Identifying optimal translocation policies given factors associated with adult spring-run Chinook Salmon translocation mortality

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Abstract

Translocation is a common management tactic used to conserve animal populations by circumventing high mortality locations or events and enhance population abundance, reintroduce fish to historical habitats, or mitigate for fish passage limitations. The conservation of spring-run Chinook Salmon *Oncorhynchus tshawytscha* populations in the Willamette River typifies the challenges associated with large-scale translocation programs. The objectives of this study were to 1) evaluate factors associated with translocation mortality events and 2) identify optimal translocation policies that minimize mortality risk and effort. We used an information-theoretic approach evaluating factors hypothesized to influence translocation mortality. Factors found to influence survival in this analysis varied between the two dams evaluated but were related to operations and annual or in-river conditions. Specifically, the amount of time it took to load fish and the density of fish in tank trucks were positively associated with translocation mortality. Instream flows and thermal exposure also were identified as factors associated with translocation mortality; however, outplant location was not. We further used the results of model selection to predict mortality risk in an effort to identify optimal translocation policies for varying numbers of fish to translocate and transport truck volume. Lastly, we discuss how this analysis can be incorporated into an adaptive management approach providing managers a way to integrate research, monitoring, and management to improve understanding of factors associated with translocation mortality and refine optimal translocation policies.

<A>Introduction

The process of moving organisms from one location to another (hereafter translocation) is a common management tactic used to conserve animal populations. Managers use translocations to enhance survival by circumventing high mortality locations or events and enhance population abundance (e.g., stocking). For example, managers collect and translocate adult Pacific salmon *Oncorhynchus spp.* upstream when in-stream conditions limit migration or pose a mortality risk in the Central Valley of California (Mosser et al. 2013) and basins like the Willamette River in Oregon (Beidler and Knapp 2005; Keefer et al. 2010; NMFS 1999). Natural resource agencies also collect juvenile salmon smolts and translocate them downstream with barges and trucks in the Columbia River Basin to minimize cumulative mortality associated with multiple dam passage (Muir et al. 2006; Naughton et al. 2004; Schreck et al. 2006). Conservation hatchery operations rear at-risk species such as Brook Trout *Salvelinus fontinalis* and Pallid Sturgeon *Scaphirhynchus albus* and translocate individuals to natural systems within their native range to augment populations (Humston et al. 2012; Steffensen et al. 2010). Colorado River Cutthroat Trout *O. clarki pleuriticus* collected from donor populations were translocated to streams where models predicted reintroduction efforts would likely be successful (Harig and Fausch 2002). Translocation has obvious and immediate conservation benefits, but the handling and transport of these fish during translocation is an additional source of stress and mortality. This additional mortality source can be problematic when translocating threatened or endangered species, and significant mortality occurs.

The conservation of spring-run Chinook Salmon (hereafter Chinook Salmon) populations in the Willamette River typifies the challenges associated with large-scale translocation programs. A variety of reasons including habitat loss due to the construction of 13 dams on five tributaries without fish passage facilities resulted in Upper Willamette River (UWR) Chinook Salmon listing as threatened under the U.S. Endangered Species Act in 1999 (NMFS 1999). An adult translocation program using trucks with tanks to transport fish began in the 1990's as a conservation strategy initially to provide an additional prey base for listed Bull Trout *Salvelinus confluentus*. The program changed into an effort to increase natural production of Chinook Salmon *Oncorhynchus tshawytscha* and Steelhead Trout *O. mykiss* in their historic habitats once natural production from these outplanted fish was detected (Beidler and Knapp 2005; Keefer et al. 2010; NMFS 1999). Mortality of translocated individuals has varied among years since the initiation of the adult translocation program. Mortalities of adult fish during translocation limits natural production and wastes scarce management resources. Thus, understanding the factors associated with mortality during translocation is important to develop translocation policies that minimize mortalities in translocation programs. In this study, we investigated the mortality of UWR Chinook Salmon transported in tank trucks as part of the translocation program with the objectives to 1) evaluate factors associated with translocation mortality and 2) identify optimal translocation policies that minimize mortality risk and effort.

