Applying the California Environmental Flows Framework to Little Shasta River

September 2022

Sarah Yarnell, Ann Willis, Robert Lusardi, and Ryan Peek

Center for Watershed Sciences, University of California, Davis

Contents

An Application of the California Environmental Flows Framework to Little Shasta River

Prepared by Sarah Yarnell, Ann Willis, Robert Lusardi, and Ryan Peek with funding from the California Wildlife Conservation Board

Purpose and Summary

The Shasta River in Siskiyou County, northern California, was historically one of the most productive salmon streams in the state. Groundwater from cold, nutrient-rich springs provided nearly ideal aquatic habitat conditions that supported large Chinook and coho salmon populations. More than a century of aquatic and riparian habitat degradation along the Shasta River and its tributaries has resulted in dramatic decline in wild salmon populations, including the federally threatened Southern Oregon/Northern California Coast (SONCC) coho salmon (Moyle et al. 2017, Moyle 2002). The observed decline of wild salmon populations in the Shasta River coincided with the development of both surface and groundwater sources in support of irrigated agricultural activities throughout the Shasta Basin, including the Little Shasta River. Water storage and diversions led to reductions in the quantity and quality of coldwater habitat for rearing coho salmon, particularly during summer. Adjudicated water rights did not consider the needs of native fishes; as a result, surface water supplies are managed to prioritize agricultural and other water use. While progress had been made reconciling ecological water needs and human uses in some of the highest priority reaches, stream flows are insufficient for supporting healthy ecosystem conditions in most of the Shasta River (Moyle et al. 2017, NMFS 2014, NCRWQCB 2006, NRC 2004).

As one of the most downstream tributaries to the Shasta River, the Little Shasta River is uniquely positioned to play a vital role in the overall recovery of the Shasta River watershed. Originating at 1,830 m in elevation and extending approximately 41.7 km (25.9 mi) west from the Cascade Mountains of northern California until its confluence with the Shasta River within the lower Klamath Basin, the Little Shasta River could contribute to important life history diversity within the broader Shasta River watershed because of its mixed source hydrology. While the mainstem Shasta River receives the majority of its flows from productive groundwater springs emerging from volcanic terrain, the Little Shasta River derives its streamflow from both surface runoff (snowmelt and wet season rainfall) over predominantly volcanic and metavolcanic terrain and groundwater fed from several springs. Such hydrologic diversity suggests that the Little Shasta River may be able to strongly contribute to the recovery of native fishes within the Shasta River watershed; however, the Little Shasta River regularly experiences precipitous declines in flow volume during the annual irrigation season, leading to flow disconnections within the stream channel. As such, the Little Shasta River requires streamflow enhancement to restore instream habitat and recover native biota.

Streamflow enhancement projects throughout California currently rely on local assessments of aquatic and instream flow needs as the state lacks a standardized, systematic approach to establishing streamflow criteria that support a range of ecosystem functions. The California Environmental Flows Framework (CEFF), recently developed by the Environmental Flows Workgroup under the California Water Quality Monitoring Council, provides a framework for establishing instream flow protections statewide (ceff.ucdavis.edu; CWQMC-EFW 2021). CEFF supports evaluation of overall condition relative to ecosystem flow requirements using a functional flow approach (Yarnell et al. 2015), and provides tools and methodological guidance to assess site-specific flow needs in light of changing conditions associated with climate change, land use development, and competing water uses (Stein et al. 2021). CEFF was developed in coordination with the California State Water Quality Control Board, California Department of Fish and Wildlife, and associated partners in academia and non-governmental organizations to improve stream flows throughout the state.

This project seeks to guide future enhancement of stream flows in the Little Shasta River, a regionally important and high priority fish-bearing stream, using the functional flows approach as outlined in CEFF (CWQMC-EFW 2021). Current planning and implementation of stream restoration and flow enhancement projects in the Little Shasta River support native aquatic species; however, they lack a proposed hydrologic regime that meets multiple ecologic and geomorphic objectives. Applying CEFF to define ecological flow criteria supportive of anadromy and ecosystem functions would significantly aid current and future flow enhancement projects in the Little Shasta River by providing a target hydrologic regime needed for successful implementation. This report details the results of applying CEFF to determine ecological flow criteria (Sections A and B) and provides some recommendations and considerations for future efforts to apply CEFF section C in the Little Shasta River. Yarnell et al. (2022) provides a summary of the results from this CEFF application along with discussion of how springs and groundwater influence streamflow conditions in the Little Shasta River, and other groundwater-influenced streams more broadly.

Overview of the California Environmental Flows Framework

The California Environmental Flows Framework (hereafter "CEFF") was developed by a technical team within the California Environmental Flows Working Group, a sub-group hosted by the California Water Quality Monitoring Council that includes scientists and managers from resource agencies, academia, and non-governmental organizations. CEFF establishes a technical process for developing environmental flow targets for rivers throughout the state. CEFF is based upon ***functional flows***, a scientific concept that emphasizes the biological, chemical, and physical functions of flowing water that sustain native aquatic species and riparian ecosystems. Managing streams using functional flows represents a holistic approach for improving ecosystem health—one that delivers broad benefits for people and nature while also accommodating human demands on the system.

CEFF was established to support resource managers tasked with defining ***ecological flow criteria***—quantifiable metrics that describe ranges of flow that must be maintained within a stream and its margins throughout the year to support healthy ecosystems—for California's river and streams. CEFF aims to produce consistent, scientifically-supported ecological flow criteria that can be used to determine ***environmental flow recommendations*** that satisfy ecosystem water needs and other water management objectives. Environmental flow recommendations are expressed as a "rule set" of flow requirements that are informed by ecological flow criteria but also take human uses and other water management objectives into consideration.

The technical approach of CEFF rests upon the scientific concept of ***functional flows***—distinct aspects of a flow regime that sustain ecological, geomorphic, or biogeochemical functions, and support the specific life history and habitat needs of native aquatic species (Yarnell et al., 2015). Managing for functional flows preserves essential patterns of flow variability within and among seasons but does not mandate the restoration of full natural flows nor maintenance of historical ecosystem conditions. In addition, a functional flows approach is not focused on the habitat needs of a particular species, but rather, focuses on preserving key ecosystem functions, such as sediment movement, water quality maintenance, and environmental cues for species migration and reproduction, that maintain ecosystem health and are broadly supportive of native freshwater plants and animals.

CEFF focuses on the following five basic functional flow components that represent significant drivers of ecological processes in California, and are defined in Yarnell et al. (2020) (Figure 1):

- **Fall pulse flow**, or the first major storm event following the dry season. These flows represent the transition from dry to wet season and serve important functions, such as moving nutrients downstream, improving streamflow water quality, and signaling aquatic species to migrate or spawn.
- **Wet-season baseflow**, which support native aquatic species that migrate through and overwinter in streams.
- **Wet-season peak flows**, which transport a significant portion of sediment load, inundate floodplains, and maintain and restructure river corridors.
- **Spring recession flow**, which represents the transition from high to low flows, provide reproductive and migratory cues for native aquatic species, and redistribute sediment.
- **Dry-season baseflow**, which support native aquatic species during the dry-season period when water quality and quantity limit habitat suitability.

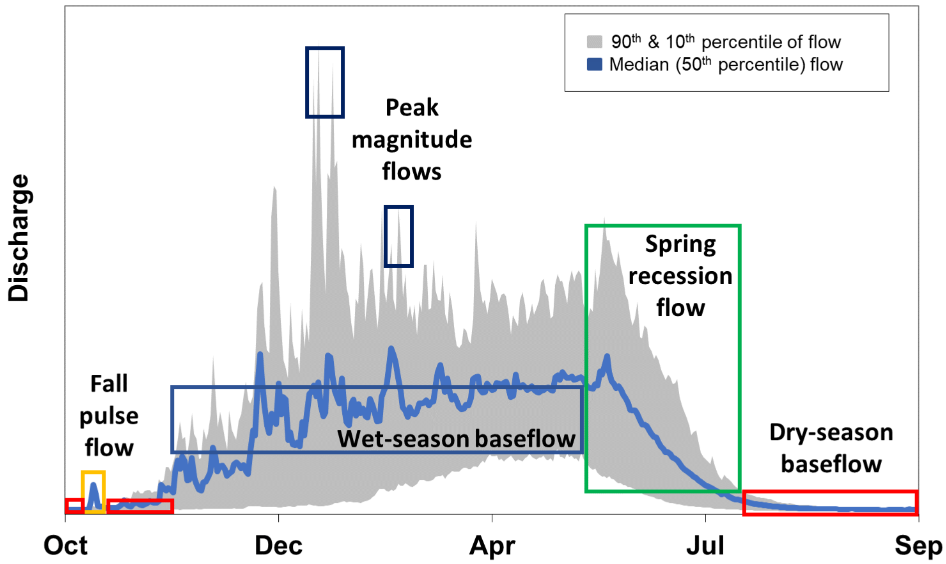

Figure 1. Functional flow components (colored boxes with labels) for California illustrated over a representative hydrograph (Figure from Yarnell et al. 2020). Blue line represents median (50^{th} percentile) daily discharge. Gray shading represents 90^{th} to 10^{th} percentiles of daily discharge over the period of record.

The five functional flow components identified for California provide the basis for determining ecological flow criteria and assessing potential stream flow alteration in CEFF. Each functional flow component is quantified by several functional flow metrics that describe the magnitude, timing, frequency, duration, or rate of change of flows within the flow component. Details on the definition of each functional flow metric, including calculation methods, can be found in Yarnell et al. (2020) and CWQMC-EFW (2021). Together this suite of functional flow metrics can be used as ecological flow criteria for any stream location in the state.

The initial steps of CEFF provide guidance on setting broad ecological management goals and identifying specific location(s) of interest (LOI(s)) within the geographic region. CEFF then provides a set of ecological flow criteria that quantify the range of instream flow conditions at each LOI supportive of ecological processes under natural (i.e. non-altered) flow conditions. In instances where non-flow impairments, such as altered physical habitat or poor water quality, may limit the ability for the natural range of functional flow metrics to support desired ecological functions, CEFF provides further guidance for determining appropriate ecological flow criteria. In later steps of CEFF, the ecological flow criteria are then compared with current streamflow conditions at each LOI to assess potential flow alteration. Depending on management objectives, these ecological flow criteria can be translated into environmental flow recommendations or assessed in relation to anthropogenic water needs to determine environmental flow recommendations that balance ecological and non-ecological objectives. Further information about CEFF, including a CEFF application guidance document and FAQs, can be found at *ceff.ucdavis.edu*.

The remainder of this report is organized to follow and detail the steps outlined in CEFF (Version 1.0, April, 2021) to determine ecological flow criteria at a representative location on lower Aliso Creek. The main goal was to determine ecological flow criteria (Sections A and B), to assess flow alteration (Section C, step 9), and provide recommendations for future management considerations (Section C, step 10). We summarize considerations for Section C, however, additional work in collaboration with community stakeholders should be undertaken if the goal is to develop final environmental flow recommendations. The findings of CEFF sections A and B can be used as a basis for dialogue among stakeholders to determine final environmental flows that integrate human use with ecological functions.

Section A – Identifying ecological flow criteria using natural functional flows

Step 1: Define ecological management goals

Site Context

The geographic focus of this assessment was the Little Shasta River watershed (Figure 2). Three distinct stream reaches—headwaters, foothills, and bottomlands—have been identified in the Little Shasta River that reflect different geomorphic and hydrologic conditions (SVRCD, McBain, and Trush, 2013). The steeper and higher elevation forested headwaters are fed by surface runoff from winter rainfall and spring snowmelt and control the hydrologic and thermal regime of the river. The foothills reach is dominated by herbaceous and shrub land cover with a lower gradient (<4%) and wider channel, creating more diverse channel habitats, with flow that is fed by the headwaters and supplemented by discrete groundwater-fed springs. The bottomlands reach is the lowest gradient (<1%), where the stream channel shifts from a hydrologically losing to gaining reach. The bottomlands are dominated by agricultural and herbaceous land cover and exhibit wide shallow channels with limited habitat complexity that creates warmer water temperatures and supports extensive riparian wetlands.

Objective: To identify ecological management goals for the study area and the corresponding ecosystem functions that must be supported by ecological flow criteria to satisfy those goals

Outcome of Step 1:

- A well-defined study area accompanied by a written description and map with watershed boundaries, the stream network, and LOIs (stream reaches)
- A list of LOIs with a short description of why they were selected
- A list of ecological management goals
- A list of ecosystem functions (associated with each functional flow component) that must be supported by ecological flows to achieve ecological management goals

Three locations of interest (LOIs) were selected based on these differing reach types to characterize varying flow and habitat conditions within the Little Shasta River watershed. Numbered from downstream to upstream (e.g., LOI 1 is the most downstream reach, LOI3 is the most upstream reach), the LOIs represent conditions within the bottomlands reach near the confluence with the Shasta River, the transition between the bottomlands and foothills reaches, and the foothills reach.

LOI 1 (NHD COMID 3917946) at the downstream end of the bottomlands reach characterizes the cumulative influence of runoff and groundwater accretion in the watershed and illustrates the overall flow regime prior to the Little Shasta's confluence with the Shasta River. LOI 2 (NHD COMID 3917950) characterizes the stream where the Little Shasta transitions from the foothills reach to the bottomlands reach and where shallow groundwater interacts with surface water conditions and adjacent wetlands. (C. Esposito and L. Foglia, pers. comm., Feb. 24, 2021). Both LOI 1 and LOI 2 also show how effects from surface diversions, agricultural use, and groundwater levels influence wetland habitat and streamflow during various seasons. LOI 3 (NHD COMID 3917198), located in the foothills reach, characterizes flow conditions in the upper limit of naturally accessible habitat for fish resulting from cumulative surface runoff and spring flow from several discrete groundwater sources; it is also the stream reach where an active stream gage is located.

Figure 1. The Little Shasta River watershed, tributary to the Shasta River in Northern California. Streamlines reflect differing geomorphic and hydrologic conditions, including small tributaries and three primary stream reaches: headwaters, foothills, and bottomlands. Groundwater dependent ecosystems (GDEs) are shown as green shaded polygons. Locations of interest are shown as orange squares, and flow gages are shown as blue diamonds. Background images shows topographic map with elevation contours and private versus public (US Forest Service) land designation. LOI 3 is coincident with the LSR flow gage. USGS gage 11516900 in the upper watershed is no longer active; USGS gage 11517000 on the main Shasta River just upstream of the Little Shasta confluence is currently active.

Ecological Management Goals

Establishing ***ecological management goals***, or the desired ecological or biological response that occurs due to a management action aimed at improving or maintaining overall stream health or conditions, allows for the critical evaluation of whether functional flow criteria at each LOI adequately address management needs. We reviewed existing reports and studies associated within the Little Shasta River to further understand watershed conditions and develop desired ecological outcomes for the various locations of interest.

The majority of available reports focused on the condition of native aquatic and riparian species in the Little Shasta River, including fish, birds, and vegetation, and advocated for conservation actions to support overall biodiversity and ecological functionality of the river. In general, habitat conditions varied across stream reaches, with more extensive riparian habitat in the foothills reach and fragmented groundwater-dependent ecosystems (GDEs) and wetlands identified in the bottomlands reach (Figure 2; CWHR 2021). GDEs are particularly important climate refugia, where groundwater discharge via surface springs or shallow subsurface flow can provide dry season baseflow critical for sustaining aquatic habitat when precipitation is low or lacking (Howard and Merrifield, 2010). Such groundwater inputs typically create cool water upwelling in streams when hot temperatures and low flows in the dry season can limit instream productivity and physiologically stress fish and other aquatic organisms (Cunjak, 1988; Davidson et al., 2010). As a result, the existing wetlands, GDEs, and riparian habitat help to support a rich diversity of native species in the Little Shasta River, including not only native fishes, but special status species including gray wolves, bald eagles, and sandhill cranes (CWHR 2021). Improving riparian habitat conditions and enhancing streamflows to support and maintain GDEs are important conservation actions to ensure native species communities persist and remain robust.

