Appendix K

Estimate of the Number of Spring-Run Chinook Salmon Supportable by River Rehabilitation in the Narrows Reach of the Lower Yuba River

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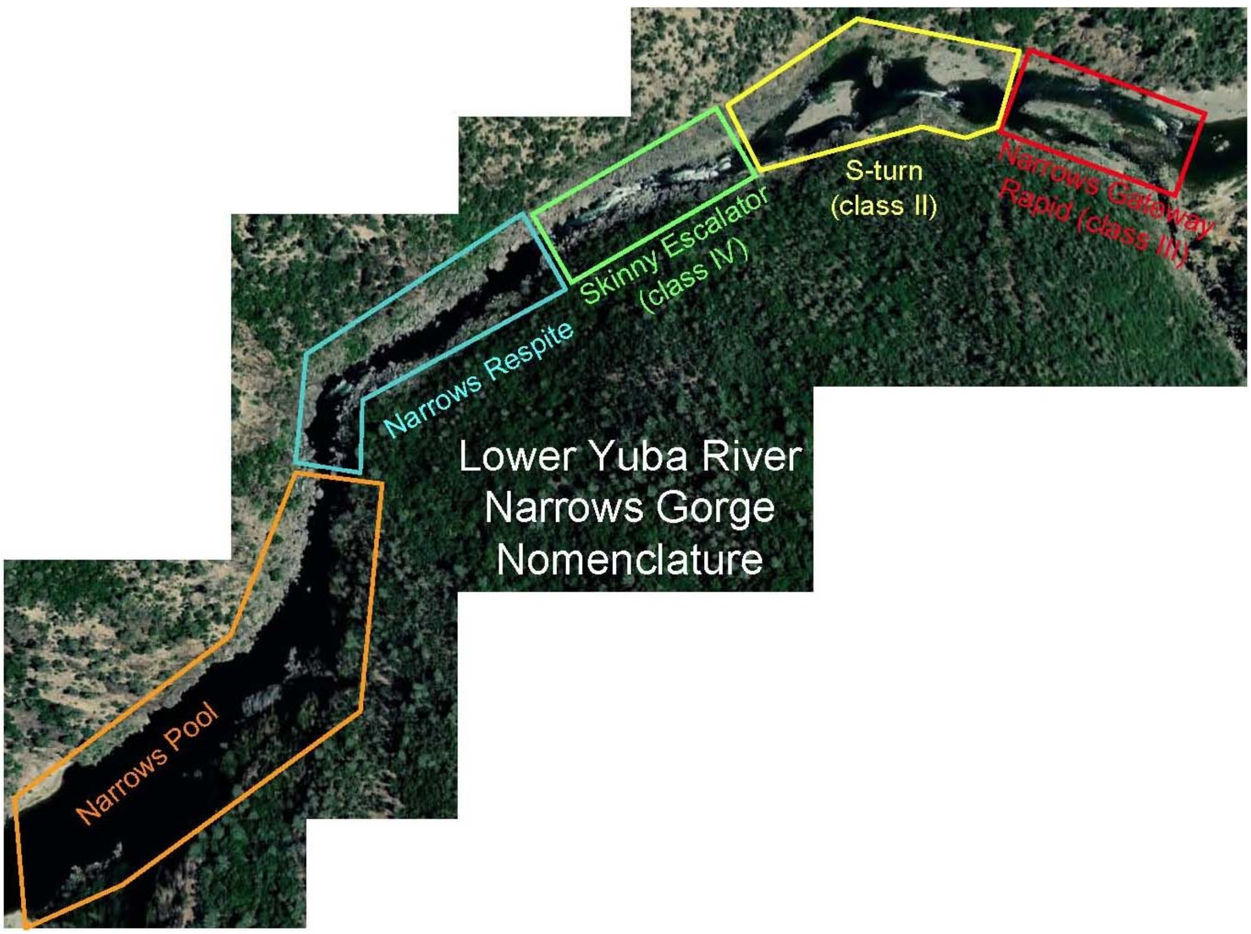

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1. INTRODUCTION

The Habitat Expansion Agreement for Central Valley Spring-Run Chinook Salmon and California Central Valley Steelhead (HEA) seeks to expand spawning, rearing, and adult holding habitat for these salmonids in the Sacramento River basin. A key goal is to accommodate an estimated net increase of 2,000 to 3,000 adult spawning spring-run Chinook salmon as compared to the habitat available under any relevant requirement or commitment. This goal is referred to as the Habitat Expansion Threshold (HET).

A draft Habitat Expansion Plan (HEP) has been developed in which two different sets of actions are proposed to achieve the HET. One set of actions involves rehabilitating selected areas of the lower Yuba River (LYR) between Englebright Dam and the confluence with the Feather River. Different parts of the LYR serve different salmonid species and their freshwater lifestages. Of all the Pacific salmonids, spring-run Chinook salmon (SRCS) are the most likely to migrate to the upstream limit of the accessible river at Englebright Dam and attempt to spawn there. The narrow river valley below the dam may be divided into two reaches: 1) the Englebright Dam Reach (EDR) that starts at the dam and ends at the confluence with Deer Creek and 2) the Narrows Reach (NR) that starts at the end of the EDR and ends at the onset of permanent alluvial fill in the river valley at the end of the bedrock canyon constriction (Fig. 1.1). Both of these reaches have received relatively little monitoring or scientific investigation relative to the rest of the river, and the NR has received even less than the EDR.

The purpose of this report is to investigate the status of the NR and envision options for river rehabilitation there in support of a rejuvenated SRCS population. Specific objectives with respect to the NR include 1) characterization of the current hydrogeomorphic condition, 2) historical aerial photo analysis to ascertain causes of the current condition, 3) scoping of river rehabilitation opportunities and constraints, and 4) estimation of the number of SRCS that could be supported by the rehabilitation possibilities.

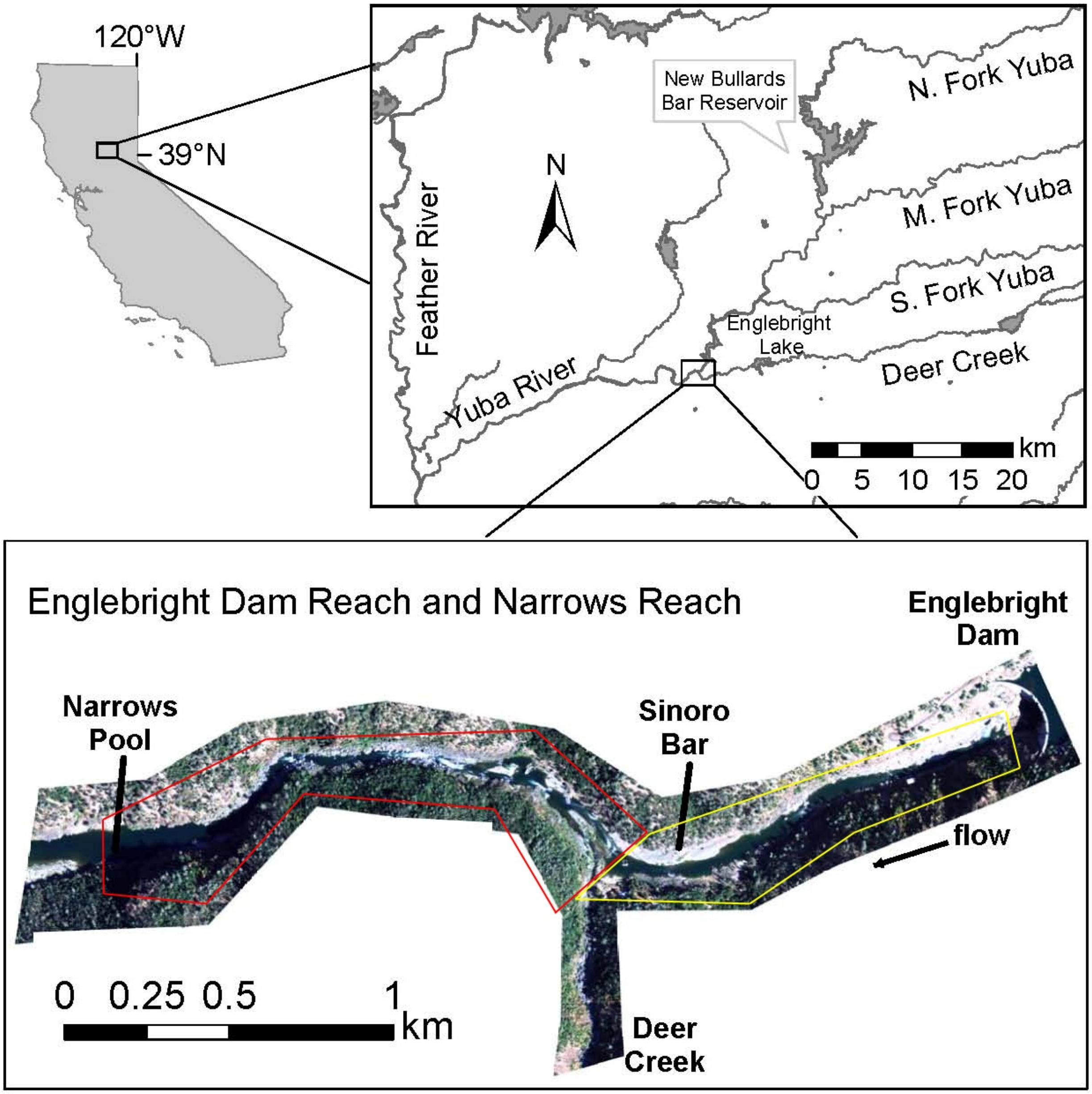

Figure 1.1. Location map and aerial imagery of the Englebright Dam Reach (yellow polygon) and Narrows Reach (red polygon) in the Yuba River watershed.

2. REACHES OF THE UPPER LYR

In geomorphology it is understood that the landscape exhibits different spatial patterns and processes when viewed at different spatial scales (Grant et al., 1990; Rosgen, 1996; Pasternack, 2008a). As a result, geomorphologists use a hierarchical framework for evaluating landscapes in which different methods and concepts are applied for each scale of analysis. The commonly used scales of analysis include hydraulic-unit (10^{-1} to 10^{0} W), geomorphic-unit (10^{1} W), reach (10^{2}-10^{3} W), and larger catchment spatial scales, where W is channel width. Spatial scales are referenced to channel width, because many observers have recognized a similarity of forms among systems of different absolute size that are governed by the same underlying processes. Note that there exists a gap for channel lengths of 10^{1} to 10^{2} W, which some geomorphologists consider to be an assemblage of geomorphic units and others simply call a reach, because they are not investigating the larger spatial scales beyond that.

In light of these concepts, the LYR may be partitioned into different units at each spatial scale. For this study it is not necessary to evaluate the entire LYR, but for context it does help to consider the top ~12 km from a reach-scale perspective. Downstream of the confluence of the South Yuba River with the mainstem Yuba River (above Englebright Reservoir), the mainstem flows through a narrow valley that includes Englebright Dam. The narrow valley ends at an abrupt, sudden expansion that denotes the onset of a perennial alluvial valley and riverbed in a reach known as Timbuctoo Bend (Fig. 2.1). In turn, Timbuctoo Bend ends just after the highway 20 bridge, because there is another abrupt, significant expansion in channel width at that location. Therefore, on the basis of abrupt changes in valley width, it is possible to distinguish three reaches at the 10^{2} W spatial scale in the topmost part of the LYR- a narrow valley, Timbuctoo Bend, and then a wide valley.

Moving down to the spatial scale of reaches at the 10^{1} to 10^{2} W spatial scale, there are geologically controlled variations in valley width and channel slope within the narrow valley between the confluence with the South Yuba River and the onset of Timbuctoo Bend. There are also tributaries that produce sediment and locally influence valley morphology, as well as Englebright Dam that artificially divides the valley into a reservoir upstream and a narrow river valley downstream. Taken together, these four factors- valley width, bed slope, tributary confluence, and man-made structures- may be used to delineate geomorphically distinct areas of the river at this reach scale.

Applying the controlling factors to the narrow valley downstream of Englebright Dam, there are four significant geomorphic controls revealed. The longitudinal profile of the river bed in the EDR shows a constant slope through the reach, but there is an unusually high rapid crest (Fig. 2.2). This feature creates a hydraulic backwater effect during flows <50,000 cfs and thus it serves as a major sediment transport barrier. There are no slope data available for the channel between the confluence of Deer Creek and the top of Timbuctoo Bend. The longitudinal profile of the wetted channel width during an extremely high flood event of 96,100 cfs (December 31, 2005) is representative of the role of valley width at the smaller reach scale (Fig. 2.3). It shows an abrupt increase in width at the onset of Sinoro Bar that is a significant geomorphic control. Next, the impingement of Deer Creek into the Yuba River is a significant geomorphic control. Although the reservoir on Deer Creek blocks sediment delivery to the Yuba now, there remains a strong asynchronous timing of floods out of Deer Creek and the Yuba River due to their different hydrological regimes. Deer Creek usually floods first, with its quicker rain-fed response. This means that Deer Creek flood flows impinging on the Yuba at an almost 90° angle cause a significant hydrodynamic barrier to bedload transport down the Yuba on the rising limb of a Yuba flood (note that bedload transport tends to be higher on the rising limb than the falling limb, because the water surface slope can be greater, driven by unsteady flows). Finally, there is a dramatic abrupt width decrease ~1,600’ downstream of the confluence with Deer Creek.

