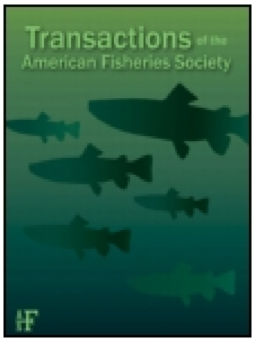

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[Article]

Downstream Passage of Steelhead Kelts through Hydroelectric Dams on the Lower Snake and Columbia Rivers

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Abstract.—After spawning, iteroparous steelhead *Oncorhynchus mykiss* from the Columbia River basin must navigate several hydroelectric dams on their way to the Pacific Ocean. We used radiotelemetry to investigate migration rates, downstream passage routes, and success of adult steelhead kelts migrating past lower Snake River and Columbia River dams during the springs of 2001 and 2002. Seaward-migrating kelts were collected, radio-tagged, and volitionally released from the juvenile bypass facilities at Lower Granite Dam (LGR) on the Snake River and at McNary Dam (McN) and John Day Dam (JDD) on the Columbia River. Migration success rates from LGR to the study area exit (8 km east of Portland, Oregon) were poorer during the low-flow nonspill conditions of 2001 (4.1%) than in the more typical flow year of 2002 (15.6%). Kelts tagged and released at Columbia River dams had substantially higher migration success than those released on the Snake River; 59.6% and 62.3% of the kelts released at McN and 63.6% and 80.0% of those released at JDD were contacted at the study area exit during 2001 and 2002, respectively. Kelt dam passage was predominately via spillways and surface flow routes, and during periods of spill 90.0% or more kelts typically passed via nonturbine routes. Only 47.2% of kelts were guided out of turbine intakes by screen systems during nonspill periods. Turbine passage, the primary alternative route during nonspill periods, may be a substantial source of kelt mortality. The poor migration success rate of Snake River kelts in both 2001 and 2002 suggests that additional management (i.e., kelt reconditioning, transportation, or both) may be warranted to boost iteroparity rates in this population.

Populations of Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* in the Columbia and Snake River basins are declining and many risk extinction (NMFS 2000; McClure et al. 2003). Steelhead, the anadromous form of the rainbow trout, is now listed as endangered (upper Columbia River) or threatened (Snake and mid-Columbia rivers) under the Endangered Species Act (ESA; NMFS 2004). Causes of the decline are numerous and include overharvest (Ebel et al. 1989), continued loss and degradation of rearing and spawning habitat (Thurow et al. 1997), failed hatchery supplementation practices (Waples 1991; Reisenbichler and Rubin 1999), and mortality associated with passage through the numerous dams and impoundments in the Columbia River basin (Raymond 1988; Venditti et al. 2000; Budy et al. 2002).

In anadromous Pacific salmon, iteroparity is limited to trout species. Postspawn salmonids attempting seaward migrations are commonly referred to as ‘‘kelts.’’ Like juvenile salmonids, adult steelhead kelts must navigate downstream through the Federal Columbia River Power System (FCRPS) on the Snake and Columbia rivers, and some have to navigate past as many as 10 different main-stem dams (Figure 1). Each spring thousands of kelts are enumerated at hydroelectric dams on the lower Snake and Columbia rivers (Wertheimer et al. 2003; Evans et al. 2004a). Evans et al. (2004a) estimated that 17% of the ESA-listed Snake River steelhead population was observed as kelts in the Lower Granite Dam (LGR) juvenile bypass facility during a 10-week monitoring period in the spring of 2000. The majority of these kelts were considered to be in good or fair morphological condition (Evans et al. 2004a), presumably capable of completing their downstream migration to the ocean and returning to spawn again.

Iteroparity rates in steelhead populations from the Pacific Northwest from as low as 1% to more than 51% have been reported, depending on the year and geographic location of the population (Fleming 1998; Lohr and Bryant 1999). In populations where iteroparity exists, this life history adaptation may be fundamental to ensuring pop-

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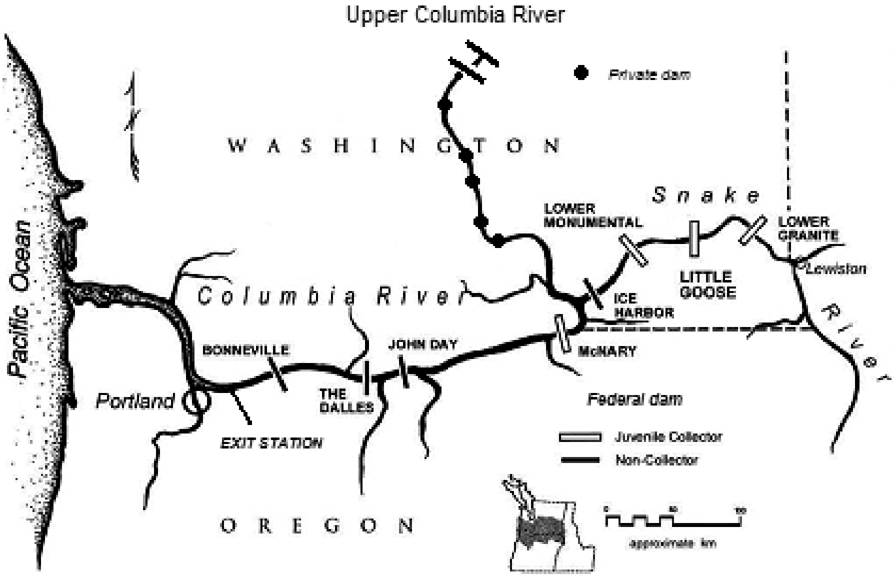

FIGURE 1.—Study area showing locations of Federal Columbia River Power System dams on the lower Columbia River in Washington and Oregon and the lower Snake River, Washington, including Lower Granite, McNary, and John Day dams, where steelhead kelts were radio-tagged and released in 2001 and 2002.