Multiple existing reports and studies also identified enhancing and preserving aquatic habitat for native fishes, particularly steelhead (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*), as a key priority in the Little Shasta River (NMFS 2014; Nichols et al. 2017; Lukk et al. 2019; SVRCD, McBain, and Trush 2013). Like most of the larger Shasta River watershed, native fish populations in the Little Shasta River have precipitously declined as stream conditions have deteriorated. Preliminary work suggests that the upper foothills reach of the Little Shasta River contains high-quality, coldwater habitat and robust food webs that currently support native coldwater fishes (e.g., resident *Oncorhynchus mykiss*) of multiple age classes and could support juvenile coho salmon, which have not been detected in the watershed in recent decades (Nichols et al. 2016, 2017; Lukk et al. 2019). Dispersed, discrete groundwater-fed springs located in the foothills reach historically provided cold nutrient-rich water to the stream throughout the year, while off-channel springs and shallow groundwater connections with the stream in the bottomlands reach supported extensive riparian and wetland habitat. Historically, these low-lying wetlands likely supported a diverse aquatic community throughout the year with a variety of warm surface-water and cool groundwater-influenced habitats through which native fish migrated during spring, summer, and autumn. Nutrients from upstream springs would have likely contributed to primary and secondary productivity in the bottomlands reach and supported higher order consumers such as steelhead and juvenile coho salmon (Lusardi et al., 2020). Together, these reaches provided habitat conditions that supported various life history stages of salmonids, each playing a distinct and important role in the stream's overall potential to support the broader recovery of migratory fishes (Lukk et al. 2019).

Results from several studies indicate the primary limiting factors on anadromous fish production in the Little Shasta River are the lack of hydrologic connectivity and poor water quality (e.g., temperature) throughout the bottomlands and lower foothills reaches (Nichols et al. 2016, Lukk et al. 2019). All groundwater springs are fully appropriated and diverted for off-channel water use (e.g., irrigation, stockwater), and shallow groundwater connections with the stream channel are limited or lacking through the dry season. Existing coldwater habitat in the foothills reach thus is disconnected from the bottomlands in spring during the coho outmigration period and throughout summer. Additionally, this intermittency in streamflow persists into the fall, limiting access to high quality adult spawning habitat in the foothills reach. Improving streamflows during the spring and fall migration periods and maintaining existing coldwater habitat in the foothills reach is crucial for rearing juvenile salmonids, particularly under warming climate conditions that may adversely affect stream temperature conditions and limit salmonid recovery (Willis and Lusardi 2021; Moyle et al. 2017). As a result, substantial investments have been made in the Little Shasta watershed to support the recovery and conservation of anadromous fishes, with efforts primarily targeting the extent of and access to coldwater habitat for steelhead and coho salmon.

Ecological management goals selected for this analysis focused on responses that directly intersect with an identifiable functional flow component (e.g., floodplain inundation during wet season peak flows to support wetland habitat). Other goals that did not directly relate to a functional flow component were deemed beyond the scope of this project, even if they were aligned with the overall goal of supporting native ecosystems. For example, gray wolves, while not directly related to aquatic and riparian management, would benefit from healthy riparian and stream habitat (CDFW 2015; CWHR 2021). Building on the available studies and reports, the following ecological management goals related to instream flow conditions were identified at each LOI:

Ecological Management Goals for LOI 1 (Bottomlands reach):

- Preserve and maintain natural ranges of all functional flow components to support native aquatic and riparian communities
- Improve and sustain perennial flow with hydrologic connectivity in most years and good water quality conditions that provide sufficient dissolved oxygen conditions.
- Promote and sustain riparian plant communities, GDEs, and associated riparian birds
- Improve passage and migratory conditions for adult steelhead, Chinook, and coho salmon during fall and early winter and passage for outmigrating juvenile salmonids during spring
- Enhance winter floodplain habitat and lateral hydrologic connectivity for salmonid rearing and other native aquatic species such as amphibians

Ecological Management Goals for LOI 2 (Foothills-Bottomlands reach transition):

- Preserve and maintain natural ranges of all functional flow components to support native aquatic and riparian communities
- Improve and sustain perennial flow with hydrologic connectivity in most years and good water quality conditions that provide sufficient dissolved oxygen conditions.
- Promote and sustain riparian plant communities, GDEs, and associated riparian birds
- Improve passage and migratory conditions for adult steelhead, Chinook, and coho salmon during fall and early winter and passage for outmigrating juvenile salmonids during spring
- Enhance winter floodplain habitat and lateral hydrologic connectivity for salmonid rearing and other native aquatic species

Ecological Management Goals for LOI 3 (Foothills reach):

- Preserve and maintain natural ranges of all functional flow components to support native aquatic and riparian communities
- Preserve and maintain year-round, high quality coldwater habitat for native fishes
- Enhance winter side channel habitat and lateral hydrologic connectivity for salmonid rearing and carbon and nutrient cycling
- Promote and sustain riparian plant communities and associated riparian birds

Using Table 1.2 from CEFF (CWQMC-EFW 2021), a set of ecosystem functions needed to achieve the above ecological management goals was selected for each of the five functional flow components (Table 1).

Table 1. A summary of functional flow components and associated ecosystem functions that must be supported to achieve ecological management goals in the Little Shasta River watershed.

Functional Flow Component	Ecosystem Function(s)
Fall pulse flow	Flush fine sediment and organic material from substrate, increase longitudinal hydrologic connectivity, increase riparian soil moisture, increase nutrient cycling, reactivate exchanges with hyporheic zone, decrease water temperature and increase dissolved oxygen, cue native fish migration
Wet season baseflow	Maintain longitudinal hydrologic connectivity, support hyporheic exchange, support riparian habitat along channel margins, support fish migration and spawning
Wet season peak flow	Scour and deposit sediment and large wood in channel and floodplains, increase lateral hydrologic connectivity, recharge groundwater via floodplain inundation, increase nutrient cycling on floodplains and channel, support riparian vegetation diversity via disturbance, riparian succession, and extended inundation in floodplains, limit non-native species and in-channel vegetation encroachment through disturbance and displacement.
Spring flow recession	Increase sorting of sediments via increased sediment transport and size selective deposition, recharge groundwater via floodplain inundation, increase lateral and longitudinal connectivity, decrease water temperatures, increase export of nutrients and primary producers from floodplain to channel, provide hydrologic cues for native fish outmigration, support juvenile native fish rearing, increase hydraulic habitat diversity and habitat availability resulting in increased macroinvertebrate diversity, arthropod diversity, native fish diversity, and general biodiversity, provide hydrologic conditions for riparian species recruitment, limit riparian vegetation encroachment into channel
Dry season baseflow	maintain channel margin riparian soil moisture, export organic nutrients, maintain coldwater habitat in upper reaches, maintain suitable dissolved oxygen levels, support primary and secondary producers

Step 2: Obtain natural ranges for functional flow metrics

> **Objective:** To download natural functional flow metrics and characterize natural functional flow components at locations of interest.
>
> **Outcome of Step 2:**
>
> - A table of natural functional flow metric values associated with each functional flow component for each LOI, downloaded from the California Natural Flows Database (rivers.codefornature.org).

Statewide statistical models have been developed to predict natural functional flow metrics for all stream reaches in California (Grantham et al. 2022). The modeling approach incorporated climate data, watershed characteristics, and streamflow data from reference gages in California located on streams with minimal disturbance to natural hydrology and land cover (Falcone et al. 2010). Functional flow metrics were calculated at each reference gage from daily flow values, using algorithms described by Patterson et al. (2020). Separate models were then developed for each functional flow metric, using machine learning methods to relate functional flow metric values to watershed and climate characteristics, following the approach described by Zimmerman et al. (2018). Additional details of the modeling approach, input data, and performance evaluation are provided in the CEFF guidance document and Grantham et al. (2022).

Natural functional flow metrics can be viewed and downloaded from the California Natural Flows Database (rivers.codefornature.org). Metrics are quantified as a range of values expected to occur at LOIs under natural conditions over a long-term period of record (10 or more years). The range of predicted metric values are defined by quantiles (the 10th, 25th, 50th, 75th, and 90th percentiles below which predicted values fall). In addition to reporting the expected range of values for each metric across all years, predictions are also provided for wet, moderate, and dry water year types.

Local issues with the National Hydrography Dataset (NHD) stream network used in the functional flow metric modeling, as well as groundwater characteristics of the Little Shasta River, required some additional work to accurately represent the hydrologic characteristics at each LOI. The underlying NHD stream network used in the modeling and displayed in the Natural Flows Database incorrectly showed that seasonal flow conveyed through open ditches was included as part of the natural flow patterns of the Little Shasta River. This resulted in erroneous predictions of natural monthly flows and functional flow metrics where the Montague Conservation Water District canal crosses the Little Shasta River at river kilometer 16.7 and extending downstream, including LOI 1 and LOI 2. Attempts to correct the modelled functional flow metrics for these downstream LOIs were unsuccessful (see Appendix A for details). However, a comparison of predicted functional flow metrics to historical gage data upstream of LOI 3 confirmed that predicted functional flow metrics upstream of the Montague canal were representative of natural flow patterns (Table 2; see also step 9 for comparison with gage data). Therefore, the remainder of this analysis focuses on determining ecological flow criteria at LOI 3. Further site-specific hydrologic modelling to calculate functional flow metrics at LOI 1 and LOI 2 is beyond the scope of this project, but recommended for further conservation efforts.

The modeling approach used to determine predictions of natural functional flow metrics throughout the state incorporates a suite of watershed and climate variables that largely relate to surface runoff characteristics (Grantham et al. 2022). Streams with substantial groundwater contributions, such as the Little Shasta River, may require additional analysis to correctly account for large groundwater inputs or discrete spring sources (Yarnell et al. 2022).

Multiple groundwater springs and seeps contribute baseflow to the Little Shasta River and its tributaries throughout the upper headwaters reach and near Table Rock at the eastern edge of the Little Shasta Valley where porous volcanic rocks overlay less permeable Quaternary alluvium (Figure 3). Historical flow data prior to agricultural development and spring diversions are unavailable for the Little Shasta watershed, but information on spring discharge volumes and monthly flows dating back to the early decades of the 20th century can be found from Shasta Watermaster reports and is summarized in Nichols et al. (2016). These historical accounts indicated that, collectively, springs contributed in excess of 20 cfs to the Little Shasta River in the foothills reach (Adams et al., 1912). These spring-fed baseflows are augmented by surface runoff from winter rainfall and spring snowmelt in the headwaters, which contribute mean monthly flows ranging from less than 5 cfs during the dry season (typically June-October) to over 50 cfs during the wet season (Nov-May) and annual peak flows of 200–800 cfs (historical data, USGS gage 11516900). Together, rainfall and snowmelt provided seasonal hydrologic variability on top of the stable, cool groundwater supported baseflows throughout the year.

The natural functional flow metric models include predictor variables that characterize the climatic and physical characteristics of the contributing watershed area, including precipitation, temperature, geology, elevation, and drainage area (Grantham et al. 2022). Although baseflow contributions are potentially accounted for in a groundwater recharge index in the models (Wolock 2003), the predicted baseflow components were generally underestimated at LOI 3 (Table 2), indicating that the models were not capturing the effects of spring contributions. For example, predicted dry season baseflow magnitude across all years ranged from 1-20 cfs, averaging 9 cfs (Table 2). However, additional year-round groundwater discharge of 10 cfs from Cleland Spring (also called Cold Spring), just upstream of LOI 3 (Figure 2), would nearly double the estimates of natural summer baseflow. Further discussion of comparisons between predicted functional flow metrics and observed flow metrics is provided in step 9 below. To account for spring-fed groundwater contributions not reflected in the models, we added this discrete spring flow volume of 10 cfs to the predicted dry season and wet season baseflow magnitudes and the fall pulse flow at LOI 3 (Table 3).

We also evaluated the potential for subsurface groundwater inputs from locally adjacent high groundwater levels to support and sustain baseflow conditions during the dry season at LOI 3 and the downstream LOIs in the bottomlands reach. Although limited data was available to quantify the interactions between surface flow, groundwater, and the associated groundwater-dependent ecosystems in the Little Shasta River, groundwater modelling results indicated that portions of the stream vary between gaining and losing conditions as it traverses the valley. Modelled losses to or gains from the Little Shasta River appear to be small relative to spring contributions (pers comm, L. Foglia), but additional on-going study will provide insight to whether gaining reaches may prolong higher baseflow duration, support higher soil moisture in riparian areas, and contribute to healthier stream and wetland conditions. Thus, no further adjustments accounting for shallow subsurface flow contributions to baseflow were made to the baseflow functional flow metrics at this time.

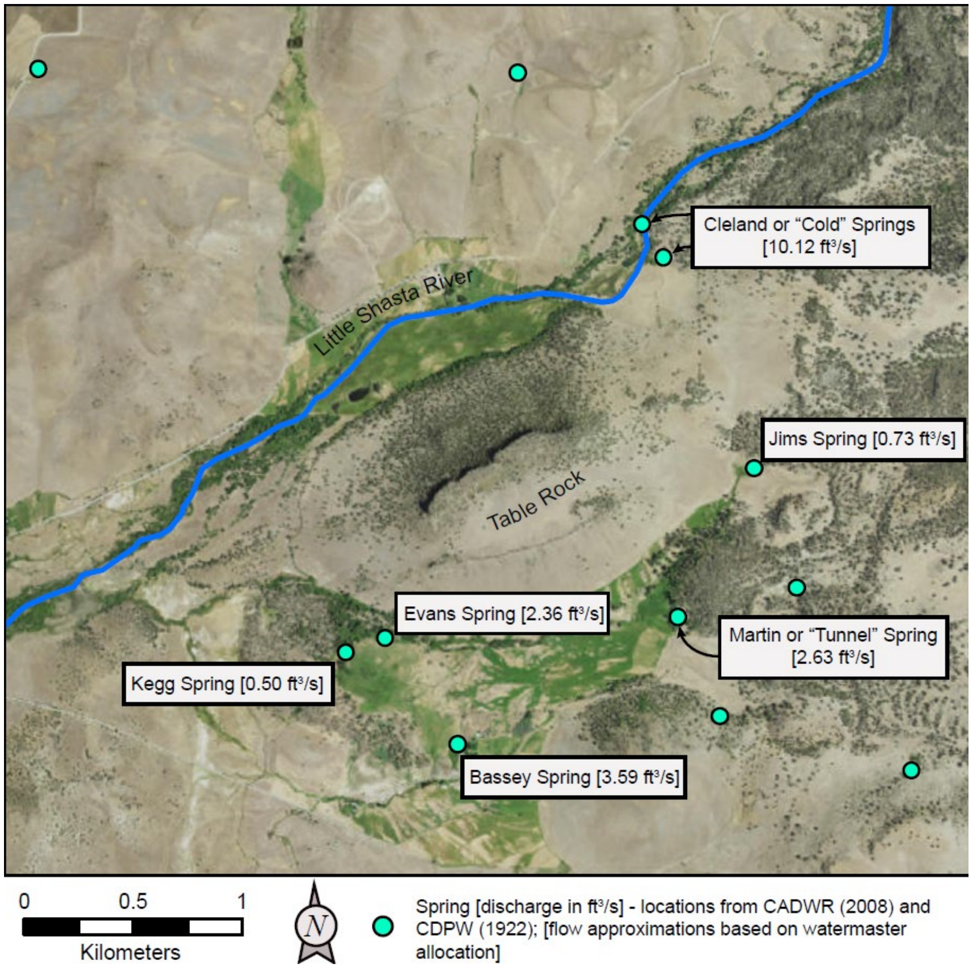

Figure 2. Springs and estimated historical discharges (in cubic feet per second) based on early 20th century Watermaster reports (reproduced from Nichols et al. 2016). Evans Spring and Cleland (Cold) springs are shown on Figure 1 for reference.

Table 2. The predicted natural functional flow metrics (FFM) from the Natural Flows Database for LOI 3 in the foothills reach of the Little Shasta River. Values reflect medians and 10th-90th percentiles of each functional flow metric for all water year types combined, as well as dry, moderate, and wet year types. Magnitude metrics are expressed in cubic feet per second (cfs), duration metrics are expressed as the number of days, frequency metrics are expressed as the number of events per wet season, and timing metrics are expressed in day of water year, where day 1 = Oct 1. Definitions for each metric and types of baseflows are provided in CWQMC-EFW (2021).