Although all four of these notable geomorphic controls are important at the geomorphic-unit scale, a decision to break up the upper LYR into reaches was made on the basis of the largest impact that transcends the reach scale, which was judged to be the role of Deer Creek. Width expansions and contractions affect the location of sediment storage in a river (White et al., 2010), but a tributary junction influences the source inputs of water, sediment, and biological materials as well as temperature and sediment storage. Consequently, the LYR is conceptually divided at the reach scale at the confluence with Deer Creek into the Englebright Dam Reach and the Narrows Reach (Figs. 1.1 and 2.1). The roles of the other geomorphic controls are thus considered within the context of the geomorphic-unit scale. It is conceivable to divide the river into finer reaches at all geomorphic controls, but then the scale of consideration becomes so small that it is no longer a reach scale assessment. This is the reasoning behind the currently used differentiation between the EDR and NR, which is important to understand in the context of the goals of this study.

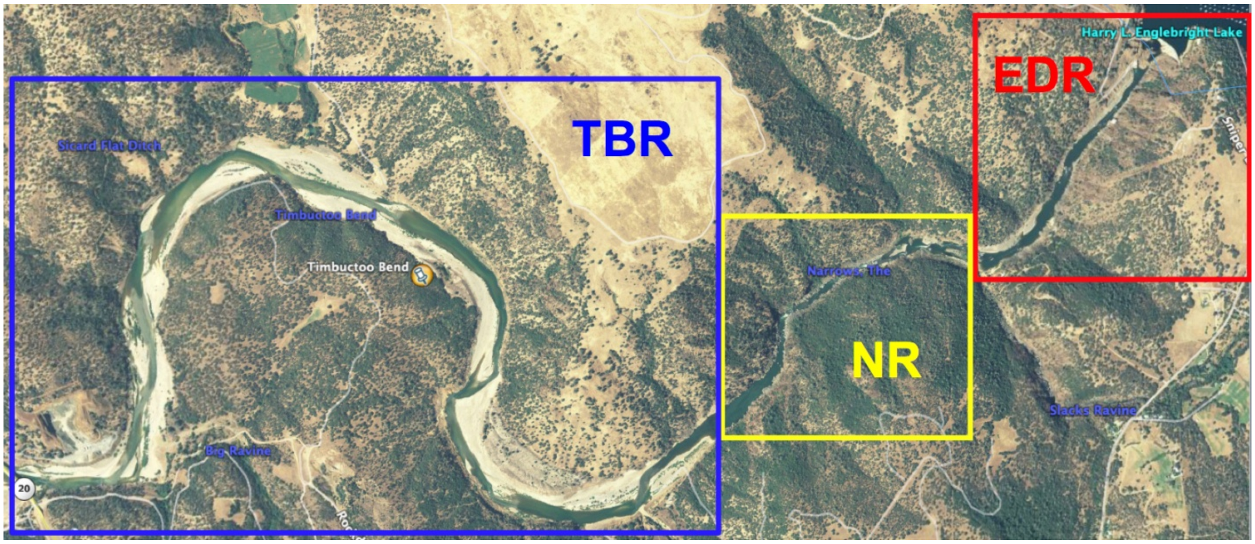

Figure 2.1. 2006 aerial image of the upper LYR delineating the Englebright, Narrows, and Timbuctoo Bend Reaches.

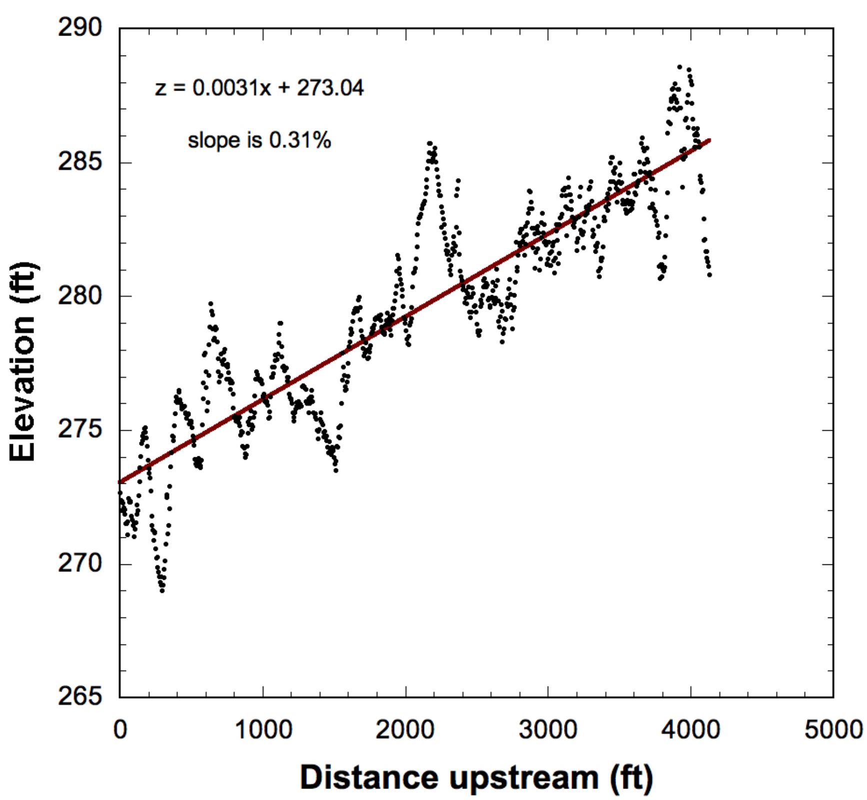

Figure 2.2. Longitudinal bed-elevation profile along 855 cfs thalweg in the EDR. The thalweg was determined using depth and velocity predictions from the SRH-2D model of the EDR. No slope break is evident in this profile.

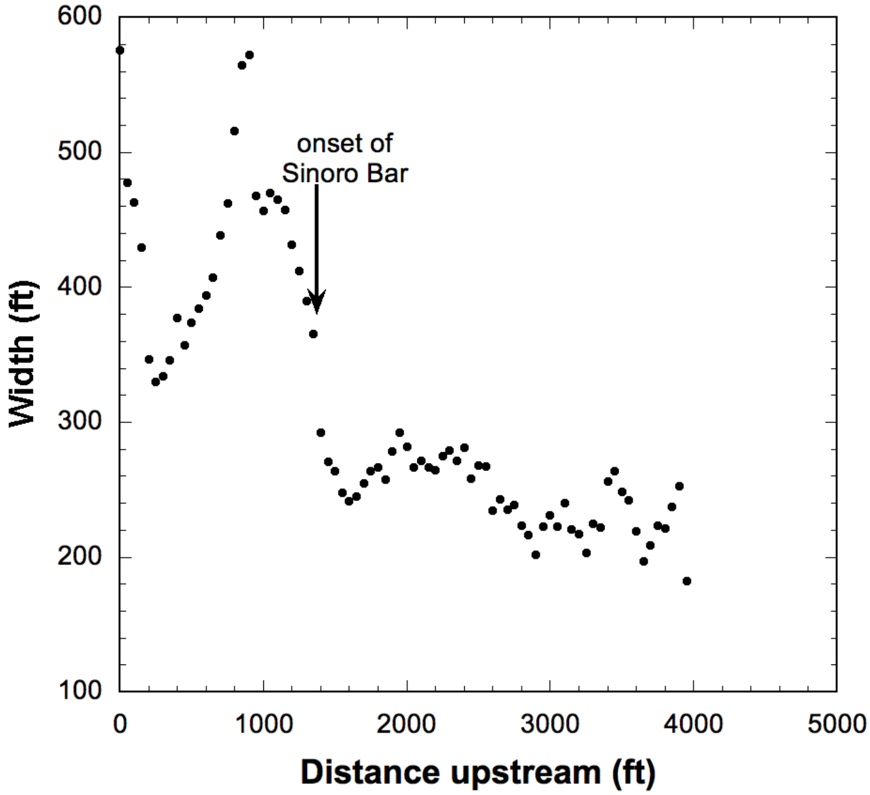

Figure 2.3. Longitudinal wetted channel width profile along the EDR centerline at 96,100 cfs. The wetted channel area for this discharge was determined using depth predictions from the SRH-2D model of the EDR. Note that the distance upstream along the centerline does not match the distance upstream along the 855 cfs thalweg in Fig. 2.2.

3. EDR ASSESSMENT RECAP

For ~10 years, stakeholders participating in the LYR Technical Working Group have discussed opportunities and constraints for river rehabilitation and enhancement in the EDR. Through interpretation of historical areal photos funded by a federal grant from the U.S. Fish and Wildlife Service, Pasternack et al. (2010) determined that the majority of degradation in the EDR in the vicinity of Sinoro Bar was caused by mechanized gold mining. Secondarily, the presence of Englebright Dam was responsible for a lack of natural, river-rounded gravel/cobble influx, as well as delivery of shot rock to that area in the 1997 flood. Equally as important, deposition of hydraulic gold mining debris in the EDR also caused large cobbles and boulders to become fixtures in the EDR at Sinoro Bar. These historical findings provided the basis for LYR stakeholders to subsequently recognize the opportunity for a direct intervention in the Sinoro Bar area to rehabilitate the river to undo the harm caused by mechanized mining and then to enhance the river to optimize physical habitat conditions for the freshwater life cycle of SRCS and to enable geomorphic sustainability. Consequently, a proposal was submitted to the HEA steering committee to consider a project in the Sinoro Bar area. Finally, that led to the Pasternack (2010) report that evaluated the geomorphic condition in the EDR and estimated the number of SRCS that could be supported by performing river rehabilitation in that reach as part of a potential HEA project.

Pasternack (2010) proposed river rehabilitation in the Sinoro Bar area of the EDR (Fig. 3.1). The goals would be to 1) undo the harm imposed by mechanized gold mining and overly coarse, angular rocks and 2) implement SRCS habitat enhancements to provide an array of sustainable, fish-preferred channel features at the hydraulic-unit and geomorphic-unit spatial scales. Such a project would entail excavating out the existing infill- estimated at a maximum of 128,940 m^3 (168,650 yds^3)- and then installing roughly the same volume of a mixture of river-rounded gravel/cobble, but distributed according to a carefully vetted design able to yield the necessary array of physical habitat needed to support the different SRCS lifestage requirements. In terms of ecological benefits of such a project relative to HEA goals and specifically the HET, 20 different estimates of supported SRCS were calculated based on different assumptions about the project area, fish behavior, and available adult SRCS. The potential for the project to support SRCS that otherwise presently have no support in that area was most reasonably estimated to be in the range of **10,116-12,644** adult SRCS (full range of uncertainty was 6,136-33,504). When population constraints due to full lifecycle constraints were considered (e.g., ocean and estuarine conditions) as an additional constraint, the most reasonable range of likely supported fish (rather than potential for support) under current conditions was **1,977-5,246**. In other words, the project would create fantastic conditions capable of supporting a large number of SRCS, but in fact there are far fewer SRCS in the LYR currently; thus, in actuality the likely supported run under current conditions would be smaller than the full potential. One benefit of having such a large excess of high-quality physical habitat available is that it would enable both fall-run and spring-run Chinook salmon to utilize the same area without having the fall-run decimate SRCS redds. The potential habitat from a Sinoro Bar project is large enough to meet both runs' needs.

Figure 3.1. Oblique photo of the Sinoro Bar area proposed for river rehabilitation as part of the HEA. The proposed project would start at the house-sized boulder in the lower right of the photo and end at the top of the rapid barely visible at the farthest downstream location in the photo (top center).

4. NARROWS CURRENT CONDITION

A primary objective of this study involved investigating the current condition of the Narrows Reach using available information and a new reconnaissance. The Narrows Reach is a remote part of the LYR that has received relatively little scientific investigation. Beak Consultants, Inc. (1989) conducted fish surveys in the EDR and NR, which they lumped together as a single reach they called the "Narrows Reach". They also did habitat simulation, from which they concluded that the area had little fry habitat and virtually no juvenile habitat at that time. For the terrestrial land, there exists a topographic map with 2' contours (NGVD29 datum) from the 1999 Army Corps aerial photogrammetry survey. A 2005-2007 topographic and bathymetric survey of the EDR conducted by UC Davis stopped at the top of the Narrows Gateway rapid for logistic reasons and lack of scientific need. As part of that effort, some NR hillside photography is available. In 2009, the Yuba Accord River Management Team (RMT) installed a water level and temperature sensor in S-turn. For the 2009-2010 spawning season, the RMT performed weekly redd mapping in EDR and NR. That is being repeated for the 2010-2011 spawning season as well. On October 1, 2010 a site recon was conducted to observe NR conditions. Based on the available information, a geomorphic analysis and a Chinook spawning analysis under current conditions was performed to characterize the two upper geomorphic units that are amenable to river rehabilitation.

