
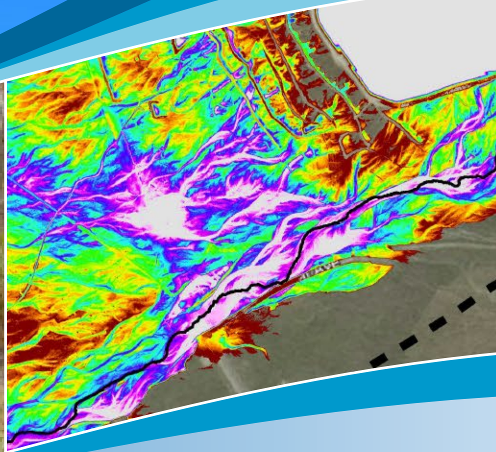


High-Flow Study of Seven Oaks Dam: Phase 2 Final Report

August 2019

ICF

HIGH-FLOW STUDY OF SEVEN OAKS DAM:
PHASE 2 FINAL REPORT

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Acronyms and Abbreviations

BA	Biological Assessment
BO	Biological Opinion
CBD	Center for Biological Diversity
CWA	Clean Water Act
D_i	Diameter of the sediment grain size for which *i* percent is finer than
HFS	High Flow Study
kg/s	kilograms per second
lb/ft^2	pounds per square foot
LOTUS	Long term experimental plots
LSAA	Lake and Streambed Alteration Agreement
MSHMP	Multi-species Habitat Management Plan
Pa	pascals
PAO	proportion of area occupied
RAFSS	Riverside alluvial fan sage scrub
SAR	Santa Ana River
SBKR	San Bernardino kangaroo rat
SBVMWD	San Bernardino Valley Municipal Water District
SBVWCD	San Bernardino Valley Water Conservation District
SOD	Seven Oaks Dam
spineflower	slender-horned spineflower
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
WCM	Water Control Manual
woolly star	Santa Ana River woolly star
WSPA	Woolly Star Preserve Area

Chapter 1
Introduction

1.1 Phase 1 Report Findings

The U.S. Fish and Wildlife Service (USFWS) issued a Biological Opinion (BO) in December 2002 for Seven Oaks Dam (SOD) calling for intermittent high-flow release events from SOD. As articulated in the BO, it was anticipated that water releases would be made to maintain and enhance habitat for listed species under a finalized Santa Ana River Woolly Star Preserve Area (WSPA) Multi-species Habitat Management Plan (MSHMP), as outlined in the Biological Assessment (BA) for the Seven Oaks Dam Project (USACE 2000a). Among the species listed are the slender-horned spineflower (*Dodecahema leptoceras*) (spineflower), San Bernardino kangaroo rat (*Dipodomys merriami parvus*) (SBKR), and Santa Ana River woolly star (*Eriastrum densifolium*) (woolly star).

The 2002 BO issued by USFWS addressed conservation measures and management recommendations associated with spineflower, SBKR, and woolly star, which are hereafter referred to as *the species of interest*. One conservation recommendation specified in the BO was acquisition of floodplain habitat along the upper Santa Ana River (SAR) and below SOD for species conservation purposes. To this end, approximately 760 acres of land were purchased and used to form the WSPA. The 2002 BO called for additional conservation measures to manage the species of interest for recovery within the WSPA. A multi- species adaptive management plan was prepared to guide management of the preserve area, resulting in the MSHMP. This document was intended to guide management of WSPA lands to recover the three species of interest. Management recommendations issued in prior documents were incorporated or referenced in the MSHMP.

The primary objective of the high-flow release conservation measures outlined in both the BA and the MSHMP is to mitigate for potential negative changes in floodplain characteristics and listed species' habitat brought about by construction and operation of SOD. The BA and MSHMP describe these releases, coupled with diversion dikes, as being intended to create directed overbank flows for the benefit of listed species. High-flow release measures identified in the 2002 BO have not been implemented. In addition, there is a perception and concern that many of these measures may not have the ability to create the intended mitigation result if implemented as proposed in the MSHMP. Therefore, to better understand the issues of concern, in March 2019 ICF completed a report *High-Flow Study of Seven Oaks Dam: Phase 1 Final Report* (hereafter referred to as the Phase 1 Report). This Phase 1 Report analyzed the potential of those measures to achieve the desired biological mitigation result described in the 2002 BO and 2012 MSHMP both within the WSPA and in other areas of the SAR watershed outside of the WSPA.

The Phase 1 Report demonstrated there is additional capacity within the current SOD Water Control Manual (WCM) guidelines (USACE 2003) to create or contribute to high-flow events up to approximately 5,000 cfs within the study area. Yet no flow releases for the purpose of habitat renewal have taken place in the two decades since start of operations at SOD. Flow contributions from SOD are likely to be limited to 5,000 cfs or less, in spite of the dam's rated gate outflow capacity of 7,000 cfs. The most important limit on releasing flows that would contribute to ecologically meaningful flow events from SOD is the WCM limit to 50 cfs during rising conditions, which effectively prevents timing releases with high-flow contributions from tributaries. Mill Creek will continue to contribute substantial flood flows to the SAR. However, SOD has not been making high-flow releases that could additively contribute to Mill Creek flows in a manner predicted in the Technical Report for the BA (USACE 2000b). Releases have not been synchronized with Mill Creek peak flows to date during the operation of SOD.

The Phase 1 Report included analysis of the extent of overbanking flows in the study area[1] from releases from SOD under the WCM and in combination with high flows from tributaries (i.e., Mill, City, and Plunge creeks). Overbanking is used herein as a general term to describe flooding outside of the active channel, which includes inactive channel braids, high bars, floodplains, historic channels, or onto the terrace. The Phase 1 Report demonstrated the modeled inundation limits without additional enhancement measures (e.g., breaching of berms, bank lowering, construction of flow obstructions) are restricted to the main channel, and no overbank flows into areas of substantial size outside of the Santa Ana River active channel[2] are predicted to produce flood disturbance on a scale large enough to alter successional trends within the study area and therefore satisfy the requirements of the BA/BO and MSHMP. Modeled flooding of the study area would disturb pioneer and intermediate seral stages almost exclusively. Mature and mature/NNG surfaces are the most beneficial areas for introducing disturbance intended to return the surface to earlier seral stages. This is because existing habitat within these surfaces is less optimal for the species of interest, and species observations within these areas are low or absent. Without human manipulation of the land surface, mature and mature/NNG surfaces cannot be flooded.

1.2 Phase 2 Study Objectives

This Phase 2 Report addresses several study questions not addressed in the Phase 1 Report. A focus of the Phase 2 report is identification of practical measures that could be implemented to renew habitat for the listed species within the major constraints identified in the Phase 1 Report.

This Phase 2 Report has four key study objectives:

1. Definition of what constitutes “fluvial disturbance” in terms of its importance for creating physical processes needed for listed species habitat renewal;
2. Development and evaluation of structural enhancement measures that could be implemented to create fluvial disturbance under a wide range of flow scenarios;
3. Evaluation of non-fluvial disturbance techniques for habitat renewal. Treatments could include mechanical clearing of vegetation, deposition of clean sand, controlled flooding, and weed abatement; and
4. Evaluation of treatment trade-offs and prioritize the species of interest. The evaluation used the local scale SBKR habitat model developed by the San Diego Zoo, as well as occurrences and known habitat suitability features for spineflower and woolly star. Non-fluvial disturbance manipulations proposed in the MSHMP are evaluated for their potential ease of implementation and beneficial effects.

[1] The study area covered by the Phase 1 High-Flow Study includes those areas considered in the SOD BA (USACE 2000a), BO (USFWS 2002), the WSPA and adjacent properties, and the SAR corridor from SOD to the San Bernardino Airport

[2] The active channel is defined for this study as areas of the channel that are flooded frequently enough to scour sediment and limit or prevent establishment of vegetation.

1.3 Science Advisory Committee

The science advisory committee for this study is composed of science experts from Stillwater Science, Blue Octal Solutions, and the San Diego Zoo. Representing Stillwater Science were Christian Braudrick, Bruce Orr, and Wendy Katagi. Representing Blue Octal Solutions were Mike Lamb and J. Toby Minear. Representing the San Diego Zoo were Debra Shier, Rachel Chock and Thea Wang.

The High-Flow Study investigators responsible for preparing this report were composed of the ICF technical team, including Brendan Belby, Manna Warburton, Greg Nichols, and Scott Fleury.

The litigants in the lawsuit against the U.S. Army Corps of Engineers (USACE) regarding failure to assess harm to federally protected species from the operations of SOD were observers to the science advisory committee meetings and webinars. The litigants include Endangered Habitats League (EHL), Center for Biological Diversity (CBD), San Bernardino Valley Municipal Water District (SBVMWD), and San Bernardino Valley Water Conservation District (SBVWCD). Representing EHL were Dan Silver, Gerald Braden, and Chris Campbell. Representing CBD were Ileene Anderson and Tiffany Yap. Representing SBVMWD was Heather Dyer, and representing SBVWCD was Jeff Beehler.

Chapter 2
Conditions of Fluvial Disturbance

The Phase 1 Report focused on the areal extent of overbank flooding of areas outside of the active SAR channel. The Phase 1 Report did not focus on the extent to which overbanking would provide the types of fluvial disturbance necessary to create and maintain habitat for the listed species.

Simply creating overbanking flows that inundate areas outside of the active channel itself is not necessarily sufficient for either desired scour and removal of dense vegetation or deposition of fresh sand deposits. Defining the physical processes required of overbank flows to create necessary fluvial disturbance in the form of vegetation removal or burial and sediment sorting is a key focus of this Phase 2 study.

The study's science advisory team (Stillwater Sciences and Blue Octal Solutions, LLC) conducted new studies for the Phase 2 study that aided in defining the conditions of fluvial disturbance as they relate to renewal of habitat conditions of the listed species. The findings of these studies were incorporated by ICF into the new analysis performed for Phase 2. The science advisory studies are also presented in their entirety in Appendix 1 and 2.

Stillwater Sciences (2019) examined aerial imagery spanning the period from 1970-2016 and quantified: 1) the degree to which SAR lateral erosion into older sediment deposition surfaces occurs; and 2) extent of vegetation scour under the current flow regime.

Blue Octal Solutions (2019) conducted new fieldwork to assess channel substrate sizes in the study area and patterns of erosion and deposition related to February 2019 flooding. The fieldwork results were incorporated into analysis to determine requirements for uprooting of channel vegetation and deposition of fresh sand deposits.

As reported by Stillwater Sciences (2019) in their study *Seven Oaks Dam Scour Analysis* (Appendix 1).

> "Braided rivers in arid environments, such as the Santa Ana, have a vegetation and erosion cycle tied to floods. During high flows, much of the vegetation in the active channel corridor is uprooted or buried by sediment deposition. The uprooting occurs through sediment erosion around the roots or direct uprooting … but both result in vegetation mortality and creation of fresh surfaces. For convenience, we refer to these surfaces as scoured, but they could potentially be depositional surfaces. Subsequently, during years with smaller floods, vegetation becomes re-established within at least part of the scour zone, with vegetation density increasing gradually through time until it is uprooted during the next large flood. This pattern has implications for pioneer species such as SBKR, spineflower, and woolly-star, which thrive in relatively fresh sandy deposits following large floods. In particular, SBKR prefers habitats ranging from recent sand deposits without grasses and sparse shrubbery. To create and maintain SBKR habitat therefore requires periodically creating new sand deposits through scour and/or burial of vegetation more frequently than dense vegetation (particularly grasses) can become established in these deposits, but not so frequently that SBKR populations cannot maintain their population. Prior to human modification of the basin, large floods every 30 years or so likely created new surfaces for the SBKR to establish on that were unlikely to be inundated during the next 30 years." (page 1 in Stillwater Sciences 2019).

A similar conclusion about the concern of too frequent flooding within the active channel belt was reached by Blue Octal (2019) in their study *Thresholds for vegetation removal and sediment* *transport: Literature review, field measurements and analysis to improve San Bernardino Kangaroo Rat habitat in the upper Santa Ana River, California* (Appendix 2).

> "The current flood regime appears to be capable of creating the desired disturbances (vegetation removal, bar migration, sand deposition) in the active channel belt that are favorable for SBKR habitat. However, a major problem is that the active channel-belt is flooded too often to develop favorable habitat, whereas the neighboring terrain is not flooded often enough. One solution that would not require a contribution from Seven Oaks Dam would be to divert the entire river away from the currently active channel belt. This would allow the then-abandoned channel-belt to be colonized by SBKR. At the same time, the new flood pathway would likely scour vegetation, migrate bars and deposit sand. In 30 years the flood routing could be shifted again, allowing colonization again of the once active channel belt." (page 14 in Blue Octal 2019).

The altered flood regime and construction of levees that laterally confine sections of the channel contribute to limit the active channel belt to a relatively narrow zone compared to the pre-alteration condition. When flood events do happen, they tend to inundate the same portions of the channel belt as opposed to outbreaks into much more widespread flood areas, such as the 1969 Channel.

Both Stillwater Sciences (2019), and Blue Octal (2019) report that uprooting SAR vegetation and causing scour and fill processes that will sort sediment to create suitable habitat is a key fluvial disturbance overbanking should attempt to provide. Vegetation removal by means of flowing water with high enough levels of drag force to overcome plant root resistance is difficult, and that instead uprooting is most likely achieved through undermining and burying plants through bar migration (Blue Octal 2019). Flood events must create shear stresses high enough to cause bar migration that will remove or bury vegetation. The conditions of fluvial disturbance include shear stress thresholds for migration of sand and cobble bars important for creating fluvial disturbance and removing vegetation (Blue Octal 2019). ICF used the reported values provided by Blue Octal (2019) to bin the calculated shear stress output into one of six different classes (Table 2-1). Migration of sand bars was split into low and high-end categories. Migration of cobble bars was split into three categories – a low-end, high-end, and maximum end. A breakpoint was added at 125 pascals (Pa), or 2.61 pounds per square foot (lb/ft^2) in English units, since 125 Pa was identified by Blue Octal (2019) as an ideal condition for migration of both sand and cobble bars.

2.1 Key Findings for the Conditions of Fluvial Disturbance

- Uprooting or burial of SAR vegetation through fluvial scour or sediment deposition is a key component of fluvial disturbance;
- Migration of sand and gravel bars at defined shear stress thresholds is the most likely way to remove or bury vegetation and deposit fresh sand needed for species colonization; and

Desired fluvial disturbances such as sand deposition, bar migration, and vegetation removal are occurring in the active channel belt under the current flood regime, but the active channel belt is too active. Fluvial disturbance within the active channel belt occurs too frequently for successful colonization by SBKR. Blue Octal (2019) and Stillwater Sciences (2019) suggest that after the desired fluvial disturbance processes occur within a portion of the active channel belt, the recently disturbed area be isolated and protected for a period of approximately 30 years before disturbing again.

Chapter 3
Development of Enhancement Measures to Create Fluvial Disturbance

Stillwater Sciences (2019) examined: 1) the degree to which lateral erosion into older surfaces occurs; and 2) the extent of vegetation scour under the current high flow regime. A key finding of Stillwater's study is that SAR bank erosion since 1969 along the study reach is rare and that creation of new habitat by lateral migration and channel widening is unlikely to occur. Due to the coarseness of the boulder banks, structural measures designed to promote increased bank erosion would have to be very large to divert a sufficient volume of water into the banks to cause erosion (Stillwater Sciences 2019). The coarseness of the poorly sorted and matrix supported bank sediment is also described by Blue Octal (2019) as coarser grained than the channel bed and likely composed of debris flow deposits. The older debris flow deposits could be the main source of cobbles and boulders to the existing channel (Blue Octal 2019).

Three enhancement measures were developed for the Phase 2 study (see locations in Figure 3-1). The locations of the enhancement measures were determined through engagement with the project stakeholders and a site visit on February 25, 2019. The objective of each enhancement measure is to direct Santa Ana River flow into terrain that is currently infrequently flooded to create new areas of fluvial disturbance with the aim of returning the terrain to earlier seral stages. All three enhancement measures are located downstream of the confluence with Mill Creek to take advantage of Mill Creek flood water and sediment supply in creating fluvial disturbance. The enhancement measures would function by diverting water into existing but inactive channel braids, floodplain areas, or the historic 1969 Channel. The enhancement measures do not attempt to create habitat through appreciable bank erosion and an increase in lateral migration since the likelihood of success with this approach is low (Stillwater Sciences 2019).

The Phase 1 Report concluded that flooding of mature surfaces would likely result in impacts on populations of the species of interest through incidental flooding of surrounding lower-elevation habitats, particularly in downstream reaches. This has broad implications for any future proposals to flood portions of the study area for purposes of habitat renewal because of the likelihood of short-term impacts on populations of the species of interest associated with flood disturbance. Short-term impacts are expected to be offset by long-term benefits to these species if there are sufficient numbers to repopulate disturbed areas.

The enhancement measures are preliminary designs. As described in the modeling section in Chapter 4, existing conditions were initially modeled to understand flow paths and flow conveyance distributions amongst the numerous channel braids. Subsequent iterations were performed to evaluate different configurations and dimensions of the structures to test performance, including the ability to divert and block flow and the flood magnitude at which the they would be overtopped. The dimensions and quantities reported for the measures are approximate and modifiable if more advanced design work is performed. All of the enhancement measures incorporate rock to create a hardened feature on the landscape that would create a flow obstruction to force flow into areas it would not flow into otherwise. The gradation of the sediment sizes used to form the measures has not yet been determined. For this analysis, it is assumed that the measures are static features that remain immobile during flood events. Large boulders would most likely be needed to create the framework stability of the measures.

All three enhancement measures could be constructed at the same time or only one or two at a time. The effect of one enhancement measure could affect the performance of one or more enhancement measures downstream – primarily through alteration of flow paths and changing the amount of flow available at the downstream measure(s). The tradeoffs and suggested prioritization of the enhancement measures are discussed in Chapter 5.

3.1 Enhancement Measure 1 – Reactivate 1969 Channel

The Phase 1 Report identified the 1969 breakout area channel as the most likely area to produce overbank flows outside the main channel of the SAR using enhancement measures. This channel is identified as “The 1969 Channel” because the major January 25, 1969 flood was the last time Santa Ana River floodwater actively flowed in this channel. The channel existed prior to 1969, as seen in the historic imagery presented in the Phase 1 Report. A map comparing the 1969 Channel with imagery from 1970 and 2015 is presented in Figure 3-2. In the 1970 image, the 1969 Channel extended in a northwest alignment all the way to Plunge Creek. The alignment of the upper portion of the 1969 Channel nearest the SAR is still intact and visible in the 2015 image. However, since 1970, SBVWCD’s Basin 18 was constructed and the 1969 Channel now terminates in this basin. The lower portion of the 1969 Channel nearest Plunge Creek visible in 1970 is now largely non-existent because of the large quarry located west of Basin 18 that exists in its former path.

Disturbance of this area has been essentially non-existent since the 1969 flood for the period 1970-2016 and is limited to a single isolated area mapped by Stillwater Sciences (2019) as mid-channel island scour south of the existing active SAR channel (see Figure 4 in Appendix 1).

Possibly, in response to the 1969 flood event, a rock wall was constructed to plug the inlet to the 1969 Channel and prevent future floodwater from entering (see detailed map of inlet in Figure 3-3). The rock wall is approximately 100 feet long by 25 feet wide and 5-6 feet tall. It is composed of rather uniform boulder material. Photos of the rock wall (Figure 3-4 and Figure 3-5) shows the feature in relation to the active SAR and 1969 Channel. The enhancement measure to reactivate the 1969 Channel would include the following actions in the vicinity of the SAR and the inlet to the 1969 Channel:

- Excavate approximately 260 cubic yards of the rock wall channel plug to open floodwater access into the channel. The northwest portion of the rock wall would be preserved since it would function as a high bank to aid in directing water into the 1969 Channel.
- The excavated material would be placed immediately to the southwest to form a 4-foot high bank that would direct floodwater into the 1969 Channel rather than allowing it to follow existing topography that would cause it to flow to the west down an existing SAR high flow channel and quickly reenter the mainstem SAR.
- Lower berm along the SAR active channel’s north bank by 3 feet to allow floodwater to access an existing high flow channel that connects the active channel with the 1969 Channel.

- Construct a flow splitter up to 6 feet tall on the SAR active channel's north bank to create a flow obstruction that would divert a portion of the active channel's flow into the 1969 Channel. The amount of material needed to construct the flow splitter is approximately 400 cubic yards.

A longitudinal profile of the 2015 LiDAR ground elevations extending from the active SAR into the 1969 Channel is shown in Figure 3-6. The profile shows how the north bank berm and rock wall channel plug create topographic barriers that prevent SAR floodwater from entering the 1969 Channel. The flow path distance from the active SAR to the rock wall channel plug is 500 feet. The earthwork required to construct Enhancement Measure 1 is listed in Table 3-1. Planview maps show the existing condition (Figure 3-7) and proposed condition (Figure 3-8) contours.

As presented in the modeling in Chapter 4, once SAR floodwater enters the 1969 Channel, it flows almost entirely unobstructed at a 2.1% channel slope for nearly 8,000 feet before entering SBVWCD's Basin 18 (see 1969 Channel and Basin 18 longitudinal profile in Figure 3-9). The slope of the 1969 Channel is similar to the average bed slope of the SAR downstream of Mill Creek at 1.9%

(see SAR longitudinal profile in Figure 3-10). The SAR bed slope upstream of Mill Creek is steeper at 2.9% (Figure 3-10). Approximately two-thirds of the way down the 1969 Channel, the channel intersects a canal (Figure 3-1). This enhancement measure would cut a notch and lower the canal's west bank by up to five feet to allow 1969 Channel floodwater to continue unobstructed across the canal. A rock plug up to six feet tall would be constructed to create a new south bank for the 1969 Channel where it intersects the low spot of the canal.

SBVWCD Basin 18 is 4,000 feet long and up to 600 feet wide. This enhancement measure includes constructing a spillway at the northwest corner of Basin 18 to provide a floodwater outlet to Plunge Creek instead of uncontrolled spill into the surrounding terrain, which includes the large quarry to the west. The preliminary design spillway located along the rim of Basin 18 is 150 feet long, 40 feet wide, with an average cut of 1.0 feet (Table 3-1). Approximately 250 cubic yards of cut would be required to construct the spillway. Water would flow over the spillway and eventually join Plunge Creek 1,500 feet from the spillway. Discussion with San Bernardino County Flood Control, SBVWCD, and other land managers would be necessary to advance this measure.

The total amount of earthwork estimated to implement Enhancement Measure 1 is 1,166 cubic yards of cut and 896 cubic yards of fill over 0.66 acres (Table 3-1).

3.2 Enhancement Measure 2 – Increase Flooding in Northerly Channel Branches

Enhancement Measure 2 is located just downstream of the Mentone Pipeline crossing of the SAR (Figure 3-1). A training wall exists on the north bank of the SAR where it crosses the Mentone Pipeline. The wall is nearly 2,000 feet long, 60-80 feet wide, and has a top height approximately 10 feet above the SAR active channel bed. The grading to construct the wall appears evident in the 1970 photograph (Figure 3-2) and was likely constructed to protect the pipeline from lateral channel migration and to limit overbanking into the northerly floodplain area. The protection the wall provides has effectively cut off more than 300 feet of the SAR northern active channel belt. SAR floodwater is now constricted to a 440 feet wide channel at the Mentone Pipeline whereas it used to be over 700 feet prior to the training wall. As the SAR flow crosses the pipeline, the alignment of the channel and topography cause most of the flow to continue down the southwest channel instead of the northerly channel.

Fluvial disturbance of this area has been quite minimal since the 1969 flood for the period 1970-2016 and is limited to small, isolated areas mapped by Stillwater Sciences (2019) as mid-channel island scour (see Figure 4 in Appendix 1). Some areas of lateral bank erosion are mapped on the south bank of the active SAR channel (Stillwater Sciences 2019).

Enhancement Measure 2 would construct a rock obstruction on the mid-channel island downstream of the pipeline crossing to split flow and direct a larger portion of the flow into the northern channel braid that extends for 4,000 feet prior to rejoining the active SAR (Figure 3-11). The flow splitter's dimensions are 140 feet by 65 feet with an average height of 3 feet and maximum height of 5 feet (Table 3-1). Fill would be placed in the channel downstream of the flow splitter to create a new bank and partially plug a channel braid in order to assist with directing the flow into the northerly channel. The bank would be 150 feet long, 2.5 feet tall on average, and up to 5 feet maximum height. In association with the bank fill, an approximate 200 foot long by 70 feet wide section of channel would be deepened by one foot, on average, to attract flow and also assist with conveying floodwater to the northerly channel. It is possible that fluvial erosion alone in response to the flow splitter and bank fill would deepen the channel and that this channel deepening would not be necessary. This could be reevaluated in the future.

Enhancement Measure 2 was designed to only divert a portion of the SAR flood flow into the northerly channel. There may be some risk in completely blocking the southerly channel and forcing all of the flood flow into the northerly channel in this already artificially constricted area that could cause channel downcutting and threaten the Mentone Pipeline. Discussion with San Bernardino County Flood Control and others would be needed on the depth of the pipeline at the crossing, as well as further analysis of permissible shear stresses to determine the maximum blockage.

The total amount of earthwork estimated to implement Enhancement Measure 2 is 470 cubic yards of cut and 1,650 cubic yards of fill over 0.65 acres (Table 3-1).

3.3 Enhancement Measure 3 – Increase Flooding in Southerly Channel Branches

Enhancement Measure 3 is located on the south side of the SAR channel belt and the western end of the Redlands Airport (Figure 3-1). A historic photo time-series of this location shows it was an active portion of the SAR channel belt in 1968 and underwent substantial fluvial disturbance during the 1969 flood, as evident in the 1970 comparison image (Figure 3-12). By 1977, a training wall was constructed for nearly 2,000 feet across the channel, presumably to protect against possible lateral migration into the Redlands Airport. By October 2, 1995, a breach occurred in the training wall and the SAR flowed through the downstream portion of the walled off area. The cause of the break is uncertain but it may be due to a March 5, 1995 flood event with reported 9,000 cfs from the SAR upstream of Mill Creek plus an additional unknown contribution from Mill Creek (Table 3 in the Phase 1 Report). Historic imagery available post-1995 show this area has become increasingly vegetated.

Fluvial disturbance of this area has been minimal since the 1969 flood for the period 1970-2016 and is limited to small, isolated areas mapped by Stillwater Sciences (2019) as mid-channel island scour (see Figure 3 and Figure 4 in Appendix 1).

The Enhancement Measure 3 site includes not only the area immediately south of the breached training wall but also the larger inactive channel belt continuing for over 5,000 feet downstream along the Redlands Airport and south of the active SAR channel.

Enhancement Measure 3 would construct three rock flow obstructions in an active SAR channel braid to divert a portion of flood flows into the channel area south of the breached training wall (Figure 3-13). Each structure would be 70-80 feet long, 30-50 feet wide, average height of 4-5 feet, reaching maximum heights of 8 feet (Table 3-1). Three separate structures are used to gradually turn a portion of the flow south yet allow some water to continue to flow down the active SAR channel braid in-between the structures. An approximate 180 foot long by 30 feet wide section of channel on the upstream side of the structures would be deepened up to 1.7 feet to attract flow and also assist with conveying floodwater into the southerly channel. It is possible that fluvial erosion alone in response to the flow splitters would deepen the channel and that this channel deepening would not be necessary. This could be reevaluated in the future.

As presented in the modeling section in Chapter 4, the action of forcing water into the channel braid south of the breached training wall allows floodwater to continue flowing southwesterly into the downstream and largely inactive channel braids of the Enhancement Measure 3 site. Once flow reaches this area, the existing topography results in much of the floodwater to quickly turn northwest and reenter the existing active SAR channel. To prevent the flow from rejoining the SAR so soon another flow obstruction would be constructed to keep the water headed southwest. The rock obstruction would be 320 feet long by 40 feet wide. The average height of 2 feet (maximum of 5 feet) would be relatively low compared to the other proposed obstructions.

Enhancement Measure 3 was designed to only divert a portion of the SAR flood flow into the southerly channel that flows through the breached training wall. There may be a risk in completely blocking the active SAR channel and forcing all of the flood flow into this channel and toward the Redlands Airport. Discussion with the airport managers, San Bernardino County Flood Control, and others would be required to assess the feasibility of diverting more SAR flood water into this area.

The total amount of earthwork estimated to implement Enhancement Measure 3 is 102 cubic yards of cut and 2,341 cubic yards of fill over 0.63 acres (Table 3-1).

Chapter 4
Sediment Transport Evaluation of Enhancement Measures

The extent of flooding and fluvial disturbance associated with the proposed enhancement measures under various flood scenarios was evaluated using hydraulic modeling tools and sediment transport analysis.

4.1 Hydrograph Development for Enhancement Analysis

The three enhancement measures were evaluated under a range of flow conditions to test their performance at different frequency flood events. Three alternative flow release scenarios that could be effective in providing overbank flow in the WSPA were evaluated. Two of them incorporate a release of 5,000 cfs from SOD, while the third relies entirely on Mill Creek flow. Synchronizing a SOD release with a natural Mill Creek peak flow would be an important change in the operation of the dam that has not occurred to date. Chapter 5 in the Phase 1 report demonstrated that the most restrictive limit on releasing flows that would contribute to ecologically meaningful flow events from SOD is the rising condition limit to 50 cfs, which effectively prevents timing releases to be synchronized with high-flow contributions from tributaries. Mill Creek will continue to contribute substantial flood flows to the SAR. However, SOD has not been making high-flow releases that contribute to Mill Creek flows in a manner predicted by USACE (2000b). As described in the Phase 1 Report, this would require entering into discussions with USACE and Orange County Flood Control District representatives to determine the likelihood of a change in operation as well as exploration of other constraints not detailed in the WCM.

The three hydrographs used for evaluation of the enhancement measures are described below.

4.1.1 Scenario 1: Seven Oaks Dam 5,000 cfs Release with No Mill Creek Contribution

A synthetic hydrograph was developed for a flood scenario in which the only flow contribution is a Seven Oaks Dam release. The hydrograph begins at 50 cfs and rises to a peak release of 5,000 cfs at 15 hours before receding back down to 50 cfs again at 36 hours (Figure 4-1). A peak flood release of 5,000 cfs from the dam was selected because this magnitude has been released before from the dam and releases greater than 5,000 cfs are unlikely as described by the constraints analysis in Chapter 5 of the Phase 1 Report. The total flow volume for the 1.5-day hydrograph is 4,587 acre-feet.

4.1.2 Scenario 2: 20,000 cfs Mill Creek Flood with No Seven Oaks Dam Release

This flood hydrograph simulates the January 25, 1969 Mill Creek flood that had an estimated peak of 20,000 cfs at the Yucaipa gage, which is the largest flood for the gaging record. A comparison was performed of the seven largest peak flow events that occurred on Mill Creek between 1927-1980 to understand the durations of Mill Creek flood events (Figure 4-2). Note the comparison is based on mean daily discharge records since 15-minute discharge records are not available online. The durations of the flood events graphed in Figure 4-2 are correct but the peak discharges are greater than the graphed mean daily discharges. Large Mill Creek floods typically rise from a low-flow condition to the peak in less than two days, and the vast majority of flow increase occurs in less than one day. Peak flows typically recede back down to low-flow conditions in about two days. The takeaway from the analysis is that Mill Creek rapidly reaches flood stage and peak flows typically persist for hours, not days. The 1969 flood event, which has a mean daily discharge of 4,510 cfs in Figure 4-2, but an estimated peak instantaneous discharge of 20,000 cfs, is an exception to the quick rising and falling hydrographs of the other years. The 1969 flood rose to its peak in a day, but receded from the peak rather slowly over the course of three days. The Mill Creek hydrograph developed for this study simulates the 1969 gage hydrograph. The estimated peak instantaneous flow of 20,000 cfs was used for the peak and the flow magnitudes and durations were set to minimize the difference in total flow volume between the model hydrograph and gage hydrograph. The peak of the model hydrograph (Figure 4-1) was set to have a shorter duration than the 1969 gaged hydrograph in order to better simulate the flood durations of the other Mill Creek flood hydrographs that are more typical than what occurred in 1969.

4.1.3 Scenario 3: Seven Oaks Dam 5,000 cfs Release with 20,000 cfs Mill Creek Contribution

The same Santa Ana River and Mill Creek hydrographs described in Scenarios 1 and 2 were combined to create this hydrograph (Figure 4-1). Based on the findings of SOD operational constraints described in Chapter 5 of the Phase 1 Report, this is a rather idealistic scenario in which the peak of the Seven Oaks Dam release is timed perfectly to match the peak of the Mill Creek hydrograph to create a combined 25,000 cfs peak discharge.

Since publication of the Phase 1 Report, another flooding event occurred in the upper SAR watershed in February 2019. Analysis presented in Table 7 of the Phase 1 Report that shows flood levels for several SAR tributaries and the SAR near E Street gage was updated to estimate the flood magnitude of Mill Creek for this event, which does not have a gage. The recurrence intervals for the flood events in neighboring watersheds ranged from 3 to 11 years, with an average of 8 years (see updated Phase 2 Table 4-1). If a similar recurrence interval event occurred on Mill Creek, the coarsely estimated flow is 2,500 cfs. The combined 15-minute records of USGS gages 11051499 and 11051502 represent SOD release, and on the same date of February 14, 2019, their combined flow was 121 cfs (1.5-year recurrence interval post-SOD). This event is another instance in which a SOD release was not made in coordination with Mill Creek peak flooding.

4.2 2D Model Setup

Two-dimensional hydraulic modeling was performed using the SRH-2D numerical model (Lai 2008). The SRH-2D numerical model was created by the U.S. Bureau of Reclamation at its Technical Service Center in Denver, Colorado. The model is a 2D depth-averaged velocity, finite element model well suited for simulating hydraulics in braided channel morphologies and lateral flow onto overbank areas. SRH-2D uses a flexible hybrid mesh of structured quadrilateral and/or triangular cells that provides a good balance of modeling accuracy and time to complete model runs. All model setup, including mesh generation and boundary condition establishment, was performed in the Surface-water Modeling System software published by Aquaveo (Aquaveo 2009). The same model mesh used for the Phase 1 analysis was expanded to include the 1969 Channel and Basin 18. A new model mesh was created for this Phase 2 analysis. Its upstream limit is the Mentone Pipeline crossing of the SAR at Opal Avenue and it extends downstream for 12,000 feet to 2,000 feet upstream of Orange Street. The models upstream and downstream of the Mentone Pipeline were run independently from each other to reduce model computation times, though the modeled water surface elevations from each model aided establishment of boundary conditions for the other model. Elevations in both models are based on LiDAR flown in 2015. The resolution of the modeling meshes is 3-foot spacing between model nodes in channel areas, which is the same resolution of the raster cell size in the LiDAR elevation surface. Further description of modeling parameters, including roughness specification, is described in Chapter 6 of the Phase 1 Report.

4.3 Modeled Flow Scenarios

The modeling of the 1969 Channel was performed as an unsteady condition model with infiltration losses. The model's hydrograph is shown in Figure 4-1. ICF included infiltration losses for this model since flow losses in the 1969 Channel and percolation in Basin 18 are important considerations for evaluating how much flow Basin 18 can store and route to Plunge Creek without uncontrolled spill into the quarry to the west. The same methods used to model infiltration losses described in Chapter 6 of the Phase 1 Report were used for this Phase 2 analysis.

The 2D model downstream of the Mentone Pipeline was run under steady state conditions. Seven different discharges ranging from 438 cfs to 25,000 cfs were modeled. Since the model is located downstream of the confluence of Mill Creek with the SAR, the source of the water (Mill Creek or SAR) does not affect the model results. The lowest flow modeled of 438 cfs could be a SOD release, or an approximate 2.33-year event on Mill Creek (see Table 4 in Phase 1 Report), or some combination of SAR and Mill Creek flows. The highest flow modeled of 25,000 cfs represents the Scenario 3 hydrograph of a 20,000 cfs event on Mill Creek timed with a 5,000 cfs SOD release. The other modeled flows include 2,500 cfs, 5,000 cfs, 7,500 cfs, 10,000 cfs, and 15,000 cfs. The intent of the flow scenario selection is to include multiple flows so conditions could be evaluated over a large range of flood events. The 5,000 cfs event was specifically selected since releases greater than 5,000 cfs are unlikely as described by the constraints analysis in Chapter 5 of the Phase 1 Report.

4.4 Sediment Transport Approach

Sediment transport analysis was performed as the principal way to evaluate the effectiveness of the enhancement measures to move sediment and create fluvial disturbance that is essential for meeting species habitat goals. Three different methods were used to evaluate sediment transport: 1) bar migration analysis utilizing new work performed for the Phase 2 Study performed by Blue Octal in 2019 (see Appendix 2); 2) incipient motion analysis; and 3) Rouse mode of sediment transport analysis.

4.4.1 Sediment Texture

4.4.1.1 Channel Bed Samples

The texture of the sediment in the bed of the SAR and the 1969 Channel is very diverse, poorly sorted, and ranges from fine-grained sand to large boulders. Blue Octal (2019) performed new sediment grain size measurements for the Phase 2 study (Appendix 2). Two of the sample sites were in the 1969 Channel and the other four were in active and inactive sections of the SAR in the vicinity of the enhancement measure sites. ICF compiled the Blue Octal sediment data and created cumulative frequency distributions and particle size-class frequency histograms charts in Figures 4-3 to 4-8. Summary statistics of the sediment data are provided in Table 4-2. As reported by Blue Octal (2019), the sediment is strongly bi-modal. All samples are very poorly sorted to extremely poorly sorted and the dominant size class for all six samples is 0.5 mm (medium sand), with 20% to 50% of a sample's total sediment in this size class. The samples tend to have little sediment in the 4 mm to 16 mm size classes (very fine to medium gravel) and higher percentages of 64 mm to 256 mm size classes (coarse gravel and cobble). Boulder size material typically comprises less than 10% of the samples.

Three additional sediment samples previously collected for a SOD study (Wright and Minear 2019) in the SAR channel near Greenspot Road and near Orange Street, as well as a Mill Creek location near Greenspot Road, were analyzed and included in this report (Figures 4-9 to 4-11). The SAR sediment sample near Greenspot Road is noticeably coarser than either of the Blue Octal samples collected downstream of Mill Creek or the SAR sample near Orange Street. Sand-size material comprises only 7.8% of the Greenspot Road sample compared to 55%-67% of the samples in the SAR downstream of Mill Creek. Sediment sizes from the Mill Creek location, where the channel is nearly twice as steep as the SAR near Grenspot, are nearer to the sizes in the SAR downstream of Mill Creek but with higher percentages of gravel and less sand.

4.4.1.2 SBKR Habitat Sediment Samples

Researchers from the San Diego Zoo studying SBKR habitat suitability in the study area provided sediment data from six locations where they sampled substrate in 2018. The locations span the range of SBKR habitat suitability and are mapped in Figure 4-12. Histogram charts of the samples showing the D_{50} (diameter at which 50% of the material is finer than) and D_{90} (diameter at which 90% of the sample is finer than) are shown in Figure 4-13 and Figure 4-14, respectively. Of the six sites, only Alabama, Cone Camp and Amazon were recommended for inclusion as being representative of suitable habitat (Debra Shier, email pers com. 2018). ICF calculated the D_{50} (0.51 mm, medium/coarse sand) and D_{90} (1.42 mm, very coarse sand) particle sizes for the three select San Diego Zoo samples for use in the sediment transport analysis described below. The D_{50} of the Sand Diego Zoo samples is quite similar to the dominant size class (0.5 mm) and D_{50} of the Blue Octal (2019) channel bed samples that ranged from 0.56 mm to 0.97 mm (Table 4-2). This indicates that ample supply of sediment of a suitable size for creation of SBKR habitat exists in the SAR downstream of Mill Creek and in the 1969 Channel.

4.4.2 Sediment Supply

Wright and Minear (2019) performed a study to evaluate how sediment trapping at SOD affects sediment transport on the upper SAR, and the extent to which unregulated tributaries replenish sediment supply to the mainstem SAR. Construction of SOD results in trapping of bedload at the dam and has effectively reduced the sediment supply of the SAR in the reach between the dam and the confluence with Mill Creek to zero (Wright and Minear 2019). Transport of sediment in this reach is largely limited to recruitment of sediment from the channel bed and banks, which leads to winnowing of the finer sand and gravel sediment out of the reach and a remaining coarse substrate. This is reflected in the coarseness of the particle size measurements performed in the SAR location near Greenspot Road in which 65 percent of the sediment is cobble and boulder size (Table 4-2).

Figures 3-5 in Wright and Minear (2019) were interpreted to determine the sediment transport capacities of the SAR upstream of Mill Creek, and on Mill Creek itself, for flows of similar magnitudes. The transport capacity of combined sand, gravel, and cobble of the SAR upstream of Mill Creek is approximately 1,000 kg/s for a flow of 4,308 cfs. Transport of the sand size fraction is 200 kg/s (20% of the total). Construction of the dam has reduced the transport capacity of the SAR in this reach by about 90% (Wright and Minear 2019). For comparison, for a flow of 5,590 cfs on Mill Creek, the transport capacity of combined sand, gravel, and cobble of the SAR upstream of Mill Creek is approximately 5,600 kg/s. Transport of the sand size fraction is 1,700 kg/s (30% of the total). For a fairly similar flow magnitude, the total transport capacity of Mill Creek is over five times more than on the SAR upstream of Mill Creek. Mill Creek's sand transport capacity is over eight times greater than the SAR.

Mill Creek is the largest source of coarse sediment to the mainstem SAR (Wright and Minear 2019) due to its steep slope, availability of coarse bed sediment, and high peak flows (Wright and Minear 2019). Even with SOD, the SAR downstream of Mill Creek is expected to remain depositional (Wright and Minear 2019). The findings of the Wright and Minear study suggest that Mill Creek will continue to supply sediment in the quantities and sizes sufficient for scour and fill processes that support bar migration and deposition of fresh sand needed for species colonization.

4.4.3 Shear Stress Calculations

Shear stress is the driving factor in transporting sediment. It was calculated using depth and velocity output from the 2D hydraulic model and the following method for this study.

The local shear velocity (u^*) related to grain-induced resistance, from which local shear stress (τ) was calculated, was determined from a variation of Keulegan's (1938) resistance law for rough flow presented by Wilcock (2001) as:

$$\frac{U}{u^*} = 8.1\left(\frac{h}{k_s}\right)^{0.167}$$

where U is flow velocity (ft/s), h is flow depth (ft), and k_s is the bed roughness height (ft) calculated as $0.84D_{90}$ particle size (Wilcock and Kenworthy 2002). The D_{90} particle sizes were calculated from particle size sampling reported by Blue Octal (2019) and presented in Figures 4-3 to 4-8.

4.4.4 Bar Migration Analysis

As previously mentioned, Blue Octal (2019) reported thresholds for migration of sand and cobble bars important for creating fluvial disturbance and removing vegetation. ICF used the reported values to bin the calculated shear stress output into one of six different classes (Table 2-1).

Migration of sand bars was split into low and high end categories. Migration of cobble bars was split into three categories – a low end, high end, and maximum end. A breakpoint was added at 125 pascals (Pa), or 2.61 pounds per square foot (lb/ft^2) in English units, since 125 Pa was identified as an ideal condition for migration of both sand and cobble bars.

4.4.5 Incipient Motion Analysis

Incipient motion analysis was performed to calculate the riverbed particle sizes expected to be mobilized by the shear stresses of the different modeled flows. Whether or not a particle on the streambed is entrained by the flow or remains in place largely depends on (1) randomness (grain placement and turbulence), and (2) balance of driving fluid drag (F_D) and resisting gravity forces (F_G).

$$F_D \propto \tau_0 D^2, \text{ and } F_G \propto (\rho_s - \rho) g D^3$$

and

$$\frac{F_D}{F_G} \propto \frac{\tau_0}{(\rho_s - \rho) g D} = \Theta = \tau^*$$

where D is grain diameter, ρ_s is sediment density, ρ is water density, and τ_0 is bed shear stress. The dimensionless bed shear stress (Θ, commonly called the Shields number, or τ^*) is a measure of sediment mobility. If τ^* is greater than the threshold required for sediment motion (τ^*_c, critical dimensionless bed shear stress), then sediment motion is predicted to occur.

Figure 4-15 shows the τ^*_c curve for initiation of motion (commonly referred to as the Shields curve) used in this study from which the shear stress required to mobilize different size particles was determined (see Figure 4-16 for the same curve with dimensional units). This version of the Shields curve flattens out at a τ^* of 0.47 as the particle Reynolds number (R_{ep}) that is based on sediment size approaches coarse gravel (32-64 mm) and coarser particles (Buffington and Montgomery 1997). If the calculated τ^* value plots above the τ^*_c curve, then sediment motion is predicted to occur, whereas if the value is under the curve, then no motion is predicted to occur. The curve shows that as particle size increases from coarse sand to gravel, the increased resistance to movement from the weight of the particle exceeds the additional drag exerted on the particle, and thus the critical dimensionless shear stress required for movement increases. Note that the initiation of motion analysis does not consider how the relative variability of grain sizes in a sediment mixture influence

τ^*_c for individual particle sizes (D_i) within the mixture, nor does it account for particle embeddedness on τ^*_c.

4.4.6 Primary Mode of Sediment Transport

The mechanism by which sediment is transported in the SAR can be characterized by two modes. The relatively coarser size particles weigh more and are typically transported as *bedload*, which consists of transport along the riverbed by rolling, sliding and saltating. The relatively finer particles that weigh less can be transported as *suspended load* higher up in the flow's water column supported by turbulence (see Figure 4-17). The mode of transport is particularly important for the sand-size particles that are essential for SBKR habitat. Transport of sand higher up in the water column as suspended load provides greater opportunity for more widespread deposition of the sediment on relatively high elevation floodplain surfaces rather than being limited to transport along the active channel as bedload.

The primary mode of transport can be predicted based on the ratio of a particle's fall velocity v_s and shear velocity U_*. The fall velocity (also referred to as settling velocity) indicates how quick a particle will sink through the water column to the bed, with larger particles sinking quicker than smaller particles. Particle fall velocities for the San Diego Zoo D_{50} (0.51 mm) and D_{90} (1.42 mm) particle sizes were calculated as 0.24 ft/s and 0.53 ft/s, respectively, using the following equation presented in Ferguson and Church (2004).

$$w = \frac{RgD^2}{C_1 v + (0.75 C_2 RgD^3)^{0.5}}$$

w = particle fall velocity

D = particle diameter

R = submerged specific gravity

g = acceleration of gravity

v = kinematic viscosity of the water

C_1 = constant in Stokes' equation for laminar settling (18)

C_2 = constant asymptotic value of the drag coefficient (1 for natural grains)

Shear velocity is a measure of shear stress expressed in units of velocity that indicates the velocity gradient and level of turbulence near the riverbed. Julien (2009) reports that in most rivers, incipient motion of sediment begins where the ratio $U_*/v_s \cong 0.2$, and bedload is dominant where the ratio U_*/v_s is less than about 0.4 (see Table 4-3). A mixed load transition load exists where $0.4 < U_*/v_s < 2.5$ in which both bedload and suspended comprise the total sediment load. Most of the sediment is transported as suspended load when $U_*/v_s > 2.5$.

4.4.6.1 Rouse-Vanoni Profile

The Rouse-Vanoni profile describes how the concentration of suspended sediment varies throughout the water column – from the bed to the water surface. Calculations of the Rouse-Vanoni Profile were performed to understand how the concentration of the sand-size sediment important to SBKR changes throughout the water column depending on flow magnitude. How the suspended sediment is transported is of importance to this study by understanding if the sand size material is more likely to be transported near the bed as migrating bars or more generally suspended throughout the water column and thus available for transport and deposition over terrain elevated above the bed (e.g., floodplains). The following approach was used (Parker 2004):

$$\frac{c}{c_b} = \left[\frac{(1-\varsigma)/\varsigma}{(1-\varsigma_b)/\varsigma_b}\right]^{\frac{v_s}{\kappa U_*}}, \qquad \varsigma = \frac{z}{H}, \qquad \varsigma_b = \frac{b}{H}, \qquad c_b = E$$

c	=	volume concentration of suspended sediment averaged over turbulence
c_b	=	near-bed value of c at z = b
v_s	=	particle settling velocity
U*	=	shear velocity

κ = von Karman constant (0.4)

ς = vertical coordinate in the water column (equals 0 on the bed surface and H on the water surface)

ς_b = position near the bed surface where the volumetric concentration of suspended sediment is c_b

z = Distance in water column above bed

H = Total flow depth

b = reference distance above the bed where sediment entrainment is specified

E = dimensionless rate of entrainment of bed sediment into suspension

4.5 Model Results

The 2D model results are presented separately for the 1969 Channel (Enhancement Measure 1) and the SAR downstream of the Mentone Pipeline (Enhancement Measures 2 and 3).

4.5.1 Enhancement Measure 1 – Reactivate 1969 Channel

As described above in Chapter 3, the 1969 Channel terminates in SBVWCD's Basin 18. To the west of Basin 18 is a large quarry located where the 1969 Channel used to continue through. A major constraint of diverting SAR floodwater into the 1969 Channel is rapid filling of Basin 18 leading to uncontrolled spill over the basin's western rim and into the surrounding terrain, including the quarry. The ideal situation is controlled spill over the northwest corner of Basin 18 and routing of floodwater into Plunge Creek. ICF performed iterations to determine the magnitude and duration of flood flow that could be diverted from the SAR and into the 1969 Channel without causing uncontrolled spill. The iteration presented in this report shows that for a peak SAR flow of 5,000 cfs, implementation of Enhancement Measure 1, including construction of the flow splitter and rock wall channel plug removal, would result in diversion of 646 cfs from the active SAR into the 1969 Channel. The amount of water that would be diverted into the 1969 Channel over the entire modeled hydrograph is presented in Figure 4-18. Model iterations showed that increasing the amount of water diverted into the 1969 Channel not too much beyond 646 cfs would result in uncontrolled spill in Basin 18. Based on the configuration developed for Enhancement Measure 1, a SAR peak flow of 5,000 cfs upstream of the diversion is sufficient to obtain the desired 1969 Channel flow.