ulation stability, especially in environments where harsh and variable conditions can eliminate genetic contributions from a spawning cohort (Legget and Carscadden 1978). Reduced genetic contributions from stocks formerly supplemented by repeat spawners may play an important role in the decline of Columbia River basin steelhead populations (NMFS 2000). Iteroparity rates in Columbia River steelhead populations above McNary Dam (McN), the fourth furthest downstream hydroelectric facility on the main-stem Columbia River at river kilometer (rkm) 465 (measured from the mouth of the Columbia River), have been reported between 2% and 4% (Whitt 1954; Hockersmith et al. 1995; Busby et al. 1996), while rates in nonimpounded tributaries below Bonneville Dam (BON), the furthest downstream hydroelectric facility on the main-stem Columbia River at rkm 234, have been reported as high as 17% (Leider et al. 1986). Fleming (1998) estimated an average iteroparity rate of approximately 10% in steelhead populations throughout North America. Natural causes that relate to varying respawning rates among iteroparous salmonids include phylogenic constraints, environmental conditions, geographic location, sex, size at maturity, and differences in the energy investment of spawning among different stocks and species (Fleming 1998). Causes for disparate respawning rates in impounded sections of the Snake and Columbia rivers probably include factors such as loss of habitat, poor water quality, and impoundment effects related to hydropower facilities (Pautzke and Meigs 1940; Larson and Ward 1955; Withler 1966; Ducharme 1969; Carscadden and Leggett 1975; Hynes et al. 1981).

Impacts to salmonids associated with dam passage have been the primary focus of federal mitigation efforts in the Columbia River basin (NPPC 1986), as hydroelectric dams are known to delay the migration timing and reduce the survival of endemic stocks (Raymond 1969, 1979; Venditti et al. 2000). In recent decades, most hydroelectric dam mitigation efforts have focused on improving passage of out-migrating juvenile salmonids, including structural and operational changes at dams that reduce delays in migration and mortalities associated with passage (Raymond 1979, 1988; NPPC 1986). Most of these modifications are based primarily upon the swimming performance of juvenile salmonids (Booth et al. 1997) and the natural surface orientation of smolts (Andrew and Geen 1960). Juvenile bypass systems have been constructed at many main-stem dams to guide migratory fishes out of turbine intakes with the use of large screens or away from intakes through bypasses that use surface discharge (Johnson et al. 2000, 2005). Similarly, volitional water releases allow for direct fish passage beneath raised spillway gates, a more benign passage route than tur-

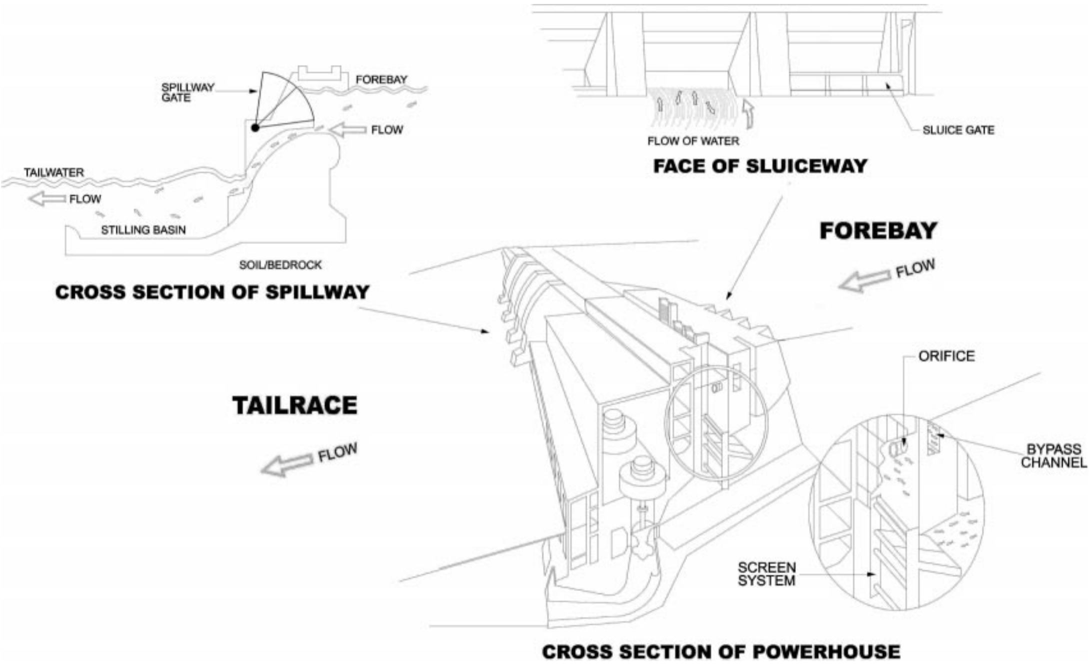

FIGURE 2.—Schematic showing downstream fish passage routes (i.e., spillway, bypass system, and ice and trash sluiceway) at Federal Columbia River Power System dams, including forebay and tailrace areas.

bine passage (Schoeneman et al. 1961). Many of these mitigation efforts have been shown to benefit juvenile salmonids (Muir et al. 2001; Williams et al. 2001); however, to what extent these practices benefit or harm adult steelhead kelts attempting seaward migration is poorly understood.