4.1. Narrows Reach Geomorphic Units

The first step in the analysis of the Narrows Reach is to describe its physical geography in terms of the sequence of geomorphic units it contains and establish a nomenclature in support of discussions. At the geomorphic-unit scale (1-10 W), the factors that are commonly used to delineate individual units in a valley-constrained reach include abrupt changes in bed slope, bankfull width (W_{bf}), bankfull depth (D_{bf}), and representative bed material size, which for a river with a gravel/cobble substrate is taken as the size at which 90% of material is smaller (d_{90}). Using these factors, five geomorphic units were identified and named (Fig. 4.1). Starting at the upstream end, the first unit is named Narrows Gateway. It is a cobble bar/fan complex that forms a Class III whitewater rapid at the confluence of Deer Creek and the Yuba. The bar/fan complex ends at a constriction associated with a large bedrock peninsula. The second unit is named S-turn, because the flow is forced to bend around a sequence of four alternating bedrock outcrops. There are two large gravel/cobble bars in S-turn. This unit ends at the major valley constriction previously described in section 2. At this point the narrow valley becomes an even narrower canyon with high walls. The narrow canyon is divided into two geomorphic units on the basis of slope, depth (D), and d_{90}/D. First is the Class IV whitewater rapid herein named Skinny Escalator. This unit is narrow, shallow, steep, and strewn with large emergent and partially submerged boulders. After that there is a calm stretch of deeper water called Narrows Respite that still moves at a moderate velocity due to low width. Few emergent or partially submerged boulders are present. Where there is one such cluster, a small rapid is present.

Finally, the Narrows Reach ends with the large Narrows Pool. Valley width expands in the pool, but the defining aspect of the pool's terminus is taken to be the presence of an emergent gravel/cobble lateral bar on river left at low flow. That denotes the onset of Timbuctoo Bend.

Only the first two NR geomorphic units presently contain alluvial bars with gravel and cobble, so those were the areas focused on for detailed analysis for potential river rehabilitation. Each of those geomorphic units was investigated independently, since they are divided by a width constriction. For this purpose, the 2009 National Agricultural Imagery program (NAIP) aerial photo of the NR was used (Fig. 1.1), since that is the most recent imagery available. First, polygons were carefully drawn around the alluvial area of each unit and the total area determined. Second, the valley centerline length was measured. Third, the mean width was calculated by dividing total area by centerline length. Fourth, the height change was estimated using the Army Corps 1999 2' contour map of the terrestrial land in the Narrows. In that mapping effort, no bathymetric surveying was done in the EDR or NR. However, it is possible to identify the contour line closest to the water's edge and get its elevation (NGVD29 datum converted to NAVD88 by Dr. Pasternack's lab group in 2007). Such near-edge water surface elevations were obtained at the top and bottom of each unit and the difference calculated. For the Narrows Gateway unit, 1.3' of height was subtracted from the total calculated, because in Pasternack (2010) that much height is reserved for use in rehabilitating the Sinoro Bar area. Finally, the water surface slope available for use in river rehabilitation was calculated as height change divided by centerline length. Final results of the analysis are presented by Table 4.1.

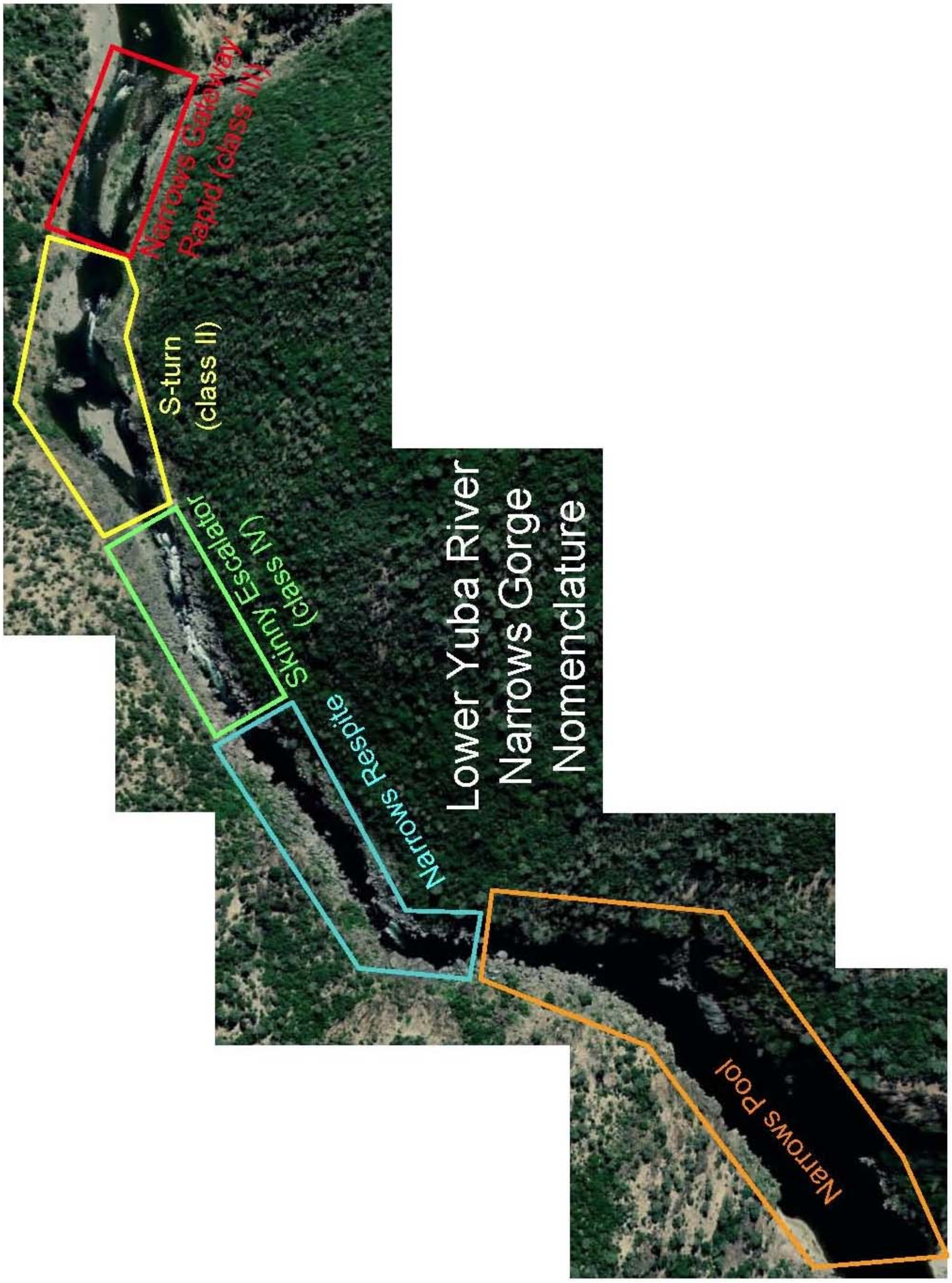

Figure 4.1. 2009 NAIP aerial photo of the Narrows Reach showing geomorphic-unit delineations and establishing a nomenclature for the individual features at this spatial scale.

Table 4.1. Results of spatial geomorphic analysis of the Narrows Reach.

	Geomorphic Unit	
Geomorphic variable	Gateway	S-turn
Total area (m^2)	15833	17210
Centerline length (m)	217.9	324.6
Mean width (m)	72.7	53.0
Height change (m)	2.44 (2.04)*	3.05
Slope	1.12% (0.94%)*	0.94%
*Parenthetical for Gateway is value after 1.3' is used for Sinoro Bar project		

4.1.1. Narrows Gateway

The Narrows Gateway geomorphic unit is influenced by several independent hydrogemorphic controls. Both the Yuba River and Deer Creek directly contribute flow and sediment into it. Two different physical valley constrictions may play a role in controlling the stage associated with the discharge input. There are two bedrock outcrops at the end of the geomorphic unit that constrict the channel. Since these outcrops are high, they produce a stage-independent areal constriction until they are overtopped. Down in S-turn there is a second constriction that is much narrower at low flow (Fig. 4.2), but since the north side of the channel is a lateral bar at that location, the constriction effect decreases as stage increases. Without doing 2D modeling it is not possible to ascertain the relative roles of each.

In terms of hydraulic-unit scale features in the Narrows Gateway, a site recon and aerial photo interpretation were used to visually estimate what was present (Fig. 4.2-4.3). The morphological unit classification of Pasternack (2008b) was used to define these units at the 0.1 to 1 W spatial scale. Given the steep slope of the channel here and the constricting role of the cobble bar, the features are primarily high-velocity units – rapids, chutes, and runs. The two pools are forced by bedrock outcrops and are deep. In the side channel there is riffle habitat, but the flow is regulated by Lake Wildwood on Deer Creek. Vegetation has grown onto much of the bar, indicating that it is not actively changing in recent years.

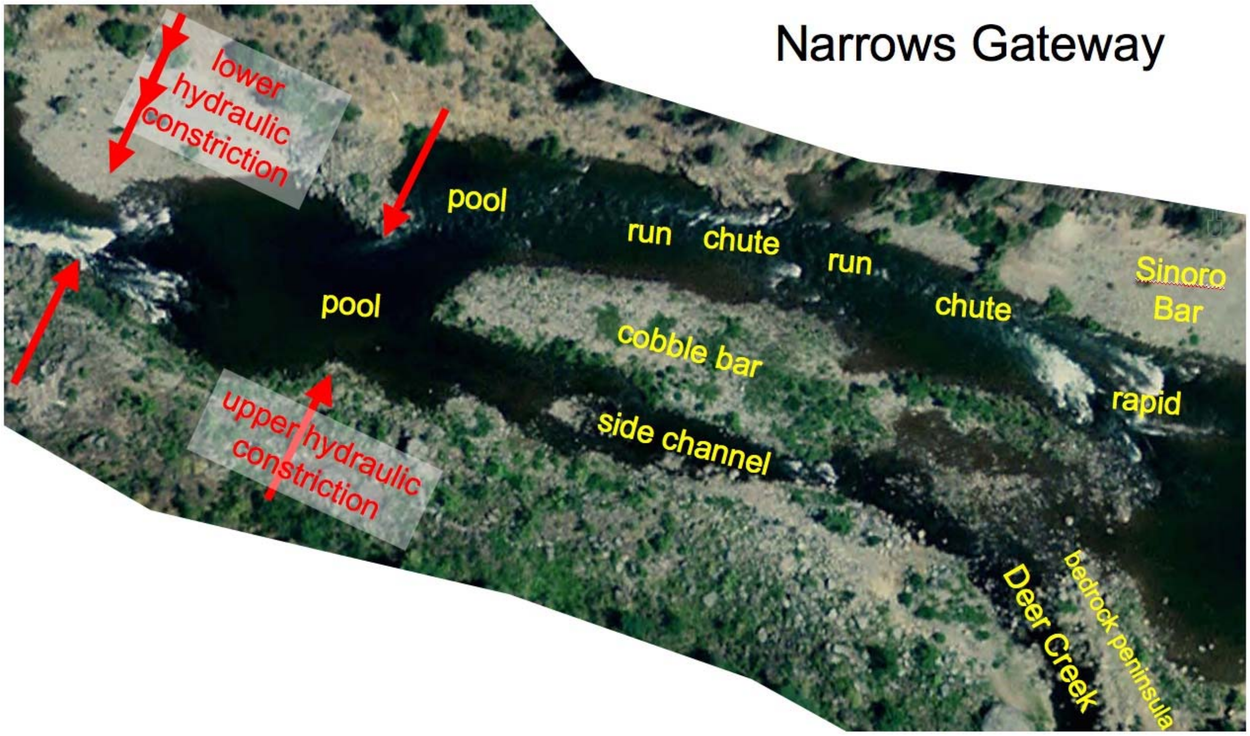

Figure 4.2. 2007 aerial photo of Narrows Gateway showing the interpretation of features at the hydraulic-unit scale.

Figure 4.3. High oblique view of Narrows Gateway taken on 11/29/2006.

4.1.2. Narrows S-turn

The aerial photo of Narrows S-turn shows several large bedrock outcrops and alluvial bars, but it does not give much of an impression of the flow pattern (Fig. 4.4). At ground level, the flow is seen to contort around the alternating bedrock outcrops, hence the name. The locations of two large cobble bars are indicative of the spatial variation of flow on the receding limb of mobilizing floods. The upper bar is along the bank located in the lee of the first bedrock outcrop on the north side of the river. That outcrop is a high peninsula that pushes flow to the south side where a deep scour hole has formed. The lower bar is in the center of the channel in the transitional area where width is decreasing steadily to the narrowest constriction at the end of the unit (Fig. 4.5). The main channel drops over a rapid and then is entrenched into alluvium on river left along the medial bar, while the side channel is at a higher elevation and more gradually drops along its length. The S-turn medial bar is widest in the widest part of the channel and narrows as the channel narrows (Fig. 4.4). The north side of the bar that is in the lee of another large bedrock outcrop on the north side of the channel is the highest area and is stable enough to have a dense cluster of willows (Fig. 4.6). The side channel to the north of the medial bar has an excellent diversity of SRCS physical habitat conditions for all lifestages, except that the substrate is overly coarse. Backwater and bank areas have microhabitat suitable for rearing. There is a deep pool in which several SRCS adult spawners were observed to hold, and down the side channel there is shallow, swift flow diverging over a riffle crest suitable for spawning and embryo incubation. No redds were observed there in the 2009-2010 survey and none on the recon visit on 10/1/2010. However, several adult SRCS were observed going in and out of the pool at the upper end and one adult fish was observed swimming around the lower end of the side channel.

