REVIEW OF THE TRINITY RIVER RESTORATION PROGRAM FOLLOWING PHASE 1, WITH EMPHASIS ON THE PROGRAM'S CHANNEL REHABILITATION STRATEGY

Prepared for
Trinity River Restoration Program

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1 INTRODUCTION

The Trinity River Restoration Program (hereafter the Program) requested that their Science Advisory Board (SAB) evaluate the channel rehabilitation projects built by the Program to mitigate the downstream effects of the Trinity and Lewiston Dams on naturally spawning salmon. Such projects were identified and recommended in the Program's flow evaluation study (USFWS and HVT 1999) and their efficacy was to be assessed after half of them were built (hereafter referred to as Phase 1). The rehabilitation projects involve mechanical alteration of the channel, riparian planting, wood placement, and gravel augmentation (bar placement and high-flow injection) to restore fish and wildlife habitat in accordance with the Record of Decision (ROD; USDOI 2000). These actions are part of the Program's management strategy of fostering a dynamic channel and floodplain system with a proper bed substrate and temperature regime for salmonids via managed dam releases, sediment augmentation or retention, and bank rehabilitation (USFWS and HVT 1999). The ultimate goal of these actions is to restore salmonid populations, with a specific focus on in-river production of presmolts from the restoration reach, which extends 64 kilometers along the mainstem river from Lewiston Dam to the confluence of the North Fork Trinity River.

The Program requested development of a review document that would assess Phase 1 activities within the context of the Program's foundational documents (USFWS AND HVT 1999; USDOI 2000) and provide direction for the second phase of implementing channel rehabilitation projects. In addition they posed a series of basic questions, including "Are we on the right track?" "Which rehabilitation projects and design elements are successful?" "What should be done for Phase 2?" The answer to these questions depends on how one defines success (i.e., what the goals and metrics are, and how much change is enough). As mentioned above, the primary geomorphic objectives of the Program are to create a dynamic fluvial system that would increase suitable fish and wildlife habitat and restore the wild salmon fishery, with the latter being, presumably, the *fundamental objective*. As such, it is important to note that the channel rehabilitation projects are *means* toward achieving the *fundamental objective*. For example, creation of fish habitat without a corresponding increase in fish production would not be considered a Program success. Moreover, to evaluate the rehabilitation projects in terms of the above objectives, multiple spatial and temporal scales must be considered beyond evaluation of as-built features and associated habitat at rehabilitation sites. In this regard, it is important to recognize that Program management activities aimed toward achieving a more dynamic river system involve not just channel form, but also the interplay of channel structure and geomorphic processes, seasonally dynamic flow regimes, and seasonally targeted water temperatures that collectively create a system-wide distribution of habitats that may exhibit considerable spatial and temporal variability in suitability for specific fish life stages. Success in meeting Program goals is ultimately measured in annual quantitative assessments of in-river production of juvenile salmonid fishes. Consequently, to form any view of successes achieved by the Program during Phase 1 required a substantial broadening of the scope and complexity of our task, making it more of a comprehensive review of Program activities.

In addition, we were charged with conducting an unconventional review for an advisory board. Rather than reviewing a report produced by the Program, the SAB was asked to compile information and develop a comprehensive report that would provide an independent and impartial assessment of Phase 1 activities and progress toward achieving Program goals and objectives, along with recommendations for Phase 2. This involved reviewing and synthesizing existing Program publications, as well as conducting original work using available data and the assistance of a support contractor. Given the preponderance of information and reports produced by the Program and the geographical separation among the SAB members, Program staff, Partners, and support contractor, this became a daunting task stretching over many months.

The report summarizes Phase 1 activities and the physical and biological responses from 2005-2011, followed by recommendations for Phase 2. A series of appendices (A-H) provide supporting information and analyses. Where possible, we used four spatial scales to capture changes over time: (1) *river system* or *restoration reach* ~ the 64 km (40 mile) mainstem river from Lewiston Dam to the North Fork Trinity River confluence; (2) *reach* ~ segments of the mainstem river having a particular set of characteristics, such as a given channel morphology, sediment load, or hydrology; (3) *project* or *site* ~ a length of mainstem channel and its floodplain and terrace that was influenced by a channel rehabilitation project, or in some cases, a suite of related projects; and (4) *design element* or *feature* ~ a component of a channel rehabilitation project, such as a side channel, bench, or skeletal bar (USFWS AND HVT 1999; HVT et al. 2011).

In conducting our review, it quickly became apparent that our task would be hampered by insufficient data and/or insufficient time since project implementation to observe geomorphic changes and associated fish population responses. Ideally, we would examine dynamic responses to different project designs at site and system scales and consequent changes in fish production. However, those data were not available. Instead, the available data mainly documented constructed changes in low-flow habitat, limited geomorphic responses, and fish abundance at system scales. The Program's habitat monitoring focusses on low-flow, juvenile, rearing habitat because it is a spatially and temporally consistent flow for sampling and because it is similar to flows during the critical winter and early spring rearing periods (Alvarez et al. 2013). Geomorphic responses were limited not from a lack of effort, but because of insufficient time since project completion and from physical constraints that were not fully appreciated in the foundational documents and associated conceptual models; in particular, the occurrence of mining terraces, bedrock boundaries, and legacy bed material (large sediment that is difficult for post-ROD flows to move) make the river less alluvial and less responsive than originally hypothesized. This is compounded by the fact that few geomorphically effective flows (i.e., wet-year and extremely wet-year ROD flows) occurred during the study period and many such events are needed over time to create a dynamic fluvial environment, particularly for this river system given the above physical constraints. Although the available data were informative and allowed some assessment of progress toward Program goals and objectives, additional information is needed to fully assess the synergistic effects of Program activities (management of flow, temperature, sediment, and channel morphology) over space and time to understand the effects on fish production. To move the Program Partners and the public toward better understanding the dynamic nature of the river system, our primary recommendation is that the Program focus immediate attention toward development of a Decision Support System (DSS). A DSS is a series of linked physical and biological models that will allow the Program to (1) predict site and system response to alternative management actions in relation to ROD and stakeholder objectives; (2) make such predictions in a timely fashion (ahead of monitoring results); (3) focus and refine monitoring efforts; and (4) provide a necessary tool for adaptive management. Additionally, it will help to better structure and integrate Program activities and increase the defensibility and transparency of management actions.

2 SUMMARY OF FINDINGS

2.1 Phase 1 Activities

Details of the Phase 1 channel rehabilitation activities are given in Appendices C and G and are summarized here. During Phase 1 (2005-2010), 15 rehabilitation projects were completed along the course of the restoration reach (Table 1, Figure 1). Projects were initially focused on removing riparian berms that had encroached on the river following dam closure, lowering floodplains to match the post-ROD flow regime, and creating point bars that would promote a dynamic river. The conceptual model for these activities was that if restraining features were removed, fluvial processes would take over, creating a more dynamic and complex river that, in turn, would offer more productive habitat for fish and wildlife (USFWS AND HVT 1999; USDOI 2000). It was also recognized that the river could not be restored to pre-dam conditions and that it would have to be scaled down to the post-ROD flow regime (USFWS AND HVT 1999). However, the initial rehabilitation projects produced little immediate dynamic geomorphic response. Consequently, the degree of mechanical intervention and complexity of projects increased over time. The intent of these more intensive projects was, in part, to create immediate habitat and to construct large-scale channel features that would interact with flood flows and drive more rapid channel changes. This change in design strategy was based on lessons learned and, in general terms, is a type of adaptive management, but represents a shift from the foundational notion that a more dynamic river could be created with minimal bank reconstruction (USFWS AND HVT 1999; HVT et al. 2011) . The rehabilitation strategy of minimal mechanical intervention was not well-defined in the flow evaluation report (USFWS and HVT 1999), and although nearly all features being used in present designs were anticipated in that document, there is a strong perception among some Partners and some of the public that channel rehabilitation projects are much larger and more complex than anticipated. Differences in the requisite degree of mechanical intervention and the expected habitat end point (e.g., driving fluvial processes *vs.* constructing habitats) have not been fully resolved within the Program or with the public. The size and design of the projects should match the Program's basic premise of promoting dynamic fluvial processes leading to a new channel form that is expected to provide significantly increased spawning and rearing habitat for anadromous salmonids (USFWS and HVT 1999). This is in keeping with the Program strategy that "restoring salmonid populations must be founded on rehabilitating and managing fluvial processes that create and maintain habitats vital to anadromous fish" (USFWS and HVT 1999). This instills the interplay of mechanical intervention with management of flow, sediment, and water temperature.

The stated goals for the early projects tended to be general, typically invoking ROD objectives without specifically articulating how they would be achieved beyond the concepts stated in the foundational documents (USFWS AND HVT 1999; USDOI 2000). Objectives have become more specific as projects have become more complex and as design guidelines have been developed (HVT et al. 2011). In addition, predictive numerical models are now being used by the Program to assess salmon rearing habitat availability and potential geomorphic responses for a given project design. However, fish population response has not been linked to habitat change over time through modeling efforts as called for in the Program's foundational documents, nor in most cases are the models used to compare predicted outcomes from alternative site designs. Projects have rarely been treated as opportunities for hypothesis testing. As such, the primary Program activities related to channel rehabilitation activities involve implementation and monitoring.

Several important advances have occurred with regard to the design process as it has evolved over time: (1) it is a collaborative effort, involving Program staff and Partners from a broad range of disciplines; (2) projects are designed through consensus-based decision making; (3) predictive models are increasingly being used; and (4) the Program has recently used the Stream Project decision model (Baker and Wilcock 2012) to evaluate design options, quantify public input, and convey options to the public.

Table 1

Channel Rehabilitation Sites Constructed in the Trinity River Restoration Reach during Phase 1 (from Appendix C, Section 1)

Phase 1 Site	Date Completed	Location (river miles)	Length (miles)
Pear Tree	2006	72.9 – 73.2	0.30
Elkhorn	2006	73.7 – 74.3	0.55
Valdor Gulch	2006	74.8 – 75.7	0.90
Conner Creek	2006	77.0 – 77.4	0.40
Hocker Flat	2005	78.0 – 79.1	1.10
Reading Creek	2010	92.2 – 93.1	0.90
Indian Creek-Vitzthum Gulch	2007	93.9 – 96.9	2.97
Trinity House Gulch	2010	104.0 – 104.4	0.40
Lowden Ranch	2010	104.4 – 105.3	0.89
Bucktail-Dark Gulch	2008	105.5 – 107.0	1.53
Sawmill	2009	108.9 – 109.7	0.80
Hoadley Gulch	2008	109.8 – 110.1	0.30
Lewiston Cableway	2008	110.2 – 110.5	0.28
Deadwood Creek	2008	110.5 – 111.0	0.50
Sven Olbertson	2008	111.2 – 111.6	0.41

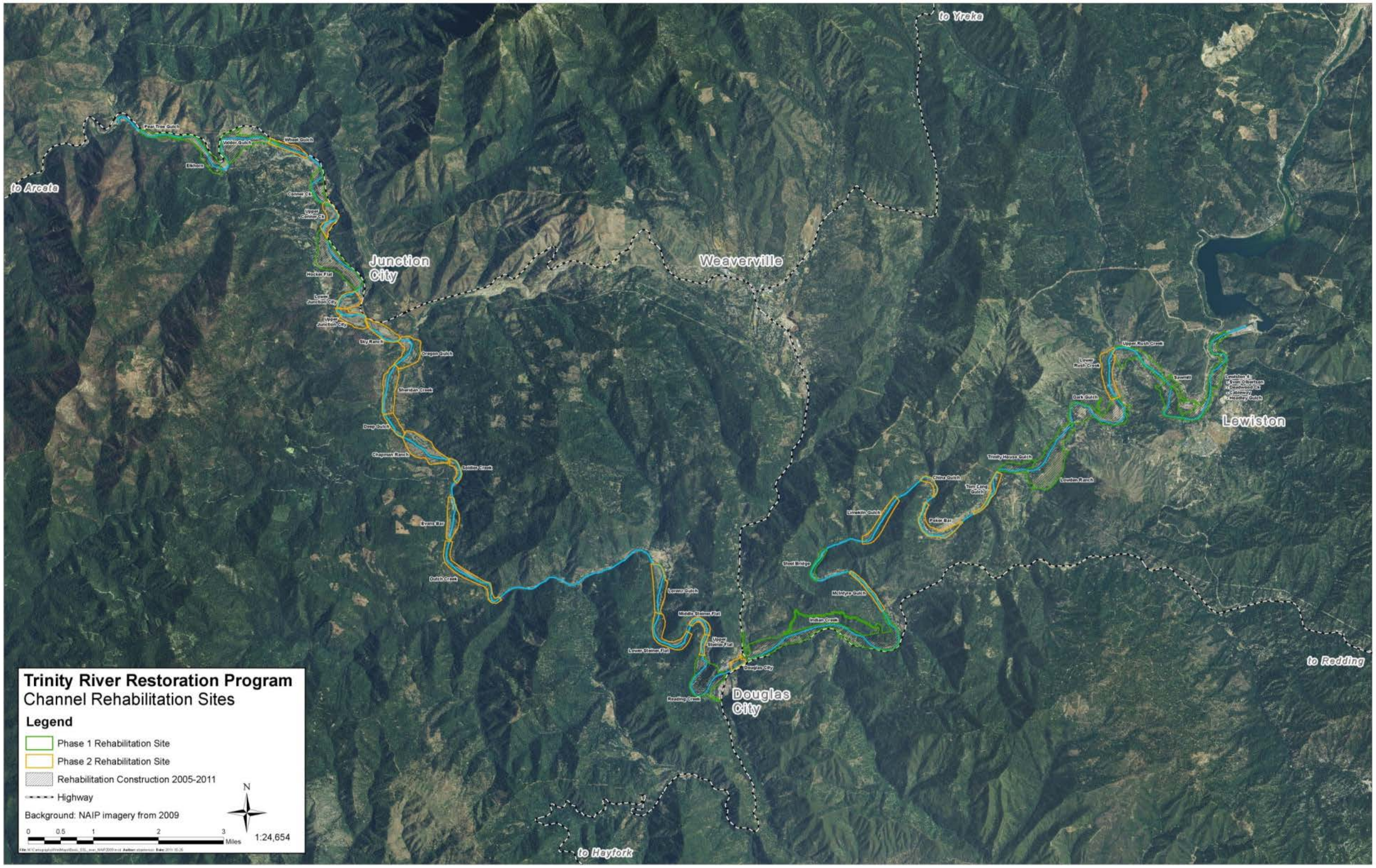


Figure 1

Phase 1 and 2 channel rehabilitation sites in the Trinity River restoration reach. See Appendix C for further detail.