Flow Component	Flow Metric	All years Natural FFM at LOI 3 Median (10th – 90th percentile)	Dry Natural FFM at LOI 3 Median (10th – 90th percentile)	Moderate Natural FFM at LOI 3 Median (10th – 90th percentile)	Wet Natural FFM at LOI 3 Median (10th – 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	28 (7-74)	19 (4-51)	28 (8-75)	38 (12-128)
	Fall pulse timing (WY day)	32 (6-61)	40 (3-61)	32 (7-61)	29 (8-57)
	Fall pulse duration (days)	4 (2-8)	4 (2-8)	4 (2-8)	4 (2-8)
Wet-season baseflow	Wet-season baseflow (cfs)	11 (1-28)	8 (0.9-20)	11 (1-27)	19 (2-41)
	Wet-season median flow (cfs)	33 (5-69)	12 (2-40)	31 (4-68)	53 (23-123)
	Wet-season timing (WY day)	74 (23-149)	69 (15-157)	92 (24-150)	78 (33-141)
	Wet-season duration (days)	121 (59-211)	125 (64-220)	111 (59-209)	117 (57-201)
Peak flows	2-year flood magnitude (cfs)	143 (19-514)	143 (19-514)	143 (19-514)	143 (19-514)
	2-year flood duration (days)	2 (1-5)	2 (1-5)	2 (1-5)	2 (1-5)
	2-year flood frequency (# per season)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood magnitude (cfs)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)
	5-year flood duration (days)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood magnitude (cfs)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)
	10-year flood duration (days)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)

Flow Component	Flow Metric	All years Natural FFM at LOI 3 Median (10th – 90th percentile)	Dry Natural FFM at LOI 3 Median (10th – 90th percentile)	Moderate Natural FFM at LOI 3 Median (10th – 90th percentile)	Wet Natural FFM at LOI 3 Median (10th – 90th percentile)
Spring recession flows	Spring recession magnitude (cfs)	90 (25-308)	53 (11-213)	88 (24-293)	170 (65-465)
	Spring timing (WY day)	223 (161-251)	217 (152-251)	222 (168-250)	224 (180-250)
	Spring duration (days)	78 (41-127)	87 (39-151)	77 (41-122)	73 (42-121)
	Spring rate of change (percent decline per day)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)
Dry-season baseflow	Dry-season baseflow (cfs)	9 (1-20)	7 (0.7-17)	9 (0.9-20)	13 (2-32)
	Dry-season high baseflow (cfs)	11 (2-35)	6 (1-27)	11 (2-35)	17 (3-51)
	Dry-season timing (WY day)	299 (264-334)	299 (263-335)	299 (267-333)	300 (265-332)
	Dry-season duration (days)	148 (81-227)	147 (78-228)	149 (81-227)	149 (81-226)

Table 3. The predicted natural functional flow metrics (FFM) from the Natural Flows Database for LOI 3 in the foothills reach of the Little Shasta River, with adjustments to baseflows to account for discrete spring contributions of 10 cfs. Adjusted values are shown in bold. Values reflect medians and 10th-90th percentiles of each functional flow metric for all water year types combined, as well as dry, moderate, and wet year types. Magnitude metrics are expressed in cubic feet per second (cfs), duration metrics are expressed as the number of days, frequency metrics are expressed as the number of events per wet season, and timing metrics are expressed in day of water year, where day 1 = Oct 1. Definitions for each metric and types of baseflows are provided in CWQMC-EFW (2021).

Flow Component	Flow Metric	All years Natural FFM at LOI 3 Median (10th – 90th percentile)	Dry Natural FFM at LOI 3 Median (10th – 90th percentile)	Moderate Natural FFM at LOI 3 Median (10th – 90th percentile)	Wet Natural FFM at LOI 3 Median (10th – 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	**38 (17-84)**	**29 (14-61)**	**38 (18-85)**	**48 (22-138)**
	Fall pulse timing (WY day)	32 (6-61)	40 (3-61)	32 (7-61)	29 (8-57)
	Fall pulse duration (days	4 (2-8)	4 (2-8)	4 (2-8)	4 (2-8)
Wet-season baseflow	Wet-season baseflow (cfs)	**21 (11-38)**	**18 (10-20)**	**21 (11-37)**	**29 (12-51)**
	Wet-season median flow (cfs)	33 (5-69)	12 (2-40)	31 (4-68)	53 (23-123)

Flow Component	Flow Metric	All years Natural FFM at LOI 3 Median (10th – 90th percentile)	Dry Natural FFM at LOI 3 Median (10th – 90th percentile)	Moderate Natural FFM at LOI 3 Median (10th – 90th percentile)	Wet Natural FFM at LOI 3 Median (10th – 90th percentile)
	Wet-season timing (WY day)	74 (23-149)	69 (15-157)	92 (24-150)	78 (33-141)
	Wet-season duration (days)	121 (59-211)	125 (64-220)	111 (59-209)	117 (57-201)
Peak flows	2-year flood magnitude (cfs)	143 (19-514)	143 (19-514)	143 (19-514)	143 (19-514)
	2-year flood duration (days)	2 (1-5)	2 (1-5)	2 (1-5)	2 (1-5)
	2-year flood frequency (# per season)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood magnitude (cfs)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)
	5-year flood duration (days)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood magnitude (cfs)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)
	10-year flood duration (days)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
Spring recession flows	Spring recession magnitude (cfs)	90 (25-308)	53 (11-213)	88 (24-293)	170 (65-465)
	Spring timing (WY day)	223 (161-251)	217 (152-251)	222 (168-250)	224 (180-250)
	Spring duration (days)	78 (41-127)	87 (39-151)	77 (41-122)	73 (42-121)
	Spring rate of change (percent)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)
Dry-season baseflow	Dry-season baseflow (cfs)	**19 (11-30)**	**17 (11-27)**	**19 (11-30)**	**23 (12-42)**
	Dry-season high baseflow (cfs)	**21 (12-45)**	**16 (11-37)**	**21 (12-45)**	**27 (13-61)**
	Dry-season timing (WY day)	299 (264-334)	299 (263-335)	299 (267-333)	300 (265-332)
	Dry-season duration (days)	148 (81-227)	147 (78-228)	149 (81-227)	149 (81-226)

Step 3: Evaluate whether the natural ranges of functional flow metrics will support functions needed to achieve ecological management goals

Maintaining functional flows within their natural range is hypothesized to support ecosystem functions and sustain healthy ecosystem conditions for native freshwater species (CWQMC-EFW 2021). However, historical and ongoing land- and water-management activities have the potential to degrade the physical, chemical, and biological conditions of rivers and streams, such that the natural ranges of functional flow metrics may be less effective in supporting ecosystem functions.

Objective: To perform an evaluation of factors that may limit the ability of the natural range of functional flow metrics to support essential ecosystem functions

Outcome of Step 3:

- Identification of functional flow components where there is evidence that their natural range of flow metrics will not be supportive of ecological management goals, and a list of associated limiting factors and potentially affected ecosystem function(s); these focal components will be subject to further investigation in Section B to develop their corresponding ecological flow criteria.

Here, we evaluate factors that may limit the effectiveness of the natural range of functional flow metrics in supporting ecosystem functions within the Little Shasta River. We focus on the potential influence of ***non-flow*** aspects, including physical habitat, water quality, and biotic interactions (flow-related impacts such as diversions and groundwater pumping will be addressed in steps 8-12), on the relationship between natural functional flows and ecosystem functions, identified in Step 1, that are essential to achieving ecological management goals.

Though considerable investments have been made to implement conservation actions in the Little Shasta River, surrounding land use activities potentially affect the relationship between streamflow and stream function. Two potential effects of cattle grazing and pastureland cultivation include changes to channel geomorphology (i.e., incision) and water quality (i.e., high nutrient loads and warmer water temperatures). Unfenced stream reaches where unrestricted cattle grazing occurs in the foothills and bottomlands reaches lack riparian vegetation that may support improved water quality or prevent channel incision. Bare banks lack the mature riparian vegetation that can provide bank stability, trap sediment and organic matter, and provide shade to the stream channel. In addition, spring-fed systems provide naturally derived nutrient levels that support high aquatic productivity relative to surface-dominated streamflows (Lusardi et al. 2016). Groundwater-derived baseflows typically also provide relatively cool water during the dry season, helping to mitigate physiologically stressful seasonal extremes in temperature (Davidson et al. 2010). As a result, geomorphic, water quality, and stream temperature processes may be impaired for some of the functional flow components (see Table 4), and desired functionality might not be achieved by the natural range of functional flow metrics. These issues are explored in more detail in Section B.

Table 4. Potential *non-flow* limiting factors that may alter the relationship between the natural range of functional flow metrics and their intended functions for each functional flow component at the location of interest. Flow-related factors are discussed in step 8.

Functional Flow Component	Potential Non-flow Limiting Factor	Affected Ecosystem Function(s)
Fall pulse flow	None identified	Reference flow ranges should provide suitable functionality
Wet-season baseflow	None identified	Reference flow ranges should provide suitable functionality
Wet-season peak flow	Channel incision	Potentially limiting to all floodplain functions
Spring flow recession	Channel incision	Potentially limiting to all floodplain functions
Dry-season baseflow	Water quality	Potentially limiting to maintenance of coldwater habitat in upper reaches, maintenance of suitable dissolved oxygen levels, and support of primary and secondary producers.

Step 4: Select ecological flow criteria

Ecological flow criteria are selected for all functional flow components for which the natural range of metrics is expected to support ecosystem functions. These ecological flow criteria are defined as the median (50th percentile) metric value and bounded by the 10th to 90th percentile range of metric values for each flow component. The median represents the long-term value around which annual values should center. The 10th to 90th percentile values represent the lower and upper bounds, respectively, in which annual values of the metric are expected to vary. Ecological flow criteria can be defined for all water years, or by water year type (e.g. wet, moderate, dry).

Objective: To select ecological flow criteria for all functional flow components (unless it is determined in Step 3 that further assessment is required for one or more components) to support ecological management goals using natural functional flow metrics.

Outcome of Step 4:

- Ecological flow criteria values for functional flow components where the natural range of functional flow metrics are expected to support ecological management goals.

Following the assessment in Step 3, channel incision may be a limiting factor for achieving floodplain functions associated with peak flow magnitudes and the spring recession magnitude. In addition, the absence of groundwater-fed spring flow from the stream channel and the associated changes in water quality may be a limiting factor for achieving functions related to maintenance of coldwater habitat in the upper reaches associated with the dry-season baseflow magnitude. Therefore, the magnitudes of these flow metrics will be further evaluated in steps 5-6 to determine the degree to which alterations to physical habitat and water chemistry may affect the relationship between the natural range of functional flow metrics and their intended function. Based on the outcome of that evaluation, flow criteria may be adjusted. The remaining functional flow metrics related to timing, duration, and rate of change during wet season peak flows, the spring recession, and dry season baseflow, as well as all metrics associated with the fall pulse flow and wet season baseflow are selected as ecological flow criteria for LOI 3 (Table 5).

Table 5. Ecological Flow Criteria for the Little Shasta River (LOI 3) for those functional flow components where additional evaluation of non-flow factors is not needed. Values reflect medians and 10^{th} – 90^{th} percentiles in parentheses of functional flow criteria for all water year types, as well as dry, moderate, and wet year types.

Flow Component	Flow Metric	All Years Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Dry Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Moderate Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Wet Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	38 (17-84)	29 (14-61)	38 (18-85)	48 (22-138)
	Fall pulse timing (WY day)	32 (6-61)	40 (3-61)	32 (7-61)	29 (8-57)
	Fall pulse duration (days)	4 (2-8)	4 (2-8)	4 (2-8)	4 (2-8)

Flow Component	Flow Metric	All Years Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Dry Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Moderate Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Wet Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)
Wet-season baseflow	Wet-season baseflow (cfs)	21 (11-38)	18 (10-20)	21 (11-37)	29 (12-51)
	Wet-season median flow (cfs)	33 (5-69)	12 (2-40)	31 (4-68)	53 (23-123)
	Wet-season timing (WY day)	74 (23-149)	69 (15-157)	92 (24-150)	78 (33-141)
	Wet-season duration (days)	121 (59-211)	125 (64-220)	111 (59-209)	117 (57-201)
Peak flows	2-year flood magnitude (cfs)	To be determined	To be determined	To be determined	To be determined
	2-year flood duration (days)	2 (1-5)	2 (1-5)	2 (1-5)	2 (1-5)
	2-year flood frequency (# per season)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood magnitude (cfs)	To be determined	To be determined	To be determined	To be determined
	5-year flood duration (days)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood magnitude (cfs)	To be determined	To be determined	To be determined	To be determined
	10-year flood duration (days)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
Spring recession flows	Spring recession magnitude (cfs)	To be determined	To be determined	To be determined	To be determined
	Spring timing (WY day)	223 (161-251)	217 (152-251)	222 (168-250)	224 (180-250)
	Spring duration (days)	78 (41-127)	87 (39-151)	77 (41-122)	73 (42-121)
	Spring rate of change (percent)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)
Dry-season baseflow	Dry-season baseflow (cfs)	To be determined	To be determined	To be determined	To be determined
	Dry-season high baseflow (cfs)	To be determined	To be determined	To be determined	To be determined
	Dry-season timing (WY day)	299 (264-334)	299 (263-335)	299 (267-333)	300 (265-332)
	Dry-season duration (days)	148 (81-227)	147 (78-228)	149 (81-227)	149 (81-226)

Section B – Develop ecological flow criteria for focal flow components requiring additional consideration

Step 5: Develop detailed conceptual model relating focal flow components to ecological goals

Objective: To develop a conceptual model to visualize the relationship between functional flow components and the physical, chemical, and biological factors that influence ecological management goals

Outcome of Step 5:

- A detailed conceptual model for each LOI (or study area, if it includes multiple LOIs that can be addressed by the same conceptual model) that illustrates the flow-ecology relationships that influence ecological responses and management goals expressed as ecological performance measures.

A conceptual model that explicitly links flow components with ecological management goals will assist in understanding and visualizing how physical habitat, water quality, or biological interactions may affect the relationships between flow and ecological response. The conceptual model also guides collection of the data required to quantify these ecological response relationships (if needed) as described in Step 6. The structure of the conceptual model will have a significant influence on the quality and nature of the results, and as such, should be developed through an open, collaborative process informed by stakeholders.

Based on our analysis in step 3, there is concern that channel incision will affect the functionality of the wet season peak flows and the spring recession flow with respect to adjacent floodplain habitat. For example, if the channel is greatly incised, the natural 2-year flood magnitude may not inundate the floodplain in most years as expected, but rather a higher magnitude flow would be needed to achieve floodplain inundation and the associated ecosystem functions. Figure 4 provides an example conceptual model detailing the relationships between the peak flows and spring recession, physical habitat in the floodplain, associated key ecosystem functions, and the related ecological management goals identified in step 1. To determine if channel incision is potentially limiting the functionality of higher flow, an assessment of channel cross-sections using a Light Detecting and Ranging (LiDAR) survey of the Little Shasta River would illustrate areas where incision may occur. This analysis is presented in Step 6.

