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DATA GAPS AND PRIORITY UNCERTAINTIES

This appendix supports the Limiting Factors Analysis for Lower Trinity River Chinook salmon (*Oncorhynchus tshawytscha*) and follows the general process outlined in Hamilton and Murphy (2018). It summarizes priority data gaps and uncertainties and identifies monitoring needs to support future refinement of the LCM and LFA. Table 1 summarizes the key data gaps, uncertainties, and monitoring needs identified through the limiting factors analysis. Priorities are based on the expected influence of each uncertainty on model performance, hypothesis testing (see main report for hypothesis descriptions), and limiting-factor rankings, together with the strength of available Trinity-specific empirical support. In practice, higher priority was assigned to uncertainties that affect high-leverage life-stage transitions, strongly influence interpretation of adult escapement, and are weakly constrained by local data; lower priority was assigned to factors with more limited expected influence, stronger empirical support, or primarily episodic effects. Highest-priority gaps therefore reflect processes that strongly influence adult escapement but lack sufficient Trinity-specific data, making them the most important opportunities for targeted monitoring and model refinement. The sections that follow Table 1 provide supporting detail for each priority tier.

Table 1. Priority ranking of Trinity River Chinook salmon data gaps, uncertainties, and recommended monitoring needs identified through the Limiting Factors Analysis.

Priority Tier	Life Stage	Process / Factor	Key Data Gap or Uncertainty	Affected Hypotheses	Effect on LFA Diagnosis	Recommended Monitoring / Data Need
Tier 1	Juvenile rearing	Capacity, growth, survival	Juvenile rearing capacity, density dependence, growth, and survival are weakly constrained by Trinity-specific empirical data.	H_9–H_{11}	High influence on TRRP-controlled processes and model calibration.	Estimate habitat capacity, fish density, growth, and survival by reach.
Tier 1	Juvenile outmigration	Trinity–Klamath survival and size-selective mortality	Survival and size-selective mortality below the Trinity–Klamath confluence are poorly quantified.	H_{12}–H_{13}, H_{18}–H_{19}	Limits inference about where mortality occurs during migration.	Expand RST coverage, tagging, biotelemetry, and stock-origin identification.
Tier 1	Estuary and early marine	Origin, growth, survival	Trinity-origin fish are difficult to distinguish from Klamath-origin fish in estuary and early marine habitats.	H_{12}–H_{13}, H_{15}	Limits partitioning of mortality among downstream, estuary, and marine stages.	Develop stock identification tools and targeted estuary survival and growth studies.
Tier 2	Juvenile life history	Yearling strategy	The proportion, survival, and adult contribution of	H_9, H_{11}, H_{17}	Limits representation of life-history	Monitor juvenile age structure, tag cohorts, and evaluate

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			naturally produced yearlings are poorly understood.		diversity and carryover effects.	life-history pathways.
Tier 2	Incubation and emergence	Substrate and survival	Spatial information on gravel suitability, fine sediment, and egg-to-fry survival is limited.	H_5–H_8	Reduces confidence in reach-specific incubation limitations.	Map habitat, monitor redds, and estimate egg-to-fry survival by reach.
Tier 2	Processes linking life stages	Carryover effects	Links among juvenile size, timing, condition, and survival across life stages are not well quantified.	H_{16}–H_{17}	Limits evaluation of delayed and cross-stage effects.	Coordinate tagging, monitoring, otolith sampling, and cohort tracking.
Tier 3	Ocean and harvest	Stock-specific survival and attribution	Trinity-specific ocean survival, stock composition, and harvest attribution are limited.	H_{14}–H_{15}	Reduces precision in separating marine survival and harvest effects.	Improve tagging, stock identification, and integration with fishery datasets.
Tier 3	Klamath corridor out-migration conditions	Environmental drivers of migration mortality	Interactions among flow, temperature, and disease during Klamath migration remain uncertain.	H_{12}, H_{15}	May influence episodic and chronic migration mortality.	Coordinate basin-wide monitoring and modeling of flow, temperature, disease, and survival.
Tier 3	Juvenile production metrics	Linkage to survival	Abundance estimates are not consistently linked to life-stage-specific survival and growth.	H_9–H_{13}	Limits calibration and validation of the life cycle model.	Integrate abundance, size, growth, and survival monitoring.
Tier 4	Spawning	Capacity and distribution	Reach-scale spawning capacity, suitability, redd superimposition, and habitat distribution remain uncertain.	H_4	Helps define thresholds where spawning could become limiting.	Conduct habitat surveys and finer-scale spawning-capacity analyses.
Tier 4	Adult holding	Behavior and habitat use	Adult holding habitat use, density, and temperature thresholds are limited, especially	H_2–H_3	May become important under warmer or higher-density conditions.	Use telemetry and targeted habitat-use observations.

