Supplement to “A watershed-specific formula to predict salmon reproduction using functional flow metrics”

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# 1 History of flow-ecology relationships

A river’s flow regime is often referred to as a “master variable” controlling geomorphic, chemical, and other conditions in its aquatic ecosystems, and organisms that have evolved to persist in specific flow regimes are commonly negatively affected by flow alteration (Bunn and Arthington 2002; Poff et al. 2010). Consequently, in recent decades a diverse body of research has sought to identify and quantify ecological responses to changes in flow.

Work on this topic spans multiple categories of ecological response, hydrologic predictor, and ultimate cause of hydrologic alteration. Two widely studied ecological response metric categories are, firstly, the stream health index, based on density and species richness of macroinvertebrates observed at designated sampling sites (e.g., Monk et al. 2006; Guareschi et al. 2014; Kevic et al. 2018; Mazor et al. 2018; Larsen et al. 2021; Peek et al. 2022), and secondly, fish diversity and community assemblage (e.g., McManamay et al. 2013; Peterson and Freeman 2016; Cartwright et al. 2017; Sinnathamby et al. 2018; Hain et al. 2018; Guedes et al. 2020; Yao et al. 2021). Ecological responses can also be based on the abundance of a single or a few species, often of fish (Stewart-Koster et al. 2011; Booth et al. 2014; DeWeber and Peterson 2020; Hale et al. 2023), as well as the extent of habitat types (Chowdhury and Driver 2007; Arriana Brand et al. 2011) and the presence of organisms including vegetation and plankton (Riis et al. 2008; Catford et al. 2014; Qian, Liu, and Chen 2016; Tesfaye et al. 2017; Saby et al. 2022). Hydrologic predictors range widely **insert IHA and ELOHA**, with a heavy emphasis on extreme (low or high) flow events and the duration of components of the flow regime (e.g., Ayllón et al. 2014; Lamouroux and Olivier 2015; McManamay and Frimpong 2015; Bower et al. 2022). Causes of the change in hydrology include the operation of dams, changes in human water use, climate change, and natural flow variability (e.g., Alomía Herrera and Carrera Burneo 2017; Gao, Xie, and Zou 2020; White et al. 2018; Daneshvar et al. 2017; Herbst et al. 2019).

Investigations of flow-ecology relationships can also be grouped by approach Brummer et al. (2016). In experimental flow studies the flow is directly manipulated with dam releases and biological responses are monitored (e.g., Konrad et al. 2011). In longitudinal studies, long-term ecological and hydrological records can be used to infer local or regional correlations (e.g., Mellado-Díaz et al. 2019). Finally, in space-for-time approaches, the hydrology of multiple river systems in a region is used to populate the distribution of different hydrologic behavior, and ecological monitoring is related to flow differences between streams (e.g., Monk et al. 2008; Riis et al. 2008; Catford et al. 2014; Bower et al. 2022). Space-for-time analyses require considerably fewer resources than experimental flows and longitudinal studies, and thus are more numerous (Brummer et al. 2016).

Bridging the gap between science and policy has been a persistent challenge in this field. In many cases a key research motivation is to support decision-making in a variety of contexts, including dam operation, river restoration, and regulations of water extraction and land use (Richter et al. 2006; Han et al. 2015; Sinnathamby et al. 2018; Bradley et al. 2017; Brummer et al. 2016). But historical approaches based on relationship-finding are several steps removed from the policy-making process (Webb et al. 2018). For example, the Ecological Limits of Hydrologic Alteration (ELOHA) framework or similar approaches can generate flow-ecology relationships or flow standards for particular rivers, but cannot translate specific management decisions into hydrologic or ecological outcomes (Richter et al. 2006; Cartwright et al. 2017).

An ideal framework for supporting decision-making would involve two key steps, firstly connecting land and water management actions to flow changes, and secondly connecting flow changes to ecological responses (Peterson and Freeman 2016; DeWeber and Peterson 2020; Acero Triana, Chu, and Stein 2021). Both steps can involve complex models and substantial uncertainty, often representing an interdisciplinary challenge. Threshold values for “sufficient” flows would be ideal for a management context (Rosenfeld 2017), but can be difficult to identify and in some cases may not exist (Lueders and McManamay 2023). Additionally, identifying natural flow regimes may be less immediately relevant to water resource management than an approach which can quantify ecological responses to “designer” or functional flows (which can often be controlled or influenced by dam releases) (Arthington, Bernardo, and Ilhéu 2014; Webb et al. 2018), with the caveat that the designer flows approach may risk overlooking ecological flow needs that are not currently monitored (Bower et al. 2022). Finally, stakeholders in at least one study requested flow-ecology relationships based on empirical monitoring, rather than more easily-simulated proxies like flow changes or thermal exposure (DeWeber and Peterson 2020).

The present study is a longitudinal “bottom-up” analysis, using empirical data and a case study, to identify flows most critical to support two specific species, and thus address the second of the two key links identified above. We use empirical data to develop a predictive model of a biological response to measurable (and simulatable) changes in flow metrics. We refer to this model as a “hydrologic benefit function” (i.e., intending to quantify the ecological services provided by flow) for a single species. This provides the critical link to evaluate fish outcomes resulting from future alternative watershed management practices which affect the hydrology of a stream ecosystem. A forthcoming companion study will investigate the other link, simulating flow changes from watershed management actions using an appropriate hydrologic model, then use hydrologic benefit functions to summarize the ecologic outcomes of a portfolio of water and land use scenarios.

## 1.1 Previous work and limitations of a hydrologic predictor approach

In many previous studies of flow-ecology relationships (especially related to fisheries), predictors used to model the ecological response are flow-derived metrics, because flow data is often continuous and more abundant than other data types. Such models rely on the assumption that flow, directly or as a proxy for other variables (e.g., habitat) is the limiting factor in ecological recruitment, and thus that changes in flow can be directly translated to a population response. However, this ignores ecological theory. Under many circumstances, complex internal population feedbacks (such as high juvenile fish density leading to some juvenile fish mortality) or community dynamics (food webs) will be the limiting factors on fish population size. Consequently, many authors have argued that models of fish population responses to hydrologic changes should explicitly include ecological population modeling in addition to physical factors such as flow or geomorphology (Rosenfeld 2003; Anderson et al. 2006; Lancaster and Downes 2010; Acreman et al. 2014; Shenton et al. 2012). Additionally, in at least one case, fish population differences were not successfully predicted with a model based only on flow metrics; other variables such as water temperature were necessary to capture population shifts (McManamay et al. 2013).

In spite of these known limitations, the HB function proposed here uses only hydrologic predictors. In part this is a pragmatic approach, as this work is intended to set the foundation for assessing flow conditions in speculative hydrologic models, which do not simulate non-hydrologic, ecologically-relevant factors such as water quality or internal population dynamics. Furthermore, previous work suggests that seasonal flow availability is a major limiting factor on the local coho salmon fishery, supporting the hydrologic predictor only approach in this case (SRWC and Siskiyou RCD 2005; NMFS 2014).

# 2 Scott River watershed setting and water use

## 2.1 Geography, climate and hydrology

The Scott River drains a 2,109 km2 (814 square mile) watershed known as Scott Valley, flowing generally from south to north and joining the Klamath River after flowing through a steep canyon (Figure ??). The Scott is a major tributary to the Klamath, which drains an area spanning sections of Northern California and Southern Oregon (Figure ??, inset map). Scott Valley has a Mediterranean climate with distinctive seasons of cool, wet winters and warm, dry summers. This seasonality in water input creates highly seasonal flow in the Scott River and tributary streams, where the beginning of a water year coincides with low flow conditions that immediately precede the onset of winter precipitation (Figure 1).

In most dry-to-average water years, sections of the Scott River become seasonally dewatered (NCRWQCB 2005; Figure 5 in Tolley, Foglia, and Harter 2019). This occurs when the elevation of the water table drops below the bottom of the river channel, as streams and groundwater are highly interconnected in the Scott River watershed. Tributary streams, particularly along their alluvial fan apeces, and the upper Scott River are sources of recharge to the aquifer (Mack 1958; Harter and Hines 2008). Groundwater discharge sustains streamflow in low-lying areas, especially during the dry season of August through October or November (Tolley, Foglia, and Harter 2019). For consistency with regulatory and management programs in this region, this document uses units of cubic feet per second (cfs) when reporting hydrologic fluxes.

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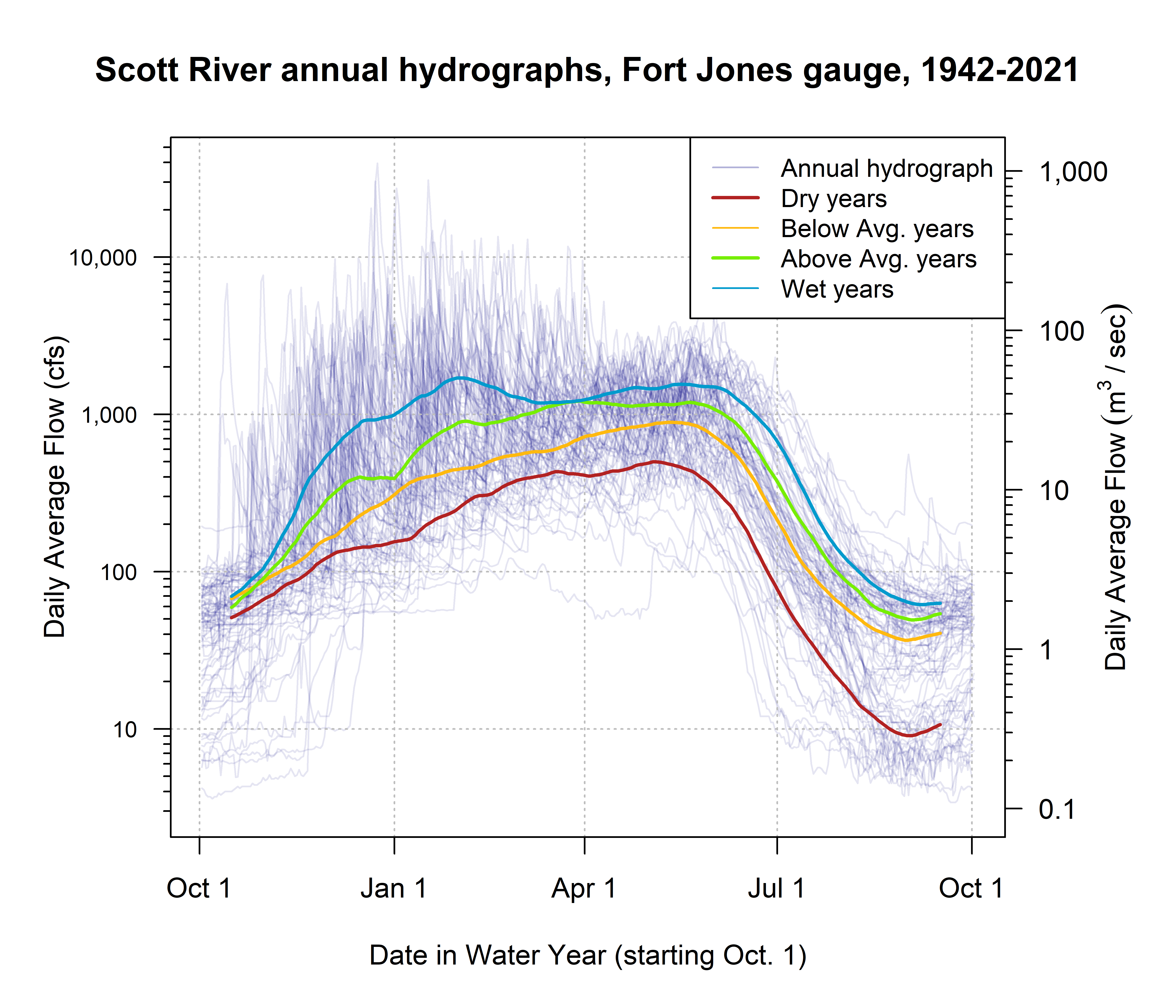


Figure 1: Each translucent line traces one annual hydrograph measured at the Fort Jones gauge, and the darker lines illustrate the 30-day smoothed median daily flow in Dry, Below Average, Above Average, and Wet water year types, for water years 1942-2023. The water year type is defined by quartiles of the distribution of total annual flow.

## 2.2 Water uses and management objectives

Water in Scott Valley is used for agricultural, domestic, and municipal supply. It also facilitates recreation and provides Native American cultural services, among other designated beneficial uses (NCRWQCB 2006). Because the watershed is undammed, managers and water users influence Scott River flow primarily via diversion of surface waters and pumping of groundwater. Consequently, the most powerful tool available to manage Scott River water flow is regulation of land use and thus water demand (Siskiyou County 2021).

Historically, local regulation of land use has focused on maintaining the rural and agricultural character of Scott Valley (Scott Valley Area Plan Committee 1980). Regulating land use to improve ecological outcomes would entail significant economic, political and social risks, because much of the economic activity in this area is related to agriculture. The primary crops grown in Scott Valley are pasture for cattle feed and alfalfa (Siskiyou County 2021). In addition to local economic impact, Scott River conditions influence fish population dynamics both within the watershed and in the broader Klamath system. The health of the Klamath salmon run has implications for commercial fishing, recreational activities, and cultural practices of Native American tribes in the region, including the Quartz Valley Indian Community and the Karuk and Yurok Tribes (Mansfield et al. 2012).