<A>Methods

<B>Study area

The Willamette River is a 7^{th} order tributary draining 29,728 km^2 to the Columbia River (Hulse et al. 2002). A waterfall located in the lower part of the watershed, Willamette Falls, demarks the lower and upper Willamette River (Figure 1). Fish ladders at the falls provide upstream passage for anadromous fish returning from the Pacific Ocean to spawn in natal

Willamette River tributary reaches. Anadromous fishes of the UWR include Chinook Salmon, Coho Salmon *O. kisutch*, Steelhead Trout *O. mykiss*, and Pacific Lamprey *Entosphenus tridentatus*. Once fish ascend the Willamette Falls fish ladder, they migrate upstream until they encounter impassable dams located on the major UWR tributaries (Figure 1). Oregon Department of Fish and Wildlife (ODFW) and U.S Army Corps of Engineers (USACE) hatchery operations capture returning adult Chinook Salmon in traps located at impassible dams (Figure 1) (Beidler and Knapp 2005; Keefer et al. 2010).

Our study evaluated translocation mortality of spring-run Chinook Salmon trapped and translocated from Foster and Dexter dams located on the South Fork of the Santiam River and the Middle Fork of the Willamette River, respectively (Figure 1). The fish traps located at these two dams capture fish that volitionally enter and ascend a fish ladder to a trap located near the base of the dams. The Foster Dam fish trap operates year round. The trap located at Dexter Dam opens to intercept arriving Chinook Salmon by June. Fates of trapped Chinook Salmon include: 1) use as broodstock in hatchery operations; 2) outplanting downstream to provide additional recreational fishing opportunities (hatchery origin only); or 3) translocation using trucks to stream reaches upstream of impassible dams to repopulate those reaches (mostly natural origin fish from Foster; mostly hatchery origin fish from Dexter) (Figure 1).

Translocation operations.—Fish traps located at Foster and Dexter dam are physically unique for each location but operate similarly. The trap at Foster Dam is on the south bank and the trap at Dexter Dam is on the north bank (USACE 2014). An older, less efficient trapping system at Foster Dam was used in years prior to 2014 when a new trap came on line; these differences did not affect our results. The facilities at Dexter Dam were unchanged over the course of this study. Basic descriptions of the traps and trapping protocols can be found in hatchery specific management plans (ODFW 2016a; ODFW 2016b; USACE 2014). The traps consist of a concrete fish ladder that leads to a raceway with the downstream exit blocked by a weir. A mechanical crowder forces the fish into a much smaller upstream chamber confining the fish where they can be anesthetized and netted for stocking into a tank truck. Once a desired number of fish have been collected the crowder is removed; this means that fish to be loaded for subsequent trips may experience several crowding and un-crowding events. How long the fish have been holding below the fish ladder before entry or in some cases how long the fish have been holding in the raceway are not known. Fish that volitionally enter the trap at both locations remain in the trap until processing. Processing at both locations followed 4 steps: crowding of fish in trap, removal of a portion of the crowded fish and exposure to CO_2 (Foster Dam began using AQUI-S 20E in 2014) at sedation or nearly anesthetic levels, handling of sedated fish to determine sex, origin (natural or hatchery), checking for tags (passive integrated transponder, coded wire, floy), and assigment to one of the 3 fates previously described. Hatchery staff then loaded fish into transport truck tanks containing local source, oxygenated water. Fish captured in the trap were regularly processed (i.e., weekly) and more frequently (i.e., daily) if fish numbers in the trap were high—at the discretion of the ODFW hatchery personnel. Drivers recorded the number of fish transported and the number dead on arrival at liberation site, including moribund, for each translocation occasion.

<B>Data analysis

We identified factors hypothesized to affect translocation mortality and organized those factors into 3 levels. The levels represented included factors acting annually to set the stage for elevated translocation mortality within a year, daily weather and trap conditions influencing mortalities occurring that day, and occasion specific factors influencing mortalities during translocations (Table 1). Additionally, each hypothesis was represented by numerical values used to predict translocation mortalities and an information-theoretic approach used to evaluate the relative evidence for each hypothesis.

Annual conditions.—Annual conditions such as run size, water temperature, and flows were hypothesized to influence translocation mortality (Table 1). We characterized run size and timing as the total number of fish counted at the Willamette Falls passage facilities and the day of the year that 50% of the total run passed the facilities, respectively. Stream flows and thermal exposure during migration were characterized for two different time periods defined as 1) the period from the first fish passing the Willamette Falls facility to the time of outplanting, and 2) the day that 50% of the total run passed the facilities to the time of outplanting. For each of these time periods, we calculated discharge at the respective dams using data from USGS gages on the South Santiam River (USGS: 14187200) and Middle Fork Willamette River (USGS: 14150000) for Foster and Dexter dams, respectively. Finally, we calculated cumulative water temperatures for each period as total degree days using water temperatures measured at the respective USGS gages, listed above.

