelerate outmigration suggests that some fish were losing their proclivity to emigrate. Evaluating the dam and reservoir required that we hold fish for 3 to 7 weeks beyond their normal release date. For operational reasons the dam cannot be inflated until discharge is less than 28.3 m^3/s. We inflated the dam and began releasing fish immediately after the flows dropped below this threshold. However, the prolonged holding period may have induced desmolting or parr-reversion (Zaugg and Mclain 1972; Clarke and Hirano 1995). Our saltwater challenge results from 2000-2002 supported this contention and showed an increasing trend in plasma sodium values from early March to June.

The increasing trend we observed in sodium concentrations corresponds to seasonal patterns in steelhead Na^+K^+-ATPase activity (an enzyme associated with sodium transport across the gills) reported in other studies (Zaugg and Maclain 1972; Zaugg 1981). Although published plasma sodium reference values for steelhead are scarce, smolts capable of adapting to seawater typically have concentrations less than or equal to 170 mmol/L (Blackburn and Clarke 1987). Median plasma sodium concentrations exceeded 170 mmol/L in all 2001 and 2002 test groups. The declining proportion of passing fish we observed in 2001 corresponds to a general increase in plasma sodium values from April 25 to May 29. Higher sodium values in 2002 may also explain the lower percentage of fish that entered the forebay that year. While 170 mmol/L has been cited as a sodium threshold for successful adaption to seawater (Blackburn and Clarke 1987), specific sodium levels have not been linked to smolt migratory behavior and fish that revert to parr can regain smolt characteristics (Zaugg and McLain 1970; Clarke and Hirano 1995). Zaugg (1982) found coho salmon that had reverted to parr in a hatchery migrated seaward after release. However, most smolts we detected in the forebay exhibited a strong urge to emigrate immediately after release and it seems likely that this smaller mobile fraction of the study population was still capable of seawater adaptation. To avoid including fish that may no longer have been smolts, we only used residence and travel time data from fish that moved steadily downstream and passed the dam.

Other potential factors responsible for the low percentage of migrant fish included effects related to surgery, loss due to predation, or tag failure. Long term and 48 h pre-release survival of our dummy and radio tagged fish was nearly 100% in both years. Numerous studies have found minimal growth, survival, and behavioral effects from surgical tag implantation and the technique is recommended for use in smolts (Lucas 1989; Peake et al. 1997; Adams et al. 1998a; Martinelli et al. 1998). We did not observe behavioral differences between dummy tagged and control fish in 2001 or 2002. Growth of dummy tagged fish also did not differ significantly from controls in 2001. We cannot fully explain the significantly lower growth of dummy tagged fish in 2002. Both treatment and control groups were held together and dummy tagged fish, suffering from some level of stress after surgery, likely competed less effectively for food. We used automatic feeders and reduced the daily ration in 2002. The reduced quantity of food was probably insufficient to satiate the control fish and may have created a greater growth difference between the groups.

Although we collected mobile tracking data to indicate the presence or absence of fish in the study reaches, the data was not precise enough to determine subtle fish movements between surveys. We, therefore, could not determine if stationary fish were alive or dead. The manufacturer of our radio telemetry equipment (LOTEK Inc.) reports low transmitter failure rates and other researchers have attributed the sudden loss of signals to predation (Jepsen et al. 1998). High steelhead mortality during seaward migration is common and the 25-37% loss rates we observed have been reported in other studies (Ward and Slaney 1990; McMichael et al. 1992; Tipping et al. 1995). Tipping et al. (1995) found hatchery smolt losses of 19.8 percent over 4.7 km of a small stream. Ward and Slaney (1990) and McMichael et al. (1992) found 42 percent losses over 10 km of a small river and 36 percent losses over 11 km of a large river.

Because impoundments can delay emigration, concentrate smolts, and tend to have habitat conditions that favor predators, smolt mortality rates may be elevated in reservoirs (Poe et al. 1991; Vigg et al. 1991; Jepsen et al. 1998). We found, however, that signal loss rates were generally similar among reaches in both years. A higher percentage of signals were lost in the reservoir in 2002 but this increase was probably related to the release of fish at the upstream end of the impoundment. Because we did not directly observe predators, we cannot attribute our smolt losses to either piscivorous fish or birds. However, the sudden disappearance of signals suggests that avian predators may have been responsible for much of the assumed mortality. Osprey, mergansers, and herons were routinely observed feeding in Wohler Pool. Because Wohler Pool is a seasonal reservoir, it does not provide year round habitat conditions that would favor a large stable population of piscivores such as Sacramento pikeminnow, largemouth bass, and smallmouth bass. Annual boat electrofishing surveys in the reservoir have found relatively few native or non-native predatory fishes in size classes large enough to consume smolts (Chase et al. 2002). On average, fish that disappeared before the end of their transmitter's battery life resided in the reaches for more than a week. This extended period suggests that the non-migrant portion of the population may have been more susceptible to predation.