The purpose of this study was to use radiotelemetry to investigate the migration behaviors, dam-specific passage routes, and success rates of steelhead kelts migrating through the lower Snake and Columbia rivers. Emphasis was placed on evaluating kelt migration rates and migration successes through the lower Snake and Columbia rivers and dam-specific passage routes at BON, John Day (JDD), and The Dalles (TDD) dams on the lower Columbia River. Because we were unable to address assumptions fundamental in the use of radiotelemetry to determine survival rates (e.g., tagged individuals have the same probability of surviving as nontagged individuals, survival and capture probabilities are not affected by sampling; Burnham et al. 1987; Skalski et al. 2001), migration success rates are provided as a proxy for kelt survival rates. Finally, the results from this study were used to assess how different management practices may be used to improve downstream travel, main-stem dam passage, and iteroparity rates of steelhead kelts in the Columbia River basin.

Study Area

Migrating steelhead kelts were captured, radiotagged, and released at three different FCRPS dams: LGR, located on the Snake River at rkm 694; McN, located on the Columbia River at rkm 465; and JDD, located on the Columbia River at rkm 345 (Figure 1). The migration rates and downstream passage of each radio-tagged kelt was monitored from release to the study area exit positioned at Government Island, which is located on the Columbia River at rkm 181, roughly 53 rkm below BON, the lowermost dam on the Columbia River (Figure 1).

Downstream migrants and fishes falling back through FCRPS projects have several passage options, and in some cases these options differ by project. In general, a fish approaching a lower Snake River or Columbia River dam can either pass the dam by way of the spillway (if in operation) or enter the powerhouse (Figure 2). Fish entering the powerhouse deep in the water column must pass through the turbines, whereas those entering the powerhouse higher in the water column may be diverted by screen systems that are positioned to guide fish out of the upper portion of the turbine intake into gatewells (Figure 2). Orifices within gatewells allow fish to pass into bypass channels that either route smolts to the tailrace or to raceways at juvenile salmon collector facilities at LGR, McN, Little Goose Dam (LGO), and Lower Monumental Dam (LMN; Merchant and Barilla 1988) for eventual transport by barge or truck around the FCRPS. The downstream end of the bypass channel contains a set of spaced bars (referred to as a ‘‘separator’’), which separates juveniles from adults and sorts juvenile salmonids by size. No screen systems are present at TDD, where fish enter either unscreened gatewells (with orifices that lead to a sluiceway) or over lowered gates into a debris sluiceway that routes fish to the tailrace (Figure 2). Two separate powerhouses and an unattached central spillway comprise the BON project. At the first powerhouse (B1), migrants may avoid turbines either by traveling over lowered gates into a sluiceway or through a screened bypass system. The second powerhouse (B2) contains a screened bypass system and a debris chute that was not operated during either year in which this study was conducted.

Methods

Fish sampling and tagging.—We sampled steelhead kelts at LGR, McN, and JDD by removing adults during their downstream migration from the dam’s juvenile bypass facility. Adult steelhead were diverted (at JDD) or directly dipnetted (at LGR and McN) from the bypass separator and transferred to a nearby sampling tank containing aerated river water with a buffered solution of clove oil at 30 mg/L (Prince and Powell 2000; Pirhonen and Schreck 2003). Because both prespawn (i.e., mature) and postspawned (i.e., kelt) adult steelhead are encountered at bypass facilities (Evans et al. 2004a), it was necessary to distinguish between the two maturational types, thereby ensuring that prespawn fish were not retained for radio transmitter attachment. We used the ultrasound imaging techniques of Evans et al. (2004b) to distinguish prespawn steelhead from kelts at LGR, McN, and JDD based on the presence or absence of mature gonads. Concurrent with the ultrasound examination, data on fork length (cm), external condition (rated by degree of damage as ‘‘good,’’ ‘‘fair,’’ or ‘‘poor’’; Evans et al. 2004a), and rearing type (hatchery or naturally produced) were also recorded. Rearing type was based on the presence or absence of fin clips. Only those kelts considered to be in good or fair morphological condition were selected for radio-tagging, as prior research demonstrated that kelts in poor condition are unlikely to survive the long migration distance after release (Evans 2002).

The sampling and tagging of kelts from LGR, McN, and JDD in 2001 and 2002 coincided with the peak downstream migration of kelts in the lower Snake and Columbia rivers: 15 April to 30 June (Evans et al. 2004a). A predetermined number of kelts were selected for tagging based on their condition and availability at the dams. Kelts classified as either in good or fair condition were placed in a V-shaped surgical trough for radio tag attachment. Uniquely coded Lotek radio tags (Lotek Engineering, Inc., Newmarket, Ontario) designed for juvenile fish (weighing 2.1 or 1.5 g in water and measuring 29 or 20 mm in length, respectively) were used. Minimum radio tag life for the 2.1-g tags was estimated at 46 d for a 3-s pulse rate and 68 d for a 5-s pulse rate, whereas the 1.5-g tags (5-s pulse rate) had a minimum tag life of 40 d. Because of their longer migration distance, kelts released from LGR were equipped with longer-life tags. We used the tagging technique developed by Wertheimer et al. (2001) to allow kelts to feed after release. Tags were attached externally to each fish with a wrap of polyolefin that had a 0.05-cm tube underneath to accommodate either a size 1 chromic gut resorbing suture (2001) or a nonabsorbable suture (2002). The suture was attached to a sterilized needle, passed through the cartilage at the base of the dorsal fin (posterior to the 3rd and 6th dorsal fin rays), and tied with a surgical knot on the distal cartilage surface. Conservative radio tag to body weight standards for biotelemetry applications were met by attaching the radio tags below 2% of the body weight of tagged kelts (Brown et al. 1999; Matter and Sandford 2003). After tagging, kelts were allowed to recover in a holding bin located just posterior to the separator. Once normal swimming behavior was observed (~15 min posttagging), fish were allowed to volitionally enter the bypass channel to resume their downstream migration.