2.2 Geomorphic Context and Channel Response

Channel response to rehabilitation actions depends on the geomorphic context (i.e., the physical setting of a specific site), which includes factors such as channel slope and confinement, bank and bed materials (alluvial versus bedrock), position in the stream network relative to tributary inputs of sediment and water, and the legacy of past natural and anthropogenic events. Geomorphic context constrains channel formation, sediment transport, and flow patterns; influences the dynamics of aquatic and riparian habitats; and predisposes the success or failure of rehabilitation actions. The notion of geomorphic context is well recognized by the Program and our discussion of the issue largely synthesizes existing Program knowledge. We then examine evidence of channel response to Phase 1 management activities in terms of whether the responses are consistent with Program objectives and hypotheses. Further detail of geomorphic topics is provided in Appendix C.

2.2.1 Geomorphic Context

The restoration reach is a partially confined gravel-bed river that exhibits a mixture of alluvial and bedrock-controlled channel morphologies, with alluvial tendencies increasing in the downstream direction (HVT et al. 2011; Beechie et al. 2012). Valley bottoms are narrow and sinuous, indicating frequent contact of the channel with valley walls and bedrock (Figure 1), although terraces and floodplains of various widths also are evident. There are no broad alluvial valleys or steep, narrow gorges. Overall, the channel is semi-alluvial (i.e., intermittently influenced by bedrock boundaries) and has been aptly described as “an alluvial channel working through a tapestry of bedrock controls” (HVT et al. 2011).

Channel characteristics exhibit only modest differences along the restoration reach (i.e., relatively small changes in channel slope, width, and planform pattern). An important question is what the historic variation of channel morphology and habitat was like and what variation might be possible under the current post-ROD flow regime (USFWS AND HVT 1999; HVT et al. 2011; Beechie et al. 2012). The post-ROD river is a single-thread channel with a straight to meandering planform, with meanders largely imposed by confining features. While valley widths are generally too small to support a braided channel form (i.e., an unstable multi-thread channel), an anabranching morphology (a relatively stable multi-thread channel) may be possible in some locations (HVT et al. 2011; Beechie et al. 2012). If sustained through dynamic flow regimes, anabranching would produce a more complex fluvial environment as a means toward enhanced fish habitat, akin to that envisioned by the Program’s foundational documents (USDOI 2000; USFWS AND HVT 1999). Building from analyses presented in the Design Guide (HVT et al. 2011), we find that opportunities for anabranching channels may have been more common during the pre-dam flow regime than under post-ROD flows, with current opportunities for sustained anabranching predominantly limited to the North Fork Reach (Figure 2). The potential effects of channel morphology on juvenile salmonid habitat and carrying capacity in the restoration reach were recently examined by Beechie et al. (2012) for different scenarios of rehabilitation actions and restoration of fluvial processes. Results indicated that juvenile salmonid production could be increased by 1.5 to 2 times the current capacity for the management scenarios examined.

Recent work also suggests that legacy effects of mining and pre-dam flooding may strongly affect channel form and process in the mainstem Trinity River (Krause 2012a, 2012b; Krause et al. 2010). As such, the geomorphic context of the rehabilitation sites is primarily set by local controls nested within larger-scale legacy (pre-dam) effects. The Design Guide (HVT et al. 2011) provides comprehensive and detailed recommendations for planning rehabilitation treatments within this sort of reach-scale geomorphic context. Furthermore, it is recognized that the semi-alluvial nature of the river limits the extent of dynamic alluvial morphology envisioned in the Program’s foundational documents, which has led, in part, to an evolution of design strategy during the Phase 1 period, as discussed above (HVT et al. 2011; Appendix G).

The original notion presented in the foundational documents that a dynamic river could be created with minimal bank reconstruction is now seen as an over-simplification. Recognition of the existence of significant terraces and the semi-alluvial nature of the river necessitated a shift in rehabilitation strategy. It now seems that the most meaningful geomorphic context for rehabilitation may be the site scale, where juxtaposition of non-alluvial features, valley forms, mining debris, and deposits left by historic floods constrain the size, frequency, and relief of alluvial features and associated habitats that can be formed by rehabilitation practices. Despite the Program’s recognition of geomorphic context in the design process (HVT et al. 2011), it should be considered in a more systematic way through comparison of alternative designs and predicted outcomes for different geomorphic environments, followed by targeted monitoring for evaluating physical and biological response of implemented restoration actions. For example, given the nature of the river, one might implement and test dynamic rehabilitation designs in predominantly alluvial reaches, but employ static designs in constrained and semi-alluvial reaches where habitat enhancement is desired, but cannot be achieved using the conceptual model of a dynamic alluvial river as envisioned in the Program’s foundational documents. This dichotomy (i.e., driving dynamic habitat *vs*. building static habitat) leads to fundamentally different approaches, expectations, and measures of success in terms of geomorphic response and the dynamics of habitat availability for different locations within the restoration reach.

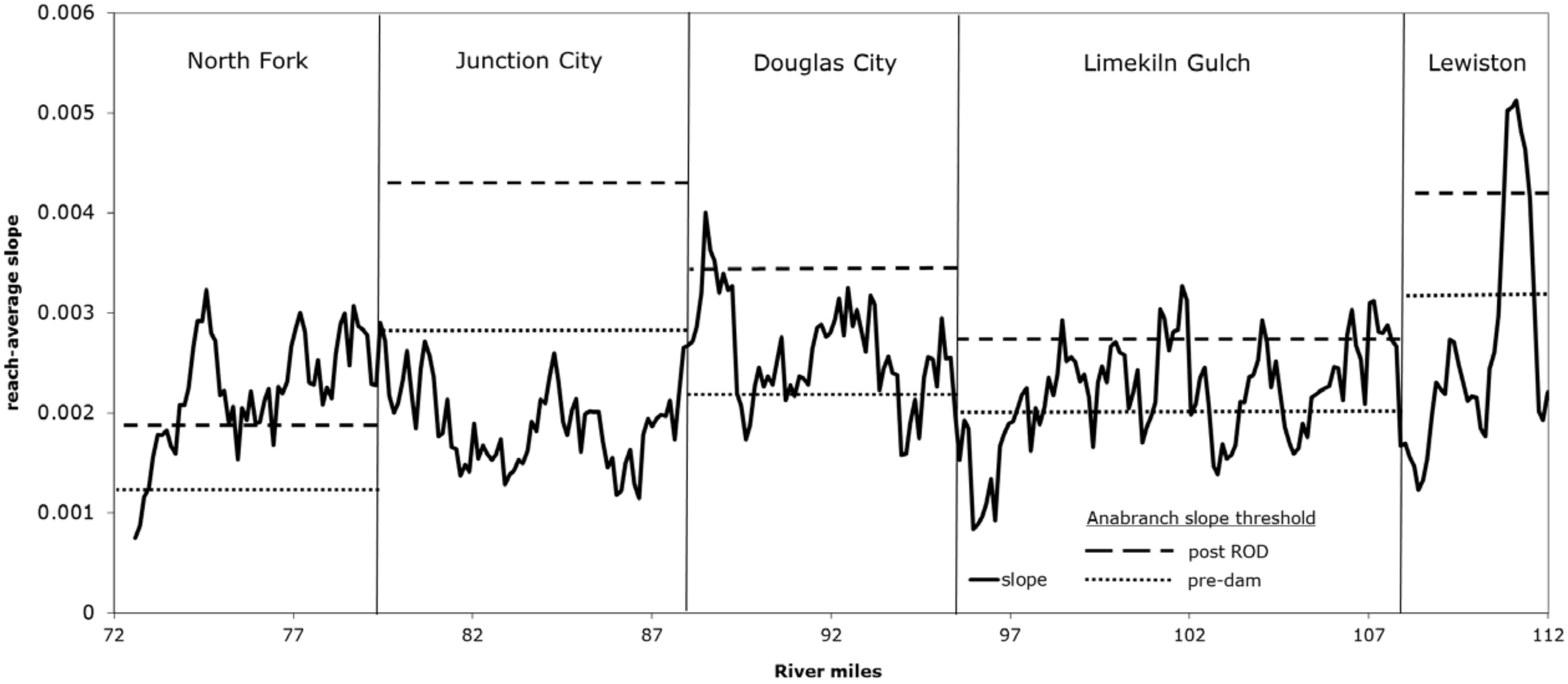


Figure 2

Reach-average channel slope compared with predicted slope thresholds for transition from meandering to anabranching channel morphology (Eaton et al. 2010) for pre-dam (dotted line) and post-ROD (dashed line) bankfull discharges in the five mainstem reaches identified in the Design Guide (HVT et al. 2011). Channel slopes above the threshold have increased anabranching potential. See Appendix C, Section 4.1.4, for further detail.

2.2.2 Channel Response

The Program's documentation of channel response to Phase 1 activities is somewhat limited and largely involves constructed changes at the rehabilitation sites. The data are limited, in part, due to the short time since implementation and whether or not sites have experienced geomorphically-effective high flows during that time (i.e., wet-year and extremely wet-year ROD flows). We first consider channel responses relative to established Program objectives, then examine other metrics and response to gravel augmentation.

2.2.2.1 IAP

The Program's Integrated Assessment Plan (IAP; TRRP and ESSA 2009b) established management objectives for implementing the ROD, as well as performance measures for assessing whether objectives are being met. In addition, the Integrated Habitat Assessment Project (IHAP; Alvarez et al. 2011) provided monitoring procedures for evaluating specific IAP objectives and the effectiveness of the Program's restoration actions. Monitoring of these performance measures provides a means of assessing physical and biological responses to rehabilitation actions at site and reach scales. In terms of channel response, we focus on IAP Objective 1 (*Create and maintain spatially complex channel morphology*) and its level 2 and 3 sub-objectives (Table 2). Monitoring reports and original analyses were used to assess the effects of rehabilitation projects in relation to IAP objectives (Appendix C, Sections 1 and 3).

Table 2

IAP Objectives Related To Creating and Maintaining Spatially Complex Channel Morphology (from Appendix C, Section 1)

Objectives			Priority
Level 1	**Level 2**	**Level 3**	
1. Create and maintain spatially complex channel morphology	1.1. Increase physical habitat diversity and availability	1.1.1 Increase the size, frequency, and topographic relief of bar/pool sequences	M
		1.1.2 Increase channel/thalweg sinuosity	H
		1.1.3 Increase geomorphic unit and substrate patch diversity	L
	1.2 Increase coarse sediment transport and channel dynamics	1.2.1 Increase and maintain target coarse sediment transport rates	H
		1.2.2 Frequently exceed channel migration, bed mobilization, and bed scour thresholds	H
		1.2.3. Encourage bed-level fluctuations on annual to multi-year time scales	L
		1.2.4 Route coarse sediment through all reaches	L

Objectives			Priority
Level 1	Level 2	Level 3	
	1.3 Increase and maintain coarse sediment storage	1.3.1 Increase bars, side-channels, alcoves, and other complex alluvial features	H
	1.4 Reduce fine sediment storage in the mainstem Trinity River	1.4.1 Transport fine sediment through mainstem at a rate greater than tributary input	H
		1.4.2 Reduce fine sediment supply from tributary watersheds	M
		1.4.3 Encourage fine sediment deposition on floodplains	L

Results show that in some cases, IAP objectives for channel response are being met, and are occurring through a mix of constructed and post-construction changes (Appendix C, Sections 6 and 7). For example, bar formation and growth was observed in the first 5 miles downstream of Lewiston Dam, indicating increased bed material storage associated with gravel augmentation (Wilcock 2010). In addition, early rehabilitation projects that included berm removal, feathered edging, and floodplain lowering have increased bed material sorting and substrate patch diversity, but have had little influence on the size, frequency, and relief of bar-pool sequences. Rehabilitation designs have evolved in response to include constructed bars, forced meanders, lowered floodplains, and side channels that utilize existing planform curvature and local forcing elements and are designed to work in combination over various spatial and temporal scales within rehabilitation sites. Although there has been limited time for flow and sediment management to alter habitat at the system scale or achieve dynamic morphology, geomorphic monitoring demonstrates the relative effectiveness of higher peak flows in 2011 at achieving geomorphic objectives regarding bed mobility and scour. Analysis of cross sections at restoration sites shows that peak flows in 2009 and 2010 resulted in minor bed mobility, while high flow releases in 2011 were much more effective at creating dynamic channel conditions through bed mobilization and scour; 27 of 35 cross-section pairs bracketing the 2011 high flow release exhibited an active bed over 20% or more of the channel width according to Program metrics (net scour or fill greater than 200 mm (typical D_{84} size of streambed sediment)).

However, not all IAP objectives could be assessed using the methods employed, and of those that were assessed, results were often inconclusive due to a high degree of variability within the limited spatial and temporal scales of measurement (Appendix C, Sections 6 and 7). Nevertheless, it is important to note that many of the sites and design features have not had sufficient exposure to repeated high flows since their construction and have had limited opportunity to evolve as designed. Consequently, lack of data necessary for any system-wide evaluation of the evolution of the restoration reach, its habitat, and fish population response preclude a comprehensive evaluation of Phase 1 activities. These factors point to the need for a longer monitoring period and more exposure to high flows before critically judging the overall effectiveness of rehabilitation actions based on IAP objectives for channel response.

2.2.2.2 Lateral Erosion and Deposition

Lacking data collected specifically for system-wide analyses, we used aerial photography to examine channel response in terms of lateral erosion and deposition. Aerial photography of the base-flow channel indicates some lateral erosion and deposition at both site and system scales following floods (Appendix C, Sections 3.3.2.2 and 6). Overall, the river has widened slightly since 2001 (Figure 3 shows greater lateral erosion than deposition). This analysis also shows that changes in the base-flow channel width at the rehabilitation sites (including both constructed changes and fluvial erosion or deposition) are small compared to changes in width outside of the sites. This is due to the fact that constructed reach lengths are relatively short (13 km) compared to the entire restoration reach (64 km) and because much of the construction occurs above the low-flow channel. However, we are not able to quantify the effects that Phase 1 rehabilitation actions may have had on fluvial processes and system-scale changes in lateral erosion or deposition with this analysis.

GIS analysis of the aerial photographs also suggests that ROD flows are capable of eroding riparian berms in some river segments (Figure 4) and may not require as much mechanical intervention as originally thought (USFWS AND HVT 1999). Our analysis indicates that from 2003 to 2011, 18% of the total berm area as mapped in 2003 may have been eroded by fluvial processes. Although the foundational documents indicated the ROD flows were incapable of eroding berms (USFWS AND HVT 1999), field observations after the large January 1997 flood revealed a range of impacts on berms, including complete removal in many locales (McBain and Trush 2000). Erosion of berms by ROD flows should be viewed as a positive outcome that may obviate the need for mechanical alteration of banks in some locations, but it does not indicate that rehabilitation projects are no longer needed. While our findings are encouraging, additional investigation is warranted because the analysis is based on remote sensing of aerial photography that includes some degree of uncertainty. Sources and magnitudes of uncertainty associated with the analysis are further discussed in Appendix C, Sections 3.3.2.2 and 4.4.