Daily weather and trap conditions.—We hypothesized that weather and trap conditions influenced translocation mortality (Table 1). The amount of cloud cover and air temperature were included as potential covariates based on previous experience handling and transporting salmonids and associated mortalities (C.B. Schreck personal observation). Maximum air temperature during transport and cloud cover were estimated using data from nearby airports (Corvallis Municipal Airport, Eugene Airport) because they were the nearest locations where daily records of temperature and cloud cover were available for the study period. We quantified trap and holding conditions that were potentially stressful by including the number of fish trapped and held before outplanting and the number of days between trap tending events.

Truck and translocation occasion data.—Several values were measured and recorded for each truck and translocation occasion that were hypothesized to influence mortality. Personnel recorded trip-specific truck-level data including truck number, outplant location, the number of fish transported and water temperatures at the collection facility holding tanks and transport tanks to the nearest 0.5^{o}C. Post trip tank water temperature was also measured to quantify change in water temperature during the trip. We calculated the difference in temperature between the collection facility and the transport truck and the start and end of the trip. Also, the amount of time that it took to load fish on the transport truck (loading time), and drive the fish to the outplant locations (hauling time) was recorded. Loading time was calculated as the difference of the loading end time and start time. If multiple transportation events were required in a day, fish were uncrowded during idle times between events and start time assigned when fish processing resumed. Hauling time was calculated as hauling end time – hauling start time. We calculated total handling time as the sum of loading time and hauling time. We estimated potential crowding during transport as the volume of the truck tank divided by the number of fish transported. The number of outplant trips per day was recorded. The water temperature at the release site was recorded but not used in this analysis because mortalities were counted in the truck tank prior to release.

Model fitting.—We fit location-specific generalized linear mixed-effects models (GLMM) to identify and quantify factors associated with the translocation mortality (Agresti et al. 2000; Venables and Dichmont 2004). The model related the proportion of dead and moribund fish at the time of outplanting to annual conditions, daily weather and trap conditions, and truck and translocation occasion conditions for each location. We fit each candidate model to the repsonse variable assuming the number of mortalites were binomially distributed with a logit link. We used separate analyses for each facility to describe mortality differences between locations and to provide the foundation for an adaptive management program (see discussion). Continuous predictor variables were standardized to a mean of zero and standard deviation of 1 to facilitate model fitting and allow comparison of the relative effect of variables that were on different scales. Repeated observations and measurements within a year, at a trapping facility, or outplanting location were potentially dependent, which would violate independence assumptions and preclude the use of traditional regression models as discussed by Royle and Dorazio (2008). Therefore, we initially fit a model with all the candidate predictors to the translocation mortality data. An examination of the model residuals ordered by date and outplant location indicated temporal and spatial autocorrelation.

There were several potential sources of statistical dependence leading to the non-random structure of the residuals. Therefore, we evaluated the relative fit of alternative variance structures for the GLMM using a model including all predictors and all possible combinations of random effects that included transport truck and truck driver, outplant location, year, and outplant occasion (i.e., each outplanting event). The best approximating variance structure was selected as the model with the smallest Akaike's Information Criteria with the small-sample bias adjustment (AICc) (Hurvich and Tsai 1989). That variance structure was used during the evaluation of the relative plausibility of the candidate models, detailed below. Plots of predicted and observed mortality rates were used to assess the fit of candidate models. All models were fit using the glmer function in the R package lme4 (Bates et al. 2012).

We developed models representing 21 hypotheses to explain variation in translocation mortality (Table 1) and used an information-theoretic approach evaluating the relative support for the candidate hypotheses (Burnham and Anderson 2002). We fit models representing each hypothesis in Table 1, as well as an intercept only model, and calculated AICc and Akaike weights following Burnham and Anderson (2002) rather than combining all possible combinations of the 21 predictors. We then retained models with AICc values lower than the intercept only model as a confidence model set and assessed the precision of the parameter estimates by calculating 95% confidence intervals of estimated parameters. Statistical inference was restricted to models retained in the confidence model set and parameter estimates where the 95% confidence intervals did not contain 0. Model weights for models retained in the confidence model set were calculated as described in Burnham and Anderson (2002) and then used to weight model predictions used to identify optimal translocation policies detailed below.

Visualizing predicted mortality and uncertainty.—We predicted the expected mortality for each model and plotted the expected values along with 95% prediction intervals to visually assess the relationships and associated uncertainty. Prediction intervals represent the unexplained variation around the estimate of fixed and random effects. The predicted mortality rates for each location (Foster and Dexter Dam) were estimated for each model retained in the confidence model set and estimates combined by weighting each prediction by the model-specific Aikake weight to account for model selection uncertainty. Weighted predictions were then summed to provide a singular mortality rate estimate given model selection uncertainty. In the case when a single model was retained in the confidence model set, the predicted values were multiplied by 1. We then used these predicted mortality rates to evaluate optimal translocation practices detailed below.