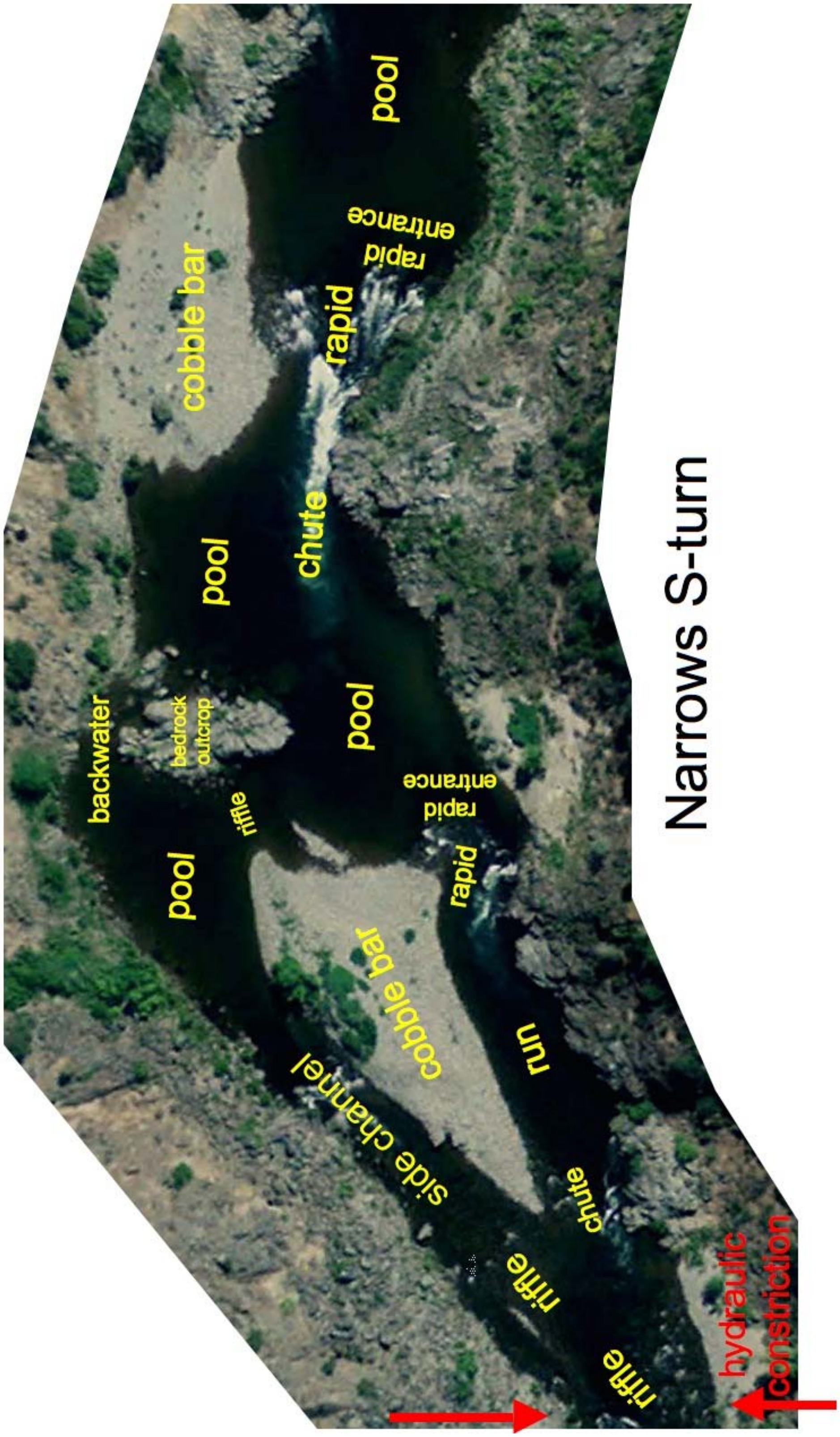

Figure 4.4. 2007 aerial photo of Narrows S-turn showing the interpretation of features at the hydraulic-unit scale.

Figure 4.5. High oblique view of Narrows S-turn and the top of Skinny Escalator taken on 11/29/2006. This view highlights the width constriction causing the deposit of the medial bar and shows the relative incision of the main channel compared to the side channel.

Figure 4.6. Medial cobble bar near the end of Narrows S-turn.

4.2. Narrows Reach 2009 Redds

The RMT has established a standard protocol for mapping all observed redds on the entire LYR in translucent water depths on a weekly basis. The protocol is available at http://www.yubaaccordrmt.com. Using this procedure, 84 redds were observed in the Narrows Reach between September 2009 and March 2010 (Fig. 4.7). The redds are concentrated in two primary and two secondary areas. One primary area was the side channel in Narrows Gateway. This is the area that receives a high outflow from Deer Creek during flushing operations in Lake Wildwood every October, which happens to be the peak of fall-run Chinook salmon spawning. Spawners were distributed all down the length of the side channel. The other primary area was the second rapid entrance in Narrows S-turn. At this site 2009 spawning was densely packed into a small area. This site was visited in 2010 during the period of phenotypic SRCS spawning and 25 adult spawners were directly observed (Fig. 4.8), with indications of many more present holding in the pool upstream of the site and in the other nearby pool to the north behind the large bedrock peninsula. In Figure 4.8 several fish are clearly discernable as well as a clean gravel substrate. Besides these primary spawning areas, there is a small amount of spawning on the large lateral bar on the north side of S-turn and at the top of the medial bar, where a submerged finger of the bar composed of gravel creates riffle-like habitat as water flows into the side channel. In the 2010 recon for this study, a large SRCS redd was observed at this location and several SRCS spawners were observed in this area and moving around nearby (Fig. 4.9). A movie was made of their activity. It appeared that the fish were all moving to the exact same spot with excellent microhabitat hydraulics, but that spot was devoid of suitably sized gravel, because it had all already been used in a large redd just downstream.

Figure 4.7. 2007 aerial photo of Narrows Gateway and S-turn showing the locations of redds in the September 2009 to March 2010 spawning period. No redds were observed in the other NR geomorphic units. (data courtesy the LYR Accord RMT)

Figure 4.8. Photo of dense (phenotypic) SRCS spawning activity on 10/1/2010 at the second rapid entrance in the Narrows S-turn geomorphic unit.

Figure 4.9. Photo of an adult SRCS (center of photo) hovering at the point of optimal microhabitat hydraulics where the substrate is on the coarse side for preferred spawning. A large redd composed of suitably sized gravel/cobble is present in the center right of the photo.

5. NARROWS REACH HISTORICAL ANALYSIS

Although knowledge of the current condition of the Narrows Reach is important baseline information for river rehabilitation, natural processes and human impacts are often revealed through a historical analysis of available information. In this case, the primary source of historical information is aerial photos taken at irregular intervals since 1937. Pasternack et al., (2010) used this set of images to investigate the history of Sinoro Bar, but the same set as well as a few others not used in that study also captured the Narrows Reach. This is the first time the historical aerial imagery of the NR has been analyzed. Photo interpretation was used to determine what landforms and physical habitat conditions were present historically. Substrate size classes (e.g., boulder, cobble/gravel, sand/mud), grain turnover, water turbidity, and presence/absence of vegetation are visually evident in the photos. For all discharges reported below, values were taken from the USGS Smartville gage only, neglecting the Deer Creek gage. The objective of this part of the study was to characterize historical changes in the NR to determine the history of sediment storage there and the extent to which fluvial landforms have changed with changes to sediment storage and in response to large floods.

5.1. Reach-scale Channel Change

At present the NR has relatively little gravel on the surface of the riverbed, especially downstream of S-turn, but that was not the case historically. We know from historical documents that an alluvial bar called Landers Bar was present in the NR (not the EDR) and that it was mined for gold. According to local landowner Ralph Mullican, gold miners built a wing dam at the mouth of Deer Creek in the ~1860s to help their effort to turn over gravel and larger rocks to get to the bottom. A derrick was used there to drag rocks onto the wing dam. Many such large rocks have hand-drilled holes in them for black powder. The first available aerial photo of the reach dates to October 21, 1937, which had a low flow of 140 cfs (Fig. 5.1). In that photo the water is turbid despite being in the dry season and there are many emergent alluvial bars throughout the NR. The emergent bars include point bars associated with constrained meandering in a narrow valley. These bars are mostly devoid of vegetation, indicating that they are active. Bedrock outcrops are very limited and in a few places only the very tops of modern outcrops poke out above the deep alluvial fill. Where the Narrows Pool is presently located, the riverbed is almost completely filled in, with half the width of the channel exhibiting a large emergent lateral bar. According to Physical Geography Prof. Allen James of University of South Carolina, during the era of intensive hydraulic mining in the Blue Point Mine area just downstream of the NR, alluvium fully blocked the flow of the river causing a lake to form and back up into the NR. He has observed backwater lake deposits up on the hillside in recent years. The 1937 photo does not exhibit any evidence of whitewater rapids in the NR. Taken together, these indicators lead to the conclusion that in 1937 the NR had a fully alluvial riverbed with some emergent floodplains constrained by bedrock walls.

In December 1937 and January 1943, large floods of 74,200 and 81,100 cfs, respectively (Smartville gage only; not considering Deer Creek) went through the NR. Englebright Dam began operation in 1942. Thereafter, the next available aerial photo is from February 22, 1947

(Fig. 5.1). That photo was taken at a higher turbid flow (1,500 cfs) in winter and it is a lower quality image, but important indicators are present. First, there are still emergent alluvial bars throughout the NR. Second, there is a large amount of alluvial at the mouth of Deer Creek and the flow is over the north side of the channel suggesting that the channel incised, leaving the deposit at the confluence at a higher emergent elevation. Third, the bedrock outcrops are more prominent. Fourth, gold dredgers had worked over the emergent lateral bar flanking the lower part of Narrows Pool and up into the Blue Point Mine canyon. Unfortunately, the water turbidity and high flow make it difficult to determine if any whitewater rapids are present in the NR, but highly visible tree shadows over the water in Skinny Escalator and Narrows Respite suggest that no rapids were there, because whitewater would not reflect such strong shadows. Taken together, these indicators lead to the conclusion that by 1947 the NR had incised substantially, but that the riverbed was still predominantly alluvial with no rapids.

On November 21, 1950 there was a flood of 109,000 cfs on the Yuba. The next aerial photo is from July 16, 1952 (2,860 cfs), and it shows dramatic change (Fig. 5.1). For the first time, the water looks black, indicating that it is translucent, not turbid. Also, no emergent alluvial bars are evident in Skinny Escalator or Narrows Respite. Bedrock outcrops in Narrows Gateway and S-turn are very prominent. An abrupt increase in water depth is evident at the constriction between S-turn and Skinny Escalator. The dredger tailings flanking Narrows Pool have mostly been swept away. Taken together, these indicators lead to the conclusion that by 1952 Skinny Escalator and Narrows Respite had lost the majority of their alluvial fill and the other geomorphic units had incised substantially, though not as much.

Unfortunately, there is a gap in the imagery from 1952-1984. In that period there were five large floods between 86,000 and 171,000 cfs. According to local landowner Ralph Mullican, a bulldozer was brought into the EDR in 1960, followed by an excavator in the 1970s. The machinery was used to access underlying gold-bearing gravel. The excavator was also used to divert the Yuba down a newly deepened channel on the south bank of the river. Photos and movies of such activities are available by contacting Mr. Mullican. The aerial photo from June 28, 1984 shows that Skinny Escalator and Narrows Respite had essentially arrived at the condition we see them in now, 26 years later (Fig. 5.2). The bedrock outcrops in Gateway and S-turn are also as prominent as they appear now. The alluvium in the upper half of Narrows Pool is no longer visible and the emergent lateral bar in that area eroded away, but swift currents visible in the photo suggest that the water is shallow there.

After the 100,000 cfs flood of February 19, 1986 there was not much change (Fig. 5.2). No other large events occurred, so the 1991 and 1996 aerial photos look similar. An important indicator shared by the 1986, 1991, and 1996 photos is that there is strong visual evidence of an alluvial riffle midway down the Narrows Pool.

The next big flood was a rain-on-snow event on January 2, 1997. The next photo thereafter is from the Army Corps topographic survey in 1999 (Fig. 5.2). In that photo the pre-existing riffle midway down the Narrows Pool is gone and there is now a very deep scour pool instead. This has been the condition of the Narrows Pool ever since.