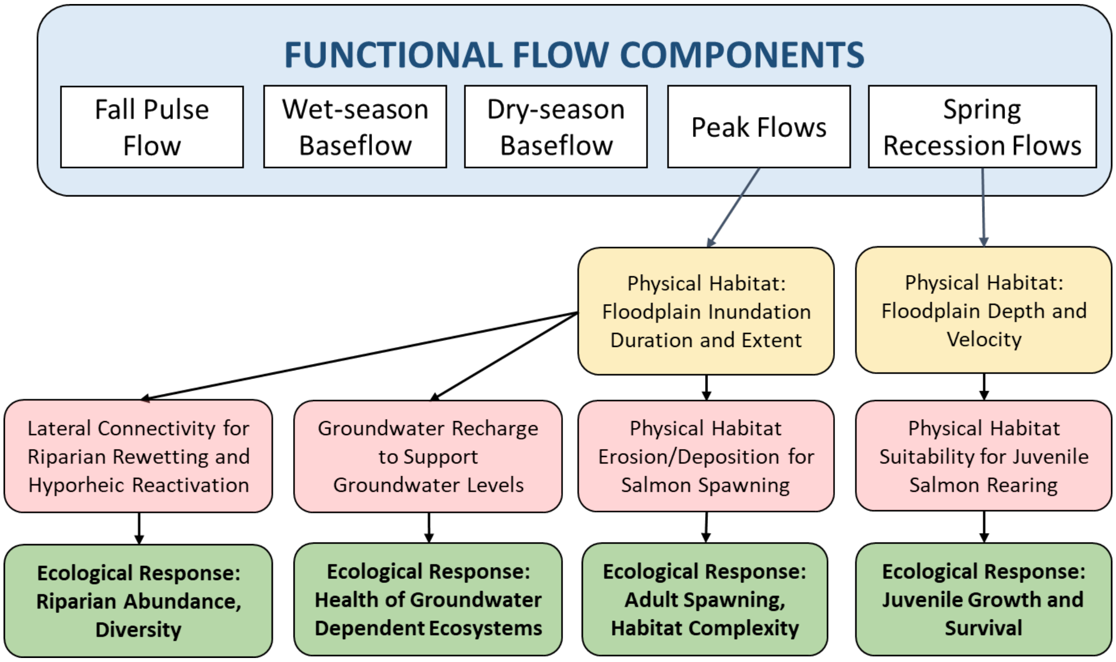

Figure 3. Example conceptual model linking peak flows and spring recession flows with physical habitat in the floodplain, key ecosystem functions (from table 1), and ecological management goals identified in step 1**.**

The absence of groundwater spring contributions presents concerns that water quality of the remaining surface water runoff may affect the functionality of the dry season baseflow with respect to stream temperatures and the quality of instream primary and secondary productivity, particularly at LOI3 (Figure 5). For example, a comparable volume of surface water runoff may create the same amount of physical habitat, but lack the thermal and nutrient properties of spring-fed sources that drive robust productivity regimes. A stream temperature or other process-based, numerical water quality model would provide information on the relationship between alternative sources of streamflows and their subsequent effect on water quality conditions (and thus ecological conditions). Such a model and analysis were developed separately from this case study (Lukk et al., 2022); details of the findings are presented in Step 6.

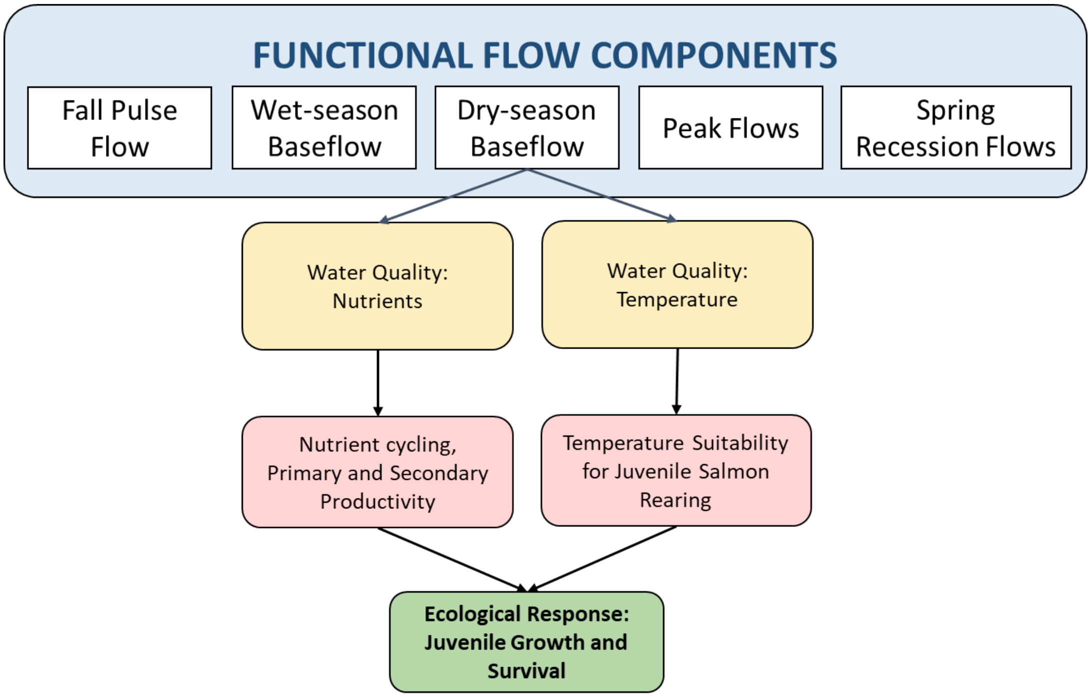

Figure 4. Example conceptual model linking dry season baseflow with water quality, key ecosystem functions (from table 1), and ecological management goals identified in step 1.

Step 6: Quantify flow-ecology relationships

Objective: To quantify flow-ecology relationships in the conceptual model using provided guidance on data sources and methods for defining these relationships

Outcome of Step 6:

- Quantitative flow-ecology relationships that relate focal functional flow components to ecological responses.

Channel incision due to surrounding cattle grazing and pasture cultivation, as well as water quality issues, were considered in greater detail due to their effects on flow-ecology relationships. Channel incision was assessed to determine whether wet season peak and spring recession flows would achieve their ecological function given the current channel geometry. Water quality was assessed to determine whether the dry season baseflow would achieve ecological functions associated with water temperature and nutrients in the upper reaches given alternative water sources present in the Little Shasta River. The results were then assessed to determine whether ecological flow criteria for these functional flow metrics required adjustment to achieve desired functions.

Physical Habitat: Channel Incision

To assess the presence and extent of channel incision, a digital elevation model of the Little Shasta watershed was created from a Light Detecting and Ranging (LiDAR) survey of the Shasta River watershed (TerraPoint 2008). The digitized streamline for the main channel was mapped onto the digital elevation model, as well as the stream reaches including each of the three LOIs. We chose to include LOI 1 and LOI 2 in this analysis as the metric for floodplain activation is defined by the 2-year flood magnitude, which is likely consistent across all LOIs. Elevation profiles for 35 unique cross-sections throughout these reaches of the Little Shasta River were extracted from the digital elevation model. Cross-sections were manually drawn to capture main channel, adjacent banks, and terraces.

After cross-sections were established, each was plotted and examined to identify the bankfull channel. Bankfull channel was defined as the point from where water would begin to overflow out of the main (deepest) channel and onto a wider floodplain. For each cross-section, the transition from bankfull to floodplain was identified by an abrupt slope break on one or both sides of the channel (Figure 6). Once the slope break point was identified, the geometry of the bankfull channel was estimated as a trapezoid. Bankfull flow was then calculated using Manning's equation:

$$Q = \left(\frac{1.49}{n}\right) * A * R^{\frac{2}{3}} * \sqrt{S}$$

Where Q is discharge in cubic feet per second, n is channel roughness, A is flow area, R is hydraulic radius, and S is channel slope. Channel roughness was estimated using field observations of the channel bed and values provided in Chow (1959). Flow area and hydraulic radius were calculated from the bankfull trapezoidal channel geometry. Channel slope was extracted from the National Hydrography Database attributes for each stream segment associated with the cross-section. Finally, the calculated bankfull flow was compared to the 2-year flood magnitude to determine whether any incision had reduced the functionality of peak flows. Specifically, if the bankfull flow was greater than the 2-year flood magnitude, then we considered the channel incised.

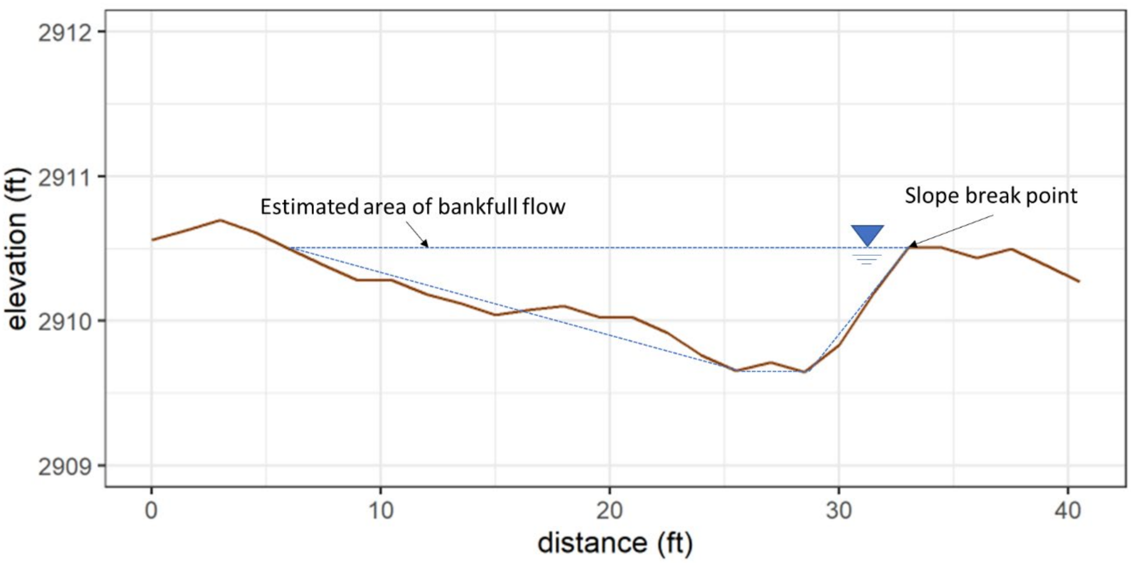

Figure 5. An example cross-section at LOI 3, which was used to assess channel incision based on current bankfull geometry. The solid brown line shows the channel cross-section profile extracted from the digital elevation model. The dashed blue line shows the estimated bankfull area. The blue triangle indicates the estimated water surface.

An examination of the bankfull flow in each cross-section showed that the Little Shasta River channel was generally not incised in any of the three stream reaches near the LOIs, with the exception of a few outliers in each reach (Appendix B). Bankfull flows were calculated at 45-519 cfs near LOI 3, 11-773 cfs near LOI 2, and 10-995 cfs near LOI 1. The majority of these values were less than the 2-year flow recurrence value of 143 (19-514) cfs (Table 2), though four of the 31 cross sections had bankfull flows that exceeded the 2-year peak flow.

Other cross-sections showed areas where the 2-year flood flow would activate the current floodplain within an incised channel, but would not reach the historical floodplain. For example, one cross-section near LOI 1 showed a current floodplain ~2.5 ft below the historical floodplain that would be inundated by the 2-year flood flow of ~150 cfs (Figure 7). Since bankfull flows within the current channel, either within an inset floodplain or within the historical floodplain, would spill out onto a floodplain surface and support peak flow ecological functions associated with floodplain inundation, we chose to retain wet season peak flow magnitudes and the spring recession flow magnitude at their original predicted values.

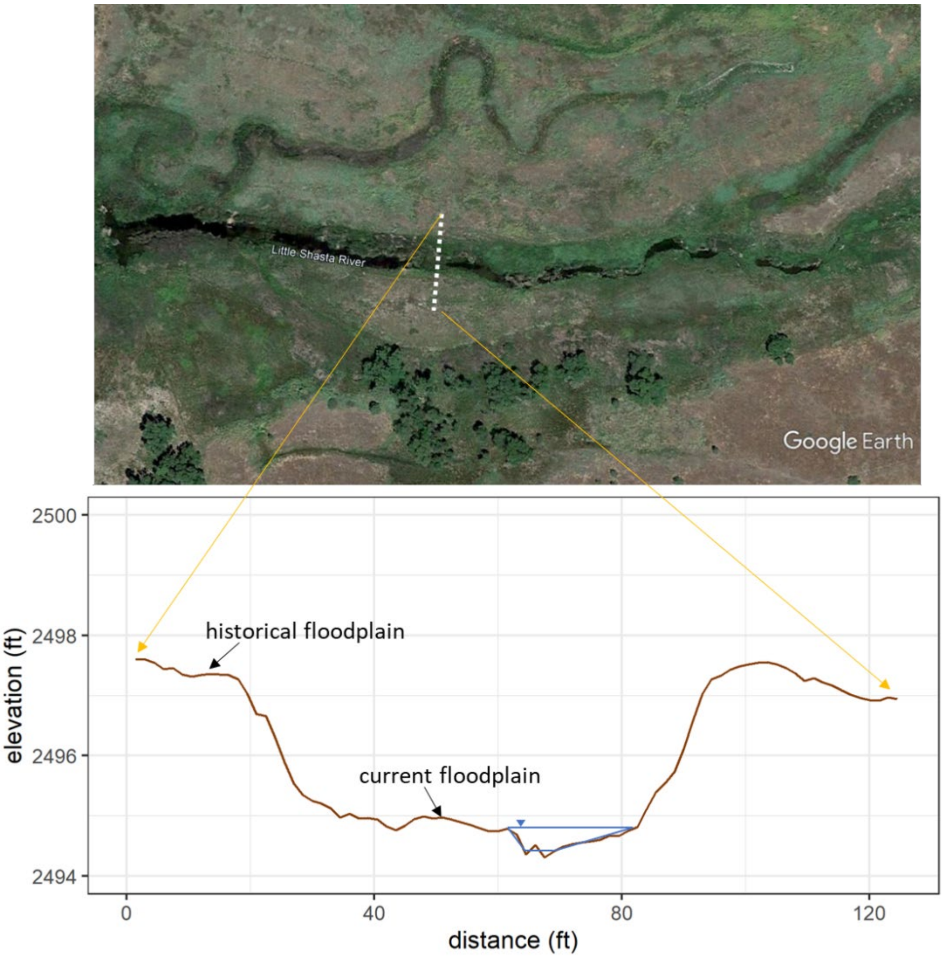

Figure 6. An example of a cross-section near LOI 1 where the 2-year peak flow would activate floodplain function for the existing channel form, but would not reach the historical floodplain. The top image shows the planform extent of the cross-section (image credit: Google Earth). The bottom plot shows the elevation profile of the cross-section, as well as the estimated bankfull channel (blue trapezoid; the blue triangle shows the water surface of bankfull flow).

The results from these analyses suggested that channel incision was modest throughout the foothills and bottomlands reaches. Peak flows, including the 2-year flood of ~143 cfs, would typically exceed the bankfull channel, inundate the adjacent floodplain, and support riparian recruitment. Recent qualitative observations of the stream channel in each of these reaches supported the findings of the cross-section analysis (Figure 8). At LOI 3 and LOI 2, the channel was confined to a single path with asymmetric cross-sectional geometry—cross-sections with steep banks on one side of the channel and gradual slopes on the opposite side—that spread higher flows across a wider cross-section (Figure 8A-B). At LOI 1, the main channel had steep banks but was not heavily incised through the low-gradient valley prior to flowing into the Shasta River (Figure 8C). However, in reaches where grazing access to the stream channel was unrestricted, incision could increase and become a limiting factor to floodplain functionality (Figure 8C). Therefore, the predicted natural range of functional flow metrics from section A for the wet season peak flows and spring recession flow would likely provide expected floodplain functionality, and we chose not to adjust the metrics from those listed in Table 2. However, as the stream throughout the bottomlands reach was likely historically a multi-channel system typical of wetlands where lower flows provided greater lateral connectivity and supported

GDEs, consideration of channel rehabilitation actions that promote habitat complexity and increase riparian interactions at lower flows is needed.

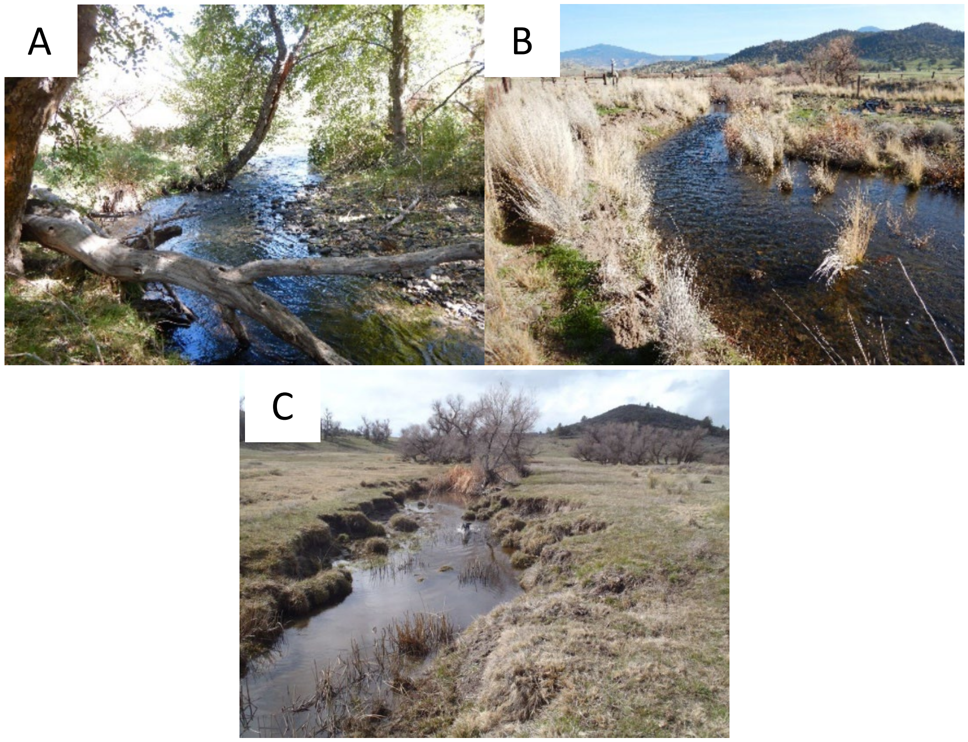

Figure 7. Photographs of the Little Shasta River channel, taken near A) LOI 3, B) LOI 2, and C) LOI 1.