Hydraulic Conditions in Dam Forebay

We hypothesized that increased velocity and depth created by concentrating dam spill would accelerate smolt passage. Due to greater river discharge at the time of measurement, velocity near the crest was highest when the dam was partially deflated. Although fish appeared to pass the dam more rapidly under the notched configuration, our velocity measurements (after adjustment for discharge) showed little difference between the notched and partially deflated conditions. Rapid passage times, despite lower unadjusted velocities when the dam was notched, suggested that the range of velocity magnitudes we observed may not have influenced smolt behavior.

A complex set of factors enhance or discourage fish emigration past obstructions and smolt guidance is a field of active research (Haro et al. 1997; Ferguson et al. 1998; Beeman and Maule 2001). The depth, shape, and resulting velocity gradients (not magnitudes) at the dam crest under the three configurations likely influenced forebay residence time. The shape of fish passage structures affects water acceleration. As water falls over a sharp crested weir it accelerates rapidly. Because smolts sense this rapid acceleration gradient and tend avoid entrainment in the flow field, sharp crested structures can discourage passage. Smolts pass more rapidly, however, if flow accelerates uniformly. Haro et al. (1997) found that an experimental surface bypass weir with a gently sloping upstream face gradually accelerated water velocity and passed Atlantic salmon smolts faster than a standard weir. When fully inflated, Mirabel Dam resembles a standard sharp crested weir. Although velocity magnitudes increased dramatically when the dam was partially deflated, we suspect the pattern of flow over the crest was more similar when the dam was fully and partially inflated than when it was notched.

Greater depth when the dam was notched may also have accelerated passage. A study that monitored the movement of resident rainbow trout through the spillways of two artificial reservoirs found that passage increased dramatically at depths greater than 0.24 m (Rischbieter 1996,1998). For safety reasons we could not directly measure depth in the area of concentrated flow at the dam crest. The deeper notch appeared to provide more uniform flow acceleration but due to signal interference in shallow water we could not use the ADCP to measure conditions in the notched portion of the crest.

Smolts entering the forebay of Mirabel Dam can choose three potential passage routes: bypass pipes at the screened pump intakes, Denil fishways, or the dam crest. Our hydraulic measurements showed that none of the potential routes exerted much influence on forebay velocity. The likelihood that smolts will discover a route is related to discharge and velocity at the passage entrance (Ferguson et al. 1998). Recommended entrance velocities for surface smolt bypass systems at large dams range from 0.6 to 1.8 m/s (Ferguson et al. 1998). The highest average water column velocity we observed in the forebay was 0.35 m/s. We did detect increased flow at the upper forebay transect when the dam was partially deflated and notched but it seems unlikely that the velocities we recorded at the lower transect would have attracted smolts from more than a few meters upstream. We suspect that the dam crest was the most common passage route simply because it is the largest structure in the forebay and passes the highest volume of flow.

The difference between river discharge recorded at USGS gauging stations, located 13 km above the dam, and flow in the forebay estimated using the ADCP was likely the result of water withdrawal. Although some flow escaped measurement at our forebay transect, it seems unlikely that the 2.2 m^3/s (78 cfs) to 4.3 m^3/s (151 cfs) discrepancy was the result of measurement error. The Water Agency operates two large groundwater collector wells above the forebay and private landowners pump surface water for irrigation along the reach between Healdsburg and the dam. Our measurements may indicate the magnitude of this withdrawal but the specific volume of flow lost to these sources is unknown and probably varies daily depending on weather conditions and pumping rates.

CONCLUSIONS

During the year 2000 study we found dramatic differences in passage success before and after the dam was inflated and evidence that the reservoir was causing migratory delay. Our ability to draw conclusions from the 2000 study, however, was partially confounded by changing environmental conditions. Our decision to establish an upstream free-flowing control reach in 2001 and 2002 yielded a more powerful evaluation of smolt migratory behavior. Increasing the number of antennas and datalogging receivers, manipulating levels of dam inflation, and measuring hydraulic characteristics in the forebay greatly improved our understanding of passage conditions.

The year 2001 and 2002 data seem robust and lead us to conclude that smolts travel through the river and reservoir at approximately the same rate even though the impoundment is a lower velocity environment. The similarity in travel rates suggests that delays associated with the impoundment are limited to the forebay. In both years most smolts passed the dam by traveling over the crest. Because most fish that reached the forebay successfully passed downstream, we believe the dam causes delay but is not a barrier to outmigration. More study is needed before we can accept or reject our hypothesis that passage will be accelerated by notching the dam and concentrating spill. Although few fish attempted passage under each configuration, forebay residence time was lowest when the dam was notched. Creating the notch required a minimal amount of trial and error and seemed operationally feasible at the water surface elevations we tested. Notching the dam holds promise as a relatively simple and effective method of reducing forebay delay.

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PERSONAL COMMUNICATIONS

Dr. Scott Foott. 2000. Pathologist, U.S. Fish and Wildlife Service California-Nevada Fish Health Laboratory, Anderson, CA.