Overall, the reach-scale historical aerial photo analysis revealed that erosion and incision took place steadily over time in the NR. By 1952 Skinny Escalator and Narrows Respite had lost the majority of their alluvial fill (Fig. 5.1). By 1984, bedrock outcrops had reached their final prominent stature and emergent bars in gateway and S-turn were mostly as they appear now. By 1999, Narrows Pool had achieved the current deeply scoured condition, and that took place by an entirely natural process (Fig. 5.2). There is no photo evidence of in-channel dredger mining occurring in Narrows Pool. A more detailed consideration of conditions and changes in Narrows Gateway and S-turn is presented next.

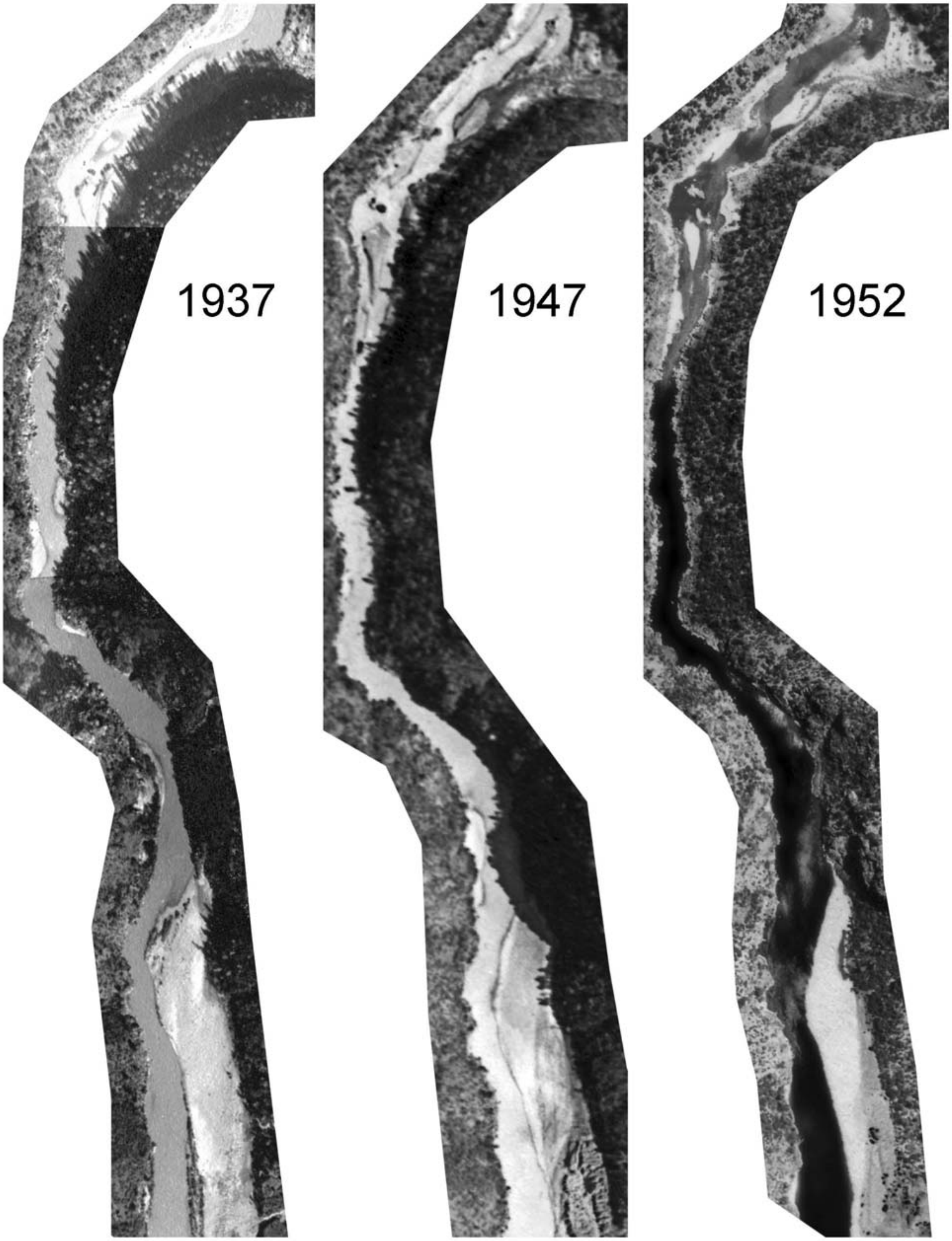

Figure 5.1. Comparison of NR aerial imagery 1937-1952.

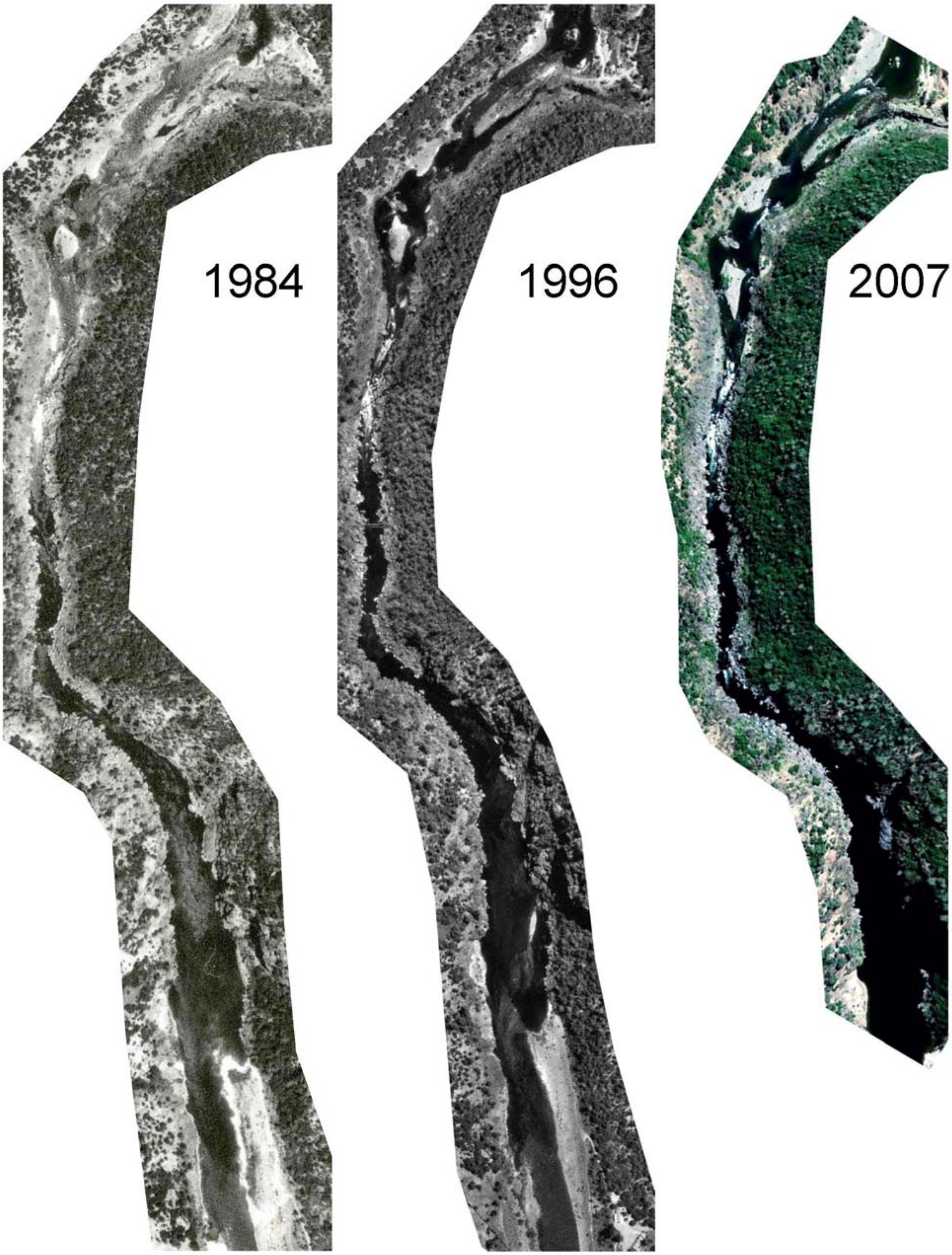

Figure 5.2. Comparison of selected NR aerial images 1984-2007.

5.2. Geomorphic-Unit Scale Channel Change

Based on the reach-scale historical analysis, the Narrows Gateway and S-turn geomorphic units have always had alluvium in them, even prior to hydraulic gold mining. When designing a river rehabilitation project for these units, knowledge about what morphological units are sustainable is helpful. Therefore, the historical aerial imagery was cropped down to these units and given closer inspection. The objective is to ascertain how dynamic morphological units have been in those areas.

Figures 5.3, 5.4, and 5.5 show a subset of the images cropped to the two upper geomorphic units. Despite the significant incision that took place over 70 years of imagery, several of the alluvial features have shown resilience and remained present. In the 2007 photo, there are three major emergent bars. All of them are present in every photo over 70 years. The bar at the confluence with Deer Creek was a lateral bar in the 1937 and 1947 photos, but thereafter there is a single isolated low-flow side channel that captures the outflow from Deer Creek along the south side of the channel. The lateral bar on the north side of the river in S-turn that is in the lee of a large bedrock outcrop was a medial bar in 1937, but once the river incised enough for the outcrop to control hydraulics there, the bar shifted behind the outcrop where it has stayed ever since. The medial bar at the end of S-turn has also persisted and its shape has shown relatively little change. In 1937, 1984, and 1986 it was shorter, while in all other years it had a tail. Present-day vegetation on that bar was not there in the 1952 photo, but was present by 1984. Since then it has expanded, indicating that the bar top is stable, with the stability aided by the vegetation. The present-day rapid at the head of Narrows Gateway was a less steep riffle that was stable in 1937-1996 despite floods and incision. The riffle was replaced by a rapid in the 1999 photo, so it must have been changed by the 1997 flood or possibly by artificial activity. Finally, there appears to have been a riffle in the transition between S-turn and Skinny Escalator over the last 70 years. Overall, the morphological units in Narrows Gateway and S-turn have been remarkably stable since 1937 despite dramatic channel incision. The explanation is that the bedrock outcrops in S-turn and the valley width oscillations throughout the reach impose a persistent suite of hydraulic controls that stabilize the morphology of geomorphic units in the NR. Unfortunately, it is not possible to discern much about riverbed grain size in the NR, but it is likely that the bars have coarsened and armored somewhat, based on what was observed during the recent site recon.

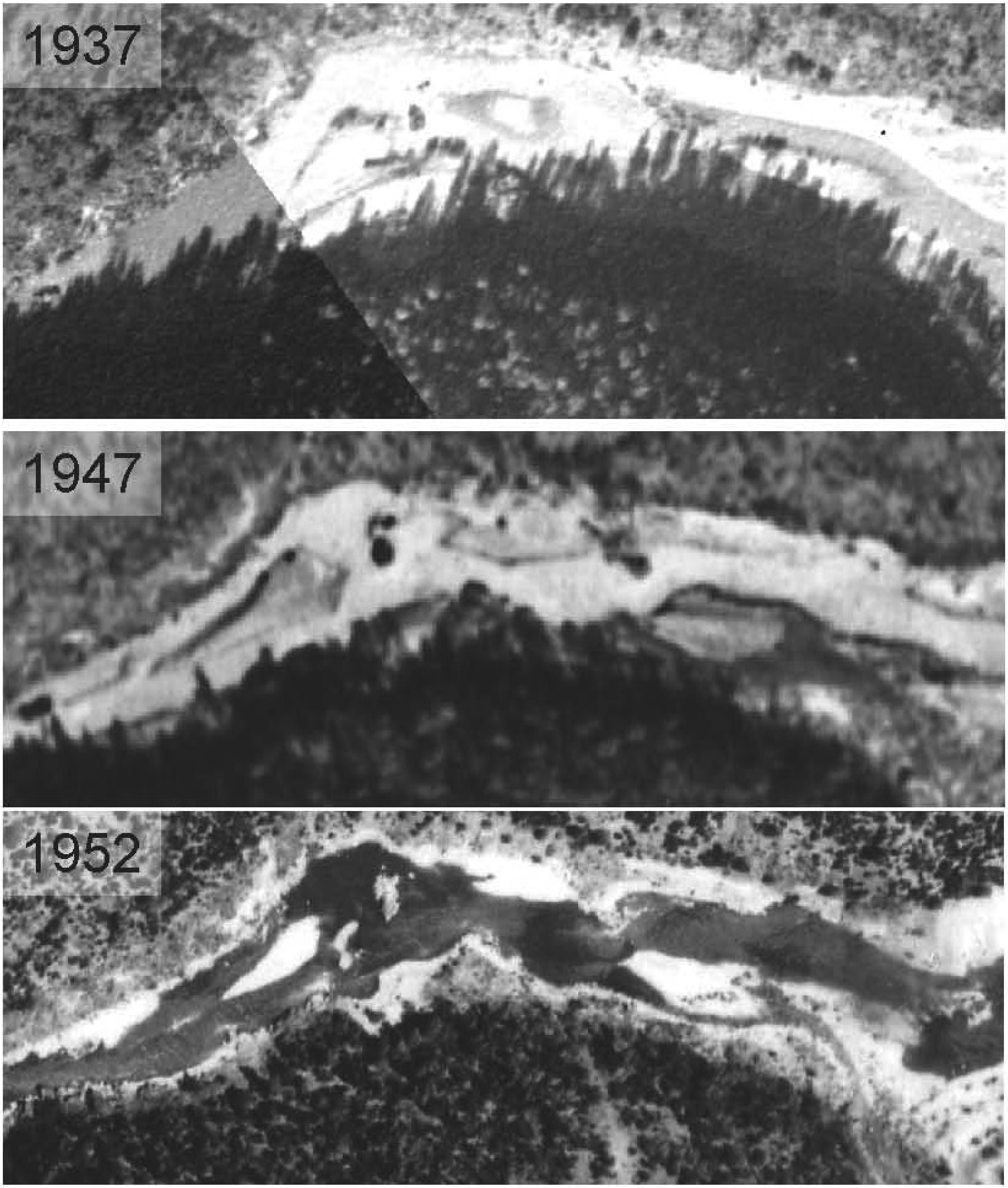

Figure 5.3. Comparison of aerial imagery of the top area of the NR 1937-1952.