The source of the 5,000 cfs could be entirely derived from a SOD release, or Mill Creek, or some combination of the two. As described in Chapter 6 of the Phase 1 Report, as flow levels increase on Mill Creek, a secondary flood channel to the west of the main channel and along the toe of the levee becomes active. The flow from this secondary channel joins the SAR well downstream of where Mill Creek's main channel flow enters, and also downstream of the 1969 Channel inlet location, and is thus unavailable to the 1969 Channel. ICF ran six different flow scenarios where the only flow contributions were from Mill Creek to further explore how much of Mill Creek's total flow is conveyed down the secondary channel from frequent to infrequent flood events. The results displayed in Figure 4-19 show the relationship between total Mill Creek flow and the flow conveyance distributions between the main primary channel branch and the secondary channel to the west. The 2-year through 100-year recurrence intervals are listed on the graph's X-axis to correlate discharge with flood frequency recurrence (as listed in Table 4 in the Phase 1 Report). For a Mill Creek 2-year event of 350 cfs, only 6 cfs (2%) of the total flow is conveyed down the western secondary channel and not available to the 1969 Channel. For a total Mill Creek flow of 20,000 cfs, 4,675 cfs (31%) of the flow is not available. To obtain the 5,000 cfs used as the SAR inflow for the Enhancement Measure 1 hydrograph, a total Mill Creek flow of 5,352 cfs is required, which has a recurrence interval of approximately 17-years based on historic Mill Creek Yucaipa gage records. Flow contributions from SOD releases would largely contribute directly to the flow in Mill Creek's primary eastern channel branch. However, mixing of SAR and Mill Creek flow has the effect of forcing additional Mill Creek down the secondary western branch. For example, with a Mill Creek flow of 20,000 cfs and no SAR flow, 4,675 cfs is routed down the secondary channel and unavailable at the 1969 Channel. If a SOD release of 5,000 cfs occurs in conjunction with 20,000 cfs on Mill Creek, the amount of flow routed down the secondary channel increases by 25% to 5,834 cfs.

The 2D modeled flow velocities for the location where flow would be diverted from the active SAR into the 1969 Channel are shown in Figures 4-20 to 4-27 for model time-steps 8 hours through 15 hours on the hydrograph (Figure 4-18). The location of the flow splitter is displayed in transparent gray and the white lines indicate the flow distribution between the active SAR and the amount of flow entering the 1969 Channel. At time-step 11 hours a small portion of the water diverted from the SAR does not continue into the 1969 Channel, but instead flows west in an existing high flow channel. Increased activation of the existing high flow channels located between the active SAR channel and the 1969 Channel occurs as flow levels increase on the SAR. The proposed flow splitter begins to overtop around 3,000 cfs.

4.5.1.1 Infiltration Losses

The routing of the hydrograph through the 1969 Channel, into Basin 18, and over the Basin 18 spillway is shown in Figure 4-28. It takes about 3 hours for flow to enter Basin 18 from the time it first enters the 1969 Channel. Once water enters Basin 18 it takes about 4 hours to fill the basin and then commence spill over the spillway added for Enhancement Measure 1. The travel time for the peak flow into the 1969 Channel (646 cfs) and the peak over the spillway (512 cfs) is about 1.5 hours. Infiltration and flow attenuation provided by Basin 18 storage reduce the peak flow that would flow into Plunge Creek by 134 cfs.

As previously mentioned, the total flow volume for the 1.5-day Santa Ana River hydrograph (Scenario 1) is 4,587 acre-feet. The portion of this total volume of water that is diverted into the 1969 Channel is 456 acre-feet (Figure 4-29). The outflow volume over the proposed Basin 18 spillway is reduced to 301 acre-feet. At the end of the model run the cumulative infiltration loss is 98 acre-feet infiltration loss (21% of the inflow volume). Since the difference between the inflow and outflow volumes is 155 acre-feet, it is expected that additional infiltration and evaporation losses would occur from ponded water remaining in Basin 18 for a longer period than was modeled.

The modeled inflow, outflow, infiltration, and surface storage volumes were used to calculate percent error in mass balance as a measure of model error by (Kallio et al. 2015):

$$\text{Percent Error}=(v\_inflow-(v\_outflow+v\_infiltration+v\_surface))/v\_inflow \times 100$$

The result is a calculated 0.7% error in mass balance between flows entering and leaving the model. This low value indicates the unsteady condition model is satisfactorily conserving mass as it accounts for infiltration losses over the course of the hydrograph.

Infiltration rates for each model time-step were calculated as the infiltration volume divided by the corresponding inundated surface area. The rate of infiltration loss varies over the course of the hydrograph (Figure 4-30). The initial infiltration loss is highest, near 6.5 inches per hour, on the rising limb of the hydrograph when water first enters the 1969 Channel and high infiltration occurs where water spills into previously un-wetted areas with dry soils. At the peak of the hydrograph the infiltration loss is 2.4 inches per hour. On the falling limb of the hydrograph the rate of infiltration loss continues to decay because sustained wetting and saturation of the inundated area's substrate causes infiltration to approach its capacity rate (Figure 4-30). At the end of the hydrograph the infiltration rate reaches the average saturated hydraulic conductivity (Ksat) for the site (0.97 inch per hour). This trend of reduced infiltration loss rates is evident in comparison of the inflow and outflow hydrographs (Figure 4-29). The differences in flow between the inflow and outflow are greater on the rising limb than on the falling limb.

4.5.2 Comparison with Measured Infiltration Losses

Scheevel Engineering (2016) reported infiltration rates for Mill Creek recharge basins with an initial rate of 3.4 feet per day decaying to 1.4 feet per day. Geoscience reviewed historic measured rates in the region and conducted new infiltrometer testing and reported infiltration rates at eight locations on upper SAR tributaries ranging from 3.0 feet per day to 7.0 feet per day (Geoscience 2012). The modeled infiltration rates (Figure 4-30) using the Green-Ampt method for this study reach a high of

6.0 feet per day and decay to 2.0 feet per day when infiltration potential equals Ksat. These results are in agreement with the reported rates used for other hydrological studies in the study area vicinity.

4.5.2.1 Bar Migration Analysis

Results of the bar migration analysis are mapped for 8 time-steps of the hydrograph used in the 1969 Channel analysis in Figures 4-31 to 4-38. The time-steps span the period of flow first entering the 1969 Channel from the SAR through the peak flow of the hydrograph. In addition to the mapping, histogram charts show the acreage (Figure 4-39) and percent of wetted area (Figure 4-40) of predicted bar migration over the hydrograph. In order to prevent the results from being skewed by the large Basin 18 conveyance area, the histograms only consider the 1969 Channel from the SAR to the Basin 18 inlet and do not include Basin 18. At hour 16, after the 646 cfs peak has entered the 1969 Channel and most of the channel is experiencing the highest flows of the hydrograph, 35% of the channel has stress levels below 0.13 lb/ft^2, which is less than the low end for sand bar movement. Shear stress levels for most of the channel (53%) are in the Sand Bar Low End category, and 11% of the channel is in the Sand Bar High End category. Less than 1% is within the Cobble Bar Low End. Enhancement Measure 3 creates sufficient shear stresses for predicted sand bar migration but not appreciable levels of cobble bar migration.

At the peak of the hydrograph, activating the 1969 Channel would produce 12.0 acres of channel area with shear stresses greater than the minimum shear stress required for bar movement (0.13 lb/ft^2). In addition, the sediment that would deposit in Basin 18 may be available for habitat depending on frequency of disturbance from maintenance activities or other disturbance. Basin 18 has 24 acres of inundated area at the peak of the hydrograph.

Note that an additional flow of 1,500 cfs was modeled as a steady flow separate from the unsteady hydrograph analysis and is included in the histogram output. This higher flow was modeled to see the effect of more than doubling the peak flow in the 1969 Channel, even though it would be problematic for creating uncontrolled spill in Basin 18. The peak of flow 1,500 cfs creates a maximum of 29.2 acres of inundation in the 1969 Channel compared to the 646 cfs peak flow of the unsteady hydrograph that creates 18.6 acres. Notably, the 10.6 acre increase in wetted area does not translate into proportional increases in sand or cobble bar migration. Instead, 9 of the 10.6 acres has shear stress levels below the low end for sand bar migration. This result suggest that routing higher flows down the 1969 Channel well beyond 1,500 cfs may be needed to produce appreciable areas of cobble bar migration since the result of increasing from 646 cfs to 1,500 cfs causes the water to spread out into a larger inundation area but not increase in depths and velocities that rapidly increases shear stress levels.

- In summary - At the peak of the hydrograph, 12.0 acres of channel area have shear stresses greater than the minimum shear stress required for sand bar movement. Of this total, 53% of the area is in the Sand Bar Low End category, and 11% is in the Sand Bar High End category.

4.5.2.2 Incipient Motion Analysis

Results of the incipient motion analysis are mapped for 8 time-steps of the hydrograph used in the 1969 Channel analysis in Figures 4-41 to 4-48. The shear stress output in the maps is binned into particle size classes ranging from silt/clay to boulder size sediment. The time-steps span the period of flow first entering the 1969 Channel from the SAR through the peak flow of the hydrograph. In addition to the mapping, histogram charts show the acreage (Figure 4-49) and percent of wetted area (Figure 4-50) of predicted sediment incipient motion over the hydrograph. Basin 18 is also excluded from the analysis as described for the bar migration analysis. For Hour 16, the peak of the hydrograph, nearly half of the total inundated area (46%) is predicted to have shear stress levels high enough to initiate motion of coarse to very coarse gravel. Nearly 38% of the wetted area is within the fine to medium gravel category. Motion of cobble size material is only 0.5 acres (3% of wetted area), which is a similar result to the bar migration analysis. Increasing the peak flow from 646 cfs to 1,500 cfs increases the acreage of small cobble movement from 0.5 acres to 2.6 acres (9% of wetted area).

4.5.2.3 Primary Mode of Sediment Transport

Results of the primary mode of sediment transport analysis for the San Diego Zoo D_{50} (0.51 mm) particle size are mapped for 8 time-steps of the hydrograph used in the 1969 Channel analysis in Figures 4-51 to 4-58. The output in the maps is binned into classes of no motion, bedload, mixed load, and suspended load. The prevalence of yellow area in the mapping results shows that sand-size material is predicted to be transported as mixed load over the course of the hydrograph. Localized areas of suspended load (red on the maps) occur and are primarily located in areas where the flow is concentrated in a relatively narrow channel width. Most of Basin 18 is mapped as an area of no motion (blue on the maps), which is not unexpected in the settling basin where shear stresses are near zero.

A Rouse-Vanoni profile is presented in Figure 4-59 for the 1969 Channel (excluding Basin 18) for hour 16 at the peak of the hydrograph. The average velocity in the 1969 Channel at this time-step is 3.3 feet/second and the average depth is 1.3 feet. The profile includes both the San Diego Zoo D_{50} (0.51 mm) and D_{90} (1.42 mm) particle sizes. Nearly all of the 1.42 mm particles are transported in close proximity to the channel bed. At 15% of the flow depth (0.2 feet), the concentration of 1.42 mm particles is only 1% of what it is nearer the bed. At the same distance from the bed the concentration of 0.51 mm particles is 14% of what it is nearer the bed. The sediment concentration profiles align with the majority mixed load mode of transport. For the most part the particle sizes important to SBKR habitat are likely to be transported near the bed and not fully suspended in high concentrations throughout the water column. This supports the finding made by Blue Octal (2019) that migration of bars is more likely to create new habitat instead of sediment deposition from shallow flow widespread over floodplain surfaces elevated relatively high above the active channel bed.

4.5.3 Enhancement Measure 2 – Increase Flooding in Northerly Channel Branches

Enhancement Measure 2 would construct a rock obstruction on the mid-channel island downstream of the Mentone Pipeline crossing at Opal Avenue to split flow and direct a larger portion of the flow into the northern channel braid that extends for 4,000 feet prior to rejoining the active SAR (Figure 3-11). Model output for a 5,000 cfs flow at the enhancement site is shown in Figure 4-60. The top image shows the velocity magnitudes and velocity vectors under the existing condition (based on 2015 LiDAR). Under the existing condition, 1,171 cfs of the 5,000 cfs total flows into the northerly branch. The bottom image shows the effect of adding the flow splitter and rock wall. The amount of flow diverted into the northerly branch is increased to 2,461 cfs (+110%). The splitter would be located close enough to the Mentone Pipeline crossing to intersect and redirect much of the flow prior to the flow continuing in a southwest alignment toward the south bank. Model iterations showed that placement of the splitter further downstream makes it too difficult to effectively turn much of the flow into the northerly channel braid. The mid-channel island splitter is just starting to be overtopped by the flow at 5,000 cfs. The effect of constructing the bank to the west of the splitter is also evident in Figure 4-60. In the existing condition there is a middle channel braid that conveys a substantial amount of flow before quickly rejoining the southern channel braid. The bank would block most of this flow from rejoining the southern channel and forces the flow to continue in a westerly direction and into the far north channel.

4.5.3.1 Bar Migration Analysis

Results of the bar migration analysis are mapped for the seven flows modeled in Figures 4-61 to 4-67. The maps show the existing condition on top and the condition with the enhancements in place on the bottom. The maps also have cross-section lines at multiple locations to show how flow conveyance would change in the channels from the existing condition. Histogram charts in Figure 4-68 show the acreage for both the existing condition and the condition with Enhancement Measure 2 in place. To aid in isolating the effect of Enhancement Measure 2, the area used for calculations only includes the northerly channel branch that Enhancement Measure 2 would direct more flow into, and not the entire modeling domain. Histogram charts in Figure 4-69 show the acreage of bar migration as a percent of wetted area for both the existing condition and condition with the Enhancement Measure 2 in place.

The shear stress and predicted bar migration trends are similar for both the existing condition and Enhancement Measure 2. Shear stress levels span the range from the minimum required for sand bar migration to the cobble bar maximum. The flow of 2,500 cfs creates the first appreciable shear stresses required for cobble bar migration. Increases in flow magnitude do not always translate into proportional increases in all types of bar migration, with the cobble bar maximum being a notable exception in which the areas progressively increase with higher flows.

The change in bar migration acreage from the existing condition to the Enhancement Measure 2 condition is shown in Figure 4-70. This figure is useful for discerning the results of multiple flows into the gains to be expected by diverting more of the flow into the northerly channel. Most of the increased acreage is in acres of channel area with shear stresses less than the minimum shear stress required for bar movement (0.13 lb/ft^2) or in the Sand Bar Low End. Enhancement Measure 2 would increase acreages by approximately an acre or less with shear stresses high enough for cobble bar high end and maximum for modeled flows of 2,500 cfs or greater.

- In summary - Enhancement Measure 2 would produce a range from 2.1 acres (2,500 cfs) to 3.6 acres (25,000 cfs) of increased channel area with shear stresses greater than the minimum shear stress required for bar movement.

4.5.3.2 Incipient Motion Analysis

Results of the incipient motion analysis are mapped for the seven flows modeled in Figures 4-71 to 4-77. Histogram charts in Figure 4-78 show the acreage for both the existing condition and condition with Enhancement Measure 2 in place. Histogram charts in Figure 4-79 show the acreage as a percent of wetted area for both the existing condition and condition with the Enhancement Measure 2 in place. Incipient motion of gravel sediment comprises the largest percentage of the total inundated areas for both conditions, followed closely by small and large cobble.

The change in incipient motion acreage from the existing condition to the Enhancement Measure 2 condition is shown in Figure 4-80. Most of the increased acreage is in the gravel size class, but also appreciable increases in movement of cobble size material at modeled flows equal to or greater than 2,500 cfs. Flow increases beyond 5,000 cfs do not translate into similar increases in transport of coarse cobble and boulder material.

4.5.3.3 Primary Mode of Sediment Transport

Results of the primary mode of sediment transport analysis for the San Diego Zoo D_{50} (0.51 mm) particle size are mapped in Figures 4-81 to 4-87. At the lowest flow modeled (438 cfs), mixed load transport (yellow areas on the maps) is the primary mode of transport for both the existing condition and Enhancement Measure 2 condition. At 2,500 cfs, pronounced areas of suspended load (red areas) are visible in primary channel areas where flow is concentrated.

Enhancement Measure 2 would not appreciably change the mode of sediment transport in the northerly channel. It would still be dominated by mixed and suspended load transport, but with increased flow areas within these categories.

A Rouse-Vanoni profile is presented in Figure 4-88 for the entire modeling domain downstream of the Mentone Pipeline for a 5,000 cfs flow with both Enhancement Measure 2 and Enhancement Measure 3 in place. The average velocity is 4.7 feet/second and the average depth is 1.6 feet. The profile includes both the San Diego Zoo D_{50} (0.51 mm) and D_{90} (1.42 mm) particle sizes. Nearly all of the 1.42 mm particles are transported in close proximity to the channel bed. At 15% of the flow depth (0.24 feet), the concentration of 1.42 mm particles is only 4% of what it is nearer the bed. At the same distance from the bed the concentration of 0.51 mm particles is 23% of what it is nearer the bed. The sediment concentration profiles align with the majority mixed load mode of transport at 5,000 cfs. For the most part the particle sizes important to SBKR habitat at discharges of 5,000 cfs or less are likely to be transported near the bed and not fully suspended in high concentrations throughout the water column. This supports the finding made by Blue Octal (2019) that migration of bars is more likely to create new habitat instead of sediment deposition from shallow flow widespread over floodplain surfaces elevated relatively high above the active channel bed.

4.5.4 Enhancement Measure 3 – Increase Flooding in Southerly Channel Branches

Enhancement Measure 3 would construct three rock flow obstructions in an active SAR channel braid to divert a portion of flood flows into the channel area south of the breached training wall (Figure 3-13). To prevent the flow from rejoining the SAR so soon another flow obstruction would be constructed to keep the water headed southwest. The enhancements would increase flow within the presently inactive channel belt continuing for over 5,000 feet downstream along the Redlands Airport and south of the active SAR channel.

Model output for a 5,000 cfs flow at the enhancement site is shown in Figure 4-89. The top image shows the velocity magnitudes and velocity vectors under the existing condition (based on 2015 LiDAR). Under the existing condition, 161 cfs of the 5,000 cfs total flows into the southerly branch within the breach in the training walls. The bottom image shows the effect of adding the flow splitters in the active SAR. The amount of flow diverted into the southerly branch is increased to 1,176 cfs (+630%).

The three splitters would decrease the amount of flow that continues down the current active SAR channel braid from 3,140 cfs to 898 cfs. Routing more flow down the southerly branch leads to increased flows in the larger inactive channel belt at the western end of the Redlands Airport. Under current conditions 52 cfs flows through this area under a total SAR flow of 5,000 cfs. Construction of Enhancement Measure 3 would increase this to 677 cfs. The model results show construction of the western flow obstruction would turn most of the flow the to the southwest and prevent it from rejoining the active SAR channel.

4.5.4.1 Bar Migration Analysis

Results of the bar migration analysis are mapped for the seven flows modeled in Figures 4-61 to 4-67. Histogram charts in Figure 4-90 show the acreage for both the existing condition and condition with Enhancement Measure 3 in place. To aid in isolating the effect of Enhancement Measure 3, the area used for calculations only includes the area that would receive more flow from Enhancement Measure 3 and not the entire modeling domain. Histogram charts in Figure 4-91 show the acreage of bar migration as a percent of wetted area for both the existing condition and condition with the Enhancement Measure 3 in place.

Shear stress levels for both conditions are high enough for low and high end sand bar migration. Minimal cobble bar migration is predicted in this area where flows are spread out over a fairly large area in multiple channel braids. Progressive increases in flow magnitude translate into progressive increases in sand bar migration.

The change in bar migration acreage from the existing condition to the Enhancement Measure 3 condition is shown in Figure 4-92. This figure is useful for discerning the results of multiple flows into the gains to be expected by diverting more of the flow into the northerly channel. Most of the increased acreage is in acres of channel area with shear stresses less than the minimum shear stress required for bar movement (0.13 lb/ft^2) or in the Sand Bar Low End. Modeled flows ranging from 2,500 cfs to 10,000 cfs provide the biggest gains in area of sand bar movement (up to 10 acres).

Enhancement Measure 3 would create minimal increases in cobble bar migration.

- In summary - Enhancement Measure 3 would produce a range from 2.1 acres (438 cfs) to 10.8 acres (7,500 cfs) of increased channel area with shear stresses greater than the minimum shear stress required for bar movement. The increase at 5,000 cfs is 10.4 acres.

4.5.4.2 Incipient Motion Analysis

Results of the incipient motion analysis are mapped for the seven flows modeled in Figures 4-71 to 4-77. Histogram charts in Figure 4-93 show the acreage for both the existing condition and condition with the Enhancement Measure 3 in place. Histogram charts in Figure 4-94 show the acreage as a percent of wetted area for both the existing condition and condition with the Enhancement Measure 3 in place. Incipient motion of gravel sediment comprises the largest percentage of the total inundated areas for both conditions, followed by sand and silt/clay.

The change in incipient motion acreage from the existing condition to the Enhancement Measure 3 condition is shown in Figure 4-95. Most of the increased acreage is in the gravel size class with minor gains in small cobble at discharges over 10,000 cfs.

4.5.4.3 Primary Mode of Sediment Transport

Results of the primary mode of sediment transport analysis for the San Diego Zoo D_{50} (0.51 mm) particle size are mapped in Figures 4-81 to 4-87. The primary mode of transport for modeled flows from 438 cfs to 5,000 cfs are mixed load transport (yellow areas on the maps). At flows greater than 5,000 cfs pockets of suspended load (red areas) are visible, particularly in the southerly channel branch within the breached training wall where flow is more concentrated than in the broader area downstream along the western end of the Redlands Airport.

At the lower modeled discharges Enhancement Measure 3 would not appreciably change the mode of sediment transport in the area. It would still be dominated by mixed load transport but with increased flow areas within these categories. Enhancement Measure 3 would increase the acreage of suspended load transport at discharges greater than 5,000 cfs.

The same Rouse-Vanoni profile described for Enhancement Measure 2 applies to Enhancement Measure 3 (Figure 4-88).

Chapter 5
Prioritization of Enhancement Measures

Evaluation of the three enhancement measures show they are all viable measures that could be implemented to increase the levels of fluvial disturbance beyond the existing condition by creating shear stress levels of sufficient magnitude to cause sand bar migration that would result in scour or burial of existing channel vegetation. One or more of the enhancement measures could be constructed at the same time or at different times. The effect of upstream enhancement measures could affect the performance of enhancement measures downstream – primarily through alteration of flow paths and changing the amount of flow and sediment available at the downstream measure(s).

Uprooting SAR vegetation and causing scour and fill processes that will sort sediment in the SAR channel is a key fluvial disturbance the enhancement measures are designed to promote. Blue Octal (2019) report that vegetation removal by means of flowing water with high enough levels of drag force to overcome plant root resistance is difficult, and that instead uprooting is most likely achieved through undermining and burying plants through bar migration. Blue Octal (2019) also report that desired fluvial disturbances such as sand deposition, bar migration, and vegetation removal are occurring in the active channel belt under the current flood regime, but that the active channel belt is too active. Fluvial disturbance within the active channel belt occurs too frequently for successful colonization by SBKR. Blue Octal (2019) suggest that after the desired fluvial disturbance processes occur within a portion of the active channel belt, the recently disturbed area be isolated and protected for a period of 30 years before allowing another fluvial disturbance to occur.

Prioritization of the enhancement measures is primarily based on their ability to create bar migration and the feasibility of isolating the channel areas affected by the enhancement measures post-initial disturbance so that they are not flooded again too soon. The cost of implementing the enhancement measures is also a factor but considered less important since the excavation quantities (Table 3-1) are similar for all three enhancement measures. Other factors, such as ease of construction access, costs of water, and tradeoffs with the other species of interest discussed in Chapter 7 will be factored in at a later date based on initial stakeholder feedback of the enhancement measures.

A comparison table of the additional acreage of bar migration created by the three enhancement measures is provided in Table 5-1. The comparison is based on a SAR total flow of 5,000 cfs. This flow was selected for the summary table since it is a flow level that could be obtained entirely from a SOD release, or entirely from Mill Creek (a recurrence interval of approximately 17-years based on historic Mill Creek Yucaipa gage records) or a combination of the two sources. An advantage of focusing on a flow level capable of being released from SOD is it allows for planning to construct the measures in advance of a known release date and then potentially blocking off and isolating the area post-release. Reliance on Mill Creek flows adds uncertainty since the date and magnitude of the next flood from unregulated Mill Creek is unknown.

5.1 Priority 1: Enhancement Measure 1 – Reactivate 1969 Channel

The 1969 Channel has not experienced appreciable fluvial disturbance since the January 25, 1969 flood. Construction of the rock wall channel plug has effectively blocked water from subsequent floods from entering this area. Implementation of Enhancement Measure 1 would produce 12.0 acres of channel area with shear stresses greater than the minimum shear stress required for bar movement (0.13 lb/ft^2) (Table 5-1). Of this total, 9.9 acres of the bar migration would be in the Sand Bar Low End category and 2.0 acres would be in the Sand Bar High End category. In addition, the sediment that would deposit in Basin 18 may be available for habitat depending on frequency of disturbance from maintenance activities or other disturbance. Basin 18 has 24 acres of inundated area at the peak of the hydrograph.

The inlet to the 1969 Channel is located in a section of SAR that has experienced little planform change over the past several decades. Nearly all of the flow is confined to a relatively narrow channel belt and the risk is low that the SAR channel belt will rapidly shift south and make it less feasible to divert water into the 1969 Channel via the proposed flow splitter. The 1969 Channel could be relatively easily isolated from future flooding post-disturbance by reconstructing the rock wall channel plug and blocking water from reentering the channel.

Furthermore, diversion of water into the 1969 Channel and into Basin 18 provides a groundwater recharge opportunity that would likely appeal to water resource managers, particularly if a SOD release is the source of the water. At the end of the 1.5-day SAR hydrograph model run used for this analysis (4,587 acre-feet, of which 456 acre-feet is diverted into the 1969 Channel), the cumulative infiltration loss in the 1969 Channel and Basin is 98 acre-feet infiltration loss (21% of the inflow volume).

5.2 Priority 2: Enhancement Measure 3 – Increase Flooding in Southerly Channel Branches

Implementation of Enhancement Measure 3 would produce 10.4 acres of new channel area with shear stresses greater than the minimum shear stress required for bar movement (0.13 lb/ft^2) (Table 5-1). As mentioned, Enhancement Measures 2 and 3 were modeled together. Under a scenario in which Enhancement Measure 3 were implemented without diversion of water upstream at Enhancement Measure 2, more flow would be available at Measure 3 and for a total flow of 5,000 cfs approximately 13 acres of bar migration would be created.

Nearly all of the bar migration would be in the Sand Bar Low End category. The bar migration would occur not only in the area immediately south of the breached training wall but also the larger inactive channel belt continuing for over 5,000 feet downstream along the Redlands Airport and south of the active SAR channel.

Enhancement Measure 3 is ranked lower than Enhancement Measure 1 (1969 Channel) because it produces less potential suitable habitat on a total acreage basis (if implemented with Enhancement Measure 2) and the magnitude of fluvial disturbance is less based on shear stress levels (i.e., the 1969 Channel has more area in the Sand Bar High End category). Enhancement Measure 3 also requires diversion of more flood water than Enhancement Measure 1. The model shows a total flow of 2,074 cfs in the SAR active channel just upstream of the point of diversion at the proposed location of the three flow splitters. The effect of the flow splitters would be obtained by diverting 1,176 cfs (57% of the total 2,074 cfs flow) into the south channel that flows through the breached training wall. For comparison, Enhancement Measure 1 accomplishes more area of bar migration with a peak flow diversion of 646 cfs.

Isolating the disturbed areas from future flooding post-disturbance is feasible but likely more challenging than isolating the 1969 Channel. The material used to construct the three flow splitters could be relocated to create a channel plug in the south channel that flows through the breached training wall. Isolating the larger inactive channel belt that continues for over 5,000 feet downstream along the Redlands Airport would be more challenging. There are several existing high flow channel braids in this area and blocking all them would require extensive work. It may be more feasible to block one or two of them located furthest south, which would isolate a subset of the total Enhancement Measure 3 site area.

Another constraint of Enhancement Measure 3 is it would divert more flood water into an area that was previously blocked from flooding by construction of a training wall, presumably to protect the Redlands Airport. Discussion with the airport managers, San Bernardino County Flood Control, and others would be required to assess the feasibility of diverting more SAR flood water into this area.

5.3 Priority 3: Enhancement Measure 2 – Increase Flooding in Northerly Channel Branches

Implementation of Enhancement Measure 2 would produce 2.0 acres of new channel area with shear stresses greater than the minimum shear stress required for bar movement (0.13 lb/ft^2) (Table 5-1). Although this measure creates more new area with high shear stresses in the cobble bar migration categories (1.3 acres), overall the total of 2.0 acres is substantially less than either Enhancement Measure 1 or 3. The relatively small increase is due to the flow patterns in the northerly channel. Unlike for Enhancement Measure 3, the diverted flow into the northerly channel of Enhancement Measure 2 does not spread out into multiple channels that are not already active during the existing condition. The diversion of additional flow into the area mostly results in increased depths and velocities in a single channel. If Enhancement Measure 2 is advanced for further design, consideration should be given to adding additional flow obstructions to the west that would force more flow out of the northerly channel and provide new opportunities for habitat creation.

The effect of the flow splitters would be obtained by diverting 2,461 cfs (50% of the total 4,961 cfs flow) into the northerly channel. For comparison, Enhancement Measure 1 accomplishes more area of bar migration with a peak flow diversion of 646 cfs.

Isolating the disturbed areas from future flooding post-disturbance is feasible. Most of the flow under the existing channel braid enters the northerly channel braid at one defined location. The material used to construct the flow splitter located on the island just downstream of the Mentone Pipeline crossing could be relocated to plug the northerly channel braid and isolate the majority of the Enhancement Measure 2 area from future flooding post-disturbance. In addition, the training wall located along the north bank at the pipeline crossing would likely aid in continuing to direct flow southwest and prevent lateral migration of the channel north and into the northerly channel.

There is risk, however, in completely blocking the northerly channel since under the existing condition this channel is active during flooding. Forcing all of the flood flow into the southerly channel in this already artificially constricted area could cause channel downcutting and threaten the pipeline. Further analysis would be needed on the depth of the pipeline at the crossing and permissible shear stresses.

Chapter 6
Evaluation of Mechanical Disturbance of the Floodplain

Overbank flood-based disturbance is considered vital for the regeneration and maintenance of habitat for the species of interest. Because the reduced probability of overbank flooding under the current operations of SOD, alternative approaches to maintaining suitable habitat for the species of interest needs to be considered. In the 2000 BA, 2002 BO and 2012 MSHMP, non-fluvial habitat renewal treatments are detailed and offered as alternatives in the case that ecological high-flow releases from SOD do not occur. Ideally, these non-fluvial treatments would mimic the scour and sediment sorting that occurred during natural flood events in the study area prior to start of operations of SOD. Before implementation can take place, these treatments must be evaluated for their effectiveness in achieving the desired outcome of regenerating the pioneer, intermediate and mature seral stage Riversidean alluvial fan sage scrub (RAFSS) habitat that the species of interest rely on.

Despite taxonomic and life history differences between the species of interest, there are some broad similarities in their reliance on flood disturbance to maintain habitat. Specifically, clean sand with a low organic and fines fraction appears to be a critical element of suitable habitat for woolly star and SBKR. For the two plant species of interest, habitats within floodplains and dominated by substrates of this nature provide a competitive advantage over other plant species (native and exotic) not adapted for the extremely low nutrient and moisture regimes found in these environments. As flood surfaces within the area age, the fraction of fines within the substrate is expected to increase (Burk et al. 2007). Fine sediments trap nutrients and moisture within the soil and promote invasion by exotic grass species. Over time, the fraction of fines in the soil increases, pushing soil humidity and nutrients past a point where the target plant species can maintain their competitive advantage and consequently, they are outcompeted and excluded, primarily by exotic grasses (Lucas et al. 2016).

Like the target plant species, there is a negative correlation between exotic grasses and SBKR occupancy both within the study area and across the region (USACE 2012; Shier, Chock, and McCullough-Hennessy 2019). The presence of exotic grasses in SBKR habitat is associated with increased nutrient and fines content in the substrate because of the same factors indicated for the plant species above (soil humidity and nutrient load). The mechanism for the negative interaction with SBKR is that exotic grasses form a mechanical barrier, preventing them from moving, foraging, or communicating with conspecifics within habitats with high cover values of these grasses (Montgomery, pers com., Shier, pers com.). SBKR needs open substrate for scent placement sandbathing to communicate with conspecifics. Thus, the barrier that exotic grasses form likely prevents critical above-ground scent placement (Shier, pers. comm.) as SBKR communicate neighbor recognition and dominance via sandbathing (Randall, 1993). This relationship links SBKR habitat preferences with the plant species of interest, in that the presence of exotic grasses will typically reduce habitat values for all three species. Differences in habitat requirements for the species of interest are summarized below in Table 6-1.

6.1 Review of Proposed Mechanical Disturbance Methods

Several methods have been proposed and/or implemented to create mechanical disturbance to achieve biological benefits for the species of interest. Methods were initially proposed in the BA/BO and later developed in the Multi-Species Habitat Management Plan (MSHMP). Data from implementation of some of these methods and more recent research from United States Army Corps of Engineers (USACE) as well as the High Flow Study (HFS) science advisors' contributions have provided information useful in evaluating potential success of these methods.

Implementation of non-fluvial habitat manipulation, as proposed in the MSHMP, is embedded within the context of a larger adaptive management framework (MSHMP Management Decision Framework) for maintaining healthy populations of the species of interest within the study area.

The framework includes multiple interlocking elements but is primarily composed of general population monitoring and experimental manipulation monitoring (directed studies). Elements of those portions of directed studies called for in the MSHMP that were publicly available are reviewed below.

The following sources of information were used in this review:

- Expert Interviews
- Scientific/Technical Literature
- SOD Regulatory Documents – Proposed Methods
- For each of the proposed manipulation techniques, the following topics were examined:
- Expected impacts and benefits to the species of interest
- Expected duration of the manipulation within the study area
- Cost of the manipulation

6.1.1 Expert Interviews – Past Disturbance Events

ICF interviewed recognized experts on the species of interest to document unpublished habitat requirement information and anecdotal observations of habitat disturbance and species response within and around the WSPA. Experts were selected because of their participation in the HFS as part of the science advisory panel (Phil Brylski and Debra Shier), or because of general recognition of their expertise with SBKR (Steve Montgomery). Phil Brylski and Steve Montgomery are small mammal biologists with extensive multi-decadal experience with SBKR and the study area. Debra Shier has nearly 25 years of experience studying heteromyids and has been conducting research on SBKR since 2012. She is associate director of Recovery Ecology at the San Diego Zoo Institute for Conservation Research and a direct contributor to the HFS effort with her research group's work on modelling landscape and micro- habitat drivers of SBKR occupancy.

As part of evaluating treatment techniques, experts were interviewed to record their accounts of past disturbance events within the study area and any observable effects on the species of interest. A review of prior disturbance events, both intentional and unintentional, may provide insight into species responses to formal habitat manipulation efforts.

6.1.2 Area B – Abandoned Industrial Plot

A prior private landholder operated an industrial site on approximately 47 acres of land that is now within the WSPA. The property was abandoned at some point before 1994 and cleared of buildings. The property was adjacent to suitable occupied habitat that remained relatively intact. High densities of SBKR have been observed within the boundaries of the disturbed habitat since the land was vacated. The habitat has now largely returned to pre-disturbance plant cover levels except for the absence of juniper. The current SBKR occupancy of the site is unknown.

6.1.3 Area D – Herbicide Experiment

Implemented by the USACE, this experiment was part of an ongoing effort to control non-native grasses within the study area. The initial experiment was an effort to measure the potential beneficial effects of herbicide application to SBKR. A moderate-scale experiment was initiated in Area D of the WSPA in October 2009 to test SBKR response to non-native grass control using Fusilade®. The treatment site was 3 acres and included a corridor (100 ft wide, 200 ft long) leading away from the site towards a historical floodpath with adjacent habitat with greater suitability for SBKR (USACE 2012). The experimental design included site preparation to cut non-native grasses, removal of dried thatch, and two applications (in February and March of 2010) of a grass-specific herbicide (Fusilade®) after sufficient precipitation to stimulate grass seed germination. Prior to treatment, the herbaceous layer was dominated by non-native annual grasses, ranging from 43 to 74 percent; grasses included red and rip-gut bromes (*B. madritensis* ssp. *rubens* and *B. diandrus*) and cheatgrass (*B. tectorum*). After treatment, annual grass cover was reduced to 24 percent, most of which was rattail fescue *(Vulpia myuros).* Initial response by SBKR to the experiment successfully showed an increase of SBKR within the treatment area. Small mammal trapping was conducted prior to treatment and again in September 2010 to document short-term response of SBKR to the treatment. While no SBKR were captured during two separate trapping bouts in 2007 and 2009 prior to treatment with fusillade, 4 SBKR were captured within approximately 1 year following the treatment (SJM Biological Consultants 2008, 2009 in USACE 2012.).

6.1.4 Area E – Burn Area

In 2013, a fire burned the mature RAFSS plant community east of Opal Avenue. The fire burned approximately 54 acres before being extinguished. SBKR trapping in the area prior to the burn had shown either zero or very low-density occupancy. SBKR were detected in high numbers for an undescribed period of time post-burn. The plant cover in the area does not appear to have fully recovered from the burn at 6 years post burn. The current SBKR occupancy of the site is unknown (P. Brylski pers com.)

6.1.5 Area E – Cleared Area

In 2007, a portion of the mature RAFSS plant community immediately adjacent to Opal Avenue was cleared by blading with earth moving equipment. Prior to disturbance, few if any SBKR were observed in that location. Following disturbance, greater numbers of SBKR were observed. The area appears to have since recovered to pre-disturbance plant cover values. The time that elapsed following disturbance before the plant community recovered to pre-disturbance values was approximately 10 years. The current SBKR occupancy of the site is unknown (P. Brylski pers com.).

6.1.6 Scientific and Grey Literature Document Review

ICF reviewed published studies to evaluate potential treatment methods including: mechanical clearing of vegetation, deposition of clean sand, sediment removal, and weed abatement. ICF selected studies to review based on their relevance to the WSPA location, habitat types, proposed actions, and target species. The first study measured the response of exotic grasses and woolly star to various habitat manipulations (Hernandez and Sandquist 2019). The second study was produced for the High Flow Study effort and included landscape and microhabitat suitability models for SBKR (Shier et al. 2019).

Long-term alluvial sage scrub (LOTUS) Experimental Site – Hernandez and Sandquist conducted an experiment to determine the effects of six vegetation and substrate treatment methods on the rare woolly star plant within the upper Santa Ana river floodplain below Seven Oaks Dam over a 13-year period (2019). They implemented treatments on seven 4 x 7-meter plots for each treatment method. These plots, along with control plots were monitored prior to any treatment. Half of each plot was re-treated after 5 years, and monitoring was completed on all areas after 7.5 and 13 years, providing data for 5 (in the re-treated areas), 7.5, and 13 years post treatment. Monitoring included quantifying percent cover (living and dead) of all plant species along transects, plant abundance and maturity of woolly star and hairy yerba santa (*Eriodictyon trichocalyx*). The results show that all treatments increased cover of woolly star and decreased cover of annual grasses when compared to the control site, however, the cut treatment and fill with 10 cm of clean sand treatment (as discussed above) provided the largest response.

SBKR Habitat Suitability Modeling – The San Diego Zoo Institute for Conservation Research assessed SBKR microhabitat use throughout the species current range, landscape, and climate features associated with SBKR occurrence to evaluate the vegetation, soil, and climate factors that affect SBKR distribution and specific habitat features associated with patch usage within areas of suitable habitat (Shier et al. 2019). These data were analyzed to develop a landscape level model including slope and elevation, annual precipitation, January minimum temperature, August maximum temperature, percent clay, fluvent soils, NDVI, alluvial scrub cover, and human development as variables influencing the likelihood of occupied habitat. Presence of alluvial scrub cover and fluvent soils are most strongly correlated with SBKR occurrence.

The microhabitat model shows a strong positive relationship between SBKR occurrence and percent sand or bare ground, low shrub cover, low to medium grass cover, and presence of cactus mouse (*Peromyscus eremicus*); and a strong negative correlation with low sand and high silt content in the soil. The model also shows trends toward a positive relationship with gravel and negative relationship with presence of duff.

6.1.7 MSHMP - Proposed Methods and Potential for Success

ICF explored the effectiveness and feasibility of mechanical manipulations of the floodplain by reviewing and evaluating the proposed non-fluvial habitat management options described in the Final Biological Assessment, Seven Oaks Dam Santa Ana River Mainstem Project (BA) (USACE 2000); Section 7 Consultation for Operations of Seven Oaks Dam (1-6-02-F-1000.10) (BO) (USFWS 2002); and Santa Ana River Woolly Star Preserve Area, San Bernardino, California Final Multi-Species Habitat Management Plan (MSHMP) (USACE 2012).

Non-fluvial habitat renewal treatment consists of manipulation of primary habitat elements (vegetation and substrate) to mimic natural flood disturbance. Vegetation manipulation ranges from herbicide application focused on control or elimination of non-native grasses to total denuding of vegetation by either mechanical scraping or through controlled burns. Substrate manipulation consists of either depositing or removing material from the soil surface. Because of research indicating a strong positive association with habitat quality for two of the target species, clean sand is the only soil type currently proposed and tested for use in deposition manipulations.

Removal of material is also proposed as a possible treatment if suitable material (clean sand) is known to be present below the existing soil horizon.

6.1.7.1 Vegetation Manipulation Methods

Non-Native Invasive Grass Control (Herbicides): A grass-specific herbicide (e.g., Fusilade) is recommended to limit the effects of treatment to the target vegetation. Herbicide application would need to be combined with removal of thatch to maximize the benefit of the treatment by increasing bare ground and removing the mechanical barrier for SBKR and allowing space for the plant species to grow. The effect of this treatment is likely to mimic that of the clearing treatment tested by Hernandez and Sandquist (2019).

Likelihood of Success: Herbicide use and removal of thatch has the potential to benefit all species to some degree by decreasing exotic grass cover. Duration is expected to be short-term (estimated at 1-2 growing seasons) as this method will not reduce the seed bank for exotic grasses. Cost is relatively low and would include: herbicide, application by backpack sprayer, and removal and disposal of dead plant material.

Mechanical Vegetation Removal: Small earth-moving equipment (e.g., bulldozer, bobcat) or hand tools may be used to remove vegetation cover to levels consistent with the San Diego Zoo Institute for Conservation Research SBKR habitat suitability model. Consideration also should be given to relative cover proportions of perennial species based on SBKR habitat associations and relevant literature. Recent experimental plots comparing the efficacy of various surface and soil treatments in improving habitat for woolly star show that vegetation clearing without soil removal resulted in lower percent cover of woolly star and higher percent cover of exotic annual grasses than treatments that included soil disturbance when sampled at 7.5, 13 (with re-disturbance at 5 years), and 13 years from the disturbance (Hernandez and Sandquist 2019). Vegetation clearing did show improved cover of woolly star over untreated control plots.

Likelihood of Success: This treatment option was shown to be successful for woolly star but is unlikely to provide similar benefits to SBKR or spineflower because of the treatment's interaction with exotic grasses. Cover by exotic grasses was approximately the same as or showed an increase from control areas in the 5- and 7.5-year post disturbance monitoring, indicating that this treatment would not benefit SBKR. Spineflower prefers mature stage RAFSS with the presence of fine sediments and juniper, so mechanical disruption that could damage the juniper would likely be detrimental to this species. Increased cover of woolly star compared to untreated areas persisted for up to 13 years. Costs for this treatment method would be moderate and would include: bobcat/bulldozer equipment costs (including transport and access to the site), Lake and Streambed Alteration Agreement (LSAA) permitting and costs for vegetation removal.

Fire: Prescribed burns may be used to reduce vegetation and thatch within areas that have higher than optimal cover of perennial and annual vegetative cover to mimic historic natural habitat disturbances. Southern California shrublands, including Riverside alluvial fan sage scrub (RAFSS) have historically experienced wildfires. Prior to human habitation, fires were the result of lightning strikes in higher elevations. While most fires occurred in the spring months, these fires tended to be smaller with fewer larger fires occurring in the autumn (Keeley 2001). Fires in coastal sage scrub, including RAFSS types, are stand-replacing fires. Historic fire return intervals are estimated at around 70 years closer to the mountain ranges (Keeley and Fotheringham 2001). The San Bernardino Mountains experienced approximately 10,000 hectares of burns each year.

Fire in coastal sage scrub results in an increase in the species richness and cover of native forbs, an increase in cover of native grasses, decreased species richness and decrease in cover of invasive grasses, increase in richness but decrease in cover of invasive forbs, and a decrease in species richness and cover of native shrubs (Conlisk et al 2016). Wildfires in the Agua Tibia Wilderness/Vail Lake area resulted in a dramatic increase in the number of slender-horned spineflower (*Dodecahema leptoceras*) immediately following the burns (USFWS 2010). In addition to showing immediate benefits to native grasses and forbs, including one target species in the MSHMP, seed abundance increased following fire and included more seeds from native plants. This has the potential to benefit SBKR immediately following a fire by opening the canopy, removing thatch, and increasing seed availability (Conlisk et al 2016). The long-term response of slender-horned spineflower and other native species to fire is unclear and largely undocumented, however it can be assumed that these benefits would diminish over time as other environmental factors continue to influence the area. Woolly star show diminished germination after fire events (USACE 2012).

While fire provides an immediate benefit to native grasses and forbs and is required for seedling recruitment of many species of Ceanothus and Arctostaphylos (Keeley 1998), an increase in fire return intervals can lead to type conversion, generally to grasslands dominated by non-native grasses and forbs (Keeley 2005) which would result in degradation of the habitat for all the species of interest. Fires return intervals of less than 3-5 years are expected to interrupt the ability of native shrub species from reseeding and lead to type conversion to grasslands (Keeley 2005). Conversion from a shrub dominated habitat to grasslands would be detrimental to all target species since they require the more open canopy found in RAFSS and show negative interactions with an abundance of exotic grasses (Debra Shier pers com. 2019, Hernandez and Sandquist 2019, USFWS 2010).

Likelihood of success: Fire has the potential to benefit habitat condition for SBKR by reducing total cover and exotic grass cover, while increasing native forb and grass cover in the first years following a fire. Fire is unlikely to benefit either woolly star or spineflower. Woolly star has shown decreased germination after fire (USACE 2012), which has the potential to reduce populations. Junipers do not respond positively to fire (Keeley and Fotheringham 2001), thus any treatment that would likely damage junipers is unlikely to benefit spineflower. There are no direct studies showing the expected longevity of any benefits from fire in RAFSS, however increases in native grass and forb cover and reduction in exotic grass cover was shown to last for two to five years following burns (Conlisk et al. 2016). It is unclear how long these responses would persist outside of that period. Costs of implementing this treatment method are uncertain, primarily because of external logistical challenges. Costs would include: development of a burn plan, burn permits, implementation of a controlled burn by fire-fighters, and access to the site for fire safety vehicles. This treatment method would also have additional constraints since the public in fire prone areas tends to be averse to prescribed burns due to fears of uncontrolled fire escapement.

6.1.7.2 Substrate Manipulation Methods

Soil Removal. Removal of aboveground vegetation and the top 10-20 cm of soil would mimic floodplain scour and was examined at the LOTUS site in the upper Santa Ana River floodplain (Hernandez and Sandquist 2019). Removal of 20 cm would remove the physical and biological soil crust, litter, micro-organics, silts, clays and most seeds, leaving the underlying substrate exposed. The Hernandez and Sandquist study showed that this method resulted in the highest cover of woolly star both 5 and 7.5 years after treatment. There was no statistical difference in results between the treatment methods at the 13-year monitoring point. Cut treatment areas also showed the lowest cover of exotic grasses both 5 and 7.5 years after treatment, with no significant difference between the treatments at the 13-year monitoring point. (Hernandez and Sandquist 2019).

Likelihood of Success: While there are no studies available quantifying the impacts of this treatment on SBKR, the reduction in fine sediment and exotic grasses would likely improve the quality of habitat for SBKR in the treatment area based on the microhabitat preferences of SBKR documented in Shier et al. (2019). This treatment is likely to benefit both woolly star and SBKR by reducing both exotic grasses and fine sediments. It is unlikely to benefit and would likely be detrimental to spineflower if implemented in areas of mature seral stage RAFSS. Beneficial effects are expected to persist beyond 13 years (Hernandez and Sandquist 2019). Costs of implementing this treatment method would be moderate to high and would include heavy equipment costs (including transport and access to the site), soil disposal costs, and permitting costs. Implementation of this treatment method would require an LSAA. Implementation of this treatment method within the boundary of waters of the United States or waters of the state would also require Clean Water Act (CWA) section 401 and 404 permitting and permitting under the Porter-Cologne Water Quality Control Act Dredge and Fill Procedures. Mitigation may be required for impacts to waters of the US or waters of the state.

Sand Deposition: Deposition of sand would mimic deposition resulting from flood flows. Hernandez and Sandquist (2019) implemented treatments of 10 cm, 20 cm, and 30 cm of clean sand in the upper Santa Ana River watershed. They found that deposition treatments had significantly less cover of woolly star at 5 years post disturbance, however at 7.5 years 10 cm and 20 cm of deposition had similar cover to the cut treatment, which showed the highest amount of cover.

Treatment areas with 10 cm of fill had lower cover of exotic grasses at both 5 and 7.5 years after treatment, with the 20 cm plots having similarly low coverage at 7.5 years after treatment. Plots with 30 cm of fill did not show similar beneficial results as 10 cm and 20 cm of fill, however they provided greater benefits to woolly star habitat than untreated areas, and those areas that were left untreated or only had surface vegetation removed.

Likelihood of Success: As with the cut treatment, sand deposition would likely improve the habitat within the treatment areas for SBKR by reducing fine sediment and exotic grass cover. Beneficial effects are expected to persist beyond 13 years (Hernandez and Sandquist 2019). Costs of implementing this treatment method would be moderate to high and would include heavy equipment costs (including transport and access to the site), clean sand and transport, and permitting costs. Implementation of this treatment method would require an LSAA. Implementation of this treatment method within the boundary of waters of the United States or waters of the state would also require Clean Water Act (CWA) section 401 and 404 permitting and permitting under the Porter-Cologne Water Quality Control Act Dredge and Fill Procedures. Mitigation may be required for impacts to waters of the US or waters of the state.

Hydraulic Sediment Spreading: As a supplemental manipulation technique, water could be used to spread clean washed sand through a habitat manipulation site. Water would be sourced from some nearby or available source other than SOD. Sand deposited at the edges of existing channel paths, followed by hydraulic spreading may more closely approximate flood processes associated with "washing" substrate (e.g., flush excess organics from sandy sediments) and sand deposition.

Likelihood of Success: Hydraulic spreading has not yet been assessed and there is no data to support the potential benefits or drawbacks of the technique. Use of water would likely result in a more natural appearance, would wash the substrate being deployed, and would provide additional water which is often a limiting factor for plants in the region. But hydraulic spreading would also come with attendant risks to SBKR and other animal species that may potentially occupy manipulation sites. Cost of implementing this treatment method would be moderate to high and would likely be limited to sites that were accessible by road.

