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Comparative Studies Are Needed to Contextualize Stranding in Hydropeaking River Systems

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Ecologically, a major consequence of hydropeaking is fish stranding, whereby fish become isolated from the main river channel in pools or on dry substrate after a high-flow event from a hydroelectric dam (Young et al. 2011; Nagrodski et al. 2012). Stranding is well-documented on rivers with hydropeaking regimes (Halleraker et al. 2003; Insulaire et al. 2024; Irvine et al. 2015; Nagrodski et al. 2012), whereas in naturally flowing rivers stranding is believed to be uncommon, notwithstanding seasonally inundated floodplain systems (Brown et al. 2001; Sommer et al. 2005). There has been much effort devoted to reducing fish stranding on hydropeaking rivers (Bruder et al. 2016; Moreira et al. 2019), yet the baseline occurrence of fish stranding on rivers with natural flow regimes largely remains unknown such that it is difficult to contextualize stranding on hydropeaking systems.

In this paper, we embrace a comparative approach to assess the stranding risk of fishes on rivers in northern Ontario with natural and hydropeaking flow regimes. Study objectives were to: (1) quantify the frequency, duration, and down-ramping rates of high-flow events and (2) use remote photography to quantify fish stranding densities (fish m^{-2}) occurring on rivers with different flow regimes.

Four rivers located near the north shore of eastern Lake Superior, Ontario, Canada were included in this study, representing two rivers with natural flow regimes (Batchawana River [BR] and Goulais River [GR]) and two rivers with hydropeaking regimes (Magpie River [MPR] and Michipicoten River [MR]; See Table S1).

To characterize the annual hydrologic conditions, historical discharge data for all four rivers were obtained from January 1, 1996, to December 31, 2024. On the BR and GR, the data were obtained from the Water Survey of Canada HYDAT database from gauges 02BF001 and 02BF002, respectively. On the MPR and MR, the data were obtained from their respective generating stations (provided by Brookfield Power Ltd.). To identify and calculate the frequency of annual high-flow events on each river, the Streamflow Analysis and Assessment Software (SAAS v4.1) was used (Metcalfe and Schmidt 2016). For all rivers, high-flow events were defined as starting when the hourly rise was $\geq 0.5\,\text{cm}\,\text{h}^{-1}$ and ending when the hourly decrease was $\leq -0.2\,\text{cm}\,\text{h}^{-1}$. The duration was calculated in minutes, and the mean down-ramping rate was calculated using the mean hourly discharge data for each high-flow event in RStudio (R Core Team 2023). All data were log transformed to meet the assumptions of normality and then fitted using linear mixed-effects models with the "lmer" function from the "lme4" package with study year as a random effect (Bates et al. 2015). The model was analyzed using the "Anova" function from the "car" package, and post hoc comparison was performed using the "emmeans" function from the "emmeans" package using a Tukey's HSD correction factor if required (Fox and Weisberg 2018; Lenth 2023).

To quantify fish stranding density, we used remote photography methods (see Glowa et al. 2023 and Davis et al. 2026 for description of camera mounts and site selection) from June to October in 2023 and 2024 on each river. Cameras were deployed at 8 random sites (sites selected randomly from a digital elevation model) identified to be susceptible to fish stranding, and 3 strategic sites (sites with characteristics known to strand fish (e.g., potholes, gentle slopes)) for each river in 2023, and 2024 excluding the MR (See Davis et al. 2026 for increased site selection on MR in 2024).