Priority Tier	Life Stage	Process / Factor	Key Data Gap or Uncertainty	Affected Hypotheses	Effect on LFA Diagnosis	Recommended Monitoring / Data Need
			for spring-run Chinook.			
Tier 4	Hatchery interactions	Release timing and contribution	Assumptions about hatchery release timing, contributions, and interactions with natural-origin fish are simplified.	H_{11}	Affects representation of size structure and early life history.	Refine release strategies and evaluate interactions with tagging studies.
Tier 5	Incubation stressors	Hydrologic disturbance	Scour and dewatering frequency and magnitude are not well quantified and are episodic.	H_8	Unlikely to drive systemwide limitation under typical conditions.	Use periodic monitoring, event-based studies, and future stochastic model functions.
Tier 5	Nutritional stressors	Thiamine deficiency	Prevalence and severity of thiamine deficiency are uncertain but appear episodic and limited in scope.	H_8	Not considered a primary constraint under current conditions.	Use periodic screening and targeted investigation.
Tier 5	Adult immigration	Routing and survival	Adult immigration survival appears better constrained than juvenile and estuary-related transitions.	H_2	Appears compounding or context-dependent rather than primary.	Continue monitoring and refine survival estimates as post-dam-removal conditions develop.

Tier 1 – Highest Priority (High impact, low support)

Juvenile rearing (capacity, growth, survival): Quantitative estimates of juvenile rearing capacity, density dependence, growth, and survival within Trinity River reaches remain weakly constrained by empirical data. This uncertainty directly affects hypotheses related to rearing limitation (H_9–H_{11}) and represents the strongest source of uncertainty in TRRP-controlled processes influencing escapement. Improved field-based estimates of habitat capacity, fish density, growth rates, and survival are needed to calibrate the life cycle model and evaluate the biological response to flow and habitat restoration.

Juvenile outmigration (Trinity–Klamath survival and size-selective mortality): Survival rates and size-selective mortality during downstream migration below the Trinity–Klamath confluence are poorly quantified because monitoring infrastructure is limited. This gap limits evaluation of hypotheses related to downstream mortality and carryover effects (H_{12}–H_{13}, H_{18}–

H_{19}). Expanding rotary screw trap (RST) coverage, implementing tagging studies, and quantifying survival by size class would substantially improve understanding of where and how mortality occurs during migration. RST monitoring in the Klamath would need to include genetic, tagging, or biotelemetry studies to distinguish stock origin.

Estuary and early marine (origin, growth, survival): The ability to distinguish Trinity-origin fish from Klamath-origin fish in the estuary and early marine environment is currently limited, constraining estimates of survival, growth, and residence time. A recent study initiated in the estuary may provide some useful information, but genetic sampling or biotelemetry components would be needed to differentiate Klamath and Trinity stocks and their use of the estuary. This uncertainty affects hypotheses related to downstream and marine limitation (H_{12}–H_{13}, H_{15}) and systemwide diagnosis. Development of stock identification tools (e.g., genetics, otoliths) and targeted studies of estuary survival and growth are needed to better partition mortality and evaluate estuary function.