6.2 Scale of Manipulation

The MSHMP objectives tie success of the plan to baseline conditions observed at the start of operations for SOD. Baseline conditions were proposed to be collected and then periodically examined to determine whether current values are within 10% of historic values. When current values for acreage of specific habitat types, or population densities or PAOs drop below the threshold, specific activities are called for in the MSHMP, including additional monitoring and implementation of habitat manipulation to create new habitat. This framework differentiates habitat manipulation into two types, with experimental habitat manipulation proceeding initially, and renewal manipulation proceeding only after experimental habitat manipulation has proven the effectiveness of the manipulation technique.

6.2.1 Scale of Experimental Manipulation

As stated in the MSHMP, the size of experimental treatments should be the smallest appropriate size with which to measure the effect of the treatment. For the species of interest, the scale varies by species.

For woolly star, experimental treatments at the sub-hectare scale (28 square meter experimental plots) yielded measurable results (Hernandez and Sandquist 2019). The MSHMP recommends that experimental manipulation focusing on woolly star be coordinated with SBKR habitat manipulation experiments. As detailed in the SBKR recommendations, these scales are larger than the treatment sizes for woolly star alone.

For SBKR, experimental treatments are proposed on the scale of 2.5 to 3 acres. The MSHMP states the following…

> *Experiments should be of sufficient size to accommodate large trapping-grid configurations sufficient for obtaining a robust measure of abundance and minimizing edge effects. Results from the 2005 pilot trapping study and 2006-2009 Reference surveys indicate that large trapping grids of 225 traps within a 2.47-acre (1 hectare) area provide reliable abundance estimates (USFWS 2006, 2010). Therefore, experiments should be a minimum of 2.5 to 3 acres (1 to 1.2 hectares) to accommodate large trapping grids and minimize edge effects.*

For spineflower, experimental treatments at the sub-hectare scale (2-3 square meters per individual plot) are recommended by the MSHMP. It is likely that ongoing work to determine effective strategies for promoting spineflower on the WSPA is taking place, but documentation was not available to ICF at the time of publication.

6.2.2 Scale of Habitat Renewal Manipulation

Once specific restoration treatments have been vetted and deemed appropriate, USFWS specifies in the 2002 BO that the target treatment size is 10-20 acres every 5-10 years. This would result in a total of 200 acres of habitat being manipulated over the course of the 100-year life of the project.

Although not specified by the 2002 BO, it is assumed that treatment acreage will not overlap between periods.

6.3 Summary of Non-Fluvial Mechanical Disturbance Methods

Expert accounts of past disturbance indicate SBKR are disturbance oriented and likely to respond positively to a variety of disturbance techniques. The consensus among the experts when discussing disturbance was that disturbed habitats must be near intact occupied habitat for colonization to take place. Furthermore, the experts expressed a consensus opinion that experimental and habitat scale manipulations should have some non-rectangular shape and be strongly interconnected with other disturbed areas and with occupied habitat.

Successful habitat manipulation benefitting SBKR and woolly star is likely to include modification of soil texture. Manipulations that result in the presentation of clean washed sand at depths of 10 cm or greater are likely to result in benefits for SBKR and woolly star habitat. If soils are already appropriate, then it may be possible to restrict manipulation to clearing or reducing vegetative cover and controlling exotic grasses. SBKR are likely to be reliant on habitat corridors for invasion of manipulated areas. Larger manipulations that include seeding with woolly star could result in benefits for both species. Restoration and habitat manipulation of spineflower will need to be done separately and on a smaller scale, once experimental manipulation studies for the species are complete.

Despite similar reliance on flood disturbance for regenerating their habitat, the three species differ in their habitat requirements. Because of their reliance on pioneer and intermediate successional stage RAFSS surfaces, woolly star and SBKR may be able to be managed simultaneously. Management actions that promote regeneration of RAFSS surfaces into pioneer and intermediate phases may ultimately benefit spineflower, but may potentially require decades to transition into the mature and juniper phase stands associated with typical spineflower habitat.

Implementation of the mechanical disturbance techniques described should take place within an adaptive management framework like that described in the MSHMP. Degraded habitat with low or no occupancy by the species of interest, or other special status species should be selected for manipulation over less degraded habitat. Implementation will require monitoring of the manipulated area to ensure that habitat targets are met and to record the duration of the action.

Predictions made at smaller experimental scales may diverge from observations once manipulation is applied at larger scales.

Chapter 7
Evaluation of Treatment Trade-offs and Prioritization of Species of Interest

Treatments for the purposes of habitat renewal must be evaluated to assess the tradeoffs between potential benefits and impacts prior to implementation. The type, size, and timing of both fluvial and non-fluvial treatments will have different impacts and benefits on SBKR, spineflower, and woolly star. The goal of any habitat manipulation as stated in the MSHMP is to maintain the species of interest within the study area through the 100-year life of the project. A framework for initiating habitat manipulation in the study area was previously developed and presented in the MSHMP. This framework sets specific thresholds based on monitoring of baseline conditions for the species of interest within the WSPA which are presented and reviewed in this document.

The strategy described in the MSHMP begins with habitat and species-specific monitoring to establish baseline values for the species of interest. Following the establishment of baseline values, trend monitoring is to be implemented to ensure that habitat and population values are stable within a margin (listed generally as 10% for population values, and as an acreage target for habitat values). Alongside the MSHMP general monitoring effort, experiments to vet various non-fluvial manipulations are proposed. At the 15-year mark after start (2002 – 2017), non-fluvial habitat manipulation techniques are expected to have been vetted and be available as treatment options, should treatment be triggered by negative fluctuation in population or habitat monitoring results.

The scale of any proposed habitat manipulation will need to be carefully selected because of the high probability of impacting multiple special status species during implementation. USFWS and CDFW have provided guidance with regards to prioritizing the species of interest when considering habitat manipulation, and that guidance is presented in this document. Additionally, the duration of any effects on species and habitats resulting from manipulation must be considered alongside potential impacts to evaluate effectiveness. Alongside the MSHMP thresholds and targets aimed at maintaining the species of interest, USFWS has proposed specific acreage amounts that should be disturbed for the purposes of maintaining early and intermediate stage RAFSS surfaces within the study area, and this target will need to be considered as well.

ICF reviewed the microhabitat suitability model for SBKR (Shier, Chock, and McCullough-Hennessy 2019), as well as available occurrence and scientific data on habitat suitability for SBKR, spineflower and woolly star to identify common features of appropriate habitat and propose target values for evaluating habitat manipulation.

7.1 Adaptive Management Thresholds for Initiating Habitat Manipulation

Any active manipulation of habitat in the study area should be embedded in a decision framework that guides the degree and extent of manipulation. The MSHMP lays out both an overarching goal, supporting goals, and a decision tree framework for evaluating when habitat manipulation should take place. The stated goal of the MSHMP is:

Coordinate and manage WSPA lands to sustain Santa Ana River woolly star, slender-horned spineflower, and San Bernardino kangaroo rat populations and their habitats during the 100-year life of the SARP.

- To fulfil the stated goal, the following supporting objectives are defined in the MSHMP.

BO Conservation Measure 1: Evaluate (further) the impacts from Seven Oaks Dam operation

1. *Establish Baseline conditions and understanding of covered species' biology and habitat processes for the WSPA*
2. *Implement long-term monitoring of covered species' populations and habitats for the WSPA*
3. *Plan and implement directed studies to address priority data gaps associated with the Decision Framework*

BO Conservation Measure 2: Test and select appropriate management actions

1. *Define covered species' habitat associations and experimental designs*
2. *Conduct and evaluate experimental management treatments*
3. *Select appropriate management options and approaches for the WSPA*

BO Conservation Measure 3: Implement management actions within the WSPA and other historic floodplain areas within the local sponsors' jurisdiction to sustain covered species*

1. *Define and implement administrative MSHMP procedures for the WSPA*
2. *Develop MSHMP goals, objectives, and implementation process to achieve the outcomes dictated in the 2002 and 1989 Biological Opinions*
3. *Implement the Decision Framework to objectively review effectiveness of management and monitoring plans within the WSPA*
4. *Implement adaptive habitat management (over 100-year project life) using all previously collected information to develop management prescriptions for the WSPA*
5. *Implement public outreach and stakeholder coordination to enhance success of management activities for covered species within the WSPA and expand successful management strategies beyond WSPA, if authorized and funded by others*
6. *Manage data to facilitate information exchange and transfer in support of WSPA management decisions*

The MSHMP focuses on the species of interest (woolly star, spineflower, SBKR) and more generally on their habitat associations. Plan elements and decision trees address each separately, but they are integrated within a larger adaptive management approach as illustrated in Figure 7-1. The program elements are complex and interlocking, with successive elements being contingent on implementation of preceding elements.

Within the framework of the MSHMP adaptive management program, it appears that USACE is currently at the third box in the diagram in Figure 7-1 (Conduct habitat manipulation experiments) but may not have completed those objectives. It is assumed that the first and second objectives (establishing baseline conditions and filling critical data gaps) are already completed. However, information documenting the results of either the baseline conditions effort or the critical data gaps effort was not available to ICF during the Phase 2 report period. Information regarding baseline conditions for the species of interest and general habitat will be critical in making informed decisions regarding implementation of any proposed habitat manipulation.

7.1.1 Species Thresholds for Implementing Habitat Manipulation

7.1.1.1 Woolly Star

For woolly star, the manipulation threshold in the MSHMP is given as two elements and is as follows:

> *Determine if woolly star demography metrics (growth rates) are consistent with Baseline (≥1) or whether management/monitoring plans and schedules should be altered*
>
> *Determine if early-intermediate RAFSS acreage is ≥ 385 acres within the WSPA or whether management/monitoring plans and schedules should be altered*

Population growth rates for each known site within the study are to be estimated using a software suite (RAMAS/STAGE Ecological & Environmental Software) designed to assess the vulnerability of the species. These annual measures are to be compared against 11 years (1997-2008) of demographic data to evaluate the annual population growth rate for woolly star. If ANOVA testing indicates a significant negative difference between annual monitoring and baseline measures, then the manipulation threshold is met.

Recent population growth rates are currently unavailable, but in a report completed by Psomas and California State University Fullerton (2004), growth rates of all known populations from 1996 to 2003 were generally negative and declining from previous years. Figure 7-2 shows that following this precipitous decline, populations rebounded, apparently in correlation with increased rainfall in following years. Additional reports on the status of woolly star in the study area have been produced but are not available to ICF at the time this review took place. Based on the large fluctuations in population numbers from year to year evident in the 1996 to 2011 period, it may be challenging to set an appropriate baseline with which to compare against future monitoring data.

Because woolly star populations are highly dependent on annual rainfall, demographic metrics may be affected by fluctuation in precipitation (Figure 7-2). The large fluctuations in woolly star population density and assumed dependence on rainfall highlight a potential problem with tying habitat manipulation actions to population metrics. Manipulation interventions may not alter population trajectories if those trajectories are primarily influenced by climate and not by habitat. An additional risk, even during optimal rainfall and climate conditions, is succession of flood surfaces within the study area out of the RAFSS successional stages and into other degraded community types due to ongoing human disturbance and climatic shifts.

The MSHMP also links initiation of habitat manipulation with the combined surface area of early and intermediate stage RAFSS communities within the study area. The preservation of 385 acres of suitable habitat (defined as early and intermediate RAFSS surfaces) has been identified by previous work as being necessary to support a minimum viable population of woolly star. A 2009 re-survey of fluvial surfaces within the study area found that 549.4 acres of the 782.9 acres within the WSPA boundaries was composed of the early and intermediate RAFSS that woolly star is dependent on.

The survey found that 458.2 acres of this was early stage, with the remaining 91.2 being intermediate. If there is no significant degradation of the RAFSS communities on these surfaces (through human disturbance, wind-borne sediment deposition, or invasion by non-native grasses), it is likely that this implementation threshold for woolly star will not be met in the foreseeable future (30+ years).

7.1.1.2 Spineflower

For spineflower, the manipulation threshold is given as a single element and is as follows:

Determine if spineflower population metrics (patch numbers) are consistent with Baseline or whether management/monitoring plans and schedules should be altered

In the same manner as woolly star, spineflower population metrics appear to be dependent on rainfall patterns (Figure 7-3). Data presented in the 2012 MSHMP and 2014 general overview indicate that patch size and population density are variable, but dependent on late winter rainfall, once early winter rainfall germination requirements are met. As for woolly star, the dependence by spineflower on environmental conditions (rainfall) may make it difficult to set appropriate baseline conditions to compare future population survey results against.

7.1.1.3 San Bernardino Kangaroo Rat

For SBKR, the manipulation threshold is given as a single element and is as follows:

Determine if SBKR occupancy metrics are consistent with Baseline or whether management/monitoring plans and schedules should be altered

SBKR occupancy metrics are tied to proportion of area occupied (PAO) within the WSPA. Results from the years 2006 to 2011 indicate no clear trend in occupancy patterns among the subarea units (A-F) (Figure 7-4). Additionally, no specific thresholds for PAO values are given in either the 2012 MSHMP or the 2014 overview, but it is assumed that if annual surveys detect PAO values below a baseline established earlier, it would trigger habitat manipulation.

In a similar fashion to the plant species of interest, SBKR population values are expected to be dependent on annual rainfall. SBKR are granivorous that use both pit caches and larders to store seeds and may be able to survive a single low-rainfall season by exploiting seed caches (Randall 1993, USACE 2012), but prolonged drought conditions are expected to have significant impacts to population density. Habitat manipulation actions triggered by low PAO values in comparison with the baseline are unlikely to result in benefits to SBKR until subsequent shifts into non-drought conditions occur.

7.1.1.4 Habitat

For habitat, the manipulation threshold is given as a single element and is as follows:

Determine if composition of habitat types within the WSPA is consistent with Baseline or whether management/monitoring plans and schedules should be altered

Habitat manipulation thresholds are contingent on thresholds for the species of interest. If species thresholds are met separately from habitat composition thresholds described above, then manipulation is triggered. ICF assumes that baseline habitat values are those given in Table 7-1 (in the 2012 MSHMP and reproduced below as Table 3).

In their discussion of floodplain vegetation and soil types along the uppers Santa Ana river, Burk et al. states that the basic categories of RAFSS successional stage described in Table 7-1 do not adequately represent the complex mosaic of habitat present within the study area (2007). Tying manipulation thresholds to these coarser surface area evaluations may result in under-representation of the availability of specific habitat types.

It is generally assumed that habitats will continue to transition through the RAFSS habitat types in a manner similar to how succession has taken place in the study area previously. There is however the possibility that newly or recently disturbed habitat types may transition into other plant communities based on fluctuating climatic conditions and increased wind born dust and nitrogen deposition.

7.1.2 Status of habitat manipulation experiments

Within the various objectives outlined in the MSHMP, the most relevant in relation to this portion of the High Flow Study are BO conservation measure 1.1 (establishment of baseline conditions for the species of interest) and BO conservation measure 2.5 (evaluation of experimental management treatments). At the time of drafting this document (June 2019) ICF is not aware of any published documents demonstrating the accomplishment of these objectives pertaining to measure 1.1 other than a 2014 presentation by USACE and an independent scientific publication documenting the results of habitat manipulation for woolly star. The presentation states that experimental treatments and monitoring for the species of interest were in progress, with some experiments having been implemented and additional work was planned (USACE 2014).

Small- and large-scale woolly star seeding and monitoring experiments are indicated as being implemented in the 2014 USACE presentation, of which the small-scale experiments have been corroborated by a recent publication documenting the results (Hernandez and Sandquist 2019). Larger scale (2.5-3 acres) experiments aimed at SBKR but limited to the application of herbicide have also been indicated has having been implemented. This is assumed to be the Area D herbicide experiment that took place in 2009 as detailed in Task 6 under the expert account by Steve Montgomery and also described in the 2012 MSHMP. However, other treatments, such as vegetation removal, sand deposition, and water releases were marked as being in the planning stage in 2014.

Small-scale habitat manipulations aimed at spineflower are marked as being implemented, but ICF does not have any independent documentation of the scale or results of these experiments.

7.1.3 Critical Features of Appropriate Habitat

Although there are missing elements (status of baselines for the three species and supporting habitat), there is a consensus picture of which habitat types already present within the study area are most important for the species of interest. As expected, these elements are strongly associated with the flood disturbance that drives habitat succession. There are well-documented associations between the target species and more recently disturbed flood surfaces (Burk et al. 2007, Phase 1 Report).

Spineflower have slightly different habitat associations and ultimately will need to be considered separately. As stated in the 5-year review for the species published by USFWS (2010), plants are found in alluvial fan scrub on benches and terraces in areas receiving little surface disturbance from flooding (Boyd et al. 1989; Rey-Vizgirdas 1994; Wood and Wells 1997 in USFWS 2010). The species is associated with older alluvial benches and terraces and infrequent flood events are needed to maintain suitable habitat conditions. But unlike woolly star and SBKR, spineflower appear to require more mature and/or juniper phase RAFSS and potentially cryptogrammic soil crusts to persist.

Because of the association of spineflower with slightly older RAFSS surfaces (intermediate to mature), there may not be a single common feature of appropriate habitat that is shared by all three species of interest. There is however strong overlap between the habitat characteristics for SBKR and woolly star. Both species are associated with pioneer and intermediate RAFSS surfaces within the study area (ICF 2019). Presence of both species is also negatively correlated to the presence and density of non-native grasses (USACE 2012). Non-native grasses have a strong positive association with increased organic and fines fractions in the substrate. Both associations are likely to be highly correlated, with invasion by non-native grasses being the driver of negative habitat effects on both SBKR and woolly star, and with grass invasion being promoted by wind-born dust deposition.

The main source of habitat type conversion or negative effect on habitat quality within habitat types is the presence of non-native grasses. Habitat manipulations that result in reduced NNG cover will likely benefit SBKR and woolly star. However, it is uncertain whether non-fluvial manipulations that reset surfaces to early RAFSS stages favoring SBKR and woolly star will ultimately age into the intermediate and mature RAFSS communities favored by spineflower.

7.1.4 Evaluation of Habitat Manipulation Methods

7.1.4.1 Woolly Star

Evaluation of habitat manipulation for woolly star is complete. An analysis of soil geomorphic treatments has indicated that habitat manipulation facilitated recruitment of woolly star (Hernandez and Sandquist 2019). Long-term experimental plots (LOTUS) were initially set up in 1999 on mature alluvial sage scrub habitat within the WSPA last disturbed during the 1867 flood event. Treatments included vegetation clearing, diking (discing), cutting and removing the top 20 cm of topsoil, and filling with 10, 20, or 30 cm of clean sand (F10, F20, F30). The sand used in the experiment ranged in size from 0.5 to 2.0 mm and was washed prior to being used. Plots were revisited in 2006, 7.5 years after the initial disturbance. Once the 7.5-year sampling took place, a subset of plots were re-disturbed and then re-sampled in 2012, 13.5 years after the initial disturbance.

Among treatments, the cut, F10 and F20 plots showed significant increases in woolly star cover compared to both control and other treatment types at 7.5 years post disturbance. This trend continued in the 5-year re-disturbed plots, with the cut treatment having significantly more woolly star cover than all other treatments and the control. At 13.5 years post disturbance, the F10 plots had the highest woolly star coverage, but there were no significant differences in cover among treatments, indicating that at least with respect to woolly star, treatment effects can be expected to persist for a decade or more. Across all plots and treatments, the control and dike plots consistently showed the lowest values of woolly star coverage.

The analysis also measured the response of exotic grasses to the various treatments. In the 7.5-year plots, annuals were most abundant in the clear and dike plots. The cut, F10 and F20 plots had the lowest cover values for annual grasses. In the 5-year re-disturbed plots, there were significant differences between the highest cover (clear) and lowest cover (cut), but not amongst any other treatment types. At 13.5 years post disturbance, there were no significant differences in cover among treatments. This provides additional support for the observation that treatment effects can be expected to persist for a decade or more.

Hernandez and Sandquist draw the conclusion that alteration of the physiochemical properties of the soil will be critical to the success of any future habitat manipulation aimed at increasing the density or distribution of woolly star. Supporting their observation, Thomey found that nitrogen in the LOTUS sand deposition plots was significantly lower than in control plots (2003). Other work also indicates that reduced soil nutrient and moisture levels were correlated with optimal habitat for woolly star (Lucas et al. 2016; Burk et al. 2007).

7.1.4.2 Spineflower

Evaluation of habitat manipulation for Spineflower is not complete, or results have not been published. This element is missing and represents a significant hurdle to addressing probable outcomes associated with habitat manipulation.

7.1.4.3 SBKR

Evaluation of habitat manipulation for SBKR is not complete, or results have not been published. This element is missing and represents a significant hurdle to addressing probable outcomes associated with habitat manipulation. In place of formal evaluation of habitat manipulation, ICF reviewed a body of published and anecdotal evidence indicating potential SBKR response to various habitat manipulation types presented in Chapter 6 as well as results from the San Diego Zoo's effort to model SBKR habitat, which are presented below in Table 7-2. Green and red boxes were significantly different from each other, with the density of SBKR expected to decrease when moving from green to red values. In the table, green values represent optimal conditions for the habitat type in question, and red values represent sub-optimal conditions.

When examined as a single factor in predicting SBKR presence and density, sediment particle size (range from clay to gravel) was not informative. However, sites with SBKR present typically had higher concentrations of sand and lower concentrations of clay and silt. Sites with high densities of SBKR always had sand fractions greater than 80% and clay fractions lower than 7% (Table 7-3).

Taken together, Table 7-2 and Table 7-3 provide guidance regarding habitat values to target during both fluvial and non-fluvial manipulations. Optimal SBKR habitat has low shrub and grass cover, with greater than 60% bare ground, and a large (>80%) sand fraction. The habitat manipulation methods described in Chapter 6, particularly the soil manipulation methods, should be able to reliably achieve these values.

There is an attendant increased risk of take of SBKR associated with fluvial habitat manipulation or with any non-fluvial manipulations with a soil manipulation component. Fluvial manipulation is likely to result in take of SBKR if they are present within the area being flooded. Research on closely related species indicates that heteromyids will typically not abandon burrows during flood events (Thibault and Brown 2004 & Anderson et al. 2000 in USACE 2012). Likewise, SBKR may not abandon their burrows during excavation or soil spreading, which would result in incidental take if they were not trapped out of the area prior to implementation. It is therefore recommended that any proposed habitat manipulations include a pre-disturbance trapping effort to capture and relocate any SBKR that may be present within the treatment area.

7.2 Downstream Effects

One constraint in considering habitat renewal treatments with a fluvial component is the effect on downstream resources. Flood pulses associated with ecological flow releases may propagate downstream for some distance and potentially endanger infrastructure, the public, habitat and sensitive species. Logistical constraints associated with flow releases include public safety and risks to in-channel infrastructure, but there are also conservation constraints associated with sensitive species that inhabit the downstream channel of the Santa Ana River.

The primary species of concern when considering fluvial treatments that may propagate downstream is the Santa Ana sucker (*Catostomus santaanae*). Santa Ana suckers are small bodied benthic fishes adapted to the flashy streams and rivers of the arid southwest (Moyle 2002). Santa Ana suckers may respond positively to flood disturbance within the range of their adaptive capabilities (Richmond et al. 2018), but disturbance outside this range may result in impacts to the species. Flood disturbance outside typical temporal ranges may be particularly deleterious. This is because breeding usually takes place immediately following winter rains and may extend through summer if conditions are optimal (Saiki et al. 2007).

Flow releases from SOD have been observed to carry a high fines/particulate component (H. Dyer pers com.). Deposition of fines and sand within occupied habitat is likely to result in significant degradation of habitat values for sucker (Thompson et al. 2010), and these effects are expected to be magnified during times when eggs, newly hatched larvae, and young-of-year are present. Ecological flow releases from Seven Oaks Dam that take place between March 15 and July 15 and propagate downstream into habitat occupied by sucker may result in burial of eggs and mortality of larvae and young-of-year.

Because of these potential effects, ICF recommends that treatments including a fluvial component capable of propagating into downstream habitat be restricted to the traditional wet season. These recommendations are identical to guidance presented in the MSHMP as well as guidance provided verbally by the resource agencies (USFWS/CDFW), stipulating that water releases within the study area with the possibility of propagating downstream should be restricted to winter wet periods.

Based on this, the appropriate time window for releases should be from November 1 to March 15. Dry season releases are also not advised because of the mismatch between flooding and seasonal biological elements such as seed release, germination, and small mammal activity patterns.

7.3 Species Priority and Summary

Codification of species priorities is taken from the HFS Phase 1 workshop, during which USFWS and CDFW verbally advised the group of what the hierarchy of importance should be with regards to evaluating the effects of manipulation.

1. All known spineflower populations are to be avoided. No habitat manipulation activities should be proposed for locations containing extant populations.
2. Known extant populations of SBKR should be avoided if possible. Relocation of a few individuals is possible, but locations without SBKR should be considered first.
3. Known populations of woolly star should be avoided if possible.

4. Fluvial treatments must consider impacts to downstream species, including Santa Ana sucker.

Species priorities should be adhered to when vetting proposed habitat manipulation sites. Because of their rarity within the study area information and gaps regarding habitat preference, spineflower are to be avoided. Extant populations of SBKR and woolly star should also be avoided, with SBKR taking priority over woolly star. It may be possible to mitigate impacts to SBKR by trapping them out of proposed disturbance areas prior to implementing habitat manipulation (Table 7-4). This prioritization aligns with recommendations made in the Phase 1 report regarding the selection of appropriate habitat manipulation sites. Mature and disturbed RAFSS surfaces with high exotic grass cover will typically match the species priorities provided above, depending on the disturbance type.

The 2012 MSHMP presents a framework for evaluating when to conduct habitat manipulation on behalf of the species of interest. The habitat manipulation thresholds described in the MSHMP are tied to baseline conditions and annual monitoring results for the species of interest and their supporting habitat within the study area. This information is currently unavailable and represents a critical data gap that hinders the current analysis in fully evaluating potential disturbance techniques.

The status of habitat manipulation experiments for the species of interest appear to be incomplete. Woolly star treatments have been vetted and shown to be effective. SBKR treatments are unavailable, but expert observations and recent habitat modeling work indicates that they are likely to respond positively to similar disturbance regimes as those tested for woolly star. SBKR have similar habitat requirements to woolly star and the two species may be able to be managed together. No information is available for spineflower and no recommendations regarding beneficial habitat manipulations can be made. However, it is likely that spineflower will respond poorly to the disturbance techniques proposed for the other two species and must be managed separately.

The critical features of any beneficial habitat manipulation will be reduced exotic grass cover and increased clean sand fraction in the substrate. Manipulations of this type should result in net positive benefits for SBKR and woolly star if conducted in areas where the species can readily colonize the newly manipulated habitat. Because of climatic shifts in weather pattern and ongoing human disturbance of the study area, succession may not continue to progress through the RAFSS community types from pioneer to mature and may become more heavily dominated by invasive non-native grasses at all seral stages. This results in uncertainty regarding whether habitat manipulation will ultimately result in beneficial effects to spineflower.

Downstream effects should be avoided if possible, but if any manipulation with a fluvial component propagates downstream, it must be restricted to time periods when natural flood disturbance is expected within the system. This means that fluvial habitat manipulation will need to be restricted to winter or early spring periods to minimize any potential negative effects to downstream populations of Santa Ana sucker.

Chapter 8
Conclusions

The Phase 1 Report demonstrated there is additional capacity within the current SOD WCM guidelines (USACE 2003) to create or contribute to high-flow events up to approximately 5,000 cfs within the study area (the dam's rated gate outflow capacity is 7,000 cfs), but no flow releases for the purpose of habitat renewal appear to have taken place in the two decades since start of operations at SOD. Furthermore, SOD has not been making high-flow releases that contribute to Mill Creek flows in a manner predicted in the Technical Report for the BA (USACE 200b). Releases have not been synchronized with Mill Creek peak flows to date during the operation of SOD.

The Phase 1 Report demonstrated that the modeled inundation limits without additional enhancement measures (e.g., breaching of berms, bank lowering, construction of flow obstructions) are restricted to the main channel, and no overbank flows into areas of substantial size outside of the Santa Ana River active channel are predicted to produce flood disturbance on a scale large enough to alter successional trends within the study area and therefore satisfy the requirements of the BA/BO and MSHMP. Without human manipulation of the land surface, mature and mature/NNG surfaces cannot be flooded.

A focus of the Phase 2 report is identification of practical measures that could be implemented to renew habitat for the listed species within the major constraints identified in the Phase 1 Report.

This Phase 2 Report reached the following conclusions for the four key study objectives:

8.1 Conditions of Fluvial Disturbance

The science advisory team (Stillwater Sciences and Blue Octal Solutions, LLC) conducted new studies for the Phase 2 study that aided in defining what constitutes the fluvial disturbance needed for desired habitat conditions. The findings of these studies were incorporated by ICF into the new analysis performed for Phase 2.

Stillwater Sciences (2019) examined aerial imagery spanning the period 1970-2016 and quantified:
1) the degree to which SAR lateral erosion into older sediment deposition surfaces occurs; and
2) the extent of vegetation scour under the current high flow regime. A key finding of Stillwater's study is that SAR bank erosion since 1969 along the study reach is rare and that creation of new habitat by lateral migration and channel widening is unlikely to occur because of the coarse texture of the boulder banks.

Blue Octal Solutions (2019) conducted new fieldwork to assess channel substrate sizes in the study area and patterns of erosion and deposition related to February 2019 flooding. The fieldwork results were incorporated into analytical analysis to determine requirements for uprooting of channel vegetation and fresh sand deposition.

Key Findings include:

- Stillwater Sciences and Blue Octal both report that uprooting SAR vegetation and causing scour and fill processes that will sort sediment to create suitable habitat is a key fluvial disturbance overbanking should attempt to provide. Vegetation removal by means of flowing water with high enough levels of drag force to overcome plant root resistance is difficult, and that instead uprooting is most likely achieved through undermining and burying plants through bar migration (Blue Octal 2019). Flood events must create shear stresses high enough to cause bar migration that will remove or bury vegetation. The conditions of fluvial disturbance include shear stress thresholds for migration of sand and cobble bars important for creating fluvial disturbance and removing vegetation (Table 2-1) (Blue Octal 2019). ICF used the reported values provided by Blue Octal (2019) as one of the parameters to evaluate the effectiveness of the three proposed enhancement measures at creating bar migration.

- The altered flood regime and construction of levees that laterally confine sections of the SAR contribute to limit the active channel belt to a relatively narrow zone compared to the pre-alteration condition. When flood events do happen, they tend to inundate the same portions of the channel belt as opposed to outbreaks into much more widespread flood areas, such as the 1969 Channel. Desired fluvial disturbances such as sand deposition, bar migration, and vegetation removal are occurring in the active channel belt under the current flood regime, but the active channel belt is too active. Fluvial disturbance within the active channel belt occurs too frequently for successful colonization by SBKR. Blue Octal (2019) and Stillwater Sciences (2019) suggest that after the desired fluvial disturbance processes occur within a portion of the active channel belt, the recently disturbed area be isolated and protected for a period of 30 years before disturbing again. ICF incorporated the recommendation of isolating recently disturbed areas into the development and evaluation of the enhancement measures.

8.2 Use of Structural Measures to Enhance Habitat

Three enhancement measures were developed for the Phase 2 study (see locations in Figure 3-1). The objective of each enhancement measure is to direct Santa Ana River flow into terrain that is currently infrequently flooded to create new areas of fluvial disturbance with the aim of returning the terrain to earlier seral stages. All three enhancement measures are located downstream of the confluence with Mill Creek to take advantage of Mill Creek flood water and sediment supply in creating fluvial disturbance. The enhancement measures would function by diverting water into existing but inactive channel braids, floodplain areas, or the historic 1969 Channel.

All of the enhancement measures incorporate rock to create a hardened feature on the landscape that would create a flow obstruction to force flow into areas it would not flow into otherwise. All three enhancement measures could be constructed at the same time or only one or two at a time. The effect of one enhancement measure could affect the performance of one or more enhancement measures downstream – primarily through alteration of flow paths and changing the amount of flow available at the downstream measure(s).

The extent of flooding and fluvial disturbance associated with the proposed enhancement measures under various flood scenarios was evaluated using 2D hydraulic modeling tools and sediment transport analysis, which included bar migration analysis, incipient motion analysis, and mode of sediment transport analysis for the sand size particles identified by the San Diego Zoo as preferred habitat for SBKR.

8.2.1 Enhancement Measure 1 – Reactivate 1969 Channel

Possibly in response to the 1969 flood event, a rock wall was constructed to plug the inlet to the 1969 Channel and prevent future floodwater from entering (Figure 3-4 and 3-5). Enhancement Measure 1 would excavate the rock wall channel plug at the entrance to the 1969 Channel to open floodwater access into the channel. A flow splitter up to 6 feet tall on the SAR active channel's north bank would be also be constructed to create a flow obstruction that would divert a portion of the active channel's flow into the 1969 Channel. Once in the 1969 Channel the water would flow almost entirely unobstructed for 8,000 feet before entering SBVWCD's Basin 18. A spillway would be constructed at the northwest corner of Basin 18 to provide a floodwater outlet to Plunge Creek instead of uncontrolled spill into the surrounding terrain, which includes the large quarry to the west. Water would flow over the spillway and eventually join Plunge Creek 1,500 feet from the spillway.

- Model iterations showed that increasing the amount of water diverted into the 1969 Channel not too much beyond 646 cfs would result in uncontrolled spill in Basin 18. Based on the configuration developed for Enhancement Measure 1, a SAR peak flow of 5,000 cfs upstream of the diversion is sufficient to obtain the desired 1969 Channel flow.
- The modeled cumulative infiltration loss is 98-acre-feet over the course of the 1.5-day 1969 Channel hydrograph with a total volume of 456 acre-feet (21% of the inflow volume). Most of this loss would be groundwater recharge in Basin 18.
- At the peak of the hydrograph, 12.0 acres of channel area have shear stresses greater than the minimum shear stress required for sand bar movement. Of this total, 53% of the area is in the Sand Bar Low End category, and 11% is in the Sand Bar High End category.
- Basin 18 has 24 acres of inundated area at the peak of the hydrograph. Fresh sediment deposition would occur in the basin and may provide additional habitat for listed species depending on frequency of disturbance from maintenance activities or other disturbance.

8.2.2 Enhancement Measure 2 – Increase Flooding in Northerly Channel Branches

A training wall exists on the north bank of the SAR where it crosses the Mentone Pipeline, likely to protect the pipeline. The protection the wall provides has effectively cutoff more than 300 feet of the SAR northern active channel belt and fluvial disturbance of this area has been minimal since the 1969 flood (Stillwater Sciences 2019). As the SAR flow crosses the pipeline, the alignment of the channel and topography cause most of the flow to continue down the southwest channel instead of the northerly channel.

Enhancement Measure 2 would construct a rock obstruction on the mid-channel island downstream of the pipeline crossing to split flow and direct a larger portion of the flow into the northern channel braid that extends for 4,000 feet prior to rejoining the active SAR. Fill would be placed in the channel downstream of the flow splitter to create a new bank and partially plug a channel braid in order to assist with directing the flow into the northerly channel.

- Would produce a range from 2.1 acres (2,500 cfs) to 3.6 acres (25,000 cfs) of increased channel area with shear stresses greater than the minimum shear stress required for bar movement.

- Would increase acreages by approximately an acre or less with shear stresses high enough for cobble bar high end and maximum for modeled flows of 2,500 cfs or greater
- Compared to the other enhancement measures, flow diverted into the northerly channel does not lead to comparable increases in inundated area. Most of the diverted flow is confined to a single channel braid in which depths and velocities increase more than spreading out of flow into new formerly inactive channels. Consideration should be given to modifying this enhancement measure by adding additional obstructions in the downstream portion to cause inundation into additional channel braids.

8.2.3 Enhancement Measure 3 – Increase Flooding in Southerly Channel Branches

Enhancement Measure 3 is located on the south side of the SAR channel belt and the western end of the Redlands Airport. Post-1970, a training wall was constructed for nearly 2,000 feet across the channel, presumably to protect against possible lateral migration into the Redlands Airport. By October 2, 1995, a breach occurred in the training wall and the SAR flowed through the downstream portion of the walled off area. Fluvial disturbance of this area has been minimal since the 1969 flood (Stillwater Sciences 2019).

Enhancement Measure 3 would construct three rock flow obstructions in an active SAR channel braid to divert a portion of flood flows into the channel area south of the breached training wall. To prevent the flow from rejoining the SAR so soon another flow obstruction would be constructed to keep the water headed southwest. The enhancements would increase flow within the presently inactive channel belt continuing for over 5,000 feet downstream along the Redlands Airport and south of the active SAR channel.

- Would produce a range from 2.1 acres (438 cfs) to 10.8 acres (7,500 cfs) of increased channel area with shear stresses greater than the minimum shear stress required for bar movement. The increase at 5,000 cfs is 10.4 acres.
- Minimal cobble bar migration is predicted in this area where flows are spread out over a fairly large area in multiple channel braids. Progressive increases in flow magnitude translate into progressive increases in sand bar migration.

8.2.4 Prioritization of Enhancement Measures

All three enhancement measures are viable measures that could be implemented to increase the levels of fluvial disturbance beyond the existing condition. Prioritization of the enhancement measures is primarily based on their ability to create bar migration and the feasibility of isolating the channel areas affected by the enhancement measures post-initial disturbance so that they are not flooded again too soon. The cost of implementing the enhancement measures is also a factor, but considered less important since the excavation quantities (Table 3-1) are similar for all three enhancement measures.

The performance comparison of the enhancement measures is based on a SAR total flow of 5,000 cfs. Priority 1: Enhancement Measure 1 – Reactivate 1969 Channel

- Would produce 12.0 acres of new channel area with shear stresses greater than the minimum shear stress required for bar movement.

- Requires 646 cfs to achieve these shear stress increases.
- The sediment that would deposit in Basin 18 may be available for habitat depending on frequency of disturbance from maintenance activities or other disturbance. Basin 18 has 24 acres of inundated area at the peak of the hydrograph. Infiltration in the basin provides a groundwater recharge opportunity.
- The active SAR channel where the flow splitter would be constructed to divert water into the 1969 Channel has experienced little planform change over the past several decades, which provides a relatively stable location to construct a point of diversion.
- The 1969 Channel could be relatively easily isolated from future flooding post-disturbance by reconstructing the rock wall channel plug and blocking water from reentering the channel.

8.2.4.1 Priority 2: Enhancement Measure 3 – Increase Flooding in Southerly Channel Branches

- If implemented in conjunction with Enhancement Measure 2, would produce 10.4 acres of new channel area with shear stresses greater than the minimum shear stress required for bar movement. If implemented individually, the increase would be 13 new acres.
- Requires 1,176 cfs to achieve these shear stress increases.
- Isolating the disturbed areas from future flooding post-disturbance is feasible but likely more challenging than isolating the 1969 Channel, particularly in the larger inactive channel belt that continues for over 5,000 feet downstream along the Redlands Airport in which there are several existing high flow channel braids in this area and blocking all them could require fairly extensive work. It may be more feasible to block one or two of them located furthest south, which would isolate a subset of the total Enhancement Measure 3 site area.
- Discussion with the airport managers, San Bernardino County Flood Control, and others would be required to assess the feasibility of diverting more SAR floodwater into this area adjacent to the Redlands Airport.

8.2.4.2 Priority 3: Enhancement Measure 2 – Increase Flooding in Northerly Channel Branches

- Would produce 2.0 acres of new channel area with shear stresses greater than the minimum shear stress required for bar movement.
- Requires 2,461 cfs to achieve these shear stress increases.
- Isolating the disturbed areas from future flooding post-disturbance is feasible. Most of the flow under the existing channel braid enters the northerly channel braid at one defined location. The material used to construct the flow splitter located on the island just downstream of the Mentone Pipeline crossing could be relocated to plug the northerly channel braid and isolate the majority of the Enhancement Measure 2 area from future flooding post-disturbance.
- There is risk in completely blocking the northerly channel since under the existing condition this channel is active during flooding. Forcing all of the flood flow into the southerly channel in this already artificially constricted area could cause channel downcutting and threaten the pipeline. Further analysis would be needed on the depth of the pipeline at the crossing and permissible shear stresses.

8.3 Evaluation of Mechanical Disturbance of the Floodplain

Expert accounts of past disturbance indicate SBKR are disturbance oriented and likely to respond positively to a variety of disturbance techniques. The consensus among the experts when discussing disturbance was that disturbed habitats must be near intact occupied habitat for colonization to take place. Furthermore, the experts expressed a consensus opinion that experimental and habitat scale manipulations should have some non-rectangular shape and be strongly interconnected with other disturbed areas and with occupied habitat.

Successful habitat manipulation benefitting SBKR and woolly star is likely to include modification of soil texture. Manipulations that result in the presentation of clean washed sand at depths of 10 cm or greater are likely to result in benefits for SBKR and woolly star habitat. If soils are already appropriate, then it may be possible to restrict manipulation to clearing or reducing vegetative cover and controlling exotic grasses. SBKR are likely to be reliant on habitat corridors for recolonization of manipulated areas. Larger manipulations that include woolly star planting could result in benefits for both species. Restoration and habitat manipulation of spineflower will need to be done separately and on a smaller scale, once experimental manipulation studies for the species are complete.

Despite similar reliance on flood disturbance for regenerating their habitat, the three target species differ in their habitat requirements. Because of their reliance on pioneer and intermediate successional stage RAFSS surfaces, woolly star and SBKR may be able to be managed simultaneously. Management actions that promote regeneration of RAFSS surfaces into pioneer and intermediate phases may ultimately benefit spineflower but will require decades to transition into the mature and juniper phase stands associated with typical spineflower habitat.

Implementation of the mechanical disturbance techniques described should take place within an adaptive management framework like that described in the MSHMP. Degraded habitat with low or no occupancy by the species of interest, or other special status species should be selected for manipulation over less degraded habitat. Implementation will require monitoring of the manipulated area to ensure that habitat targets are met and to record the duration of the action.

Predictions made at smaller experimental scales may diverge from observations once manipulation is applied at larger scales.

8.4 Evaluation of Treatment Trade-offs and Prioritization of the Species of Interest

Species priorities should be adhered to when vetting proposed habitat manipulation sites. Because of their rarity within the study area information and gaps regarding habitat preference, spineflower are to be avoided. Extant populations of SBKR and woolly star should also be avoided, with SBKR taking priority over woolly star. It may be possible to mitigate impacts to SBKR by trapping them out of proposed disturbance areas prior to implementing habitat manipulation, and then re-releasing them following disturbance. This prioritization aligns with recommendations made in the Phase 1 report regarding the selection of appropriate habitat manipulation sites. Mature and disturbed

RAFSS surfaces with high exotic grass cover will typically match the species priorities provided above, depending on the disturbance type.

The status of habitat manipulation experiments for the species of interest are incomplete or unavailable. Woolly star treatments have been vetted and shown to be effective. SBKR treatments are incomplete or unavailable, but expert observations and recent habitat modeling work indicates that they are likely to respond positively to similar disturbance regimes as those tested for woolly star. No information is available for spineflower and no recommendations regarding beneficial habitat manipulations can be made. However, it is likely that spineflower will respond poorly to the disturbance techniques proposed for the other two species and must be managed separately.

The critical features of any beneficial habitat manipulation will be reduced exotic grass cover and increased clean sand fraction in the substrate. Manipulations of this type should result in net positive benefits for SBKR and woolly star if conducted in areas where the species can readily colonize the newly manipulated habitat. Because of climatic shifts in weather pattern and ongoing human disturbance of the study area, succession may not continue to progress through the RAFSS community types from pioneer to mature and may become more heavily dominated by invasive non-native grasses at all seral stages. This results in uncertainty regarding whether habitat manipulation will ultimately result in beneficial effects to spineflower.

Downstream effects should be avoided if possible, but if any manipulation with a fluvial component propagates downstream, it must be restricted to time periods when natural flood disturbance is expected within the system. This means that fluvial habitat manipulation will need to be restricted to winter or early spring periods to minimize any potential negative effects to downstream populations of Santa Ana sucker.

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Chapter 10
Figures

This chapter contains figures mentioned throughout the High-Flow Study of Seven Oaks Dam: Phase 2 Final Report.