Tag retention.—Because the suture harness tagging technique used in this study is relatively new, we assessed tag retention rates to ensure that tagged specimens were not losing their radio tags during migration. Complete absorption of a size 1 chromic gut resorbing suture does not occur for at least 90 d, whereas 89% of the tensile strength in nonabsorbable suture is maintained for 1 year (Terhune 2002). Because of the higher tensile strength of the nonabsorbable suture, retention tests were only conducted on the resorbing suture used in 2001. Tag retention was tested both in the field and in a laboratory in 2001. Field evaluation was conducted by inserting Floy tags (a highly visible, external ‘‘spaghetti’’-like tag) opposite the radio transmitter in kelts released from LGR in 2001 (n = 197). U.S. Army Corps of Engineers (COE) personnel working at two downstream collector dams (LGO and McN) monitored their respective facility 24 h a day for Floy-tagged kelts throughout the study period. Upon discovery of a Floy-tagged kelt in the separator, COE personnel visually noted the presence or absence of a radio tag without handling the specimen. Laboratory evaluations were conducted by tagging and retaining 15 kelts in two 1.8-m circular tanks and monitoring the fish for a 46-d period to determine tag retention rates and suture life.

Telemetry systems.—Transmissions from radio-tagged kelts passing dams on the lower Snake River and at McN were monitored by fixed-station aerial arrays located in the forebay (referred to as ‘‘entrance’’ stations; Figure 2) and tailrace (referred to as ‘‘exit’’ stations; Figure 2) areas of the powerhouse. Projects downstream of JDD and McN were equipped with entrance, exit, and underwater fixed-station arrays located in and around dam passage structures (Figure 2). Passage below BON was monitored with three sets of telemetry exit arrays originating near Reed Island (rkm 200) and culminating at the western end of Government Island (rkm 181; Figure 1). Tagged kelts were detectable to a depth of 8 m directly below aerial antenna arrays, while underwater antennas had a range of about 6 m (Venditti et al. 2000). Because of the attenuation of radio signals in water, kelts traveling at depths greater than 8 m below turbine intake screen systems or passing the spillway could have escaped detection. We calculated radio tag detection efficiency for river reaches based on the number of tagged specimens that were not detected passing a river reach but were subsequently confirmed at a downstream location. Although such estimates represent maximum detection efficiencies, we believe they are useful for discovering ‘‘gaps’’ in coverage throughout the monitoring range. Telemetry arrays similar to the systems deployed in this study are described in more detail by Johnson et al. (2000), Venditti et al. (2000), and Boggs et al. (2004).

Data analysis.—Telemetry signal receptions (‘‘contacts’’) from radio-tagged kelts were chronologically arranged for each individual coded tag, creating a sequential history for each fish. Telemetry data were then manually proofed with maps showing zones of coverage of each unique telemetry array. Manual proofing of the data allowed for rapid recognition of a kelt’s arrival at a telemetry array, route-specific passage determination (if available), and removal of noise. Criteria used in verifying the presence of a tagged kelt included the signal’s power level, the period of signal reception (3- or 5-s intervals), and the distribution of contacts within and among arrays. Telemetry records were only accepted if the record of a tag’s plausible passage history was supported by telemetry contacts before and after each contact.

We used the fish passage efficiency metrics of Whitney et al. (1997) to assess kelt passage efficiencies from bypass structures. The effectiveness of systems that rely on water discharge (e.g., spill, surface bypass, and sluiceways) to pass fish away from turbines are reported as the percentage of fish passed by that route divided by the proportion of total project discharge through that route. Employed metrics are defined as follows:

$$\text{Passage efficiency} = \frac{\text{nonturbine passage}}{\text{nonturbine passage} + \text{turbine passage}};$$

$$\text{Spillway efficiency (SPE)} = \frac{\text{spillway passage}}{\text{nonturbine passage} + \text{turbine passage}};$$

$$\text{Sluice efficiency (SLE)} = \frac{\text{sluice passage}}{\text{sluice passage} + \text{turbine passage}};$$

$$\text{Guidance efficiency} = \frac{\text{guided passage}}{\text{guided passage} + \text{turbine passage}};$$

$$\text{Spillway effectiveness} = \frac{\text{SPE}}{\text{(spill discharge/project discharge)}}; \quad \text{and}$$

$$\text{Sluice effectiveness} = \frac{\text{SLE}}{\text{(sluice discharge/powerhouse discharge)}}.$$

Forebay residence times (Venditti et al. 2000) and migration rates (km/h; Giorgi et al. 1997; Matter and Sandford 2003) were measured to further evaluate kelt passage behavior. Forebay residence times are defined as the amount of time between the first and last radio signal contact in the near-dam (~100 m) areas of the forebay. Migration rates were determined from the initial contact in the dam’s tailrace until first contact in the next dam's tailrace. Passage histories were derived from kelt forebay (i.e., spillway, powerhouse) contacts and subsequent contacts from screen systems, bypass channels, sluiceways, and the tailrace below the powerhouse and spillway.

Migration rates were calculated for fish passing river reaches (tailrace to tailrace) rather than for kelts passing reservoirs (tailrace to forebay) because of the lack of forebay telemetry contacts in the lower Snake River. Migration rates were only calculated for kelts that were contacted by consecutive telemetry arrays, resulting in smaller sample sizes than the actual number of kelts passing each river reach or project. Migration success was determined based on the total number of kelts released minus the number detected within a given river reach (i.e., the pool, forebay, and tailrace region of the river within a hydroelectric impoundment). As with many telemetry studies, fish loss within and among river reaches cannot always be attributed to specific causes; for example, loss can be attributed to mortality (by natural or unnatural [e.g., dam passage] causes), tag loss, tag malfunction, or missed detection.

The distribution of kelt travel time data (km/h) was nonnormal because of the presence of outliers; therefore, we used a distribution-free and outlier-sensitive test (i.e., Wilcoxon rank-sum test) to compare travel times within and among river reaches. Passage efficiency metrics were compared with chi-square or Fisher exact tests (depending on the expected frequencies) under the assumption that kelts would pass available routes with equal probabilities. Simple regression analysis was used to evaluate the association between river discharge (m^3/s) and median kelt travel times (km/h) for kelts passing monitored river reaches. Means are expressed as $x \pm$ SD. Statistical significance was set at alpha is less than 0.05.