Tier 2 – High Priority (Moderate–high impact, moderate/low support)

Juvenile life history (yearling strategy): The proportion, survival, and contribution of naturally produced yearling (1+) fish to adult escapement are poorly understood. This gap affects hypotheses related to rearing, life-history diversity, and effects that carry over across life stages (H_9, H_{11}, H_{17}). Improved monitoring of juvenile age structure, tagging of cohorts, and evaluation of life-history pathways are needed to better represent these dynamics in the model. This may require changes in trap deployment to capture yearling outmigration periods.

Incubation and emergence (substrate and survival): There is limited spatially explicit information on spawning gravel suitability, fine sediment distribution, and egg-to-fry survival across Trinity River reaches. These uncertainties affect hypotheses related to incubation constraints (H5–H8) and reduce confidence in diagnosing reach-specific limitations. Reach-scale habitat mapping, redd monitoring, and direct estimates of egg-to-fry survival would substantially improve inference.

Processes linking life stages (carryover effects): Linkages among juvenile size, timing, condition, and survival across life stages are not well quantified. This limits evaluation of hypotheses related to carryover effects and life-cycle dynamics (H_{16}–H_{17}). Addressing this gap requires coordinated tagging and monitoring programs that track cohorts across multiple life stages to quantify trade-offs and delayed effects. This may include otolith sampling during carcass surveys to link life history pathways to contributing adult returns—in addition to the existing CWT-based cohort reconstructions.

Tier 3 – Moderate–High Priority (High impact, moderate support)

Ocean and harvest (stock-specific survival and attribution): Trinity-specific data on ocean survival, stock composition, and harvest attribution are limited, reducing precision in separating the relative roles of marine survival and harvest (H_{14}–H_{15}). Improved tagging programs, stock identification, and integration with fishery datasets would support more accurate estimates of these effects.

Klamath corridor (environmental drivers of migration mortality): Uncertainty remains in how flow, temperature, and disease interact to affect juvenile survival during migration through the Klamath River. This affects hypotheses related to downstream mortality and environmental stressors (H_{12}, H_{15}). This gap is retained in Tier 3 because Klamath corridor conditions may have high biological consequences but are supported by enough basin-scale information to make the uncertainty more bounded than Tier 1 juvenile survival and estuary gaps. Coordinated basin-wide monitoring and modeling of these drivers would improve understanding of episodic and chronic mortality patterns. Because post-dam-removal conditions may alter these drivers, this gap should be reassessed in future LFA updates and could warrant a higher priority if monitoring indicates stronger effects on juvenile outmigration survival.

Juvenile production metrics (linkage to survival): Existing monitoring provides estimates of abundance but is less effective at linking production metrics to life-stage-specific survival and growth. This limits calibration and validation of the life cycle model across multiple hypotheses (H_9–H_{13}). Integrated monitoring designs that couple abundance, size, growth, and survival estimates are needed to strengthen model performance.

Tier 4 – Moderate Priority (Moderate impact, moderate–high uncertainty)

Spawning (capacity and distribution): Reach-scale estimates of spawning capacity and suitability, redd superimposition, and habitat distribution are uncertain, limiting evaluation of density-dependent effects (H_4). While spawning is not identified as a primary limitation, improved habitat surveys and finer-scale analysis would better define thresholds at which spawning becomes limiting.

Adult holding (behavior and habitat use): Information on adult holding habitat use, density, and temperature thresholds—for spring-run Chinook—is limited. This constrains evaluation of hypotheses related to holding habitat under different escapement scenarios (H_2–H_3). This gap is placed in Tier 4 because it may become important under warmer or higher-density conditions, but current evidence does not indicate that adult holding is a dominant constraint relative to juvenile rearing, outmigration, estuary, or broader Klamath corridor uncertainties. Telemetry studies and targeted habitat-use observations would improve understanding of this life stage.