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Figure 3-1. Overview Map of the Santa Ana River Enhancement Measures

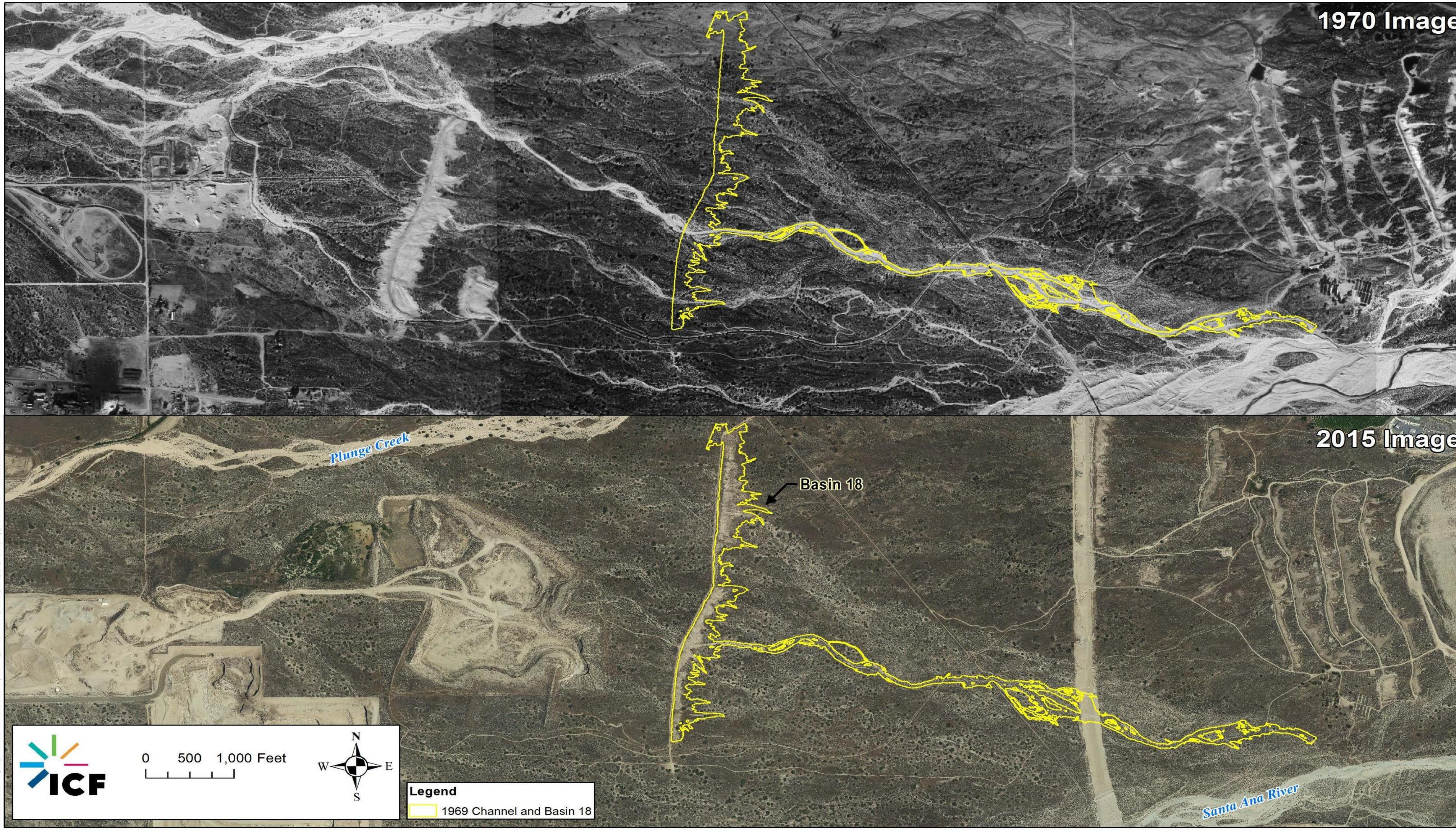

Figure 3-2. Comparison of the 1969 Channel in 1970 and 2015 Imagery

Figure 3-3. Overview Map of Enhancement Measure 1 in the Vicinity of the Active SAR and 1969 Channel Inlet

Figure 3-4. Photo View to the East of the Rock Wall Channel Plug in Relation to the Active Santa Ana River and 1969 Channel

Figure 3-5. Photo View to the Northwest from Atop the Rock Wall Channel Plug Looking Down the 1969 Channel

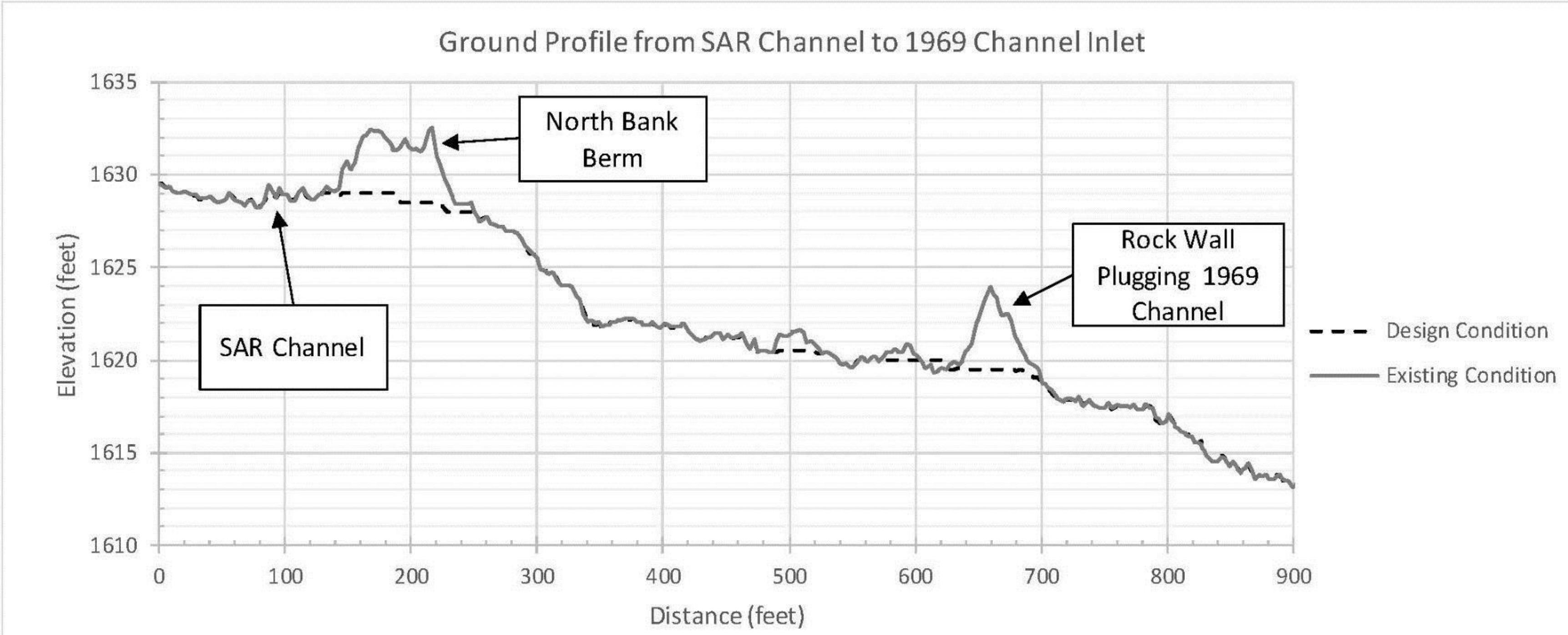

Figure 3-6. Longitudinal Profile of 2015 LiDAR Ground Elevations from the Active Santa Ana River into the 1969 Channel

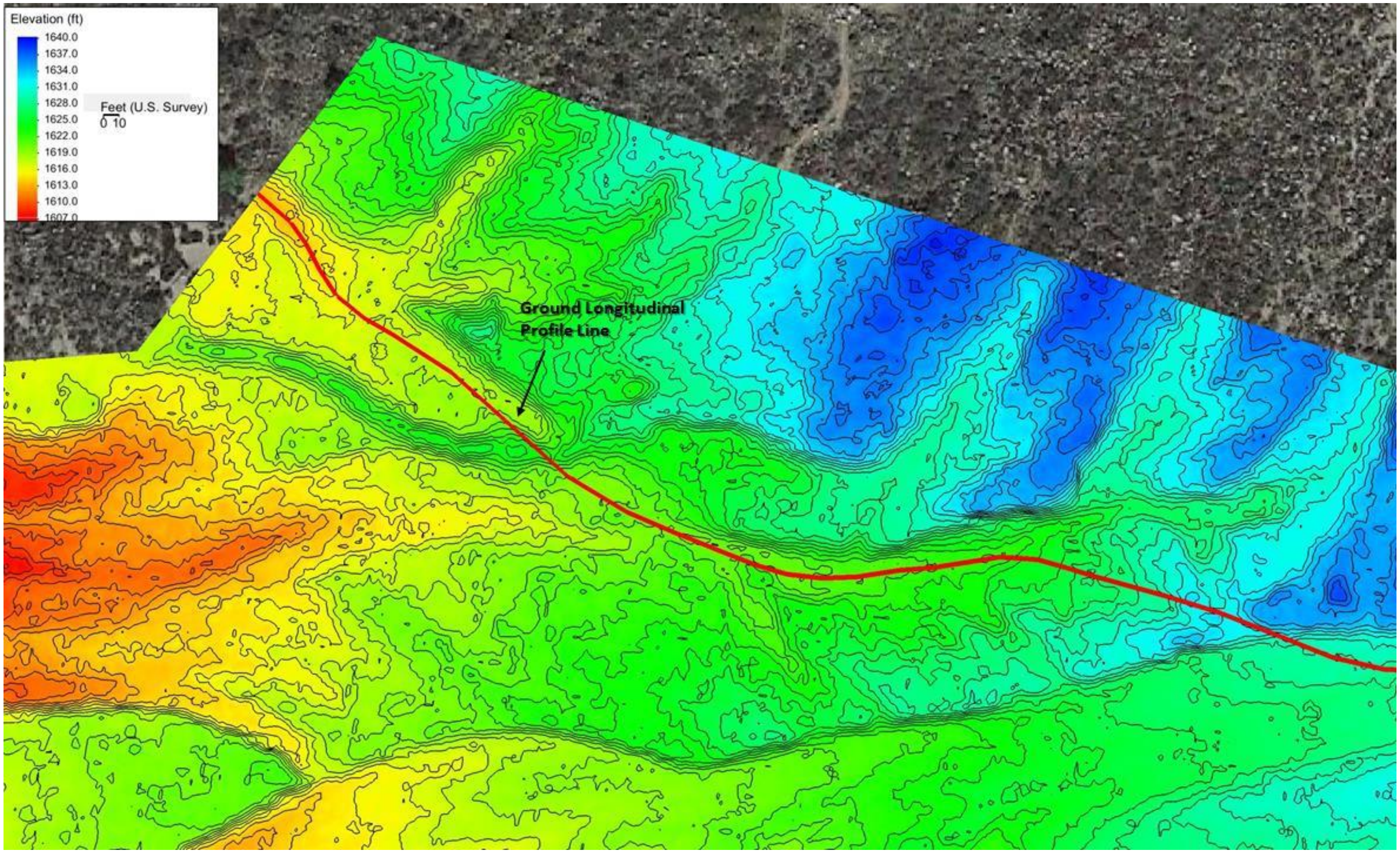

Figure 3-7. Existing Condition Ground Elevations with 1 foot Contours from 2015 LiDAR at the 1969 Channel Inlet

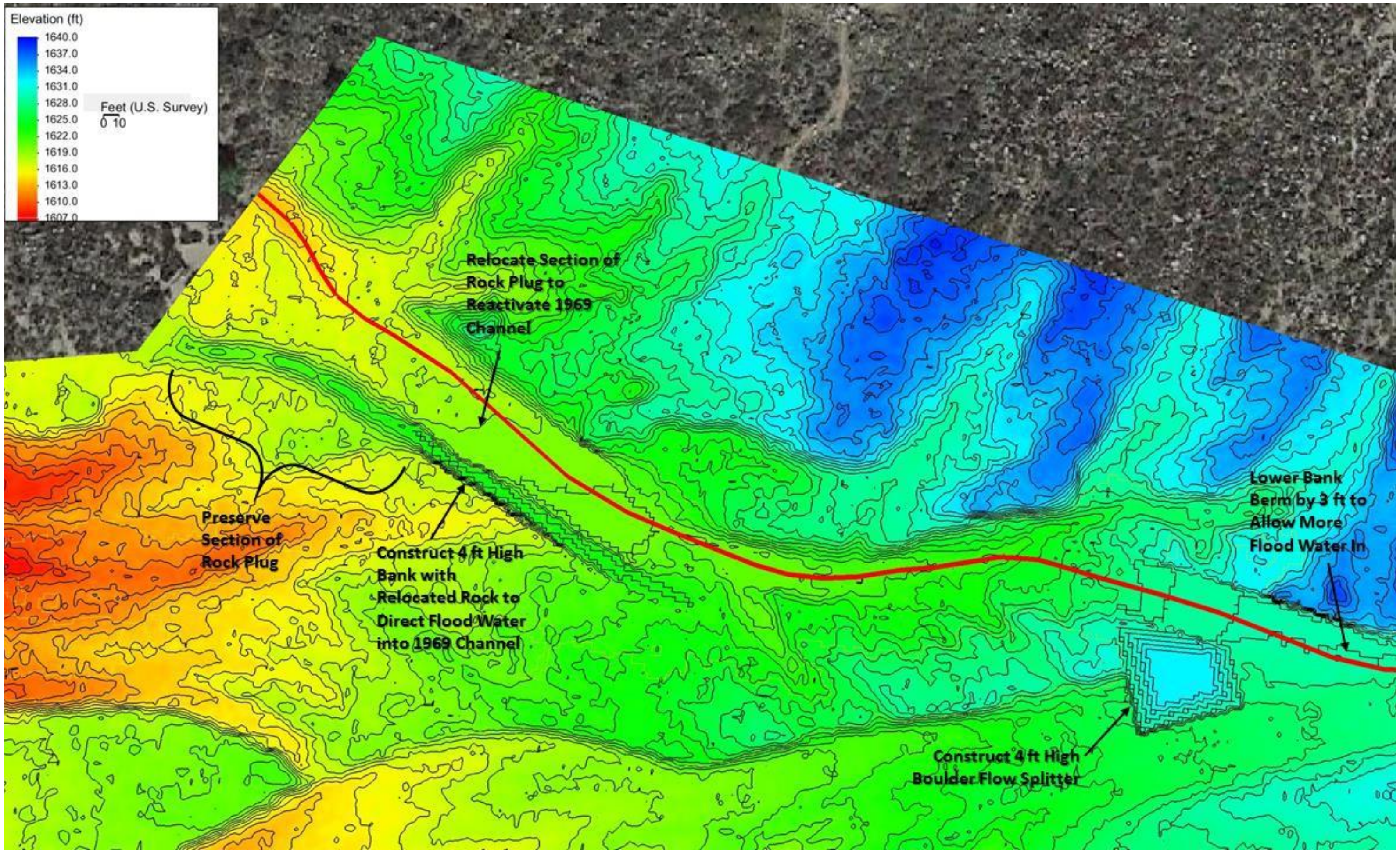

Figure 3-8. Proposed Condition Ground Elevations with 1 foot Contours from 2015 LiDAR at the 1969 Channel Inlet

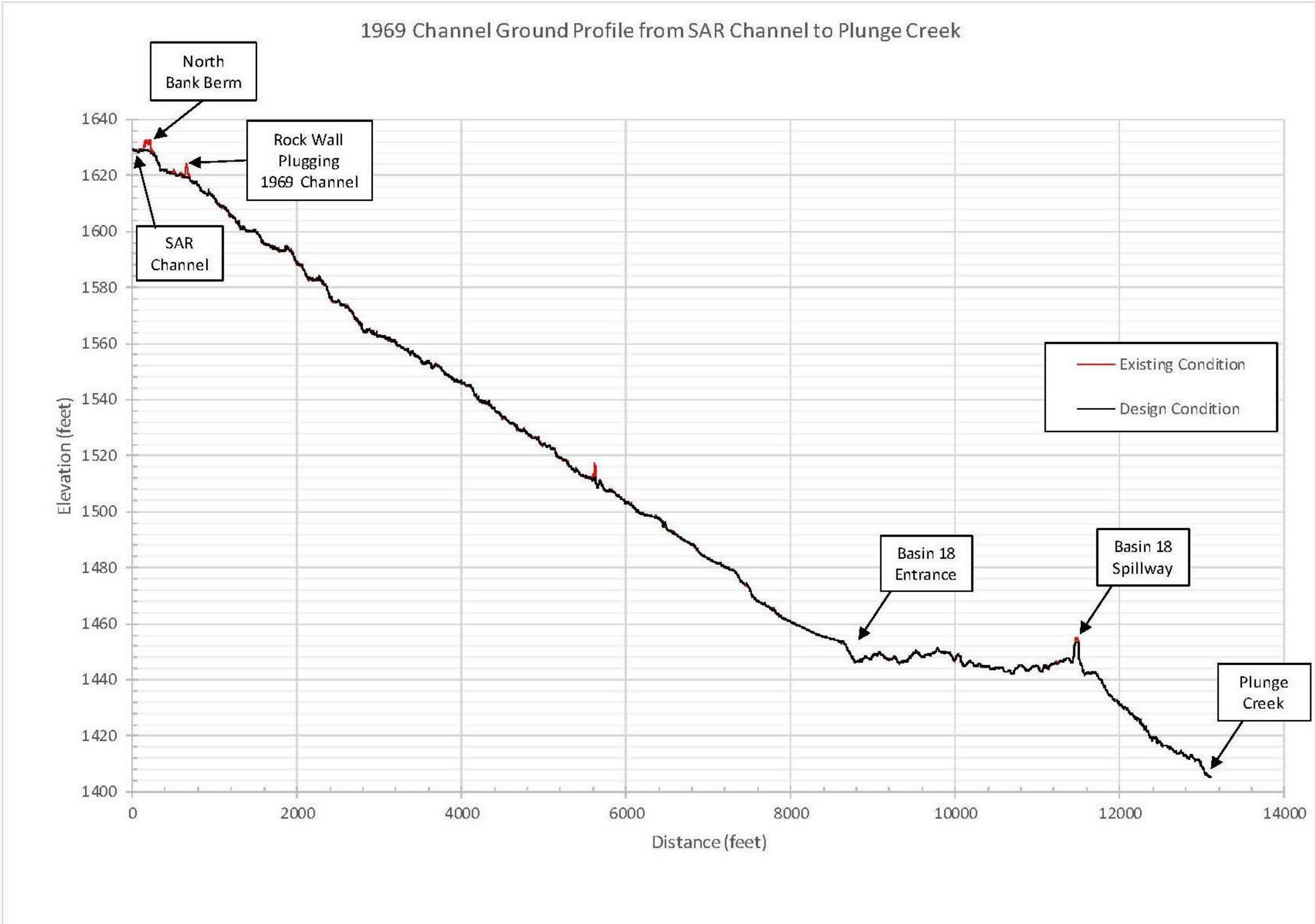

Figure 3-9. Longitudinal Profile of 2015 LiDAR Ground Elevations for the 1969 Channel from the Active Santa Ana River to Plunge Creek

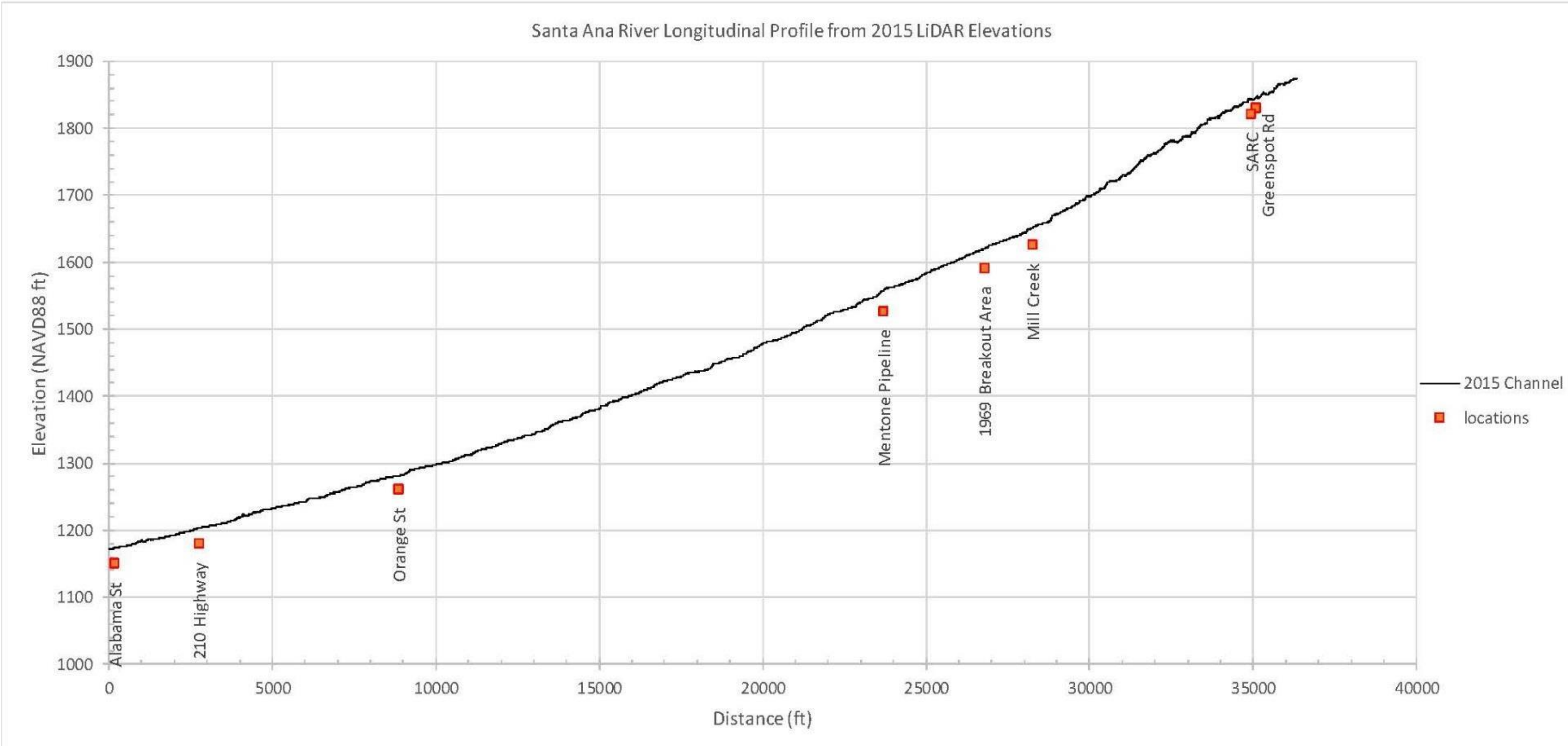

Figure 3-10. Longitudinal Profile of 2015 LiDAR Ground Elevations for the Active Santa Ana River from Greenspot Rd. to Alabama St

Figure 3-11. Overview Map of Enhancement Measure 2 Downstream of the Mentone Pipeline Crossing at Opal Avenue

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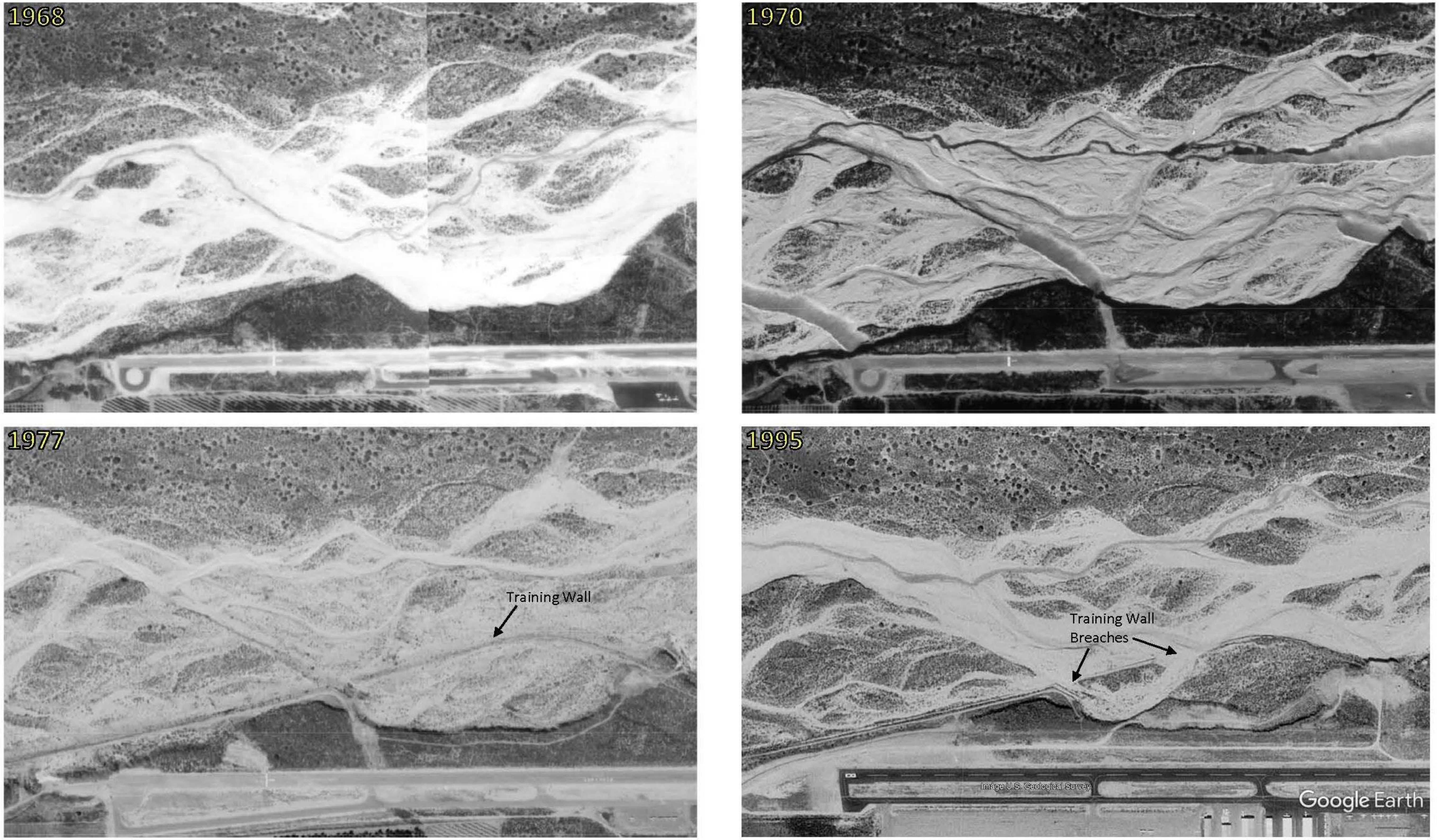

Figure 3-12. Historic Photo Time-Series of Channel Changes at Location of Enhancement Measure 3 near Western End of Redlands Airport

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Figure 3-13. Overview Map of Enhancement Measure 3 at the Western end of the Redlands Airport

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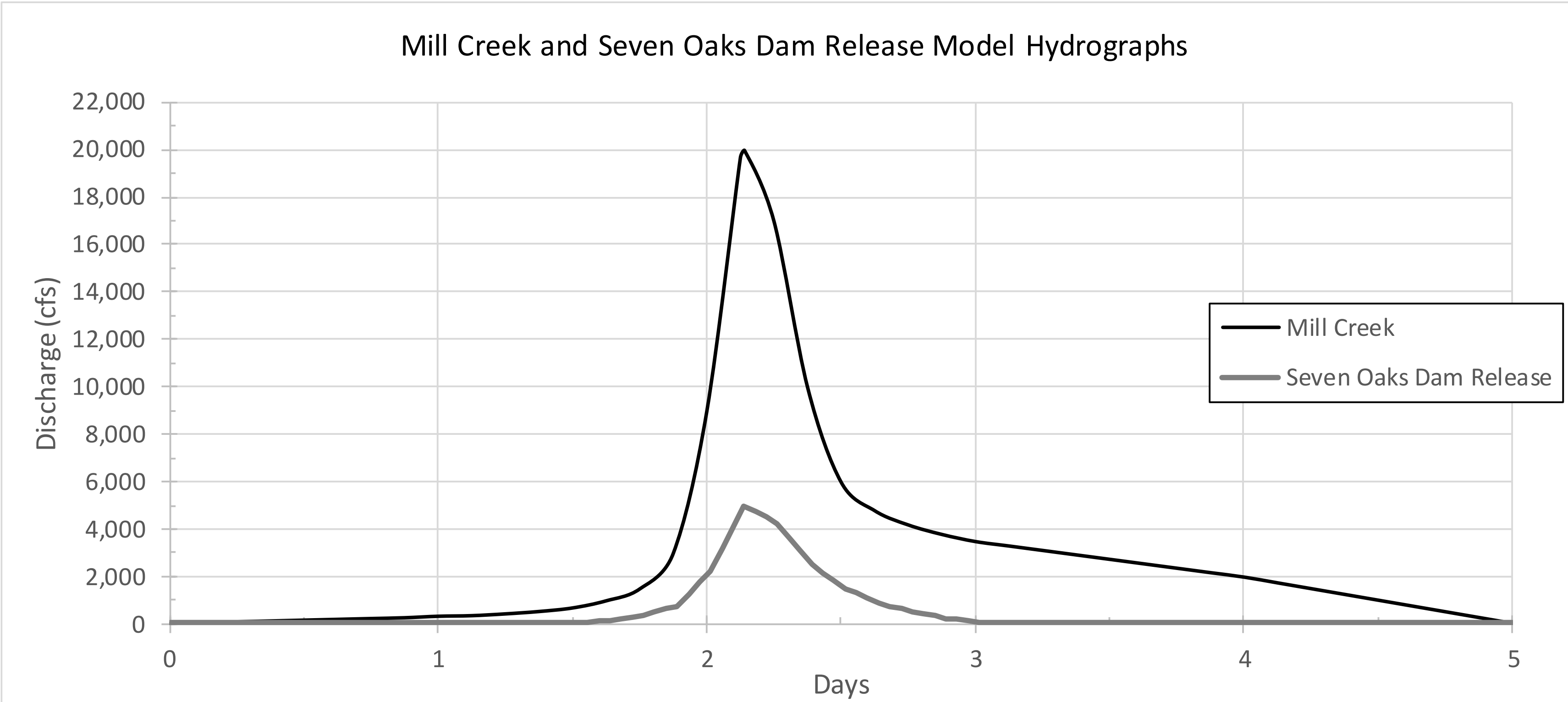

Figure 4-1. Mill Creek and Santa Ana River Dam Release Hydrographs Developed for the Modeling Analysis

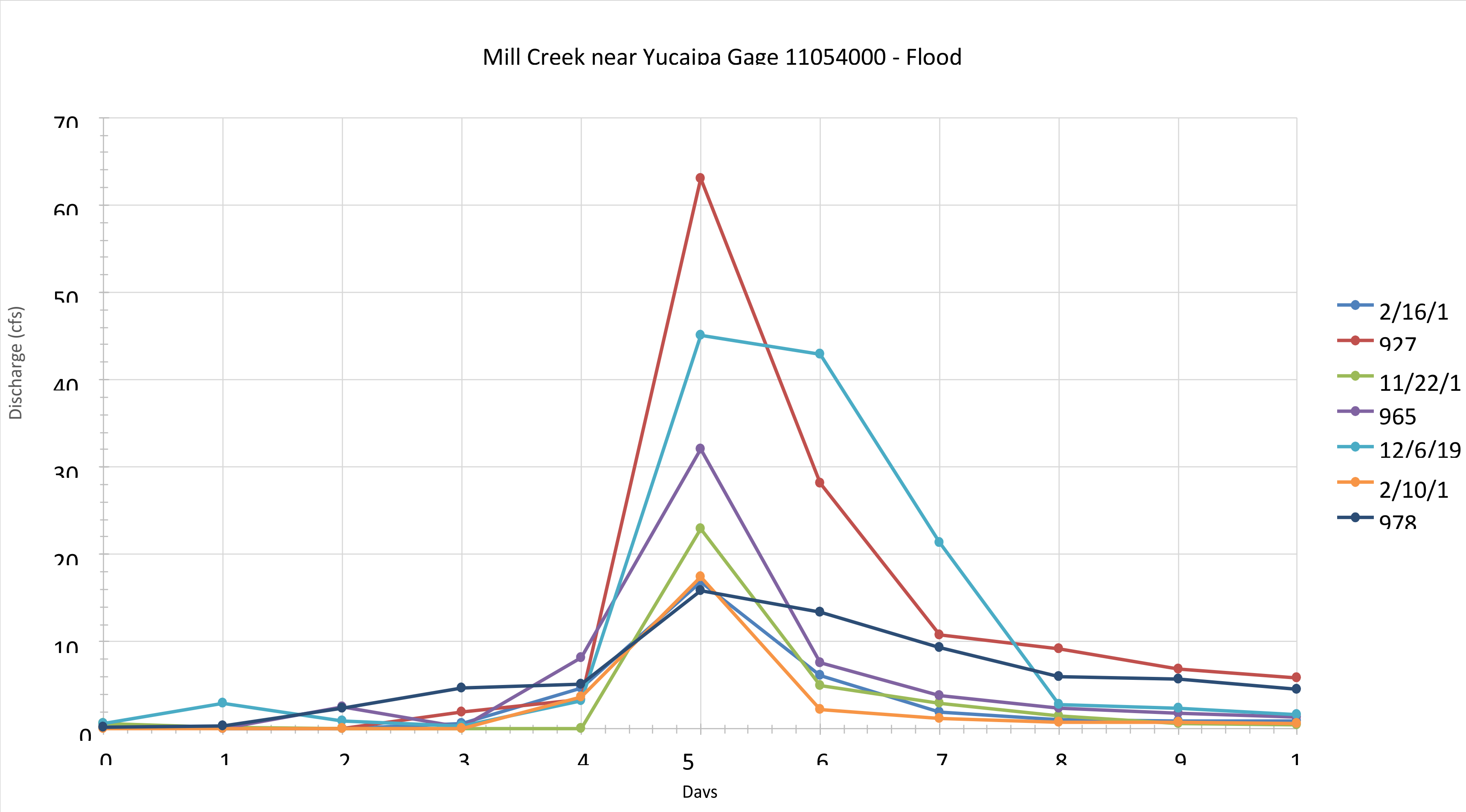

Figure 4-2. Comparison of Mill Creek Peak Flow Hydrographs Based on Yucaipa Gage Mean Daily Discharge Records

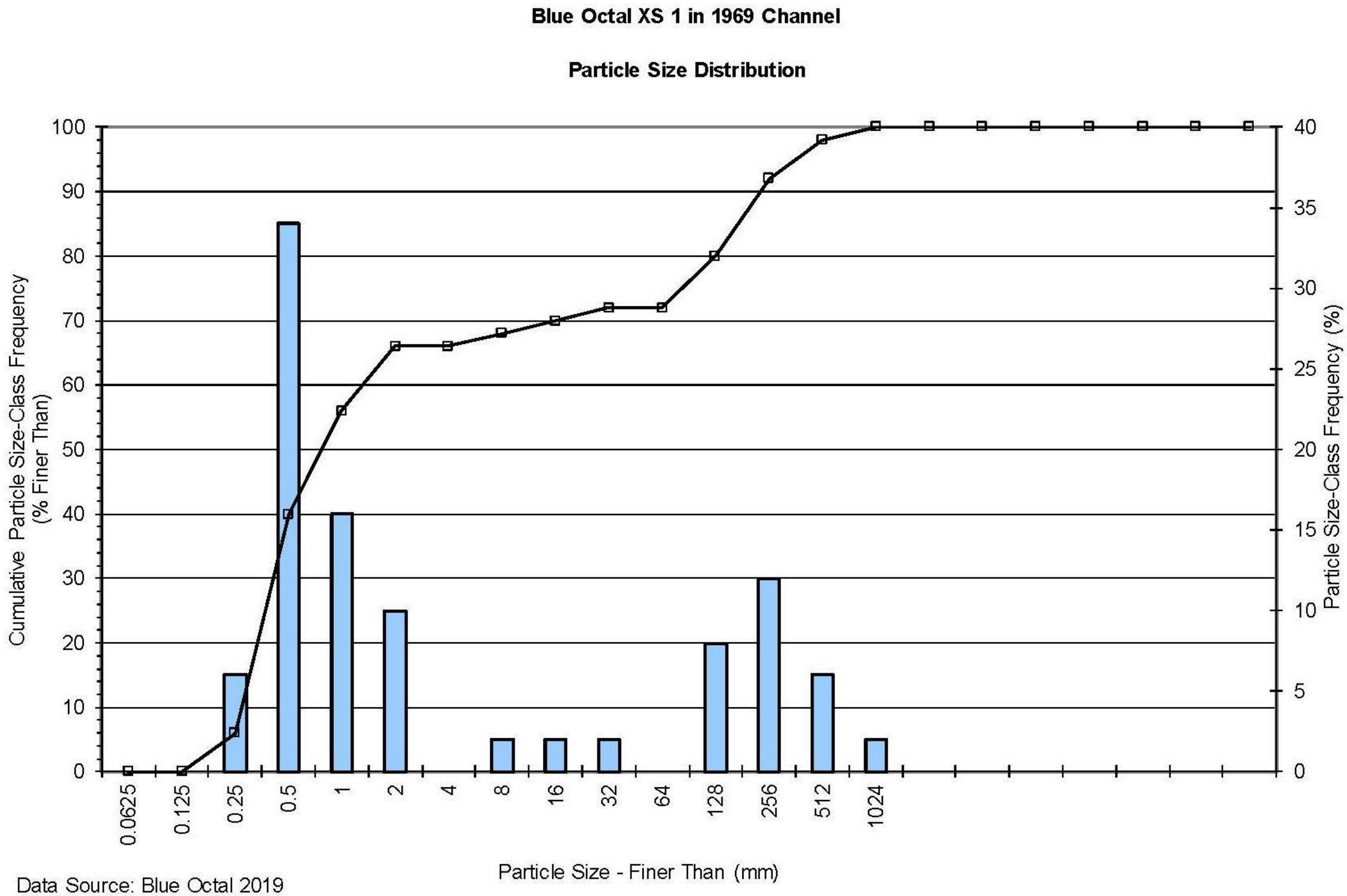

Figure 4-3. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS1 in the 1969 Channel

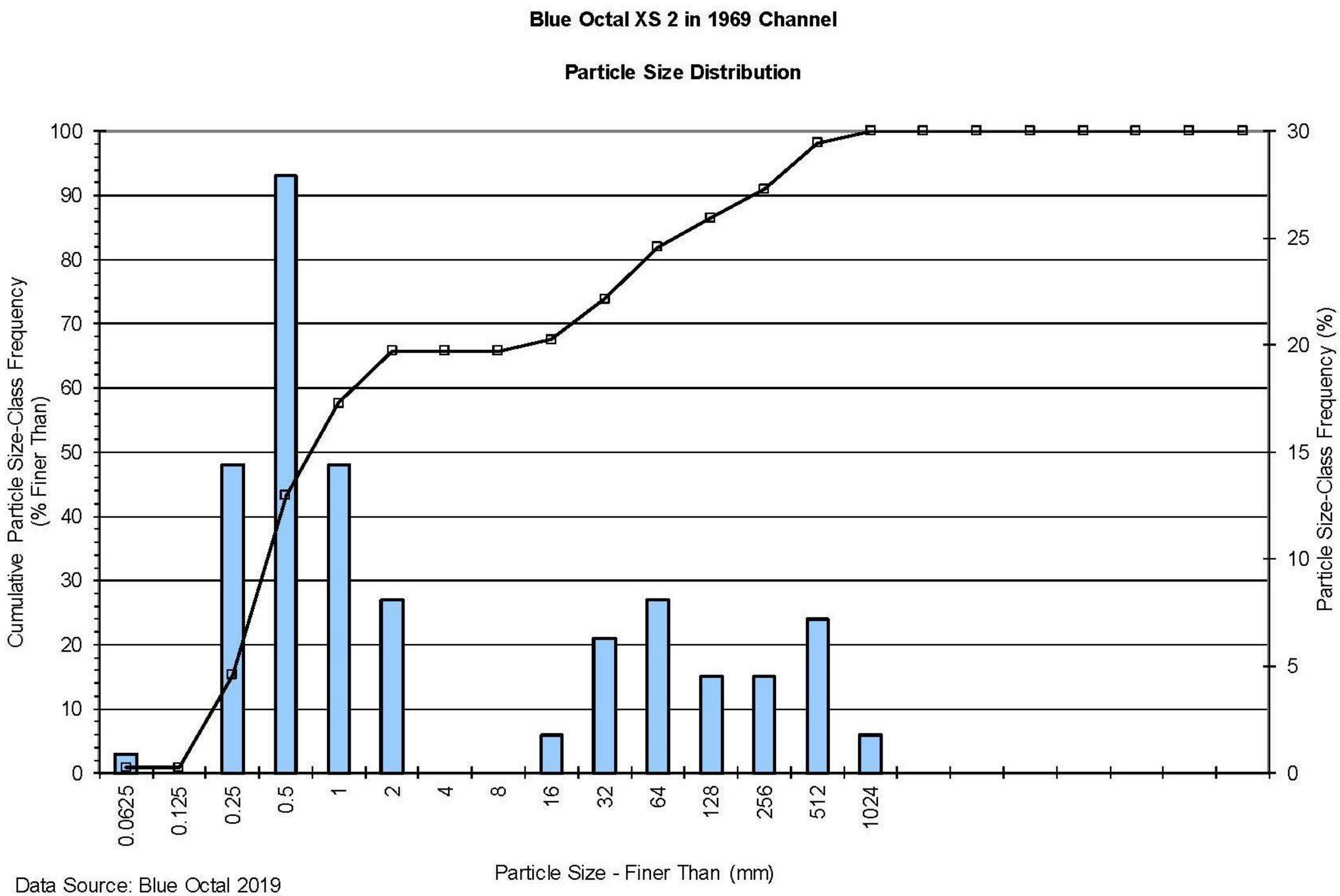

Figure 4-4. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS2 in the 1969 Channel

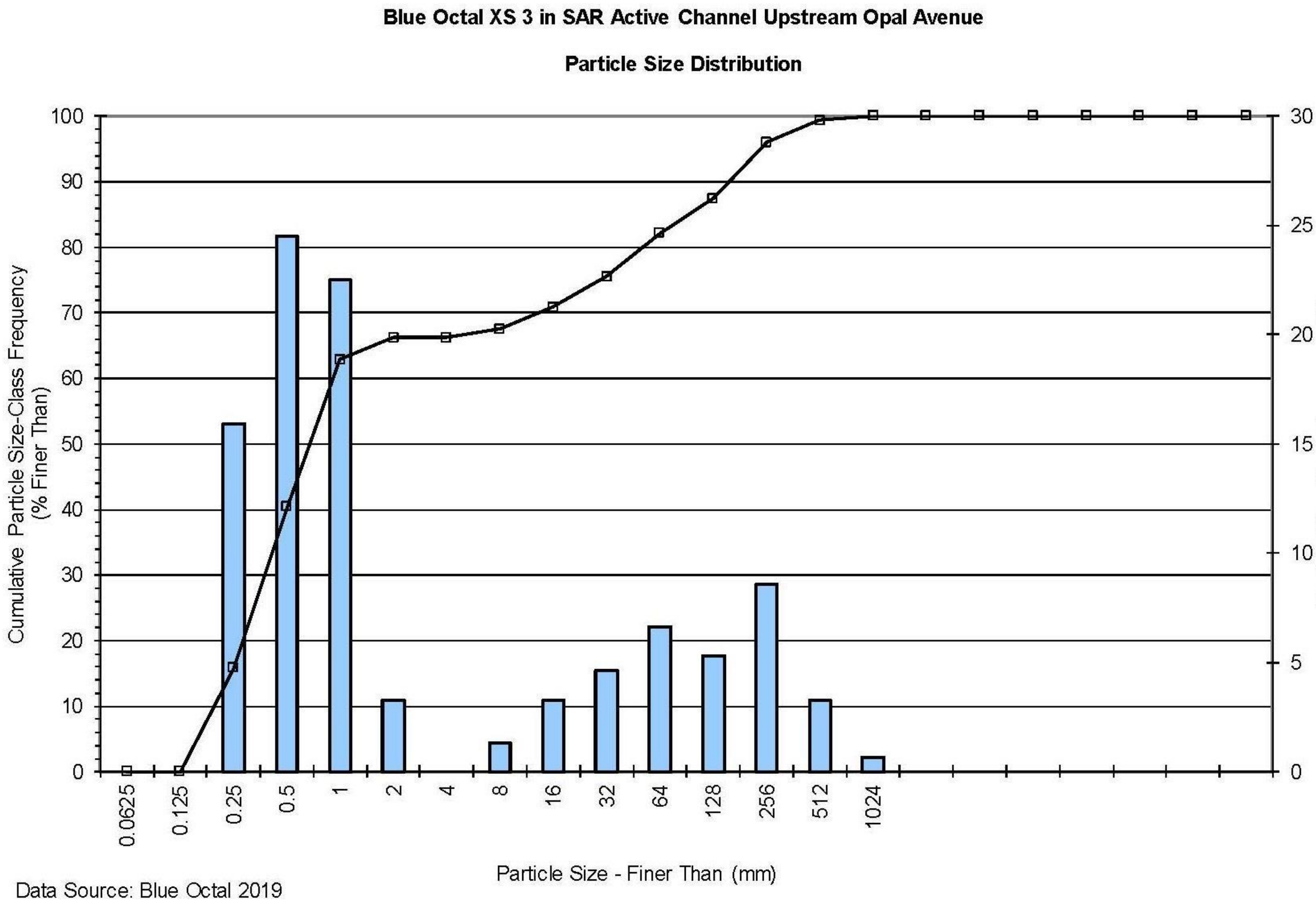

Figure 4-5. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS3 in the Active SAR Channel Upstream of Opal Avenue

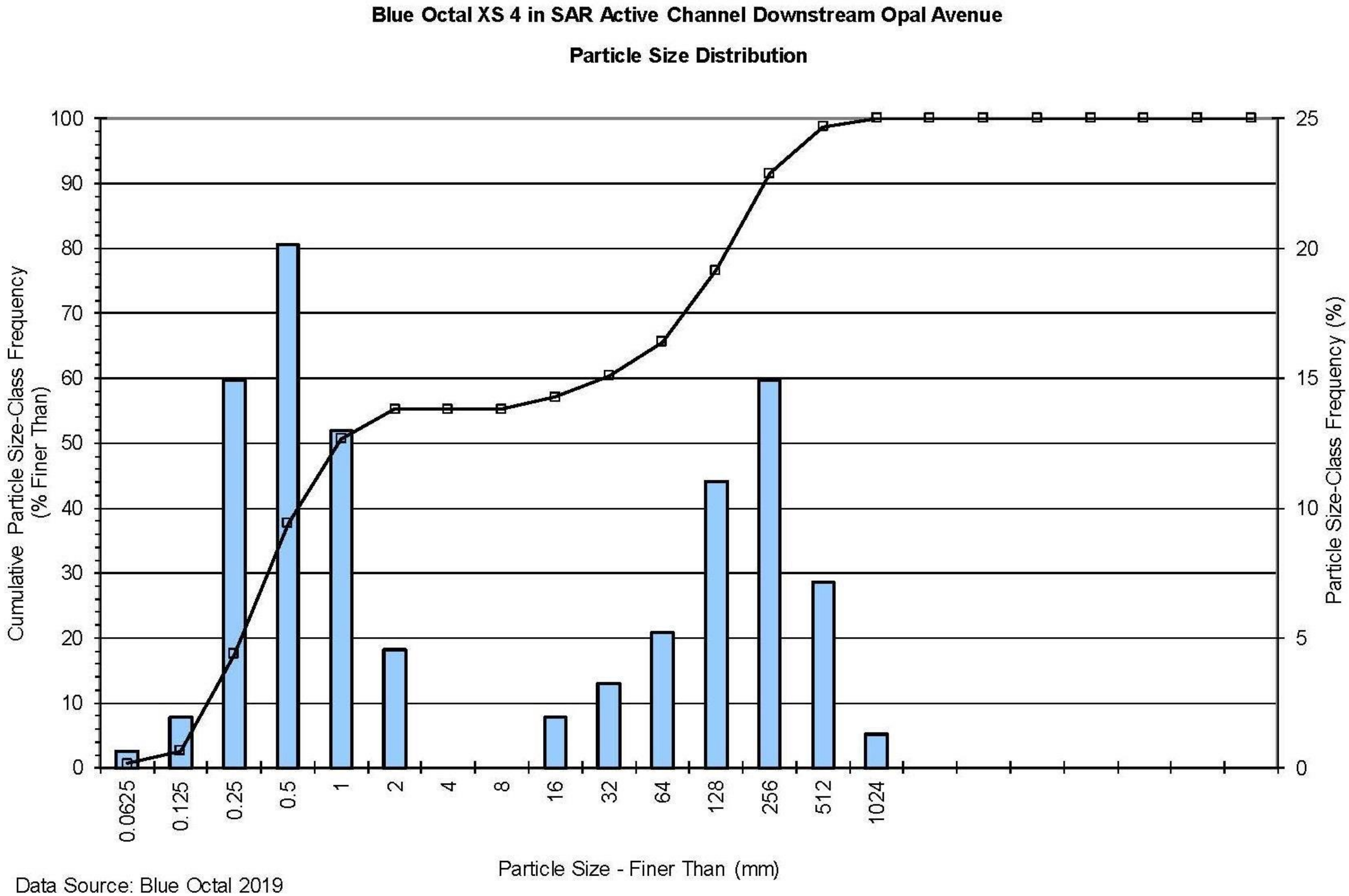

Figure 4-6. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS4 in the Active SAR Channel Downstream of Opal Avenue

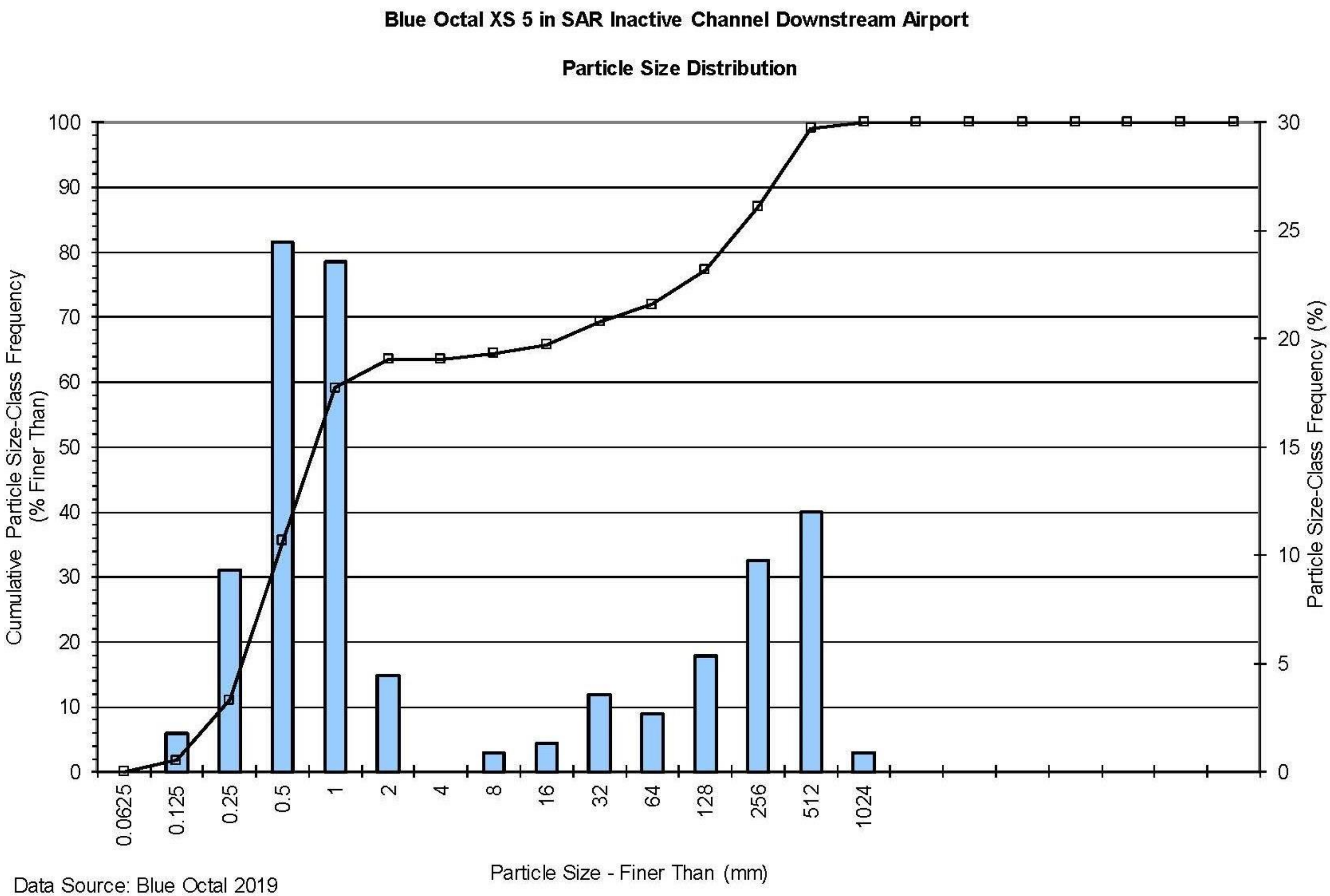

Figure 4-7. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS5 in the inactive SAR Channel Downstream of Redlands Airport

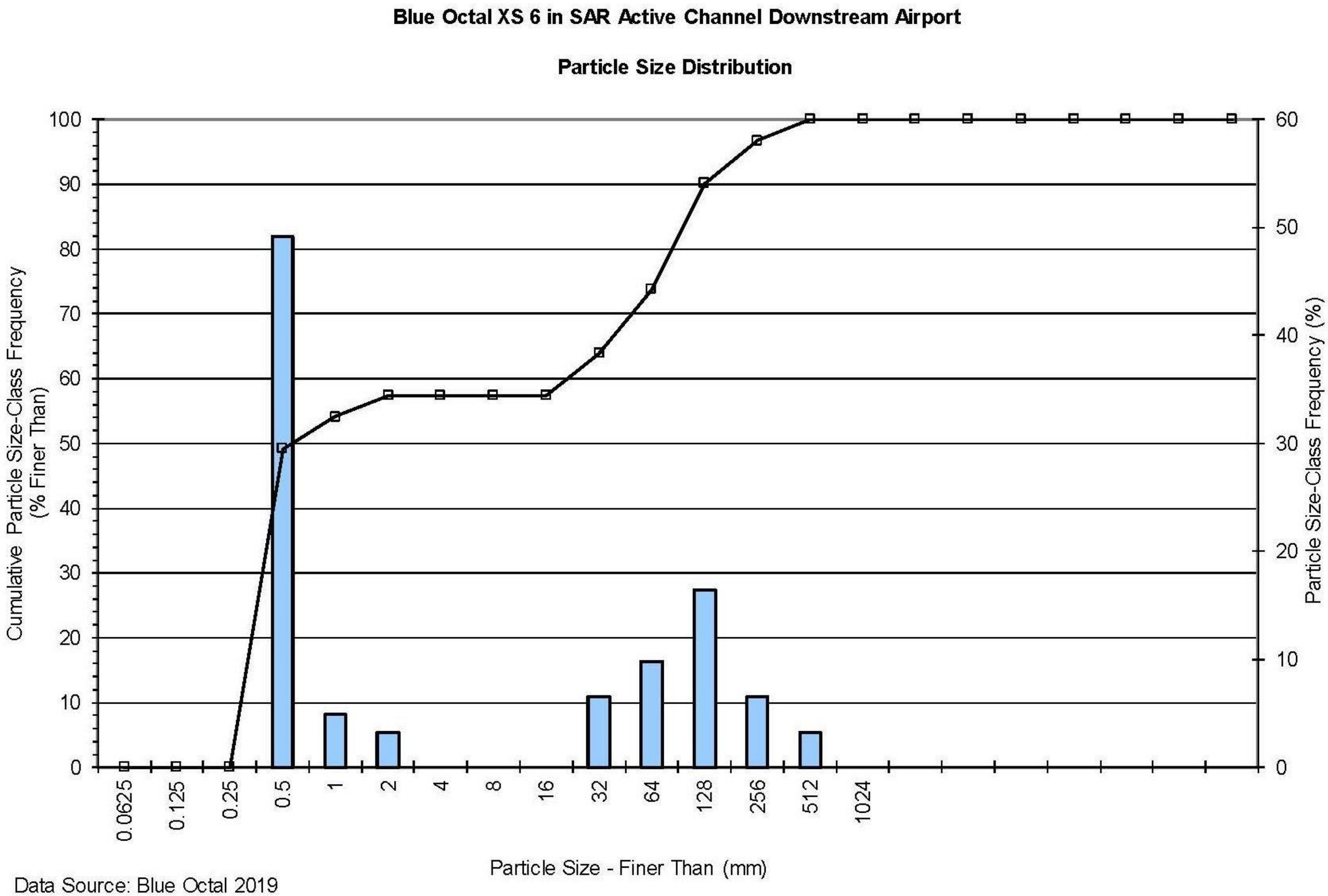

Figure 4-8. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample XS6 in the Active SAR Channel Downstream of Redlands Airport