Recent management activity has included the leasing of surface water rights from landowners to enhance summer flows (e.g., SRWT 2018), the prioritization of stream reaches for habitat restoration (SRWC 2018), several pilot projects to construct and assess the impact of beaver dam analogs (BDAs) on aquatic habitat and fish populations (Yokel 2018), a coordinated rescue effort to relocate juvenile salmon that were cut off from outmigrating by disconnected river reaches (CDFW 2015), and the development of long-term groundwater management plan by Siskiyou County and local stakeholders (Siskiyou County 2021).

## 2.3 Historical assessments of Scott River flow-ecology relationships

Flow-ecology relationships have been investigated before in the Scott River Watershed, but the empirical “flow-to-ecology” link described above has not been quantified. Over the past three decades, several organizations and agencies have conducted extensive monitoring and published a series of reports and plans regarding the salmon fisheries in the Scott River watershed. In the 1990s, fall flows in the Scott River were reported to be too low in some years to allow for Chinook spawning in September-November (CRMP and SRWC 2000), but in the mid-2000s it was reported that low fall flows rarely affected the later (November-January) spawning runs of steelhead and coho salmon (SRWC and Siskiyou RCD 2005). More recently, fall flows have affected coho salmon as well as Chinook, as the late onset of winter storms has delayed coho spawning in some water years (e.g., CDFW 2015). In the mid-2000s, a local conservation organization identified the lack of suitable summer and winter rearing habitat as a probable limitation on Scott River coho smolt production (SRWC and Siskiyou RCD 2005). Several years later, in a NOAA Fisheries Coho Recovery Plan, NMFS identified the juvenile life stage as the most limited in the population (NMFS 2014).

# 3 Species of concern - coho and Chinook salmon

### 3.0.1 Life cycle and status of coho salmon (*Oncorhynchus kisutch*)

Returning adult coho spawn in natal streams between November and January (Knechtle and Giudice 2020), and juvenile coho spend approximately one full year in freshwater streams before migrating to the ocean as smolts (Moyle 2002; McMahon 1983). In the Scott River system these natal streams are the tributaries along the margins of the valley floor (SRCD 2004).

In previous studies, the strongest predictor of juvenile coho abundance in a stream system was spatial habitat (Bradford, Taylor, and Allan 1997; Nickelson et al. 1992; Bustard and Narver 1975), although adequate food and cover were also important (McMahon 1983). The primary mechanism for spatial constraints on abundance appears to be that juvenile coho become more territorial as they grow (McMahon 1983).

Some coho salmon return to spawn at age 2 as grilse, but the majority (e.g., 92.4% in 2020) return after more than one year in the ocean, giving the Scott coho salmon run its characteristic 3-year cohort return interval (Knechtle and Giudice 2020).

Coho salmon in the Scott Valley are listed as threatened under the federal and California Endangered Species Acts (ESAs). They belong to the Southern Oregon / Northern California Coast (SONCC) Evolutionarily Significant Unit (ESU), which was listed as threatened under the federal and state ESAs in 1997 and 2005, respectively. State-wide, coho populations have declined more than 90% since the 1940s (Brown, Moyle, and Yoshiyama 1994).

### 3.0.2 Life cycle and status of Chinook salmon (*Onchorhynchus tsawytscha*)

Chinook salmon in the Scott Valley are a candidate for listing under the federal ESA, and are not listed under the California ESA. They belong to the Southern Oregon / Northern California Coast (SONCC) Evolutionarily Significant Unit (ESU). Typically, adult Chinook salmon return to spawn in Scott Valley streams in the fall months September-December when flows are sufficient for salmon passage (Knechtle and Giudice 2020; Magranet 2015, 2017). Chinook in this watershed hatch in the spring and migrate to the ocean in their first year of life (Agrawal et al. 2005). Chinook spend the majority of their life in the ocean, and return to their natal streams shortly before spawning (Groot and Margolis 1991). However, substantial variability exists within this broader structure: Chinook salmon exhibit variation in multiple life stages, including time of seaward migration, age of maturity, and timing of return to natal stream (Groot and Margolis 1991; Bourret, Caudill, and Keefer 2016).

As recently as 2013, the SONCC Chinook population was stable and becoming more complex (Wainwright et al. 2013). However, in monitoring from 2015-2020, the number of returning adults (the escapement) was 65% below historical average, and the change in the Scott River Chinook population has been more rapid than the decline in the overall Klamath Basin Chinook run (California Department of Fish and Wildlife 2021). Ocean conditions may have contributed to a broad decline in Chinook populations from Alaska to California (Welch, Porter, and Rechisky 2021). Some studies have found that the leading cause of declining Chinook populations are ocean conditions, including including temperature, upwelling currents and food resources (Hunt, Mulligan, and Komori 1999), while others have identified hatchery practices as the primary cause (Quiñones et al. 2014).

# 4 Hydrologic Metrics

## 4.1 Functional Flows Background

Table 1: Explanation of functional flows used in this analysis (Patterson et al. 2020; Baruch et al. 2024). Each type of metric, for each threshold value (e.g., 100 cfs or 50th flow percentile), produces one value per water year.

| Abbrev. | Full Name | Thresholds | Description |
| --- | --- | --- | --- |
| DS\_Dur\_WS | Dry Season Duration | -- | Dry-season baseflow duration (# of days from start of dry season to start of wet season) |
| DS\_Tim | Dry Season Onset Timing | -- | Dry-season baseflow start timing (water year day of dry season) |
| DS\_Mag | Dry Season Flow Magnitude | 50th and 90th flow percentile | Percentile of daily flow within dry season. |
| FA\_Dur | Fall Pulse Duration | -- | Duration (# of days) of the fall pulse event |
| FA\_Tim | Fall Pulse Timing | -- | Start date of fall pulse event in water year days |
| FA\_Mag | Fall Pulse Magnitude | -- | Peak magnitude of fall pulse event (maximum daily peak flow during event) (cfs) in relevant lifestage. |
| FA\_Dif\_num | Fall Pulse Magnitude (modified) |  | Difference between peak fall pulse discharge and dry season median discharge (Baruch et al. 2024). |
| Wet\_BFL\_Dur | Wet Season Baseflow Duration | -- | Wet-season baseflow duration (# of days from start of wet-season to start of spring season) |
| Wet\_BFL\_Mag | Wet Season Baseflow Magnitude | 50th and 10th percentile | The magnitude of the median rate of baseflow (i.e., non-storm flow) during the wet season. |
| Wet\_Tim | Wet Season Onset Timing | -- | Start date of wet-season in water year days |
| Peak\_Dur | Duration of high-flow events | 2, 5, and 10-year return interval | Number of days exceeding the 2, 5 and 10 year recurrence intervals of annual peak flow (50%, 20%, and 10% exceedance values). |
| Peak\_Fre | Frequency of high-flow events | 2, 5, and 10-year return interval | Number of times that flow crosses over the threshold values for the 2-, 5- and 10-year flow (50%, 20%, and 10% exceedance values). |
| Peak\_Tim | Timing of first high-flow event in a water year | 2, 5, and 10-year return interval | Timing of first exceedance of threshold value for the 2-, 5- and 10-year flow (50%, 20% and 10% exceedance values), in water year days |
| Peak | Magnitude of high-flow events | 2, 5, and 10-year return interval | Single value for each threshold corresponding to the 2-, 5- and 10- year flow exceedance values, in cfs |
| SP\_ROC | Spring Recession Rate of Change | -- | Spring flow recession rate (median daily rate of change over decreasing periods during the recession) |
| SP\_ROC\_Max | Maximum Spring Recession Rate of Change |  | Maximum daily rate of change over decreasing periods during the recession |
| SP\_Dur | Duration of Spring Recession |  | Period elapsed from the start date of the spring recession until the start date of the following dry season. |
| SP\_Mag | Magnitude of Spring Recession |  | Flow magnitude on the start date of the spring recession (the "peak" of the snowmelt pulse). |
| SP\_Tim | Spring Onset Timing | -- | Start date of spring flow recession in water year days |
| Mean\_Ann\_Flow | Mean Annual Flow | -- | Mean daily flow rate over a full water year. |
| WY\_Cat | Water Year Category | -- | Category of water year (Dry, Moderate, Wet) |

## [1] FALSE



Figure 2: Figure 2 from Yarnell et al., 2020. Illustration of five functional flow categories identified for a mixed rain-snowmelt runoff river in California.

## 4.2 Hydrologic Metrics Designed for This Study

Table 2: Explanation of custom hydrologic metrics designed for this study, which are less complex than functional flows in that they do not rely on signal processing techniques. Each type of metric, for each threshold value (e.g., 120 cfs), produces one value per water year. Metric names used in predictive modeling also include abbreviations for salmon life periods (Table 3 below); e.g., f1\_recon\_120, referring to the timing of flow exceeding 120 cfs in a ohort's first fall season.

| Abbrev. | Full Name | Thresholds | Description |
| --- | --- | --- | --- |
| recon | River Reconnection Day (for a given life stage and threshold) | 20, 120 | The day, usually in the fall, on which the Scott River gains a certain degree of connectivity. Defined as the first day on which FJ Gauge flow rises above a designated threshold (e.g., 20 cfs) (units of days after Aug. 31). Assigned to a salmon lifestage using a season identifier such as f1 (first fall, experienced by a cohort's spawning parents). Example: f1\_recon\_20 |
| discon | River Disconnection Day (for a given life stage and threshold) | 20, 120 | The day, usually in the spring or early summer, on which the Scott River loses a certain degree of connectivity. Defined as the first day on which FJ Gauge flow drops below a designated threshold (e.g., 120 cfs) (units of days after Aug. 31). Assigned to a salmon lifestage using a season identifier such as s2 (second spring, experienced as outmigrating smolt). Example: s2\_discon\_120 |
| num\_days\_gt\_90\_pctile | Number of days of high-flow events | 90th flow percentile | Number of days in a water year in which the FJ daily average flow exceeded the 90th percentile flowrate in the full FJ Gauge record. |

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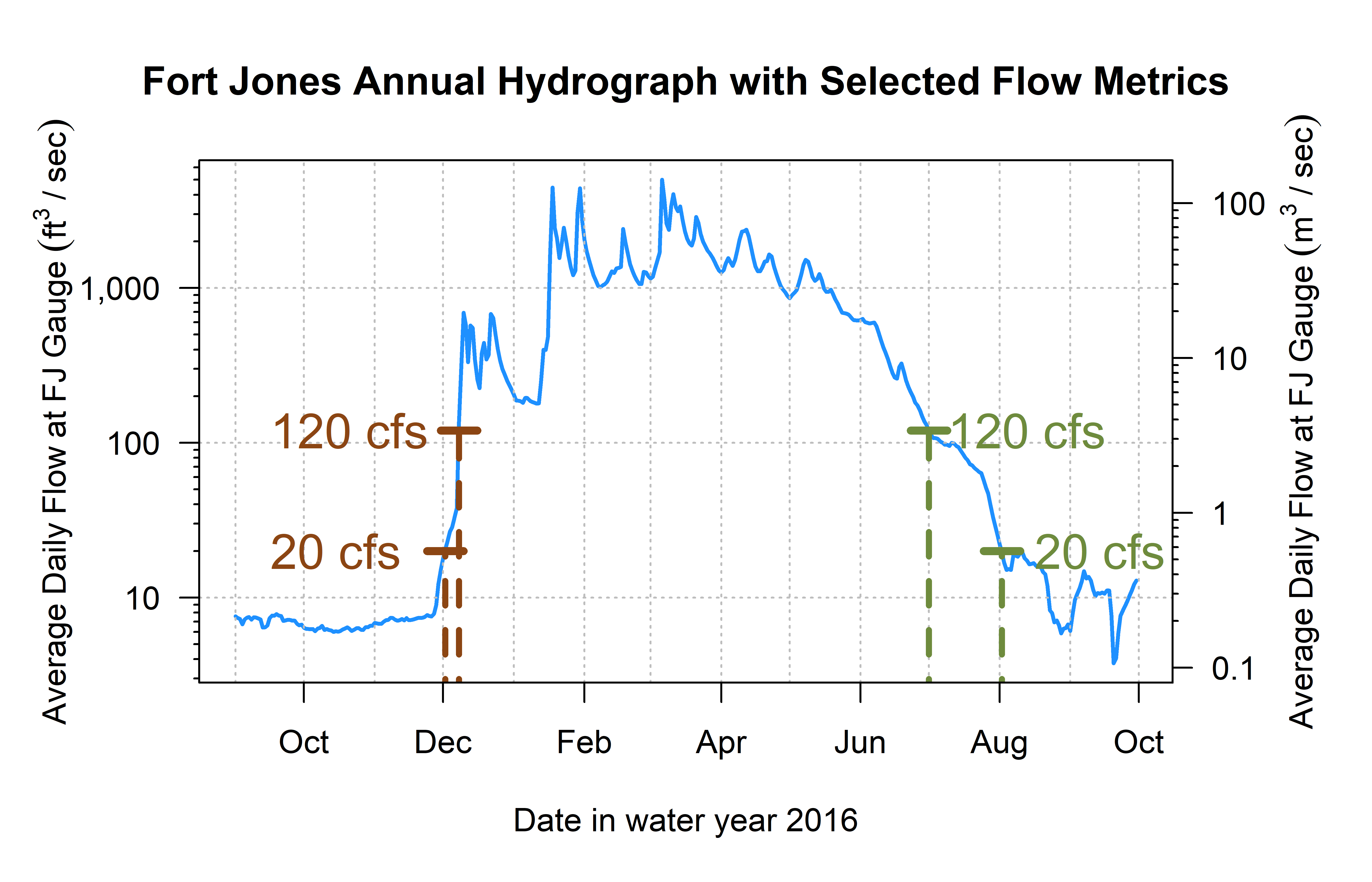


Figure 3: Reconnection and disconnection dates are highlighted for one water year. Two example thresholds, 20 and 120 cfs (0.57 and 3.4 cms, respectively) are highlighted, which correspond to distinct river connectivity (and salmon habitat access) conditions in the Scott River watershed as observed at the Fort Jones gauge (see Results for more detail on selection of flow thresholds).