Hatchery interactions (release timing and contribution): Current assumptions regarding hatchery release timing, contributions, and interactions with natural-origin fish are simplified and uncertain. This primarily affects hypotheses related to size structure and early life history (H_{11}). Refining hatchery release strategies and evaluating interactions through tagging studies would improve representation of these effects. Note that fractional marking also introduces potential variance in juvenile trap and adult weir monitoring programs, with expansions requiring consideration of fractional marking strategies.

Tier 5 – Lower Priority (Low impact or episodic)

Incubation stressors (hydrologic disturbance): The frequency and magnitude of disturbance events such as scour and dewatering are not well quantified but are considered episodic and condition-dependent (H_8). These processes are unlikely to drive systemwide limitation under typical conditions, so periodic monitoring and event-based studies are sufficient to track their influence. Separately, the current model does not explicitly represent episodic events or stochasticity; adding these functions in future model iterations would improve the ability to test disturbance-related hypotheses when event-based data become available.

Nutritional stressors (thiamine deficiency): The prevalence and severity of thiamine deficiency in Trinity River Chinook populations are uncertain but appear to be episodic and limited in scope (H_8). This factor is not considered a primary constraint under current conditions. Periodic screening and targeted investigation are sufficient to monitor potential impacts.

Adult immigration (routing and survival): Based on currently available data and pre-dam-removal conditions, immigration survival through the Klamath–Trinity corridor appears better constrained than many juvenile and estuary-related transitions and is not sufficient alone to explain the recovery gap (H_2). Adult immigration is therefore retained in Tier 5 because it appears to be a compounding or context-dependent influence rather than a primary limiting transition under current assumptions. Continued monitoring and refinement of survival estimates remain appropriate, particularly as post-dam-removal conditions develop, but this gap is currently lower priority relative to uncertainties that more directly affect juvenile survival, estuary function, and interpretation of adult escapement.

Future Consideration: Post-Dam Removal Klamath River System Shifts

An important source of uncertainty not explicitly incorporated into the current limiting factors analysis is the potential for fundamental system shifts associated with the recent removal of four hydroelectric dams in the Klamath River, completed in 2024. This large-scale restoration has reconnected more than 350–400 miles of historical habitat and fundamentally altered flow regimes, water temperature patterns, sediment transport, water quality, and fish passage conditions throughout the Klamath River (NOAA Fisheries 2024; California State Water Resources Control Board 2024). Early observations and projections indicate that dam removal may result in rapid ecological responses, including more natural temperature regimes, reduced harmful algal blooms, and expanded salmon access to previously blocked habitats, although these benefits may be accompanied by short-term increases in sediment transport and transitional changes in water quality (NOAA Fisheries 2024; California State Water Resources Control Board 2024). The magnitude and direction of biological responses remain uncertain, particularly with respect to salmon survival, because dam removal is expected to alter key processes such as migration pathways, timing, thermal exposure, and pathogen dynamics (Bartholomew et al. 2023).

These system-wide changes could substantially affect adult immigration through the lower Klamath, juvenile outmigration through the Klamath River and estuary, and the broader interpretation of survival bottlenecks in the LFA. For example, removal of thermal "reservoir effects" associated with impoundments may improve temperature conditions during adult migration, while increased connectivity and altered migration pathways could change exposure to disease, sediment, or other stressors during juvenile outmigration (Bartholomew et al. 2023). Because the Klamath River remains in an early post-removal transition, the magnitude, direction, and variability of these effects are likely to change over multiple years as physical and biological processes stabilize.

Post-dam removal conditions should therefore be treated as a system-wide uncertainty that may affect several existing priority gaps rather than as a separate life stage or standalone priority item. The current tiering reflects present evidence: juvenile outmigration, Klamath corridor conditions, estuary function, adult holding, and adult immigration may all respond to dam removal, but they differ in expected influence on the current LFA diagnosis and in the strength of existing support. Coordinated basin-wide monitoring of survival, migration timing, disease risk, habitat conditions, and estuary function will be needed to determine whether post-removal changes alter the relative importance of these gaps or warrant adjustments to their priority rankings in future LFA updates.

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