Fish inhabiting rivers with hydropeaking generating stations experienced annual hydrological patterns that differed from rivers with natural flow regimes (Figure 1). For example, fish experienced more high-flow events on the hydropeaking rivers compared to the rivers with natural flow regimes ($p<0.001$). The mean annual frequency of high-flow events was similar between hydropeaking rivers (MPR (146 ± 81) and MR (163 ± 79); $p=0.722$), and different between naturally flowing rivers (BR (6 ± 2) and GR (4 ± 2); $p=0.007$). On the BR and GR, the high-flow events normally coincided with spring freshet or in the fall during large rain events. That pattern is similar to what has been observed on other naturally flowing rivers in northern Ontario where there tend to be relatively few high-flow events with the largest and longest events occurring during spring freshet (Jones et al. 2014; Alonso et al. 2017). On hydropeaking rivers, fish tend to experience high-flow events across the entire year. Therefore, fish on hydropeaking rivers must respond to changes in flow fluctuations daily, increasing their susceptibility to stranding (Irvine et al. 2015; Haas et al. 2016). Although high-flow events occurred more frequently on the hydropeaking rivers, the mean annual duration of high-flow events was longer on the natural rivers (BR (354.0 ± 115.0 h) and GR (449.0 ± 213.0 h)) than on the hydropeaking rivers (MPR (31.7 ± 23.2 h) and MR (39.3 ± 29.2 h)) ($p<0.001$). On hydropeaking rivers, fish must respond quickly to changes in flows as the mean annual down-ramping rate was significantly faster than on the natural rivers ($p<0.001$). Fish on the MR ($-11.9 \pm 3.76\,m^3 s^{-1} h^{-1}$) experienced the fastest down-ramping rate which was significantly faster than the MPR ($-8.04 \pm 3.84\,m^3 s^{-1} h^{-1}$; $p<0.001$). On the BR ($-0.47 \pm 0.11\,m^3 s^{-1} h^{-1}$) and GR ($-0.43 \pm 0.13\,m^3 s^{-1} h^{-1}$), fish experienced similarly slow down-ramping rates ($p=0.999$), giving fish more time to respond to receding flows, decreasing their probability of becoming stranded. Decreasing the down-ramping rate has been a successful mitigative strategy for stranding on other hydropeaking rivers (Auer et al. 2017; Moreira et al. 2019).

A total of 125 fish were observed stranded on the hydropeaking rivers, while no fish were identified as stranded on the natural rivers using remote photography over the study period despite similar sampling effort (Table 1). Although sampling effort was comparable among rivers, the limited number of high-flow events observed on the rivers with natural flow regimes resulted in less total area surveyed (m^2) compared to the rivers with a hydropeaking flow regime. Of the fish found stranded on the hydropeaking rivers, 123 fish were stranded on the MR and two fish were stranded on the MPR.

We observed higher fish stranding densities on rivers with hydropeaking flow regimes than natural flow regimes. This was expected given that fish stranding is highly documented on rivers with fluctuating flows associated with hydroelectric generating stations (Young et al. 2011; Nagrodski et al. 2012). Yet, most studies of hydropeaking systems fail to include a relevant comparator, making it impossible to determine the extent to which there is a net change in stranding relative to natural systems. The observed differences in fish stranding densities between the MPR and MR can be explained by the presence of larger substrate (mm) and a plunge pool at the base of Steephill Falls Generating Station (GS) on the MPR, which acts to dampen the change in discharge from the GS, resulting in slower observed vertical and horizontal down-ramping rates (Davis et al. 2026). Together, these factors likely reduce the occurrence of fish stranding on the MPR, despite there still being a hydropeaking GS (Hauer et al. 2017; Glowa et al. 2023; Insulaire et al. 2024). The lack of fish stranding observed on the MPR, BR, and GR is not a result of low fish abundance (see Supporting Informations for Fish Community Sampling and Table S.2 for results).

We cannot confidently conclude that fish stranding does not occur on naturally flowing rivers. However, it is presumably a comparatively rare occurrence and largely restricted to periods where floodplains and pools become disconnected from the main river channel after high flow events (e.g., spring freshet; flash floods; Brown et al. 2001; May and Lee 2004; Walker et al. 2018). The BR and GR both lack a connected floodplain and are snowmelt-dominated such that flow variation is seasonally predictable (Poff et al. 2010). This may contribute to the reduced fish stranding risk as the BR and GR are likely to only experience a few high-flow events annually, where banks will become inundated with water and strand fish. However, rivers with natural flow regimes that have connected floodplains and intermittent or flashy dynamics may be more susceptible to fish stranding. For example, Brown et al. (2001) found six fish stranded during a flooding event as ice broke-up in one winter over a 3-year telemetry study in the Grand River, ON. On the BR and GR, there is no connected floodplain, eliminating one of the only known sources of fish stranding on naturally-flowing rivers (Brown et al. 2001; Nagrodski et al. 2012). Fish stranding can occur in pools that become disconnected from the main river after high-flow events, which often trap juvenile fish (Swales and Levings 1989; Walker et al. 2018). Ice dams that formed in a high-elevation California stream created pools where Rainbow Trout (*Oncorhynchus mykiss*) and Brown Trout (*Salmo trutta*) were found stranded (Maciolek and Needham 1952). On the BR, two pools disconnected from the main river channel existed within our study reach and remained wetted throughout the duration of our study from hyporheic flow. Backpack electrofishing was performed (in a haphazard manner) in one pool in August of 2023 and six fish were captured. These fish may benefit by experiencing faster growth rates than those in the main river channel given sufficient resources and adequate temperature and oxygen (Swales and Levings 1989). Mortality can occur from avian or mammalian predators, although we observed no evidence of predation.