Water Quality: Temperature and Nutrients

In addition to exploring the quantity of spring-fed contributions that historically contributed to the Little Shasta flow regime, and dry season baseflow in particular (see section A step 2 above), the quality of spring-fed versus surface runoff flow was explored to determine the effects of differing water quality conditions on ecological function during the dry season. A time series of temperature data was available for a single spring source in the Little Shasta: Evans Spring, downstream of LOI 3. Lukk et al. (2022) presented a detailed assessment of stream temperatures in the Little Shasta River given instream dedications of either spring-fed or surface runoff water sources. The results showed that the water quality differences between spring-fed water and surface runoff were not equivalent – the same quantity of spring-fed water had greater cooling effects on overall stream temperatures than surface runoff (Table 6). When an additional 2.5 cfs of spring water was added to existing streamflows during the dry season, water temperatures averaged 15.4 C, compared to 16.5 C when the same quantity of surface water was added to streamflow. Further, minimum stream temperatures were 12.8 C with an addition of 2.5 cfs of spring water compared to 14.5 C when 2.5 cfs of surface water was added to existing streamflows. Thus, maintenance of coldwater habitat (a key desired function) during the dry season was more likely to be achieved under the natural range of dry season baseflows if water was sourced at least partially from spring-fed sources. We therefore decided that further adjustments or increases in dry season baseflow to provide cooler stream temperatures was not required.

Table 6. A summary of the average 7-day minimum, average, and maximum water temperatures resulting from dedicating 2.5 cfs of water from different sources: spring-fed (i.e., Evans Spring) or surface runoff. Values in parentheses show the temperature reduction of each alternative management scenario compared to the baseline. Table adapted from Lukk et al. (2022).

Scenario	minimum (°C)	average (°C)	maximum (°C)
Baseline	14.6	16.8	19.6
Evans Spring: Historical Channel Reconnection	12.8 *(-1.8)*	15.4 (*-1.4)*	19.0 *(-0.6)*
Evans Spring: Historical Channel Reconnection + Restoration	12.8 (*-1.8)*	15.2 (*-1.6)*	18.3 *(-1.3)*
Surface runoff instream dedication	14.5 (*-0.1)*	16.5 (*-0.2)*	18.5 *(-1.1)*

Macroinvertebrate and fish assemblage response to water quality conditions and the broader ecology of the Little Shasta River was recently studied (Lukk et al. 2019; Willis and Lusardi 2021). Lukk et al. (2019) compared benthic macroinvertebrate communities at LOI 3 (foothills reach) and LOI 2 (transition to Bottomlands reach) and found greater densities of invertebrates at LOI 2 (~4900 invertebrates·m^{-2}). However, the community at LOI2 was dominated by pollution tolerant organisms when compared with LOI 3 (average density~2,360 invertebrates·m^{-2}). LOI3, however, exhibited greater diversity (nearly two-fold greater) than LOI2, indicative of superior water quality conditions (e.g., temperature and dissolved oxygen) and flow consistency. These results were consistent across response indices (e.g., taxonomic richness, EPT index, etc.) indicating that good water quality conditions were prevalent at LOI 3 (Willis and Lusardi 2021). In particular, the Hilsenhoff Biotic Index (HBI), used to examine water quality sensitivity of macroinvertebrates (Hilsenhoff 1987), indicated that water quality at LOI3 was in "good" condition. Conversely, the HBI at LOI2 was qualified as "fair water quality with significant organic pollution". Both Lukk et al. (2019) and Willis and Lusardi (2021) found that poor water quality and low flows (including disconnected habitats) observed throughout LOI 2, in part, were responsible for observed differences in the abundance and diversity of macroinvertebrates between LOIs.

Good water quality conditions and sustained flows at LOI 3 indicate the stream is capable of supporting robust prey resources for native fishes. Based on snorkel surveys, Lukk et al. (2019) observed a diverse assemblage of native fishes at LOI 3, including rainbow trout (*Oncorhynchus mykiss*), Klamath smallscale sucker (*Catostomus rimiculus*), marbled sculpin (*Cottus klamathensis)*, speckled dace (*Rhinichthys osculus)*, and adult lamprey (*Lampetra sp*.). Brown trout were also represented by multiple age classes at LOI 3. While low and disconnected flow conditions precluded snorkel surveys at LOI 2, visual observations at LOI 2 noted non-native green sunfish (*Lepomis cyanellus*) in isolated pools (Lusardi, personal communication) and a lack of native species. Further, no anadromous salmonids (e.g., coho, Chinook salmon) were observed during any survey during the study, suggesting that streamflow conditions (e.g. water quality, discharge, hydrologic connectivity) strongly limited the dispersal and/or reproduction of salmonids within the Little Shasta River (Lukk et al. 2019).

Thus, given the high quality of spring-fed sources, both in terms of cool water temperatures and high naturally occurring nutrients associated with robust and diverse food webs at LOI3, ecological flow criteria for the dry season baseflow were not adjusted beyond the natural predicted range, presuming that spring flow contributions, over surface water contributions, represent the primary water source during the dry season.

Step 7: Define ecological flow criteria for focal flow components

Objective: To select ecological flow criteria for each focal functional flow component that support the ecological management goals defined in Step 1

Outcome of Step 7:

- Ecological flow criteria for all flow components defined from Sections A and B.

Based on the information gathered in steps 5 and 6, ecological flow criteria can be defined for each focal flow component. These new criteria are then combined with those defined in step 4 to develop a comprehensive set of criteria for all five functional flow components (and their associated functional flow metrics).

Based on additional information discussed in steps 5 and 6 above, we suggest ecological flow criteria for dry season baseflow magnitudes reflect the changes associated with historical spring-fed contributions to the Little Shasta River (see Table 2) but do not need further adjustment to account for water quality conditions as long as that flow is primarily sourced by the natural cold nutrient-rich springs (Table 7). Similarly, based on the analysis of the LIDAR-derived digital elevation model, channel incision is minor to moderate throughout the foothills and bottomlands reaches, and peak flows, such as the 2-year median flood of 143 cfs, would inundate the adjacent floodplain and support floodplain-related functions. Thus, the predicted natural range of functional flow metrics from section A step 2 for the wet season peak flows and spring recession flow would likely provide expected functionality, and the metrics were not adjusted (Table 7). However, as the stream was likely historically a multi-channel system typical of wetlands where lower flows provided greater lateral connectivity and supported groundwater-dependent ecosystems, consideration of channel rehabilitation actions that promote habitat complexity and increase riparian interactions at lower flows is needed (see step 10 below).

Table 7. Final Ecological flow criteria for the Little Shasta River (LOI 3). Values reflect medians and 10th – 90th percentiles in parentheses of functional flow criteria for all water year types, as well as dry, moderate, and wet year types.

Flow Component	Flow Metric	All years Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Dry Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Moderate Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)	Wet Ecological Flow Criteria at LOI 3 Median (10th – 90th percentile)
Fall pulse flow	Fall pulse magnitude (cfs)	38 (17-84)	29 (14-61)	38 (18-85)	48 (22-138)
	Fall pulse timing (WY day)	32 (6-61)	40 (3-61)	32 (7-61)	29 (8-57)
	Fall pulse duration (days	4 (2-8)	4 (2-8)	4 (2-8)	4 (2-8)
Wet-season baseflow	Wet-season baseflow (cfs)	21 (11-38)	18 (10-20)	21 (11-37)	29 (12-51)
	Wet-season median flow (cfs)	33 (5-69)	12 (2-40)	31 (4-68)	53 (23-123)
	Wet-season timing (WY day)	74 (23-149)	69 (15-157)	92 (24-150)	78 (33-141)
	Wet-season duration (days)	121 (59-211)	125 (64-220)	111 (59-209)	117 (57-201)
Peak flows	2-year flood magnitude (cfs)	143 (19-514)	143 (19-514)	143 (19-514)	143 (19-514)
	2-year flood duration (days)	2 (1-5)	2 (1-5)	2 (1-5)	2 (1-5)
	2-year flood frequency (# per season)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood magnitude (cfs)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)	165 (115-1,000)
	5-year flood duration (days)	1 (1-3)	1 (1-3)	1 (1-3)	1 (1-3)
	5-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood magnitude (cfs)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)	373 (162-2,090)
	10-year flood duration (days)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	1 (1-2)	1 (1-2)

Flow Component	Flow Metric	All years Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Dry Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Moderate Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)	Wet Ecological Flow Criteria at LOI 3 Median (10^{th} – 90^{th} percentile)
Spring recession flows	Spring recession magnitude (cfs)	90 (25-308)	53 (11-213)	88 (24-293)	170 (65-465)
	Spring timing (WY day)	223 (161-251)	217 (152-251)	222 (168-250)	224 (180-250)
	Spring duration (days)	78 (41-127)	87 (39-151)	77 (41-122)	73 (42-121)
	Spring rate of change (percent)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)	0.056 (0.04-0.08)
Dry-season baseflow	Dry-season baseflow (cfs)	19 (11-30)	17 (11-27)	19 (11-30)	23 (12-42)
	Dry-season high baseflow (cfs)	21 (12-45)	16 (11-37)	21 (12-45)	27 (13-61)
	Dry-season timing (WY day)	299 (264-334)	299 (263-335)	299 (267-333)	300 (265-332)
	Dry-season duration (days)	148 (81-227)	147 (78-228)	149 (81-227)	149 (81-226)

Section C – Developing environmental flow recommendations

Steps 8-12 below will be completed in consultation with watershed community members and stakeholders. They are included here for reference of the next steps in CEFF along with some comments and discussion of information provided in studies reviewed for this analysis. An initial assessment of flow alteration per step 9 is provided to help inform community discussions. Additional details on these steps can be found in the CEFF guidance document (CWQMC-EFW 2021) at ceff.ucdavis.edu.

Step 8: Identify management objectives

The ecological flow criteria developed in Steps 1-7 represent the ecological objectives for the study area. Development of environmental flow recommendations also requires consideration of non-ecological objectives, which for the Little Shasta River may include meeting municipal and agricultural water.

Based on prior studies and conversations with some community members in the Little Shasta study area, there is a flow-related concern regarding water uses associated with agricultural wells and diversions that affect local streamflow and groundwater levels. Further discussions with all stakeholders in the basin are needed to identify non-flow management objectives and determine what additional studies or data may be needed to assess these water objectives.

Objective: To identify the full set of management objectives that should be considered in determining environmental flow recommendations, including both ecological management goals (from Step 1) and non-ecological management goals, in addition to any regulatory requirements

Outcome of Step 8:

- A full set of management objectives, both ecological and non-ecological, and associated performance measures
- Relevant regulatory requirements necessary to evaluate objectives
- List of key stakeholders and a process for ongoing stakeholder engagement

Step 9. Assess Flow Alteration

Objective: To evaluate whether flow conditions at the location(s) of interest (LOI) are likely unaltered, likely altered, or indeterminate by comparing present-day ranges of functional flow metrics for functional flow components to the ecological flow criteria defined in Step 7

Outcome of Step 9:

- Determination of which functional flow metrics and flow components are altered
- Comparison of current and reference annual hydrology using dimensionless hydrographs (optional)
- Identification of likely causes of hydrologic alteration

There is a limited amount of flow data available within the Little Shasta River basin; however, we explored available gage data to assess historical and current flows. To evaluate whether historical observed flows at the USGS gage located upstream of Cold Spring and LOI3 (see Figure 2) were altered compared to the natural functional flow metrics (FFM) predicted for that stream segment (one stream reach upstream of the stream reach associated with LOI3), we compared the natural range of functional flow metrics to the observed historical range of metrics calculated from the daily flow data. This comparison also provided insight on the degree to which the natural functional flow metric predictions accounted for flow contributions from the discrete springs in the area. Additionally, in order to determine whether current observed flows at LOI 3 were likely altered, the observed functional flow metric ranges at the existing LSR stream gage were compared to the ecological flow criteria ranges.

When comparing natural predicted and observed functional flow metrics quantitatively, observed conditions were considered *likely unaltered* if both the median observed value and more than 50% of the observations fell within the 10th to 90th interpercentile range of natural values. Observed conditions were considered *likely altered* if the median observed value fell outside the 10th to 90th interpercentile range of natural values. Alteration was *indeterminate* if the median observed value fell within the 10th to 90th interpercentile range of natural values but less than 50% of the observations fell within the 10th to 90th interpercentile range of natural values. For metrics that were considered likely altered, the direction of alteration was categorized as high or low and early or late, depending on the metric units. Further details on this evaluation are provided in CEFF Appendix J: Assessing Flow Alteration.

The historical USGS gage (11516900) was located upstream of LOI3 and Cold Spring and was operational from October 1957 - September 1978 (WY 1958-1978). With no known impacts to streamflow at this location during this period, we considered this gage to be of reference quality, such that observed flows likely reflected a natural flow regime. Daily discharge data was downloaded from USGS, and the suite of functional flow metrics was calculated using the Functional Flows Calculator API client package in R (version 0.9.7.2, https://github.com/ceff-tech/ffc_api_client). These metrics were then compared to the predicted natural functional flow metrics obtained from the Natural Flows database to determine the degree to which the modeled natural flow predictions corresponded to observed reference flows. Figure 9 shows the dimensionless hydrograph for the observed daily flows at the USGS gage and highlights the predominantly snowmelt-driven flow regime. Table 9 provides the predicted natural and observed historical functional flow metrics at the USGS gage, as well as the results of the alteration analysis. All metrics were found to be likely unaltered, with the exception of the 5-year flood duration, which was found to be indeterminate as more than 50% of the annual observed values fell outside the range of predicted natural values. These results provided confidence that the predicted natural functional flow metrics were appropriately characterizing natural reference flows in these upper foothill reaches upstream of the discrete spring inputs.

In the next stream reach downstream at LOI3, the predicted natural flow metrics (shown in Table 2) were very similar to the natural flow metrics at the USGS gage location (Table 9) with only a few cfs increase in many of the magnitude metrics, as would be expected with the slightly larger upstream watershed area at LOI3. However, as LOI3 is downstream of Cold Spring with a flow input of 10 cfs year-round, we would expect this additional flow contribution to be included, particularly in the baseflows. As it was not, we thus chose to add this discrete flow contribution to the ecological flow criteria for LOI3, as discussed in step 2 above. Yarnell et al. (2022) provides further discussion of groundwater contributions to streams, both broadly and within CEFF, and includes this case study of the Little Shasta River as an example.