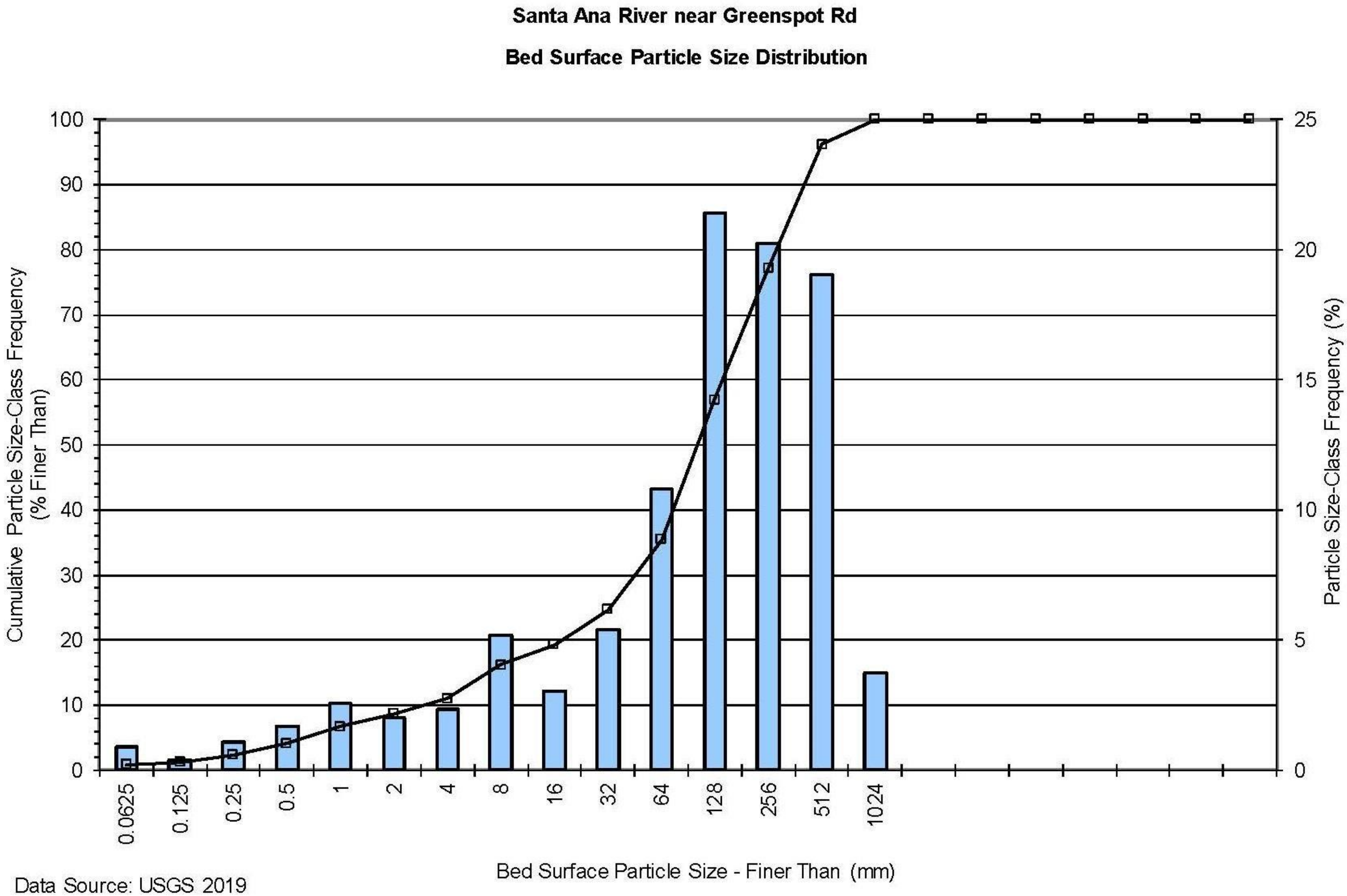

Figure 4-9. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample in SAR near Greenspot Road Upstream of Mill Creek

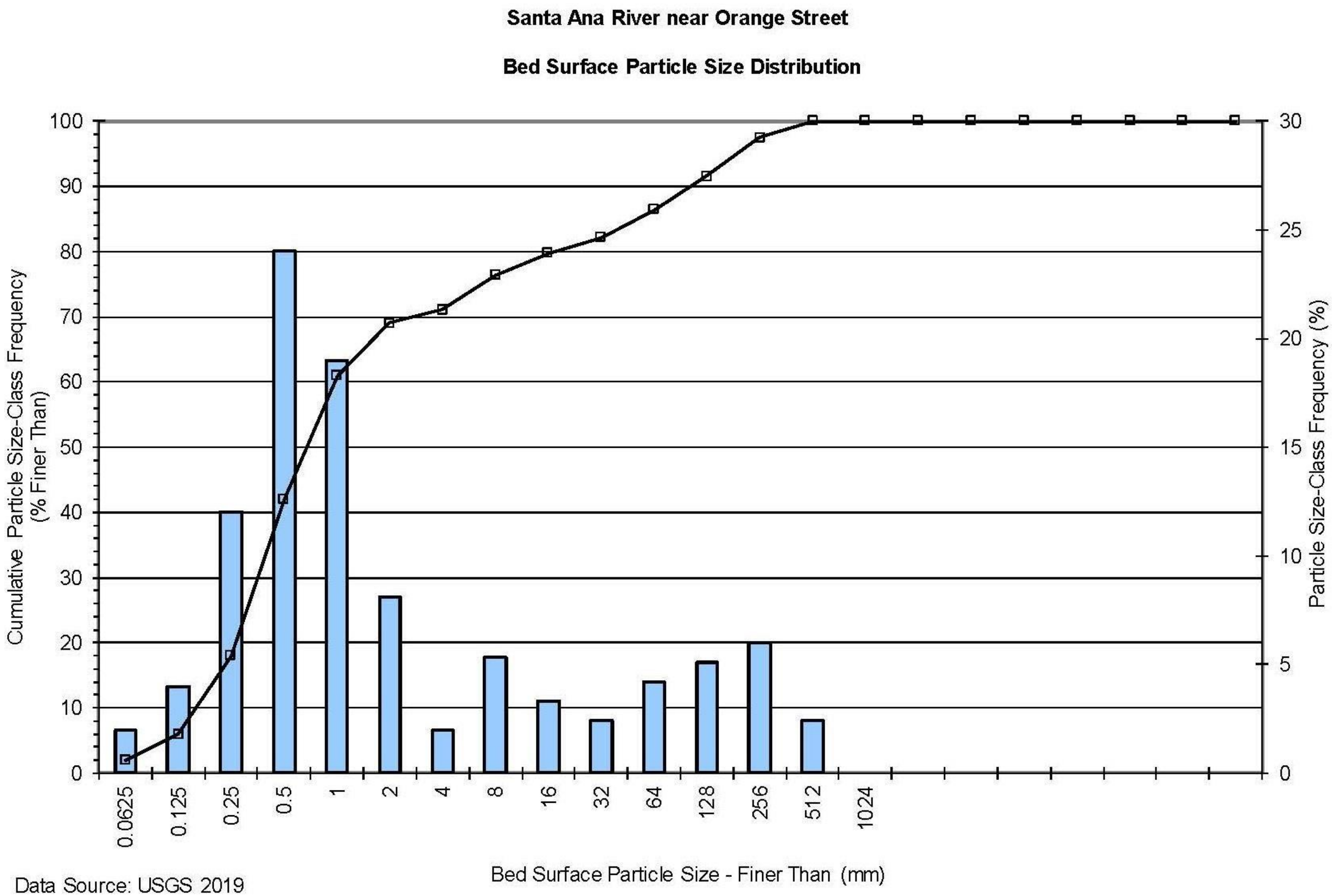

Figure 4-10. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample in SAR near Orange Street

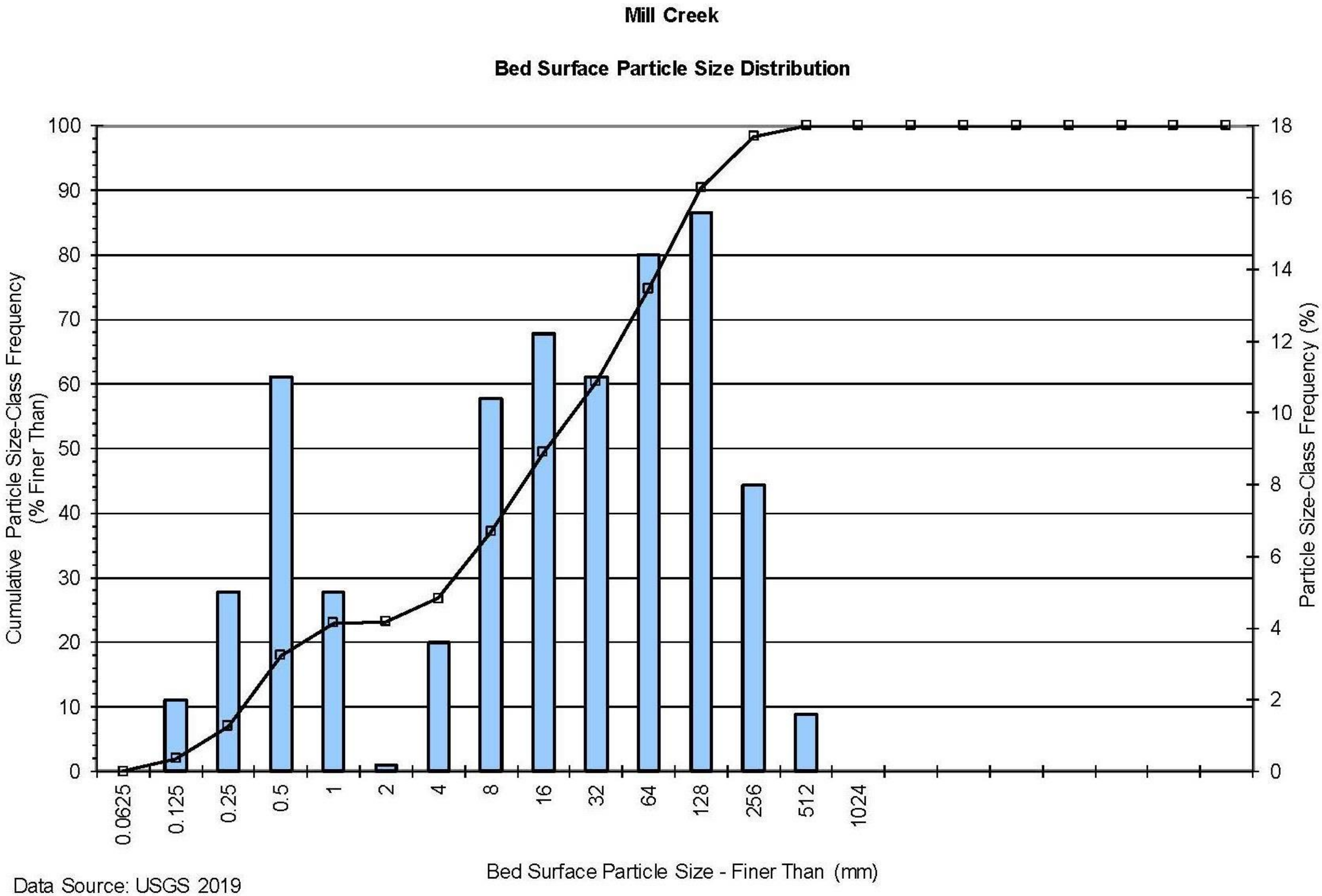

Figure 4-11. Cumulative and Individual Particle Size-Class Frequency Plots for Bed Sediment Sample in Mill Creek near Greenspot Road

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Seven Oaks Dam High Flow Study

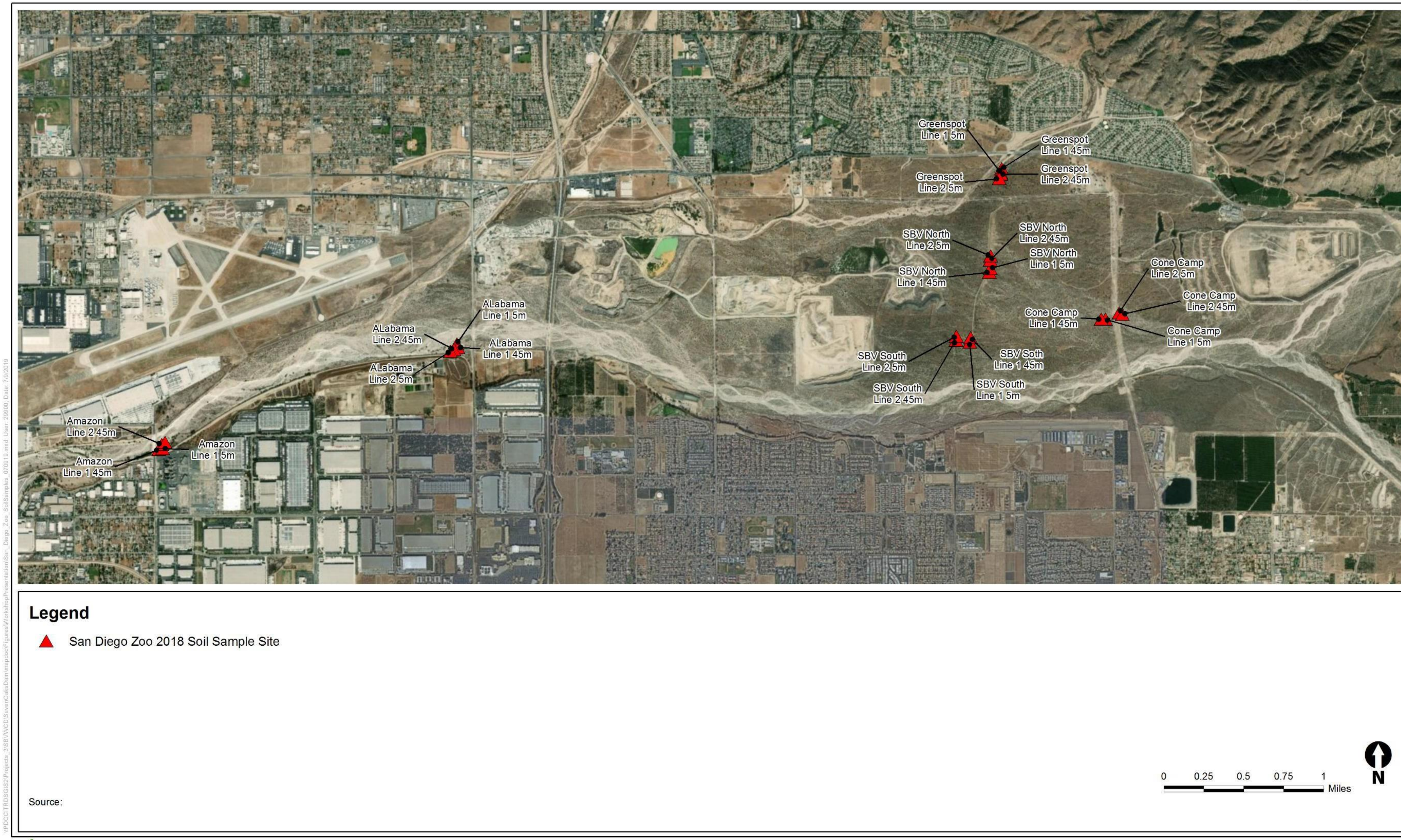

Figure 4-12. Locations of the San Diego Zoo 2018 Sediment Samples of SBKR Habitat Suitability

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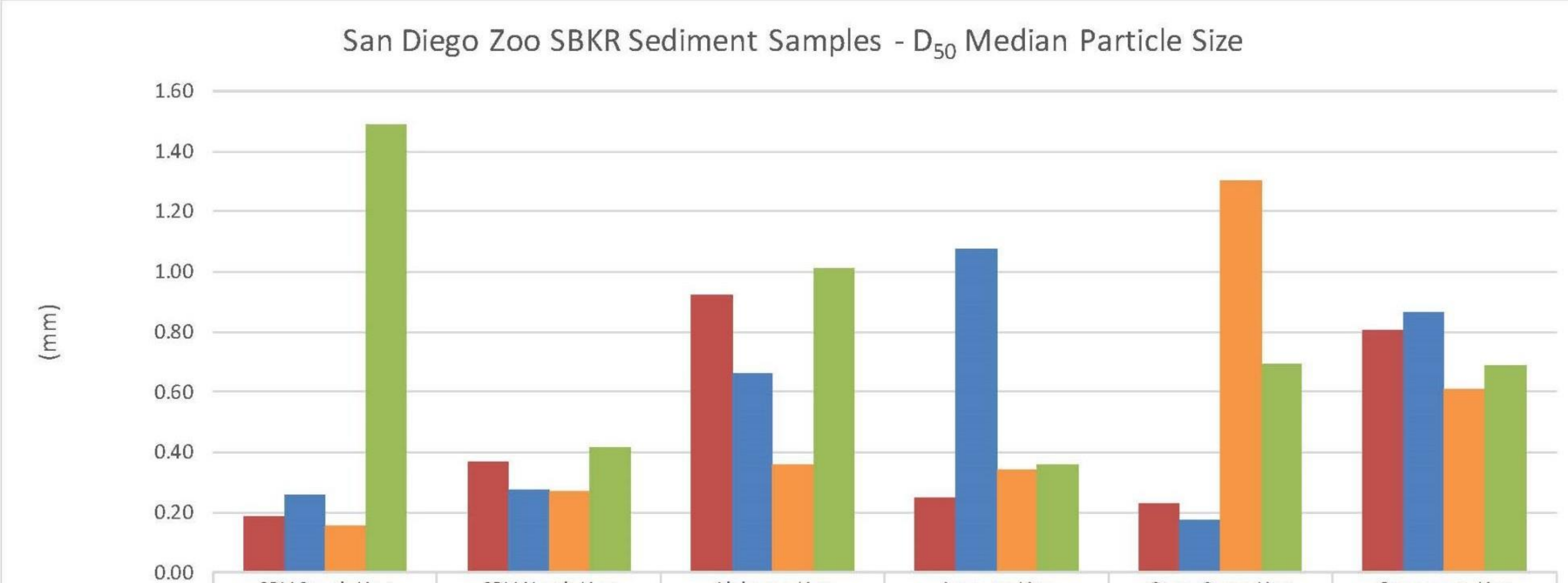
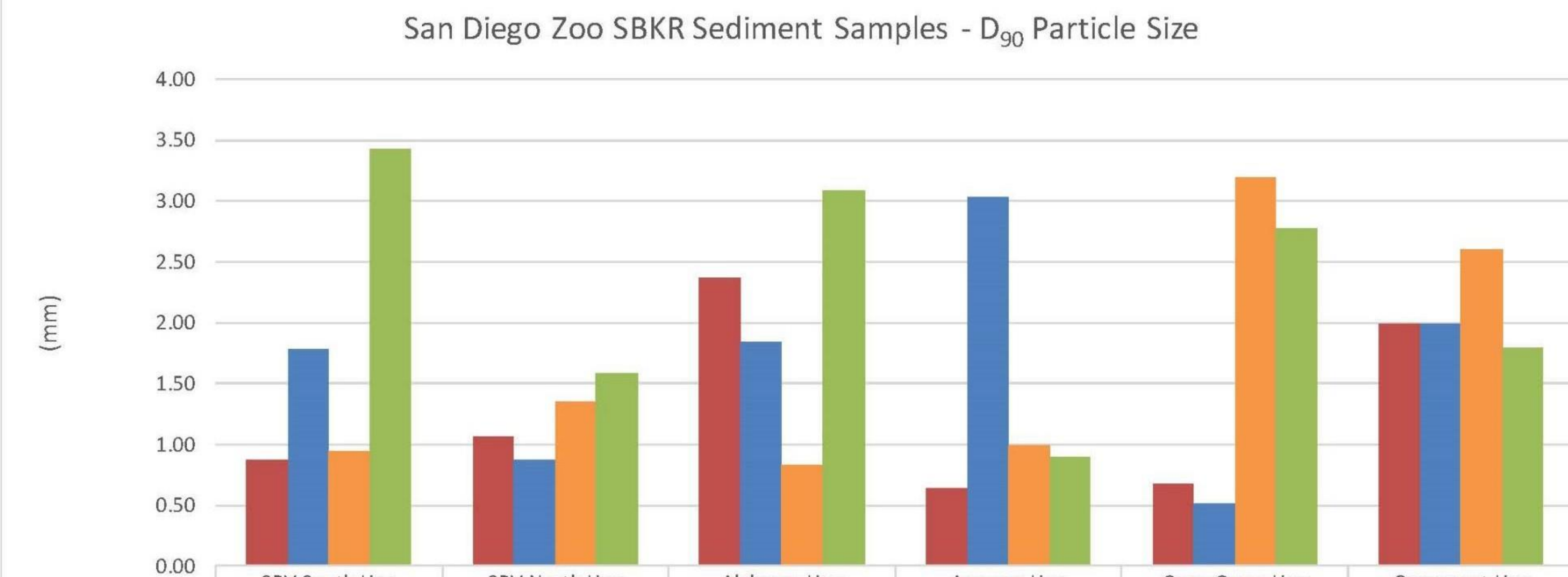


	SBV South Line	SBV North Line	Alabama Line	Amazon Line	Cone Camp Line	Greenspot Line
Transect 1 5m	0.18	0.37	0.92	0.25	0.23	0.80
Transect 1 45m	0.26	0.27	0.66	1.08	0.18	0.86
Transect 2 5m	0.16	0.27	0.36	0.34	1.30	0.61
Transect 2 45m	1.49	0.42	1.01	0.36	0.69	0.69

Figure 4-13. The D_{50} Particle Sizes of the San Diego Zoo 2018 Sediment Samples of SBKR Habitat Suitability



	SBV South Line	SBV North Line	Alabama Line	Amazon Line	Cone Camp Line	Greenspot Line
Transect 1 5m	0.87	1.06	2.37	0.64	0.68	1.99
Transect 1 45m	1.78	0.87	1.85	3.03	0.51	1.99
Transect 2 5m	0.94	1.36	0.83	1.00	3.19	2.60
Transect 2 45m	3.43	1.59	3.08	0.89	2.78	1.80

Figure 4-14. The D_{90} Particle Sizes of the San Diego Zoo 2018 Sediment Samples of SBKR Habitat Suitability

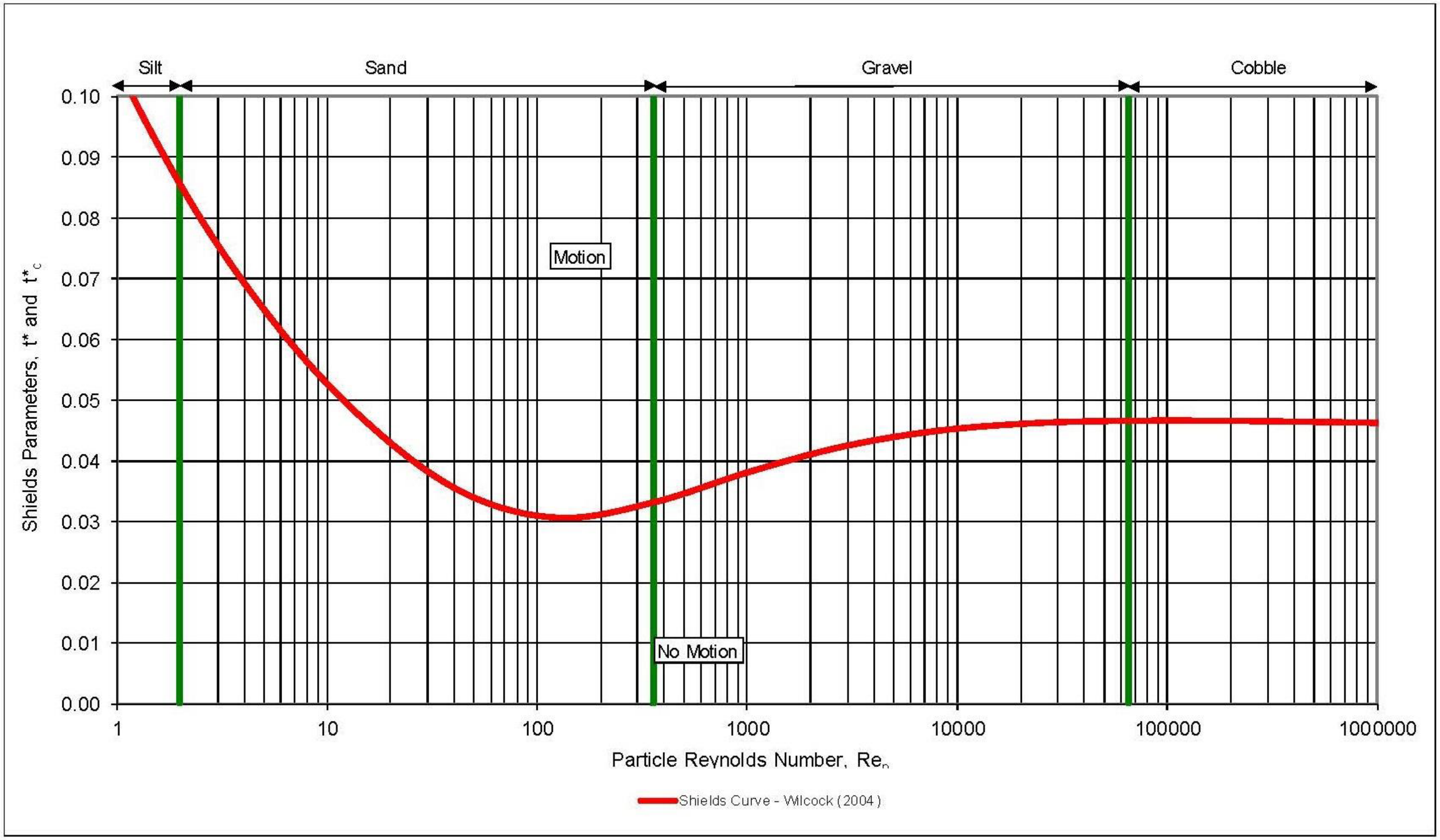


Figure 4-15. The Dimensionless Shields Curve for Incipient Motion of Sediment Used in this Study

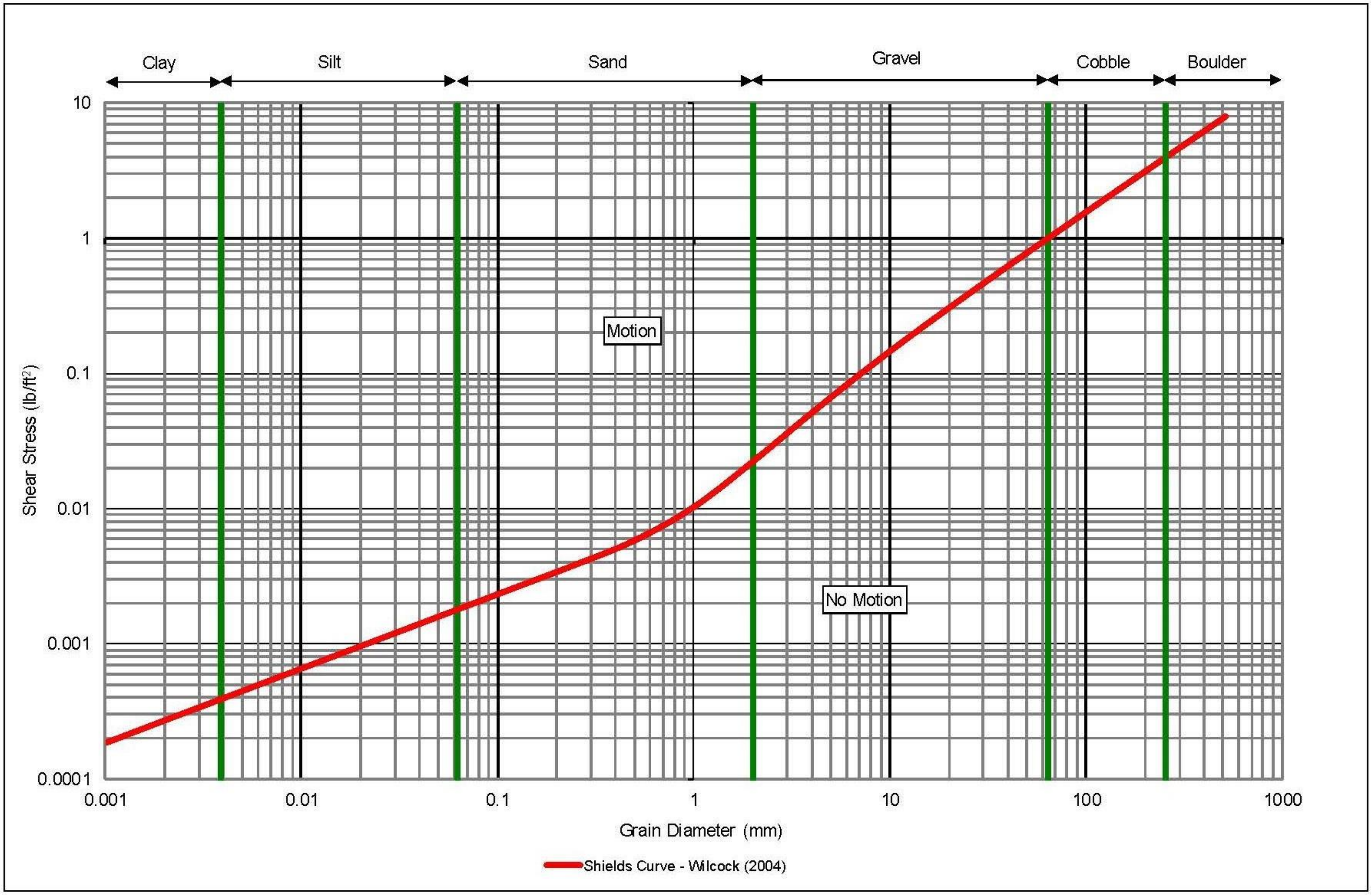
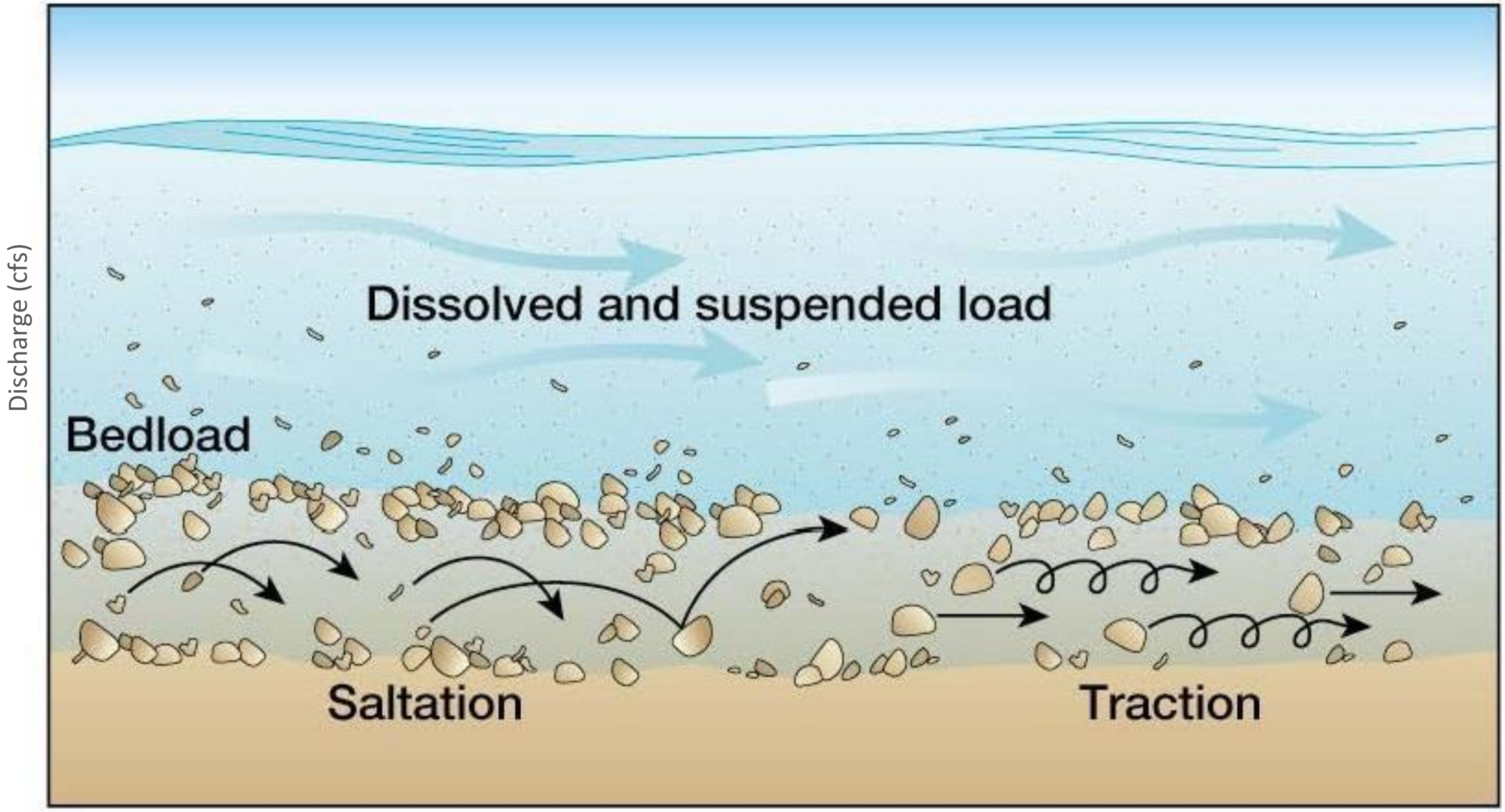


Figure 4-16. The Dimensional Shields Curve for Incipient Motion of Sediment Used in this Study



Source: http://www.geologyin.com/2016/01/how-do-streams-transport-and-deposit.html

Figure 4-17. Illustration of Bedload and Suspended Load Modes of Sediment Transport

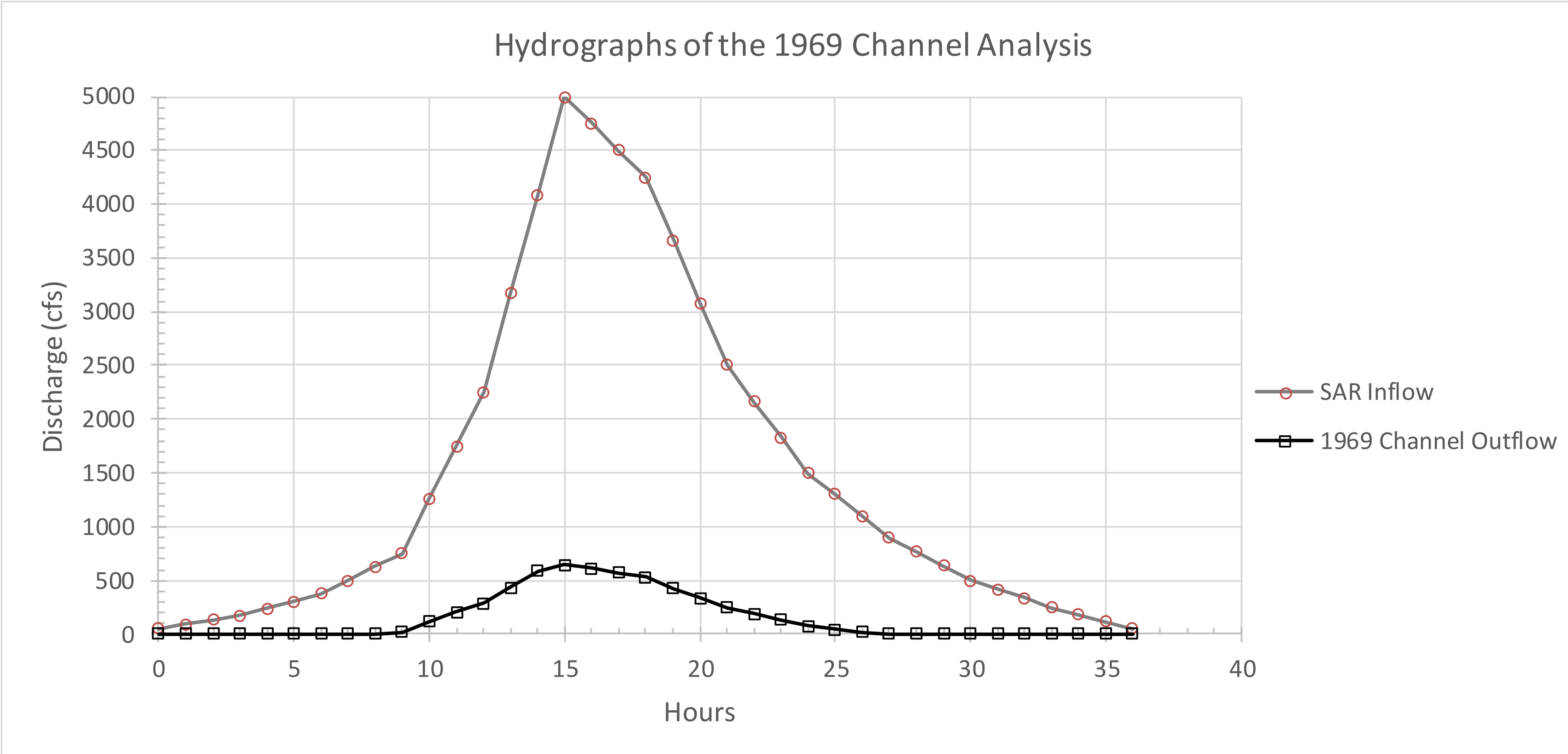


Figure 4-18. Relationship of the Amount of Water that Would be Diverted into the 1969 Channel Based on Total Santa Ana River Inflow

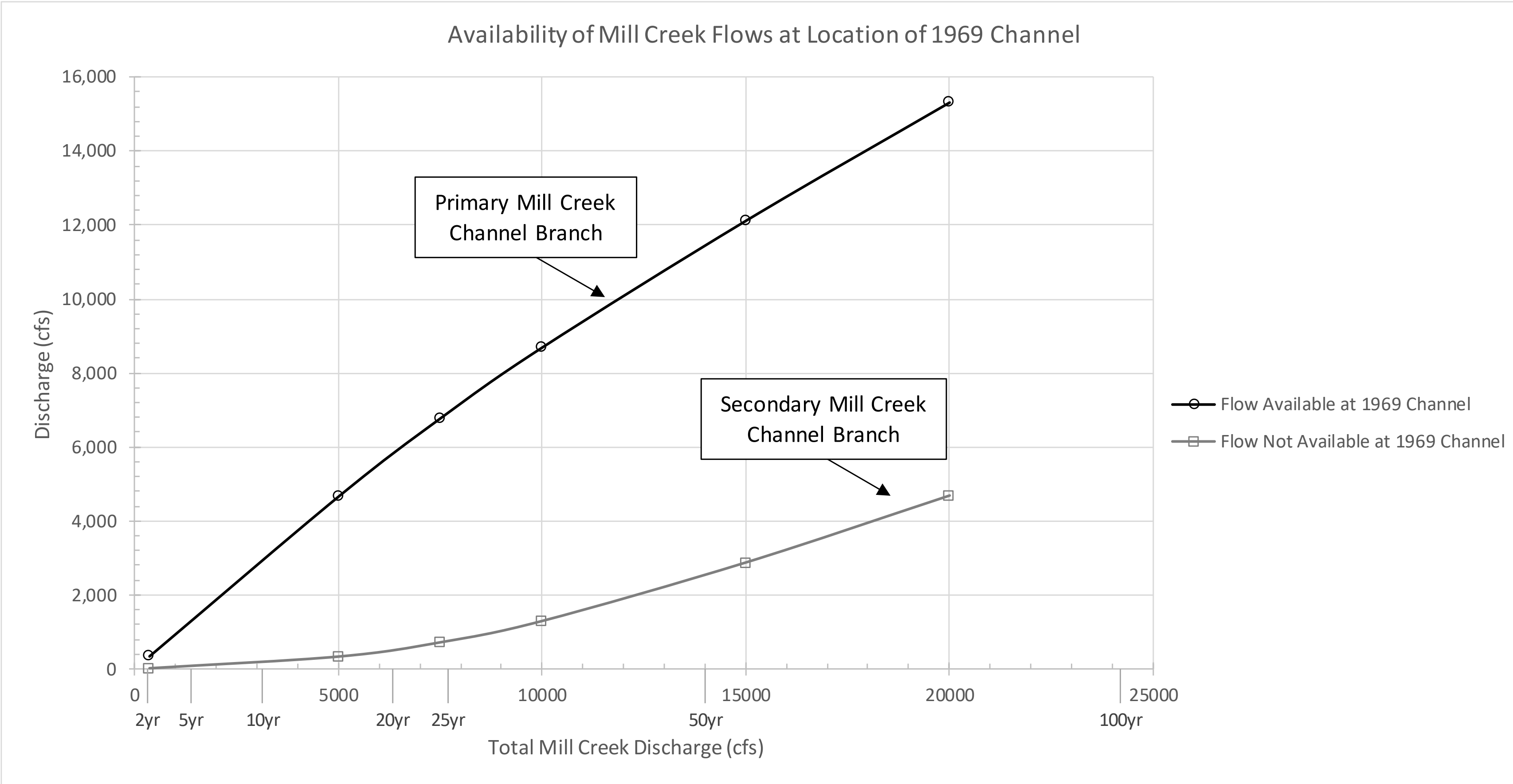


Figure 4-19. Relationship between Total Mill Creek Flow and Flow Conveyance in the Primary and Secondary Channels

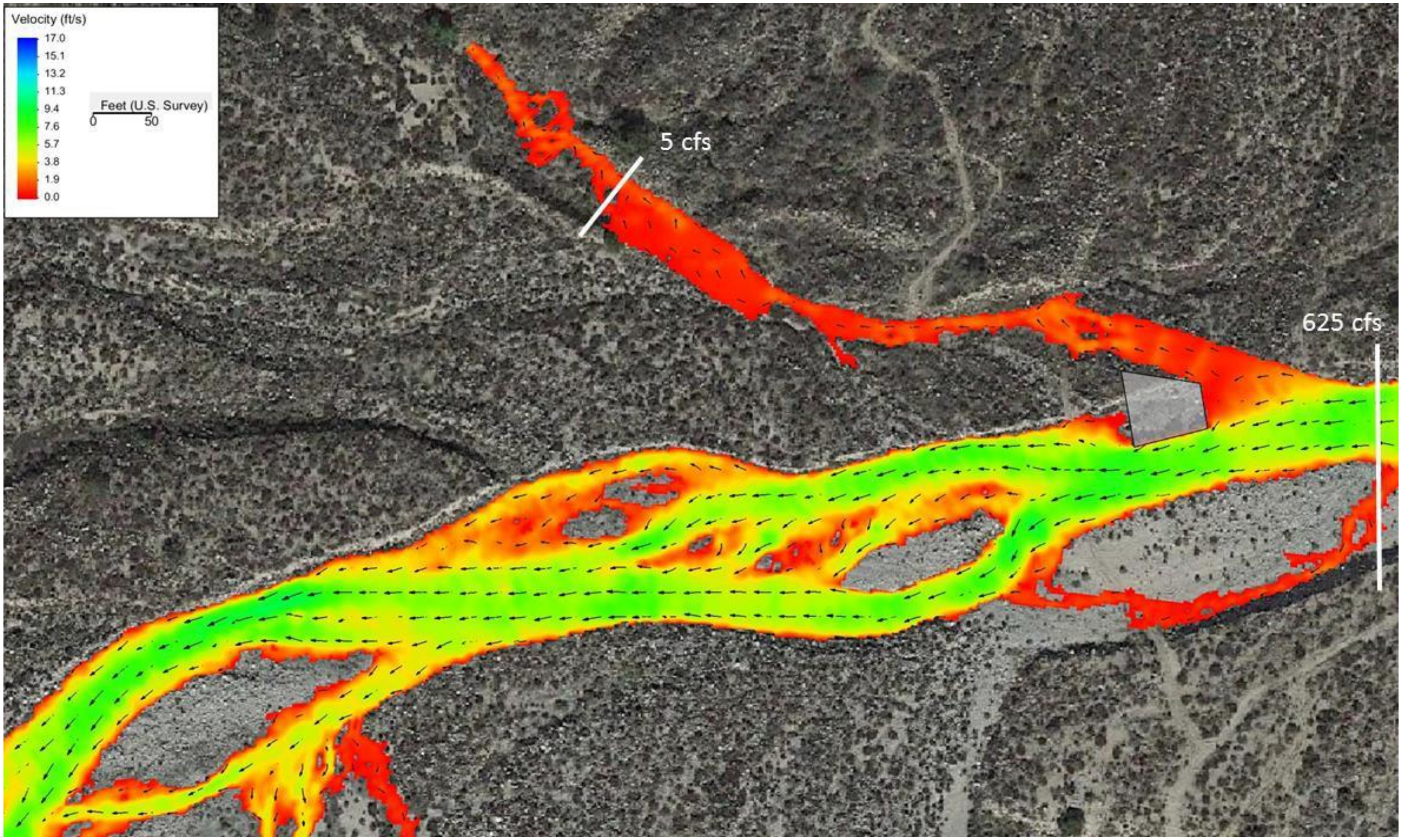


Figure 4-20. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 8 Hours on the Hydrograph

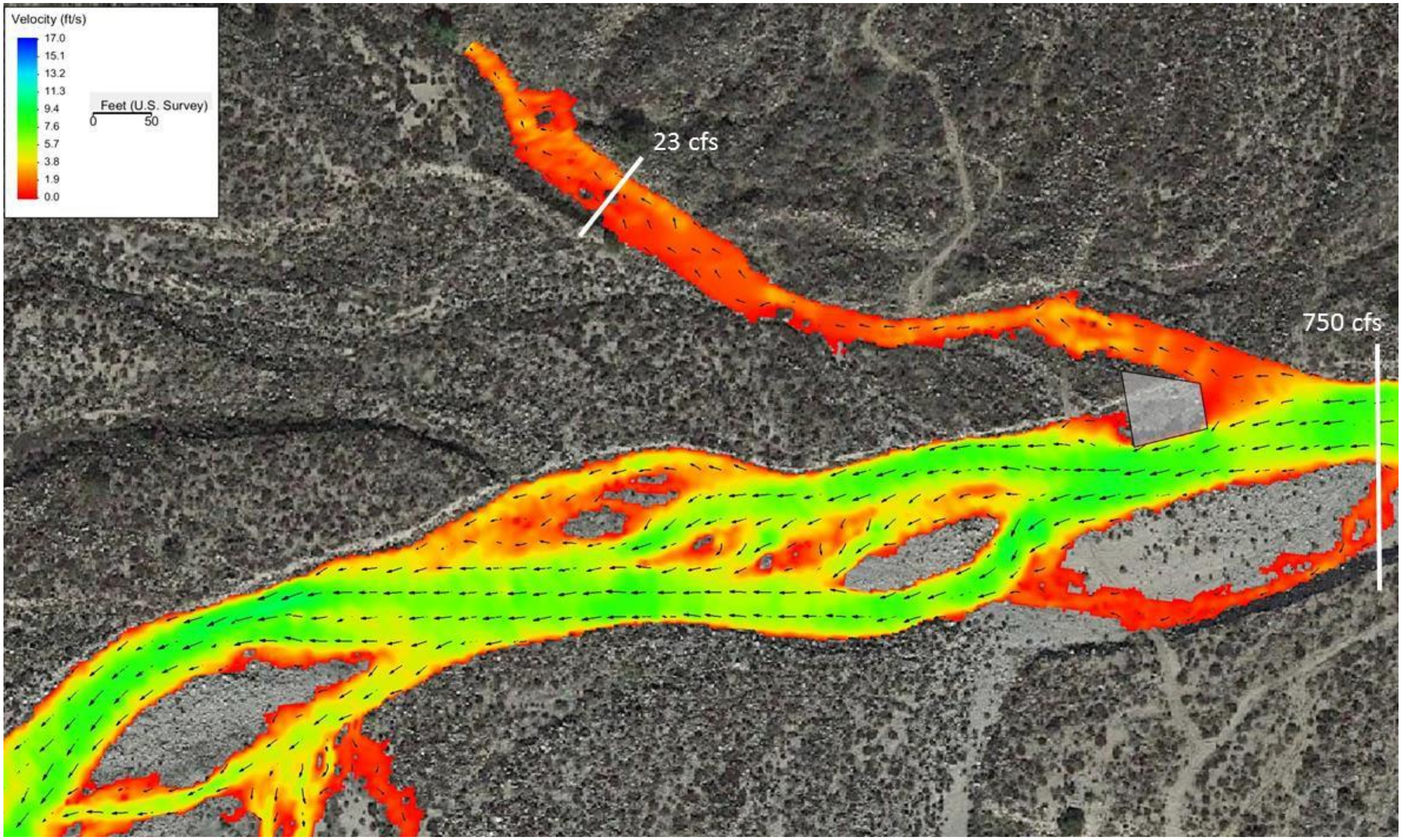


Figure 4-21. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 9 Hours on the Hydrograph