In conclusion, fish inhabiting rivers with hydropeaking regimes experience different hydrological conditions from naturally flowing rivers. To avoid stranding on hydropeaking rivers, fish must respond quickly to high-flow events by avoiding or evading river habitat that is dewatered after events occur. The results of this study provide preliminary evidence that fish stranding risk is higher on hydropeaking rivers, supporting the idea that fish stranding occurrence is largely driven by hydropeaking regimes (Glowa et al. 2023; Nagrodski et al. 2012; Young et al. 2011). To our knowledge, this is the first attempt to quantify fish stranding density on rivers with natural and hydropeaking flow regimes concurrently using a

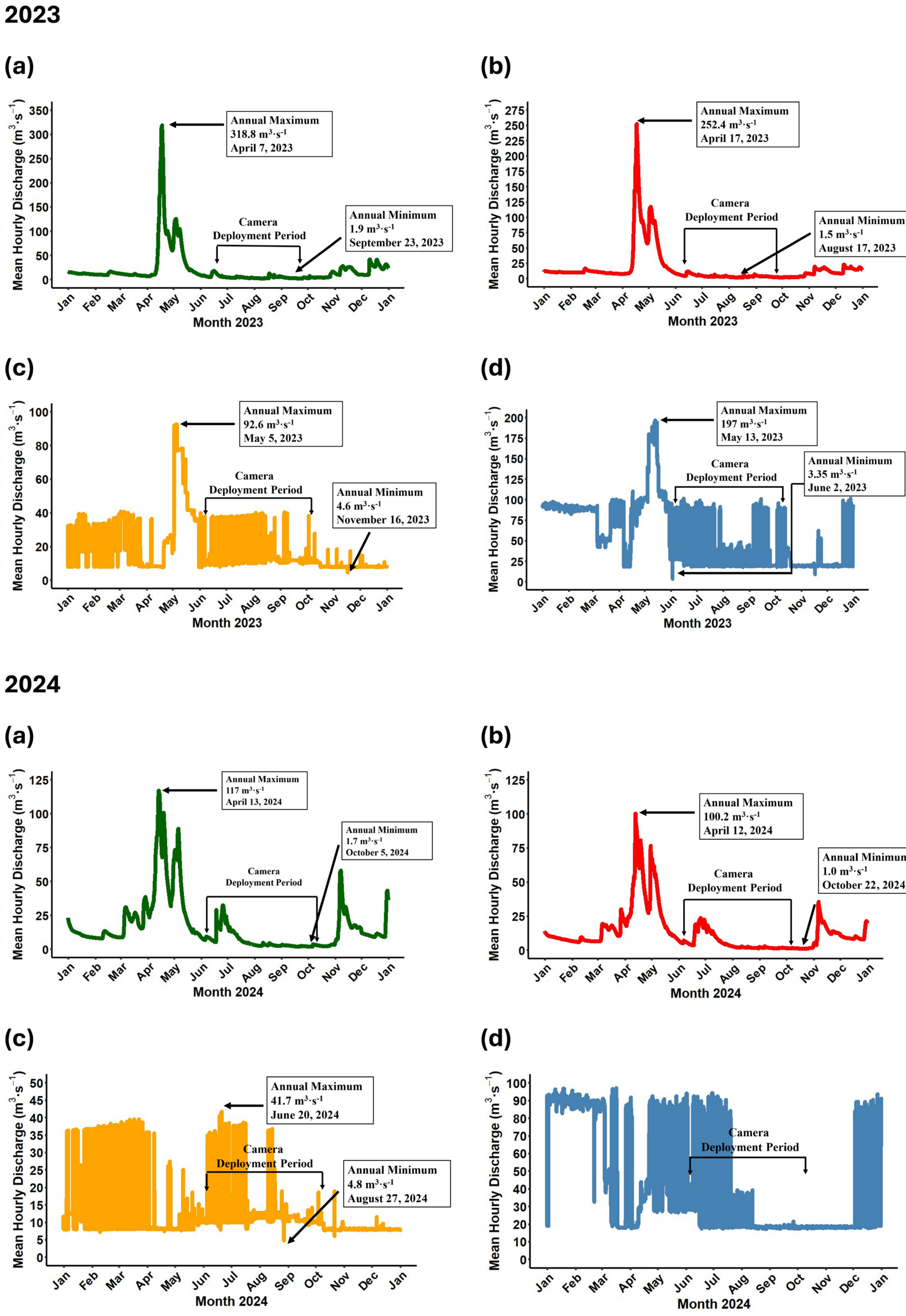

FIGURE 1 | Legend on next page.

FIGURE 1 | Mean hourly discharge ($m^3 s^{-1}$) data on all rivers (discharge data source) for 2023 and 2024, the annual maximum discharge ($m^3 s^{-1}$), the annual minimum discharge ($m^3 s^{-1}$), and the camera deployment period is depicted for each study river (a) Batchawana River (02BF001), (b) Goulais River (02BF002), (c) Magpie River (Steephill Falls GS), and (d) Michipicoten River (Scott Falls GS). Note, that on the hydropeaking rivers the annual minimum is temporary (e.g., <1 h) and not experienced over several days as seen with the rivers with natural flow regimes. On the Michipicoten River in 2024, the minimum discharge from the dam did not go lower than 17 $m^3 s^{-1}$ and the maximum discharge from the dam did not go higher than 100 $m^3 s^{-1}$.