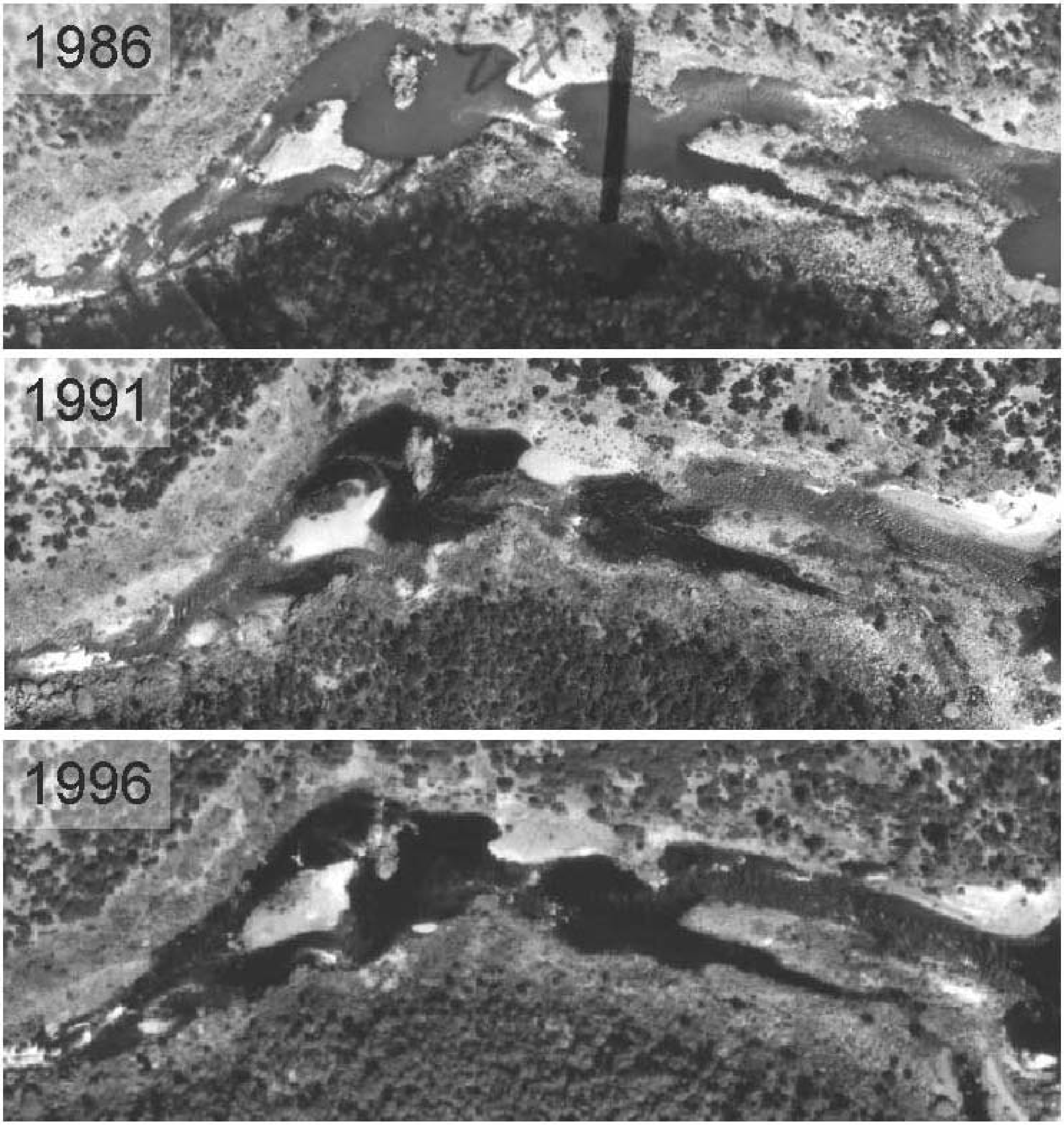

Figure 5.4. Comparison of aerial imagery of the top area of the NR 1986-1996.

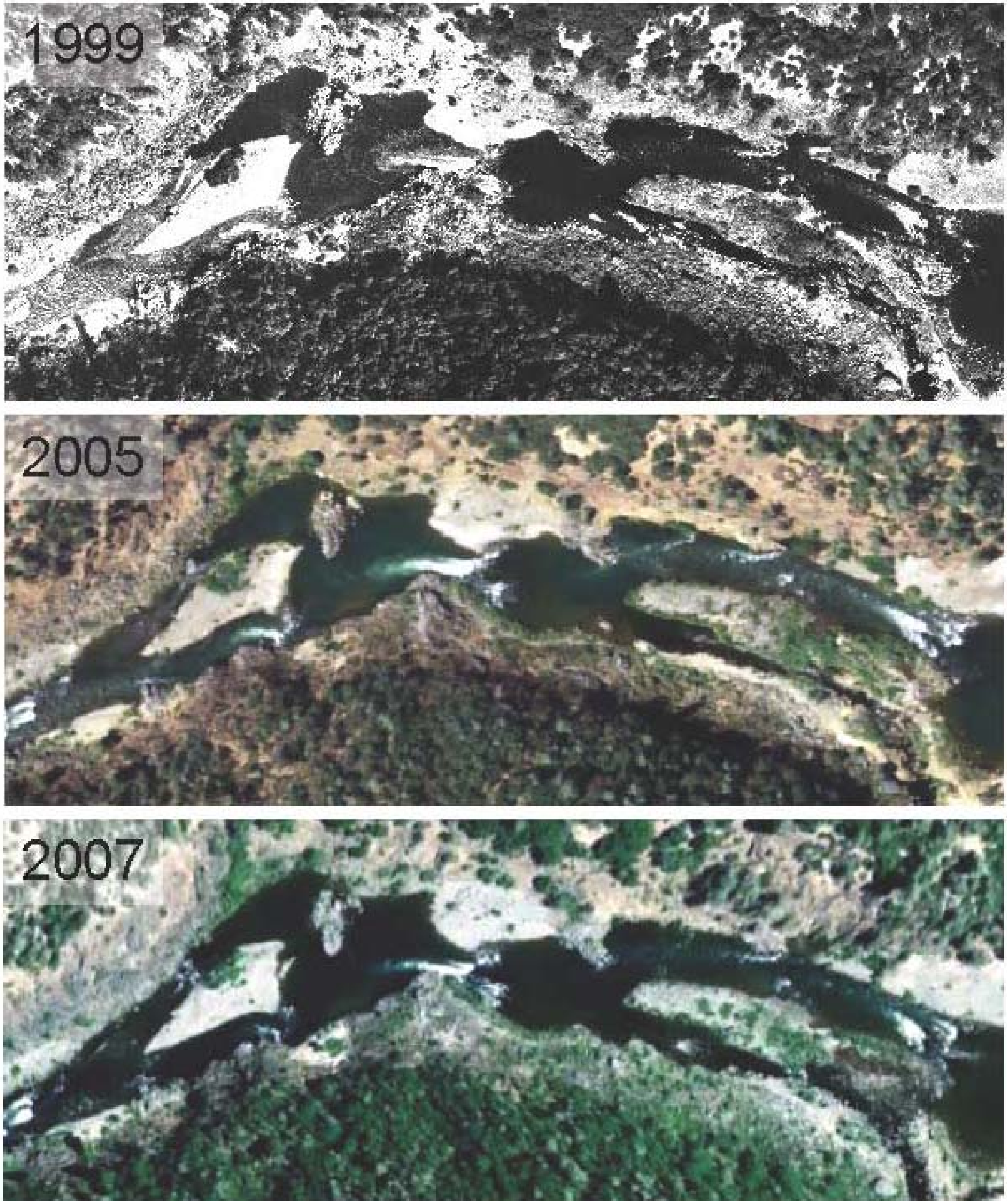

Figure 5.5. Comparison of selected aerial imagery of the top area of the NR 1999-2007.

6. NARROWS REACH ENHANCEMENT VISION

At present the Narrows Reach includes two geomorphic units with alluvial landforms capable of supporting SRCS adult holding, spawning, and embryo incubation freshwater lifestages. A small number of Chinook salmon have been observed spawning in the NR in the 2009-2010 and 2010-2011 spawning seasons. Historical analysis has revealed that the landforms in these geomorphic units have been resilient in the face of erosion and channel incision caused by the return of the river to a condition similar to its pre-mining status due to Englebright Dam blocking hydraulic mining debris from continuing to snuff the river valley, as it had prior to the dam's construction (Gilbert, 1917). The resiliency is due to the role of valley width oscillations and large bedrock outcrops that yield a persistent spatial pattern of hydraulic convergence and divergence (MacWillliams et al., 2006; Sawyer et al., 2010; White et al., 2010).

Despite the resilience in the NR, there are two discernable problems that are limiting natural SRCS production there, and both problems are solvable using river rehabilitation methods. The first problem has to do with the history of the NR filling with mining waste and then having the river incise back through it. When a river cuts down in this manner, previously active areas of the riverbed become high bars, islands, and terraces in the channel. They also can become excessively stabilized by vegetation, delaying the natural recovery process. The problem is that these features in the Narrows Gateway and S-turn units are taking up a disproportionate area of the channel, thereby constricting the remaining wetted areas. This causes these units to have narrow, moderately deep, and fast rapids, instead of riffles. Over geologic time, such features naturally come and go with glacial cycles. In this case, the problem was caused by anthropogenic impact (hydraulic gold mining) and it is appropriate and beneficial to undo that damage by hastening the natural recovery process with an active river rehabilitation project. Such a project would not only undo the historic damage, but it could also be designed in a way that is both geomorphically sustainable and biologically enhanced to support SRCS.

The second problem has to do with the fact that as the riverbed has incised, the surface has also coarsened, in a process known as armoring. Not only are the individual particles on the bed surface coarser than the natural bed material load, but the surface of the emergent bars exhibits a feature called “imbrication”, in which large particles become stacked up against each other oriented with the flow. This stacking makes the bed more resistant to erosion. In the absence of any test pit data of the underlying sediment, it is unclear how armored the river has become; however, the site recon did find some areas that were not armored, and those were being heavily used by SRCS spawners at that time. Other areas that were hydraulically preferable for spawning did not have adults active there, because the substrate was obviously too coarse.

Besides the natural process of coarsening as a river incises, there are anthropogenic factors contributing to this problem. Ever since the discovery of gold in the Yuba, gold miners have manipulated the sediment in the river by hand and machine. They built dams and diversions, used explosives, and redirected flows. Pasternack et al. (2010) reported that mechanized mining was responsible for altering and degrading Sinoro Bar just upstream of the NR. In that process, a bulldozer was used to move cobbles and boulder out of the way to get to underlying gold-rich gravels. Dislodging material and putting very coarse particles up above the ambient bed would make them much more susceptible to transport downstream into the NR, where they would be captured onto the bars during large floods. Even though Englebright Dam is providing the major benefit of *annually* holding back an additional 477,184 yds^3 of hydraulic mining waste and other sediment settling into the reservoir (Childs et al., 2003), the total absence of any EDR sediment inputs is a cause of armoring. With the available information there is no way to precisely partition blame.

Regardless of who is at fault, the opportunity exists to do a rehabilitation project that substantially enhances the geomorphic units in the Narrows Reach beyond its observed historical and present natural capability. The Watershed Hydrology and Geomorphology Lab in the Department of Land, Air, and Water Resources at UC Davis has been designing spawning habitat rehabilitation projects since 1999 using the Spawning Habitat Integrated Rehabilitation Approach (SHIRA) described by Wheaton et al. (2004a) (Fig. 6.1). Over the years, testing of numerous gravel-contouring schemes in 2D models and in actual construction (Wheaton et al., 2004b; Elkins et al., 2007; Pasternack, 2008a) has yielded a conceptual understanding of expected hydraulic attributes, geomorphic processes, and ecologic benefits. Specific design examples are illustrated on the SHIRA website at http://shira.lawr.ucdavis.edu/casestudies.htm. The website also provides peer reviewed scientific reports and journal articles that have thoroughly vetted the SHIRA framework.