Results

Radio-Tagging and Tag Retention

Kelts were radio-tagged over the course of a 7- to 8-week sampling period in both 2001 and 2002 (2-week sampling period at JDD in 2002; Table 1). In total, 853 kelts were sampled from the juvenile bypass facilities of LGR, McN, and JDD and outfitted with radio transmitters (Table 1). The majority of tagged kelts were in good external condition (73.0%) and of wild origin (65.4%). Condition data collected in 2001 and 2002 from all kelts sampled at LGR, McN, and JDD (i.e., not just those selected for tagging) indicated that an average of 46.9% were in good condition, 23.5% were in fair condition, and 29.6% were in poor condition. Weekly sampling effort, measured by the percentage of kelts sampled each week that were tagged, varied and intensified with increasing kelt numbers at the dams.

TABLE 1.—Number of steelhead kelts radio-tagged and released at Columbia River basin bypass facilities at Lower Granite (LGR), McNary (McN), and John Day (JDD) dams during the springs of 2001 (15 April to 31 May) and 2002 (15 April to 21 June).

Year	Location	Sampling weeks	Number of kelts tagged and released		
			Wild	Hatchery	Total
2001	LGR	8	116	81	197
	McN	7	37	15	52
	JDD	7	126	28	154
2002	LGR	7	88	79	167
	McN	8	181	92	273
	JDD	2	10	0	10

Altogether, 69 of 197 radio- and Floy-tagged kelts released at LGR were incidentally recaptured and examined during the 2001 study period. Of these, 59 were recaptured and inspected at LGO and 10 were recaptured and inspected at McN. In all, 98.6% (68/69) of the examined kelts had retained their radio tags; the one missing tag was from a kelt examined at McN. Of the 15 kelts tagged and held in tanks, 100% retained their tags for the first 33 d, after which 3 individuals lost their radio tags on days 34, 42, and 46. Of those telemetered kelts that successfully reached the exit station in 2001 and 2002 ($n = 334$), 99.7% had done so within 33 d postrelease. Altogether, these results suggest that tag loss during this study was minimal.

River Discharge and Dam Operations

As a result of drought conditions in 2001, average river discharge at LGR was only 47% (1,338 ± 533 m^3/s) of the 1990–2000 average river discharge (2,846 ± 479 m^3/s), hereafter referred to as the 10-year average. Limited water resources at LGR and other lower Snake River FCRPS projects resulted in the lack of spill during the study period (15 April to 30 June 2001). Similarly, average river discharge at McN on the Columbia River in 2001 was 44% (3,531 ± 859 m^3/s) of the 10-year average (8,023 ± 813 m^3/s). Spill (30%; reported as percentage of project discharge) occurred every other night (1900–0600 hours) at McN and JDD between 25 May and 16 June and was continuous at TDD (30%) and BON (37%) between 16 May

TABLE 2.—Median and first-quartile (25th-percentile) and third-quartile (75th-percentile) migration rates (km/h) exhibited by telemetered steelhead kelts passing river reaches (tailrace to tailrace) in the lower Snake and Columbia rivers in 2001 and 2002. Lower Granite (LGR), Little Goose (LGO), Lower Monumental (LMN), and Ice Harbor (ICH) dams are located on the lower Snake River, and McNary (McN), John Day (JDD), the Dalles (TDD), and Bonneville (BON) dams (including the free-flowing reach below BON) are located on the Columbia River. Flows (m^3/s) are based on discharge measurements taken from the tailrace of the upstream dam; *P*-values are for comparisons of migration rates between river reaches in 2001 and 2002.

	2001			2002			
River reach (rkm distance)	Sample size	Average flows (SD)	Migration rate (median, first, and third quartiles)	Sample size	Average flows (SD)	Migration rate (median, first, and third quartiles)	*P*
LGR to LGO (59.5)	134	1,339 (532)	0.43, 0.30, 0.61	122	2,425 (634)	0.60, 0.46, 0.74	<0.01
LGO to LMN (46.7)	70	1,356 (574)	0.41, 0.26, 0.71	59	2,340 (654)	0.51, 0.30, 0.69	0.25
LMN to ICH (50.4)	31	1,418 (637)	0.63, 0.37, 1.05	31	2,431 (699)	1.38, 1.01, 1.85	<0.01
ICH to McN (69.9)	13	1,392 (665)	0.61, 0.45, 0.80	17	2,493 (705)	0.79, 0.66, 1.06	0.02
McN to JDD (122.9)	18	3,532 (857)	0.85, 0.51, 1.04	134	7,783 (1,808)	1.12, 0.79, 1.46	<0.01
JDD to TDD (36.9)	16	3,605 (1,022)	2.07, 1.22, 2.53	88	7,865 (1,729)	2.71, 2.17, 3.22	0.02
TDD to BON (74.9)	58	3,608 (985)	1.98, 1.41, 2.92	138	7,672 (1,664)	2.47, 1.71, 2.97	0.04
Free-flowing (53.0)	93	3,854 (736)	4.11, 3.24, 4.83	172	7,944 (1,440)	4.61, 3.42, 5.65	0.03

and 16 June, but over a much shorter spill season than usual.

River discharge at LGR and other Snake River FCRPS projects was more normal in 2002, the average river discharge at LGR being 85% (2,424 ± 633 m^3/s) of the 10-year average. Average river discharge at McN was 97% (7,782 ± 1,809 m^3/s) of the 10-year average. Spill occurred at all FCRPS projects during the study period (15 April to 30 June 2002) except at LMN, where stilling basin erosion precluded spillway operation. Spill alternated between continuous (30%) and nighttime (1900–0659 hours) spill (54%) at JDD.