## 4.3 Screening Predictors for Collinearity

Table 3: Groups of collinear predictors (absolute value of R greater than 0.7), interpretation of their hydrologic significance, and the predictor selected from each group to reduce collinearity.

| Group of Collinear Predictors | Hydrologic Significance (Coho Life Stage) | Predictor Selected from Group |
| --- | --- | --- |
| wy1\_Mean\_Ann\_Flow, s1\_discon\_20, s1\_discon\_40, s1\_discon\_120, f2\_recon\_20, f2\_recon\_40, w1\_Wet\_BFL\_Mag\_10, w1\_Wet\_BFL\_Mag\_50, s1\_SP\_Dur, s1\_SP\_Mag, wy1\_WY\_Cat, d2\_DS\_Tim, d2\_DS\_Mag\_50, d2\_DS\_Mag\_90, w1\_num\_days\_gt\_90\_pctile | How wet was the wet season? (year 1, as eggs and fry) | w1\_Wet\_BFL\_Mag\_50 |
| wy2\_Mean\_Ann\_Flow, s2\_discon\_120, w2\_Wet\_BFL\_Mag\_10, w2\_Wet\_BFL\_Mag\_50, s2\_SP\_Dur, s2\_SP\_Mag, wy2\_WY\_Cat, w2\_num\_days\_gt\_90\_pctile | How wet was the wet season? (year 2, as rearing juv.) | w2\_Wet\_BFL\_Mag\_50 |
| d1\_DS\_Tim, f1\_recon\_20, f1\_recon\_40, d1\_DS\_Dur\_WS, d1\_DS\_Mag\_50 | How dry was the dry season? (pre-spawning) | d1\_DS\_Dur\_WS |
| w1\_Wet\_Tim, d1\_DS\_Dur\_WS, f1\_FA\_Tim, w1\_Wet\_BFL\_Dur | Dry to wet season transition timing (as eggs and fry) | w1\_Wet\_Tim |
| w2\_Wet\_Tim, d2\_DS\_Dur\_WS, f2\_FA\_Tim, w2\_Wet\_BFL\_Dur | Dry to wet season transition timing (juvenile fish) | w2\_Wet\_Tim |
| f1\_FA\_Mag, f1\_FA\_Dif\_num | Fall pulse magnitude (parents' spawning) | f1\_FA\_Dif\_num |
| f2\_FA\_Mag, f2\_FA\_Dif\_num | Fall pulse magnitude (rearing juv.) | f2\_FA\_Dif\_num |

### 4.3.1 Groups 1 and 2

These metrics describe the magnitude and timing of wet-season flows (years 1 and 2), effectively characterized by the question, ‘how wet was the wet season?’ We selected w1\_Wet\_BFL\_Mag\_50 and w2\_Wet\_BFL\_Mag\_50 as the most conceptually central metric to represent the amount of water passing through the watershed during two wet seasons: w1, the first wet season, experienced by a cohort as eggs and newly-hatched alevin and fry, and w2, experienced by the cohort as overwintering parr.

### 4.3.2 Group 3

These metrics describe the magnitude and timing of dry-season flows before the cohort’s spawning. We selected d1\_DS\_Mag\_50 as the most conceptually central metric to represent the amount of water passing through the watershed during the dry season before a cohort’s parents’ spawning.

### 4.3.3 Groups 4 and 5

These metrics quantify the timing of the wet season onset and duration (year 2). We selected w2\_Wet\_Tim, the timing of the onset of the second wet season, and w2\_Wet\_BFL\_Dur, the duration of wet season baseflow, to characterize the timing of the wet season experienced by a cohort of coho as overwintering juveniles.

### 4.3.4 Groups 6 and 7

These metrics quantify the magnitude of the fall pulse flow (years 1 and 2). We selected the fall flow increase FA\_dif\_num (from Baruch et al. 2024) for both years, as it is the only fall flows magnitude metric occurring in every water year, with no missing values.

# 5 Ecological Data Features

## 5.1 Sources and methods

Table 4: Description and source information for ecological observations of the two salmonid species of concern.

| Obs. ID | Abbrev. | Description | Monitoring Details | Source(s) | Predictor Seasons |
| --- | --- | --- | --- | --- | --- |
| A | coho\_spawner\_abundance | Num. coho spawners (escapement) | Scott River Fish Counting Facility | Knechtle and Guidice 2023, CDFW | d1, f1, w1 |
| B | coho\_redds\_in\_brood | Num. obs. coho redds | Spawning ground surveys | Sources in Section 3.2 | d1, f1, w1, s1 |
| C | coho\_smolt\_abun\_est | Est. num. coho smolt | Rotary Screw Trap | Romero and Robinson, 2023 | d1, f1, w1, s1, d2, f2, w2, s2 |
| D | chinook\_spawner\_abundance | Num. Chinook spawners (escapement) | Scott River Fish Counting Facility | Knechtle and Guidice 2023, CDFW | d1, f1, w1 |
| E | chinook\_spawner\_old\_method (NOT USED in this analysis) | Num. Chinook spawners (escapement) | Temporary fish marking weir, 1985-1991; capture-recapture method, 1992-2012; video fish counting facility post-2012 | Knechtle and Chesney 2012 | d1, f1, w1 |
| F | chinook\_juvenile\_abundance | Num. Chinook juveniles | Rotary Screw Trap | Romero and Robinson, 2023 | d1, f1, w1, s1 |
| -- | coho\_smolt\_per\_fem | Coho smolt per fem. spawner | Ratio (C/A) for relevant cohort | Knechtle and Guidice 2023, CDFW | d1, f1, w1, s1, d2, f2, w2, s2 |
| -- | chinook\_juv\_per\_adult | Chinook juv. per adult | Ratio (F/D) for relevant cohort | Knechtle and Guidice 2023, CDFW | d1, f1, w1, s1 |

## 5.2 Autocorrelation in ecological records

Autocorrelation, with a lag of 3, is evident in two ecological records: the abundances of coho redds and coho smolt (Figure 4). In other words, the 3-year-lagged record of coho smolt approaches, and for redds exceeds, the 95% confidence interval that it is not random noise.

Interestingly, for coho spawner abundance, although the sign of the autocorrelation is positive at 3 and 6 year lags (which we would expect, reflecting the cohort structure), autocorrelation in the coho spawner record is weaker than in the redd and smolt records.

No significant autocorrelation is evident in the three Chinook data types, and none is observed for coho smolt per female.

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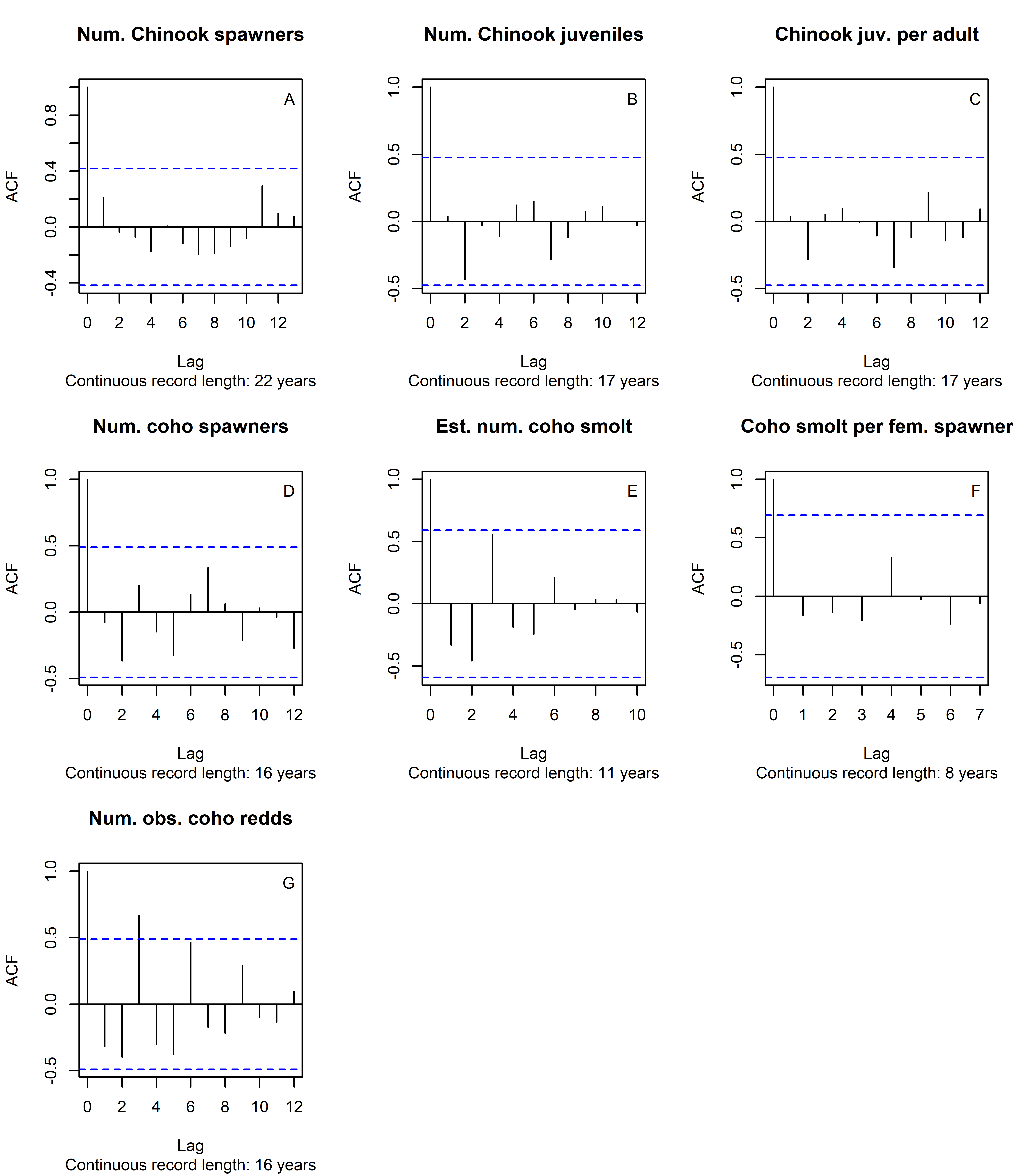


Figure 4: Autocorrelation function estimates for all available ecological outcome records.

# 6 Six statistical modeling structures - method details

**LASSO model of juveniles-per-spawner:** Cross-validation produced a clear minimum-error value for Chinook (Figure 5). For coho, we proposed an alternate lambda value that explained more percent deviance (Figure 5, middle left panel) while retaining a near-minimum test error (Figure 5, top left panel). This produced a model with three non-zero coefficients for both species (Figure 5, lower two panels; Tables 5 and 6)

**LASSO model of juvenile abundance, hydrology and spawners:** the selected predictors included spawners only for Chinook (Tables 9 and 10).

**Lasso model of juvenile abundance, hydrologic metrics only:** replicating the approach for the LASSO model of juveniles-per-spawner, we proposed an alternate lambda value for the coho model (Figure 6). Selected predictors for coho were similar to the juvenile abundance, hydrology-plus-spawners LASSO model, while for Chinook, the minimum-error model selected only one predictor (Tables 7 and 8).

**MARSS models of juveniles-per-spawner, single hydrologic covariate:** hydrology order of importance is taken from the small-sample-size-corrected Akaike Information Criterion (AICc), i.e., the lower the AICc, the better the prediction based on that hydrologic metric (Tables 11 and 12).

**MARSS models of juveniles abundance, single hydrologic covariate:** hydrology order of importance interpreted as described above (Tables 11 and 12); this is used to test the utility of adding spawners as a covariate.

**MARSS models of juvenile abundance, two covariates:** This model structure calculates a coefficient value for spawners and for any single hydrologic metric (Tables 15 and 16). For the four best models, hydrology coefficients are equal to or greater than coefficients for spawners. For worse, higher-AICc models, spawner influence grows to be much greater than the hydrology.

MARSS models tended to perform better at predicting coho than Chinook (Figures 8, 9, and 10, possibly because Chinook records did not contain significant autocorrelation (Figure 4).