This section of the report presents concepts for what actions could be taken. It is beyond the scope of this study to perform detailed design development. This is a brainstorm of opportunities and constraints.

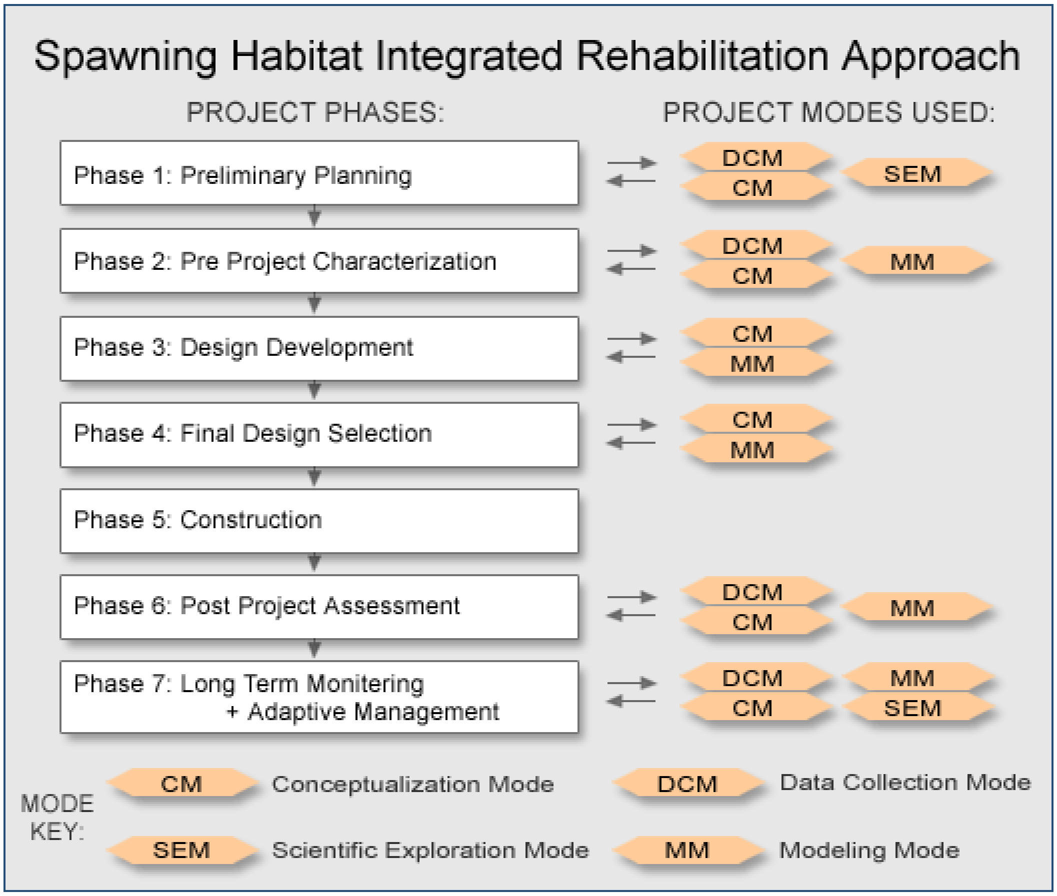

Figure 6.1. General schematic illustrating what is involved in the SHIRA framework.

6.1. Project Goals

The geomorphic goal of the potential river rehabilitation project is to re-shape the landforms in the Narrows Gateway and Narrows S-turn geomorphic units to redistribute the slope, expand the wetted width, and reduce riverbed surficial grain sizes in support of having larger riffle areas, while also retaining the existing self-sustainability of the landforms by designing in harmony with the controlling valley width oscillations and bedrock outcrops.

The ecologic goal of the potential river rehabilitation project is to enhance meso- and micro-scale physical habitats for the freshwater lifestages of anadromous salmonids, particularly SRCS.

6.2. Design Objectives And Hypotheses

A design objective is a specific goal that is aimed for when a project plan is implemented. To achieve the objective, it has to be translated into a design hypothesis. According to Wheaton et al. (2004b), a design hypothesis is a mechanistic inference, formulated on the basis of scientific literature review and available site-specific data, and thus is assumed true as a general scientific principle. Once a design hypothesis is stated, then specific morphological features are designed to work with the flow regime to yield the mechanism in the design hypothesis. Finally, a test is formulated to determine after implementation whether the design hypothesis was appropriate for the project and the degree to which the design objective was achieved. Through this sequence, a process-oriented rehabilitation is achieved. From the mathematics of differential equations, it is evident that processes derive from the physics of motion, input conditions, and boundary conditions. Changes to either input or boundary conditions impact processes, so it is possible and appropriate to design the shape of the riverbed to yield specific fluvial mechanism associated with desired ecological functions.

The design objectives and associated information for potential NR river rehabilitation are enumerated in Tables 6.1 and 6.2. These tables provide a transparent accounting of the objectives, hypotheses, approaches, and tests for the effort. From this point the next step would be to work up detailed design alternatives to determine how best to implement the proposed approaches.

Table 6.1. Design objectives and hypothesis 1-4 for a potential NR river rehabilitation project.

Design objective	Design hypothesis	Approach	Test
1. Remove excess cobbles and boulders from the riverbed where appropriate.	1A. Bed armoring hinders natural landform rejuvenation and is unsuitable for salmon spawning	Some amount of excavation is required, but then it is possible to either haul the material away or dump it down into the Skinny Escalator and let it wash into Narrows Respite and Narrows Pool where it would do no harm at those depths.	Perform pre-project and as-built Wolman pebble counts to confirm that overly coarse material has been removed. Perform annual re-surveys to determine if the river re-armors itself. Also, monitor for gravel/cobble influx from any EDR gravel augmentaiton program or Sinoro Bar rehabilitation project.
2. Reduce the elevation of emergent bars to reintegrate them into the active channel area and allow for wider riffles that are not constrained by excessively high bars	2A. Natural active emergent bars and riffles on the LYR often exist in the widest part of oscilalting valley walls and exhibit a dynamic interplay over time.	Use machinery to re-contour emergent bars.	Perform pre-project and as-built topographic surveys to document and quantify changes in landform morphology. Also, collect aerial imagery of the as-built condition.
3. Redistribute the bed slope to change rapid-pool and chute-pool sequences into riffle-pool sequences	3A. Riffle-pool sequences on the major gravel-bed rivers in the Central Valley of California typically have an optimal slope of ~0.04.	Use machinery to re-contour the riverbed using existing material and additional gravel/cobble per the slope creation method of Elkins et al. (2007)	Perform pre-project and as-built longitudinal profile surveys (or extract them from topgoraphic maps) to confirm the change in the sequence of geomorphic units. Also, collect aerial imagery of the as-built condition.
4. Allow gravel/cobble to wash downstream	4A.The NR should become an active participant in the conveyance of bed material load throughout the entire LYR.	no specific action required	Conduct annual recon of NR to track where injected gravel/cobble goes. Measure and/or simulate the spatial pattern of Shields stress and identify likely erosion areas by their values >0.06.

Table 6.2. Design objectives and hypothesis 5-8 for a potential NR river rehabilitation project.

Design objective	Design hypothesis	Approach	Test
5. Provide higher quantity of preferred-quality Chinook spawning habitat	5A. SRCS require deep, loose, river-rounded gravel/cobble for spawning (Kondolf, 2000).	Add river-rounded gravel/cobble.	Perform Wolman pebble counts of the delivered sediment stockpile and in the river after each gravel injection to insure that the mixture's distribution is in the required range.
	5B. Spawning habitat should be provided that is as close to GHSI-defined high-quality habitat as possible (Wheaton et al., 2004b)	Place and contour gravel to yield depths and velocities consistent with salmon spawning microhabitat suitability curves.	Measure and/or simulate the spatial pattern of GHSI after project construction to determine quantity of preferred-quality (GHSI>0.4) habitat present.
6. Provide adult and juvenile refugia in close proximity to spawning habitat.	6A. Structural refugia in close proximity to spawning habitat should provide resting zones for adult spawners and protection from predation and holding areas for juveniles.	Create spawning habitat in close (<10 m) proximity to pools, overhanging cover, bedrock outcrops, boulder complexes, and/or streamwood.	Measure distance from medium and high GHSI quality habitats to structural refugia and check to see that most spawning habitat is within reasonable proximity.
7. Provide morphological diversity to support ecological diversity, including behavoral choice by individuals.	7A. Designs should promote habitat heterogeneity to provide a mix of habitat patches that serve multiple species and lifestages.	Avoid GHSI optimization of excessively large contiguous areas of habitat; design for functional mosaic of geomorphic forms and habitat.	Large (>2 channel widths) patches of homogenized flow conditions in hydrodynamic model and homogenized habitat quality in GHSI model results should not be present at spawning flows.
8. Add streamwood to backwater areas and interweave it to produce cover and refugia for rearing fish	8A. Streamwood jams enhance salmonid rearing	Push the abundant streamwood along the highwater line in the EDR into the river and float it down to the backwater locations in the NR. Use machinery to position large pieces.	Conduct pre-project, as-built, and periodic snorkel surveys to assess utilization by rearing fish.

7. ESTIMATED POTENTIAL SRCS SUPPORTED

There is no single correct method for predicting what the SRCS population supportable by a rehabilitation project in the Narrows Reach would be at this stage of design development. Choices in the design process can enhance or detract from estimates. The approach used here is identical to that used in Pasternack (2010), which involved evaluating the relation between site conditions and redd occurrence, and then relating redd occurrence to the supportable SRCS adult population (Fig. 7.1). Making an estimate of the number of redds to occur in a channel area comes down to picking two things: redd density (sum of occupied and unoccupied channel surface area (m^2) per redd) and area of riffle habitat. For redd density, the same set of six values was used as in Pasternack (2010). For riffle area, two different values were used. Since both geomorphic units have an excess of available slope, the full length and area is available for riffle habitat creation, if desired. However, it is common and appropriate to create a mosaic of hydraulic units, so an area estimate holding back 20% of the total area for non-riffle units was calculated and used. Overall, this approach yielded an array of 12 different redd abundance estimates for each geomorphic unit. Finally, the spawner:redd ratios of 4:1 and 2:1 used in Pasternack (2010) were applied to convert redd abundance estimates to estimates of SRCS supported. The 4:1 ratio is the more realistic value for the LYR, but it helps to have a conservative value as well.

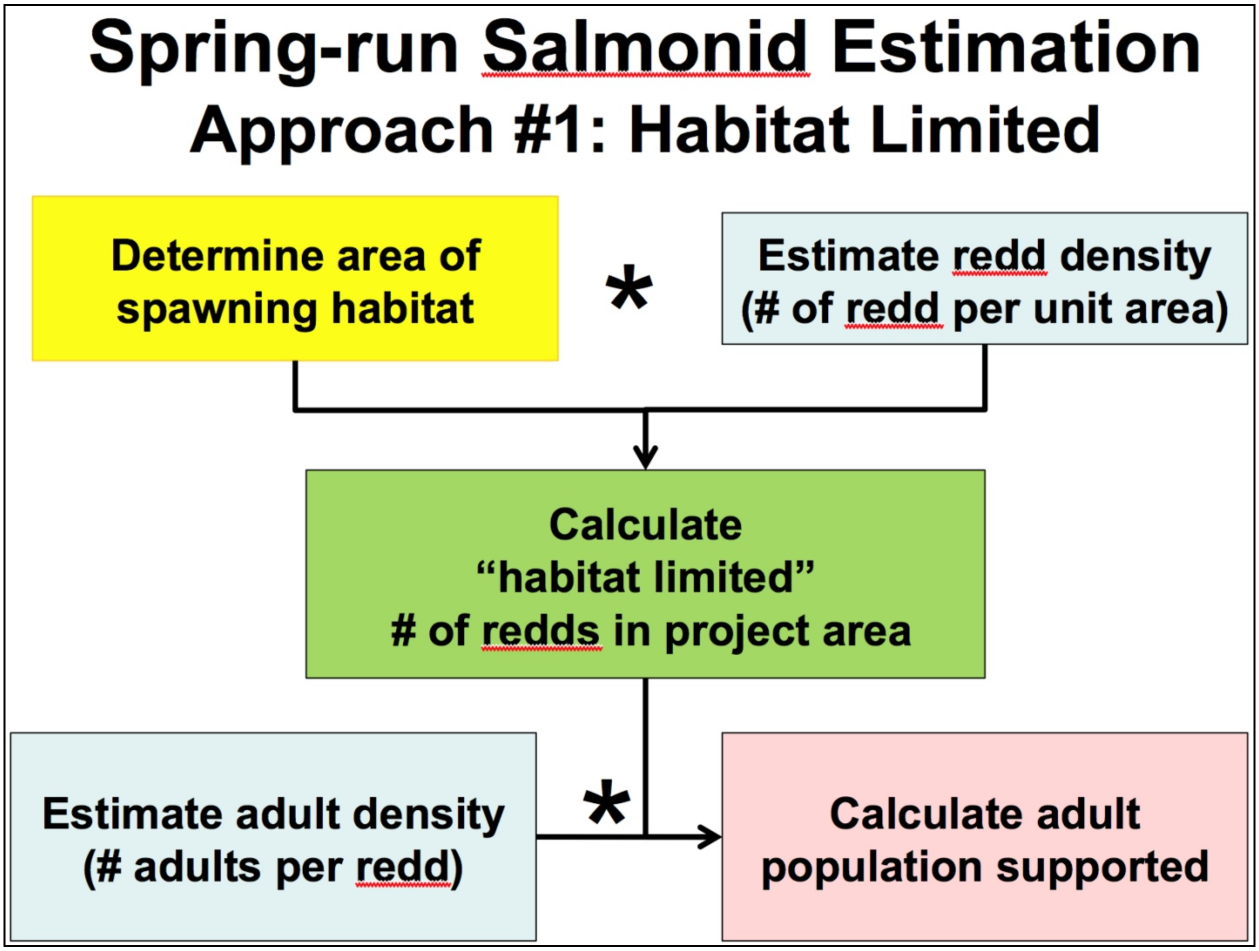

Figure 7.1 Flowchart illustrating the calculation procedure for estimating the potential number of SRCS supported through physical habitat rehabilitation in a channel area.