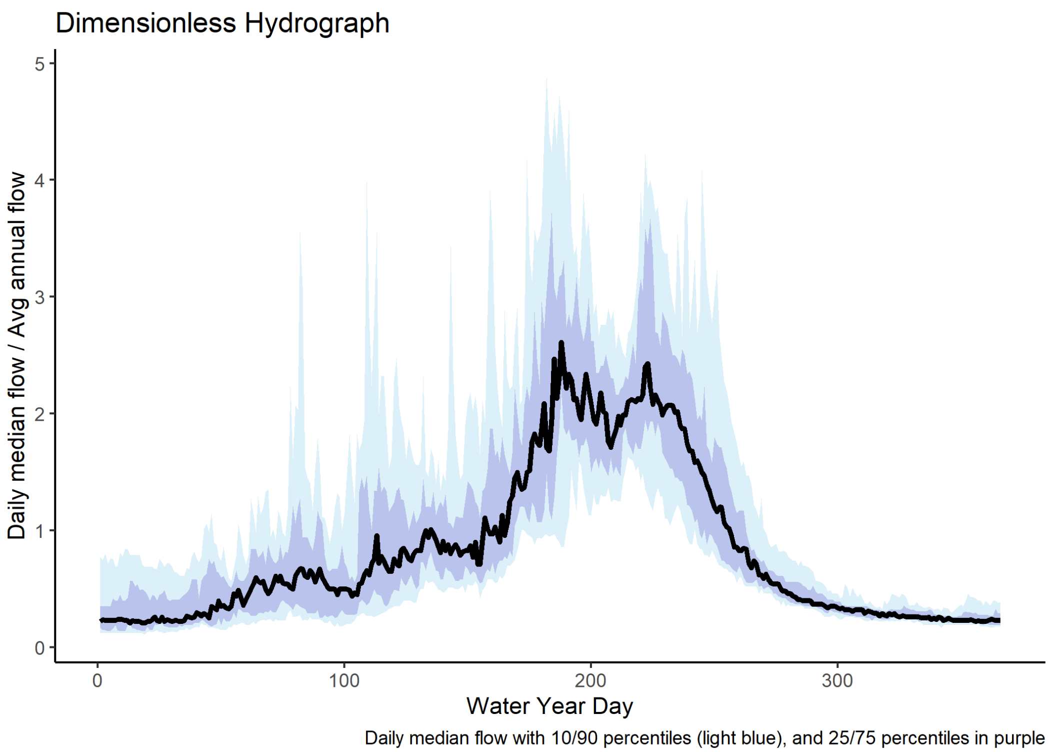

Figure 9. Dimensionless hydrograph for daily discharge collected at USGS gage 11516900 from WY 1958-1978. See figure 2 for location of gage upstream of Cold Spring on the Little Shasta River. Black line represents the daily median (50th percentile) flow over the period of record divided by the average annual flow; light blue and purple bands reflect the 10th-90th percentiles and 25th-75th percentiles of daily flow divided by average annual flow, respectively. Water Year day 1 equals October 1.

Table 9. Observed functional flow metrics and natural predicted functional flow metrics for all years combined at the USGS gage (11516900) location upstream of Cold Spring and LOI3 on the Little Shasta River. Values reflect median and 10th – 90th percentiles of functional flow metrics. Observed flows reflect hydrologic conditions from WY 1958-1978. Alteration status and direction (high/low; early/late) is also provided based on comparing observed functional flow metrics to the predicted functional flow metrics.

Flow Component	Flow Metric	Natural FF Metrics at USGS gage	Observed FF Metrics at USGS gage	Alteration Status & Direction
		median (10th-90th percentile)	median (10th - 90th percentile)	
Fall pulse flow	Fall pulse magnitude (cfs)	25 (7-68)	17 (8-22)	Likely Unaltered
	Fall pulse timing (WY day)	33 (6-61)	39 (13-55)	Likely Unaltered
	Fall pulse duration (days	4 (2-8)	2 (2-5)	Likely Unaltered
Wet-season baseflow	Wet-season baseflow (cfs)	11 (1-24)	9 (4-13)	Likely Unaltered
	Wet-season median flow (cfs)	32 (6-64)	24 (9-46)	Likely Unaltered
	Wet-season timing (WY day)	90 (24-157)	95 (35-151)	Likely Unaltered
	Wet-season duration (days)	114 (59-207)	124 (64-178)	Likely Unaltered
Peak flows	2-year flood magnitude (cfs)	88 (15-325)	130	Likely Unaltered
	2-year flood duration (days)	2 (1-5)	4 (1-9)	Likely Unaltered
	2-year flood frequency (# per season)	1 (1-3)	2 (1-4)	Likely Unaltered
	5-year flood magnitude (cfs)	122 (53-752)	208	Likely Unaltered
	5-year flood duration (days)	1 (1-3)	2 (1-5)	Indeterminate
	5-year flood frequency (# per season)	1 (1-2)	1 (1-2)	Likely Unaltered
	10-year flood magnitude (cfs)	209 (128-1570)	270	Likely Unaltered
	10-year flood duration (days)	1 (1-2)	2 (1-3)	Likely Unaltered
	10-year flood frequency (# per season)	1 (1-2)	1 (1-2)	Likely Unaltered

Flow Component	Flow Metric	Natural FF Metrics at USGS gage	Observed FF Metrics at USGS gage	Alteration Status & Direction
		median (10th-90th percentile)	median (10th - 90th percentile)	
Spring recession flows	Spring recession magnitude (cfs)	86 (29-265)	78 (36-133)	Likely Unaltered
	Spring timing (WY day)	228 (185-252)	223 (189-248)	Likely Unaltered
	Spring duration (days)	75 (42-123)	78 (69-107)	Likely Unaltered
	Spring rate of change (percent)	0.056 (0.04-0.08)	0.051 (0.04-0.07)	Likely Unaltered
Dry-season baseflow	Dry-season baseflow (cfs)	8 (1-17)	4 (3-8)	Likely Unaltered
	Dry-season high baseflow (cfs)	10 (2-34)	7 (4-16)	Likely Unaltered
	Dry-season timing (WY day)	299 (266-333)	299 (278-323)	Likely Unaltered
	Dry-season duration (days)	160 (78-235)	169 (72-226)	Likely Unaltered

The LSR gage (CDEC station ID: LSR) at LOI3 was installed in 2017 and provides 15-minute instream flow data. Figure 10 shows the observed flow data from WY 2018-2021. Annual functional flow metrics were calculated for WY 2018-2020 and were compared to the ecological flow criteria determined in section B (Table 10). Because flow data was not available after September, 2021, functional flow metrics could not be calculated for WY 2021 as the start of the following WY 2022 wet season (and thus end of the WY 2021 dry season) could not be determined. A full alteration analysis comparing the distribution of observed and natural function flow metric values (per CEFF Appendix J) and calculation of the peak flow metrics could also not be completed as a minimum of 10 years of streamflow data is required for both. For all three years, the observed duration and timing annual flow metrics were within the range of ecological flow criteria, but the wet season and dry season baseflow magnitudes were below the range of ecological flow criteria. Similarly, the dry season high baseflow magnitude, which reflects the 90th percentile of flow during the dry season typically observed in early summer, was either at or below the bottom of the range of flow criteria. The wet season median flow and spring recession magnitudes were within the range of flow criteria each year, but below the median flow criteria value, including in the wet year of 2019. A distinct fall pulse was not quantified in either WY 2018 or WY 2020, but was quantified in WY 2019. Continued flow data collection over the next five years will allow for a more comprehensive analysis of potential flow alteration.

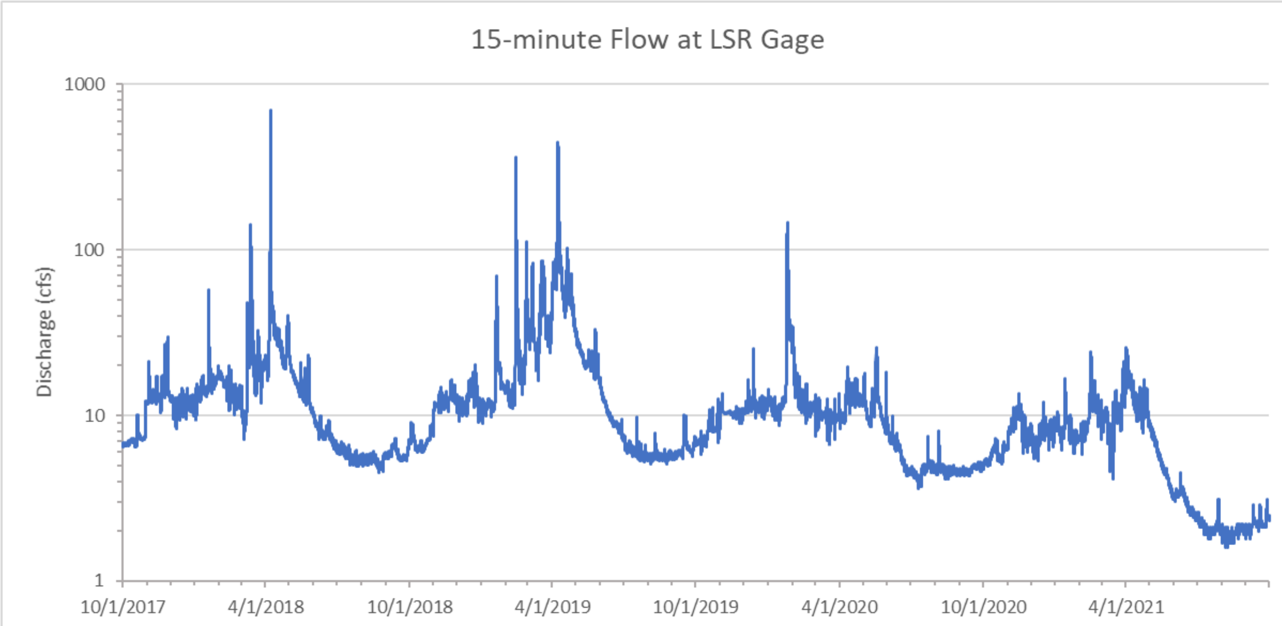

Figure 10. 15-minute discharge in cubic feet per second at the LSR gage located at LOI3 for WY 2018 - 2021. Note y-axis is shown on a logarithmic scale to highlight variability in lower values.

Table 10. Ecological flow criteria for all years combined developed from Section A and/or B for Little Shasta River (LOI 3) and observed annual functional flow metrics for each water year at the LSR flow gage at LOI 3. Flow criteria values reflect median and 10th – 90th percentiles of flow metrics. Observed functional flow metrics at LOI3 reflect the metric value calculated for each water year from 2018 to 2020. Values of NA indicate the metric was not able to be calculated due to a lack of occurrence or aseasonal irregularities in flow patterns that could not be accounted for in the metric calculation algorithms. Peak flow metrics are not included, as a minimum of 10 years of flow data is needed for calculations.

Flow Component	Flow Metric	Ecological Flow Criteria at LOI 3	Observed Metrics at LOI 3 - 2018	Observed Metrics at LOI 3 - 2019	Observed Metrics at LOI 3 - 2020
		median (10th-90th percentile)	Annual value	Annual value	Annual value
Fall pulse flow	Fall pulse magnitude (cfs)	38 (17-84)	NA	14	NA
	Fall pulse timing (WY day)	32 (6-61)	NA	53	NA
	Fall pulse duration (days	4 (2-8)	NA	3	NA
Wet-season baseflow	Wet-season baseflow (cfs)	21 (11-38)	9	11	8
	Wet-season median flow (cfs)	33 (5-69)	13	22	11

Flow Component	Flow Metric	Ecological Flow Criteria at LOI 3	Observed Metrics at LOI 3 - 2018	Observed Metrics at LOI 3 - 2019	Observed Metrics at LOI 3 - 2020
		median (10th-90th percentile)	Annual value	Annual value	Annual value
	Wet-season timing (WY day)	74 (23-149)	13	96	4
	Wet-season duration (days)	121 (59-211)	183	100	120
Spring recession flows	Spring recession magnitude (cfs)	90 (25-308)	33	65	31
	Spring timing (WY day)	223 (161-251)	196	196	124
	Spring duration (days)	78 (41-127)	86	87	158
	Spring rate of change (percent)	0.056 (0.04-0.08)	0.037	0.038	0.047
Dry-season baseflow	Dry-season baseflow (cfs)	19 (11-30)	7	6	5
	Dry-season high baseflow (cfs)	21 (12-45)	12	7	6
	Dry-season timing (WY day)	299 (264-334)	282	283	282
	Dry-season duration (days)	148 (81-227)	180	87	120

Step 10. Evaluate alternative management scenarios and address tradeoffs

Objective: To explore non-flow and flow-based strategies to satisfy ecological flow criteria, quantify the ecological consequences of failing to satisfy ecological flow criteria, and propose mitigation measures to offset impacts, if any.

Outcome of Step 10:

- Tradeoff analysis between ecological and non-ecological management objectives under alternative management scenarios
- Identification of preferred management alternative

An evaluation of the potential effects of alternative management actions on the ecological management goals from step 1 and the non-ecological management goals from step 8 should be completed in consultation with watershed community members and stakeholders. Below, we provide additional considerations and suggestions that may be helpful in future discussions.

Based on the information evaluated in steps 5 and 6, while channel incision likely does not severely limit floodplain connection currently in the lower Little Shasta valley, we suggest community members consider management actions that support increased floodplain functionality in winter and spring and promote higher stream flows in the summer. Limited floodplain connection reduces winter recharge to shallow groundwater exacerbating limited surface-groundwater connectivity during the summer and fall seasons. Actions could include, but are not limited to, strategic stream channel restoration to improve floodplain connectivity, riparian fencing and planting to promote a more robust riparian vegetation community, installation of BDAs or other large wood structures that promote instream habitat diversity and increased residency time of surface water, and voluntary water use efficiency improvements.

We also suggest the community consider conducting trade-off analyses regarding the potential effects of prioritizing fish passage functions over juvenile rearing habitat functions in LOI1 and LOI2 where agricultural water demands remain high. Currently, coldwater rearing habitat exists year-round within LOI3 and would likely be conducive to over-summering by juvenile coho salmon. However, we believe that one of the greatest limiting factors on anadromous salmonid production in the Little Shasta River is availability of flow for migration, particularly during fall (adult access) and again during spring (juvenile outmigration). As such, the community may want to explore options for first providing sufficient fall and spring flows (over discrete periods) to cue both spawning and outmigration of juvenile salmon, while also choosing to maintain viable year-round rearing habitat at LOI3. Additional actions to promote improved stream habitat throughout the year within the Little Shasta Valley could be addressed with a phased approach over time.

Lastly, based on the studies conducted to date within the Little Shasta basin, we suggest that numerous spring accretions around LOI3 likely played a vital role in providing important over-summering habitat for coldwater species, supporting robust food webs during rearing, and contributed to important salmonid life history diversity. As such, the community may want to consider analyzing potential tradeoffs of dedicating spring water to ecosystem function, while replacing or trading such diversions for less “ecologically valuable” surface runoff. Initial results of such analyses, provided by Lukk et al. (2022), suggest greater ecosystem benefits associated with spring water than surface runoff. Following any future flow dedications, detailed monitoring of ecological responses is needed to assess the effect and determine whether expectations are being met.

Step 11. Define environmental flow recommendations

Once all analyses, studies, and discussions regarding ecological and non-ecological management objectives have been completed, community members and stakeholders in the Little Shasta basin should establish their environmental flow recommendations and any associated non-flow management actions.

Objective: To select a preferred management alternative set of environmental flow recommendations in collaboration with stakeholders and agency partners based on the results from the previous 10 steps, and then to develop the final set of environmental flow recommendations

Outcome of Step 11:

- Final set of environmental flow recommendations
- List of measures to enhance the effectiveness of environmental flows or mitigate adverse effects (if final recommendations deviate from ecological flow criteria)

Step 12. Develop implementation plan

An adaptive management plan for the Little Shasta basin coordinated with an implementation plan for actions identified in step 11 will be key for future management considerations related to climate change impacts. Plans that allow for ongoing assessment and support of ecosystem functions will be essential for maintaining and increasing climate resilience within the Little Shasta River ecosystem.

Objective: To develop an implementation plan that includes an adaptive management plan and monitoring strategy that will guide implementation of environmental flow recommendations, including the associated mitigation measures

Outcome of Step 12:

- Implementation plan that includes mitigation measures and adaptive management
- Monitoring strategy that informs adaptive management

References

Adams, F., Harding, S., Robertson, R., and Tait, C. (1912). "Reports on the Irrigation Resources of California", (ed.) U.S. Department of Agriculture. (Washington, D.C.: F.W. Richardson, Superintendent of State Printing).

CDFG (California Department of Fish and Wildlife). (2015). “Draft Conservation Plan for Gray Wolves in California: Part II”.

Chow, V.T. (1959). *Open-channel hydraulics*. McGraw-Hill New York.

Cunjak, R.A. (1988). Physiological Consequences of Overwintering in Streams: The Cost of Acclimitization? *Can. J. Fish. Aquat. Sci.* 45 (3), 443–452. doi:10.1139/f88-053.