# 7 LASSO regression

LASSO (Least Absolute Shrinkage and Selection Operator) regression minimizes the following quantity:

Where:

* is the number of ecological observations;
* enumerates the brood years;
* is the number of predictors;
* enumerates the hydrologic predictors;
* is the observed value of hydrologic predictor for brood year (independent variable);
* is the observed value of ecological response in the salmon cohort with brood year (dependent variable);
* is the intercept value for the resulting linear model;
* is the coefficient value for hydrologic predictor in the resulting linear model; and
* is a tuning parameter, referred to as a shrinkage penalty.

In this formulation, sufficiently large values of lambda generally shrink the values of all coefficients to 0 (the infinite-lambda case). The infinite-lambda case produces a model consisting solely of the intercept term, which takes on a value that is the average of all the observed values. Conversely, sufficiently small values of will produce linear models incorporating information from many predictors. The selection of the appropriate value is a critical step in the regression procedure, and is best done using cross-validation within the training dataset (James et al. 2013).

## 7.1 LASSO results: juveniles-per-spawner based on hydrologic metrics

For purposes of statistical model comparison, we predicted the ratio of juveniles per spawner for coho and Chinook based on a predictor set that included only Z-scored hydrologic metrics.

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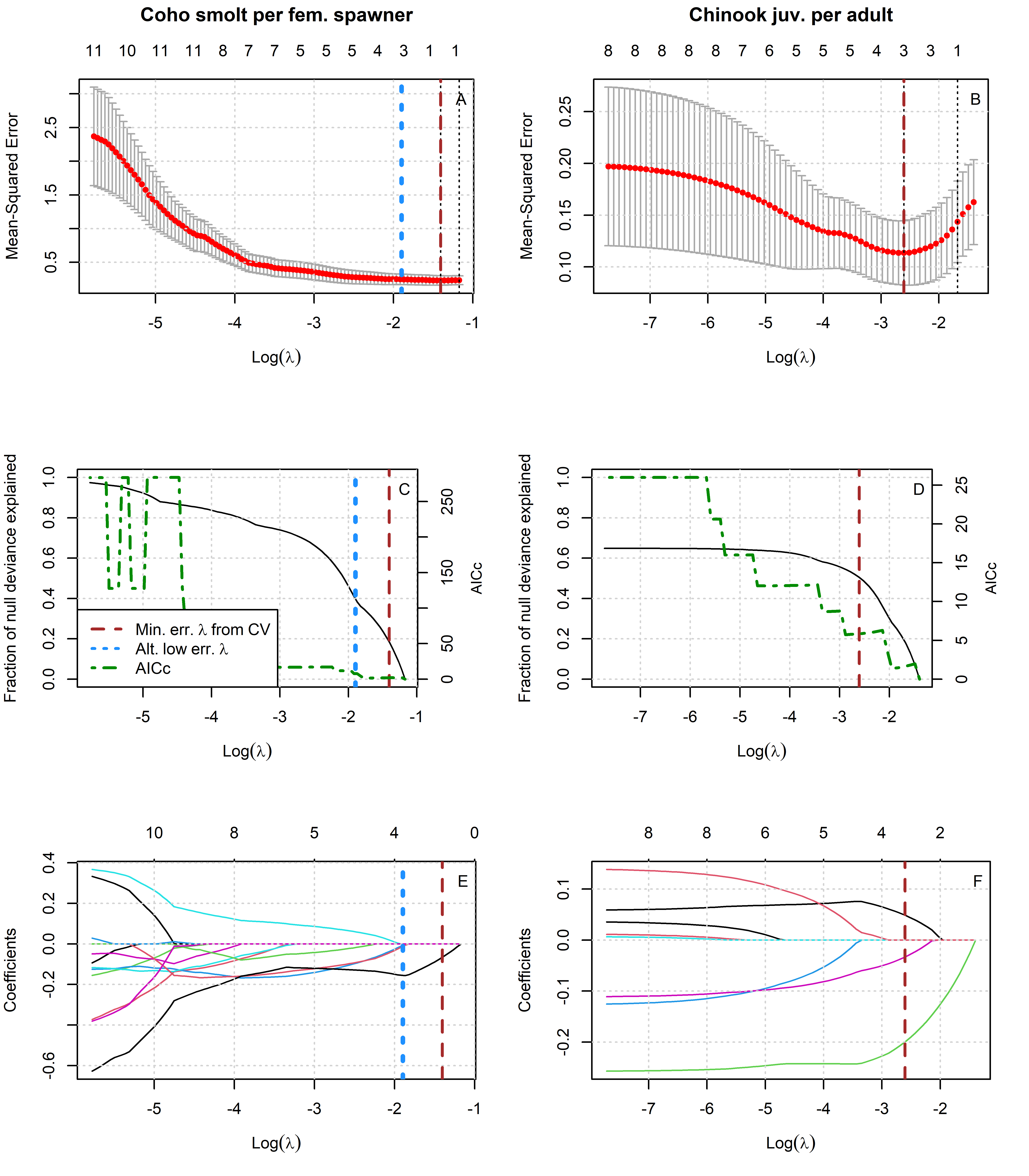


Figure 5: Results of lasso regression to predict log-transformed coho and Chinook outcomes with Z-scored hydrologic metrics. Models with more coefficients explain a greater fraction of deviance in the dataset (middle panel), but also produce higher test errors (top panel), indicating some overfitting at lower lambda values. Higher values of lambda tend to shrink the absolute values of regression coefficients toward 0 (bottom panel).

Table 5: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimated coho spf based on hydrology only, including a description of which phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 1.592 | (Intercept) |
| f1\_recon\_120 | -0.155 | Earlier fall reconnection (during parents' spawning) |
| f2\_FA\_Dif\_num | -0.012 | Smaller fall pulse (as juvenile fish) |
| w1\_Wet\_Tim | -0.007 | Earlier wet season onset (as eggs and fry) |

Table 6: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimatedChinook jpa based on hydrology only, including a description of which hydrologic phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 1.945 | (Intercept) |
| w1\_Wet\_BFL\_Mag\_50 | -0.200 | Smaller wet season baseflows (as eggs and hatchlings) |
| s1\_SP\_Tim | 0.049 | Later spring recession onset (as outmigrating smolt) |
| s1\_SP\_ROC\_Max | -0.033 | Slower max. rate of change, spring recession (as outmigrating smolt) |

## 7.2 LASSO results: juvenile abundance on hydrologic metrics only

For purposes of statistical model comparison, we predicted juvenile abundance of coho and Chinook based on a predictor set that included only Z-scored hydrologic metrics.

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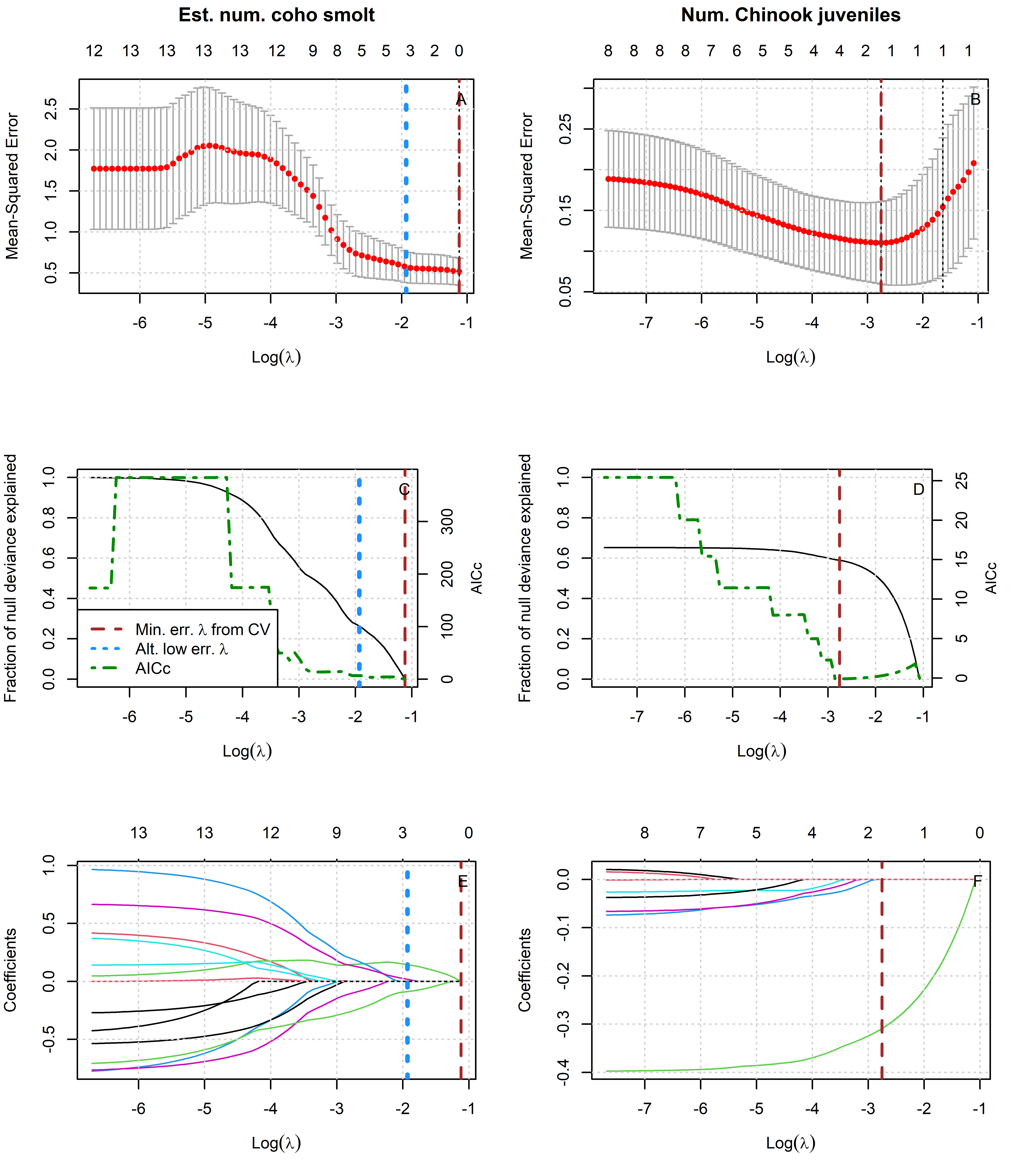


Figure 6: Results of lasso regression to predict log-transformed coho and Chinook outcomes with Z-scored hydrologic metrics. Models with more coefficients explain a greater fraction of deviance in the dataset (middle panel), but also produce higher test errors (top panel), indicating some overfitting at lower lambda values. Higher values of lambda tend to shrink the absolute values of regression coefficients toward 0 (bottom panel).

Table 7: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimated coho smolt abundance based on hydrology only, including a description of which phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 3.901 | (Intercept) |
| f1\_FA\_Dif\_num | 0.145 | Larger fall flow increase (during parents' spawning) |
| f2\_FA\_Dif\_num | -0.088 | Smaller fall flow increase (as juvenile fish) |
| s2\_SP\_ROC | 0.019 | Faster rate of change, spring recession (as outmigrating smolt) |

Table 8: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimatedChinook juv. abundance based on hydrology only, including a description of which hydrologic phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 5.450 | (Intercept) |
| w1\_Wet\_BFL\_Mag\_50 | -0.309 | Lower wet season baseflows (as eggs and hatchlings) |

## 7.3 LASSO results: juvenile abundance on hydrologic metrics and spawner abundance

For purposes of statistical model comparison, we predicted juvenile abundance of coho and Chinook based on a predictor set that included Z-scored hydrologic metrics as well as Z-scored spawner abundances.