In addition to observed berm erosion, some detrimental encroachment of vegetation has occurred and some new berms are forming (e.g., HVT and McBain and Trush 2013; 2014), but this is expected given that berms, which are more commonly called levees, naturally occur on alluvial rivers, even those with unvegetated banks (Church 1972). The Program's restoration strategy depends on a dynamic channel (USFWS AND HVT 1999) and, so far, monitoring has concentrated on vertical scour of the channel bed and bar flanks. Little attention has been paid to new bar formation and bank erosion, which are common on dynamic alluvial rivers. This process is potentially important because formation of new depositional surfaces could be providing habitat for young fish in previously unrecognized locations. The “recycling” or turnover of this sort of habitat, where recently deposited surfaces gradually become vegetated over time while fresh depositional surfaces form elsewhere, should be incorporated into the Program’s geomorphic and fish habitat monitoring.

The erosion and deposition results presented here are crude due to the limitations of aerial photography for accurately defining bank lines, but the general approach can be adapted to the Program’s existing monitoring efforts. Instead of using remotely-sensed bank lines, the wetted surface mapped in the field each year during fish habitat mapping, if precise enough, could be used to map bank lines and track erosion and deposition at sampled reaches. Mapped habitat patches from different sample years can be superimposed on the erosion and deposition patches to relate channel migration and the creation and loss of fish habitat.

Trees typically dominate the riparian berms, and the flow evaluation study assumed that direct tree toppling, from flows impinging on debris jams lodged against tree trunks, was the dominant process in berm erosion (USFWS and HVT 1999). The requisite streamflow for removing berms via tree toppling was estimated to be 14,000 cfs or higher (USFWS and HVT 1999), so if this is the only mechanism for berm removal, and the flow estimate is correct, the channel would be incapable of eroding berms under most ROD flows (USFWS and HVT 1999). However, another potential process for berm removal, which is common on migrating rivers, even those with forested riparian zones, is the under-cutting of banks via lateral scour (Thorne 1982; Nanson and Hickin 1986). This process is mentioned in the flow evaluation report (USFWS and HVT 1999), but is attributed to unregulated rivers. Bank erosion on regulated rivers is often diminished, but can occur (Bradley and Smith 1984; Dykaar and Wigington 2000). Consequently, some of the observed berm erosion may have been via bank undercutting (McBain and Trush 2000; Appendix C, Figure 4-8). More attention to bank erosion agents during routine monitoring could help to refine the assumptions regarding berm erosion in the flow evaluation report.

More detailed information regarding site and system response will be available in the future from digital elevation models (DEMs) that are being developed by the Program through a combination of terrestrial LiDAR (light detection and ranging) and bathymetric surveys (e.g., GMA 2012). These data will allow spatial analysis of changes in bed topography and sediment storage over time at a finer resolution than is currently monitored by the program. DEMs will also facilitate use of 2-dimensional flow and morphodynamic models for predicting physical and biological responses (when linked with a fish production model) and for assessing design options and management scenarios (e.g., Alvarez et al. 2011; Gaeuman 2013). Similarly, information regarding historic geomorphic changes and legacy events is forthcoming (Curtis and Guerrero in review; Krause 2012a, 2012b), which should provide context for observed responses and inform design of Phase 2 projects.

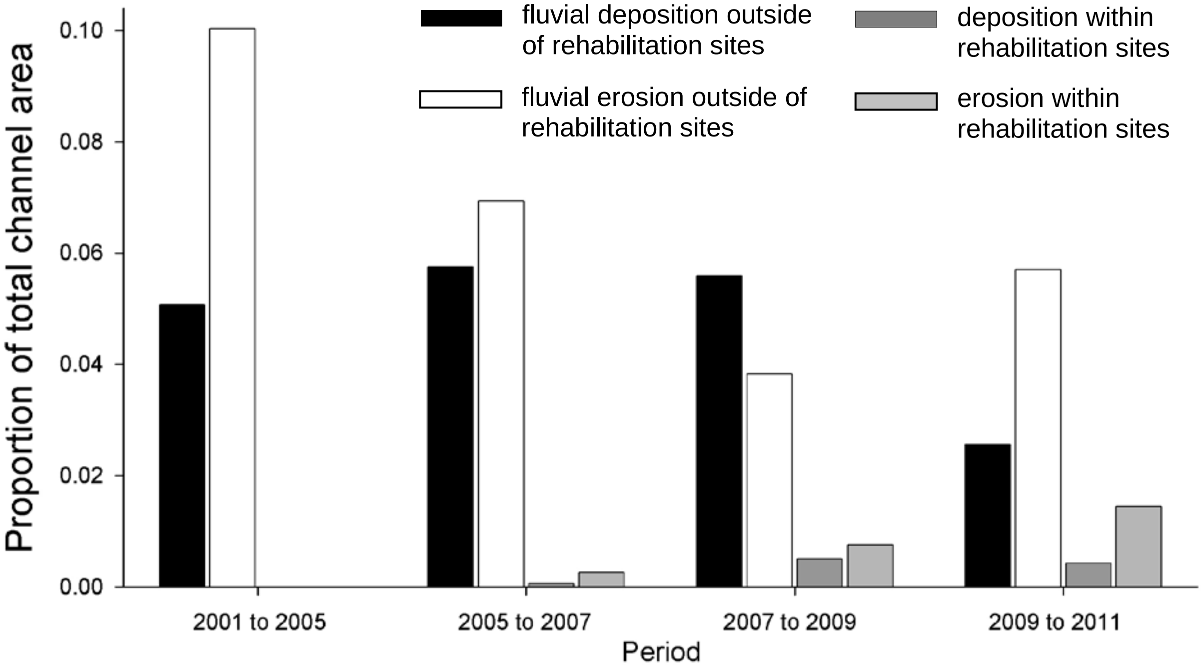


Figure 3

Lateral channel erosion and deposition inferred from changes in the position of the wetted channel edge observed on sequential aerial photographs (2001, 2005, 2007, 2009, and 2011) at summer base flow along the 64 km restoration reach. Values are expressed as a proportion of the total area of the wetted channel at base flow. Data are categorized in terms of whether erosion or deposition occurred outside or within rehabilitation sites. Changes in the wetted channel edge within rehabilitation sites may represent a combination of constructed changes and fluvial erosion or deposition. Peak flows for the Trinity River at Lewiston for each time period were respectively 7,640 (2005), 10,400 (2006), 6,890 (2008), and 12,300 (2011) cfs. The length of non-constructed channel is about five times that of the constructed channel. Construction influences are relatively small because much of the construction occurs above the low-flow channel and constructed reach lengths are relatively short (8.1 river miles) compared to the entire restoration reach (40 river miles). See Appendix C (Sections 3.3.2.2 and 4.4) for further detail of methods and results.

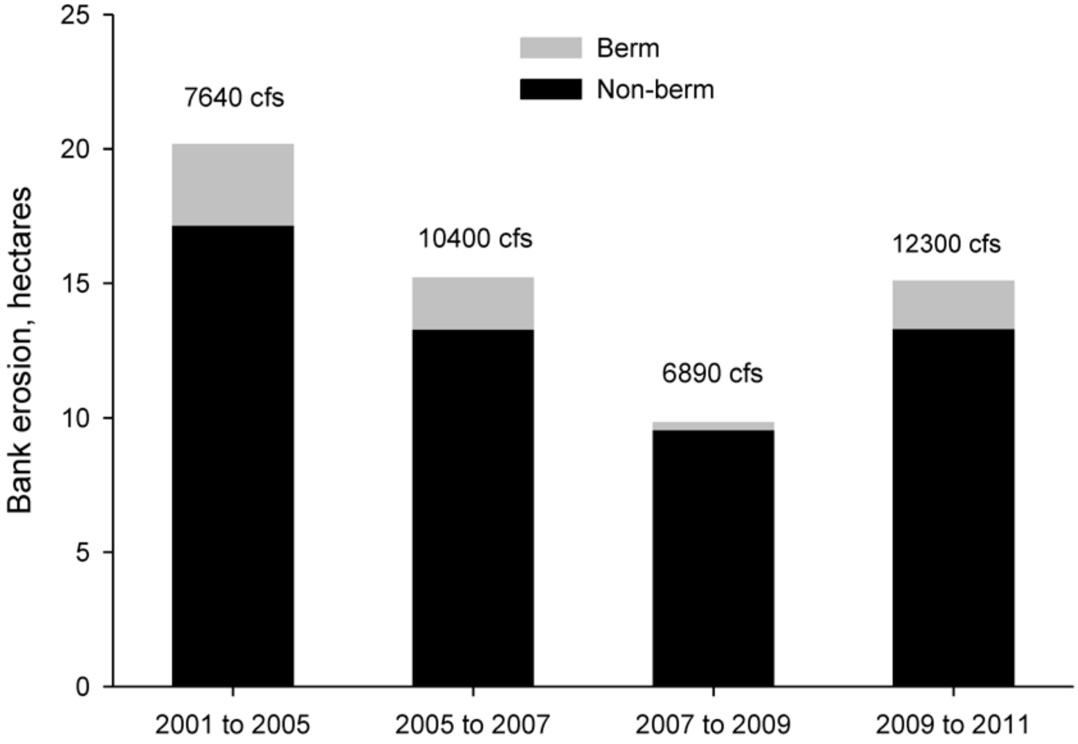


Figure 4
Bank erosion inferred from changes in the position of the wetted channel edge observed on sequential aerial photographs (2001, 2005, 2007, 2009, and 2011) at base flow along the 64 km restoration reach. Values at the top of each bar are peak flows for the Trinity River at Lewiston during the time period. Banks classified as berm or non-berm based on 2003 Program mapping. See Appendix C (Sections 3.3.2.2 and 4.4) for further detail of methods and results.

2.2.2.3 Gravel Augmentation

Gravel augmentation, including in-channel placement and high-flow injection of coarse sediment, is intended to offset sediment storage by the dams and to promote a mobile streambed, bar formation, and a supply of spawning gravels for salmonids. However, gravel augmentation has become a controversial element of rehabilitation activities due, in part, to concerns about pool filling and loss of holding habitat for adult salmonids. Recent investigation of the issue indicates that pool depths have generally increased throughout the restoration reach as a result of ROD flows and reduced fine sediment input from tributaries (Gaeuman and Krause 2013). However, pool depths have decreased near some rehabilitation sites, and terrace lowering is implicated as the cause, rather than gravel injections (Gaeuman and Krause 2013).

A recent case study documenting channel response to high-flow gravel injection at the Lowden Ranch site indicates that gravel injection dynamically built targeted bed forms as designed (Gaeuman 2013). However, major bar formation from gravel injection may be limited to injection points due to downstream dispersion of gravel.

At the restoration reach scale, gravel augmentation is the largest source of coarse sediment supplied to the river and has been input mainly in the upper portions of the restoration reach. Monitoring of coarse sediment transport indicates that bed load is actively moving through the system and that storage is increasing in all but the lower-most monitoring reach (Figure 5, Cell 4, Limekiln Gulch to Douglas City). During Phase 1, the largest increases in coarse sediment storage occurred in Cell 2 (Lewiston Gage to above Grass Valley Creek), where rehabilitation projects were concentrated (Gaeuman and Krause 2011). However, it is unclear how mechanical alteration of the channel may be altering sediment routing and storage. Reach-scale sediment routing has been predicted at the Lowden Ranch site (Gaeuman 2013), but system-wide sediment routing models have not been developed for the river at a scale that can resolve transport within and between rehabilitation reaches. Nor is it clear how the rehabilitation projects may be affecting fine sediment routing and storage, other than through mechanical removal of fine-grained riparian berms and floodplain lowering, which will locally promote overbank deposition that may enhance riparian communities.

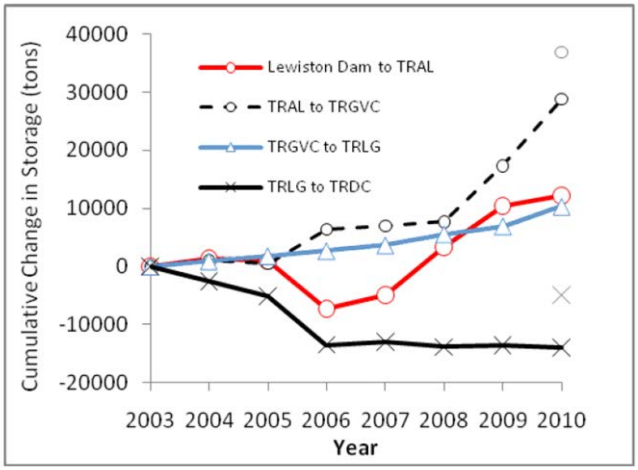


Figure 5

Cumulative changes in coarse sediment storage by budget cell for water years (WY) 2004-2010 with zero values assigned to WY2003. Cell 1=Lewiston Dam to TRAL (Trinity River at Lewiston), Cell 2=TRAL to TRGVC (Trinity River above Grass Valley Creek), Cell 3=TRGVC to TRLG (Trinity River at Limekiln Gulch), Cell 4=TRLG to TRDC (Trinity River at Douglas City). Solitary symbols indicate cumulative changes including fall 2010 construction placements (early WY2011) in budget cells 2 and 4. From Gaeuman and Krause (2011). See Appendix C, Section 7.1.3, for further discussion.

2.3 Physical Habitat Response for Anadromous Fish

As above, Program reports and original analyses were used to assess the effects of rehabilitation projects on the quantity and quality of habitat for anadromous salmon in relation to IAP objectives; specifically, sub-objectives 2.1.1 and 2.1.2 (Table 3). Results are summarized from Appendices A and C. The Program focusses mainly on juvenile rearing habitat, which is believed to be a limiting factor for Trinity River salmon. As such, more habitat information was available for juvenile salmon than adults. However, spawning surveys (redd and carcass counts) provide some information on adult habitat. We consider site- and system-scale response in turn for both juvenile and adult habitat availability. In all analyses, the results for juvenile habitat availability are preliminary due to a limited sample size to date (3 years of monitoring by the Program using the generalized random-tessellation stratified [GRTS] approach [Stevens and Olsen 2002; 2004]).