CWHR (California Wildlife Habitat Relationships Database). (2021). Available at: https://wildlife.ca.gov/Data/CWHR/Life-History-and-Range.

CWQMC-EFW (2021). “California Environmental Flows Framework”. Version 1.0, April, 2021. California: California Water Quality Monitoring Council - Environmental Flows Workgroup. Available at: https://ceff.ucdavis.edu/tech-report.

Davidson, R.S., Letcher, B.H., and Nislow, K.H. (2010). Drivers of Growth Variation in Juvenile Atlantic salmon (Salmo salar): an Elasticity Analysis Approach. *J. Anim. Ecol.* 79 (5), 1113–1121. doi:10.1111/j.1365-2656.2010.01708.x

Falcone, J.A., Carlisle, D.M., Wolock, D.M., and Meador, M.R. (2010). GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States: Ecological archives E091-045. *Ecology* 91(2), 621-621.

Grantham, T.E., Carlisle, D.M., Howard, J., Lane, B., Lusardi, R., Obester, A., et al. (2022). Modeling Functional Flows in California’s Rivers. *Frontiers in Environmental Science* 10. doi: 10.3389/fenvs.2022.787473.

Hilsenhoff WL. (1987). An improved biotic index of organic stream pollution. *Great Lakes Entomologist* 20: 31-39.

Howard, J., and Merrifield, M. (2010). Mapping Groundwater Dependent Ecosystems in California. *Plos One* 5 (6), e11249. doi:10.1371/journal.pone.0011249.

Lukk, A.K., Lusardi, R.A., and Willis, A.D. (2022). Not all water is equal: Improving stream ecosystem function and prioritizing cold source waters in a working landscape. *Journal of Water Resources Planning and Management*.

Lukk, A., Vasquez-Housely, P., Lusardi, R., and Willis, A. (2019). “Little Shasta River 2017-2019: Pre-Project Assessment of the Proposition 1 Ecosystem Restoration Grant Activities”. Report prepared for California Trout and California Wildlife Conservation Board. 45 pp.

Lusardi, R.A., Bogan, M.T., Moyle, P.B., and Dahlgren, R.A. (2016). Environment shapes invertebrate assemblage differences between volcanic spring-fed and runoff rivers in norther California. *Freshwater Science* 35(3): 1010-1022. doi: 10.1086/687114.

Lusardi, R.A., Hammock, B.G., Jeffres, C.A., Dahlgren, R.A., and Kiernan, J.D. (2020). Oversummer growth and survival of juvenile coho salmon (*Oncorhynchus kisutch*) across a natural gradient of stream water temperature and prey availability: an in-situ enclosure experiment. *Can. J. Fish. Aquat. Sci.* 77 (2), 413–424. doi:10.1139/cjfas-2018-0484.

Moyle, P.B. (2002). *Inland fishes of California: revised and expanded.* Univ of California Press.

Moyle, P.B., Lusardi, R.A., Samuel, P., and Katz, J. (2017). "State of the Salmonids: Status of California's Emblematic Fishes 2017". University of California, Davis; California Trout. Available from https://watershed.ucdavis.edu/files/content/news/SOS%20II_Final.pdf

NRC (National Research Council). (2004). "Endangered and threatened fishes in the Klamath River Basin: causes of decline and strategies for recovery." National Academies Press.

NCRWQCB (North Coast Regional Water Quality Control Board). (2006). "Staff Report for the Action Plan for the Shasta River Watershed Temperature and Dissolved Oxygen Total Maximum Daily Loads." North Coast Regional Water Quality Control Board. 55 pp.

Nichols, A.L., Lusardi, R.A., and Willis, A.D. (2017). "Little Shasta River Aquatic Habitat Assessment". Report prepared for the Nature Conservancy. 28 pp.

Nichols, A., Willis, A., Lambert, D., Limanto, E., and Deas, M. (2016). "Little Shasta River Hydrologic and Water Temperature Assessment: April to December 2015". Report prepared for the Nature Conservancy. 24 pp.

NMFS (National Marine Fisheries Service). (2014). "Final Recovery Plan for the Southern Oregon/Northern California Coast Evolutionarily Significant Unit of Coho Salmon (Oncorhynchus kisutch)." National Marine Fisheries Service. Arcata, CA

Patterson, N.K., Lane, B.A., Sandoval-Solis, S., Pasternack, G.B., Yarnell, S.M., and Qiu, Y. (2020). A hydrologic feature detection algorithm to quantify seasonal components of flow regimes. *Journal of Hydrology* 585, 124787.

Stein, E.D., Zimmerman, J., Yarnell, S.M., Stanford, B., Lane, B., Taniguchi-Quan, K.T., et al. (2021). The California Environmental Flows Framework: Meeting the Challenges of Developing a Large-Scale Environmental Flows Program. *Frontiers in Environmental Science* 9:769943. doi: 10.3389/fenvs.2021.769943.

SVRCD (Shasta Valley Resource Conservation District), McBain S., and Trush, B. (2013). "Study plan to assess Shasta River salmon and steelhead recovery needs". Report prepared for U.S. Fish and Wildlife Service: Arcata Fish and Wildlife Office.

Terrapoint. (2008). "Shasta Valley Airborne LiDAR Survey Overview". Report prepared for the Shasta Valley Resource Conservation District. 38 pp.

Willis, A. and Lusardi, R. (2021). "Final report of the Proposition 1 Ecosystem Restoration Grant Activities". December 2021. Report prepared for California Trout and the Wildlife Conservation Board. 29 pp.

Wolock, D.M. (2003). "Estimated mean annual natural ground-water recharge in the conterminous United States". US Geological Survey. Open File Report No. 2003-311. doi:10.3133/ofr03311.

Yarnell, S.M., Petts, G.E., Schmidt, J.C., Whipple, A.A., Beller, E.E., Dahm, C.N., et al. (2015). Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. *BioScience* 65(10), 963-972. doi: 10.1093/biosci/biv102.

Yarnell, S.M., Stein, E.D., Webb, J.A., Grantham, T., Lusardi, R.A., Zimmerman, J., et al. (2020). A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. *River Research and Applications* 36(2), 318-324.

Yarnell, S.M., Willis, A., Obester, A., Peek, R.A., Lusardi, R.A., Zimmerman, J., et al. (2022). Functional Flows in Groundwater-Influenced Streams: Application of the California Environmental Flows Framework to Determine Ecological Flow Needs. *Frontiers in Environmental Science* 9. doi:10.3389/fenvs.2021.788295.

Zimmerman, J.K., Carlisle, D.M., May, J.T., Klausmeyer, K.R., Grantham, T.E., Brown, L.R., et al. (2018). Patterns and magnitude of flow alteration in California, USA. *Freshwater Biology* 63(8), 859-873.

Appendix A. Updating Natural Functional Flow Metric Predictions

Overview

The underlying National Hydrography Dataset (NHD) used in the functional flow metric (FFM) modeling and displayed in the Natural Flows database incorrectly showed that seasonal flow conveyed through open ditches was included as part of the natural stream network and flow patterns of the Little Shasta River. This resulted in erroneous predictions of natural monthly flows and functional flow metrics where the Montague Conservation Water District canal crossed the Little Shasta River at river kilometer 16.7 and extending downstream, including LOI 1 and LOI 2. Upstream of the Montague canal, natural monthly flows and FFMs for the upper Little Shasta watershed were correct and served as validation data for the revision process described below.

The original FFM predictions provided in the Natural Flows database were generated using statewide datasets that were not easily adaptable to revisions at smaller individual watershed-scales. We therefore developed a process to correct the Little Shasta watershed delineation and generate updated FFM predictions for the lower Little Shasta watershed. We developed open source code in R to complete the process and successfully revised the Little Shasta streamflow network and associated sub-catchments to reflect natural conditions. While we confirmed the process for generating updated FFM predictions was correct, we were unable to recreate the exact same input dataset used in the original FFM models in the upper watershed due to uncertainty in scaling of several of the catchment attributes. Given these uncertainties as well as complexity in surface-groundwater interactions in the Little Shasta valley (see Yarnell et al. 2022 for discussion of groundwater influences), we suggest development of a local hydrologic model using the corrected watershed delineation and representing surface-groundwater interactions will provide more detailed and locally accurate predictions of functional flow metrics in the lower Little Shasta watershed.

The process for correcting the Little Shasta watershed delineation and generating updated FFM predictions is applicable to any watershed in California and is described below.

Correcting the Watershed Delineation

Watersheds across the US have been delineated into hierarchical scaled catchments associated with surface stream networks by the USGS. According to USGS: "Hydrologic Units (HUs) represent the area of the landscape that drains to a portion of the stream network. Each drainage has a unique Hydrologic Unit Code (HUC). The most current national HU dataset is the Watershed Boundary Dataset (WBD). The WBD is a companion to the National Hydrography Dataset (NHD), which contains information about the nation's surface hydrography. View both WBD and NHD using The National Map Viewer." HUCs are nested such that smaller drainages reside within larger hydrologic units as designated by their HUC number. HUC numbers range from 2 digits (large regional watersheds designated as a HUC2 scale) to 12 digits (small sub-watersheds designated as a HUC12 scale). The NHD contains both a delineated surface stream network and a set of catchments representing the area draining to a particular stream segment. Each stream segment has an associated unique COMID number, and the associated catchments are typically smaller in scale than HUC12 units. In theory, these two spatial datasets should nest and overlap directly with similar boundaries; however, in many locations including the Little Shasta watershed, this is not the case.

Figure A-1 shows the HUC8, HUC10, and HUC12 watersheds associated with the Little Shasta River (HUC10=1801020703) and the NHD catchments associated with the Little Shasta River stream network. The NHD catchments lie within the HUC8 boundary but overlap the HUC 10 and HUC12 boundaries in inconsistent ways due to an incorrect stream network delineation. Figure A-2 shows the NHD stream segments (flowlines) and associated catchments contributing to the Little Shasta River at its confluence with the Shasta River (COMID=3917946). The stream segments in the southern portion of the watershed represent the Montague canal that delivers water from Lake Shastina in the south to communities in the north. The NHD stream network has this canal incorrectly joining and contributing to the Little Shasta River, when in reality it bypasses the river and continues north. The natural topographic drainage of the Little Shasta River is most accurately represented by the HUC10 watershed boundary. We therefore needed to delineate the natural stream network within the HUC10 and ensure that the appropriate catchments were associated with each natural stream segment.

Using topographic data and field-based knowledge of the Little Shasta watershed, we distinguished natural stream segments from artificial (canal) segments within the HUC10 boundary and removed the artificial streams. We ensured each natural stream segment connected to a downstream segment and was correctly associated with the appropriate COMID number. Figure A-3 shows the natural and artificial stream segments and NHD catchments within the HUC10 boundary. We identified NHD catchments associated with each stream segment and created a revised NHD catchment layer that included all catchments occurring within and cropped to the HUC12 boundaries nested within the larger HUC10 boundary.

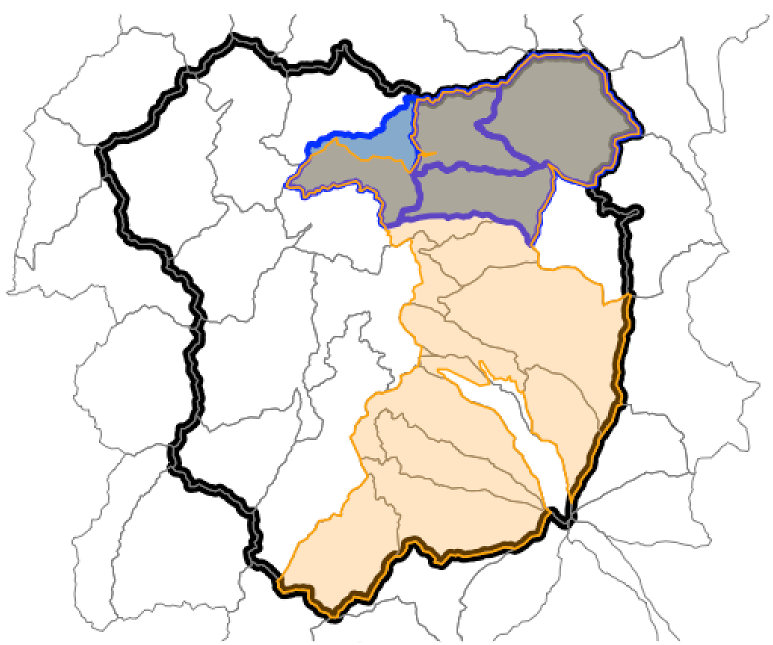

Figure A-1: Hydrologic Units and NHD catchments associated with the Little Shasta River. HUC8 boundary in black; HUC10 boundary in blue with nested HUC12 boundaries also in blue; NHD catchments in orange. Grey lines represent all HUC12 boundaries in the surrounding area.

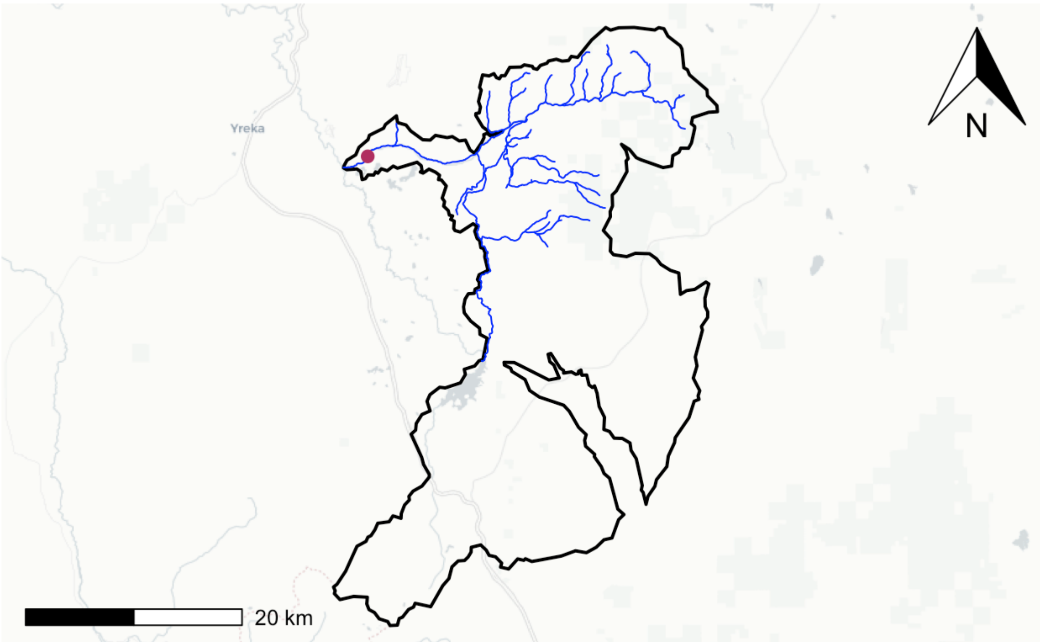

Figure A-2: NHD data for upstream catchment and flowlines associated with the Little Shasta River outlet (maroon dot, COMID=3917946).

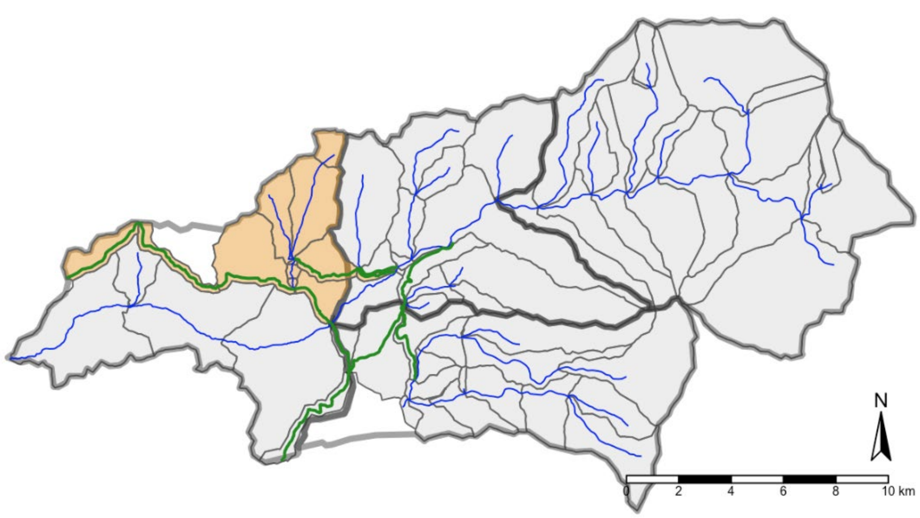

Figure A-3: HUC10 boundary (outer gray line) and nested HUC12 units (inner thick dark gray lines) for the Little Shasta River. NHD catchments within the HUC10 boundary are shown as thinner light gray lines. Blue lines show natural stream segments retained in the corrected delineation. Green lines show artificial stream segments (canals) removed. Orange catchments are those included within the HUC10 boundary but not within the original NHD catchments associated with the Little Shasta River.