<B>Identifying optimal translocation policies

From a management perspective, several hypothesized factors affecting translocation mortality are controllable during translocation operations. Specifically, the confidence model sets contained loading time for Foster Dam and density for Dexter Dam as factors associated with translocation mortality. However determining optimal location-specific loading times or density is a management challenge because hatchery locations will minimize loading time or density potentially causing confusion if personnel work at multiple hatcheries. Therefore, we identified optimal translocation policies for fish originating from Foster and Dexter Dam by calculating the number of hauls needed for a truck volume and the number of fish to be translocated. Number of hauls was selected because it provided uniformity between hatcheries and it integrates loading time and fish density. Lastly, the daily translocation effort in hours depends on the number of hauls, and therefore daily effort can be considered when identifying optimal translocation policies.

We identified the optimal translocation policy (number of hauls given truck volume and number of fish to translocate for this example) as one that maximizes survival and minimizes effort for this study. However, this requires a tradeoff. In an extreme situation, translocating one fish per haul will likely result in high survival, but the amount of effort to translocate individuals is unreasonable given personnel constraints. Translocating all outplant fish in a single haul minimizes effort but may result in elevated mortalities associated with high densities and loading times. To quantify this tradeoff we calculated a utility that combined risk of mortality and effort into a single value and used that value to identify optimal translocation policies at Foster and Dexter Dam.

We identified the optimal number of a hauls for varying numbers of fish to be outplanted and truck volumes by generating all possible combinations of number of fish outplanted (1 to 400, increments of 10), number of truck hauls (1 to 20, increments of 1), and truck volumes (1 to 11 m^3, increments of 0.5). There were 16.8K possible combinations (hereafter referred to as policy combinations). For each policy combination, we calculated the number of fish in each haul assuming the numbers of fish to be translocated were evenly distributed among the number of hauls. The density of fish was calculated as the number of fish divided by the truck volume. The loading time for each haul was calculated as the number of fish hauled times the average location-specific loading time (0.25 and 4.6 minutes per fish for Dexter and Foster dam respectively). The mortality rate was then predicted from density for Dexter Dam because this was the only factor retained in the confidence model set. The confidence model set was used to calculate model weighted predictions of the mortality rate for Foster Dam. In this example, loading time varied depending on the policy combination while the remaining factors were evaluated using mean values. Mortality rate and loading time were then used to calculate mortality risk and total daily effort values. These values were then used to select the optimal number of hauls, described below.

Mortality risk.—The biological consequences of the predicted mortality rates can be difficult to ascertain, especially when rates are low. For example, is a mortality rate of 0.005 versus 0.01 meaningful within a manager's decision-making process? Additionally, while mortality rate will be the same given similar conditions, the expected number of mortalities will depend on the number of fish translocated. For example, the expected number of mortalities from translocating 100 fish will be higher than translocating 10 under the same conditions, further complicating evaluation of varying translocation conditions and number of fish translocated. Because multiple hauls may be needed to translocate all fish and the mortality rate was predicted for each haul we estimated mortality risk as the probability of observing 1 or more mortalities over the entire daily effort. Mortality risk was calculated as 1 minus the product of probability of observing 0 mortalities in each haul calculated from a binomial distribution given the predicted mortality rate and number of fish translocated as:

$$Mortality\,risk_j = 1 - \prod_{i=1}^{Hauls_j} \frac{n_{ij}\,!}{0!\cdot(n_{i,j}-0)!} \cdot p_i^0 \cdot (1-p_{i,j})^{n_{i,j}-0} \qquad (1)$$

where j indexed each policy combination, $hauls$ was the number of hauls used to translocate fish, n is the number of Chinook Salmon translocated, p is the predicted mortality rate, and i indexes daily hauls. Policy combinations with mortality risk values approaching 1 are more likely to observe 1 or more mortalities over the translocation effort.

Daily effort.—The amount of time in hours required to complete translocation of a given number of fish and number of hauls is an important consideration to constrain translocation policies to reasonable efforts. We calculated total daily effort for each policy combination as:

$$Effort_j = \sum_{i=1}^{Hauls_j} (Loading\,time_{i,j} + 2 \cdot Hauling\,time_{i,j})/60 \qquad (2)$$

where, j indexed each policy combination, $Effort$ was the total effort in hours required to translocate fish, $Loading\,time$ was the amount of time required to load all fish, and $Hauling\,time$ was the amount of time in minutes to reach an outplant location multiplied by 2 to account for the return trip. For this study *Hauling time* was assumed to be the mean hauling time for each location, 37.4 and 77.3 minutes for Foster and Dexter dam respectively.