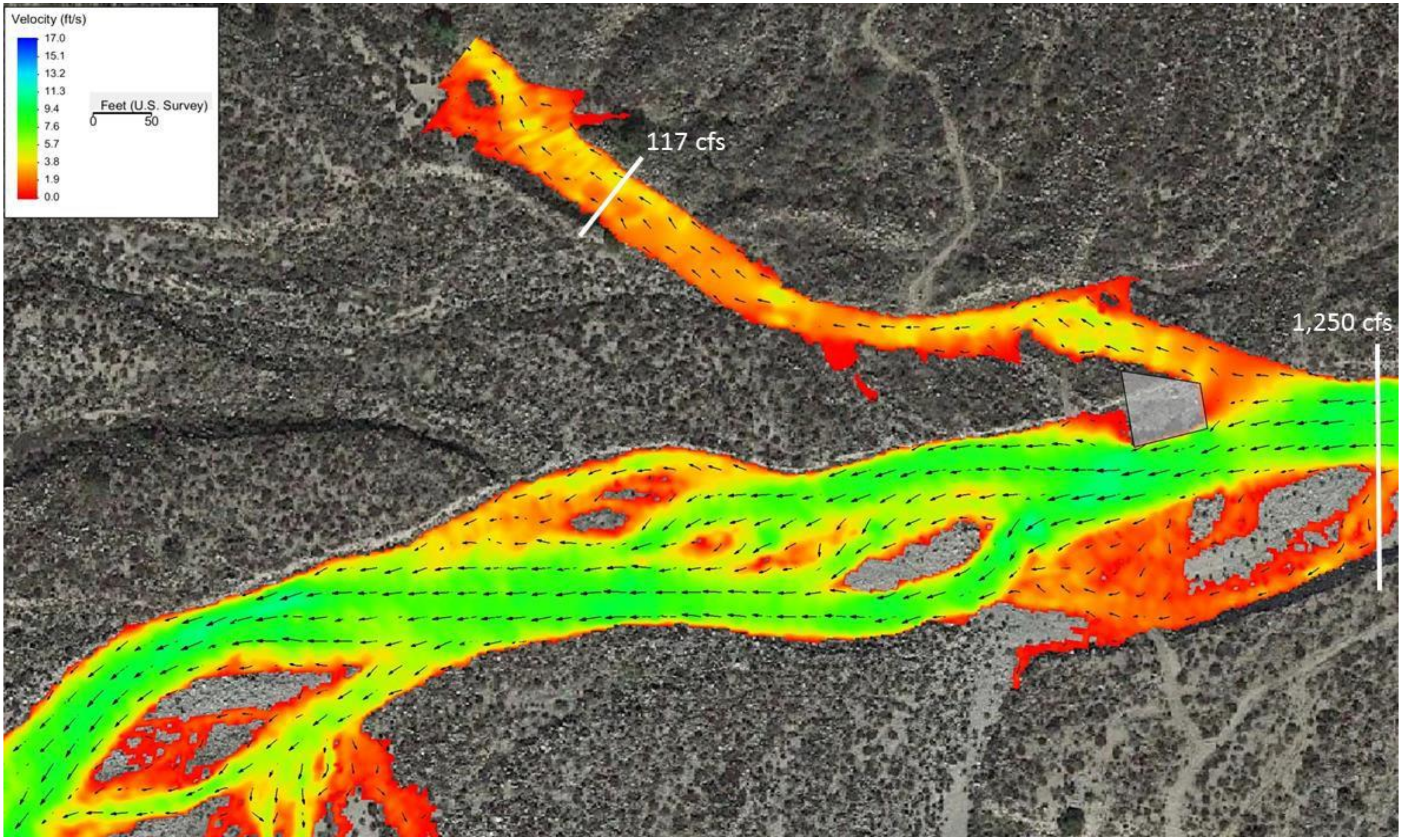


Figure 4-22. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 10 Hours on the Hydrograph

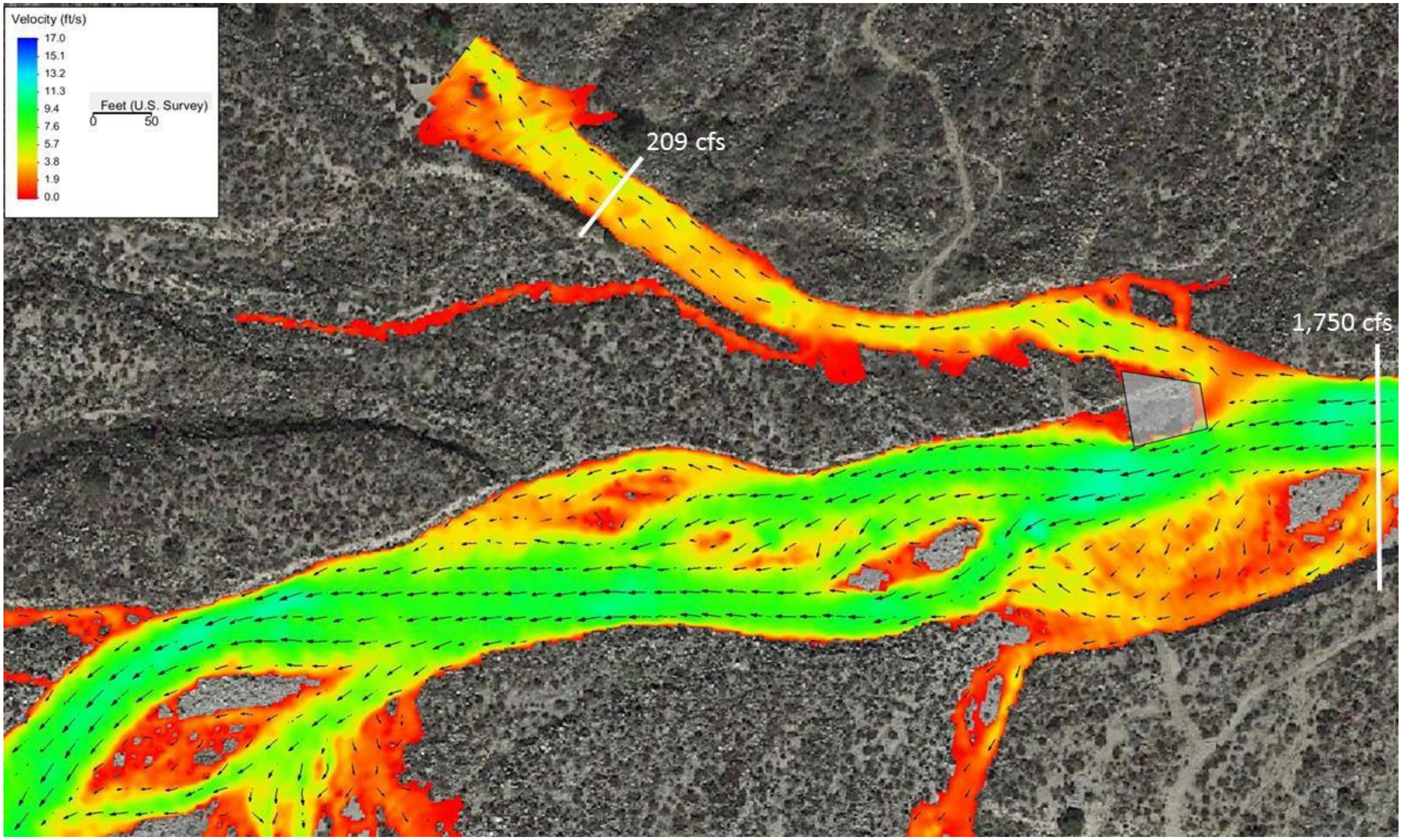


Figure 4-23. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 11 Hours on the Hydrograph

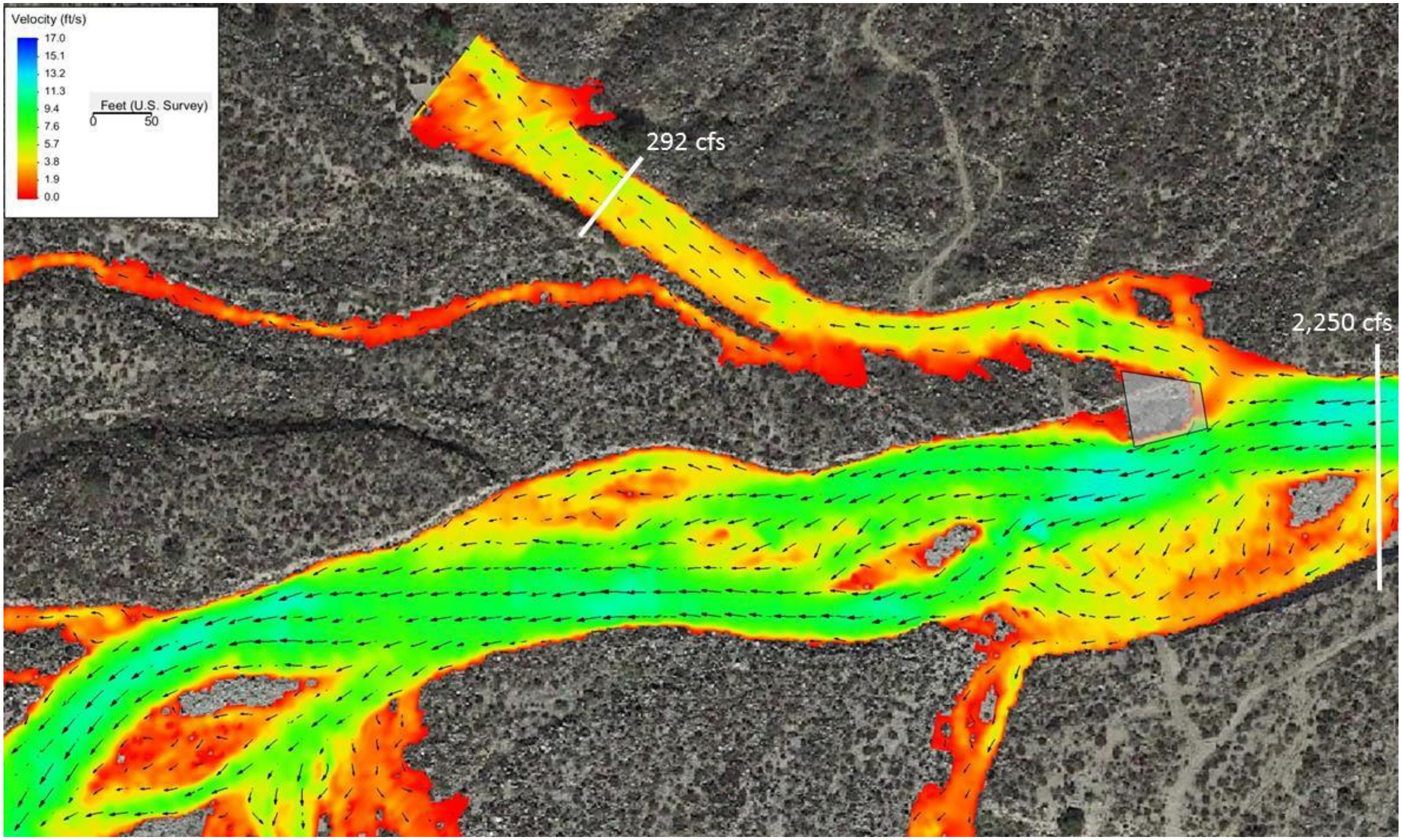


Figure 4-24. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 12 Hours on the Hydrograph

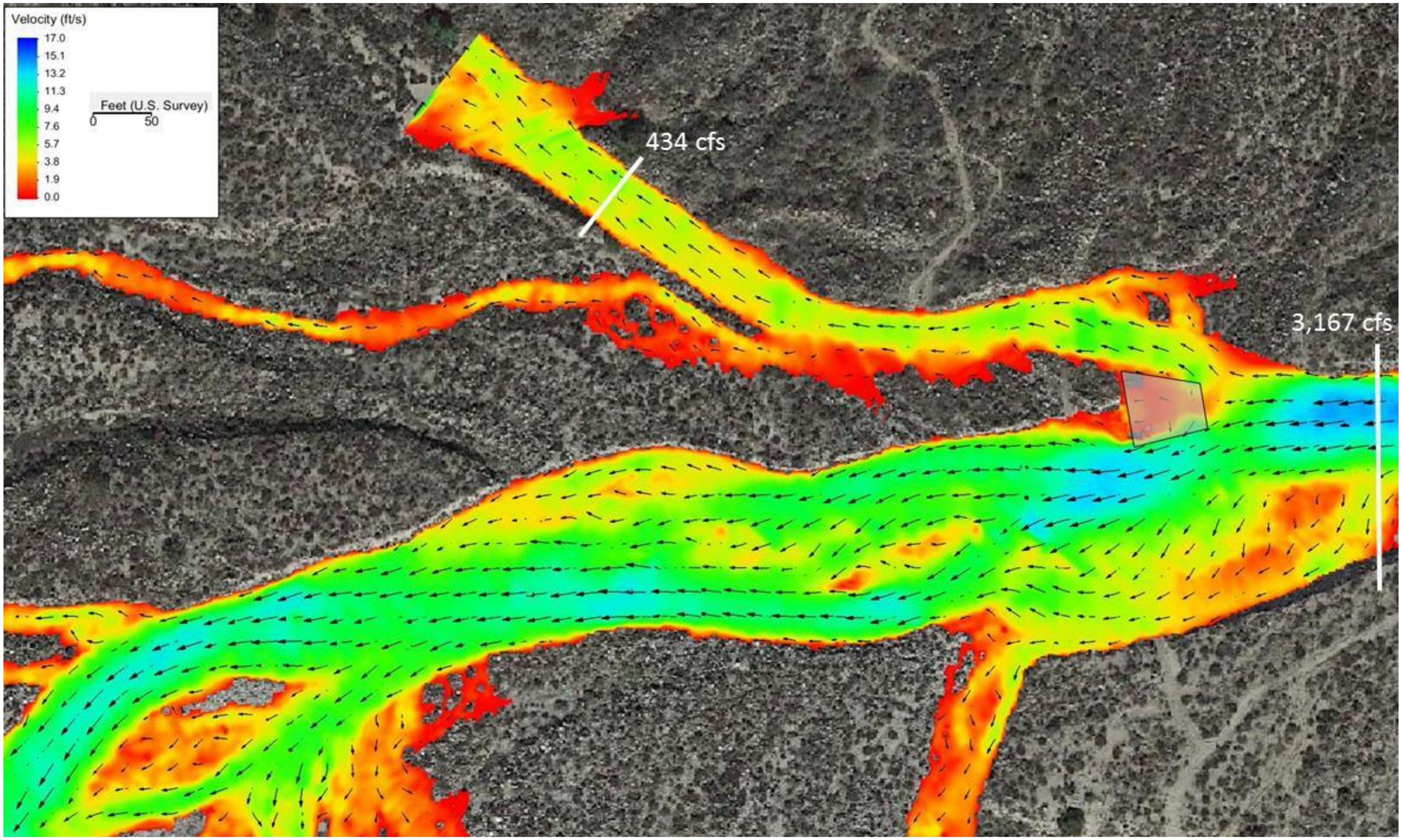


Figure 4-25. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 13 Hours on the Hydrograph

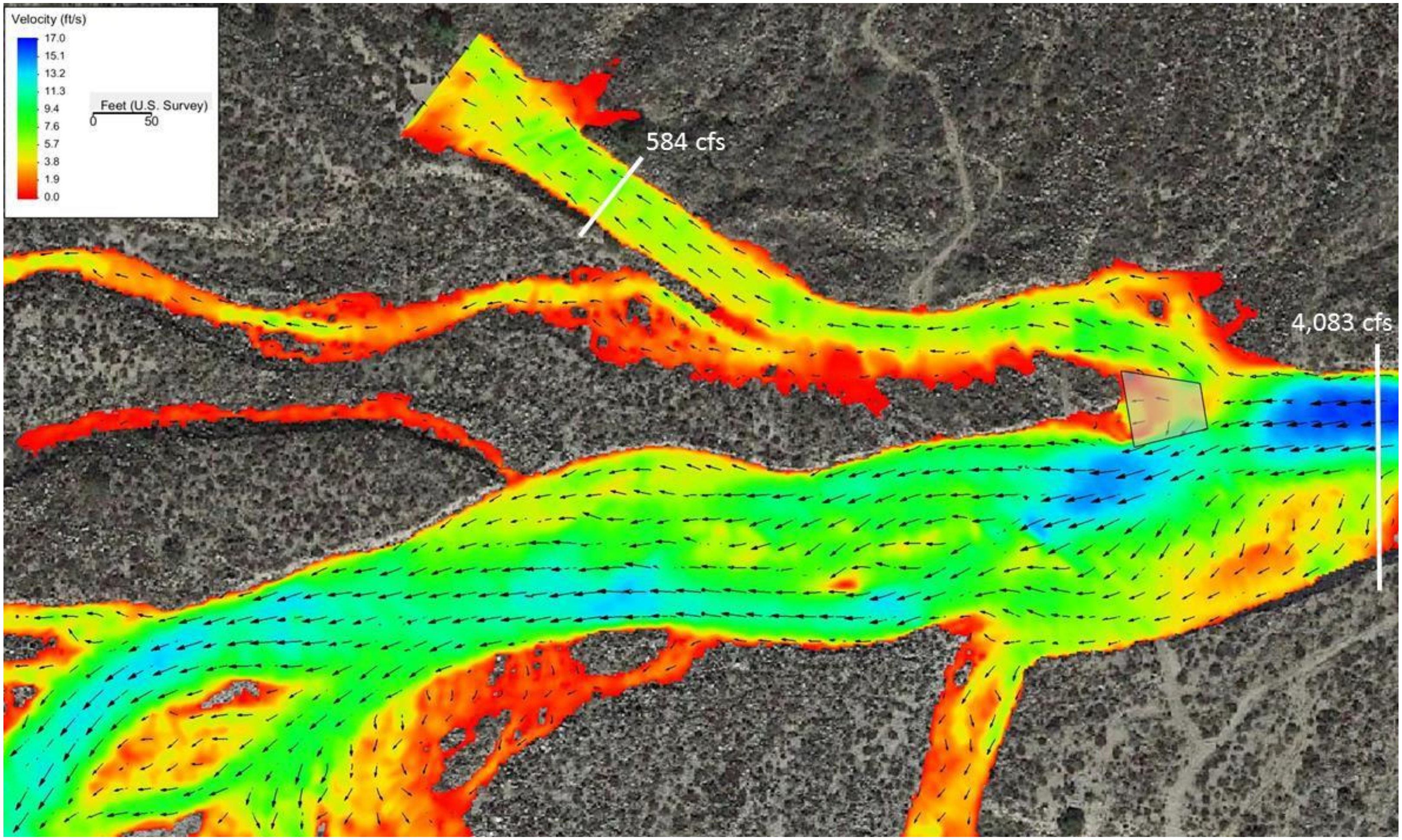


Figure 4-26. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 14 Hours on the **Hydrograph**

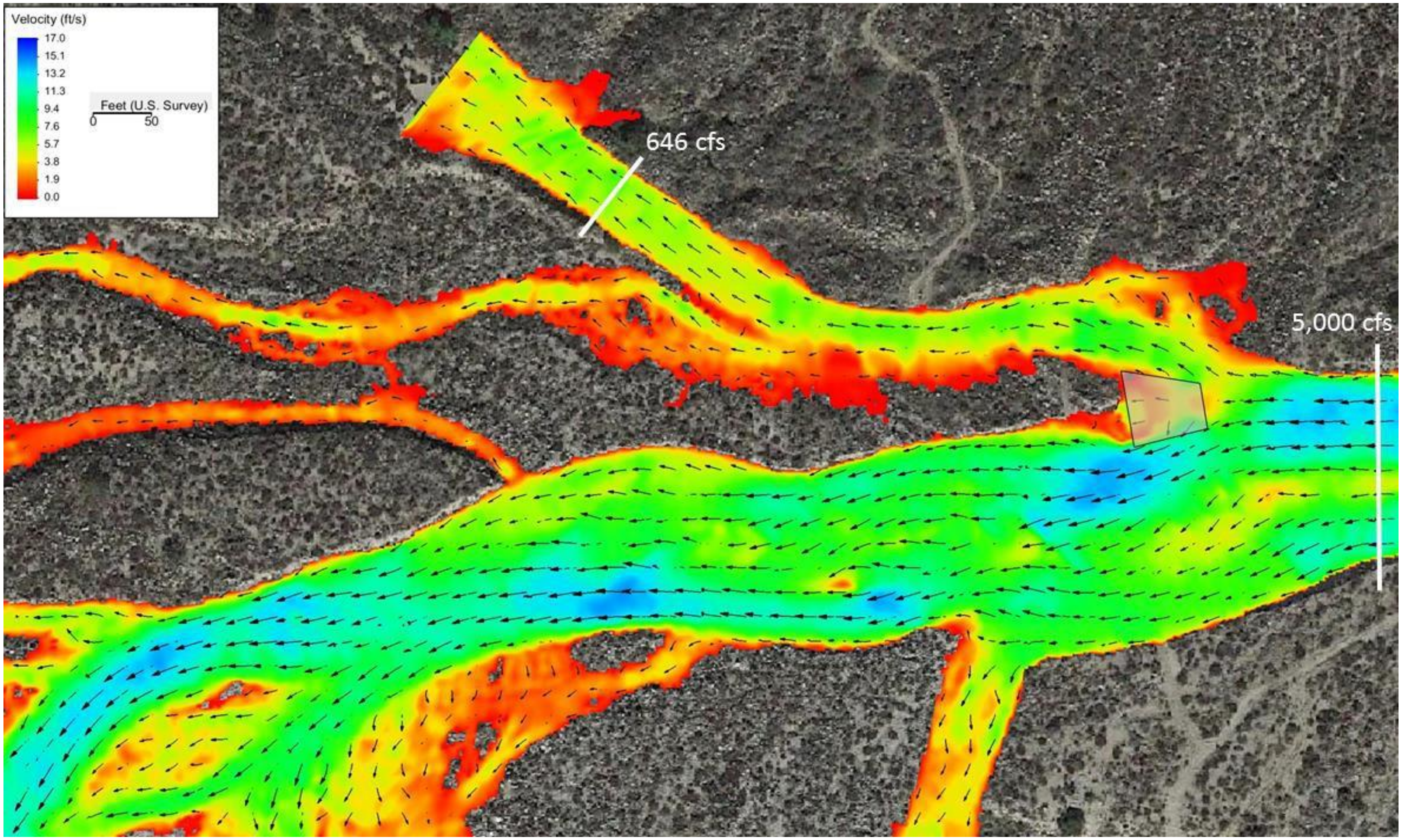


Figure 4-27. Modeled Flow Velocities and Discharge Distributions at the 1969 Channel Entrance for Time-Step 15 Hours on the Hydrograph

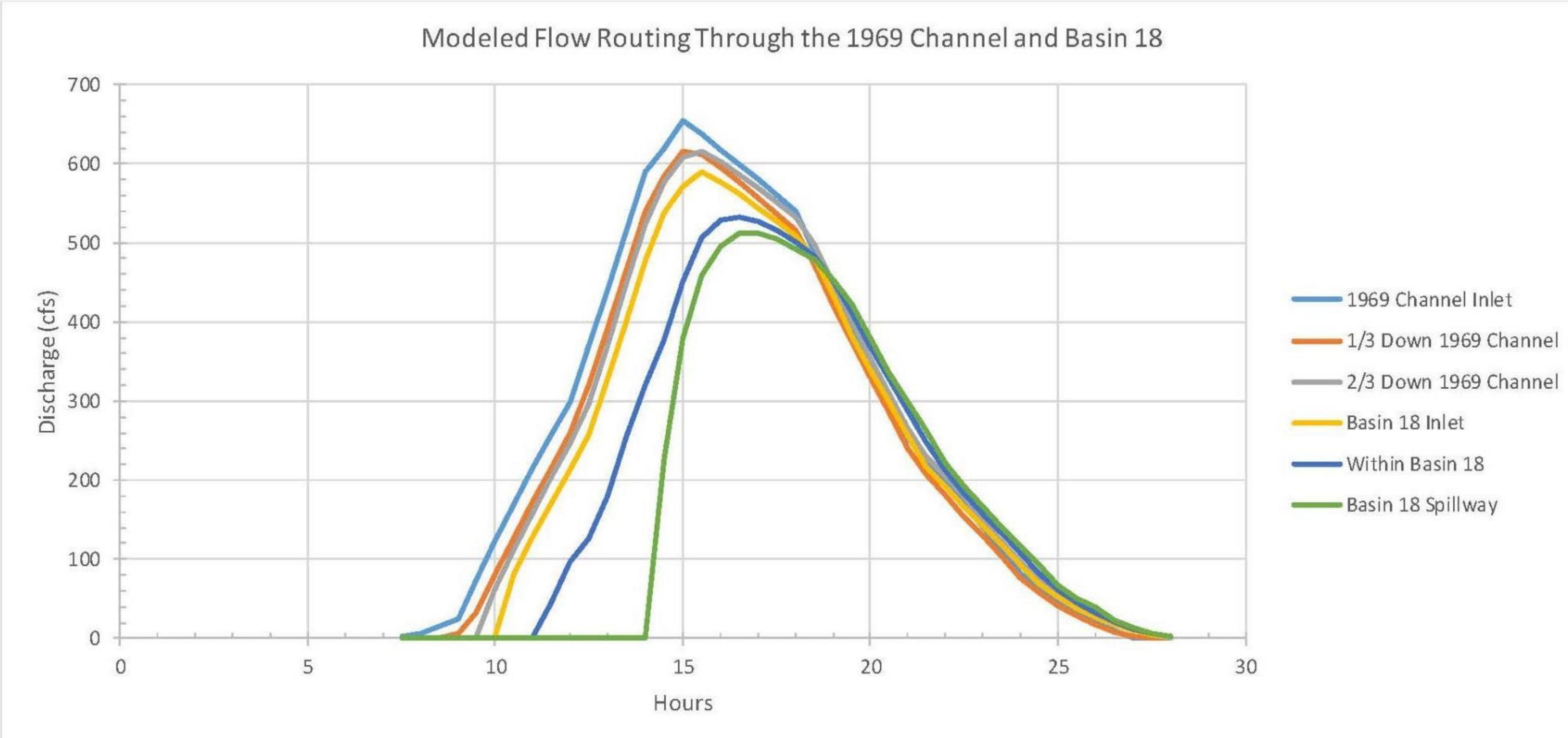


Figure 4-28. Routing of the Modeled Hydrograph through the 1969 Channel and Basin 18

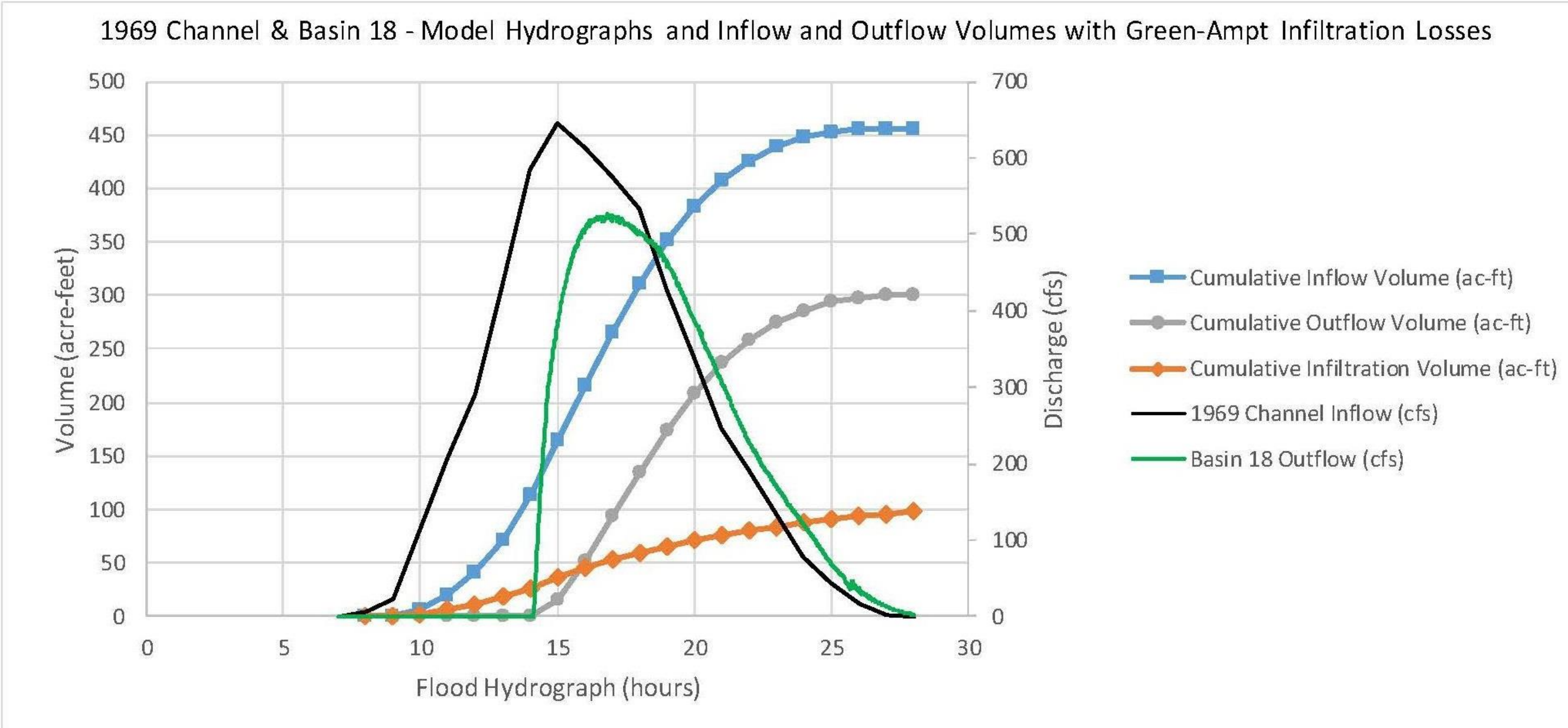


Figure 4-29. Modeled 1969 Channel and Basin 18 Hydrographs and Inflow and Outflow Volumes with Green-Ampt Infiltration Losses

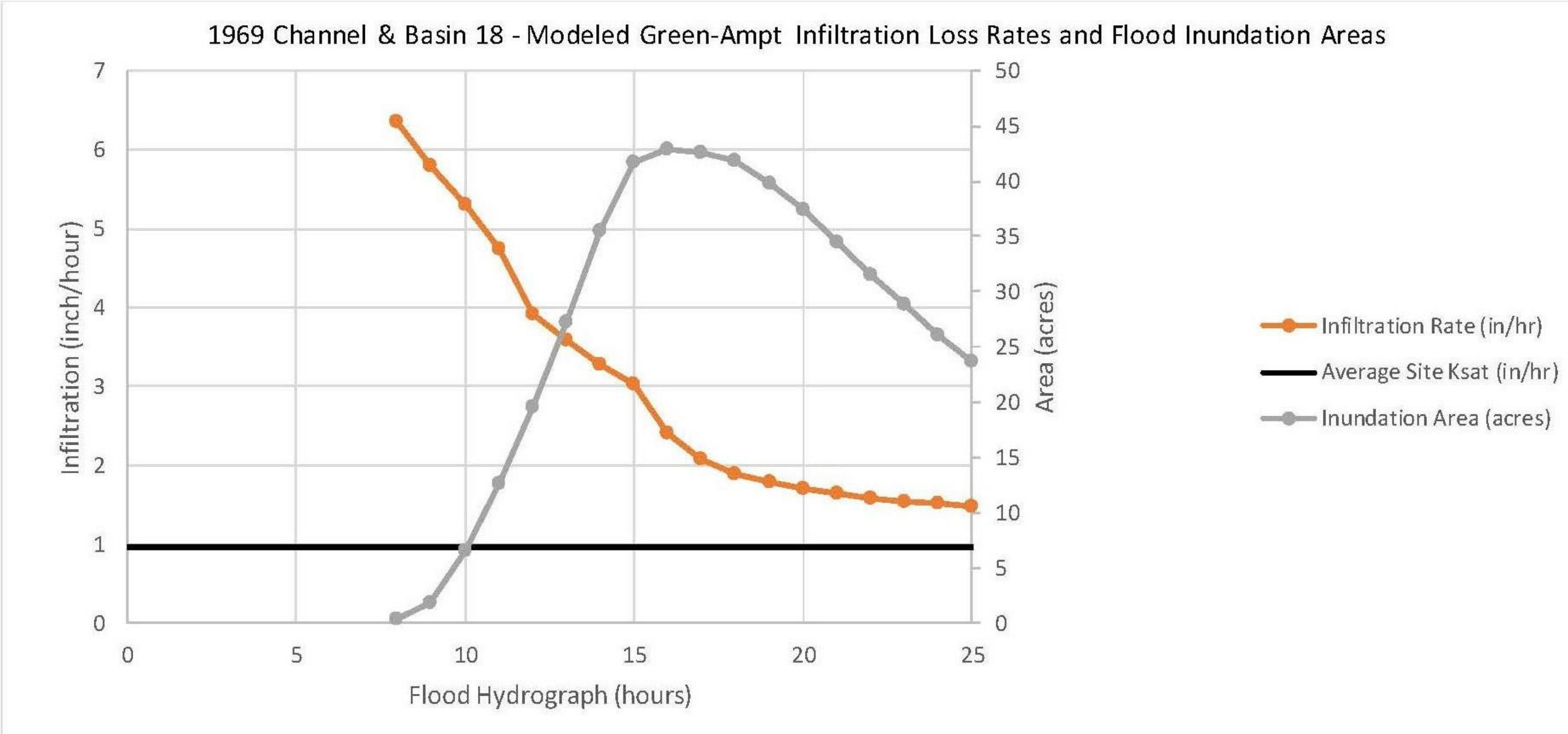


Figure 4-30. Modeled Green-Ampt Loss Rates and Flood Inundation Areas for the 1969 Channel and Basin 18