Table 3

IAP Objectives Related to Increasing Anadromous Fish Habitat (from Appendix C, Section 1)

Objectives			
Level 1	**Level 2**	**Level 3**	**Priority**
2. Increase/ improve habitats for freshwater life stages of anadromous fish to the extent necessary to meet or exceed production goals	2.1 Increase and maintain salmonid habitat availability for all freshwater (in-river and tributary) life stages	2.1.1 Increase/maintain salmonid fry and juvenile rearing habitat in the upper 40 miles of the mainstem Trinity River by a minimum of 400%[1] following rehabilitation of fluvial attributes	H(1)
		2.1.2 Increase/maintain spawning habitat quantity and quality to 2,550,000 square feet[2] in the upper 40 miles of the mainstem Trinity River	H(2)
		2.1.3 Create channel form that reduces loss of fry to stranding in the upper 40 miles of the mainstem Trinity River following rehabilitation during high flows	M
		2.1.4 Maintain or increase adult holding habitat from baseline conditions in the mainstem Trinity River	M
		2.1.5 Minimize physical impacts to lamprey habitat	M
		2.1.6 Minimize physical impacts to other native fish habitats	L
		2.1.7 Maintain or increase tributary habitat	M
	2.2 Improve riverine thermal conditions for growth and survival of natural anadromous salmonids	2.2.1 Provide optimal temperatures to improve spawning success of spring and fall-run Chinook salmon	H
		2.2.2 Improve thermal regimes for rearing growth and survival of juvenile steelhead, coho salmon, and Chinook salmon	H
		2.2.3 Improve thermal regimes for outmigrant salmonid growth and survival (dependent on water year)	H
		2.2.4 Minimize temperature impacts to other native fish habitats	L
	2.3 Enhance or maintain food availability for fry and juvenile salmonids	2.3.1 Increase and maintain macroinvertebrate populations	M

Notes:

1 This is an interim target provided in the IAP (TRRP and ESSA 2009b) and will be revisited and revised as the Program learns more; 400% is a starting point only for a measure of progress and does not reflect an estimate of the habitat increase needed to fully meet salmonid production goals.

2 This is an interim target provided in the IAP (TRRP and ESSA 2009b) and will be revisited and revised as the Program learns more.

2.3.1 Site Scale

2.3.1.1 Juvenile Rearing Habitat

Rehabilitation projects typically increased base flow juvenile rearing habitat availability for coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) at site scales (Table 4, Figure 6). Constructed increases in base-flow habitat varied widely across the sites (Table 4, Figure 6), depending on the size of the project and the design elements employed, but overall resulted in substantial increases compared to pre-construction habitat availability (Alvarez et al. 2011). To put these values in terms of potential biological importance, we use mean fish densities reported by Goodman et al. (2010) to determine potential increases in habitat capacity at the rehabilitation sites due to constructed increases in habitat (Table 5). Although fish density and habitat capacity are spatially variable along the restoration reach (Alvarez et al. 2011; Beechie et al. 2012), the Table 5 values provide useful indications of potential average changes, showing that the rehabilitation projects cause substantial increases in juvenile Chinook capacity and modest increases in coho capacity.

The reported changes in juvenile rearing habitat are obtained from measurements that are a near-census of all habitat at each rehabilitation site. As such, there is a high degree of confidence in the values compared to sampling only a portion of the total habitat at each site. However, the data may not be error free. In particular, uncertainty in the values may result from measurement errors and temporal variability of conditions (i.e., year-to-year variability of pre- and post-treatment habitat (noise) even at similar base-flow conditions) that has yet to be accounted for in Program monitoring due to the short sampling period to date. Consequently, the values reported here should be viewed as preliminary. In addition, while the constructed changes in habitat are substantial at site scales (Table 4), they comprise a relatively small amount of the total area in the restoration reach. As such, their effects on population response may be difficult to detect. On the other hand, small changes can be important if they occur in critical locations that address population bottlenecks or if populations respond nonlinearly to physical changes.

Table 4

Percent Change in Optimal and Total Rearing Habitat at Base Flow for Juvenile Chinook and Coho Salmon Within Rehabilitation Sites Following Construction

Reach	Rehabilitation Site	Fry Habitat		Presmolt Habitat	
		Optimal	Total	Optimal	Total
Lewiston	Sven Olbertson	145	67	204	57
	Lewiston Cableway and Hoadley Gulch	61	43	59	17
	Sawmill	96	42	88	29
Limekiln	Bucktail-Dark Gulch	33	28	28	22
	Lowden Ranch	140	140	177	121
	Trinity House Gulch	-32	45	-23	49
Douglas	Reading Creek	10	25	10	27

Notes:

1 Optimal habitat meets depth, velocity, and cover criteria, while total habitat includes all areas that meet any combination of depth, velocity, or cover criteria (Alvarez et al. 2011). Coho rearing habitat was limited to optimal habitat areas (Goodman et al. 2010; Martin et al. 2012).

2 Base flow is approximately 300 to 450 cfs.

3 Results are based on analyses of pre- and post-treatment data provided by the Program. Not all of the rehabilitation sites are included in this table because not all of the sites were assessed pre- and post-construction (e.g., Conner Creek, Valdor Gulch, Elkhorn, and Pear Tree Gulch) and not all were assessed using the same criteria (e.g., Indian Creek). See Appendix C, Section 7.2.1 and Alvarez et al. (2011) for further detail.

Table 5

Change in Potential Rearing Habitat Capacity at Base Flow for Juvenile Chinook and Coho Salmon Within Rehabilitation Sites Following Construction

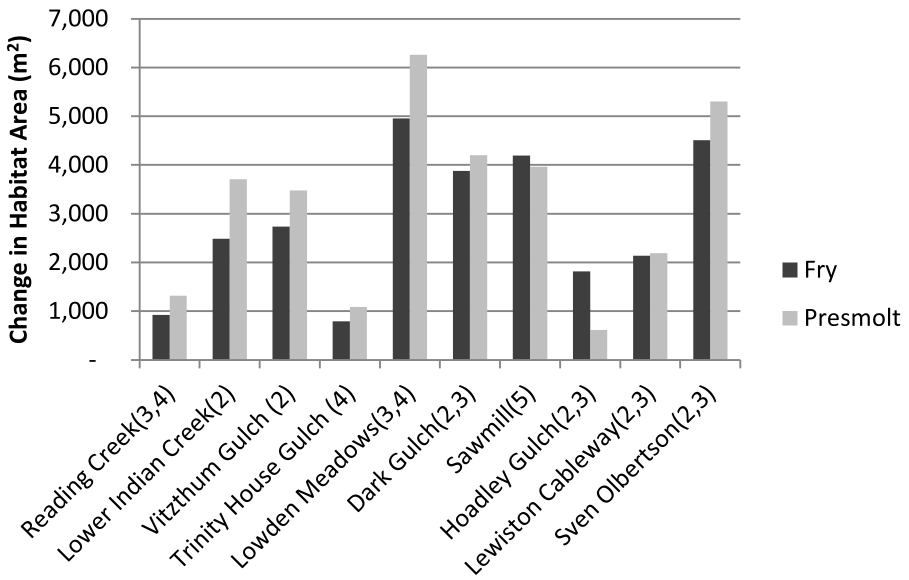
Reach	Rehabilitation Site	Chinook				Coho	
		Fry Habitat Capacity (# of fish)		Presmolt Habitat Capacity (# of fish)		Fry Habitat Capacity (# of fish)	Presmolt Habitat Capacity (# of fish)
		Optimal	Total	Optimal	Total	Optimal	Optimal
Lewiston	Sven Olbertson	13,213	58,179	14,284	55,682	93	266
	Lewiston Cableway and Hoadley Gulch	10,507	51,020	8,934	29,411	39	76
	Sawmill	20,186	54,128	16,942	41,643	61	114
Limekiln	Bucktail-Dark Gulch	7,418	50,000	6,235	44,121	21	36
	Lowden Ranch	9,157	63,962	12,760	65,778	89	230
	Trinity House Gulch	-1,152	10,245	-668	11,449	-21	-30
Douglas	Reading Creek	413	11,950	382	13,855	6	13

Notes:

1 See Table 4 notes for definitions of optimal and total habitat and for base flow values.

2 Rearing habitat capacity (# of fish) is calculated as habitat area (m^2) times mean fish density (fish/m^2) for values reported in Table 3 of Goodman et al. (2010).

(a)



(b)

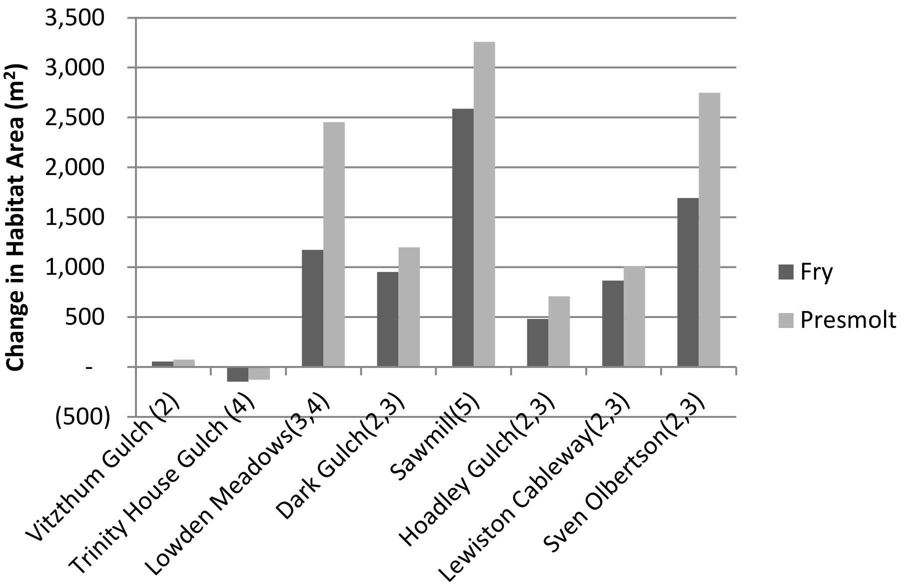


Figure 6

Change in (a) total and (b) optimal habitat area for juvenile Chinook and coho salmon at Phase 1 rehabilitation sites from pre- to post-construction condition at base flow (8.6 $m^3 \cdot s^{-1}$, 300 cfs). Note the change in vertical scale between panels. Data sources: (2) Goodman et al. (2010), (3) Alvarez et al. (2011), (4) unpub. Program data, and (5) Martin et al. (2012). See Appendix A, Section 2.1.5 for further detail.

The flow evaluation study (USFWS and HVT 1999) noted a constriction (dip) in juvenile salmon habitat under modest flows (about 350 to 2,000 cfs, Figure 7a), and one of the goals of channel rehabilitation is to alleviate this bottleneck by increasing habitat within this flow range. As part of our analysis, we examined the effect of rehabilitation activities on flow–habitat relations and this bottleneck (Appendix F). Although channel rehabilitation consistently increased the amount of juvenile rearing habitat, we find that the dip in habitat availability persists at modest flows when all habitat (constructed and naturally occurring) is considered (cf. Figures 7a and 8a). However, a nearly uniform flow–habitat relation is observed for constructed habitats (Figure 8b), demonstrating the successful removal of the bottleneck for these features.

Analysis of flow–habitat relations by design element shows that all in-river design element types provided fish habitat for both fry and presmolts across the range of flows examined (Figures 8c-i). Within a project reach, design elements provided about 48% of the total fry habitat at all flows and 44% of the presmolt habitat, indicating similar relative contributions for the two life-stages, although greater amounts of presmolt habitat were produced (Figure 8). This is likely due to the depth criteria range being larger for presmolt habitat than fry.

Although floodplain design elements provide only modest amounts of habitat (Figure 8g), they may provide important refuge during high-flow releases. Prior to floodplain construction, high flows may have forced juveniles out of the restoration reach due to channel confinement and lack of floodplain habitats.

Goodman et al. (2010) have also developed statistical models for elucidating site-scale controls on observed rearing habitat at base flow. They found that optimal habitat area was related to bank length and the proportion of low-slope channel (<0.2°) within a reach, while total habitat area was additionally related to bar length and longitudinal extent of channel rehabilitation within a sample site.

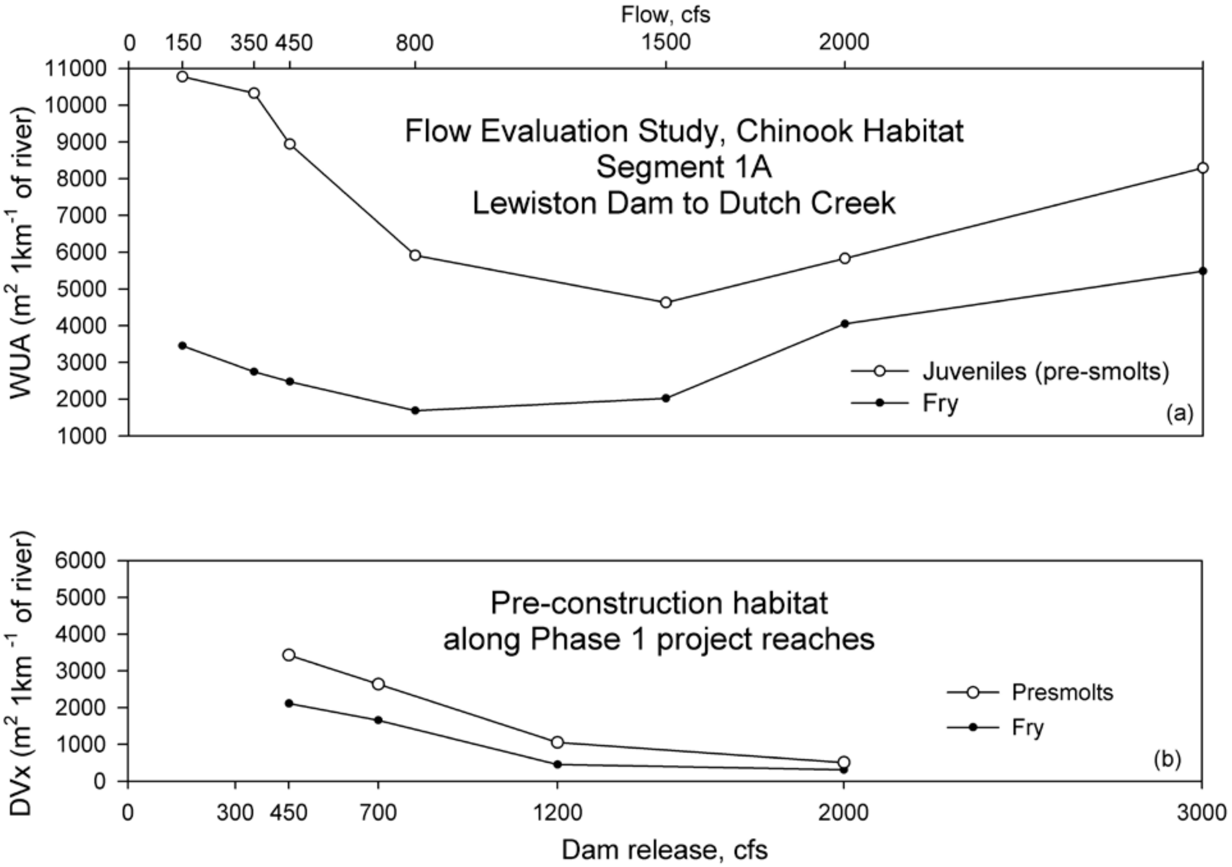


Figure 7

Physical habitat by streamflow for juvenile Chinook and coho salmon in (a) Segment 1A of the flow evaluation study (Lewiston Dam to Dutch Creek, USFWS and HVT 1999) and (b) select Phase 1 rehabilitation sites before construction (Cableway, Dark Gulch, Lowden Ranch, and Reading Creek). The flow evaluation study (USFWS and HVT 1999) reports habitat in terms of weighted useable area (a), while habitat at the Phase 1 sites is reported in terms of suitable depth and velocity (DVx). The depth criterion for presmolts in (a) was much higher (up to 3 m) than the present value used by the Program (< 1 m, b). The total centerline length of channel is 41.49 and 2.67 km, respectively, in panels (a) and (b). See Appendix F for further detail.