We ensured each NHD catchment within the HUC10 was appropriately attributed to a single COMID and created a corrected stream network that routed each stream segment and catchment to a downstream segment, culminating at the Little Shasta confluence with the Shasta River. We generated an interactive flow network to check the stream segment connections and ensure each segment in the network was correctly linked to the upstream or downstream segment appropriately (Figure A-4). To ensure the flow accumulation within the stream network was correct, we plotted the accumulated flow from upstream to downstream using the calculated "arbolate sum", which is the cumulative total length of all upstream stream segments (Figure A-5). As expected, stream segments became wider (reflecting increased cumulative length) in the downstream direction towards the Little Shasta River outlet. This flow network ensured effective surface water routing through the catchments and allowed for generation of the catchment accumulation data needed in the FFM models.

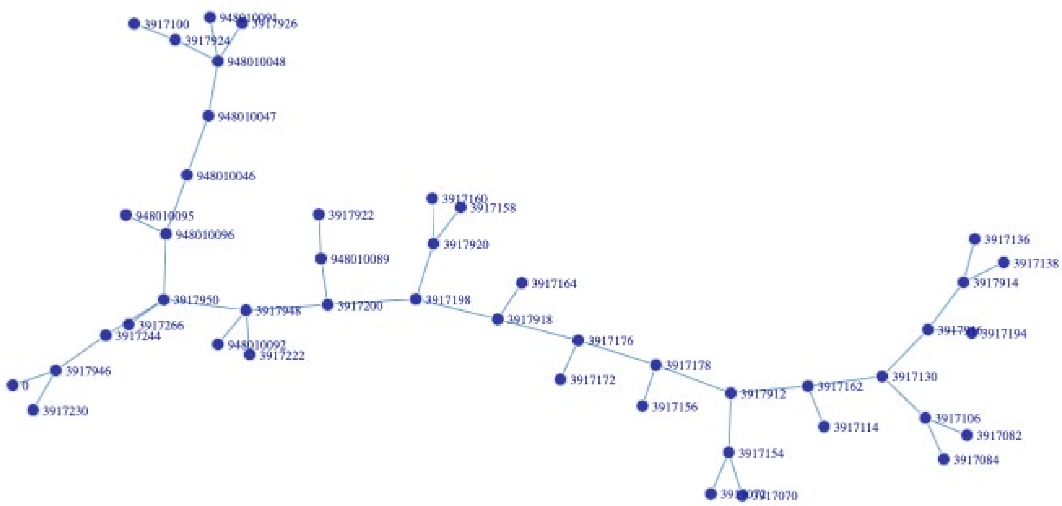

Figure A-4: Little Shasta flow network representation showing how stream segments are linked from upstream to downstream (right to left). Dots represent the upstream start of each stream segment and are labeled with the segment COMID. The downstream outlet with the Shasta River is denoted as "0".

Figure A-5: Cumulative total length of all upstream stream segments in the Little Shasta River. Greater width lines reflect greater cumulative stream length upstream.

Generating catchment data for FFM models

With the revised watershed delineation and corrected natural streamflow network, we calculated the catchment area and cumulative total drainage area for each NHD catchment. We downloaded the remainder of the catchment attributes required for the FFM models from ScienceBase (https://www.sciencebase.gov/catalog/item/5669a79ee4b08895842a1d47), which included over 250 variables describing climate, geology, and soils, among others (variable description here). The accumulation of upstream catchment attributes was then calculated for each variable for each catchment. For example, runoff associated with a catchment area was influenced by the upstream catchment areas and their associated attributes. Accumulation was calculated in a variety of ways (e.g. as the min, max, or average of upstream catchment attributes) depending on the variable; however, the most common method was to determine an area weighted average, where the area weight was the local catchment area divided by the cumulative total drainage area. In headwater catchments, the area weight equaled 1, as the local catchment area and the cumulative total drainage area was the same. Figure A-6 shows the cumulative total drainage area and area weight for each catchment. The cumulative total drainage area for the Little Shasta watershed was 238.57 km^2. The calculated accumulation values for each variable in each year in each catchment was then collated as the final input dataset for the FFM models. The FFM models are described in Grantham et al. (2022) and the CEFF technical report (CWQMC-EFW, 2021).

In the original FFM modeling effort, the downloaded catchment variables and attributes were scaled prior to calculating accumulation values, in order to provide a common set of units and magnitudes for the modeling. Unfortunately, the exact scaling factors used in the original modeling effort were unknown. We applied a variety of common scaling factors to the data, but we were unable to reproduce the exact same final input dataset for the upper watershed. However, once a known scaling factor is described, catchment accumulation values should be reproducible.

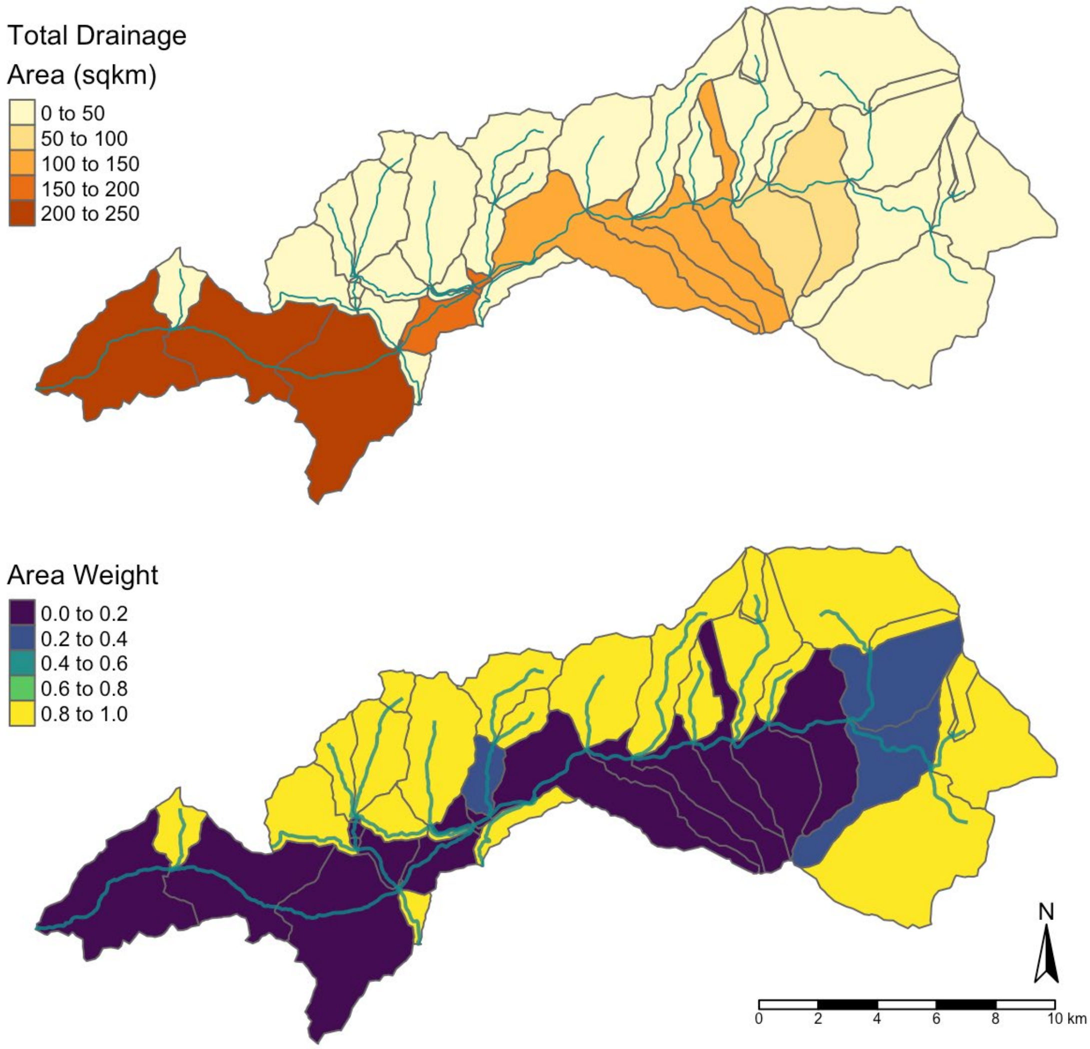

Figure A-6: Little Shasta watershed delineation showing cumulative total drainage area and area weight (local catchment area divided by cumulative total drainage area) for each NHD catchment.

The framework to derive this process and analysis was built on the {targets} package in R (version 4.1.3), which permits singular changes to any point in the workflow and allows the user to rerun only the components that are subsequently affected. The code, data, and associated descriptions can be found at: [https://github.com/ryanpeek/ffm_targets.](https://github.com/ryanpeek/ffm_targets)

Appendix B. Channel Incision Analysis

To assess the presence and extent of channel incision near each of the three LOIs, cross-sections were derived from a digital elevation model of the Little Shasta watershed. Figure B-1 shows the locations of each cross-section in the stream segments associated with each LOI. Bankfull flow was estimated at each cross-section, as described in Section B Step 6, and compared to the estimated 2-year flood magnitude. If the bankfull flow was greater than the 2-year flood magnitude, then we considered the channel incised. The channel geometry and calculated bankfull flow for each cross-section are provided in Table B-1.

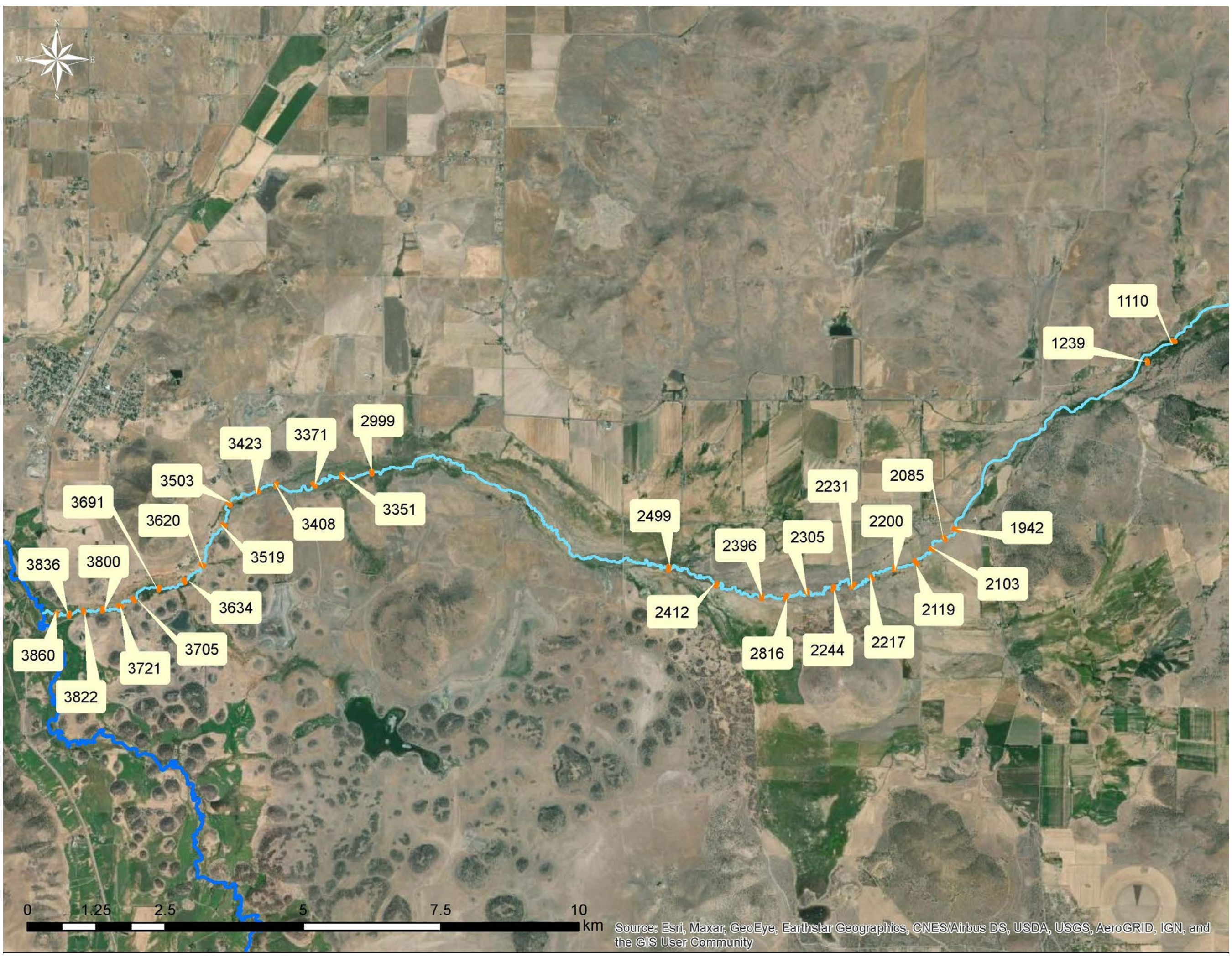

Figure B-1. Location of cross-sections assessed in the lower Little Shasta River in the stream segments associated with each LOI. Cross-section IDs correspond to data shown in Table B-1.

Table B-1. Channel geometry for each cross section used to explore incision in the Little Shasta River. Incision was determined based on whether the bankfull flow of the current geometry exceeded the 2-year flood flow of approximately 150 cfs.

cross section ID	LOI #	channel slope	Manning's n	Area (sq. ft)	hydraulic radius	bankfull flow (cfs)
2999	LOI_1	0.004555	0.03	67.02	1.48	291
3351	LOI_1	0.004555	0.03	18.62	1.18	70
3371	LOI_1	0.004555	0.03	29.93	1.15	110
3408	LOI_1	0.004555	0.03	67.79	1.85	342
3423	LOI_1	0.004555	0.03	41.97	1.07	147
3503	LOI_1	0.004555	0.03	13.29	0.55	30
3519	LOI_1	0.004555	0.03	21.49	0.75	59
3620	LOI_1	0.004555	0.03	43.61	1.36	180
3634	LOI_1	0.004555	0.03	93.59	1.77	459
3691	LOI_1	0.004555	0.03	6.41	0.3	10
3705	LOI_1	0.004555	0.03	98.68	1.6	452
3721	LOI_1	0.004555	0.03	65.97	1.87	336
3800	LOI_1	0.004555	0.03	143.1	2.99	995
3822	LOI_1	0.004555	0.03	54.75	1.56	247
3836	LOI_1	0.004555	0.03	44.83	0.83	133
3860	LOI_1	0.004555	0.03	124.67	2.16	699
1942	LOI_2	0.007159	0.048	17.28	0.5	29
2085	LOI_2	0.007159	0.048	165.36	2.37	773
2103	LOI_2	0.007159	0.048	36.04	1	94
2119	LOI_2	0.007159	0.048	83.01	1.48	284
2200	LOI_2	0.007159	0.048	94.68	1.46	320
2217	LOI_2	0.007159	0.048	15.89	0.48	26
2231	LOI_2	0.007159	0.048	86.47	1.15	249
2244	LOI_2	0.007159	0.048	49.5	0.86	117
2305	LOI_2	0.007159	0.048	8.73	0.34	11
2327	LOI_2	0.007159	0.048	72.84	1.66	268
2396	LOI_2	0.007159	0.048	23.65	0.82	55
2412	LOI_2	0.007159	0.048	74.36	2.37	347
2499	LOI_2	0.007159	0.048	26.85	0.73	57
1110	LOI_3	0.019151	0.035	12.68	0.47	45
1239	LOI_3	0.019151	0.035	59.96	1.78	519