Migration Rates and Passage Routes

Downstream travel rates were variable both among river reaches and years in the lower Snake River. Median travel rates of radio-tagged kelts ranged from a minimum of 0.41 km/h between the LGO and LMN tailraces to a maximum of 1.38 km/h between the LMN and Ice Harbor (ICH) tailraces (Table 2). Increased flows in 2002 resulted in faster kelt travel times relative to 2001; statistically significant differences were detected in all reaches except LGO to LMN. Cumulative median travel times for kelts from the LGR to the ICH tailraces were approximately 15 d (hh:mm, 348:21) in 2001 and 10 d (246:11) in 2002, whereas cumulative median travel times from the LGR to the BON tailraces were approximately 27 d (655:52) in 2001 and 19 d (459:24) in 2002.

As in the lower Snake River, median kelt migration rates and flows were significantly higher in 2002 than in 2001 in the lower Columbia River (Table 2). Kelts traveled significantly slower through the largest impounded section of the lower Columbia River—the John Day pool—in both 2001 and 2002 relative to all other impounded and nonimpounded reaches in the lower Columbia River (Wilcoxon rank-sum test: $P < 0.01$ for all within-year reach comparisons in the lower Columbia River), suggesting river flows dissipated in the John Day pool. Median kelt migration rates were significantly faster in the one nonimpounded reach (i.e., below BON) relative to each impounded section (Wilcoxon rank-sum test: $P < 0.01$ for all within-year reach comparisons in the lower Columbia and Snake rivers), suggesting greater migration speeds of kelts in the free-flowing river environment. Cumulative median travel times for kelts from the McN to the BON tailraces were approximately 9 d (213:21) in 2001 and 7 d (163:32) in 2002. Results of the regression analysis provide some evidence that average river discharge was positively associated with median kelt travel times in both 2001 ($P = 0.02$, for the test that slope differs from zero, with an R^2-value of 0.5959) and 2002 ($P = 0.04$, for the test that slope differs from zero, with an R^2-value of 0.5403).

In 2001, forebay residence times were significantly lower during spill periods at both TDD and BON (Wilcoxon rank-sum test: $P < 0.01$). During periods of spill at TDD, median forebay residence times were 1.3 h compared with 9.6 h during periods of nonspill (Table 3). Like TDD, median forebay residence times at BON were typically near 8.0 h during the nonspill period. After the allocation of water discharge through the spillway at BON, median forebay residence times were reduced from 8.0 h to 3.0 h (Table 3).

TABLE 3.—Median and first-quartile (25th-percentile) and third-quartile (75th-percentile) forebay residence times (h) exhibited by telemetered steelhead kelts passing the Dalles and Bonneville dams on the lower Columbia River during nonspill and spill periods in 2001; *P*-values are for comparisons between spill and nonspill periods.

	Nonspill			Spill			
Location	Sample size	Average flow (SD)	Forebay residence time (median, first, and third quartiles)	Sample size	Average flow (SD)	Forebay residence time (median, first, and third quartiles)	*P*
The Dalles Dam	28	3,356 (937)	9.6, 2.3, 28.9	34	3,778 (976)	1.3, 0.7, 3.0	<0.01
Bonneville Dam	62	3,580 (702)	8.0, 2.3, 17.6	47	4,038 (699)	3.0, 0.4, 6.1	<0.01

With efficiency elevated during periods of spill, project passage efficiencies differed significantly between spill and nonspill conditions during 2001 (chi-square test: $P = 0.01$). During nonspill periods, passage efficiencies at TDD and BON were similar: 64.3% ($n = 28$) of kelts passed TDD via nonturbine routes (i.e., sluiceway), whereas 57.5% ($n = 73$) of kelts passed BON via nonturbine routes (i.e., B1 sluiceway and bypass; B2 bypass). During spill periods at TDD and BON in 2001, passage efficiencies increased: 98.6% ($n = 70$) of kelts passed via nonturbine routes at TDD and 88.2% ($n = 68$) of kelts passed via nonturbine routes at BON (Table 4). At TDD, most kelts (87.1%) passed via the spillway. At BON (B1), there was high sluiceway passage efficiency (100%) and effectiveness (105.3:1), although the sample size of passing kelts ($n = 4$) was small. At BON (B2), guidance efficiency of screen systems increased from 47.2% ($n = 55$) during the nonspill period to 70.4% ($n = 27$) during the spill period.

During the greater flows of 2002, kelt passage through lower Columbia River hydroelectric dams was primarily via project spillways. At JDD, TDD, and BON combined ($n = 623$), 80.9% of the radio-tagged kelts passed via spillway ($n = 504$), compared with 7.5% via turbine ($n = 47$), 6.9% via bypass ($n = 43$), and 4.7% via sluiceway ($n = 29$). Guidance efficiencies from JDD and BON (B2) screen systems were a combined 53.2% ($n = 79$). Sluiceway efficiency at TDD was similar to the guidance efficiency at JDD and BON (e.g., 52.4%; $n = 21$). At BON (B1), high sluiceway passage efficiency (100.0%; $n = 18$) coupled with small sluiceway discharge (20 m^3/s) generated an effectiveness value in excess of 70:1 (Table 4).