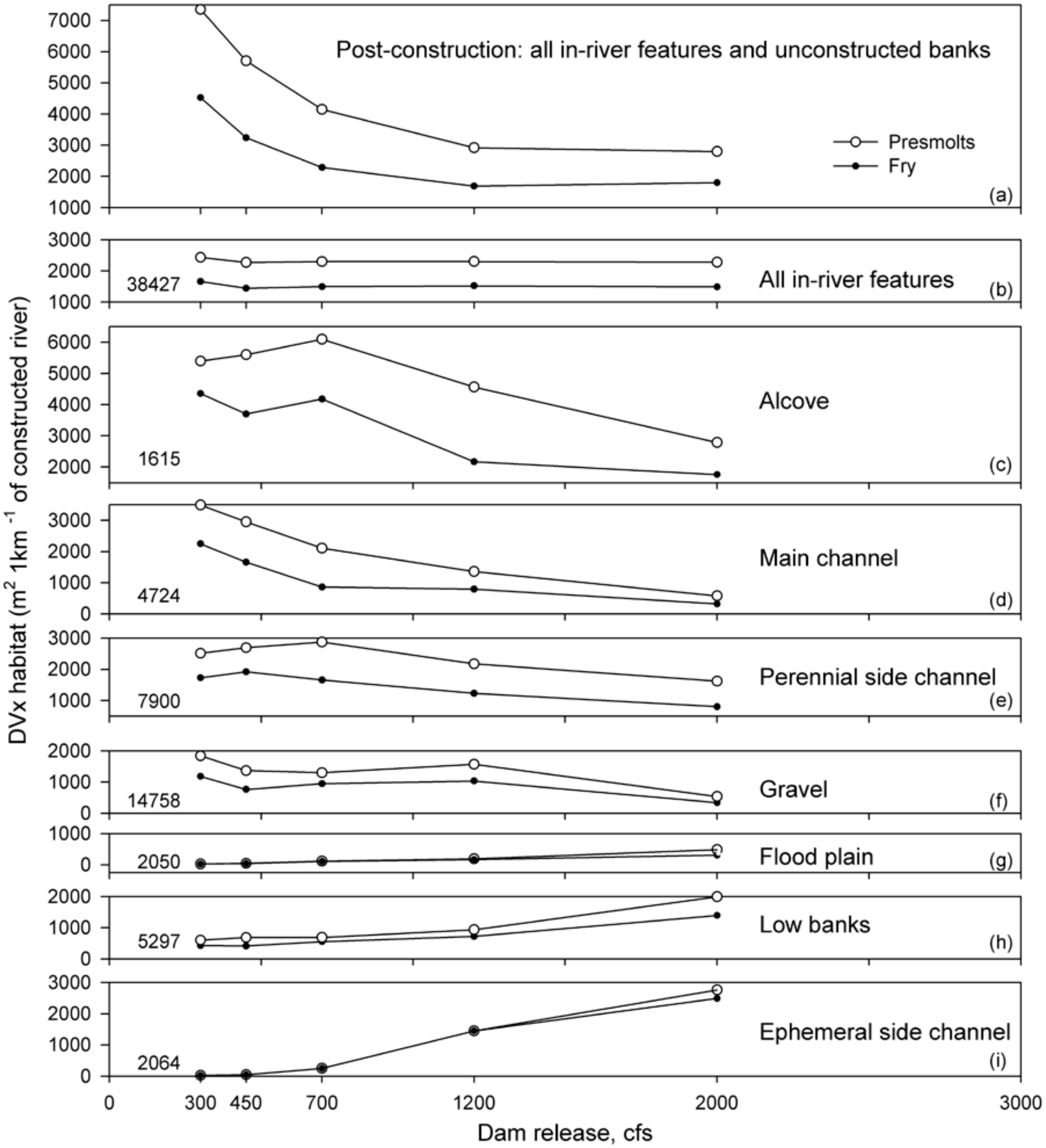


Figure 8

Suitable habitat area by streamflow for juvenile Chinook and coho salmon after channel construction at Phase 1 rehabilitation sites for which data were available (Table 3 of Appendix F). Suitable habitat is defined as meeting depth and velocity criteria (DVx) and is normalized by stream length for a given feature type. Panel (b) combines all feature types except aquatic non-river elements (wetlands and tributary connections). Numbers within each panel are the total footprint area at the sites (m^2) within the 2000 cfs wetted channel. See Appendix F for further detail.

2.3.1.2 Adult Spawning Habitat

An assessment of spawning gravel substrate at 12 sites on the mainstem river shows coarsening of both the streambed surface and subsurface due to a reduction in the percentage of fine material, which has improved spawning gravel conditions since 2000 (GMA 2010). This improvement likely results from successful management of fine sediment inputs from tributary basins and flushing flows in the mainstem river (GMA 2010). However, the effect of Phase 1 rehabilitation projects on reduction of fine sediment in the restoration reach is uncertain beyond the physical removal of berms (and the fine sediment stored within them) and floodplain lowering, which should promote fine sediment deposition during overbank flows.

In addition to changes in spawning gravel quality, redd and carcass counts provide direct observations of spawning habitat use in the restoration reach. However, the effects of Phase 1 activities on the abundance of Chinook salmon redds are inconclusive due to insufficient data and numerous confounding effects (e.g., multiple restoration treatments, interannual variability of physical and biological conditions, and inherent differences in site conditions). We present the available results in the interest of completeness (Figures 9 and 10), but stress that they are preliminary and no conclusions can be made at this time. Similar results were obtained for carcass counts of female Chinook and coho salmon (Appendix C, Section 7.2.2).

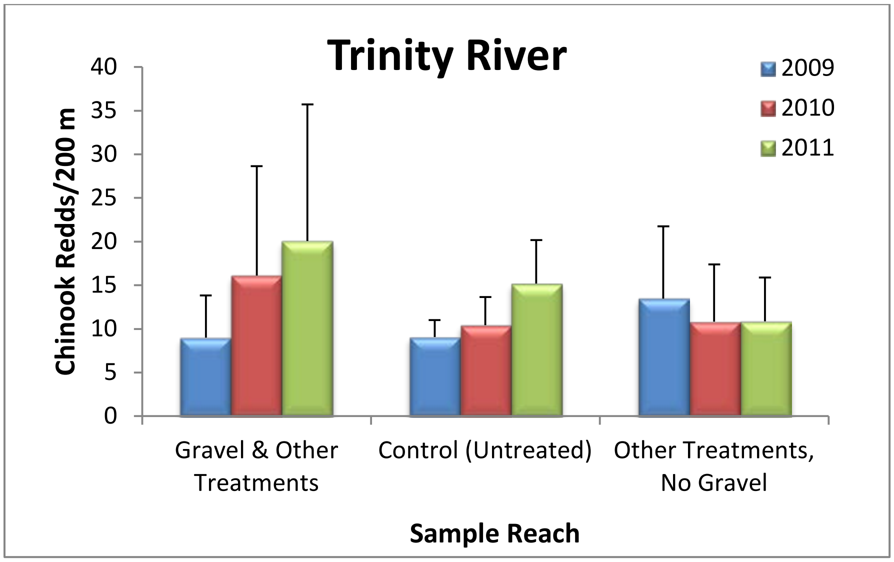


Figure 9
Mean redd densities and 95% confidence intervals for Chinook salmon (spring and fall runs) in 200-m segments of the restoration reach categorized by treatment: (i) gravel augmentation and other channel rehabilitation treatments, (ii) control (untreated), and (iii) treatments other than gravel augmentation. The figure examines whether spawners prefer gravel augmentation reaches. See Appendix C, Section 7.2.2 for further detail.

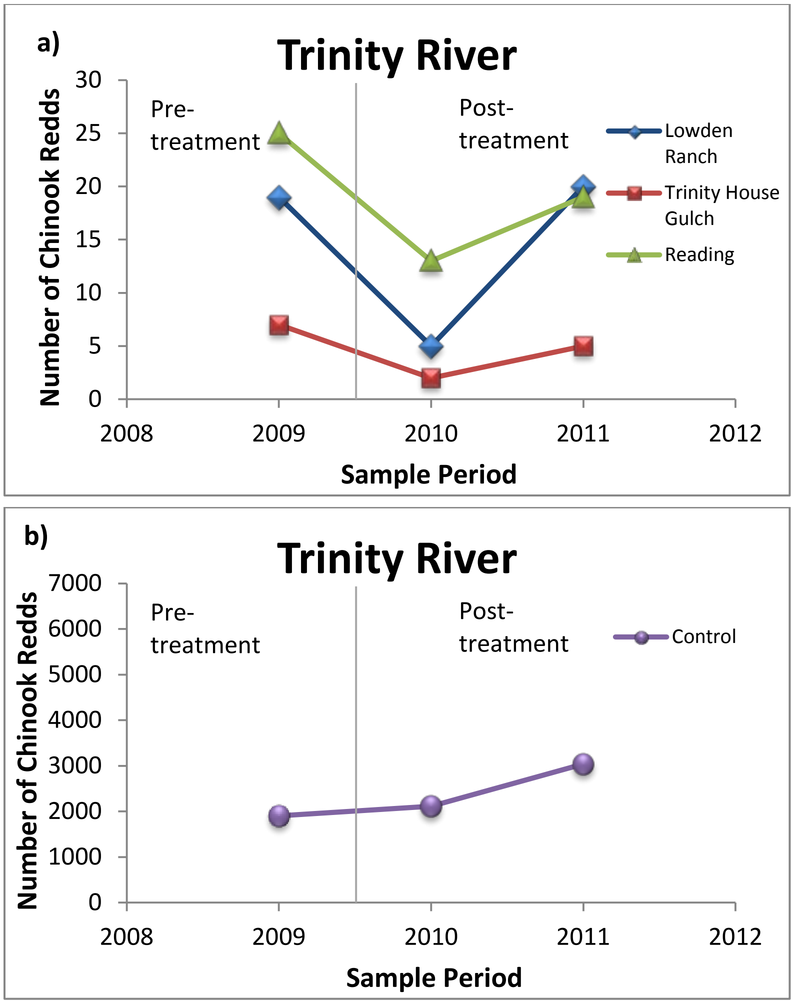


Figure 10

Number of Chinook salmon redds before-and-after channel rehabilitation, categorized by treatment: (a) gravel augmentation and other channel rehabilitation treatments and (b) control (untreated). Data in (a) were available for three rehabilitation sites, while data for (b) include control reaches throughout the restoration reach.

2.3.2 System Scale

2.3.2.1 Juvenile Rearing Habitat

System-scale monitoring shows that juvenile rearing habitat availability at base flow has not changed significantly over the three-year sampling period (Figure 11), but this is not surprising given the short sampling period and the paucity of high-flow events during that time. Independent analyses confirm the Figure 11 results and further investigate the spatial distribution of habit over time, the error structure of the data, and sources of variance (Appendix B).

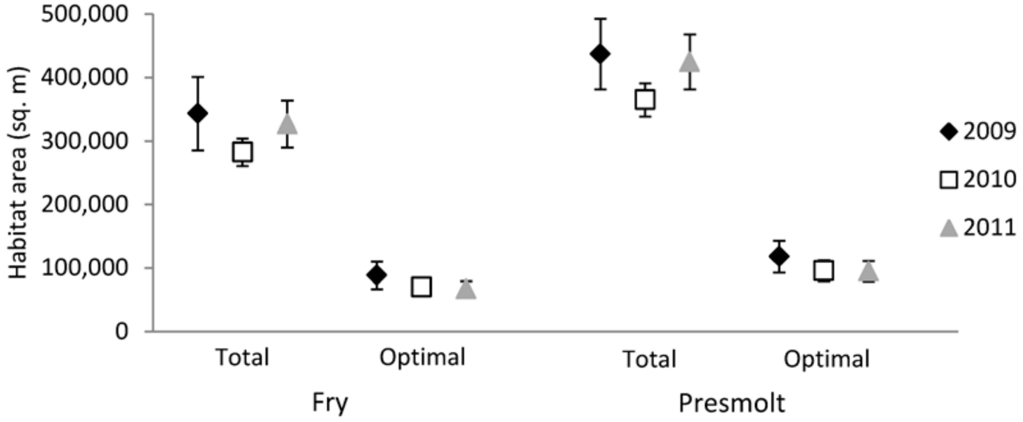


Figure 11

Total and optimal rearing habitat area for Chinook and coho salmon fry and presmolt estimated during base flow (14.4 m^3/s) from 2009-2011. Optimal habitat meets depth, velocity, and cover criteria, while total habitat includes areas that meet any combination of depth, velocity or cover criteria (Alvarez et al. 2011; 2013). Error bars indicate 95% confidence intervals. From Alvarez et al. (2013).