7.1. Narrows Gateway SRCS Estimate

The range of redd abundance estimates for the Narrows Gateway unit are presented in Table 7.1. The full range is 692-2,853 redds, but following the same reasoning as used in Pasternack (2010a), the best estimate is 1,141 redds. Applying the 4:1 and 2:1 spawner:redd ratios to that value yields **4,564** and **2,282** adults, respectively. If the most conservative set of assumptions is used, then the number of adults supportable in Narrows Gateway is estimated to be 692*2= 1,384 adults. That is still a large number of SRCS.

Table 7.1. Estimated number of redds produced for Narrows Gateway using different sets of assumptions.

	redd density (m^2 per redd)	Total rehab area (m^2)	Rehab with 20% extra area reserve (m^2)
Riffle SRCS habitat area (m^2)	n/a	15833	12666
LYR index site mean redd size	5.55	2853	2282
LYR index site mean redd size + 1 SD	8.60	1841	1472
LYR index site max redd size	14.18	1117	893
LYR index site mean redd size with equal unoccupied area	11.1	1426	1141
LMR rehabilitated riffle area redd occurrence density assuming 10% superimposition missed	16.60	954	763
LMR rehabilitated riffle area redd occurrence density	18.3	865	692

Green values indicate the most reasonable estimates

7.2. Narrows S-turn SRCS Estimate

The range of redd abundance estimates for the Narrows S-turn unit are presented in Table 7.2. The full range is 752-3,101 redds, but following the same reasoning as used in Pasternack (2010a), the best estimate is 1,240 redds. Applying the 4:1 and 2:1 spawner:redd ratios to that value yields **4,960** and **2,480** adults, respectively. If the most conservative set of assumptions is used, then the number of adults supportable in Narrows S-turn is estimated to be 752*2= 1,504 adults.

In summary, the most reasonable and most conservative estimates for the total number of SRCS potentially supported by rehabilitating the top two geomorphic units in the Narrows Reach are **9,524** and **2,888**, respectively. Both of these estimates meet the HET criteria.

Table 7.2. Estimated number of redds produced for Narrows S-turn using different sets of assumptions.

	redd density (m^2 per redd)	Total rehab area (m^2)	Rehab with 20% extra area reserve (m^2)
Riffle SRCS habitat area (m^2)	n/a	17210	13768
LYR index site mean redd size	5.55	3101	2481
LYR index site mean redd size + 1 SD	8.60	2001	1601
LYR index site max redd size	14.18	1214	971
LYR index site mean redd size with equal unoccupied area	11.1	1550	1240
LMR rehabilitated riffle area redd occurrence density assuming 10% superimposition missed	16.60	1037	829
LMR rehabilitated riffle area redd occurrence density	18.3	940	752

Green values indicate the most reasonable estimates

8. ACCOUNTING FOR REGIONAL LIMITING FACTORS

Pasternack (2010) described an alternate method for evaluating the benefits of river rehabilitation on the LYR taking into account regional limiting factors. The calculation involved starting with the actual observed maximum population of spawning Chinook salmon on the LYR in the era of modern observation since 1953 (40,000 adults), multiplying it by the fraction of spawners utilizing riffles (0.69), then multiplying that product by the estimate of the fraction of the total LYR (38 km) that is riffles (either 0.09 or 0.18) to arrive at the density of spawners per km of the LYR. Then the length of the rehabilitation site is multiplied by this fish density to arrive at the final estimate of SRCS supported in a run-limited condition (Fig. 8.1). The important point about this computation is that it has nothing to do with the local physico-chemical potential of the project area to support SRCS, and instead considers the larger problem of regional limiting factors on population size to get at the likely amount of individual Chinook salmon served by the site.

For the Narrows Reach, the estimation procedure yields a significant number of SRCS supported in a run-limited condition. The total length of the NR geomorphic units suitable for rehabilitation is 0.5425 km. The reason there are two estimates for the fraction of the LYR that is riffles is that this number has not been accurately estimated just yet (available by January 2011 most likely); it has only been estimated for Timbuctoo Bend. If the same fraction of the whole LYR is present as riffles as found in Timbuctoo Bend, then the estimated number of SRCS supported is **2,189** spawners. The more likely case is that the whole LYR has about half the length of riffles as Timbuctoo Bend, so in that case the estimated number of SRCS supported is **4,378** spawners. Either way, both values meet the HET criteria

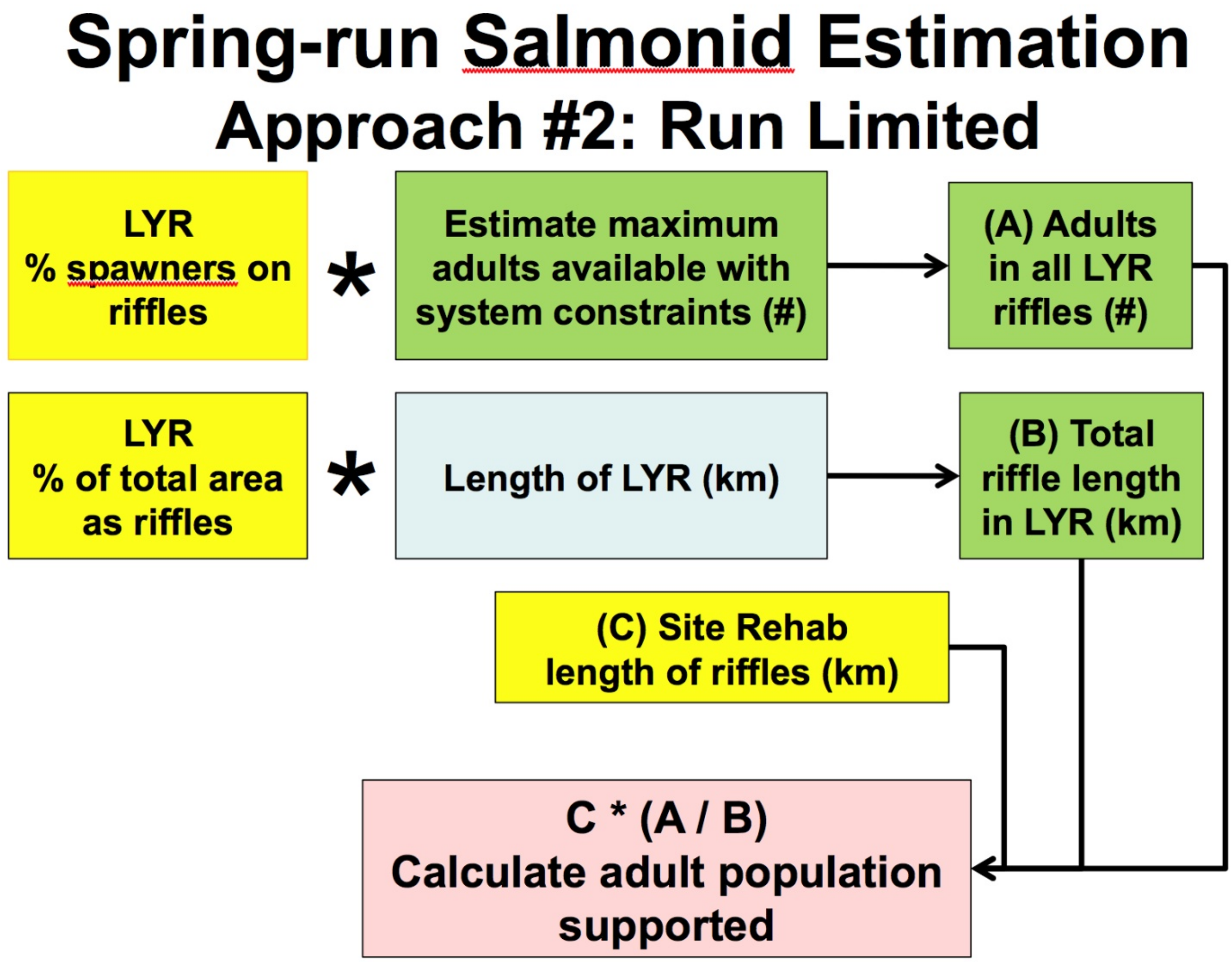

Figure 8.1. Flowchart illustrating the calculation procedure for estimating the run-limited number of SRCS supported through physical habitat rehabilitation in a channel area.

9. REFERENCES

Beak Consultants, Inc. 1989. Yuba River Fisheries Investigations, 1986-88, Summary Report Of Technical Studies On The Lower Yuba River, California.

Childs, J.R., Snyder, N.P., and Hampton, M.A., 2003, Bathymetric and geophysical surveys of Englebright Lake, Yuba-Nevada Counties, California, U.S. Geological Survey Open-File Report 03-383 http://geopubs.wr.usgs.gov/open-file/of03-383.

Elkins, E. E., Pasternack, G. B., and Merz, J. E. 2007. The Use of Slope Creation for Rehabilitating Incised, Regulated, Gravel-Bed Rivers. Water Resources Research 43, W05432, doi:10.1029/2006WR005159.

Gilbert, G.K., 1917, Hydraulic-Mining Debris in the Sierra Nevada: U.S. Geological Survey Professional Paper 105, 154 p.

Grant, G. E., F. J. Swanson, and M. G. Wolman. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, western Cascades, Oregon. Bulletin of the Geological Society of America 102:340-352.

Kondolf, G.M. 2000. Assessing salmonid spawning gravels. Transactions of the American Fisheries Society 129: 262-281.

MacWilliams, M. L., Wheaton, J. M., Pasternack, G. B., Kitanidis, P. K., Street, R. L. 2006. The Flow Convergence-Routing Hypothesis for Pool-Riffle Maintenance in Alluvial Rivers. Water Resources Research 42, W10427, doi:10.1029/2005WR004391.

Pasternack, G. B. 2008a. Spawning habitat rehabilitation: advances in analysis tools. In (D.A. Sear, P. DeVries, S. Greig, Eds) Salmonid spawning habitat in rivers: physical controls, biological responses, and approaches to remediation. Symposium 65, American Fisheries Society, Bethesda, MD, p. 321-348.

Pasternack, G. B. 2008b. SHIRA-Based River analysis and field-based manipulative sediment transport experiments to balance habitat and geomorphic goals on the lower Yuba River. Cooperative Ecosystems Studies Unit (CESU) 81332 6 J002 Final Report, University of California at Davis, Davis, CA, 569pp.

Pasternack G. B. 2010. Estimate of the number of spring-run Chinook salmon that could be supported by spawning habitat rehabilitation at Sinoro Bar on the lower Yuba River. Prepared for PG&E, Gregory B. Pasternack, Davis, CA.

Pasternack, G. B., Fulton, A. A., and Morford, S. L. 2010. Yuba River analysis aims to aid spring-run Chinook salmon habitat rehabilitation. California Agriculture 64:2:69-77.

Rosgen, D. L. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Sawyer, A. M., Pasternack, G. B., Moir, H. J., Fulton, A. A. 2010. Riffle-Pool Maintenance and Flow Convergence Routing Confirmed on a Large Gravel Bed River. Geomorphology 114:143-160.

Wheaton, J. M., G. B. Pasternack, and J. E. Merz. 2004a. Spawning habitat rehabilitation-I. conceptual approach and models. International Journal of River Basin Management 2: 3-20.

Wheaton, J. M., G. B. Pasternack, and J. E. Merz. 2004b. Spawning habitat rehabilitation-II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A. International Journal of River Basin Management 2: 21-37.

White, J. Q., Pasternack, G. B., and Moir, H. J. 2010. Valley width variation influences riffle-pool location and persistence on a rapidly incising gravel-bed river. Geomorphology 121:206-221.