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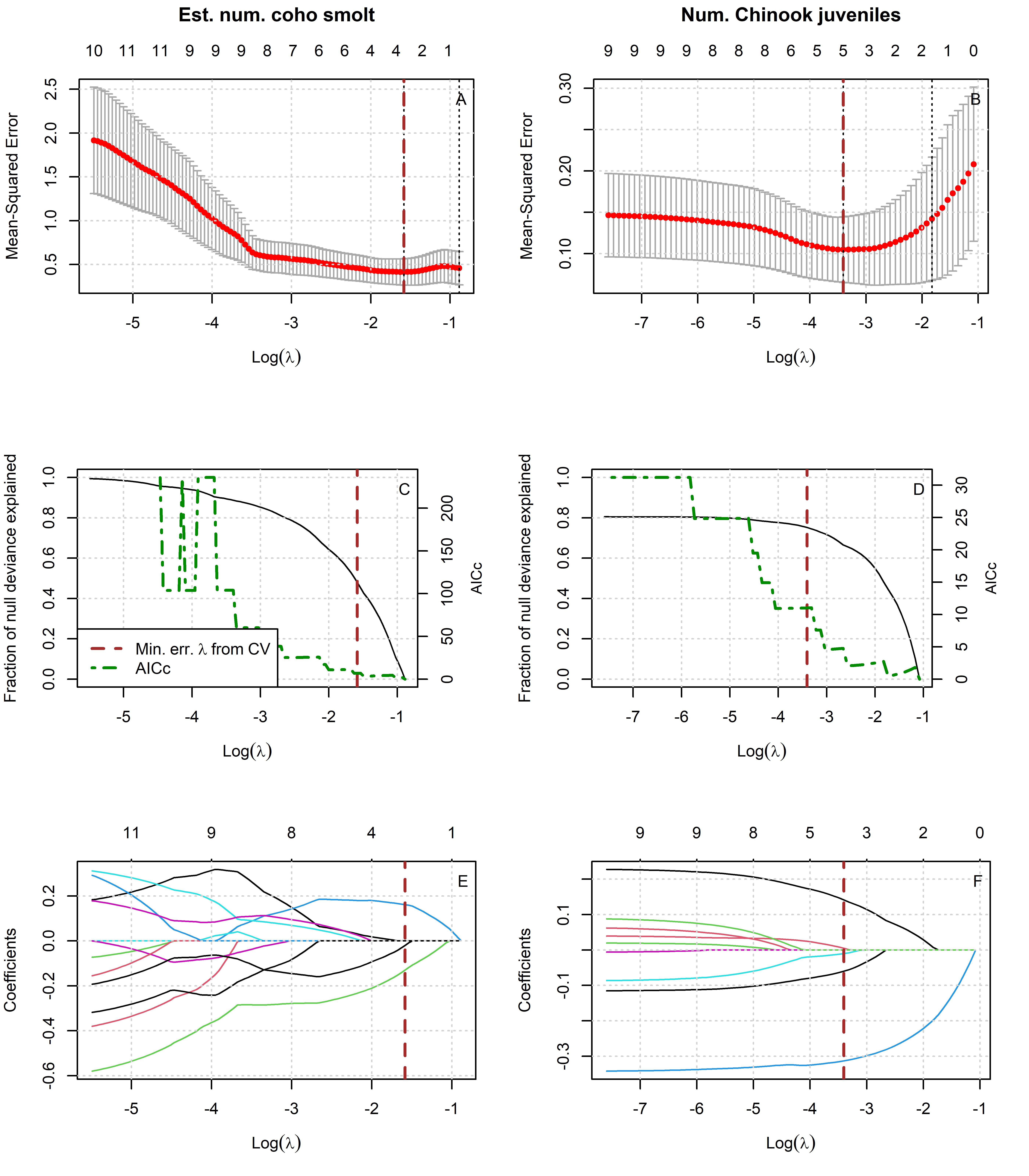


Figure 7: Results of lasso regression to predict log-transformed coho and Chinook outcomes with Z-scored hydrologic metrics and spawner abundance.

Table 9: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimated coho smolt abundance based on hydrologic metrics and spawner abundance, including a description of which phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 3.872 | (Intercept) |
| f1\_FA\_Dif\_num | 0.162 | Larger fall flow increase (during parents' spawning) |
| f2\_FA\_Dif\_num | -0.130 | Smaller fall flow increase (as juvenile fish) |
| s1\_SP\_ROC | -0.020 | Slower rate of change, spring recession (as recent hatchlings) |

Table 10: Values for the intercept and coefficient terms in the Hydrologic Benefit function for estimatedChinook juv. abundance based on hydrologic metrics and spawner abundance, including a description of which hydrologic phenomena are associated with higher ecological outcome values.

| Predictor | Value | Greater Hydrologic Benefit value associated with |
| --- | --- | --- |
|  | 5.442 | (Intercept) |
| w1\_Wet\_BFL\_Mag\_50 | -0.313 | Lower wet season baseflows (as eggs and hatchlings) |
| chinook\_spawners\_zscored | 0.142 | Abundance of spawners (parents of designated cohort) |
| s1\_SP\_ROC\_Max | -0.060 | Slower max. rate of change, spring recession (as outmigrating smolt) |
| w1\_Wet\_Tim | -0.010 | -0.01 |
| s1\_SP\_Tim | 0.005 | 0.005 |

# 8 MARSS Models

## 8.1 MARSS models of juveniles per spawner, single hydrologic covariate

For purposes of statistical model comparison, we calculated multiple MARSS models (15 for coho and 8 for Chinook) that predicted the observed ratio of juveniles-per-spawner for coho and Chinook based on a single Z-scored hydrologic metric.

Table 11: Each row corresponds to a MARSS model predicting the time series of coho spf observations using itself (up to time t) and one hydrologic metric covariate. Coefficient sign and value indicate the direction and strength of the influence of the hydrologic metric; i.e., a negative coefficient for hydrologic metric f1\_recon\_120 indicates that an earlier first fall river reconnection (120 cfs) is associated with a greater coho spf value. Models are listed in order from best (lowest AICc value) to worst. Values marked with -- indicate that gaps in the time series for the hydrologic metric prevented the calculation of a model using that covariate.

| Covariate | Coefficient | AICc |
| --- | --- | --- |
| f1\_recon\_120 | -0.403 | 21.24 |
| f1\_FA\_Dif\_num | 0.306 | 23.13 |
| w1\_Wet\_BFL\_Mag\_50 | 0.136 | 26.46 |
| d1\_DS\_Mag\_90 | 0.102 | 27.05 |
| s2\_SP\_ROC\_Max | -0.093 | 27.34 |
| f2\_recon\_120 | -0.173 | 27.5 |
| s2\_SP\_ROC | 0.085 | 27.55 |
| w2\_Wet\_BFL\_Mag\_50 | 0.085 | 27.93 |
| s1\_SP\_ROC\_Max | 0.046 | 28.25 |
| s2\_SP\_Tim | 0.029 | 28.26 |
| w1\_Wet\_Tim | -0.025 | 28.45 |
| w2\_Wet\_Tim | -0.023 | 28.47 |
| f2\_FA\_Dif\_num | 0.036 | 28.5 |
| s1\_SP\_Tim | -0.005 | 28.55 |
| s1\_SP\_ROC | 0.007 | 28.55 |
| f1\_FA\_Dur | -- | -- |
| f2\_FA\_Dur | -- | -- |

Table 12: Each row corresponds to a MARSS model predicting the time series of Chinook jpa observations using itself (up to time t) and one hydrologic metric covariate. Coefficient sign and value indicate the direction and strength of the influence of the hydrologic metric; i.e., a negative coefficient for hydrologic metric f1\_recon\_120 indicates that an earlier first fall river reconnection (120 cfs) is associated with a greater Chinook jpa value. Models are listed in order from best (lowest AICc value) to worst. Values marked with -- indicate that gaps in the time series for the hydrologic metric prevented the calculation of a model using that covariate.

| Covariate | Coefficient | AICc |
| --- | --- | --- |
| d1\_DS\_Mag\_90 | 0.069 | 28.91 |
| s1\_SP\_ROC\_Max | -0.057 | 29.17 |
| s1\_SP\_Tim | -0.026 | 29.57 |
| f1\_recon\_120 | -0.039 | 29.61 |
| w1\_Wet\_BFL\_Mag\_50 | 0.031 | 29.74 |
| w1\_Wet\_Tim | 0.006 | 29.88 |
| f1\_FA\_Dif\_num | -0.013 | 29.88 |
| s1\_SP\_ROC | 0.002 | 29.89 |
| f1\_FA\_Dur | -- | -- |

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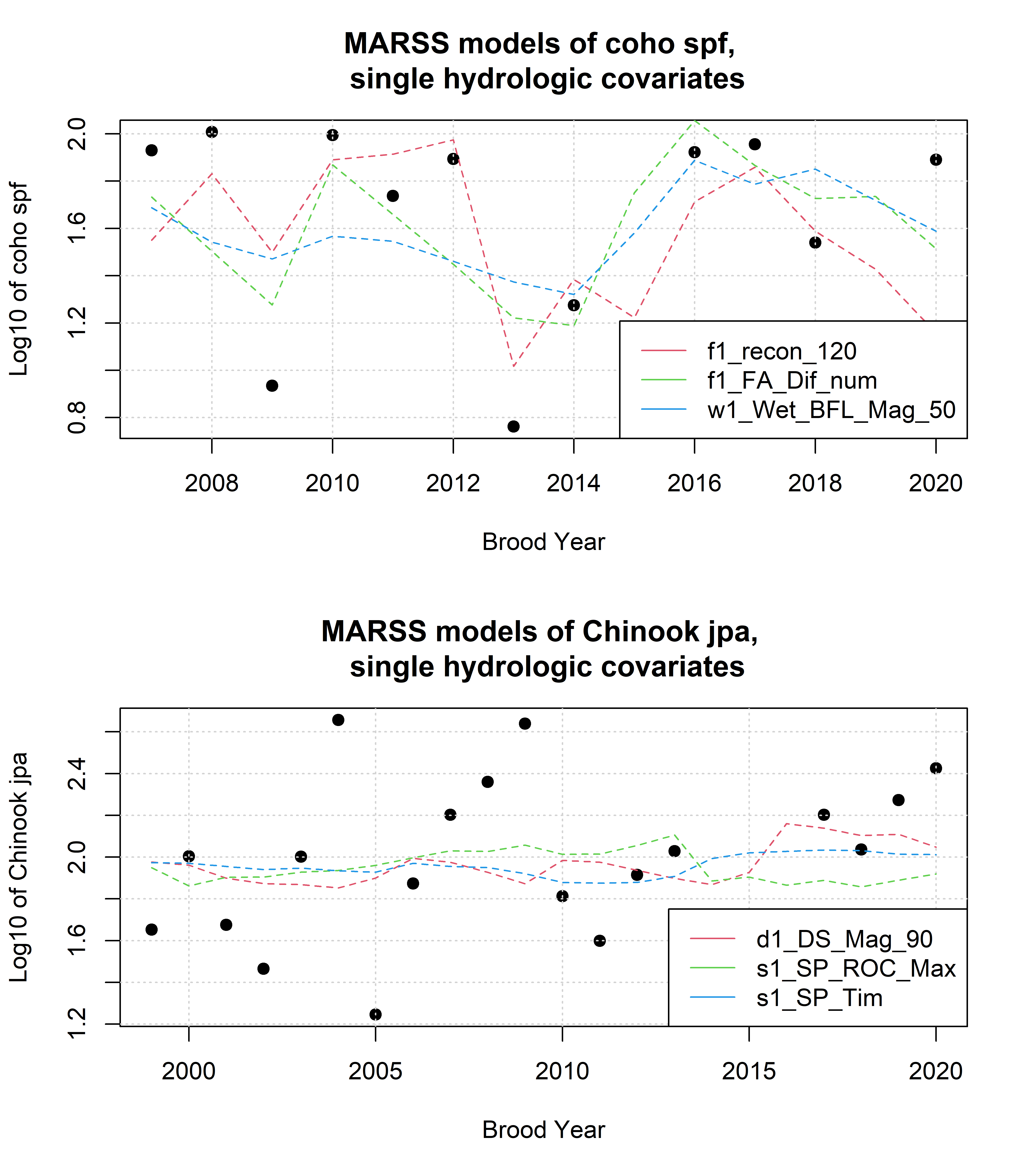


Figure 8: Results of the three best single-hydrologic-covariate MARSS models to predict log-transformed Chinook and coho juvenile-per-spawners ratios with Z-scored hydrologic metrics.

## 8.2 MARSS models of juveniles abundance, single hydrologic covariate

For purposes of statistical model comparison, we calculated multiple MARSS models (15 for coho and 8 for Chinook) that predicted juvenile abundance for coho and Chinook based on a single Z-scored hydrologic metric.

Table 13: Each row corresponds to a MARSS model predicting the time series of coho smolt abundance observations using itself (up to time t) and one hydrologic metric covariate. Coefficient sign and value indicate the direction and strength of the influence of the hydrologic metric; i.e., a negative coefficient for hydrologic metric f1\_recon\_120 indicates that an earlier first fall river reconnection (120 cfs) is associated with a greater coho smolt abundance value. Models are listed in order from best (lowest AICc value) to worst. Values marked with -- indicate that gaps in the time series for the hydrologic metric prevented the calculation of a model using that covariate.

| Covariate | Coefficient | AICc |
| --- | --- | --- |
| f1\_FA\_Dif\_num | 0.206 | 40.37 |
| f2\_FA\_Dif\_num | -0.136 | 41.55 |
| w2\_Wet\_BFL\_Mag\_50 | 0.08 | 41.74 |
| d1\_DS\_Mag\_90 | 0.058 | 41.78 |
| s1\_SP\_ROC\_Max | 0.061 | 41.78 |
| s2\_SP\_ROC\_Max | 0.06 | 41.8 |
| w1\_Wet\_BFL\_Mag\_50 | 0.059 | 41.83 |
| s2\_SP\_ROC | 0.045 | 41.83 |
| w2\_Wet\_Tim | 0.039 | 41.88 |
| s1\_SP\_Tim | 0.023 | 41.94 |
| s1\_SP\_ROC | -0.017 | 41.98 |
| f1\_recon\_120 | -0.035 | 41.98 |
| f2\_recon\_120 | -0.018 | 42.01 |
| w1\_Wet\_Tim | 0.007 | 42.01 |
| s2\_SP\_Tim | -0.002 | 42.02 |
| f1\_FA\_Dur | -- | -- |
| f2\_FA\_Dur | -- | -- |