We conducted additional analyses to develop a retroactive model for examining system-wide rearing habitat over a broader time period. To examine juvenile habitat availability at system scales, we correlated observed base-flow habitat with base-flow channel characteristics determined from aerial photographs (Appendix E-1), an approach similar to that of Alvarez et al. (2011) and Goodman et al. (2012). Using this model as a surrogate for available fish habitat, we estimated habitat availability over space and time using a sequence of aerial photographs (Appendix E-1). Results indicate that juvenile rearing habitat availability has increased since 2001 (Figure 12), but the rate of increase has been slow (1.2-1.6% per year, 12-16% in total from 2001-2011). Nevertheless, these changes represent substantial potential increases in fish numbers. Assuming the mean fish densities reported by Goodman et al. (2010), the estimated increase in system-wide optimal habitat capacity for juvenile Chinook salmon from 2001 to 2011 is 130,202 fry and 94,946 presmolts. Similarly, the potential increase in total habitat capacity for juvenile Chinook salmon is 537,337 fry and 466,518 presmolts. We caution that our analyses were limited to base-flow habitat, which represents only a portion of the amount of habitat available over the course of an annual hydrograph (e.g., Figures 7 and 8), and does not include increases in juvenile habitat due to favorable changes in water temperatures; additional analyses across the full range of flows, temperatures, fish life stages, and spatial scales are needed to fully assess the effect of Program activities on habitat availability and fish production.

Although we observe system-wide increases in fish habitat, the results indicate no discernible effect of Phase 1 activities at this scale (i.e., no apparent difference in the trend of the data before/after 2005, Figure 12). To further explore this issue, we conducted statistical analyses to examine whether restoration activities were affecting local base-flow channel characteristics that, in turn, were correlated with local juvenile habitat availability, similar to the approach of Goodman et al. (2010). Results indicate that management activities are, indeed, having local effects. We find that observed changes in local channel characteristics (and thus juvenile rearing habitat) are related to the duration of high flows, upstream gravel augmentation, proximal construction activities, and streambank characteristics (alluvial *vs*. bedrock/resistant material) (Appendix E-1).

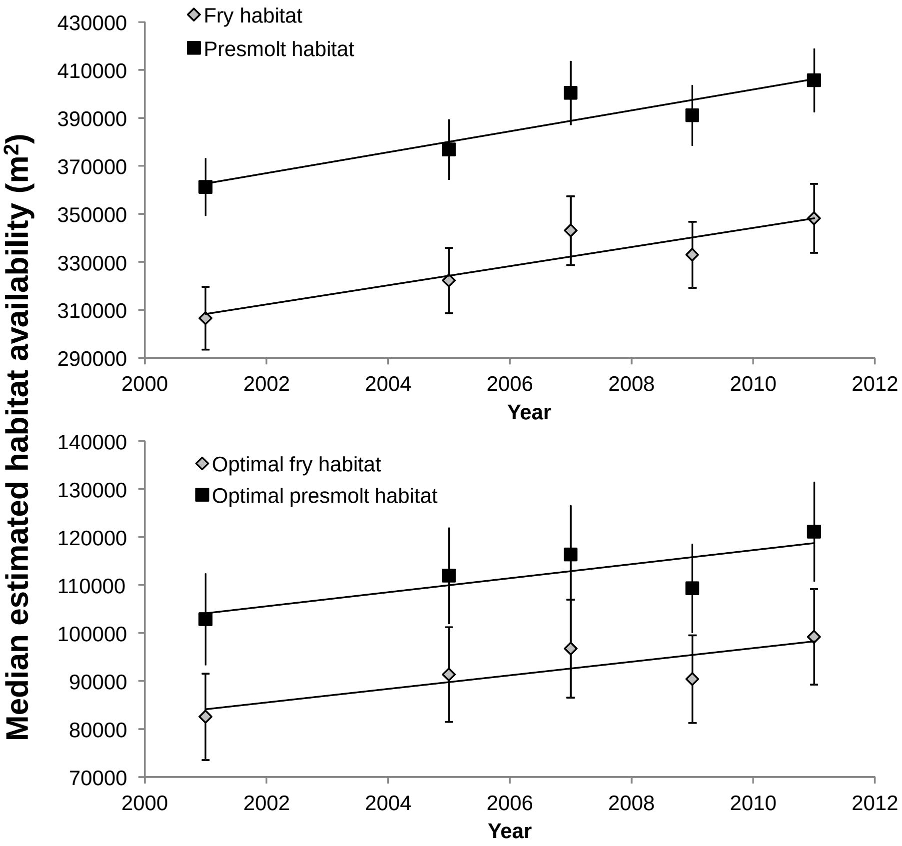


Figure 12

Increase in estimated total (top) and optimal (bottom) base-flow rearing habitat for juvenile Chinook and coho salmon in the Trinity River over the course of the Program, by life history stage. Phase 1 channel rehabilitation projects began in 2005. Vertical bars represent 95% confidence limits on estimates. Optimal habitat meets depth, velocity, and cover criteria, while total habitat includes areas that meet any combination of depth, velocity or cover criteria (Alvarez et al. 2011). See Appendix E-1 for further details.

We emphasize again that due to data limitations, the above analyses were focused only on the habitat available in the low-flow channel. Data for evaluating management-driven changes in juvenile fish habitats at higher flows is now being collected and should allow future documentation of system-wide changes in flow–habitat relations, similar to that demonstrated at site scales for the rehabilitation sites (Figure 8).

2.3.2.2 Adult Spawning Habitat

Spawning tends to be clustered near Lewiston Dam. As such, one of the Program sub-objectives is to spread the spatial distribution of suitable spawning habitat throughout the restoration reach. Recent analyses show that redds constructed by natural-origin spawners have spread further downstream from Lewiston Dam during the period from 2002-2011, but the trend is not statistically significant (Chamberlain et al. 2012) and it is unclear how it may be related to channel rehabilitation actions.

2.4 Water Temperature Regimes

Stream temperature is an important aspect of physical habitat for salmonids and the Program has been successful in managing stream temperatures within the restoration reach (Appendix A, Section 2.1.9). Overall, temperature targets were met more than 90% of the time during the summer holding period and more than 96% of the time during the two spawning periods. An examination of cumulative distributions of exceedances at Douglas City and North Fork Trinity River suggests that 60 to 70% of the exceedances were less than or equal to 1° F. These results indicate a high rate of compliance given the large number of variables associated with managing water temperature in a controlled, but large river system, exposed to tributary inflows and harsh air temperatures during summer months.

A more complex channel morphology has been created within the rehabilitation sites which, in turn, likely increases the spatial and temporal diversity of stream temperatures, offering a broader range of thermal habitats. Increased flows and shaping of the hydrograph in the post-ROD era may further modulate and diversify stream temperatures compared to pre-ROD conditions. We are not aware of any studies conducted by the Program to document the consequent effects of these factors on fish health and population response, but they have likely been beneficial and future investigation of the issue is warranted.

2.5 Fish Population Response

Documentation of fish population response to Phase 1 activities is limited. Although some positive changes in population metrics were observed during the Phase 1 period (Appendix A), mechanistic cause-and-effect relations are lacking. Here we summarize the observed responses in relation to IAP Objectives 3 and 4 (*Restore and maintain natural production of anadromous fish populations*) and specific sub-objectives as detailed in Appendix A.

We examined several data sets for natural-origin salmon (Chinook, coho, and steelhead): (1) abundance of juvenile Chinook salmon; (2) escapement of adult salmon; (3) proportion of adult salmon contributing to the total in-river run; (4) pre-spawning mortality; and (5) timing of smolt outmigration. In addition to target values specified by IAP objectives, we examined whether data trends showed any influence of Phase 1 activities (Appendix A).

The data show that the overall trend in abundance of natural-origin juvenile Chinook salmon generally increased from 2007 to 2012 for the larger Trinity basin (Figure 13a), but no systematic response was exhibited within the sub-basin containing the restoration reach (Figure 13b). Scaling the data by the number of spawners and resolving identified inconsistencies and needed corrections (Figure 13 caption) may further refine the relations shown here.

Spawning escapement trends during the Phase 1 period varied by species and phenotype and were sensitive to how sub-periods within the record were defined, making conclusions regarding the Phase 1 period tenuous (Appendix A, Section 2.1.1). The same was true for changes in the proportion of natural-origin adult salmon contributing to the total in-river run (Appendix A, Section 2.1.3). Nor were there any discernible effects of Phase 1 activities on pre-spawning mortality or smolt outmigration timing (Appendix A, Sections 2.1.10 and 2.1.11). The above results are not surprising given the recency of Phase 1 activities relative to the salmonid life cycle and the fact that several generations of fish may be needed before responses are detectable, not to mention the effect of factors beyond the control of the Program (e.g., ocean conditions, harvest, and hatchery management). The Program expects substantial increases in natural origin Chinook salmon populations within 3-4 brood cycles as a function of ensemble Program activities (management of flow, temperature, sediment, and channel structure) once dynamic fluvial processes have been restored (TRRP and ESSA 2009b).

The Program’s documentation of fish production provides valuable monitoring data, but is not mechanistically linked to Program activities, making it difficult to interpret the underlying cause-and-effect of observed changes in production. In-river fish production is the result of the dynamic nature of the river environment acting on fish life stages throughout the year from adult escapement through exiting of presmolts from the river. To quantify these interactions in the restoration reach, fish production models must now be linked with dynamic flow and dynamic water temperature models that interact with channel structure to describe the dynamic nature of habitat conditions available to in-river fish life stages. This linked modeling can be used to

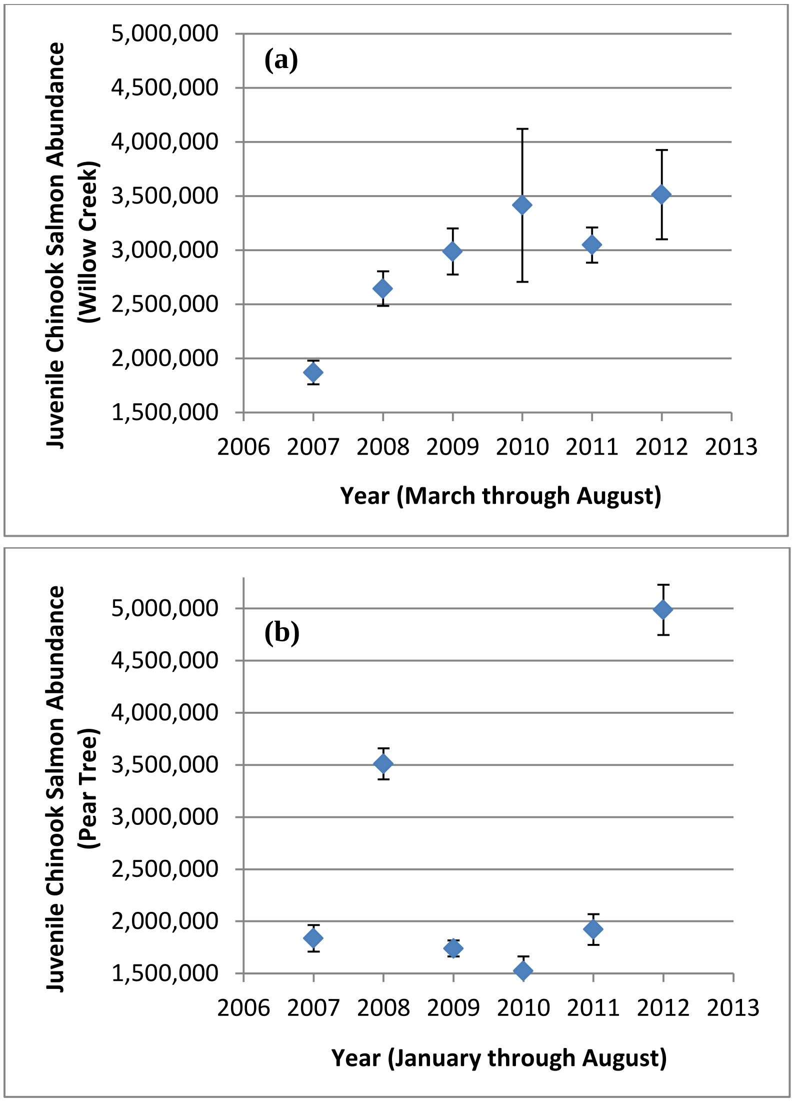


Figure 13

Abundance of natural-origin juvenile (Age-0) Chinook salmon over time for fish traps at (a) Willow Creek (near Willow Creek, CA, below the South Fork Trinity River confluence) and (b) Pear Tree (near Helena, CA, above the North Fork Trinity confluence). Error bars represent standard deviation. Trapping effort varied from year to year and this variation has not been accounted for in the figure. Potential corrections needed for the 2010 and 2011 Pear Tree data are currently being explored by the Program Partners. Data are from Pinnix et al. (2008; 2013), Harris et al. (2012), Davids et al. (2013), and Petros et al. (2013). The 2007 estimate for Willow Creek and the 2007 and 2008 estimates for Pear Tree were calculated using a Bayesian time-stratified spline-based method recommended by Schwarz et al. (2009); provided to Elizabeth Appy (Anchor QEA) by Bill Pinnix (USFWS) on March 5, 2014 and by Paul Petros (HVT) on March 10, 2014, respectively. See Appendix A, Section 2.1.2 for further discussion.

target data collection during monitoring and examine relative controls (designs, flow patterns, temperature regimes) on production (numbers and growth). For example, the linked dynamic models within SALMOD (Bartholow et al. 2000; 2003) were used to identify potential in-river fish production bottlenecks and inform the Program's initial management strategy for implementing the ROD (USFWS AND HVT 1999). Unfortunately, the Program's use of such models has not continued and, therefore, modeling results were not available for assessing Phase 1 activities. Re-examination of post-Phase 1 conditions via quantitative modeling may well show that major limitations (bottlenecks) to in-river salmonid production have evolved from the simplistic channel and low flows considered in the Program's foundational documents (USFWS and HVT 1999). Certainly conditions have improved as a result of the collective actions during Phase 1. Targeting Phase 2 data collection efforts toward developing this capability within the framework of a DSS is much needed, as discussed in the next section.

3 CONCLUSIONS

A tremendous amount of work has been accomplished by the Program and its associated partnerships in a relatively short time: (1) securing the ROD, a framework for tackling a very large physical and biological management issue; (2) bridge replacement and relocation of structures from the floodplain; (3) implementing variable annual flow releases to provide physical salmonid habitat and restore riverine processes; (4) enhancing water temperatures to near optimum conditions; (5) reducing fine sediment loads; (6) managing the coarse sediment budget; (7) intensive and innovative habitat rehabilitation work; and (8) extensive environmental monitoring. These are all clear successes, with Phase 1 activities representing an element within this larger body of work by the Program. In addition, important lessons have been learned since establishing the ROD. First, the river is much less alluvial than originally envisioned. The original and perhaps over simplistic view of the river as being fully alluvial with riparian-stabilized berms along the length of the river is now known to apply only to a much smaller portion of the restoration reach (i.e., approximately 25% of the channel). This recognition along with evolving designs for rehabilitation projects now suggests the need for a dichotomy of project designs (i.e., those that specifically drive geomorphic processes over time, producing dynamic habitat response in alluvial sections of the river *vs*. building static habitat features intended to persist over time in less alluvial reaches). Second, river terraces from past mining activity may require extensive cutting in locations where floodplain habitat is being designed for juvenile fish to use during high-flow events. Third, large-scale channel features may be needed to interact with flood flows and drive more rapid changes.