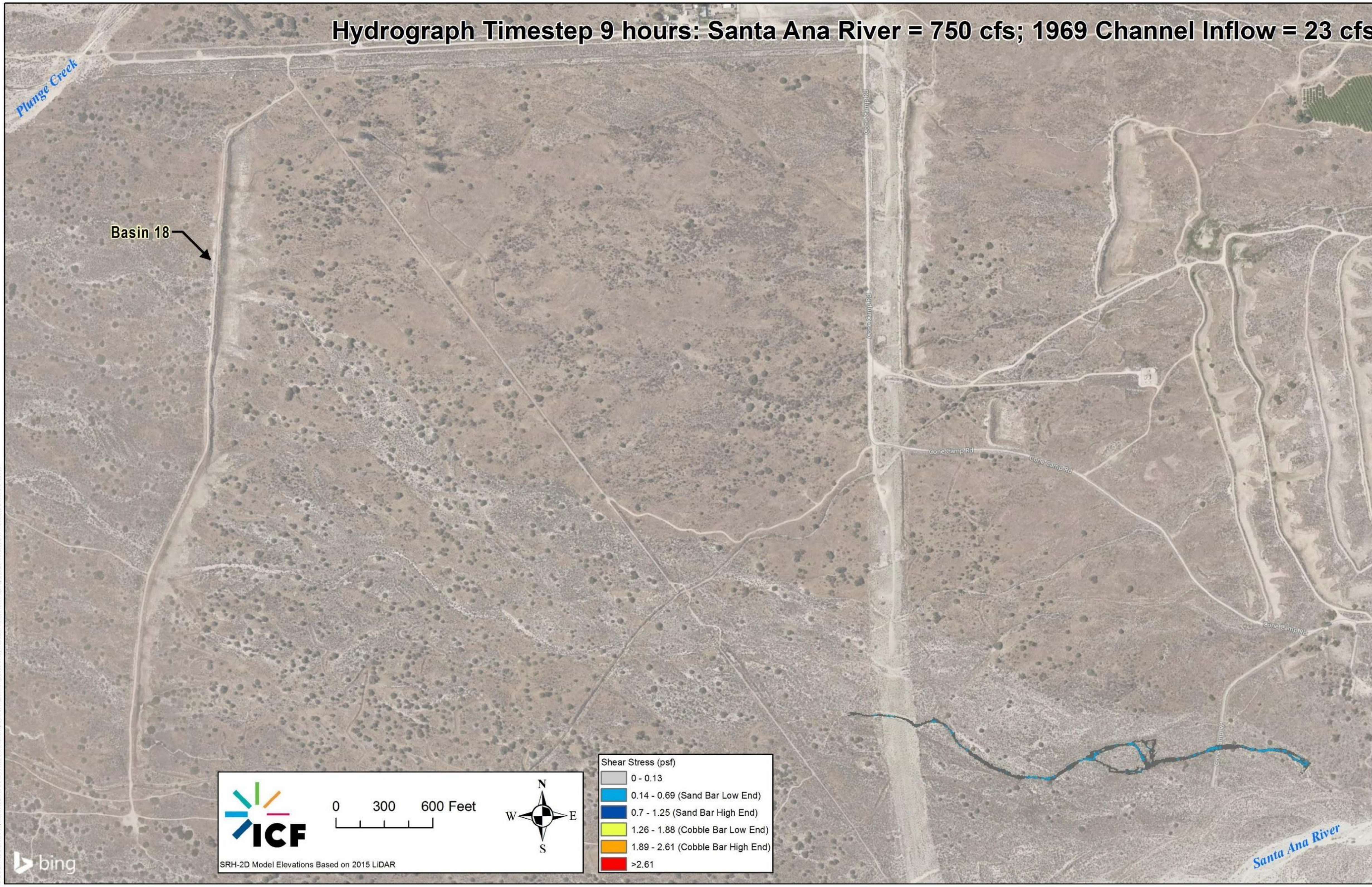


Figure 4-31. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 23 cfs

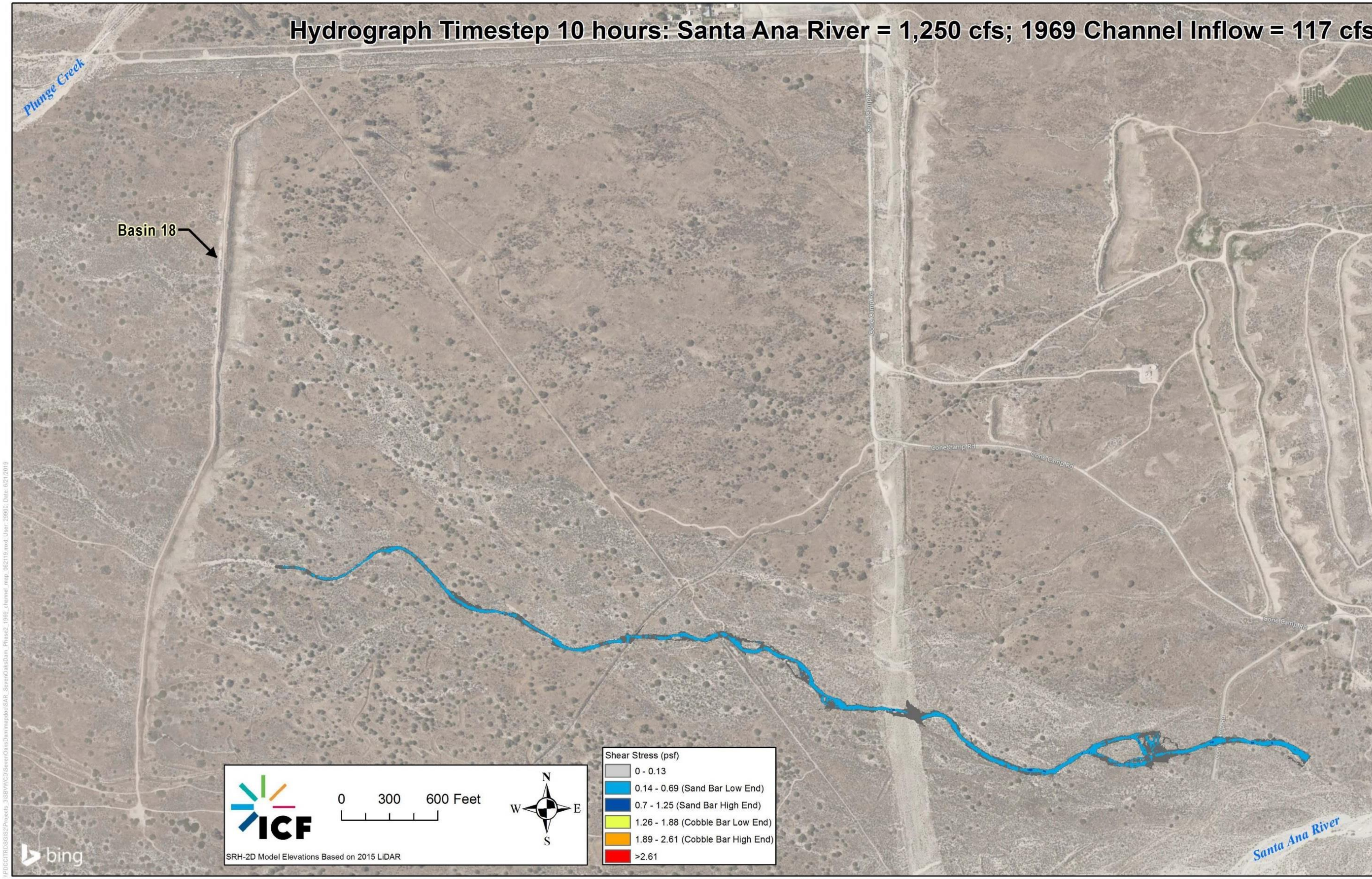


Figure 4-32. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 117 cfs

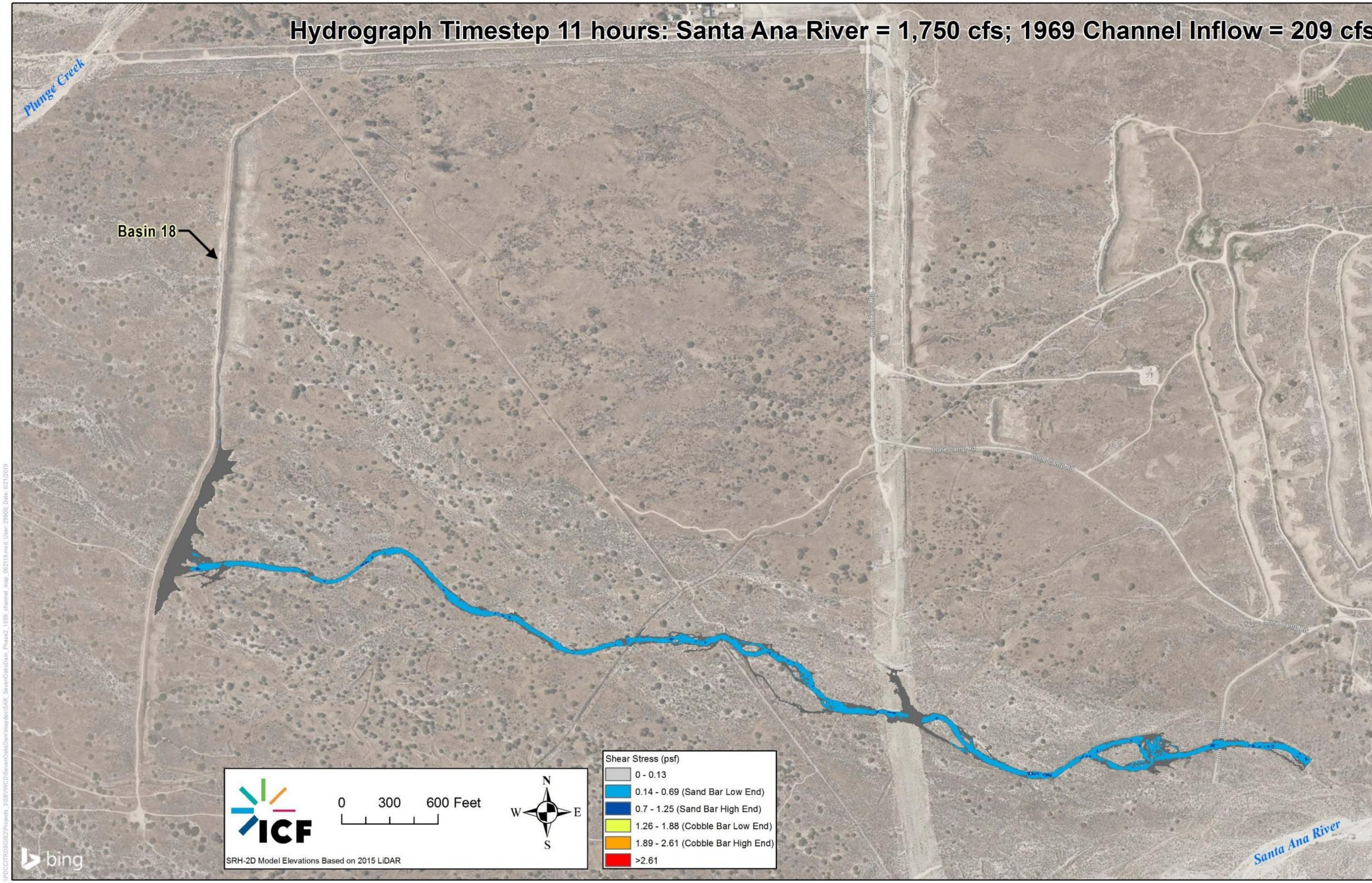


Figure 4-33. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 209 cfs

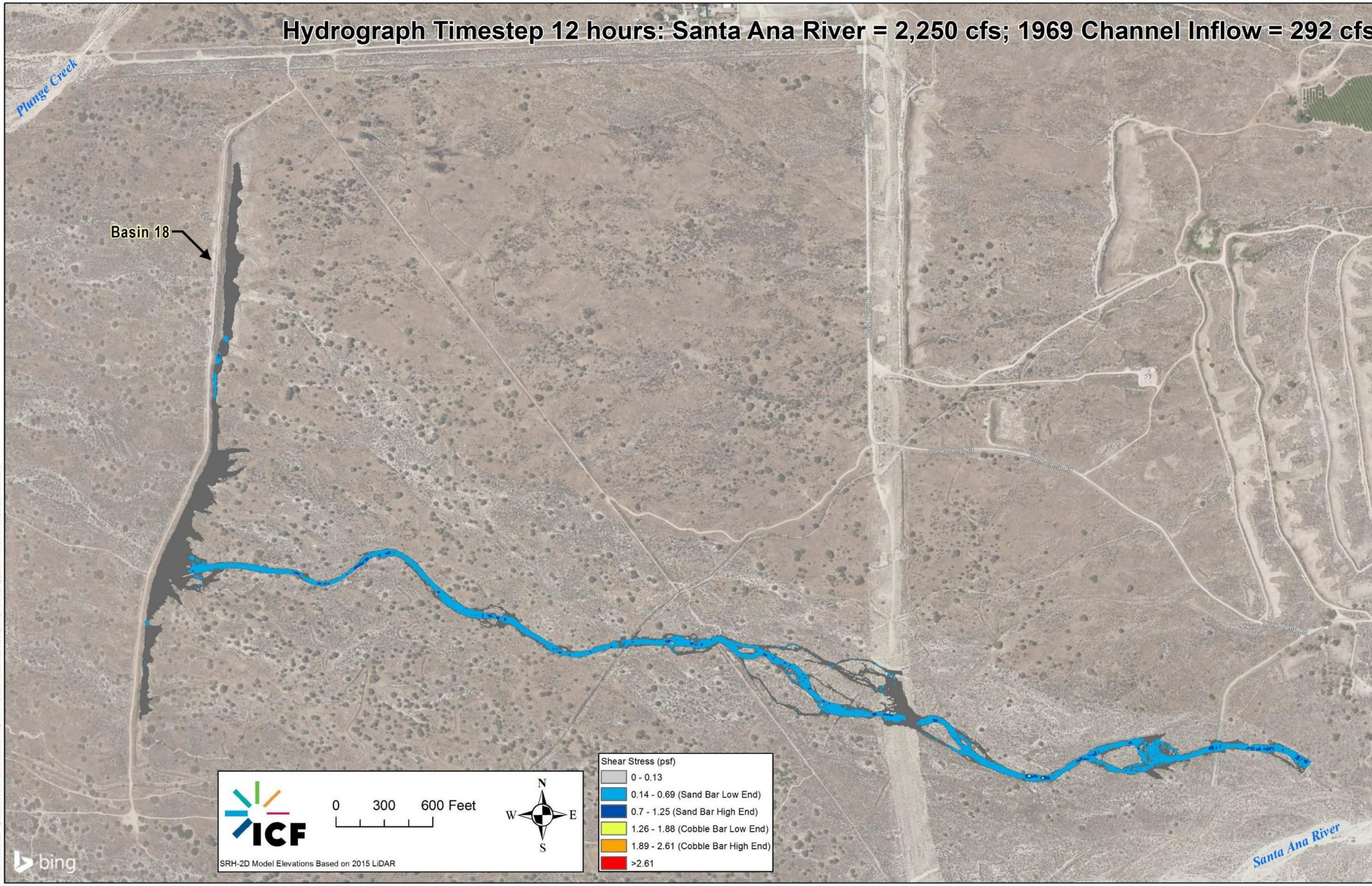


Figure 4-34. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 292 cfs

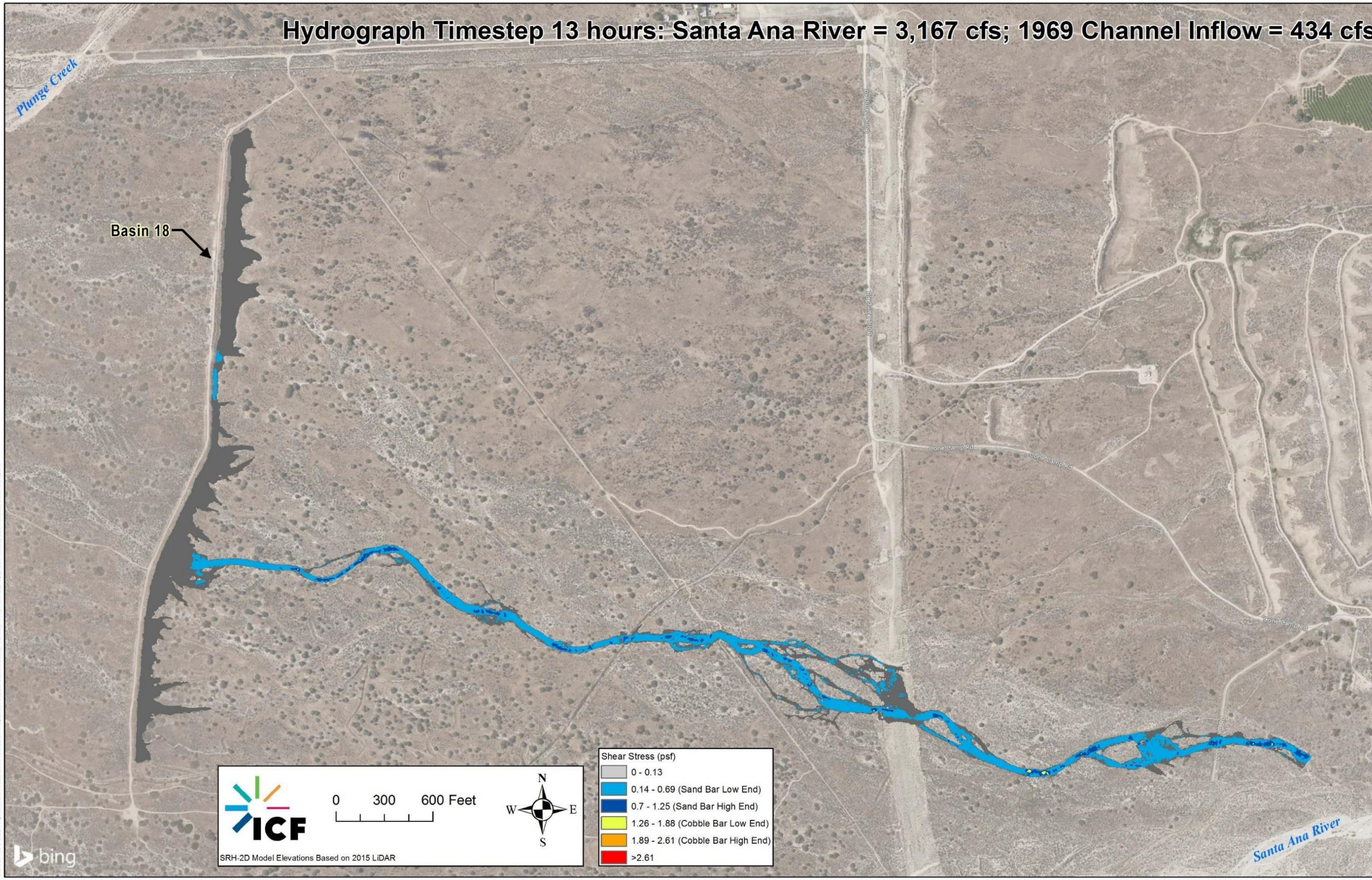


Figure 4-35. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 434 cfs

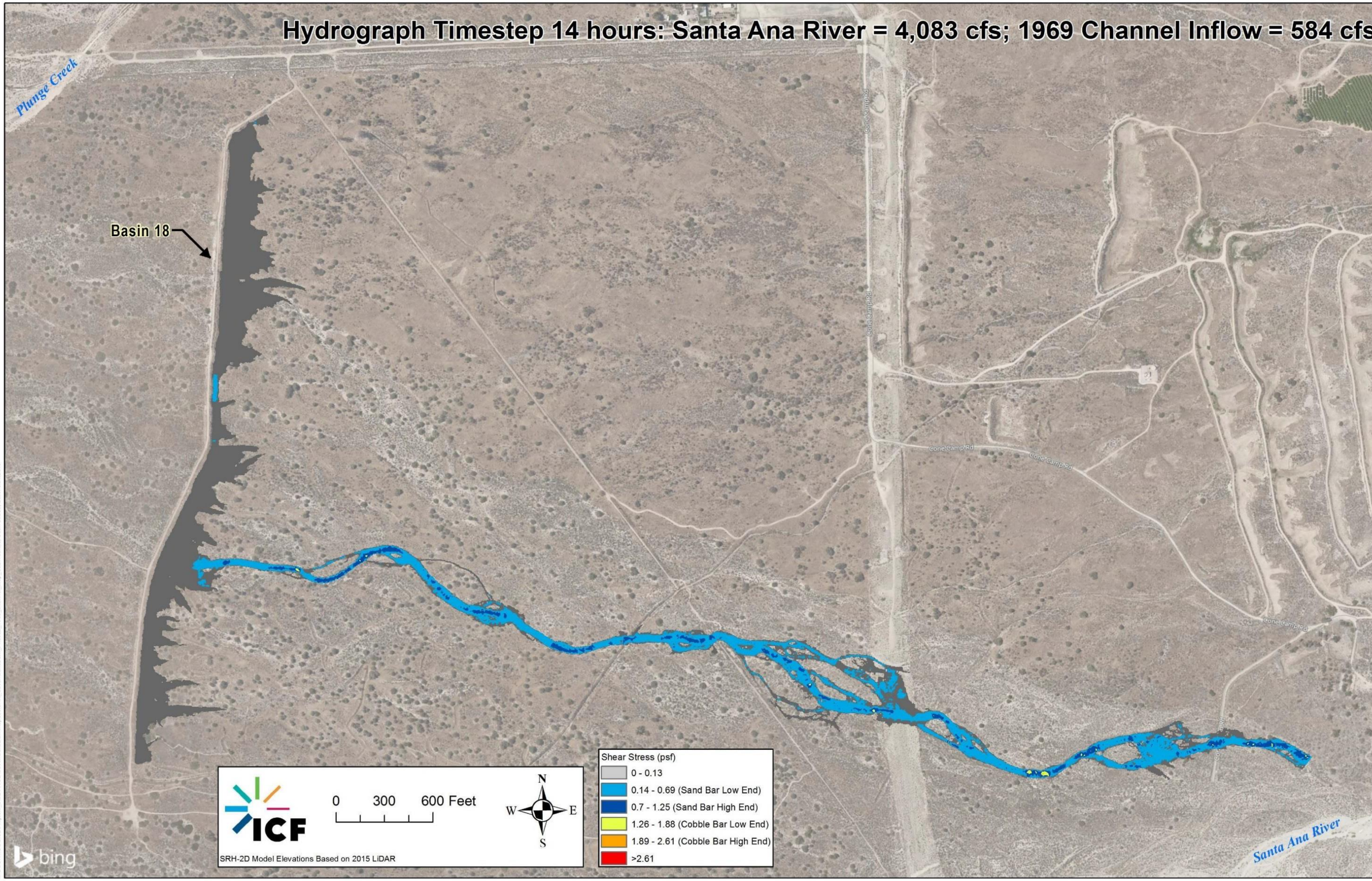


Figure 4-36. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 584 cfs

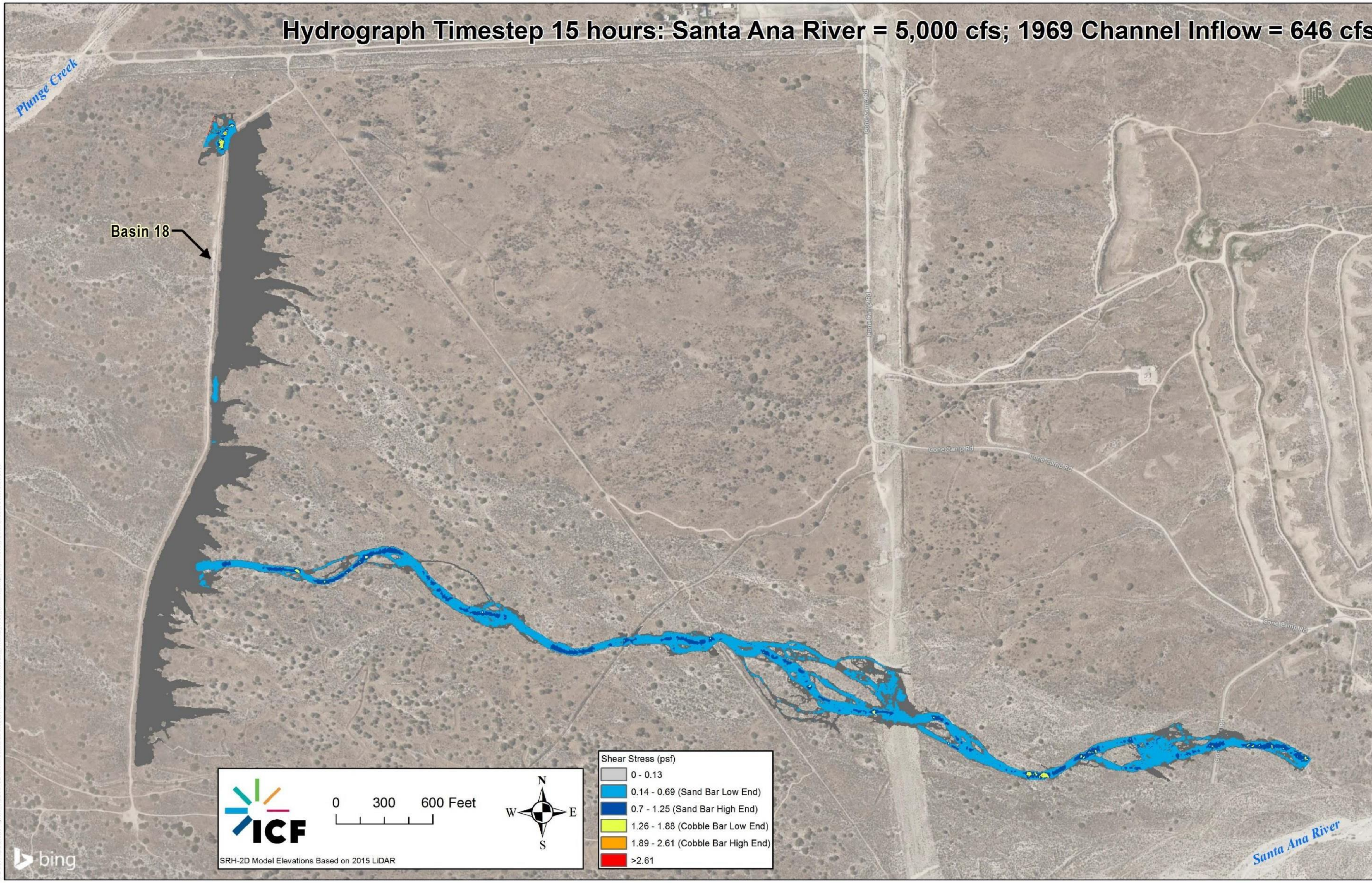


Figure 4-37. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 646 cfs

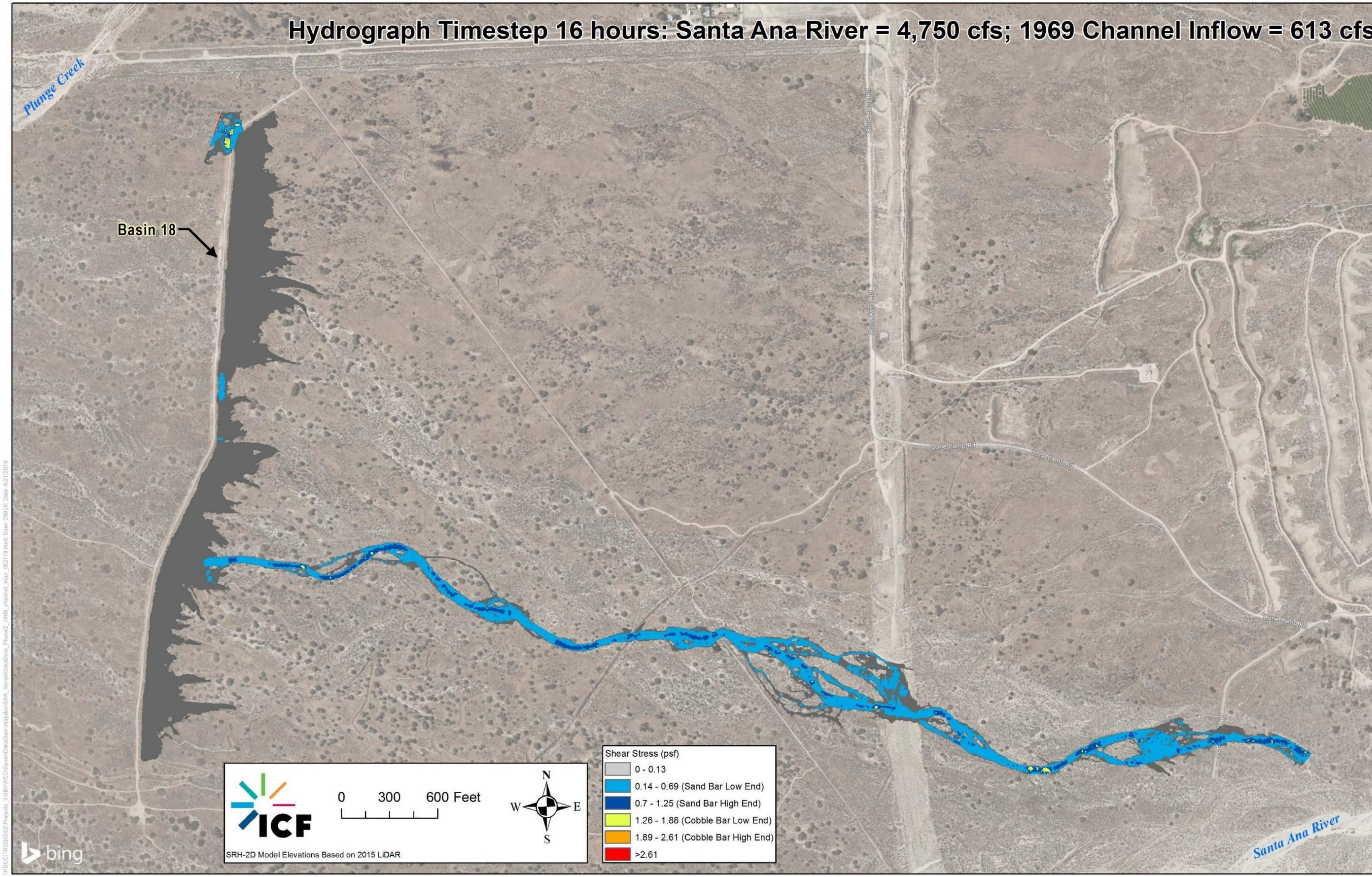


Figure 4-38. Predicted Types of Bar Migration in the 1969 Channel at Inflow of 613 cfs

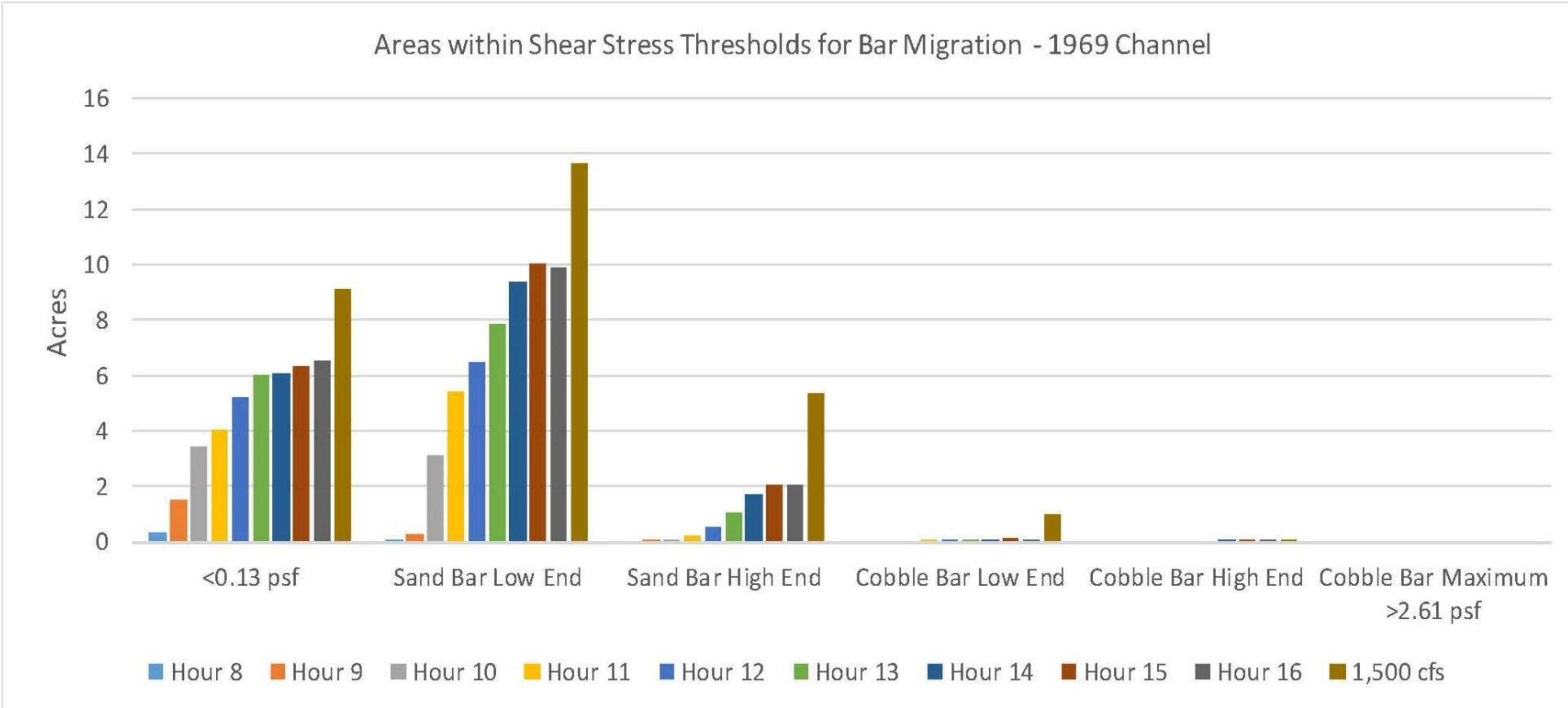


Figure 4-39. Acreages of the 1969 Channel within Shear Stress Thresholds for Bar Migration

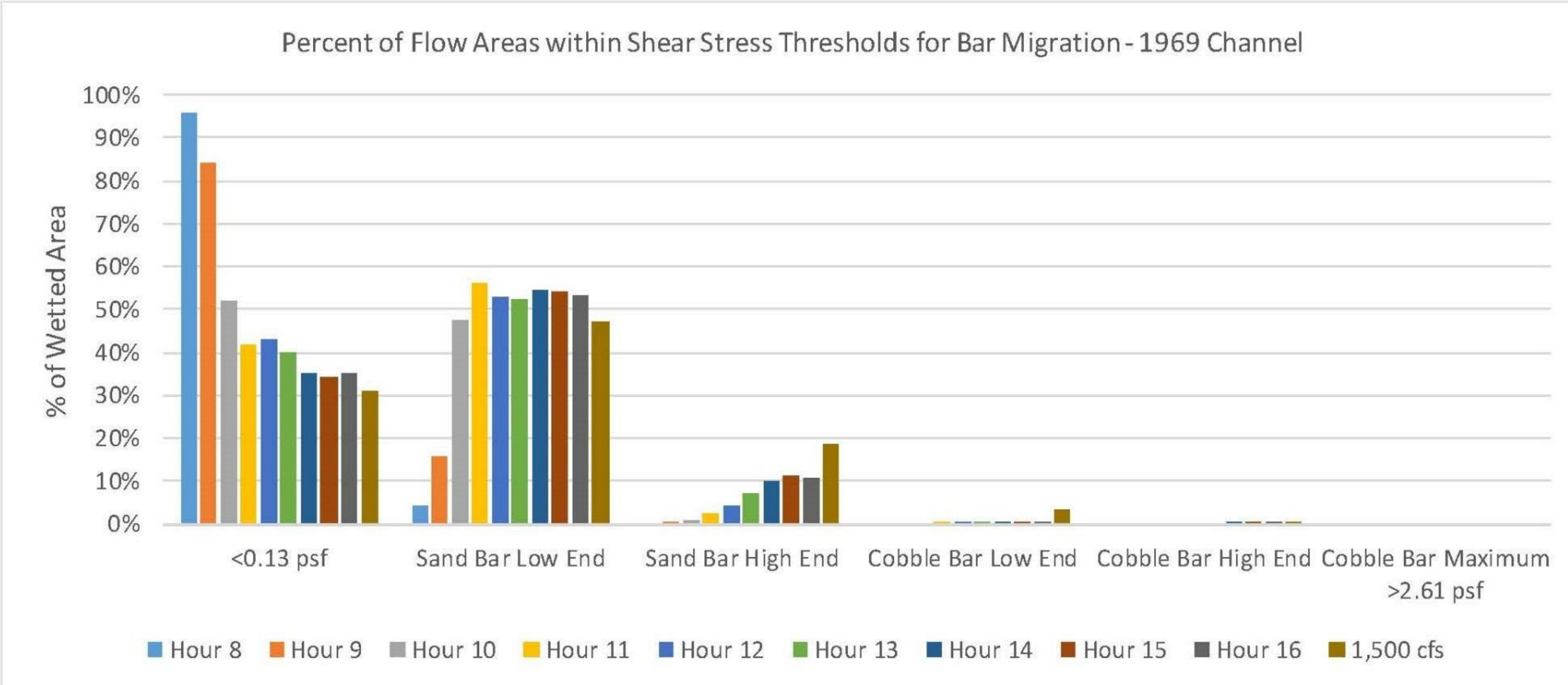


Figure 4-40. Percent of Flow Areas of the 1969 Channel within Shear Stress Thresholds for Bar Migration

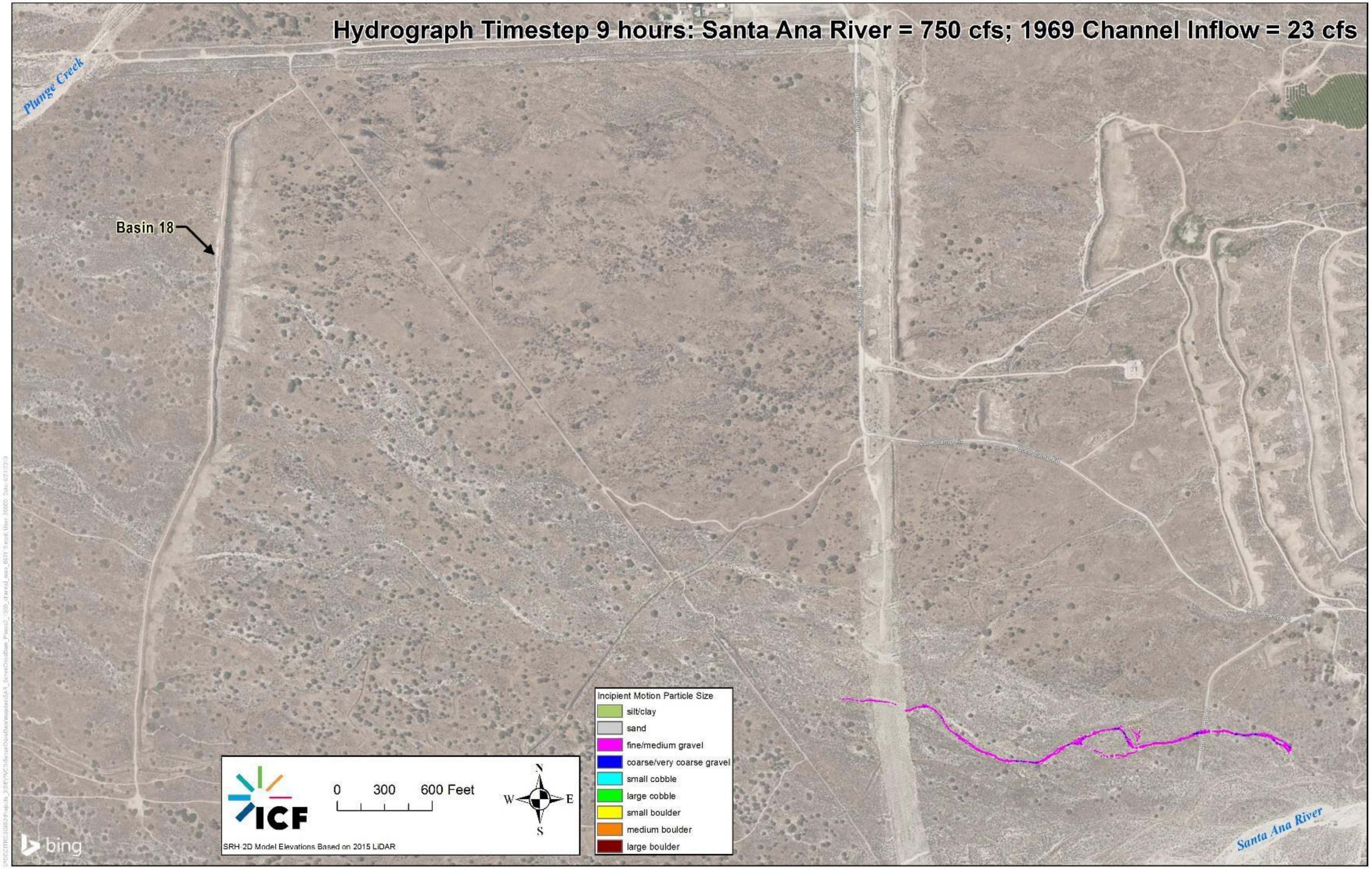


Figure 4-41. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 23 cfs

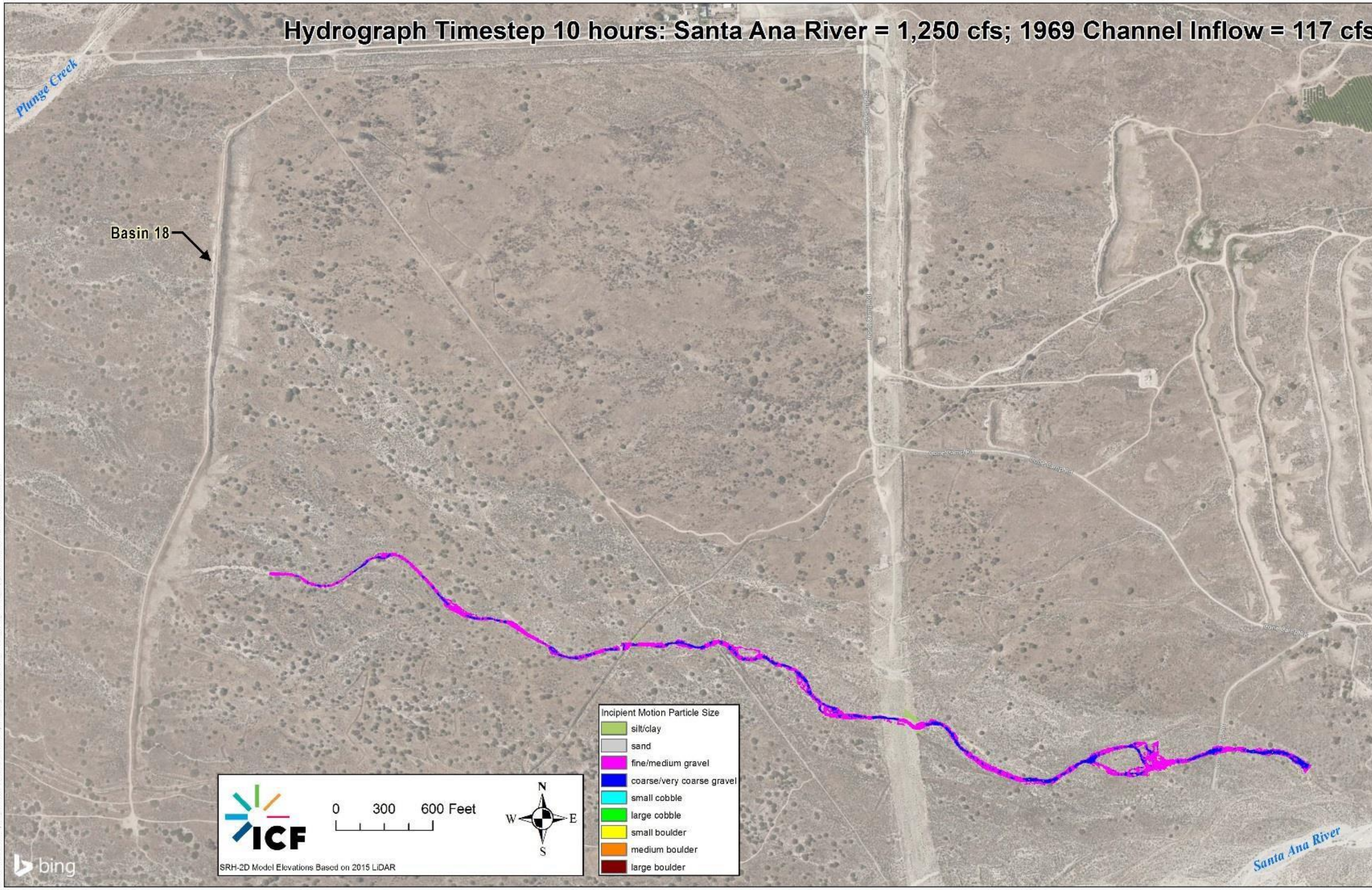


Figure 4-42. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 117 cfs

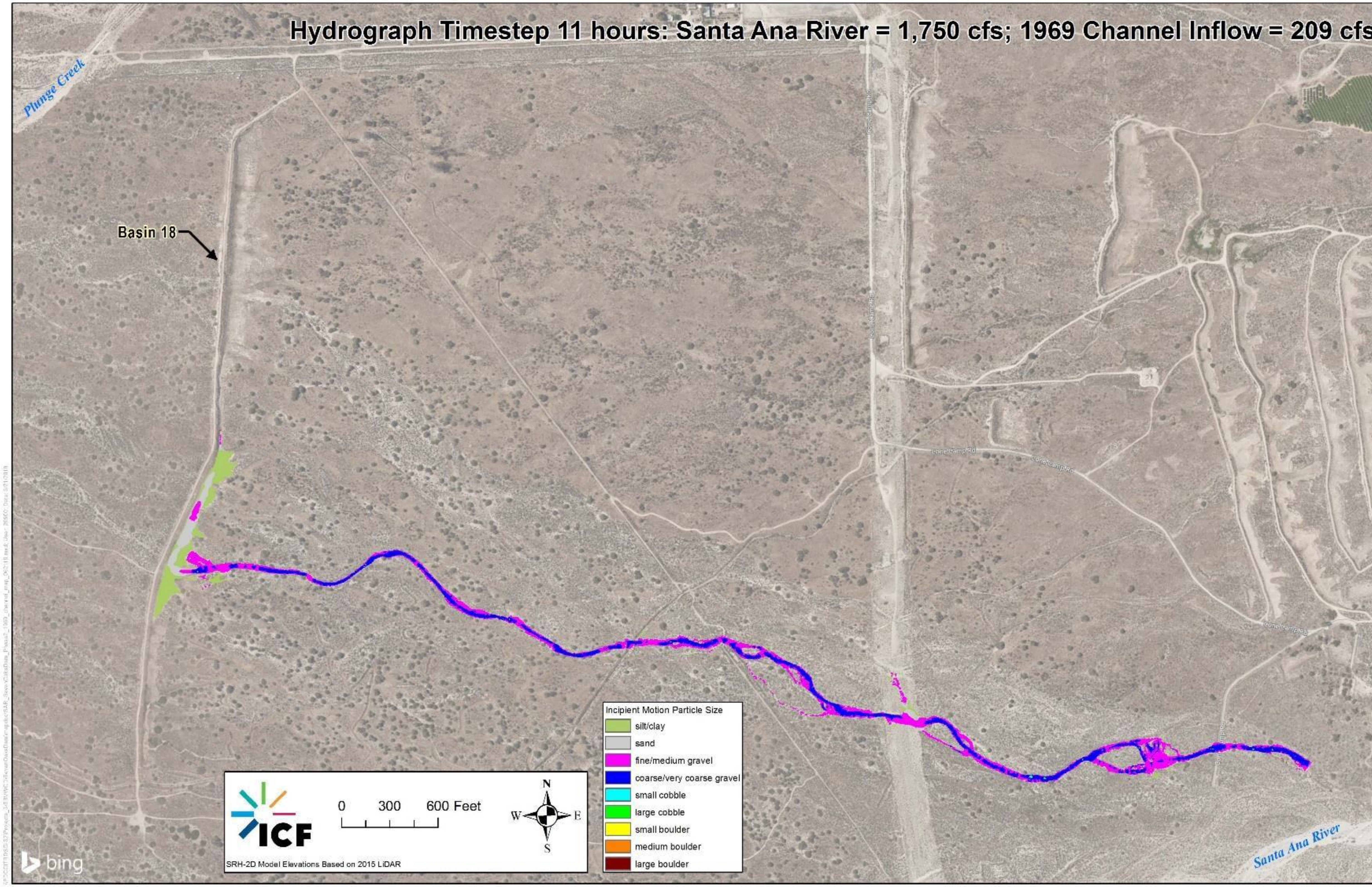


Figure 4-43. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 209 cfs

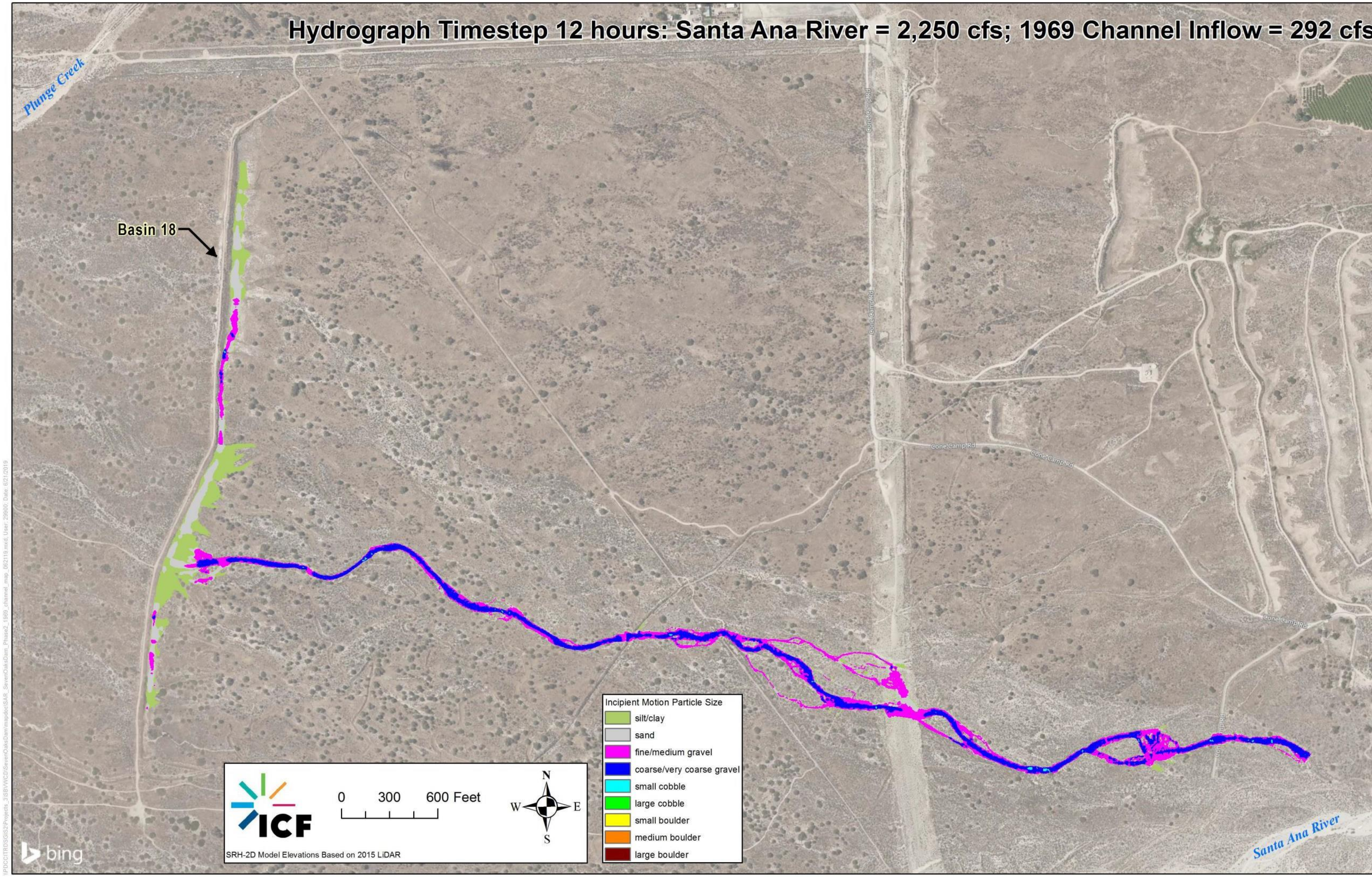


Figure 4-44. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 292 cfs

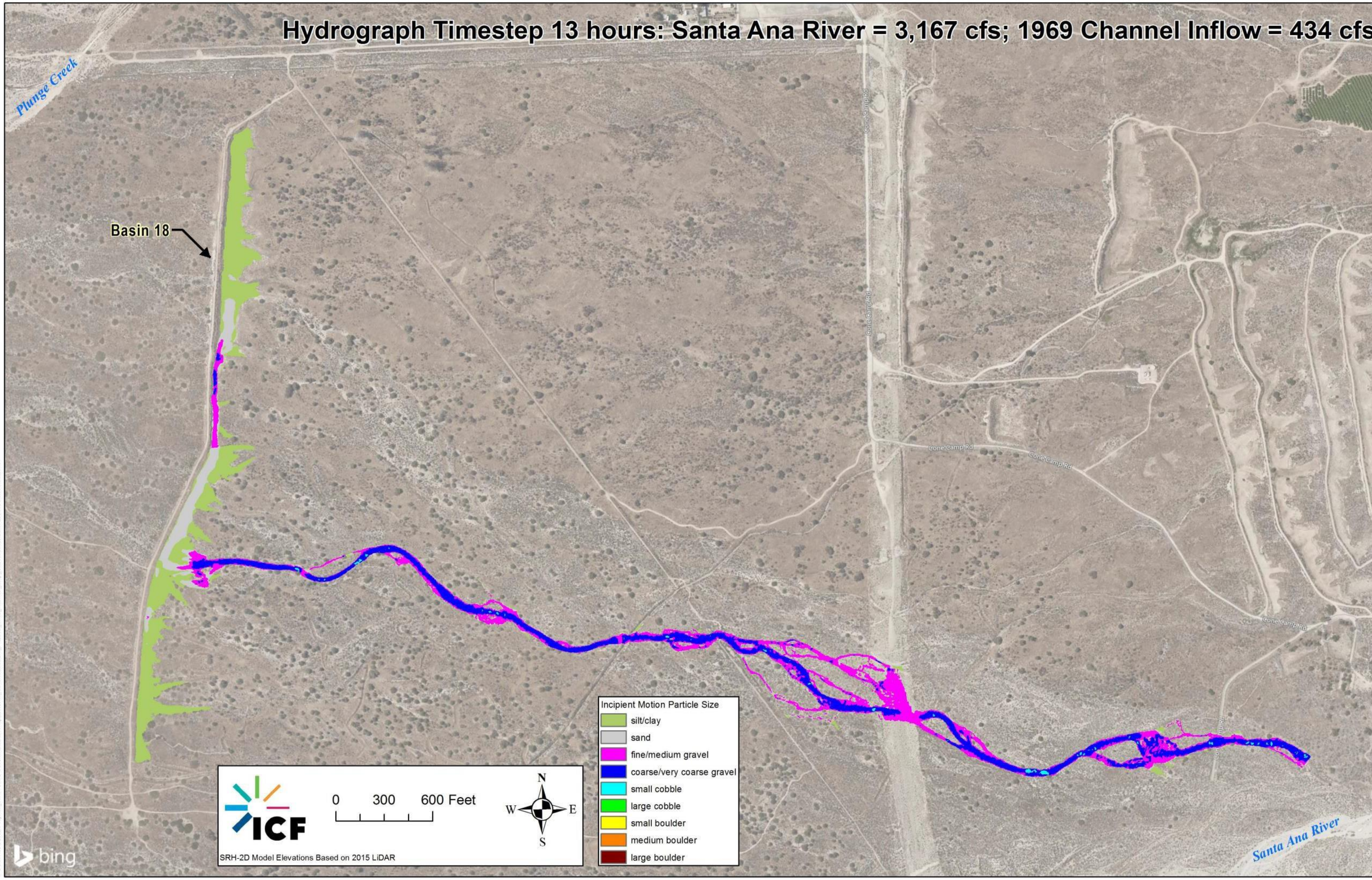


Figure 4-45. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 434 cfs

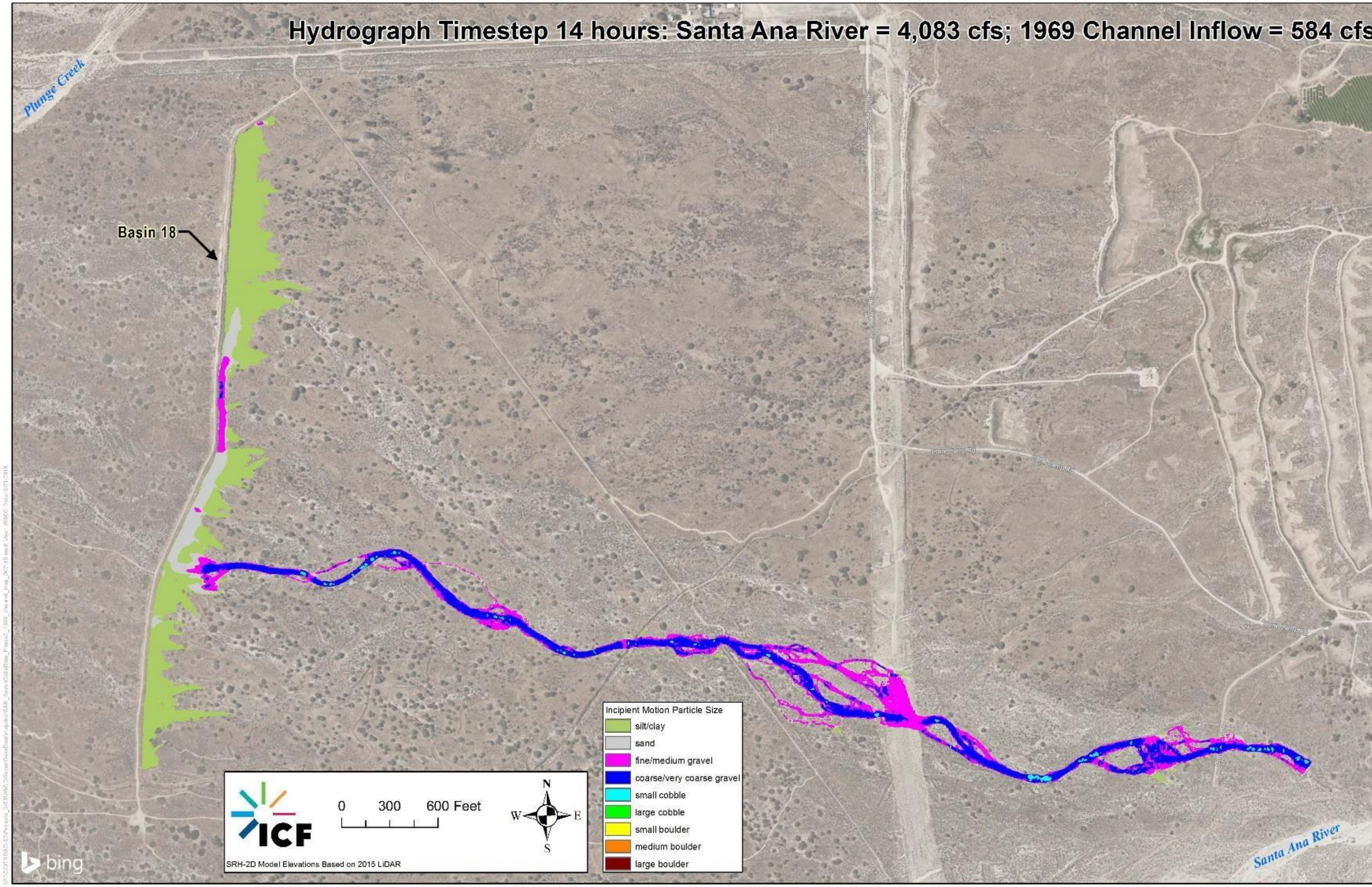


Figure 4-46. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 584 cfs

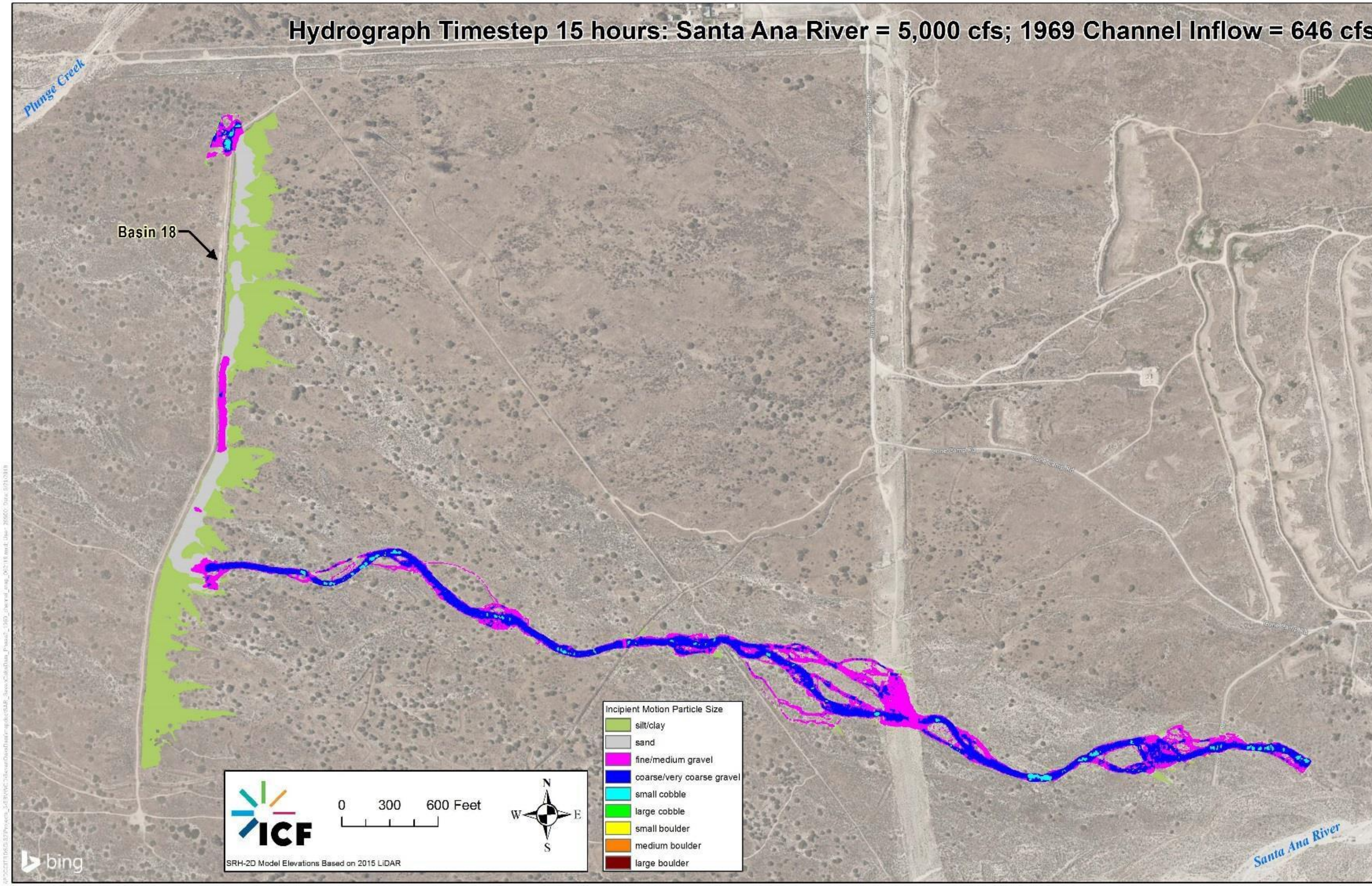


Figure 4-47. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 646 cfs

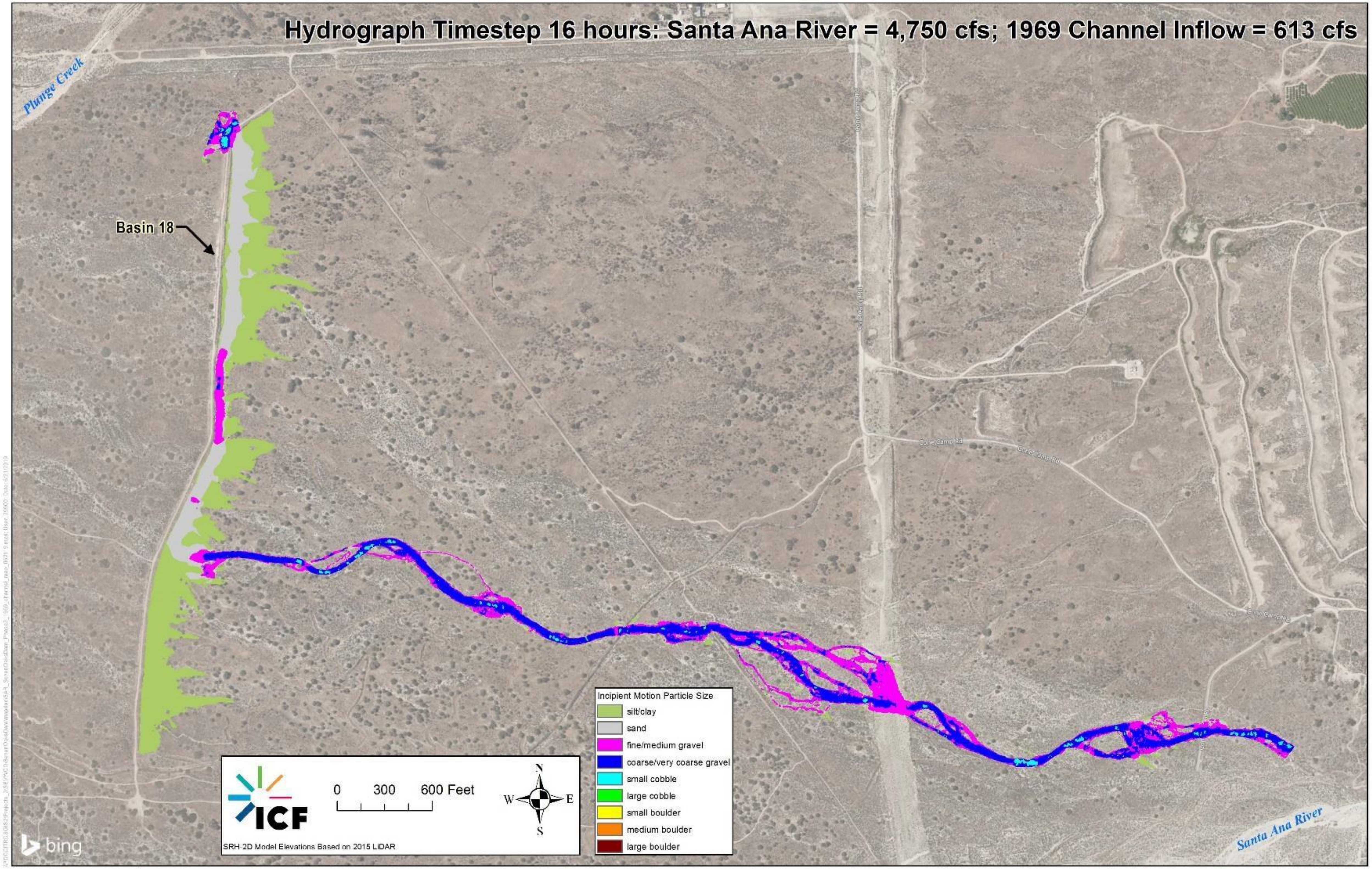


Figure 4-48. Predicted Sediment Incipient Motion in the 1969 Channel at Inflow of 613 cfs