TABLE 1 | Mean ± standard deviation of fish stranding density (fish m^{-2}) captured using remote photography for the four study rivers during camera deployment in 2023 and 2024. The number of cameras deployed each year for each camera strategy on each river are summarized. The total area surveyed (m^2) represents the area searched in each photograph after a high-flow event was observed on photographs (e.g., remote photography site experienced a high-flow event). Table has been modified from Davis et al. (2026).

River	Year	Camera strategy	Total number of camera operational days	Total number of camera failure days	Total number of high-flow events observed	Total area surveyed (m^2)	Total number of stranded fish observed	Total fish stranding density (fish m^{-2})
Batchawana	2023	Random ($n=8$)	615	161	14	106.6	0	0
Batchawana	2023	Strategic ($n=3$)	206	85	3	21.5	0	0
Batchawana	2024	Random ($n=8$)	681	271	12	92.0	0	0
Batchawana	2024	Strategic ($n=3$)	267	90	5	37.1	0	0
Goulais	2023	Random ($n=8$)	503	190	7	47.3	0	0
Goulais	2023	Strategic ($n=3$)	288	9	3	19.4	0	0
Goulais	2024	Random ($n=8$)	649	319	11	71.6	0	0
Goulais	2024	Strategic ($n=3$)	90	273	3	27.0	0	0
Magpie	2023	Random ($n=8$)	974	42	323	2188.3	0	0
Magpie	2023	Strategic ($n=3$)	365	16	129	880.2	1	0.001 ± 0.129
Magpie	2024	Random ($n=8$)	933	139	232	1716.6	1	0.001 ± 0.010
Magpie	2024	Strategic ($n=3$)	376	26	141	962.1	0	0
Michipicoten	2023	Random ($n=8$)	981	27	362	2468.8	11	0.004 ± 0.029
Michipicoten	2023	Strategic ($n=3$)	376	2	120	818.4	38	0.046 ± 0.120
Michipicoten	2024	Random ($n=24$)	2857	339	763	5508.2	17	0.003 ± 0.020
Michipicoten	2024	Strategic ($n=9$)	1077	123	283	2522.2	57	0.020 ± 0.080