<B>Identifying optimal translocation policies

Overall utility.—We calculated a utility combining the mortality risk and daily effort to identify optimal translocation policy at Foster and Dexter Dams. Because mortality risk and daily effort are on different scales, we scaled these values to a minimum of 0 and a maximum of 1 using a proportional scoring equation (Conroy and Peterson 2013). Mortality risk was scaled, so low mortality risk values approached 1, and high mortality risk values approached 0 as:

$$U_{mortality\ risk,j} = \frac{Mortality\ risk_j - \max(Mortality\ risk_j)}{\min(Mortality\ risk_j) - \max(Mortality\ risk_j)}, \tag{3}$$

where j indexed each policy combination, and *Mortality risk* was calculated from equation 1. Effort values were scaled so low daily efforts approached 1 and daily efforts equal to 12 hours was 0 as:

$$U_{effort,j} = \frac{Daily\ effort_j - 12}{12 - \min(Daily\ effort_j)}, \tag{4}$$

where j indexed each policy combination, *Effort* was calculated from equation 2, and 12 was the maximum amount of effort reasonable for a given day. We excluded policy combinations with efforts exceeding 12 hours from analysis.

The utility value used to identify the optimal number of hauls required given the number of fish to translocate and truck volume was calculated as $U_j = w_1 \cdot U_{mortality\ risk,j} + w_2 \cdot U_{effort,j}$ where U_i was the overall utility, w_1 is the weight given to the morality risk, w_2 is the weight given to the effort utility, and $U_{mortality\,risk}$ and U_{effort} are described. For this analysis, w_1 and w_2 were set to 0.5 to give equal weight to mortality risk and effort for this study. It should be recognized that weights can be changed to reflect agency objectives. For example, if minimizing mortality was more important relative to effort then w_1 can be set at a level greater than 0.5 and then $w_2 = 1 - w_1$. We determined the optimal translocation policy as the number of hauls for a given truck volume and number of fish to translocate that maximized the utility value. Policy plots were generated to illustrate the optimal number of hauls depending on the number of fish to outplant and the tank volume. Lastly, the optimal policy analysis was repeated with policy combinations where fish densities that exceeded 10.56 fish per m^3 were excluded from potential combinations to reflect the current density constraint policy (USACE 2014). and compared to the optimal policies identified using mortality risk and effort.

<A>Results

Translocation of adult spring-run Chinook Salmon during 2006 to 2013 occurred each year starting in early May and ceasing in late September. The number of fish outplanted from Foster and Dexter dams varied between locations and among years. Overall, fewer fish were captured at Foster Dam and translocated upstream varying from 259 to 1176, relative to Dexter Dam where 451 to 4183 fish were translocated annually. Additionally, fewer fish were translocated per haul at Foster Dam (16-32 fish median) relative to Dexter Dam with median number of fish translocated annually varying from 78 to 154. Within year, mortalities at each location varied from 0 to 28 and 0 to 75 fish for Foster and Dexter Dam, respectively. During the study period, these translocated fish were exposed to varying thermal and flow conditions. Degree days and average discharge from the time that the first fish passed Willamette Falls until outplanting varying from 317 to 1168 C and 64 to 189 m^3/s, respectively (Table 2). Thus, our study was conducted over a wide range of migration conditions.

A random effect of outplant occasion was identified as the best approximating variance structure in models for Foster and Dexter Dam which accounts for overdispersion in the binomial model. Confidence model sets of variables hypothesized to influence mortality varied between Foster and Dexter dams (Table 3). Hypotheses relating total handling time and density were retained in the confidence model set for Foster and Dexter Dam respectively. Confidence intervals for estimated parameters in each of these models did not include 0, indicating that mortality rate increased as loading time and density increased (Table 4; Figures 2 and 3). Additionally, total time, mean daily discharge and degree days accumulated since the first Chinook Salmon passed Willamette Falls were retained in the confidence model set for Foster Dam (Table 3). A positive relationship was estimated for total time and degree days while a negative relationship was estimated for flow conditions (Figure 2). Confidence intervals for all three of these effects did not include 0 indicating that the effects were meaningful. There was a substantial uncertainty around the predicted mortality rates due to the random effect of outplant occasion for fish originating from Foster and Dexter Dam (Figure 2 and 3); that would have otherwise been unaccounted for if this extra variation was not included as a random effect in this analysis.