Table 14: Each row corresponds to a MARSS model predicting the time series of Chinook juv. abundance observations using itself (up to time t) and one hydrologic metric covariate. Coefficient sign and value indicate the direction and strength of the influence of the hydrologic metric; i.e., a negative coefficient for hydrologic metric f1\_recon\_120 indicates that an earlier first fall river reconnection (120 cfs) is associated with a greater Chinook juv. abundance value. Models are listed in order from best (lowest AICc value) to worst. Values marked with -- indicate that gaps in the time series for the hydrologic metric prevented the calculation of a model using that covariate.

| Covariate | Coefficient | AICc |
| --- | --- | --- |
| w1\_Wet\_BFL\_Mag\_50 | -0.135 | 32.65 |
| s1\_SP\_ROC\_Max | -0.106 | 33.11 |
| w1\_Wet\_Tim | -0.043 | 34.44 |
| f1\_recon\_120 | -0.062 | 34.5 |
| f1\_FA\_Dif\_num | -0.053 | 34.85 |
| s1\_SP\_Tim | 0.019 | 34.94 |
| s1\_SP\_ROC | 0.007 | 35.06 |
| d1\_DS\_Mag\_90 | -0.006 | 35.08 |
| f1\_FA\_Dur | -- | -- |

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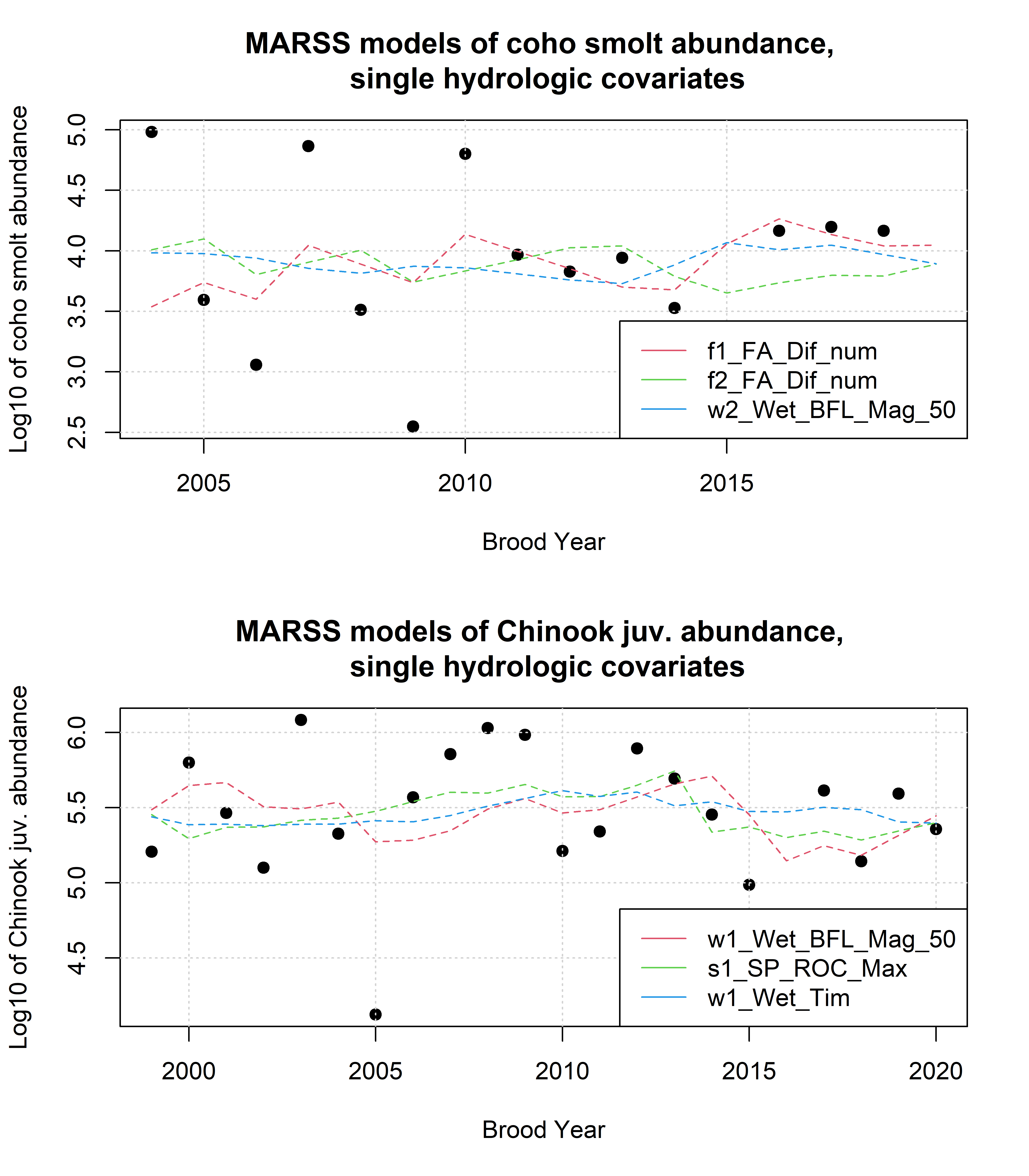


Figure 9: Results of the three best single-hydrologic-covariate MARSS models to predict log-transformed Chinook and coho outcomes with Z-scored hydrologic metrics.

## 8.3 MARSS models of juvenile abundance, two covariates (spawner abundance and one hydrologic)

For purposes of statistical model comparison, we calculated multiple MARSS models (15 for coho and 8 for Chinook) that predicted juvenile abundance for coho and Chinook based on a single Z-scored hydrologic metric and Z-scored parental spawner abundance; thus, coefficients were calculated for both the hydrology and spawner covariates.

Table 15: Characteristics of MARSS models of coho smolt abundance using one hydrologic metric and Z-scored spawner abundance as the two covariates in each model.

| Hydrologic Covariate | AICc | Hydro Coef. | Spawner Coef. | Hyd. / Sp. |
| --- | --- | --- | --- | --- |
| f1\_FA\_Dif\_num | 32.11 | 0.550 | 0.374 | 1.5 |
| f1\_recon\_120 | 37.67 | -0.605 | 0.452 | -1.3 |
| d1\_DS\_Mag\_90 | 38.16 | 0.229 | 0.338 | 0.7 |
| w1\_Wet\_BFL\_Mag\_50 | 38.27 | 0.245 | 0.301 | 0.8 |
| f2\_recon\_120 | 40.62 | -0.237 | 0.161 | -1.5 |
| w2\_Wet\_BFL\_Mag\_50 | 41.18 | 0.110 | 0.201 | 0.5 |
| s1\_SP\_ROC | 41.32 | -0.065 | 0.160 | -0.4 |
| s1\_SP\_ROC\_Max | 41.50 | 0.052 | 0.186 | 0.3 |
| w2\_Wet\_Tim | 41.50 | 0.049 | 0.176 | 0.3 |
| f2\_FA\_Dif\_num | 41.65 | -0.040 | 0.160 | -0.2 |
| w1\_Wet\_Tim | 41.66 | -0.021 | 0.171 | -0.1 |
| s2\_SP\_ROC | 41.66 | 0.017 | 0.169 | 0.1 |
| s2\_SP\_Tim | 41.67 | -0.010 | 0.159 | -0.1 |
| s1\_SP\_Tim | 41.67 | 0.007 | 0.165 | 0.0 |
| s2\_SP\_ROC\_Max | 41.68 | -0.004 | 0.167 | 0.0 |
| f1\_FA\_Dur |  |  |  |  |
| f2\_FA\_Dur |  |  |  |  |

Table 16: Characteristics of MARSS models of Chinook juv. abundance using one hydrologic metric and Z-scored spawner abundance as the two covariates in each model.

| Hydrologic Covariate | AICc | Hydro Coef. | Spawner Coef. | HtoS\_ratio |
| --- | --- | --- | --- | --- |
| s1\_SP\_ROC\_Max | 36.03 | -0.116 | 0.0573 | -2.0 |
| w1\_Wet\_BFL\_Mag\_50 | 36.06 | -0.132 | 0.0209 | -6.3 |
| f1\_recon\_120 | 37.77 | -0.062 | 0.0361 | -1.7 |
| w1\_Wet\_Tim | 37.80 | -0.040 | 0.0287 | -1.4 |
| s1\_SP\_Tim | 38.08 | 0.028 | 0.0482 | 0.6 |
| f1\_FA\_Dif\_num | 38.18 | -0.046 | 0.0318 | -1.4 |
| s1\_SP\_ROC | 38.19 | 0.021 | 0.0528 | 0.4 |
| d1\_DS\_Mag\_90 | 38.35 | 0.004 | 0.0378 | 0.1 |
| f2\_recon\_120 |  |  |  |  |
| f1\_FA\_Dur |  |  |  |  |
| f2\_FA\_Dur |  |  |  |  |
| f2\_FA\_Dif\_num |  |  |  |  |
| w2\_Wet\_BFL\_Mag\_50 |  |  |  |  |
| w2\_Wet\_Tim |  |  |  |  |
| s2\_SP\_ROC |  |  |  |  |
| s2\_SP\_ROC\_Max |  |  |  |  |
| s2\_SP\_Tim |  |  |  |  |

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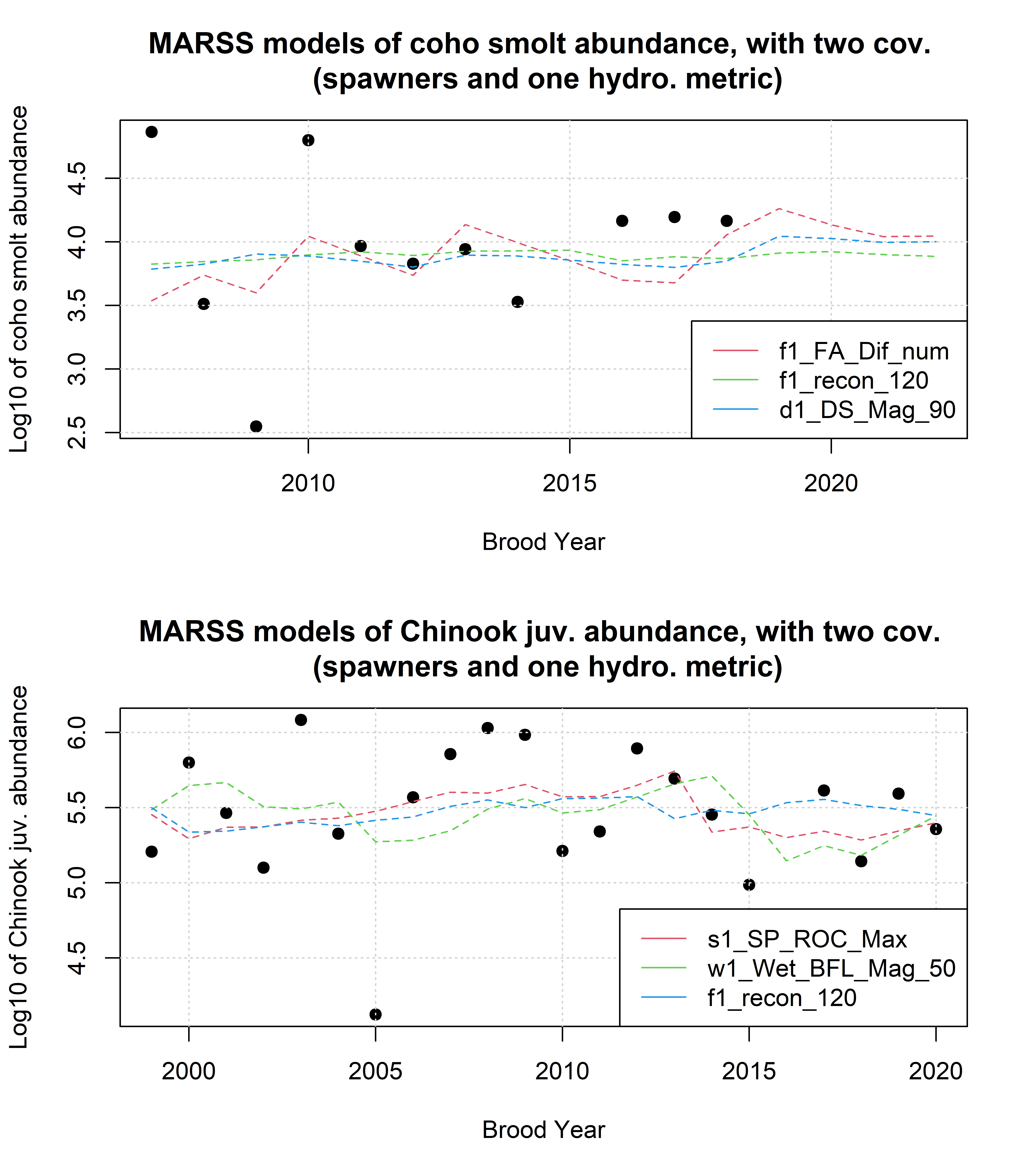


Figure 10: Results of MARSS to predict log-transformed juvenile abundance for coho and Chinook outcomes with Z-scored hydrologic metrics plus spawner data.

# References

Acero Triana, Juan S., Maria L. Chu, and Jeffrey A. Stein. 2021. “Assessing the Impacts of Agricultural Conservation Practices on Freshwater Biodiversity Under Changing Climate.” *Ecological Modelling* 453 (August): 109604. <https://doi.org/10.1016/j.ecolmodel.2021.109604>.