comparative approach. Although the BR and GR lack flashy dynamics and connected floodplains, they resemble typical rivers of the Boreal Region, representing similar conditions to the MR and MPR if there were no hydropeaking generating station. We encourage future studies of hydropeaking systems to embrace a comparative approach (with replication) to properly contextualize stranding levels. Fish stranding presumably does occur on rivers with natural flow regimes but due to the limited frequency of high-flow events (e.g., the maximum number of annual high-flow events observed on the natural rivers was 9 compared to over 300 on the hydropeaking rivers) the magnitude of fish stranding may not be comparable. We suggest extending this approach on rivers with natural flow regimes with connected floodplains and intermittent or flashy dynamics, where fish stranding risk may be higher than the BR and GR. Such information may be useful in identifying mitigation and offsetting efforts to reduce the impact of hydropeaking on fish stranding.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Alonso, C., A. Román, M. D. Bejarano, D. G. de Jalon, and M. Carolli. 2017. "A Graphical Approach to Characterize Sub-Daily Flow Regimes and Evaluate Its Alterations due to Hydropeaking." *Science of the Total Environment* 574: 532–543.

Auer, S., B. Zeiringer, S. Führer, D. Tonolla, and S. Schmutz. 2017. "Effects of River Bank Heterogeneity and Time of Day on Drift and Stranding of Juvenile European Grayling (*Thymallus thymallus* L.) Caused by Hydropeaking." *Science of the Total Environment* 575: 1515–1521. https://doi.org/10.1016/j.scitotenv.2016.10.029.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software* 67, no. 1: 1–48. https://doi.org/10.18637//jss.v067.i01.

Brown, R. S., G. Power, and S. Beltaoa. 2001. "Winter Movements and Habitat Use of Riverine Brown Trout, White Sucker and Common Carp in Relation to Flooding and Ice Break-Up." *Journal of Fish Biology* 59, no. 5: 1126–1141.

Bruder, A., D. Tonolla, S. P. Schweizer, S. Vollenweider, S. D. Langhans, and A. Wüest. 2016. "A Conceptual Framework for Hydropeaking Mitigation." *Science of the Total Environment* 568: 1204–1212. https://doi.org/10.1016/j.scitotenv.2016.05.032.

Davis, R., S. J. Cooke, and K. E. Smokorowski. 2026. "Dam It, I'm Stranded: Evaluating Fish Stranding Downstream of Two Hydropeaking Dams in Northern Ontario." *River Research and Applications* 42: 796–811. https://doi.org/10.1002/rra.70113.

Fox, J., and S. Weisberg. 2018. *An R Companion to Applied Regression*. Sage publications.

Glowa, S. E., D. A. Watkinson, T. D. Jardine, and E. C. Enders. 2023. "Evaluating the Risk of Fish Stranding due to Hydropeaking in a Large Continental River." *River Research and Applications* 39, no. 3: 444–459. https://doi.org/10.1002/rra.4083.

Haas, C., P. Zinke, K. W. Vollset, J. Sauterleute, and H. Skoglund. 2016. "Behaviour of Spawning Atlantic Salmon and Brown Trout During Ramping Events." *Journal of Applied Water Engineering and Research* 4, no. 1: 25–30. https://doi.org/10.1080/23249676.2016.1169227.

Halleraker, J. H., S. J. Saltveit, A. Harby, J. V. Arnekleiv, H.-P. Fjeldstad, and B. Kohler. 2003. "Factors Influencing Stranding of Wild Juvenile Brown Trout (*Salmo trutta*) During Rapid and Frequent Flow Decreases in an Artificial Stream." *River Research and Applications* 19, no. 5–6: 589–603. https://doi.org/10.1002/rra.752.

Hauer, C., P. Holzapfel, P. Leitner, and W. Graf. 2017. "Longitudinal Assessment of Hydropeaking Impacts on Various Scales for an Improved Process Understanding and the Design of Mitigation Measures." *Science of the Total Environment* 575: 1503–1514. https://doi.org/10.1016/j.scitotenv.2016.10.031.

Insulaire, F., N. Lamouroux, A. Barillier, et al. 2024. "Characterizing the Effects of Morphological Microstructures and Hydropeaks on Fish Stranding in Rivers." *River Research and Applications* 40, no. 5: 834–849. https://doi.org/10.1002/rra.4277.

Irvine, R. L., J. L. Thorley, R. Westcott, D. Schmidt, and D. DeRosa. 2015. "Why do Fish Strand? An Analysis of ten Years of Flow Reduction Monitoring Data from the Columbia and Kootenay Rivers, Canada." *River Research and Applications* 31, no. 10: 1242–1250. https://doi.org/10.1002/rra.2823.