Patterns in optimal translocation policies varied between Foster and Dexter dams reflecting the results of model selection. The optimal number of hauls did not vary with truck volume for Foster Dam when there was not a density constraint imposed (Figure 3). There were instances where the number of hauls decreased with increasing number of fish to translocate resulting from the exclusion of policy combinations where daily effort exceeded 12 hours, and these policies should be used with caution because they result in elevated fish densities to satisfy the effort constraint. More hauls were needed for situations where trucks with smaller volumes were available and policies exceeding a density of 10.56 fish/m^3 [i.e., the NOAA density constraint (USACE 2014)] were excluded from consideration. There also were several combinations of number of fish to translocate and truck volume where there was no policy that met density or effort constraints at Foster Dam. The optimal number of hauls varied with the number of fish to translocate and truck volume at Dexter Dam (Figure 4). For the same number of fish to outplant, fewer hauls were needed with increasing truck volume illustrating the effect of density on the optimal policy. Further constraining the optimal policy to existing maximum densities increased the number of hauls required to translocate a given amount of fish and constrained the number of optimal policies meeting effort and density constraints.

<A>Discussion

We identified factors associated with translocation mortality and then used this understanding to identify simple translocation policies minimizing the number of trips per truck per day and using trucks of sufficient size to accommodate the number of fish to be moved. These translocation policies that relate fish density in the trucks and the time it takes to load fish onto the trucks could be employed as a framework to improve survival of translocated Chinook Salmon. Translocation mortality was related to factors like loading time and density that are controllable by management and, in the case of Foster Dam, several uncontrollable factors associated with exposure to instream conditions (e.g., degree days, flow). The uncontrollable factors do not preclude using the optimal translocation policies identified in this study because optimal translocation policies can be updated given instream conditions and run timing as that information becomes available to managers. While we used average values to identify optimal translocation policies in this study, the methods we used can provide a flexible management framework that identifies translocation policies given factors such as the number of degree days and mean flow since the first Chinook Salmon passed Willamette Falls. For example, policy plots can be created for situations with similar streamflow and temperature conditions, such as water year type. Data collected from existing USGS temperature and flow gages and ODFW monitoring of fish passage at Willamette Falls can be integrated to inform translocation policies in real time and provides additional importance to these monitoring programs.

The objective of using trucks or other methods to translocate anadromous salmonids is to minimize mortality due to environmental stressors and to circumvent anthropogenic and environmental barriers. Mortality occurring during translocation events limits the efficacy of this conservation tool. Translocation of migratory fish to mitigate for migration barriers is likely to remain a conservation tool for environmental and anthropogenic conditions in the Willamette River system. For example, Chinook Salmon in the Willamette basin will continue to be translocated upstream of barrier dams (Beamesderfer et al. 2011). Also, drought conditions in the Central Valley of California have necessitated the movement of adult salmon above thermal barriers (Mosser et al. 2013) and the proposal of new translocation programs (USDOI BLM 2015; YCWA 2015). Similarly, environmental conditions in the Central Valley of California required juvenile Chinook Salmon to be translocated directly from hatcheries to the estuary, bypassing potentially lethal instream conditions in the same system (Chea 2014). While technological approaches, such as a salmon cannon (Solomon 2014), can mechanically move fish around migration barriers, these technologies cannot bypass distances comparable to truck-based translocation. However, they may provide short-term fixes to fish passage issues, such as when a crack in the Wanapum Dam on the Columbia River forced fish ladders to be shut down while the reservoir was drawn down for repairs. In this instance, adult salmon were captured and translocated by truck above the dam.

In this study, we found mortality occurring during translocation events was associated with trip specific variables at Foster and Dexter dams. The most important were the amount of time it took to load and density in the truck tank. These results are similar to findings in previous studies where the amount of time fish were transported in truck tanks was positively associated with mortality (Harmon 2009; Hasan and Bart 2007). Mortality associated with high density may be mediated by the use of salts or water conditioners to mitigate for stress and minimize potential pathogen infection or anesthetics to minimize stress in commercial operations (Harmon 2009; Harnish et al. 2011; Swanson et al. 1996; Wedemeyer et al. 1985). High salmon densities can potentially lead to horizontal transmission of diseases which may influence the health status of individual fish and also increase stress responses which may increase mortality (Ogut et al. 2005; Zuray et al. 2012). Mortality associated with *Aeromonas salmonicida,* a horizontally transferred pathogen causing furunculosis, was positively associated with Chinook Salmon densities in controlled experiments (Ogut et al. 2005; Ogut et al. 2004). In a natural setting, Traxler et al. (1998) found Sockeye Salmon mortality due to *Ichthyophthirius multlfiliis* was enhanced by fish density on the spawning grounds. *Aeromonas salmonicida*, a horizontally transferred pathogen causing furunculosis, was positively associated with Chinook Salmon densities in controlled experiments (Ogut et al. 2005; Ogut et al. 2004). This bacterial pathogen is common in adult Chinook Salmon from the Willamette River, and in our pathogen examinations of these fish in 2010 and 2011 we found 67% and 43% prevalence of infection in dead and apparently healthy fish, respectively (Kent et al. 2013).