Acreman, Mike, Angela H. Arthington, Matthew J Colloff, Carol Couch, Neville D Crossman, Fiona Dyer, Ian Overton, Carmel A Pollino, Michael J Stewardson, and William Young. 2014. “Environmental Flows for Natural, Hybrid, and Novel Riverine Ecosystems in a Changing World.” *Frontiers in Ecology and the Environment* 12 (8): 466–73. <https://doi.org/10.1890/130134>.

Agrawal, A, R S Schick, E P Bjorkstedt, R G Szerlong, M N Goslin, B C Spence, T H Williams, and K M Burnett. 2005. “PREDICTING THE POTENTIAL FOR HISTORICAL COHO, CHINOOK AND STEELHEAD HABITAT IN NORTHERN CALIFORNIA.” National Marine Fisheries Service.

Alomía Herrera, Ilia, and Patricia Carrera Burneo. 2017. “Environmental Flow Assessment in Andean Rivers of Ecuador, Case Study: Chanlud and El Labrado Dams in the Machángara River.” *Ecohydrology & Hydrobiology* 17 (2): 103–12. <https://doi.org/10.1016/j.ecohyd.2017.01.002>.

Anderson, Kurt E., Andrew J. Paul, Edward McCauley, Leland J. Jackson, John R. Post, and Roger M. Nisbet. 2006. “Instream Flow Needs in Streams and Rivers: The Importance of Understanding Ecological Dynamics.” *Frontiers in Ecology and the Environment* 4 (6): 309–18. <https://doi.org/10.1890/1540-9295(2006)4[309:IFNISA]2.0.CO;2>.

Arriana Brand, L., Juliet C. Stromberg, David C. Goodrich, Mark D. Dixon, Kevin Lansey, Doosun Kang, David S. Brookshire, and David J. Cerasale. 2011. “Projecting Avian Response to Linked Changes in Groundwater and Riparian Floodplain Vegetation Along a Dryland River: A Scenario Analysis.” *Ecohydrology* 4 (1): 130–42. <https://doi.org/10.1002/eco.143>.

Arthington, Angela H., J. M. Bernardo, and M. Ilhéu. 2014. “TEMPORARY RIVERS: LINKING ECOHYDROLOGY, ECOLOGICAL QUALITY AND RECONCILIATION ECOLOGY.” *River Research and Applications* 30 (10): 1209–15. <https://doi.org/10.1002/rra.2831>.

Ayllón, Daniel, Graciela G. Nicola, Irene Parra, Benigno Elvira, and Ana Almodóvar. 2014. “Spatio-Temporal Habitat Selection Shifts in Brown Trout Populations Under Contrasting Natural Flow Regimes.” *Ecohydrology* 7 (2): 569–79. <https://doi.org/10.1002/eco.1379>.

Baruch, Ethan M., Sarah M. Yarnell, Theodore E. Grantham, Jessica R. Ayers, Andrew L. Rypel, and Robert A. Lusardi. 2024. “Mimicking Functional Elements of the Natural Flow Regime Promotes Native Fish Recovery in a Regulated River.” *Ecological Applications* 34 (6): e3013. <https://doi.org/10.1002/eap.3013>.

Booth, Derek B., Yantao Cui, Zooey Diggory, Dirk Pedersen, Jordan Kear, and Michael Bowen. 2014. “Determining Appropriate Instream Flows for Anadromous Fish Passage on an Intermittent Mainstem River, Coastal Southern California, USA.” *Ecohydrology* 7 (2): 745–59. <https://doi.org/10.1002/eco.1396>.

Bourret, Samuel L., Christopher C. Caudill, and Matthew L. Keefer. 2016. “Diversity of Juvenile Chinook Salmon Life History Pathways.” *Reviews in Fish Biology and Fisheries* 26 (3): 375–403. <https://doi.org/10.1007/s11160-016-9432-3>.

Bower, Luke M., Brandon K. Peoples, Michele C. Eddy, and Mark C. Scott. 2022. “Quantifying Flow–Ecology Relationships Across Flow Regime Class and Ecoregions in South Carolina.” *Science of The Total Environment* 802 (January): 149721. <https://doi.org/10.1016/j.scitotenv.2021.149721>.

Bradford, Michael J., Garth C. Taylor, and J. Andrew Allan. 1997. “Empirical Review of Coho Salmon Smolt Abundance and the Prediction of Smolt Production at the Regional Level.” *Transactions of the American Fisheries Society* 126 (1): 49–64. <https://doi.org/10.1577/1548-8659(1997)126<0049:EROCSS>2.3.CO;2>.

Bradley, D. C., M. J. Streetly, D. Cadman, M. Dunscombe, E. Farren, and A. Banham. 2017. “A Hydroecological Model to Assess the Relative Effects of Groundwater Abstraction and Fine Sediment Pressures on Riverine Macro-Invertebrates.” *River Research and Applications* 33 (10): 1630–41. <https://doi.org/10.1002/rra.3191>.

Brown, Larry R., Peter B. Moyle, and Ronald M. Yoshiyama. 1994. “Historical Decline and Current Status of Coho Salmon in California.” *North American Journal of Fisheries Management* 14 (2): 237–61. <https://doi.org/10.1577/1548-8675(1994)014<0237:HDACSO>2.3.CO;2>.

Brummer, T. J., A. E. Byrom, J. J. Sullivan, and P. E. Hulme. 2016. “A Quantitative Framework to Derive Robust Characterization of Hydrological Gradients: Framework for Robust Design of Flow-Ecology Studies.” *River Research and Applications* 32 (7): 1517–29. <https://doi.org/10.1002/rra.3001>.

Bunn, Stuart E., and Angela H. Arthington. 2002. “Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity.” *Environmental Management* 30 (4): 492–507. <https://doi.org/10.1007/s00267-002-2737-0>.

Bustard, David R., and David W. Narver. 1975. “Aspects Ofthe Winter Ecology of Juvenile Coho Sahnon (Oncorhynchus Kisutch) and Steelhead Trout (Salmo Gairdneri).” *Journal of the Fisheries Resources Board of Canada* 32 (5): 667–80. <https://doi.org/10.1139/f75-086>.

California Department of Fish and Wildlife. 2021. “Scott River Best Available Scientific Information for Instream Flow Criteria.”

California Department of Fish and Wildlife, NOAA-Fisheries, Scott River Water Trust, Siskiyou Resource Conservation District, and U.S. Forest Service - Klamath National Forest. 2015. “Cooperative Scott River Coho Rescue & Relocation Effort: 2014 Drought Emergency.”

Cartwright, Jennifer, Casey Caldwell, Steven Nebiker, and Rodney Knight. 2017. “Putting Flow–Ecology Relationships into Practice: A Decision-Support System to Assess Fish Community Response to Water-Management Scenarios.” *Water* 9 (3): 196. <https://doi.org/10.3390/w9030196>.

Catford, Jane A., William K. Morris, Peter A. Vesk, Christopher J. Gippel, and Barbara J. Downes. 2014. “Species and Environmental Characteristics Point to Flow Regulation and Drought as Drivers of Riparian Plant Invasion.” Edited by Jeffrey Diez. *Diversity and Distributions* 20 (9): 1084–96. <https://doi.org/10.1111/ddi.12225>.

Chowdhury, Shahadat, and Patrick Driver. 2007. “An Ecohydrological Model of Waterbird Nesting Events to Altered Floodplain Hydrology.” In *MODSIM 2007 International Congress on Modelling and Simulation*, 2896–2902. Modeling and Simulation Society of Australia and New Zealand.

Coordinated Resource Management Planning Committee, and Scott River Watershed Council. 2000. “FINAL REPORT.”

Daneshvar, Fariborz, Amir Pouyan Nejadhashemi, Matthew R. Herman, and Mohammad Abouali. 2017. “Response of Benthic Macroinvertebrate Communities to Climate Change.” *Ecohydrology & Hydrobiology* 17 (1): 63–72. <https://doi.org/10.1016/j.ecohyd.2016.12.002>.

DeWeber, J. Tyrell, and James T. Peterson. 2020. “Comparing Environmental Flow Implementation Options with Structured Decision Making: Case Study from the Willamette River, Oregon.” *JAWRA Journal of the American Water Resources Association* 56 (4): 599–614. <https://doi.org/10.1111/1752-1688.12845>.

Gao, Ye, Yong-hong Xie, and Dong-sheng Zou. 2020. “Hydrological Regime Change and Its Ecological Responses in East Dongting Lake, China.” *Ecohydrology & Hydrobiology* 20 (1): 142–50. <https://doi.org/10.1016/j.ecohyd.2019.07.003>.

Groot, Cornelis, and Leo Margolis, eds. 1991. “Life History of Chinook Salmon (Onchorhynchus Tshawytscha).” In *Pacific Salmon Life Histories*. Vancouver: UBC Press.

Guareschi, S., A. Laini, E. Racchetti, T. Bo, S. Fenoglio, and M. Bartoli. 2014. “How Do Hydromorphological Constraints and Regulated Flows Govern Macroinvertebrate Communities Along an Entire Lowland River?” *Ecohydrology* 7 (2): 366–77. <https://doi.org/10.1002/eco.1354>.

Guedes, Gustavo Henrique Soares, Tailan Moretti Mattos, Geysa Da Silva Camilo, Wagner Uehara, Débora Lisandra De Paiva Ferreira, and Francisco Gerson Araújo. 2020. “Artificial Flow Regime Promotes Abiotic and Biotic Gradients: Testing the Concept of Longitudinal Zonation in an Off-River Reservoir.” *Ecohydrology & Hydrobiology* 20 (2): 256–64. <https://doi.org/10.1016/j.ecohyd.2020.02.002>.

Hain, Ernie F., Jonathan G. Kennen, Peter V. Caldwell, Stacy A. C. Nelson, Ge Sun, and Steven G. McNulty. 2018. “Using Regional Scale Flow–Ecology Modeling to Identify Catchments Where Fish Assemblages Are Most Vulnerable to Changes in Water Availability.” *Freshwater Biology* 63 (8): 928–45. <https://doi.org/10.1111/fwb.13048>.

Hale, Robin, Jian D. L. Yen, Charles R. Todd, Ivor G. Stuart, Henry F. Wootton, Jason D. Thiem, John D. Koehn, et al. 2023. “Is My Model Fit for Purpose? Validating a Population Model for Predicting Freshwater Fish Responses to Flow Management.” *Ecosphere* 14 (9): e4660. <https://doi.org/10.1002/ecs2.4660>.

Han, Ming, Chengyi Zhao, Gary Feng, Markus Disse, Fengzhi Shi, and Juyan Li. 2015. “An Eco-Hydrological Approach to Predicting Regional Vegetation and Groundwater Response to Ecological Water Conveyance in Dryland Riparian Ecosystems.” *Quaternary International* 380–381 (September): 224–36. <https://doi.org/10.1016/j.quaint.2015.02.032>.

Harter, Thomas, and Ryan Hines. 2008. “SCOTT VALLEY COMMUNITY GROUNDWATER STUDY PLAN.” University of California, Davis.

Herbst, David B., Scott D. Cooper, Robert Bruce Medhurst, Sheila W. Wiseman, and Carolyn T. Hunsaker. 2019. “Drought Ecohydrology Alters the Structure and Function of Benthic Invertebrate Communities in Mountain Streams.” *Freshwater Biology* 64 (5): 886–902. <https://doi.org/10.1111/fwb.13270>.

Hunt, Sharon L, Timothy J Mulligan, and Kenichiro Komori. 1999. “Oceanic Feeding Habits of Chinook Salmon, Oncorhynchus Tshawytscha, Off Northern Californi.” *Fishery Bulletin* 97 (3): 717–21.

James, Gareth, Daniela Witten, Trevor Hastie, and Robert Tibshirani. 2013. *An Introduction to Statistical Learning*. Vol. 103. Springer Texts in Statistics. New York, NY: Springer New York. <https://doi.org/10.1007/978-1-4614-7138-7>.

Kevic, Maja, Johannes Ortlepp, Uta Mürle, and Christopher T. Robinson. 2018. “Effects of Experimental Floods in Two Rivers with Contrasting Valley Morphologies.” *Fundamental and Applied Limnology* 192 (2): 145–60. <https://doi.org/10.1127/fal/2018/1177>.

Knechtle, Morgan, and Domenic Giudice. 2020. “2019 SCOTT RIVER SALMON STUDIES FINAL REPORT.” California Department of Fish and Wildlife.

Konrad, Christopher P., Julian D. Olden, David A. Lytle, Theodore S. Melis, John C. Schmidt, Erin N. Bray, Mary C. Freeman, et al. 2011. “Large-Scale Flow Experiments for Managing River Systems.” *BioScience* 61 (12): 948–59. <https://doi.org/10.1525/bio.2011.61.12.5>.

Lamouroux, Nicolas, and Jean-Michel Olivier. 2015. “Testing Predictions of Changes in Fish Abundance and Community Structure After Flow Restoration in Four Reaches of a Large River ( F Rench R hône).” *Freshwater Biology* 60 (6): 1118–30. <https://doi.org/10.1111/fwb.12324>.

Lancaster, Jill, and Barbara J. Downes. 2010. “Linking the Hydraulic World of Individual Organisms to Ecological Processes: Putting Ecology into Ecohydraulics.” *River Research and Applications* 26 (4): 385–403. <https://doi.org/10.1002/rra.1274>.