Migration Success

Migration success rates varied substantially by reach, by dam, and between years (Table 5). Of those kelts tagged and released from LGR, only 4.1% ($n = 197$) were contacted at the exit station in 2001 and 15.6% ($n = 167$) were contacted at the exit station in 2002. Of those kelts tagged and released from McN, 59.6% ($n = 52$) were contacted at the exit station in 2001 and 62.3% ($n =$

TABLE 4.—Steelhead kelt passage efficiency (PE), guidance efficiency (GE), sluiceway efficiency (SLE), spillway efficiency (SPE), sluiceway effectiveness (SLF), and spillway effectiveness (SPF) at John Day (JDD), the Dalles (TDD), and Bonneville (BON) dams on the lower Columbia River during varying spill conditions in 2001 and 2002. Percent spill at JDD is reported in terms of day : night ratio; otherwise, spill percentage is averaged over a 24-h period. Efficiency and effectiveness metrics not calculated from the entire sample (*N*) are followed by their respective sample sizes (*n*); NA = not available.

			Kelt passage						
Location	Year	Spill (%)	*N*	PE (%)	GE (%; *n*)	SLE (%; *n*)	SLF	SPE (%)	SPF
JDD	2002	0 : 54	70	91	50 (12)	NA	NA	83	1.5 : 1
JDD	2002	30 : 30	102	95	58 (12)	NA	NA	88	2.9 : 1
JDD	2002	NA	209	92	45 (29)	NA	NA	86	NA
TDD	2001	0	28	64	NA	64 (28)	19.4 : 1 (28)	NA	NA
TDD	2001	30	70	99	NA	89 (9)	23.4 : 1 (9)	87	2.9 : 1
TDD	2002	37	207	95	NA	52 (21)	26.0 : 1 (21)	90	2.4 : 1
BON	2001	2[a]	73	58	47 (55)[b]	87 (15)[c]	36.3 : 1 (15)	NA	NA
BON	2001	37	68	88	70 (27)[b]	100 (4)[c]	105.3 : 1 (4)	54	1.6 : 1
BON	2002	45	207	90	58 (50)[b]	100 (18)[c]	71.4 : 1 (18)	67	1.5 : 1

[a] Spill at the 2% level was used to provide attraction flows to fish ladders adjacent to the BON spillway. Three steelhead kelts were contacted passing the spillway during this period.

[b] GE data from the first powerhouse.

[c] SLE data from the second powerhouse.

TABLE 5.—Migration success rates and detection efficiencies of telemetered steelhead kelts passing river reaches and hydroelectric facilities on the lower Snake and Columbia rivers in 2001 and 2002. Little Goose (LGO), Lower Monumental (LMN), and Ice Harbor (ICH) dams are located on the lower Snake River, and McNary (McN), John Day (JDD), the Dalles (TDD), and Bonneville (BON) dams are located on the Columbia River.

	Success rates[a]		Detection efficiency[a]	
River reach or dam	2001	2002	2001	2002
Snake River				
LGR to LGO	0.72	0.82	0.96	0.99
LGO to LMN	0.65	0.64	0.99	0.97
LMN to ICH	0.62	0.63	0.92	0.76
Cumulative[b]	0.28	0.33	1.00	1.00
Columbia River				
McN to JDD	0.57	0.67	0.41	0.95
JDD to TDD	0.67, 0.95	0.82, 0.94	0.45, 0.72	0.97, 0.93
TDD to BON	0.76, 0.94	0.88, 0.97	0.71, 0.98	0.95, 0.94
BON to exit arrays	0.89, 0.93	0.94, 0.98	1.00, 0.99	1.00, 0.96
Cumulative[c]	0.66	0.71	1.00	1.00

[a] If one value is given, it applies to the reach; if a second value is given, it applies to the dam.

[b] Calculated for kelts released from LGR in 2001 (n = 197) and 2002 (n = 167) to the tailrace of ICH.

[c] Calculated for kelts released from McN in 2001 (n = 52) and 2002 (n = 273) and from kelts released from JDD in 2001 (n = 154) and 2002 (n = 10) to the exit arrays below BON.

273) were contacted at the exit station in 2002. Of those kelts tagged and released from JDD, 63.6% (n = 154) were contacted at the exit station in 2001 and 80.0% (n = 10) were contacted at the exit station in 2002. Migration success rates were significantly higher for individuals traveling through reaches of the Columbia River relative to the lower Snake River in both 2001 (chi-square: $P < 0.01$) and 2002 (chi-square: $P < 0.01$), presumably because of the higher flows in the Columbia River relative to the lower Snake River (Table 2). Migration success rates within river reaches were as high as 94.0% between the TDD and BON tailraces in 2002 and were as low as 57.1% between the ICH and McN tailraces in 2001 (Table 5). In general, migration success rates were relatively consistent in the lower Snake River; river reach success ranged between 61.5% and 82.0% and the higher rates were observed within the LGO reach in both 2001 and 2002 (Table 5). Maximum detection efficiencies also varied throughout the study period but were above 90.0% at most locations and years (Table 5). The lack of forebay telemetry receivers at McN and JDD in 2001, however, resulted in poor detection efficiencies at these two locations (Table 5).

Discussion

This is the first study to evaluate the effects of lower Snake River and Columbia River dam configuration and operation on steelhead kelt out-migration in the FCRPS. Like smolts (Muir et al. 2001), our data indicate that kelts can be efficiently routed past hydroelectric dams through the use of spillways. Moreover, our data suggest that the downstream surface orientations of juvenile steelhead (Johnson et al. 2000) are also observed in adults, and that out-migrating steelhead kelts can be effectively routed past hydroelectric dams through the use of surface flow bypass. These results together support the ongoing deployment and evaluation of surface bypass innovations in the FCRPS to assist out-migrating kelts.

Our data suggest that there are serious impoundment effects on kelt travel times, particularly for kelts originating from the Snake River. Dams are known to delay migration timing and reduce migration rates of Pacific salmon smolts (Raymond 1969, 1979). These delays result in smolt exposure to low flows, high water temperatures, and predation. Juvenile salmonids in the contemporary Snake–Columbia River system experience lower survival rates than they did before main-stem dam construction (Venditti et al. 2000; Budy et al. 2002). Like smolts, kelts may be negatively affected by the indirect effects of impoundment (e.g., high temperatures, low flows). Furthermore, we speculate that these indirect effects are compounded in kelts because of the fish's postspawned atrophic state. The effects of high river temperatures and low flows on stress, disease resistance, and the energetic demands of out-migration in steelhead kelts, however, remain unexplored.