There are several plausible explanations as to why trip number is positively correlated with mortality. Fish transported after earlier groups in a day may have experienced more stress because of the total duration of the stressor events or the cumulative effects of having been exposed to more stressors and sequential stressor. For example, multiple crowding and un-crowding events likely increases stress levels, and in combination with CO_2, also known to be quite stressful to fish (Schreck 1972), the effects of crowding and handling are likely exacerbated. It is well known that both duration and number of discrete stressful events could negatively affect fish fitness (see Schreck and Tort (2016) for a review of this topic).

We hypothesized that metrics indexing mainstem Willamette River migration conditions (flow, temperature) would influence translocation mortality rates. Annual and within year factors quantifying flow and temperature were hypothesized to set the stage for elevated translocation mortality. For example, Chinook Salmon were hypothesized to expend additional energy migrating through elevated stream flows and water temperatures, similar to mortality hypotheses posited by Cooke et al. (2006) for anadromous Sockeye Salmon. Counter to our expectation, mortality rates were negatively associated with mean daily discharge. It is unclear why this is the case but exposure to high flows may not result in severe depletion of energetic stores as to cause immediate mortality during truck transportation if energetic stores are sufficient. Prespawning mortality of Chinook Salmon has been positively associated with temperature in a previous study (Keefer et al. 2010). Our analysis is inconclusive but flows and thermal exposure at Foster Dam were associated with translocation mortality rates and further research is needed to provide evidence for this hypothesized effect.

We expected factors associated with run timing and size to influence the rate of translocation mortality. Abnormal run timing was associated with en route mortality of Sockeye Salmon migrating from the Pacific Ocean to natal freshwater streams (Cooke et al. 2004). Early returns of Chinook Salmon to freshwater may result in variable energetic stores for fish migrating through the system to natal stream reaches to mature sexually during summer months before spawning in the fall. This life history requires that fish return to freshwater with sufficient energetic reserves to reach their natal stream because they do not feed as adults in freshwater. Studies of Sockeye Salmon indicate that amount of energetic reserves in salmon are locally adapted to provide sufficient energy to migrate, become sexually mature, and spawn (Crossin et al. 2004b). Given the long freshwater period experienced by UWR Chinook Salmon, energetic reserves are typically high, and energetic depletion may not influence translocation mortality because this event occurs early in the run when fish likely have sufficient energetic reserves. However, among year variation in ocean conditions can influence the initial energetic status of salmon migrating to freshwater (Cooke et al. 2004; Crossin et al. 2004a), which in turn may increase prespawning mortalities rates after outplanting above barriers (Keefer et al. 2010).

It was not surprising that air temperature and cloud cover were not associated with translocation mortality. The original premise for these hypotheses was previous experiences handling and transporting salmonid species that were closer to sexual maturation, and the mechanism remains uncertain. These variables were quantified using the closest airport because these were the only locations where cloud cover was recorded which may have influenced results due to differences between local conditions and conditions recorded at airports. Both fish processing facilities at Foster and Dexter Dam provide shade while handling fish and air exposure is minimized, and therefore, factors such as sun and air exposure may not influence translocation mortality as severely as other factors like density or loading time.

Random effects associated with outplant occasion were contained in the final dam-specific models used for statistical inference. These random effects were estimates of the amount variation in transport mortality that was not accounted for by the fixed effects included in the models. Although random effects are not helpful for interpreting associations between factors, like a fixed effect, they provide insight into where additional variability may be targeted for future experimental study. In this analysis, the random effects were fairly large indicating that predicted probabilities of translocation mortality varied substantially among translocation occasions. This suggests that there are unknown trip-specific factors not included in this study that could potentially explain variation in translocation mortality. This contention is supported by the findings of Benda et al. (2015) that prespawning mortality is lower in adult Chinook Salmon allowed to mature in captivity in cool pathogen free water than in the wild.