Larsen, Stefano, Bruno Majone, Patrick Zulian, Elisa Stella, Alberto Bellin, Maria Cristina Bruno, and Guido Zolezzi. 2021. “Combining Hydrologic Simulations and Stream-Network Models to Reveal Flow-Ecology Relationships in a Large Alpine Catchment.” *Water Resources Research* 57 (4): e2020WR028496. <https://doi.org/10.1029/2020WR028496>.

Lueders, Mark B., and Ryan A. McManamay. 2023. “Species Depletion Profiles as an Alternative to Streamflow Alteration Thresholds in a Hydroecological Risk Assessment.” *Ecological Indicators* 147 (March): 109989. <https://doi.org/10.1016/j.ecolind.2023.109989>.

Mack, Seymour. 1958. “Geology and Ground-Water Features of Scott Valley, Siskiyou County, California.” Geological {{Survey Water-Supply Paper}} 1462. United States Geological Survey. <https://doi.org/10.3133/wsp1462>.

Magranet, Lindsay. 2015. “Scott River Fall Chinook Spawning Ground Surveys.” Etna, CA: Siskiyou Resource Conservation District.

———. 2017. “Scott River Fall Chinook Spawning Ground Surveys.” Etna, CA: Siskiyou Resource Conservation District.

———. 2018. “2017 Monitoring Report.” Scott River Water Trust.

Mansfield, Carol, George Van Houtven, Amy Hendershott, Patrick Chen, Jeremy Porter, Vesall Nourani, and Vikram Kilambi. 2012. “Klamath River Basin Restoration Nonuse Value Survey.”

Mazor, Raphael D., Jason T. May, Ashmita Sengupta, Kenneth S. McCune, Brian P. Bledsoe, and Eric D. Stein. 2018. “Tools for Managing Hydrologic Alteration on a Regional Scale: Setting Targets to Protect Stream Health.” *Freshwater Biology* 63 (8): 786–803. <https://doi.org/10.1111/fwb.13062>.

McMahon, Thomas E. 1983. “Habitat Suitability Index Models: Coho Salmon.” FWS/OBS-82/10.49. U.S. Fish and Wildlife Service.

McManamay, Ryan A., and Emmanuel A. Frimpong. 2015. “Hydrologic Filtering of Fish Life History Strategies Across the United States: Implications for Stream Flow Alteration.” *Ecological Applications* 25 (1): 243–63. <https://doi.org/10.1890/14-0247.1>.

McManamay, Ryan A., Donald J. Orth, Charles A. Dolloff, and David C. Mathews. 2013. “Application of the ELOHA Framework to Regulated Rivers in the Upper Tennessee River Basin: A Case Study.” *Environmental Management* 51 (6): 1210–35. <https://doi.org/10.1007/s00267-013-0055-3>.

Mellado-Díaz, Andrés, Jorge Rubén Sánchez-González, Simone Guareschi, Fernando Magdaleno, and Manuel Toro Velasco. 2019. “Exploring Longitudinal Trends and Recovery Gradients in Macroinvertebrate Communities and Biomonitoring Tools Along Regulated Rivers.” *Science of The Total Environment* 695 (December): 133774. <https://doi.org/10.1016/j.scitotenv.2019.133774>.

Monk, Wendy A., Paul J. Wood, David M. Hannah, and Douglas A. Wilson. 2008. “Macroinvertebrate Community Response to Inter-Annual and Regional River Flow Regime Dynamics.” *River Research and Applications* 24 (7): 988–1001. <https://doi.org/10.1002/rra.1120>.

Monk, Wendy A., Paul J. Wood, David M. Hannah, Douglas A. Wilson, Chris A. Extence, and Richard P. Chadd. 2006. “Flow Variability and Macroinvertebrate Community Response Within Riverine Systems.” *River Research and Applications* 22 (5): 595–615. <https://doi.org/10.1002/rra.933>.

Moyle, Peter B. 2002. “Coho Salmon, Oncorhynchus Kisutch (Walbaum).” In *Inland Fishes of California*, 245–51. University of California Press.

National Marine Fisheries Service. 2014. “Final SONCC Coho Recovery Plan.” National Oceanic and Atmospheric Administration.

Nickelson, Thomas E., Jeffrey D. Rodgers, Steven L. Johnson, and Mario F. Solazzi. 1992. “Seasonal Changes in Habitat Use by Juvenile Coho Salmon (Oncorhynchus Kisutch) in Oregon Coastal Streams.” *Canadian Journal of Fisheries and Aquatic Sciences* 49 (4): 783–89. <https://doi.org/10.1139/f92-088>.

North Coast Regional Water Quality Control Board. 2005. “Staff Report for the Action Plan for the Scott River Watershed Sediment and Temperature Total Maximum Daily Loads.” Santa Rosa, CA.

———. 2006. “ACTION PLAN FOR THE SCOTT RIVER SEDIMENT AND TEMPERATURE TOTAL MAXIMUM DAILY LOADS.” *Basin Plan Language*. https://www.waterboards.ca.gov/northcoast/water\_issues/programs/tmdls/scott\_river/060307/bpl/Basin\_Plan\_Language.pdf.

Peek, Ryan, Katie Irving, Sarah M. Yarnell, Rob Lusardi, Eric D. Stein, and Raphael Mazor. 2022. “Identifying Functional Flow Linkages Between Stream Alteration and Biological Stream Condition Indices Across California.” *Frontiers in Environmental Science* 9 (January): 790667. <https://doi.org/10.3389/fenvs.2021.790667>.

Peterson, James T., and Mary C. Freeman. 2016. “Integrating Modeling, Monitoring, and Management to Reduce Critical Uncertainties in Water Resource Decision Making.” *Journal of Environmental Management* 183 (December): 361–70. <https://doi.org/10.1016/j.jenvman.2016.03.015>.

Poff, N. LeRoy, Brian D. Richter, Angela H. Arthington, Stuart E. Bunn, Robert J. Naiman, Eloise Kendy, Mike Acreman, et al. 2010. “The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards.” *Freshwater Biology* 55 (1): 147–70. <https://doi.org/10.1111/j.1365-2427.2009.02204.x>.

Qian, Kuimei, Xia Liu, and Yuwei Chen. 2016. “Effects of Water Level Fluctuation on Phytoplankton Succession in Poyang Lake, China – A Five Year Study.” *Ecohydrology & Hydrobiology* 16 (3): 175–84. <https://doi.org/10.1016/j.ecohyd.2016.08.001>.

Quiñones, Rebecca M., Marcel Holyoak, Michael L. Johnson, and Peter B. Moyle. 2014. “Potential Factors Affecting Survival Differ by Run-Timing and Location: Linear Mixed-Effects Models of Pacific Salmonids (Oncorhynchus Spp.) in the Klamath River, California.” Edited by Christopher J. Fulton. *PLoS ONE* 9 (5): e98392. <https://doi.org/10.1371/journal.pone.0098392>.

Richter, Brian D., Andrew T. Warner, Judy L. Meyer, and Kim Lutz. 2006. “A Collaborative and Adaptive Process for Developing Environmental Flow Recommendations.” *River Research and Applications* 22 (3): 297–318. <https://doi.org/10.1002/rra.892>.

Riis, Tenna, Alastair M. Suren, Bente Clausen, and Kaj Sand-Jensen. 2008. “Vegetation and Flow Regime in Lowland Streams.” *Freshwater Biology* 53 (8): 1531–43. <https://doi.org/10.1111/j.1365-2427.2008.01987.x>.

Rosenfeld, Jordan S. 2003. “Assessing the Habitat Requirements of Stream Fishes: An Overview and Evaluation of Different Approaches.” *Transactions of the American Fisheries Society* 132 (5): 953–68. <https://doi.org/10.1577/T01-126>.

———. 2017. “Developing Flow–Ecology Relationships: Implications of Nonlinear Biological Responses for Water Management.” *Freshwater Biology* 62 (8): 1305–24. <https://doi.org/10.1111/fwb.12948>.

Saby, Linnea, Kevin L. McKee, Prakrut Kansara, Jonathan L. Goodall, Lawrence E. Band, and Venkataraman Lakshmi. 2022. “Sensitivity of Remotely Sensed Vegetation to Hydrologic Predictors Across the Colorado River Basin, 2001–2019.” *JAWRA Journal of the American Water Resources Association* 58 (6): 1017–29. <https://doi.org/10.1111/1752-1688.12965>.

Scott River Watershed Council. 2005. “Limiting Factors Analysis for Coho Salmon and Other Anadromous Fish.”

———. 2018. “Restoring Priority Coho Habitat in the Scott River Watershed Modeling and Planning Report.”

Scott River Watershed Council, and Siskiyou Resource Conservation District. 2005. “Initial Phase of the Scott River Watershed Council Strategic Action Plan.” Etna, CA.

Scott Valley Area Plan Committee. 1980. “Scott Valley Area Plan.” Siskiyou County.

Shenton, Will, Nicholas R. Bond, Jian D. L. Yen, and Ralph Mac Nally. 2012. “Putting the ‘Ecology’ into Environmental Flows: Ecological Dynamics and Demographic Modelling.” *Environmental Management* 50 (1): 1–10. <https://doi.org/10.1007/s00267-012-9864-z>.

Sinnathamby, Sumathy, Kyle R. Douglas-Mankin, Muluken E. Muche, Stacy L. Hutchinson, and Aavudai Anandhi. 2018. “Ecohydrological Index, Native Fish, and Climate Trends and Relationships in the Kansas River Basin.” *Ecohydrology* 11 (1): e1909. <https://doi.org/10.1002/eco.1909>.

Siskiyou County. 2021. “Scott Valley Groundwater Sustainability Plan.” *Scott Valley FINAL GSP*. https://www.co.siskiyou.ca.us/naturalresources/page/scott-valley-final-gsp.

Siskiyou Resource Conservation District. 2004. “Final Report Scott River Coho Spawning Assessment: 2003-2004.” Etna, CA: Siskiyou Resource Conservation District.

Stewart-Koster, B., J. D. Olden, M. J. Kennard, B. J. Pusey, E. L. Boone, M. Douglas, and S. Jackson. 2011. “Fish Response to the Temporal Hierarchy of the Natural Flow Regime in the Daly River, Northern Australia.” *Journal of Fish Biology* 79 (6): 1525–44. <https://doi.org/10.1111/j.1095-8649.2011.03072.x>.

Tesfaye, Samuale, Emiru Birhane, Toon Leijnse, and S. E. A. T. M. Van Der Zee. 2017. “Climatic Controls of Ecohydrological Responses in the Highlands of Northern Ethiopia.” *Science of The Total Environment* 609 (December): 77–91. <https://doi.org/10.1016/j.scitotenv.2017.07.138>.

Tharme, R. E. 2003. “A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers.” *River Research and Applications* 19 (5-6): 397–441. <https://doi.org/10.1002/rra.736>.

Tolley, D., L. Foglia, and T. Harter. 2019. “Sensitivity Analysis and Calibration of an Integrated Hydrologic Model in an Irrigated Agricultural Basin With a Groundwater-Dependent Ecosystem.” *Water Resources Research* 55 (9): 7876–7901. <https://doi.org/10.1029/2018WR024209>.

Wainwright, Thomas C, Thomas H Williams, Kurt L Fresh, and Brian K Wells. 2013. “CCIEA PHASE II REPORT: ECOSYSTEM COMPONENTS, FISHERIES AND PROTECTED SPECIES - SALMON: Chinook and Coho Salmon.” National Marine Fisheries Service.

Webb, J. Angus, Robyn J. Watts, Catherine Allan, and John C. Conallin. 2018. “Adaptive Management of Environmental Flows.” *Environmental Management* 61 (3): 339–46. <https://doi.org/10.1007/s00267-017-0981-6>.

Welch, David Warren, Aswea Dawn Porter, and Erin Leanne Rechisky. 2021. “A Synthesis of the Coast-Wide Decline in Survival of West Coast Chinook Salmon (Oncorhynchus Tshawytscha, Salmonidae).” *Fish and Fisheries* 22 (1): 194–211. <https://doi.org/10.1111/faf.12514>.

White, James C., Andy House, Neil Punchard, David M. Hannah, Nicholas A. Wilding, and Paul J. Wood. 2018. “Macroinvertebrate Community Responses to Hydrological Controls and Groundwater Abstraction Effects Across Intermittent and Perennial Headwater Streams.” *Science of The Total Environment* 610–611 (January): 1514–26. <https://doi.org/10.1016/j.scitotenv.2017.06.081>.

Yao, Weiwei, Ruidong An, Guoan Yu, Jia Li, and Xiaoyi Ma. 2021. “Identifying Fish Ecological Risk Patterns Based on the Effects of Long-Term Dam Operation Schemes.” *Ecological Engineering* 159 (January): 106102. <https://doi.org/10.1016/j.ecoleng.2020.106102>.

Yokel, Erich, Shari Witmore, Betsy Stapleton, Charnna Gilmore, and Michael M Pollock. 2018. “Scott River Beaver Dam Analogue Coho Salmon Habitat Restoration Program 2017 Monitoring Report.” Etna, CA: Scott River Watershed Council.