Patterns in kelt residence times in powerhouse forebay areas were similar to those observed in smolts (Venditti et al. 2000). For seaward migrating Atlantic *Salmo salar* (Fried et al. 1978) and Pacific (Venditti et al. 2000) salmon smolts, water current was found to be the main factor that influenced their passage routes and rates. Forebay residence times of out-migrating kelts were significantly reduced during spill periods, suggesting that the allocation of water flows through spillways helped move kelts past dams more quickly, as has been shown for juvenile salmonids (Anglea et al. 2001; Ploskey et al. 2001).

Kelt passage through the lower Columbia River dams was primarily via spillways (when available). During spill, project passage efficiencies were near or above 90.0%. Based on this finding, surface flow bypass innovations, such as removable spillway weirs, hold promise to enhance the overall passage effectiveness of project spillways. Our data indicate that debris sluiceways at TDD and BON (B1) effectively pass kelts, which suggests that these fish can be routed away from turbine intakes through the use of surface flow bypass. Ongoing modifications to the BON (B2) sluice chute (i.e., enlarging the cross-sectional area and extension of the outfall to areas of high water flow) provide a unique opportunity to evaluate how a surface flow bypass affects the passage behavior of steelhead kelts.

In contrast to surface flow bypass, intake screen systems provided poor kelt guidance. This may not be surprising since the design of bypass systems at the lower Snake River and Columbia River dams is based primarily on the behavior, critical swimming performance, and injury rates of juvenile salmonids (Coutant and Whitney 2000), not of adult salmonids. Improvements to bypass systems to increase guidance efficiency of kelts (e.g., entrance design criteria) will require a better understanding of the behavioral patterns and, more specifically, the critical swimming velocities of steelhead kelts. Similarly, information on the effect of the jet entry velocities (e.g., 15.2 m/s) from high-flow outfalls (Johnson et al. 2003) on kelts would allow evaluation of current outfall criteria.

The poor migration success rates observed in the steelhead kelts tagged and released on the lower Snake River probably resulted from a combination of direct mortality associated with turbine passage and indirect impoundment effects (e.g., bioenergetic exhaustion associated with passage through multiple dams and reservoirs). Data from this study support this hypothesis; higher migration success rates of kelts tagged and released at LGR were observed in 2002 relative to 2001 and are probably associated with the higher flows and presence of spill in 2002 (i.e., greater passage efficiency). Furthermore, the significantly higher migration success of kelts released in the lower Columbia River relative to those released in the Snake River in both years suggests that increased passage efficiency may not be the only factor affecting migration success and that the energetic demands of having to pass multiple dams and reservoirs may be a limiting factor. It should also be noted that kelt migration success values reported here are overestimates because they apply only to kelts in good and fair condition. Presumably, very few, if any, of the kelts in poor condition (29.6%) encountered during sampling would have survived out-migration if they had been tagged (Evans 2002). These results suggest that additional management may be warranted to boost iteroparity rates in steelhead kelts from the Columbia River basin and, in particular, stocks from the Snake and mid to upper Columbia rivers.

The results from this and other studies suggest that iteroparity rates in steelhead kelts from the Columbia River basin could be increased if (1) main-stem passage survival were increased, (2) kelts were collected and transported around the dams, and (3) kelts were captured and reconditioned in captivity. Operational modifications, structural modifications (or both) on main-stem dams may provide safer and quicker passage of kelts. Limited access to steelhead kelts in the lower Columbia River caused by a lack of collector facilities and relatively short distances to the ocean suggest that kelts from these locations might be best aided through improvements to current in-river passage conditions, such as an earlier onset of spill, surface bypass (Ferguson et al. 1998; Johnson et al. 2005), and turbine modifications (Cada 2001). Conversely, repeat spawning rates of Snake River stocks may require additional assistance owing to migration distances to the Pacific Ocean and the number of hydroelectric facilities and other obstacles along the way. Transporting kelts around main-stem dams may increase return rates of kelts from those populations by allowing a larger proportion of the run to reach the ocean and undergo gonad recrudescence (P. Anders, D. R. Hatch, and A. F. Evans, project proposal to the Bonneville Power Administration, Portland, Oregon [Project 200001700; available: www.cbfwa.org/files/province/systemwide]; Evans et al. 2004a). Research has demonstrated that steelhead kelts can be retained in a freshwater environment and artificially reconditioned to spawn again (Wingfield 1976; Evans et al. 2001). For example, iteroparity in steelhead from the Yakima River was 2% for naturally reared versus 25% for reconditioned fish (Hockersmith et al. 1995; P. Anders, D. R. Hatch, and A. F. Evans, unpublished). Finally, short-term reconditioning of kelts (e.g., 6–8 weeks of reconditioning to reinitiate the feeding response and augment fish condition) coupled with transporting kelts around main-stem dams may provide a means of increasing kelt return rates by allowing a larger proportion of kelts to reach the ocean than would occur through typical migration or direct transportation (D. Fast, Yakama Nation, personal communication). Adaptive management strategies such as these for steelhead kelts might be considered as part of a comprehensive plan to recover ESA-listed steelhead stocks in the Columbia River basin.

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ERRATUM

Erratum: Downstream Passage of Steelhead Kelts through Hydroelectric Dams on the Lower Snake and Columbia Rivers

Robert H. Wertheimer and Allen F. Evans

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Table 4, Page 860. Corrected footnotes appear below.

[b]GE data from the second powerhouse.
[c]SLE data from the first powerhouse.