The mechanistic cause of translocation mortality is uncertain. The mechanisms causing en route mortality of Sockeye Salmon proposed by Cooke et al. (2006) (i.e., energetic, reproductive, stress, and osmoregulatory status) may influence the likelihood of transportation mortality. We expected one of those factors in particular to be associated with cumulative handling that likely lead to stress such as repeated crowding and human presence during sorting operation to have a positive effect on transportation mortality. Trip number was used in the analysis to account for cumulative stress effects however this factor was associated with mortality. This result should be interpreted cautiously and not preclude the possibility of an adverse effect of stress on fish (Schreck and Tort 2016). It is likely that daily trip number may not have indexed cumulative stress as we believed or there just was not enough days where multiple trips were made as days with 2 trips accounted for 37% of observations and 3 or more trips was 13% . Pathogen status also applies when horizontal transmission of pathogens may be exacerbated by interactions of fish in tanks. Necropsies of transport mortalities were not conducted, but may provide additional insight into the potential cause of mortality. Indeed, transportation mortality of Chinook Salmon limits the efficacy of conservation translocation operations, and this study identifies several factors that can be controlled or modified to minimize transport morality. For example, a study by Benda et al. (2015) provided guidelines for potential Chinook Salmon holding strategies in cool, pathogen-free water to minimize pathogen loads.

While this study identified factors associated with translocation mortalities, these factors did not predict translocation mortality rate with absolute certainty. This result indicates that there is the potential to reduce predictive uncertainty and subsequently improve optimal hauling policies identified in this study. Specifically, the competing hypotheses evaluated in this study represent our understanding of the system and the varying support for each hypothesis quantifies uncertainty in this understanding. This analysis can provide the foundation for an adaptive management program where management actions, translocating fish, in this case, can be used iteratively to update the weights (or probabilities) for each hypothesis (Conroy and Peterson 2013). These updated weights can then be used to estimate the amount of effort and mortality risk and update the optimal hauling policies. This iterative process of learning and updating optimal translocation policies is important because it is likely that other factors unrelated to operational factors like loading time and density will become more important as optimal translocation policies that minimize mortality risk are used. For example, this study identified density as the dominant hypotheses influencing translocation mortality at Dexter Dam (Figure 3). It is likely that if translocation policies are implemented that minimize mortality risk at locations like Dexter Dam, other biotic or abiotic factors associated with translocation events will become important. While this process may appear complicated, it requires little change regarding data collection by managers. The most significant change needed is that data collected for each haul needs to be entered in a timely fashion, such that analyses can be run again and optimal translocation policies updated in time for the next translocation effort. Timely data entry can either be accomplished by prioritizing data entry post hauling or with technological fixes such as tablet computers and data entry forms that sync to an online database. Once data is available, the weights for each hypothesis retained in the confidence model set can be updated given the number of mortalities observed and optimal translocation policies revised given this new information. While this initial analysis evaluated several hypotheses, the process does not preclude the addition of hypotheses over time, such as those that might be identified as part of annual coordinating meetings. The analysis, policy evaluation, and potential adaptive management framework resulting from this study can provide managers a way to integrate research, management, and monitoring with minimal modifications to existing operations and monitoring.

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Figures

Figure 1. Study area and location of tributary populations of interest within the Willamette River basin, Oregon. Open squares denote the first impassible major tributary dams. The open triangle denotes the location of Willamette Falls. Arrow denotes north and direction of river flow.

Figure 2. Predictions (solid black line) and 95% prediction interval (gray area) for models representing hypotheses predicting the mortality rate of Chinook Salmon transported. Panels represent prediction for models retained in the confidence model set for Foster Dam located within the Willamette River basin, Oregon.

Figure 3. Predictions (solid black line) and 95% prediction interval (gray area) for models representing hypotheses predicting the mortality rate of Chinook Salmon transported. Panel represents prediction for the model retained in the confidence model set for Dexter Dam located within the Willamette River basin, Oregon.

Figure 4. Optimal translocation policies for adult spring-run Chinook Salmon trapped at Foster Dam (Top panels) and Dexter Dam (Bottom panels). Shading represents the optimal number of hauls that minimize both mortality and effort for combinations of transport truck volume and total number of fish to translocate. The right panels illustrate the optimal number of hauls with no density constraint but effort limited to 12 hours per day. The right panels illustrate the optimal number of hauls with a 10.56 fish/m^3 density and effort limited to 12 hours per day. The dotted white lines denote commonly used trucks tank volumes in Upper Willamette River spring-run Chinook Salmon translocation. White areas denote combinations where no optimal policy exists.