Returning to the first question posed to us by the Program (“Are we on the right track?”), the short answer is yes, but additional work is needed to assess progress toward achieving the Program’s *fundamental objective* (presumably the restoration of in-river fish production), as discussed below. The second question (“Which rehabilitation projects and design elements are successful?”) is similarly hampered by insufficient information, particularly with regard to the Program’s *fundamental objective*. Nevertheless, the available data suggest that the various channel design elements all contribute to increased juvenile salmonid habitat and reduce the usual constriction in habitat observed at modest flows (Section 2.3.1.1 and Appendix F). Side channels offer a potential means for maximizing habitat availability (Beechie et al. 202), but may be more prone to aggradation; so their potential benefits depend on the dynamic longevity of such features and they should only be located in reaches that have potential for an anabranching morphology (Figure 2). In addition, diversity of design elements and associated habitats is recommended, as this may promote species resilience to changing environmental conditions. Overall, the habitat created by the program has substantially increased the juvenile rearing capacity of the restoration reach and has likely had a positive effect on fish production, but the role of channel rehabilitation relative to other Program actions (e.g., management of flow, temperature, and sediment) remains to be demonstrated. The third question ("What should be done for Phase 2?") requires a longer answer and is addressed below within the context of our evaluation of Phase 1 activities.

In terms of Phase 1 rehabilitation projects, the Program is implementing the ROD, constructing fish rearing habitat, and monitoring physical and biological response relative to IAP objectives. However, given the current information available to us, we were not able to assess the efficacy of the Phase 1 actions with regard to the Program's *fundamental objective* of restoring in-river fish production. Certainly, Phase 1 activities are creating more suitable fish habitats and a more complex river, especially in terms of more spatially variable flow and water temperature regimes, but the effects on fish production are unclear due to insufficient data and insufficient time since project implementation to observe geomorphic changes and associated fish population responses. Although the Program is on track, the solution to this problem is not simply collecting more of the same data and waiting longer for the physical and biological responses to occur. Rather, there are several key elements missing from Program activities that inhibit assessing the efficacy of Phase 1 actions and progress toward the Program's *fundamental objective*:

1. The Program tends to be focused on *means objectives* (e.g., producing fish rearing habitat using channel designs and construction), rather than the *fundamental objective* of restoring in-river fish production. Similarly, many of the Program's monitoring efforts target *means objectives*, such as the availability and quality of juvenile fish habitat or the extent and degree of dynamic fluvial processes. Changes in trajectories of *means objectives* are only indicative of change toward desired improvements. Therefore, the ultimate metric is the change in the *fundamental objective* of in-river fish production, which is a function of the interactions of the *means objectives*. Toward this end, integrated modeling is needed to examine the synergistic effects of Program activities (management of flow, temperature, sediment, and channel morphology; all *means objectives*) over space and time to understand the effects on fish production (*fundamental objective*) and to evaluate the relative effects of different management actions.
2. The observed physical and biological responses to Phase 1 actions are encouraging, but rates of change are slow (Figure 12). Therefore, monitoring efforts must be supplemented by predictive models as described above to inform management actions in a timely manner and to facilitate adaptive management. The Program has recently begun to use quantitative models for predicting channel type, morphodynamics, and flow–habitat relations for evaluating design options and assessing site specific physical and biological responses (e.g., Alvarez et al. 2011; HVT et al. 2011; Beechie et al. 2012;

Gaeuman 2013), but these efforts require further integration and linkage to other Program activities, particularly fish production that supports a broader system-wide view and allows assessment of the relative effects of different management actions. In this regard, a fish production model is needed, such as SSS, the newer version of SALMOD (Bartholow et al. 2000, 2003).

3. To achieve the first two items above, Program activities and data collection must be more tightly integrated than they currently are. At the moment, Program activities are loosely organized around the ROD, but are not organized in a structured manner toward understanding system dynamics and documenting progress toward achieving the Program's *fundamental objective* of restoring in-river fish production. Annual compilation of data input to models that provide integration and an understanding of system dynamics and synergy will better inform management, foster understanding among stakeholders, and facilitate adaptive management. Toward this end, sharing of data and timely delivery of summaries for model input must be organized and scheduled.
4. The design process for channel rehabilitation projects is focused at site scales and does not yet consider the larger effects of rehabilitation actions, nor how individual projects may be interacting with one another and collectively affecting fish habitat and production. The same is true for other program activities (e.g., management of flow, temperature, and sediment). Nor are the relative effects of these activities on fish production known.
5. Formal, scientific hypothesis testing is needed. By its nature the Program is an applied effort, but it is nonetheless a science-based program and therefore requires stronger use of comparisons of alternative management actions and hypothesis testing for developing and writing study plans, making defensible decisions, and conveying results to peers and the public.
6. A formal adaptive management framework is needed, as called for in the ROD (USDOI 2000), to better structure and integrate Program activities and to increase the defensibility and transparency of management actions.

To address the above issues and to move the Program Partners and stakeholders toward a better understanding of the dynamic nature of the river system and the roles that specific *means objectives* may contribute toward fish production, our primary recommendation is that the Program focus immediate attention toward development of a Decision Support System (DSS). A DSS is a series of linked physical and biological models that allow the Program to (1) predict site and system response to alternative management actions in relation to ROD and stakeholder objectives; (2) make such predictions in a timely fashion (ahead of monitoring results); (3) focus and refine monitoring efforts to specifically assess predictions; and (4) provide a necessary tool for adaptive management and communication. Additionally, it will help to better structure and integrate Program activities and increase understanding of the roles of *means objectives* and thus the defensibility of management actions. In many ways, the DSS expands upon efforts started by the Program in defining Conceptual Models and Hypotheses (TRRP and ESSA 2009a).

The proposed DSS will shift the Program from the current focus on *means objectives* (i.e., producing fish rearing habitat using channel designs and construction) toward a focus on the *fundamental objective* (restoring in-river fish production) through a better understanding of the roles and synergistic effects of Program actions (management of flow, temperature, sediment, and channel morphology) over space and time to elucidate the effects on fish production. In addition, our intent is to more strongly focus Phase 2 on "science goals," rather than the current focus on implementation and monitoring. This requires testing the primary assumptions upon which the foundational documents and implementation plan rests. As an example, basic assumptions could be stated as: There is a measurable relation between the habitat quantity and quality that exists during a given salmon escapement, spawning, and rearing season and the recruits produced. Further, that this relation can be quantified and manipulated in order to achieve a measurable increase or decrease of the in-river salmonid production from the restoration reach within a given year. A major trade-off between optimizing habitat conditions for fish populations and releasing high flows for driving geomorphic processes may exist within any given year. By developing hypotheses and protocols for continually testing the relations between Program-managed river conditions and fish population responses, specific recommendations for a given year can be evaluated ahead of time, trade-offs debated among Program Partners, and chosen implementation strategies explained to the public. Questions that may be addressed during annual flow scheduling might include: What is the adult run size? What is the predicted water year allocation to the Program? Can adequate high flows be released to drive geomorphic processes in a desired direction? If the estimated adult run size is much smaller than average (or expected), does optimizing habitat conditions at the expense of geomorphic flow releases make sense, or could adequate suitable habitat conditions be provided at critical times and still deliver high flows for dynamically shaping channel morphology that also gradually move juvenile fish onto the floodplain, providing refuge habitats from high velocities. Although the Program addresses these issues to a certain degree each year during their flow scheduling, the proposed DSS would help to refine, focus, and integrate relevant questions and activities with regard to the *fundamental objective* of restoring in-river fish production.

Substantial guidance for the development of a DSS is provided in Appendix H and Figure 14, which illustrate the integrated modeling framework envisioned for the Program. The basic concept is to develop linked quantitative models that formally incorporate channel structure, flow, and water temperature as driving variables for estimating suitable habitat conditions over space and time throughout the restoration reach, and link this information to fish population modeling for estimating life-stage success in terms of numbers, growth and general health on an annual basis. Appendix H identifies key elements that should be considered when developing a DSS for the Trinity River (e.g., start with the above linkages within the restoration reach to better understand their dynamics, then integrate with existing work in the Klamath Basin on SSS). This appendix suggests particular models that are potentially useful to the Program, but these should not be treated as strict prescriptions. Rather, we recommend that Program personnel consider multiple approaches and different candidate models and, based on their familiarity with the system and Program objectives, choose those that best meet their understanding of component linkages and the required monitoring needs as input.

The initial Program action for DSS development is implementation of a core modeling effort that links a fish production model to channel structure, flow, and water temperature, as they define the dynamic nature of suitable fish habitats through space and time (Figure 14). The response to alternative management actions using model simulations of potential in-river fish production can be used not only to assess management alternatives, but also to illustrate predictions (forecasts) of selected management actions for public discussion prior to actual implementation. Toward this end, scoping is needed to specify the requisite input parameters and scales of information needed to drive the flow, water temperature, and habitat models that provide input to the selected fish production model (i.e., identify all other physical and biological models that are to be integrated within the DSS framework and how each model will specifically inform the fish production model; Figure 14). It is also necessary to specify how the DSS will be informed by monitoring data, what decisions are to be evaluated (i.e., the specific decision alternatives), and whether the selected models can address those decisions.

Most if not all of the Program’s existing monitoring data would be incorporated into the various models linked to the chosen fish production model, such as SALMOD or its new version, SSS. Although prior applications of such modeling efforts have used mesohabitat units to describe fish habitat availability, the Program’s current habitat sampling approach (GRTS) and existing habitat units can be used instead, as desired. However, in order to implement a model such as SSS, the Program will need to expand their current habitat sampling efforts to (1) determine flow–habitat relations across the full range of managed flows with the assistance of 2D hydraulic models (Alvarez et al. 2011) at both constructed and non-constructed sites; (2) extrapolate measurements to describe habitat suitability throughout the restoration reach; and (3) ensure that habitat sampling and extrapolations are compatible with models that simulate the dynamic nature of flow, water temperature, and habitat suitability throughout the system over space and time.

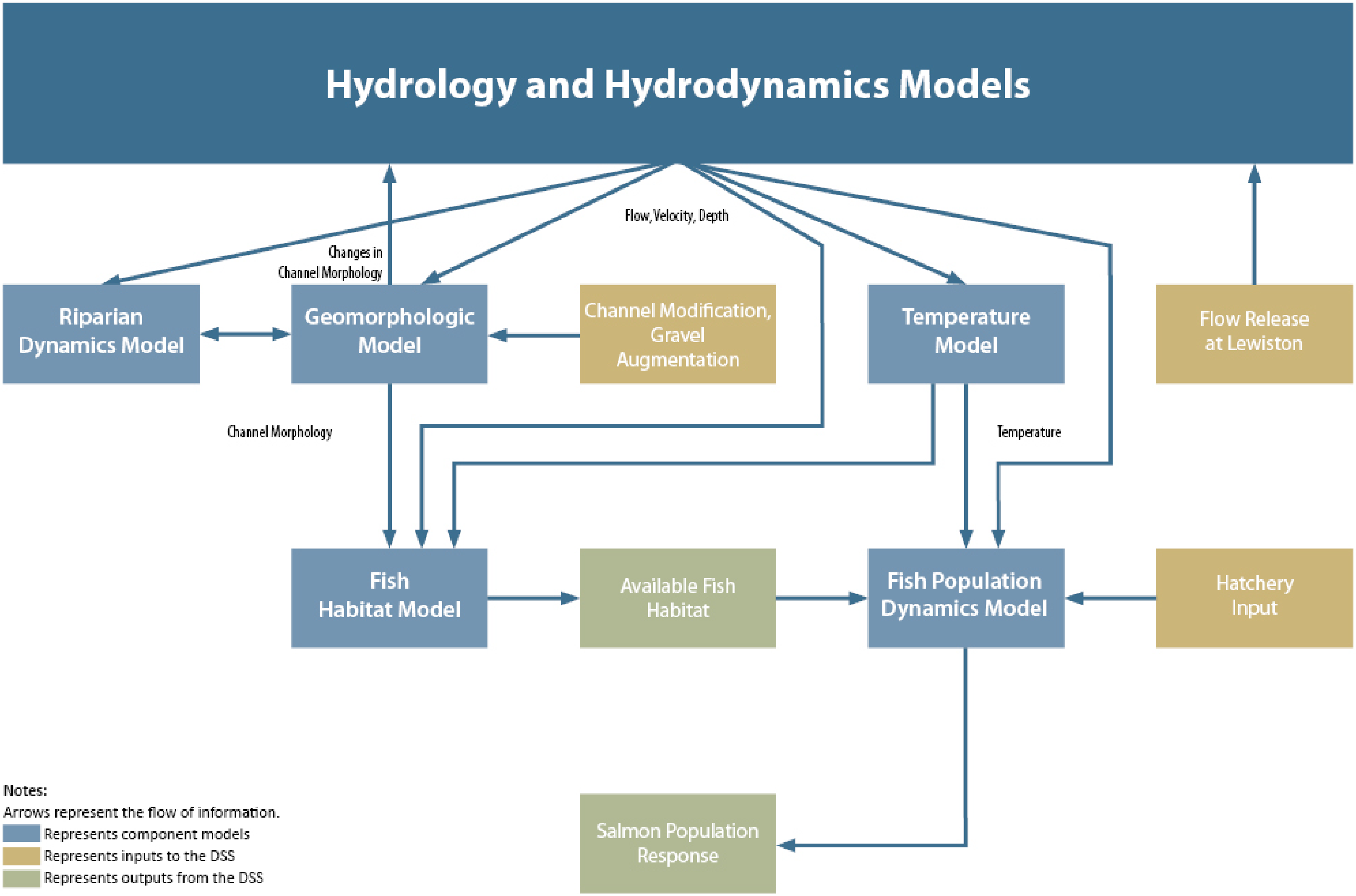


Figure 14

Model components of a Decision Support System for the Program. See Appendix H, Section 3.1 for further discussion.

The fish production model within the DSS does not supplant empirical data, such as smolt and habitat abundance, but in fact relies on such data and is tested and improved by it. The primary advantage of a DSS is rapid feedback, where possible outcomes of various management actions—either proposed or actual—can be compared and thus inform decisions, both for Phase 2 and the longer-term operation of the Program (i.e., continued gravel and flow augmentation following completion of the Phase 1 and 2 rehabilitation projects).

Beyond constructed changes in habitat, the site and system responses observed during Phase 1 are slow, and monitoring efforts must be supplemented by predictive models as part of a DSS to inform management actions in a timely manner and to facilitate adaptive management. A DSS also will integrate Program activities and provide for defensible decisions regarding workplan development, as recommended by the Independent Review Panel (Atkins 2012) and the SAB (2013).