Jones, N. E., B. J. Schmidt, and S. J. Melles. 2014. "Characteristics and Distribution of Natural Flow Regimes in Canada: A Habitat Template Approach." *Canadian Journal of Fisheries and Aquatic Sciences* 71, no. 11: 1616–1624.

Lenth, R. 2023. "emmeans: Estimated Marginal Means, aka Least-Squares Means_." R Package Version 1.8.5.

Maciolek, J. A., and P. R. Needham. 1952. "Ecological Effects of Winter Conditions on Trout and Trout Foods in Convict Creek, California, 1951." *Transactions of the American Fisheries Society* 81, no. 1: 202–217.

May, C. L., and D. C. Lee. 2004. "The Relationships Among In-Channel Sediment Storage, Pool Depth, and Summer Survival of Juvenile Salmonids in Oregon Coast Range Streams." *North American Journal of Fisheries Management* 24, no. 3: 761–774.

Metcalfe, R. A., and B. J. Schmidt. 2016. "Streamflow Analysis and Assessment Software (version 4.1): Reference Manual." Ontario Ministry of Natural Resources and Forestry. http://people.trentu.ca/~rmetcalfe/SAAS.html.

Moreira, M., D. S. Hayes, I. Boavida, M. Schletterer, S. Schmutz, and A. Pinheiro. 2019. "Ecologically-Based Criteria for Hydropeaking Mitigation: A Review." *Science of the Total Environment* 657: 1508–1522. https://doi.org/10.1016/j.scitotenv.2018.12.107.

Nagrodski, A., G. D. Raby, C. T. Hasler, M. K. Taylor, and S. J. Cooke. 2012. "Fish Stranding in Freshwater Systems: Sources, Consequences, and Mitigation." *Journal of Environmental Management* 103: 133–141. https://doi.org/10.1016/j.jenvman.2012.03.007.

Poff, N. L., B. D. Richter, A. H. Arthington, et al. 2010. "Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards." *Freshwater Biology* 55, no. 1: 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

R Core Team. 2023. “R: A Language and Environment for Statistical Computing.” R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Sommer, T. R., W. C. Harrell, and M. L. Nobriga. 2005. “Habitat Use and Stranding Risk of Juvenile Chinook Salmon on a Seasonal Floodplain.” *North American Journal of Fisheries Management* 25, no. 4: 1493–1504.

Swales, S., and C. D. Levings. 1989. “Role of Off-Channel Ponds in the Life Cycle of Coho Salmon (*Oncorhynchus kisutch*) and Other Juvenile Salmonids in the Coldwater River, British Columbia.” *Canadian Journal of Fisheries and Aquatic Sciences* 46, no. 2: 232–242.

Walker, R. H., B. M. Maitland, T. N. LaSharr, M. N. Rosing, and M. Ben-David. 2018. “Fate of Juvenile Salmonids Stranded in Off-Channel Pools: Implications for Nutrient Transfers.” *Aquatic Sciences* 80, no. 1: 10.

Young, P. S., J. J. Cech, and L. C. Thompson. 2011. “Hydropower-Related Pulsed-Flow Impacts on Stream Fishes: A Brief Review, Conceptual Model, Knowledge Gaps, and Research Needs.” *Reviews in Fish Biology and Fisheries* 21, no. 4: 713–731. https://doi.org/10.1007/s11160-011-9211-0.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Summary of the physical and hydrological characteristics of each study river. The mean annual flow ($m^3 s^{-1}$) was calculated using 29 years of historical flow data from the rivers subsequent Water survey of Canada gauges or hydroelectric generating station. The mean substrate size (cm) was calculated using a modified Wentworth Scale at randomly deployed camera locations over both study years (*n* represents the number of random cameras used to calculate substrate size). The mean of the river width (m) was calculated using the digital elevation models created from photogrammetry. The river gradient (%) was calculated using the digital elevation models created from photogrammetry. The area suitable to stranding ($m^2 km^{-1}$) was calculated using the number of sites suitable to stranding by the area of each site (225 m^2). All mean values are presented with 95% C.I. **Table S2:** Summary of annual electrofishing sampling on study rivers.