In this regard, developing a collaborative plan for the efficient and timely flow of information among Program workgroups is essential. The plan should identify Program Partner and workgroup responsibilities for data sharing, model input, analysis, and integration. This must be organized and scheduled on an annual basis for populating the DSS. Program Partners and data collectors must place highest priority on identifying where data input may be needed from others and where and when their summaries are to be delivered to others.

4 RECOMMENDATIONS

Adaptive management is a guiding principle of the Program and a stated objective of the ROD (USDOI 2000). Implementing the Program in an adaptive management framework and assessing the efficacy of management actions requires a DSS; therefore developing a DSS and its core model elements discussed above (Figure 14), should be the highest priority for the Program in the upcoming year. Important next steps and detailed recommendations regarding the specifics of DSS development are provided in Appendix H (Sections 3 and 6).

Once the DSS is developed, we recommend that it be used along with other available information to:

1. Critically assess channel rehabilitation actions needed to achieve fish population objectives. What habitats and in which locations of the river are needed to achieve objectives at local and system scales? How do Program activities (rehabilitation projects and management of flow, temperature, and sediment) collectively affect salmonid populations? What are the synergistic effects and relative roles of different management activities?
2. Formally test the foundational hypothesis that a dynamic, complex channel can be created and that, together with other Program activities, will restore fish populations. To date, this has not been demonstrated, in part, because of slow physical and biological responses and the recency of restoration actions, which have not experienced many geomorphically effective flows. In this regard, modeling can help to test the above hypothesis and inform management actions in a more timely manner. Moreover, given the semi-alluvial nature of the river and limitations imposed by ROD flows and the volume of gravel introduced by augmentation, the original vision of a dynamic river with broad, active point bars may be too optimistic.
3. Critically evaluate the change in design strategy that has occurred (i.e., minimal *vs.* intensive mechanical intervention). A key factor to quantify in this regard is the response time for creating desired channel conditions and fish populations. The desired response time greatly influences the type of management actions (i.e., size, frequency, and degree of manipulation). Inherent in the Program's current approach of intensive, complex projects is the notion that more aggressive channel rehabilitation will shorten both the response time and the adaptive management learning cycle, thereby better informing Phase 2 designs. However, these assumptions remain to be tested and may be critically limited by the frequency and magnitude of ROD flows and the associated geomorphic work. In this regard, we also recommend that the Program pursue its investigation of ways to reshape the wet-flow and extremely wet-flow allocations to increase the magnitude and efficiency of geomorphic work that it can accomplish in relation to

desired channel conditions and resultant fish production. We also recommend that the Program consider the potential benefits of several large projects *vs*. many small ones. Are large channel rehabilitation projects more effective at meeting Program objectives than small ones, and which objectives are best met by each approach? Similarly, the benefits of projects designed to drive dynamic fluvial response in alluvial sections of the river *vs*. constructing static habitat in constrained and semi-alluvial reaches should be critically evaluated.

Based on our review of Phase 1 activities and the Program in general, we recommend the following additional actions:

- Phase 2 projects should continue to use opportunistic design strategies to promote dynamic alluvial reaches where possible, while working with local constraints on channel morphology in this semi-alluvial river. Designs should be based on models involving channel morphodynamics, flow–habitat relations, and fish production, rather than based on alluvial regime theory and reach-average channel characteristics (Eaton et al. 2010; HVT et al. 2011; Beechie et al. 2012). However, regime theory can be used to assess sustainability of a proposed channel type for the local channel slope, discharge, and bed load transport rate.
- Design objectives for Phase 1 projects were initially “motherhood and apple pie” statements—invoking ROD and IAP objectives without demonstrating how they would be achieved. In contrast, recent efforts are more defensible—employing mechanistic, predictive models to evaluate as-built changes, design alternatives, and site evolution. Phase 2 projects should continue the above, more rigorous efforts in combination with a DSS and fish production model.
- Incorporate into study plans metrics for quantifying juvenile fish numbers, growth, and health as major components of fish population modeling for estimating annual in-river fish production. Examine the role of annual water temperature regimes with regard to fish growth and general health across years. As the river system evolves in response to post-ROD management actions, the Program’s foundational hypothesis of juvenile rearing habitat being the primary limiting factor may be expected to change. Use the DSS and fish population modeling as a surrogate for the actual fish population to periodically examine alternative population limiting hypotheses. For example, (1) juvenile fish production *vs*. adult escapement and (2) carrying capacity of physical habitat *vs*. water temperature and its effect on fish growth and health.
- Better articulate program and stakeholder objectives and explicitly identify the relations among objectives. The current management actions tend to address *means objectives* (e.g., create habitat), rather than *fundamental objectives* (e.g., increase fish production).

As a result, disagreement about science is often conflated with disagreement about objectives. This significantly hinders scientific advancement. Similarly, scientific disagreement should be explicitly incorporated into the process, comparing alternative models that represent the alternative scientific hypothesis about system dynamics; a process facilitated by a well-crafted DSS.

- Adopt rigorous hypothesis testing for Program activities and scientific investigations, which is critical for improving the effectiveness of such actions. Treat rehabilitation projects as opportunities to formally test the hypotheses and goals articulated by the ROD and IAP. The current management actions address, but frequently do not test, the stated hypotheses and objectives. In this regard, we recommend refinement of IAP objectives to make them testable hypotheses. We also recommend that the Program conduct more comparisons within and between restoration sites to better evaluate design elements and overall project performance; lack of information precluded us from doing this as part of our review. To the extent possible, develop process-based, mechanistic hypotheses.
- Integrate workgroup activities to better achieve Program objectives. The workgroups include interdisciplinary membership, but need better coordination and exchange of information across workgroups (development of a DSS should facilitate this integration). In addition, the internal review process of Program reports should be streamlined to disseminate findings more rapidly. Internal dissemination of information from one group to another, necessary for model input and analyses, must not be hindered by lengthy review process. Publication in peer-review journals also is encouraged to both have peer input and to better disseminate Program findings.
- Develop a system-wide 1D sediment routing model in concert with existing sediment transport monitoring and additional tracer studies to more finely resolve the sediment budget and the fate of gravel augmentation (i.e., whether the input gravel is building bars, providing spawning riffles, or filling pools).

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6 REFERENCES

Alvarez, J., A. Hilton, J. Bair, G. Hales, S. McBain, D. Goodman, J. Polos, and A. Martin, 2011. Integrated habitat assessment of the upper Trinity River, 2009, draft report. Hoopa Valley Tribe, United States Fish and Wildlife Service, Arcata Fish and Wildlife Office, and Yurok Tribe.

Alvarez, J., D.H. Goodman, A. Martin, and N.A. Som, 2013. Estimation of age-0 Chinook and coho salmon rearing habitat area within the restoration reach of the Trinity River at an index streamflow-Annual Report 2011. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Arcata Fisheries Technical Report Number TR 2013-18, Arcata, California.

Atkins, 2012. Peer review report, Trinity River Restoration Program, preliminary fiscal year 2013 science workplan. October 2012.

Baker, D. W. and Wilcock, P.R. Stream Project: Decision analysis and design guidance for stream restoration, basic multi-criterion decision analysis (MCDA) tool. November 2012.

Bartholow, J., J. Heasley, J. Laake, J. Sandelin, B. Coughlan, and A. Moos, 2000. SALMOD: A population model for salmonids. Users' manual. Version 3. U.S. Geological Survey, Midcontinent Ecological Science Center Internal Report. Fort Collins, Colorado. 80 pp.

Bartholow, J.M., J. Heasley, J. Laake, J. Sandelin, B.A.K. Coughlan, and A. Moos, 2003. SALMOD: A population model for salmonids. Users' manual. Version 3. U.S. Geological Survey, Midcontinent Ecological Science Center Internal Report. Fort Collins, Colorado. March 2002 with minor revisions December 2003. 80 pp.

Beechie, T., G. Pess, and H. Imaki, 2012. Estimated changes to Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) habitat carrying capacity from rehabilitation actions for the Trinity River, North Fork Trinity to Lewiston Dam. Fish Ecology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, Washington.

Bradley, C. and D. G. Smith, 1984. Meandering channel response to altered flow regime: Milk River, Alberta and Montana. *Water Resources Research* 30(12):1913-1920.

Chamberlain, C., S. Quinn, and W. Matilton, 2012. Distribution and abundance of Chinook salmon redds in the mainstem Trinity River 2002 to 2011. Arcata Fisheries Technical Report TR 2012-16, U.S. Fish and Wildlife Service, Arcata, California. April, 2012.

Church, M., 1972. Baffin Island sandurs: A study of arctic fluvial processes. *Geological Survey of Canada Bulletin* 216. 208 pp.

Curtis, J. A., and T. M. Guerrero, 2012. Geomorphic mapping in support of science-based river restoration, Trinity River, California. Open-File Report 2011. Draft.

Dykaar, B. D., and P. J. Wigington Jr., 2000. Floodplain formation and cottonwood colonization patterns on the Willamette River, Oregon, USA. *Environmental Management* 25:87-104.

Eaton, B.C., R.G. Millar, and S. Davidson, 2010. Channel patterns: Braided, anabranching, and single thread. *Geomorphology* 120:353-364.

Gaeuman, D., 2013. High-flow gravel injection for constructing designed in-channel features. *River Research and Application*, DOI: 10.1002/rra.2662.

Gaeuman, D., and A. Krause, 2011. 2010 bed-material sediment budget update, Trinity River, Lewiston Dam to Douglas City, California. Technical Report: TR-TRRP-2011-2.

Gaeuman, D., and A. Krause, 2013. Assessment of pool depth changes in the Trinity River between Lewiston Dam and the North Fork Trinity River. Technical Report: TR-TRRP-2013-1.

GMA, 2010. Trends in substrate composition of the Trinity River, 1991-2009. Prepared for the Trinity River Restoration Program.

GMA, 2012. 2010-2012 Trinity River bathymetric mapping. Report to the U.S. Bureau of Reclamation, Trinity River Restoration Program. Weaverville, CA.

Goodman, D., A. Martin, J. Alvarez, A. Davis and J. Polos, 2010. Assessing Trinity River salmonid habitat at channel rehabilitation sites, 2007-2008. United States Fish and Wildlife Service, Arcata Fish and Wildlife Office, Yurok Tribe, and Hoopa Valley Tribe. Arcata Fisheries Technical Report Number TR 2010-13, Arcata, California.

Goodman, D., J. Alvarez, A. Martin, N. Som, and J. Polos, 2012. Estimation of age-0 Chinook and coho salmon rearing habitat area at 12.7 $m^3 \cdot s^{-1}$ within the restoration reach of the Trinity River-Annual Report 2010. Report by the U.S. Fish and Wildlife Service, Yurok Tribe, and Hoopa Valley Tribes.

HVT et al. (Hoopa Valley Tribe, McBain and Trush, Inc., and Northern Hydrology and Engineering), 2011. Channel rehabilitation design guidelines for the mainstem Trinity River. Prepared for the Trinity River Restoration Program, January 2011.

HVT (Hoopa Valley Tribe) and McBain and Trush, 2013. Water Year 2012 Trinity River Restoration Program geomorphic and riparian monitoring report - a sub-component of the integrated habitat assessment project. Prepared for the Trinity River Restoration Program. 172 pp.

HVT (Hoopa Valley Tribe) and McBain and Trush, 2014. Water Year 2013 Trinity River Restoration Program geomorphic and riparian monitoring report. Prepared for the Trinity River Restoration Program. 96 pp.

Krause, A. F., 2012a. Geomorphic context of the Trinity River. Draft. September 6, 2012.

Krause, A. F., 2012b. History of mechanical sediment augmentation and extraction 1912 - 2011. Technical Report: TR-TRRP-2012-2.

Krause, A.F., P. Wilcock, and D. Gaeuman, 2010. One-hundred and fifty years of sediment manipulation on the Trinity River, CA. Joint Federal Interagency Conference Proceedings: 9th Federal Interagency Sedimentation Conference and 4th Federal Interagency Hydrologic Modeling Conference, June 27-July 1, 2010, Las Vegas, Nevada.

Martin, A., D.H. Goodman and J. Alvarez, 2012. Estimation of rearing habitat area for age-0 Chinook and coho salmon during winter base flows within the Sawmill rehabilitation site of the upper Trinity River, 2010. Yurok Tribal Fisheries Program, Willow Creek, CA. U.S. Fish and Wildlife Service Arcata Fisheries Data Series Report Number DS 2012-26.

McBain and Trush, 2000. Evaluation of 1997 flood impacts on riparian berms along the Trinity River, California. Prepared for Hoopa Valley Tribe Fisheries Department. Hoopa, CA. 31 pp.

Nanson, G. C., and E. J. Hickin, 1986. A statistical analysis of bank erosion and channel migration in western Canada. *Geological Society of America Bulletin* 97:497-504.

SAB (Scientific Advisory Board), 2013. SAB review of the TRRP FY14 preliminary science workplan. June 2013.

Stevens, D.L. and A.R. Olson. 2002. Variance estimation for spatially balanced samples of environmental resources. *Environmetrics* 14: 593-610.

Stevens, D.L. and A.R. Olsen. 2004. Spatially balanced sampling of natural resources. *Journal of the American Statistical Association* 99: 262-278.

Thorne, C. R., 1982. Processes and mechanisms of river bank erosion. In: *Gravel-bed Rivers - Fluvial Processes, Engineering, and Management*. R. D. Hey, J. C. Bathurst, and C. R. Thorne (eds.), Wiley, Chichester, 227-271.

TRRP and ESSA (Trinity River Restoration Program and ESSA Technologies Ltd.). 2009a. Conceptual models and hypotheses for the Trinity River Restoration Program. Final report prepared for the Trinity River Restoration Program, Weaverville, CA. 130 pp.

TRRP and ESSA (Trinity River Restoration Program and ESSA Technologies Ltd.), 2009b. Integrated assessment plan, version 1.0 – September 2009. Draft report prepared for the Trinity River Restoration Program, Weaverville, California. September 2009.

USDOI (U.S. Department of the Interior), 2000. Record of decision Trinity River mainstem fishery restoration, final environmental impact statement/environmental impact report. December 2000.

USFWS and HVT (U.S. Fish and Wildlife Service and Hoopa Valley Tribe, in consultation with the U.S. Geological Survey), 1999. Trinity River flow evaluation, final report. April 1999.

Wilcock, P., 2010. 2004-2009 Sediment budget update Trinity River, California, Lewiston Dam to Douglas City. Prepared for the Trinity River Restoration Program. Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Maryland.