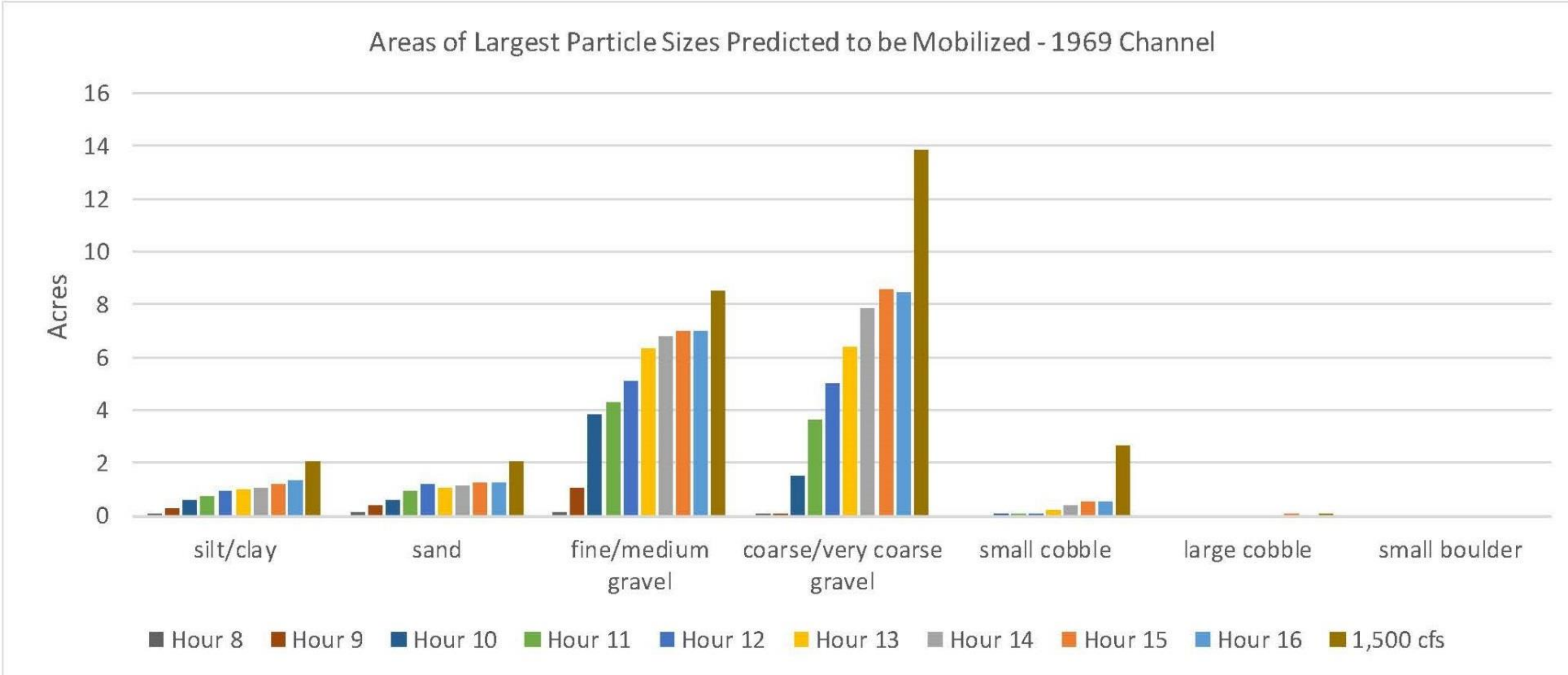


Figure 4-49. Acreages of the 1969 Channel within Shear Stress Magnitudes for Incipient Motion of Sediment Size Classes

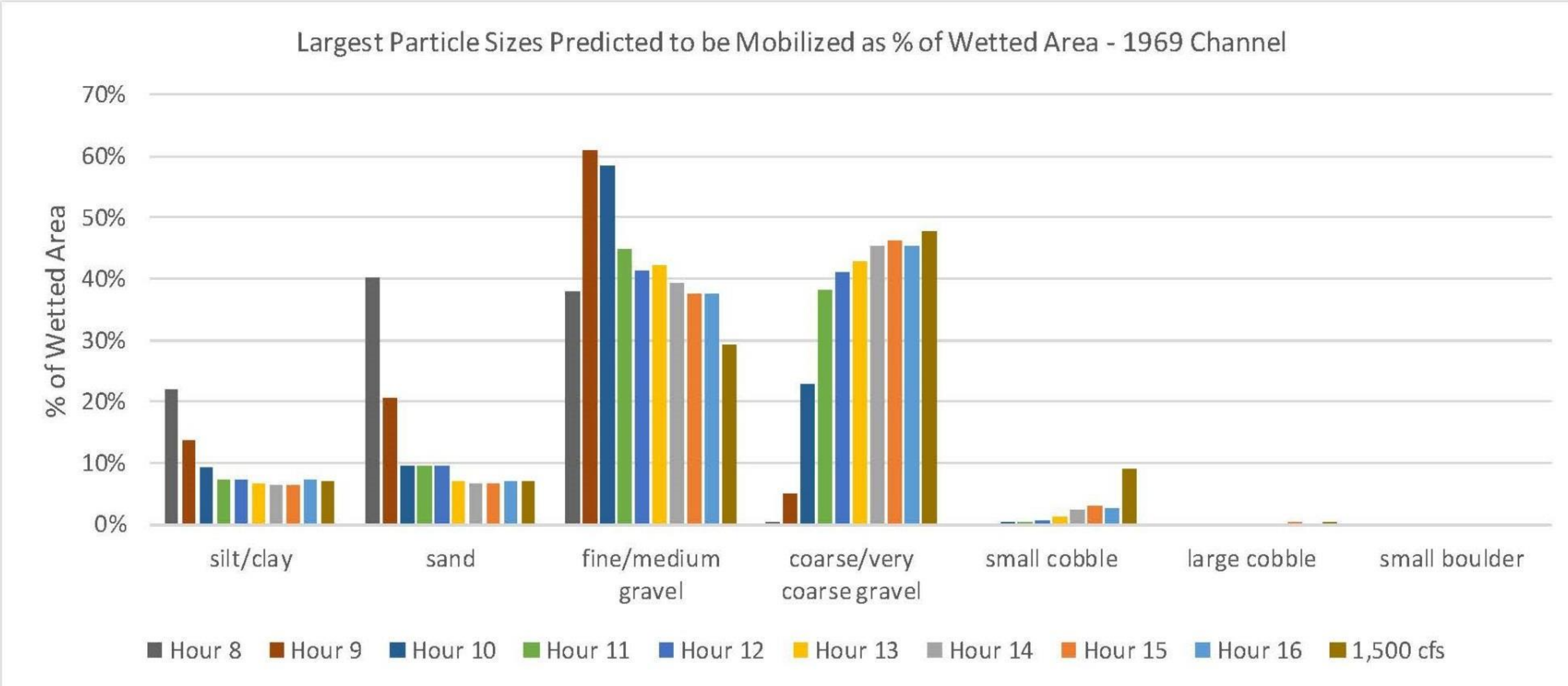


Figure 4-50. Percent of flow Areas of the 1969 Channel within Shear Stress Magnitudes for Incipient Motion of Sediment Size Classes

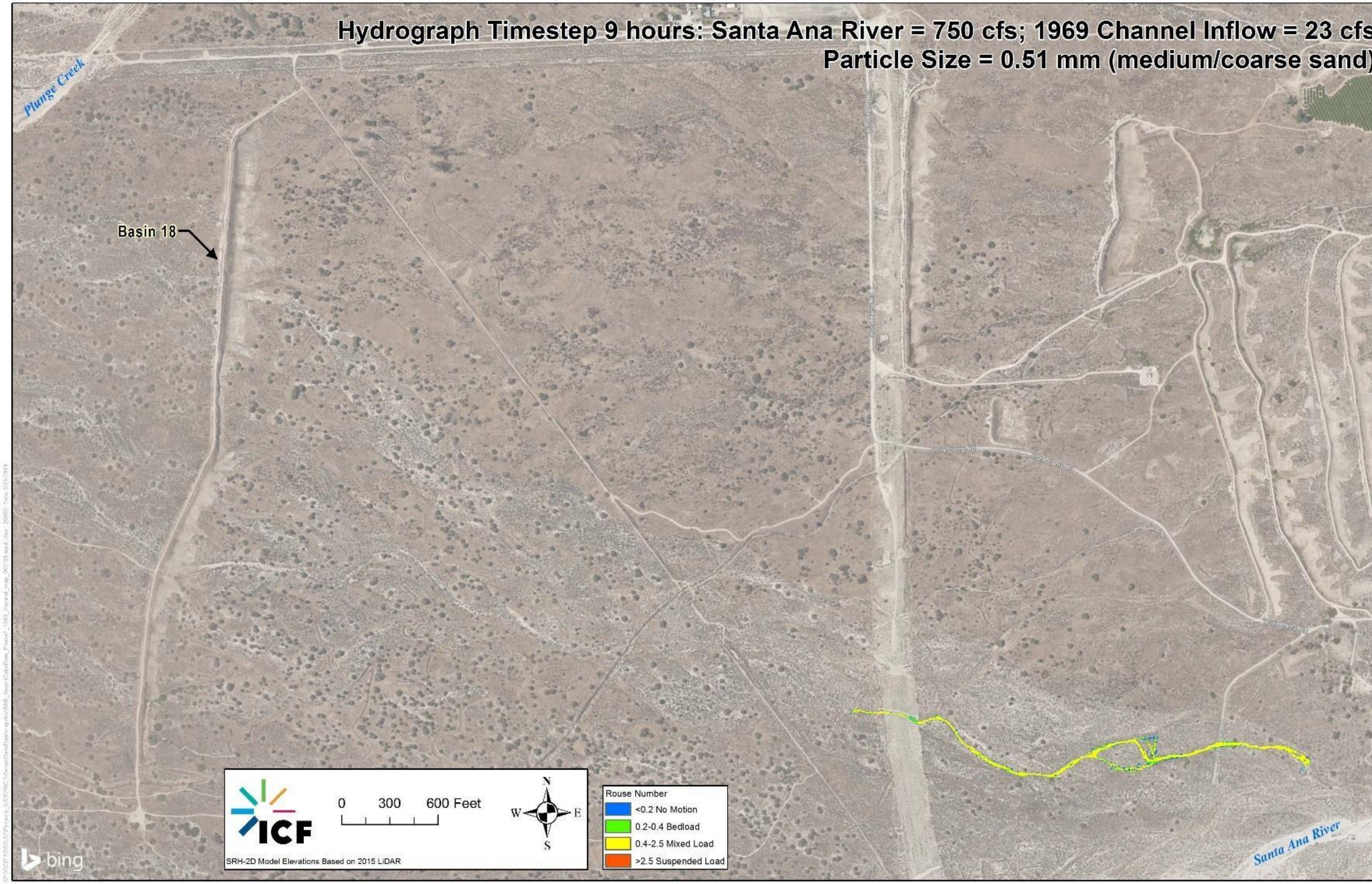


Figure 4-51. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 23 cfs

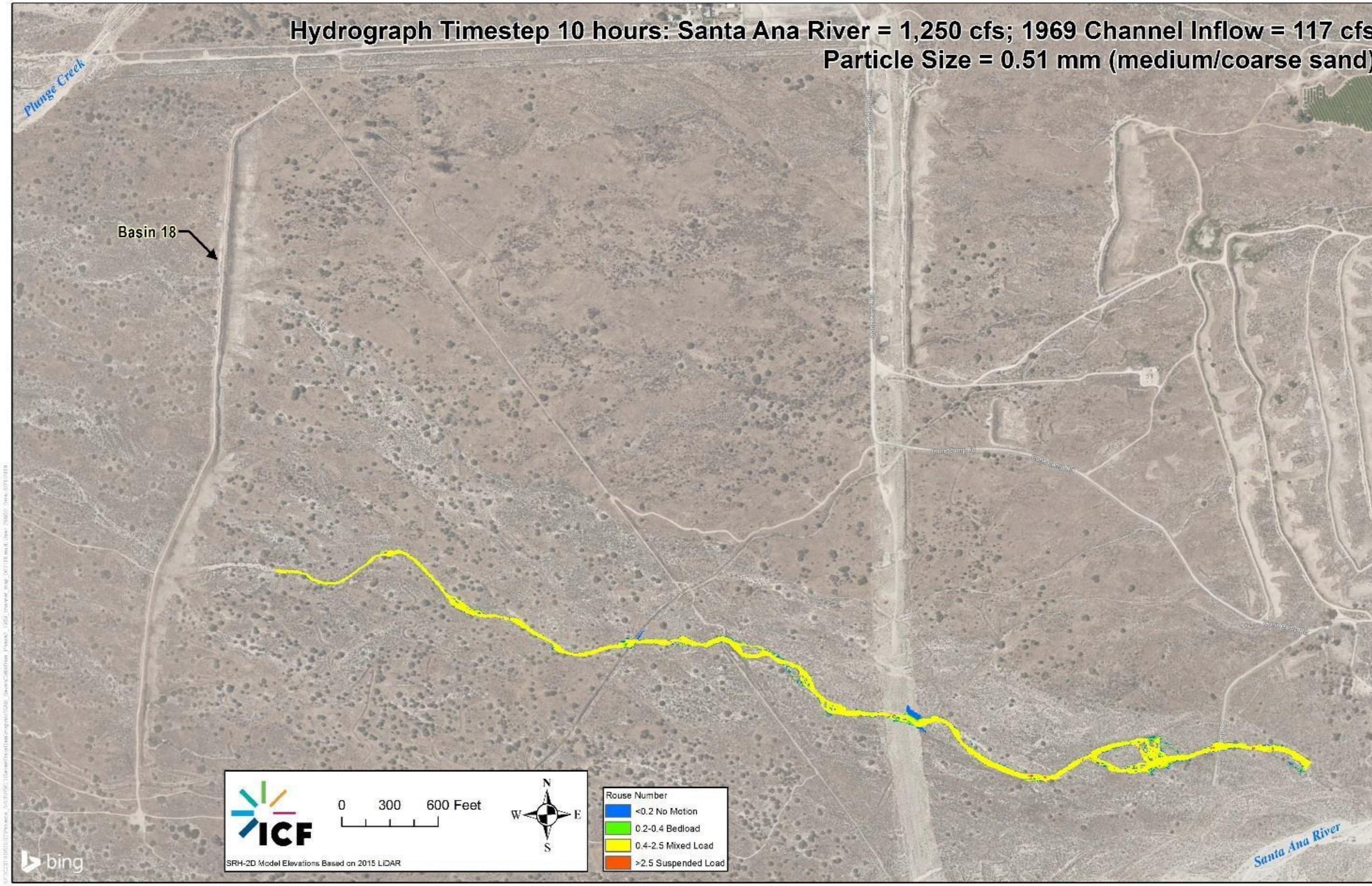


Figure 4-52. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 117 cfs

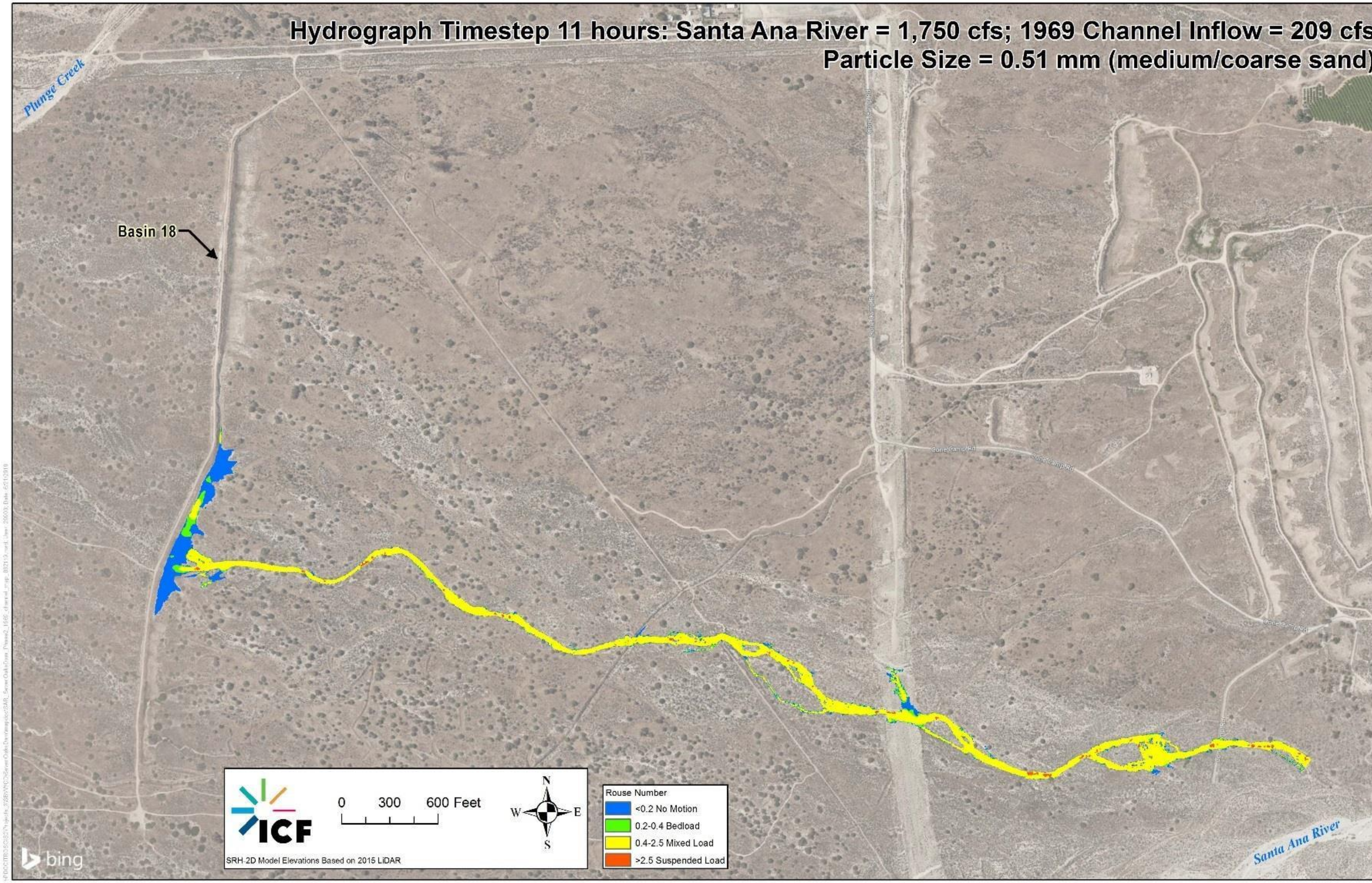


Figure 4-53. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 209 cfs

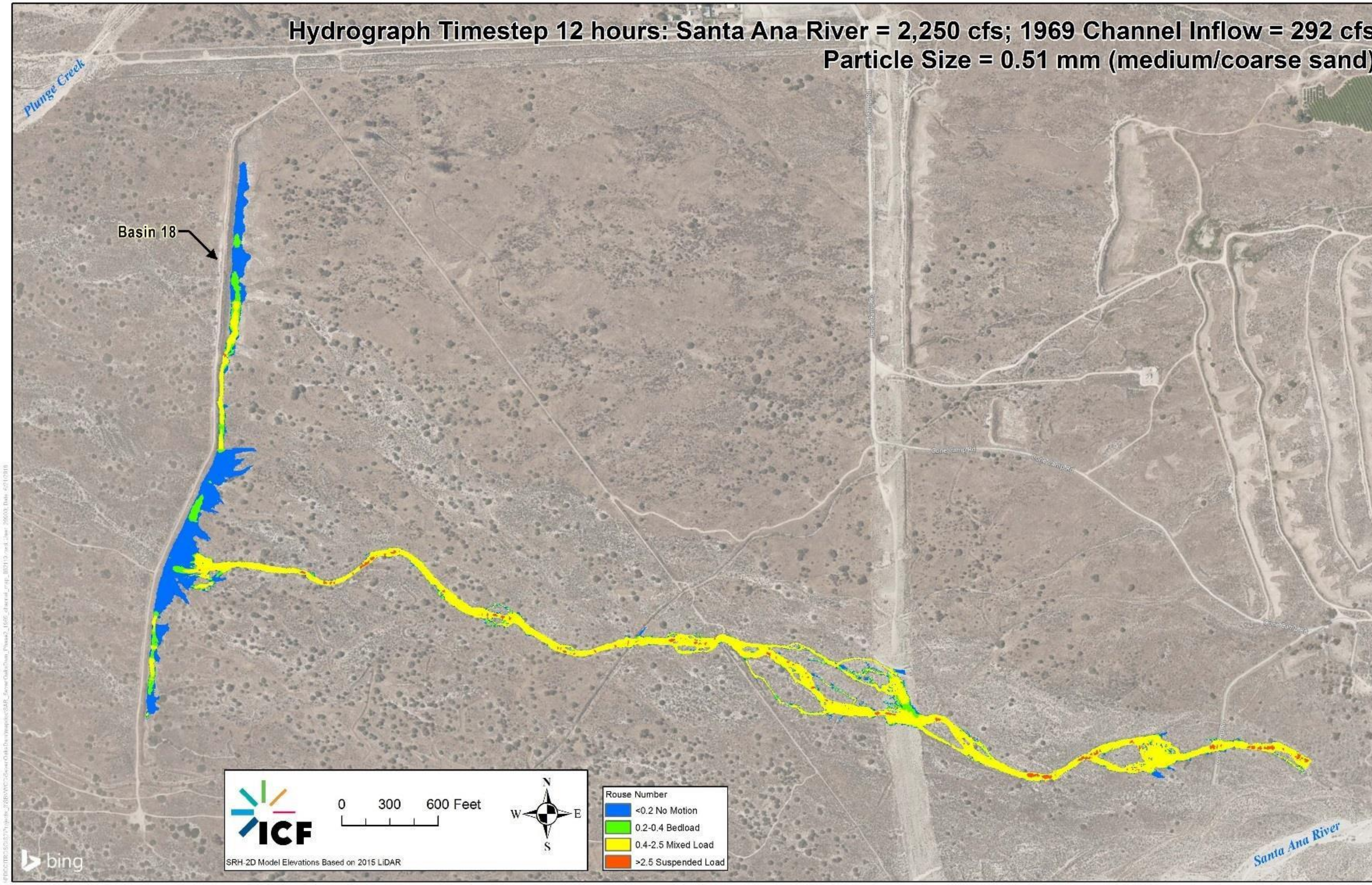


Figure 4-54. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 292 cfs

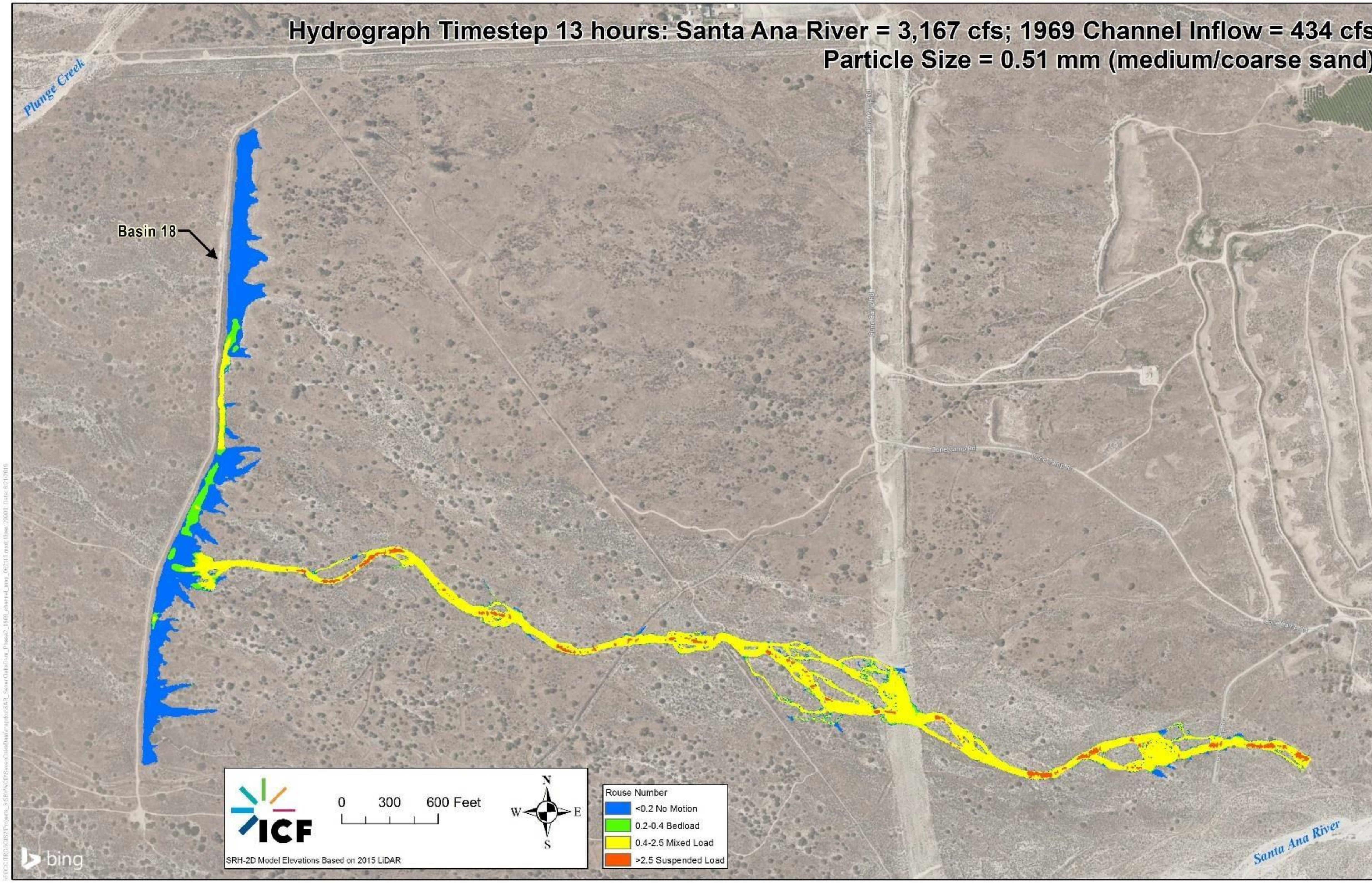


Figure 4-55. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 434 cfs

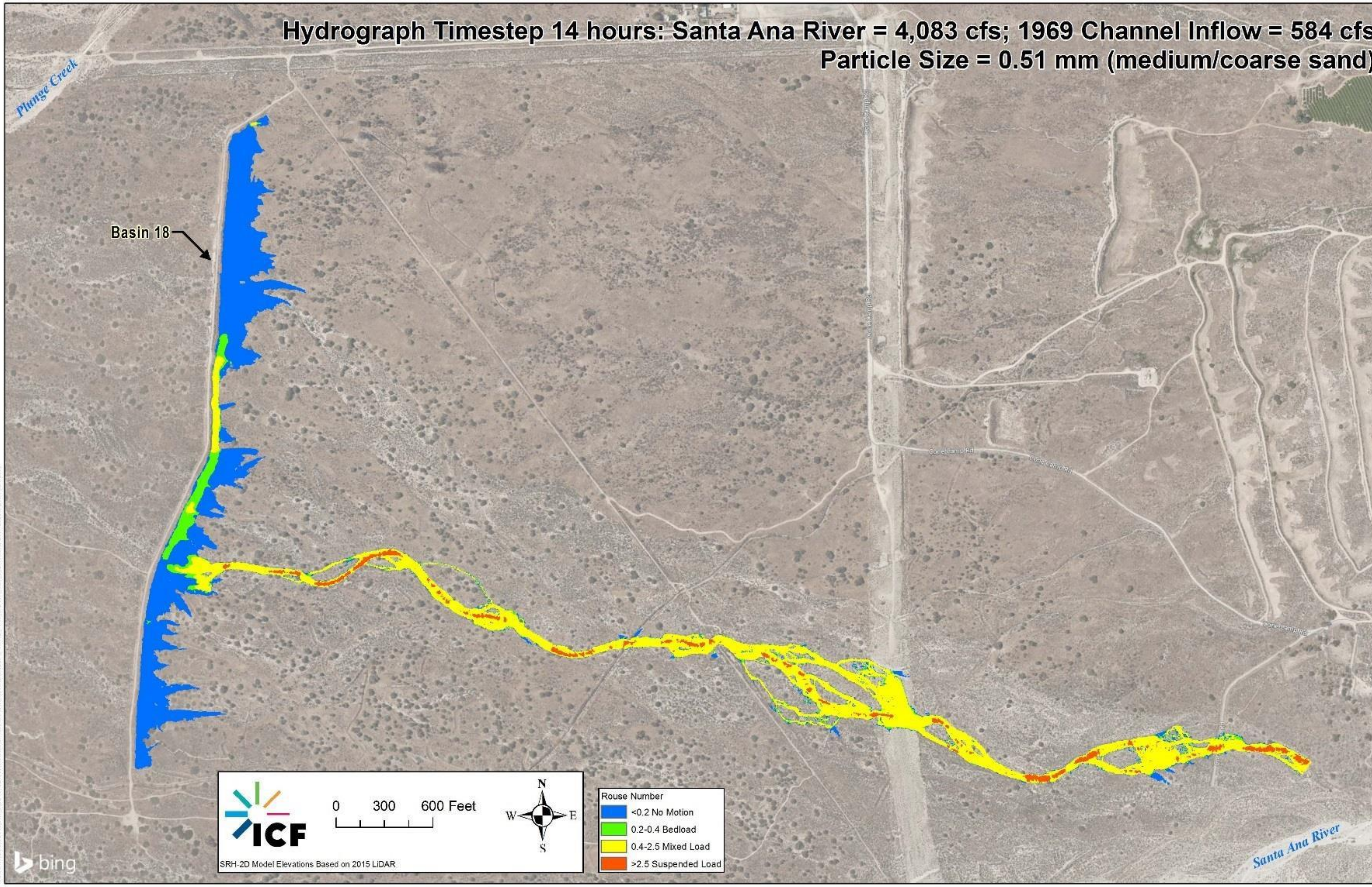


Figure 4-56. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 584 cfs

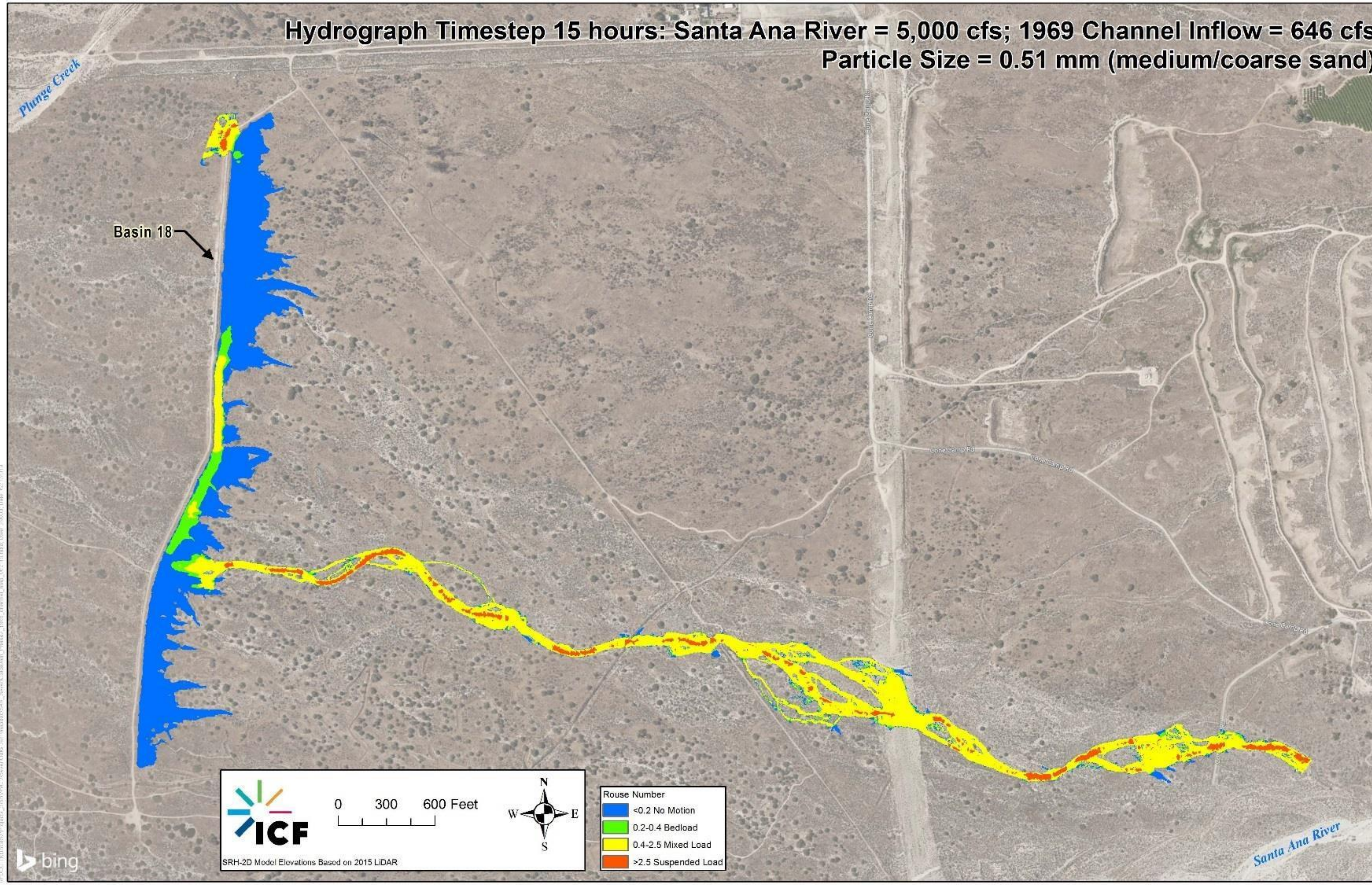


Figure 4-57. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 646 cfs

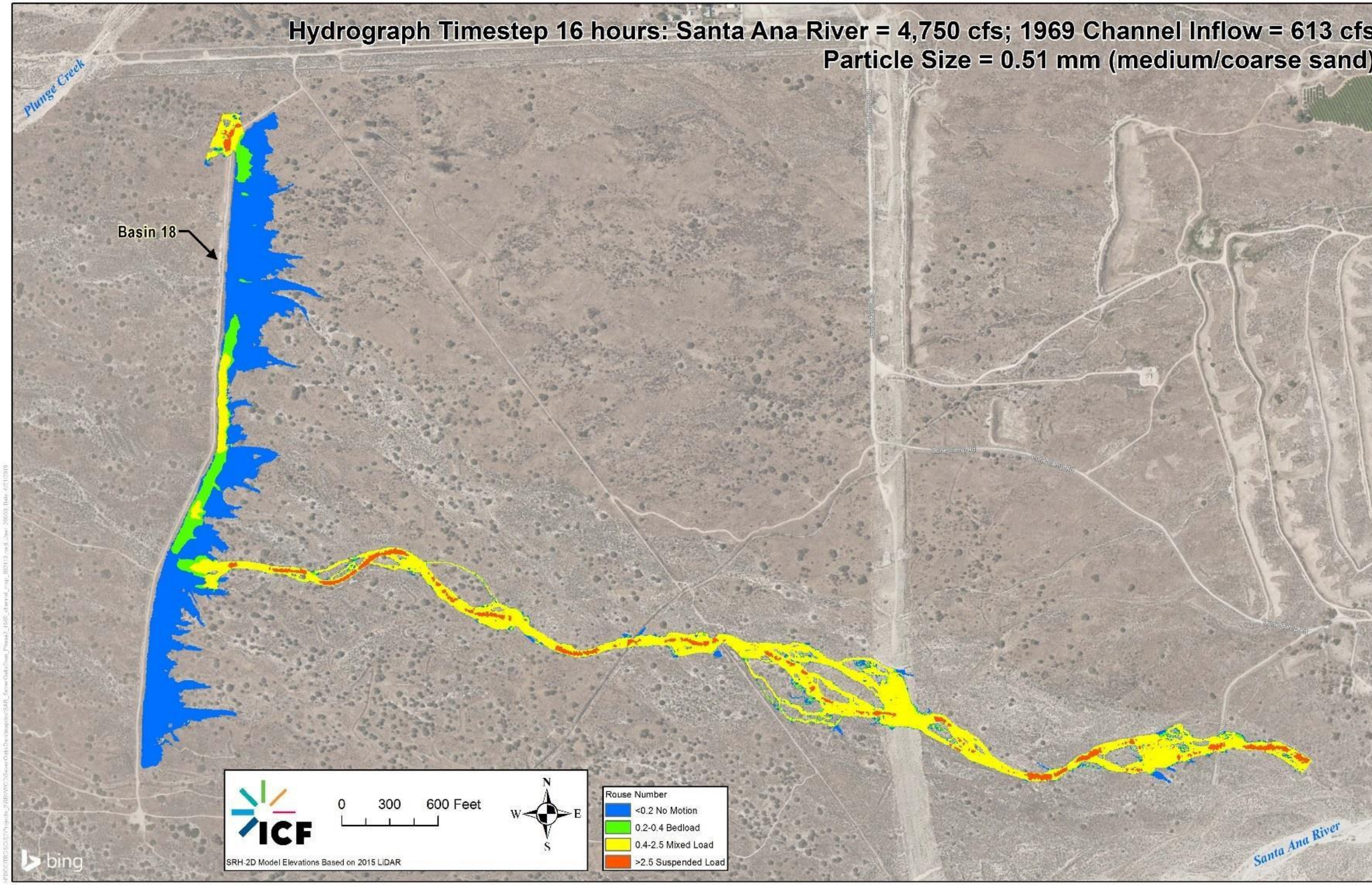


Figure 4-58. Predicted Mode of Sediment Transport in the 1969 Channel at Inflow of 613 cfs

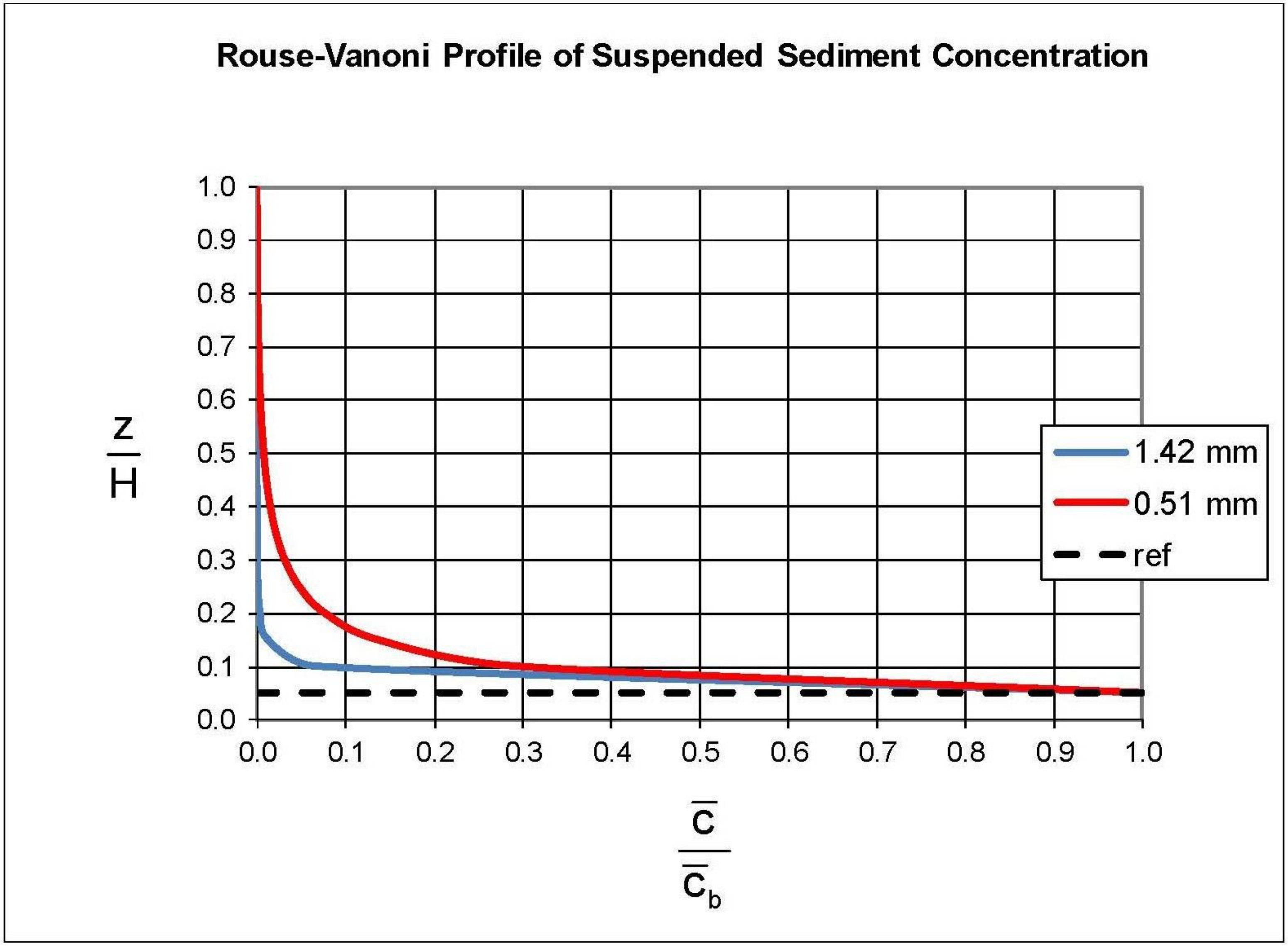
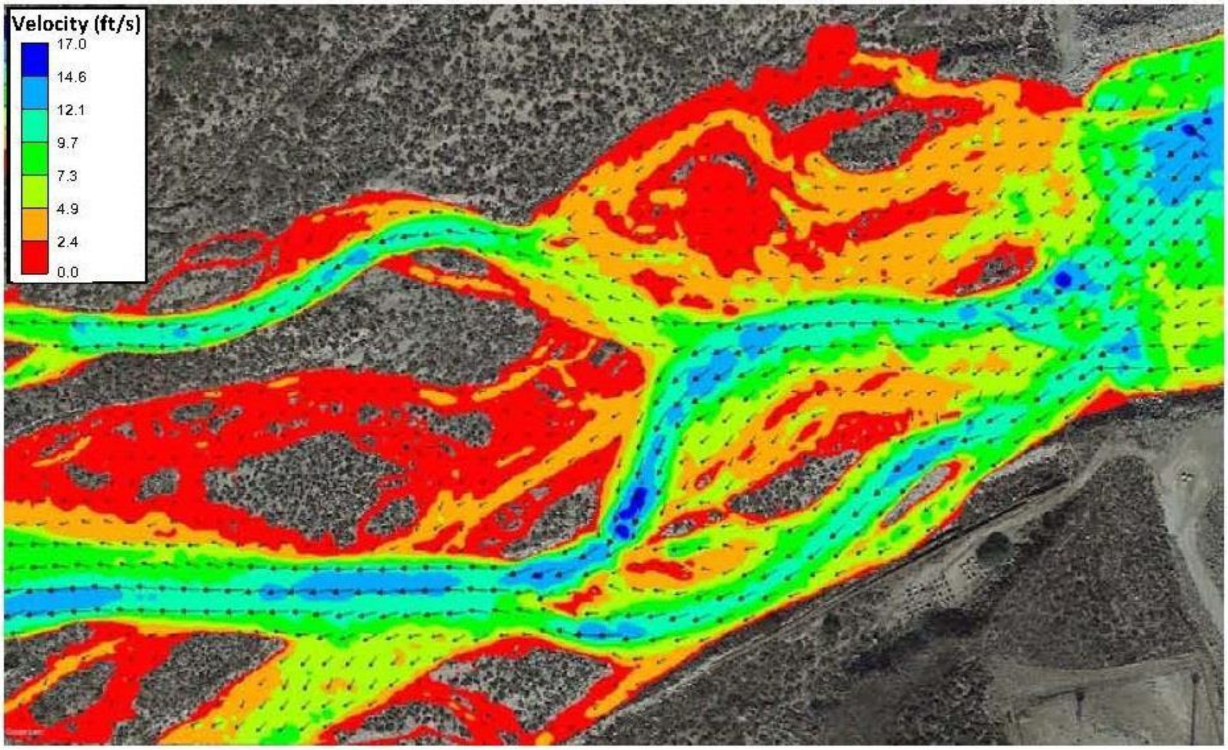


Figure 4-59. Rouse-Vanoni Profile Averaged over the 1969 Channel Inundation Area at Hour 16 in the Hydrograph for the San Diego Zoo D_{50} and D_{90} Particle Sizes



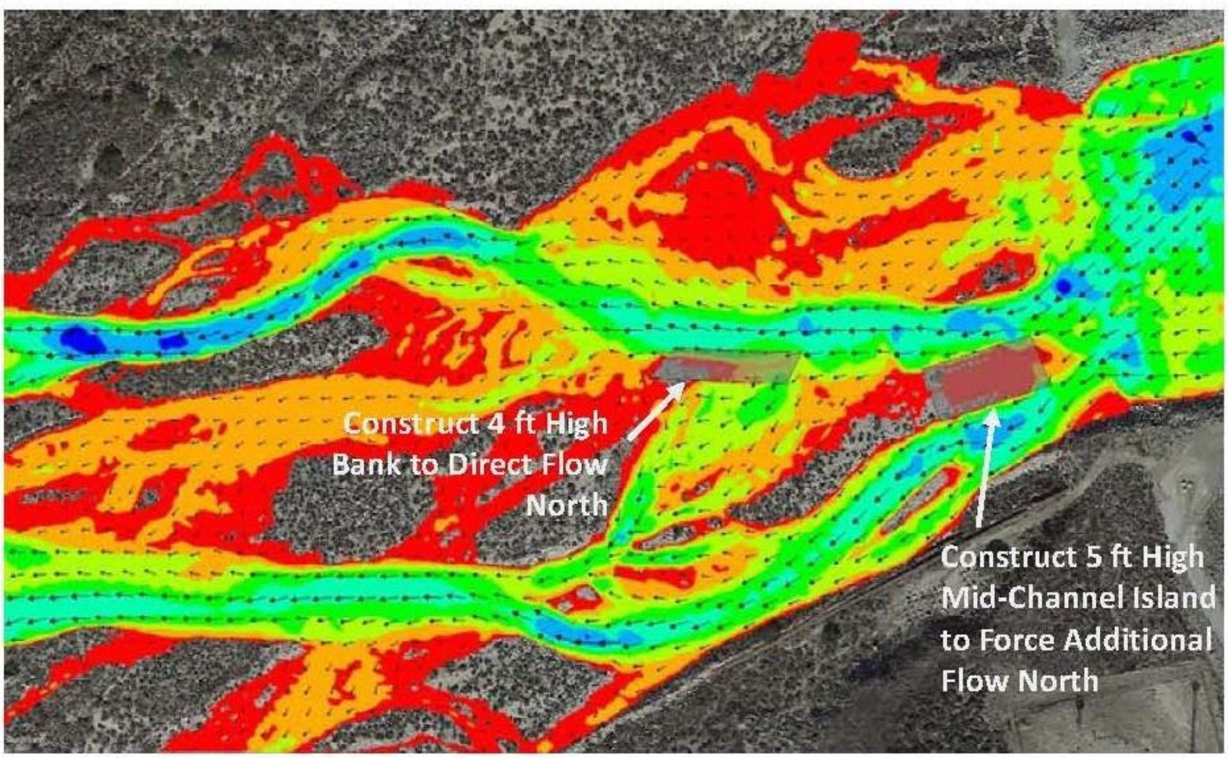


Figure 4-60. Flow Velocity Magnitudes and Vectors at 5,000 cfs for the Existing Condition (top) and with Enhancement Measure 2 (bottom)

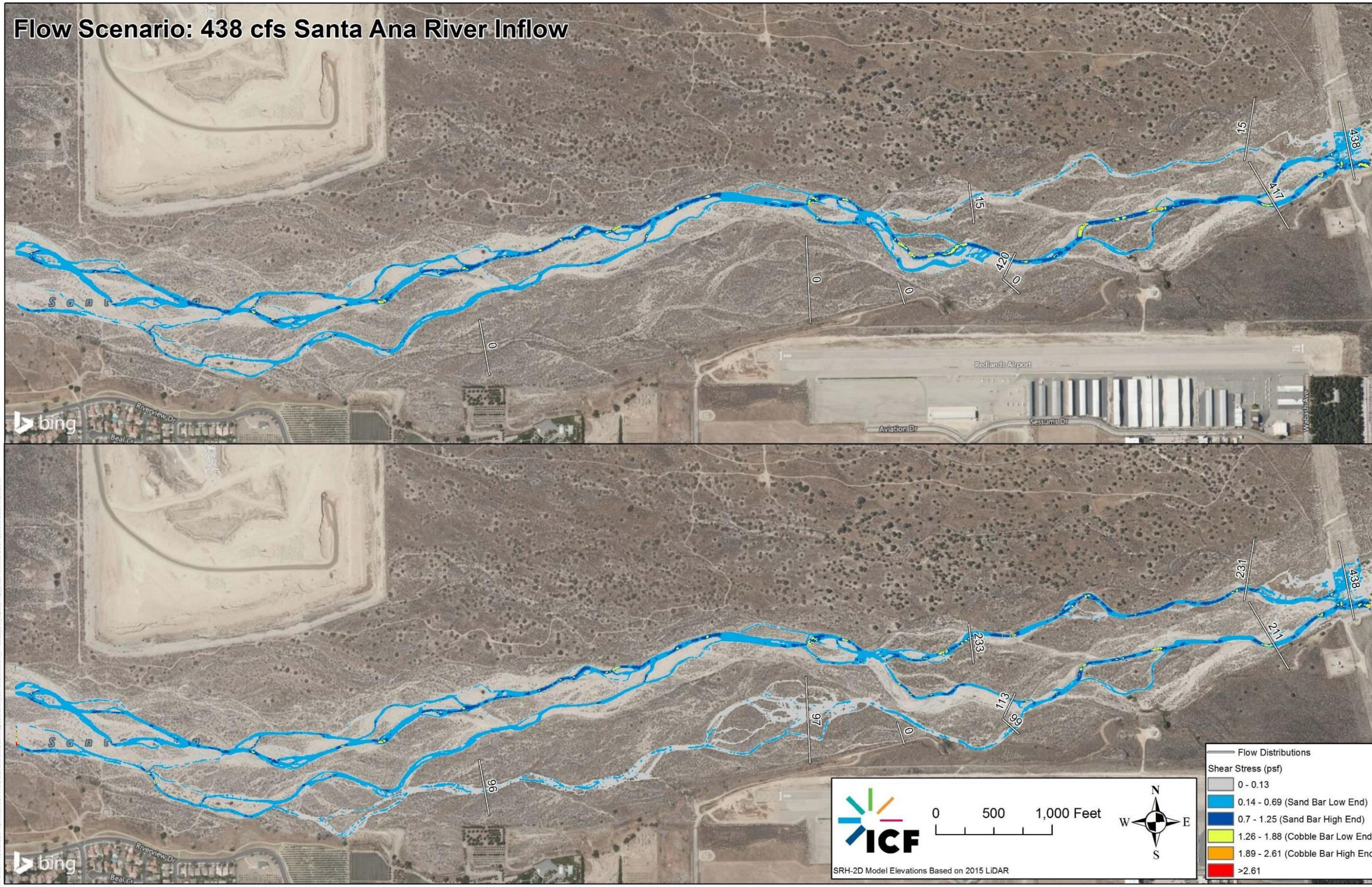


Figure 4-61. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 438 cfs (Existing Condition top; with Enhancement Measures bottom)

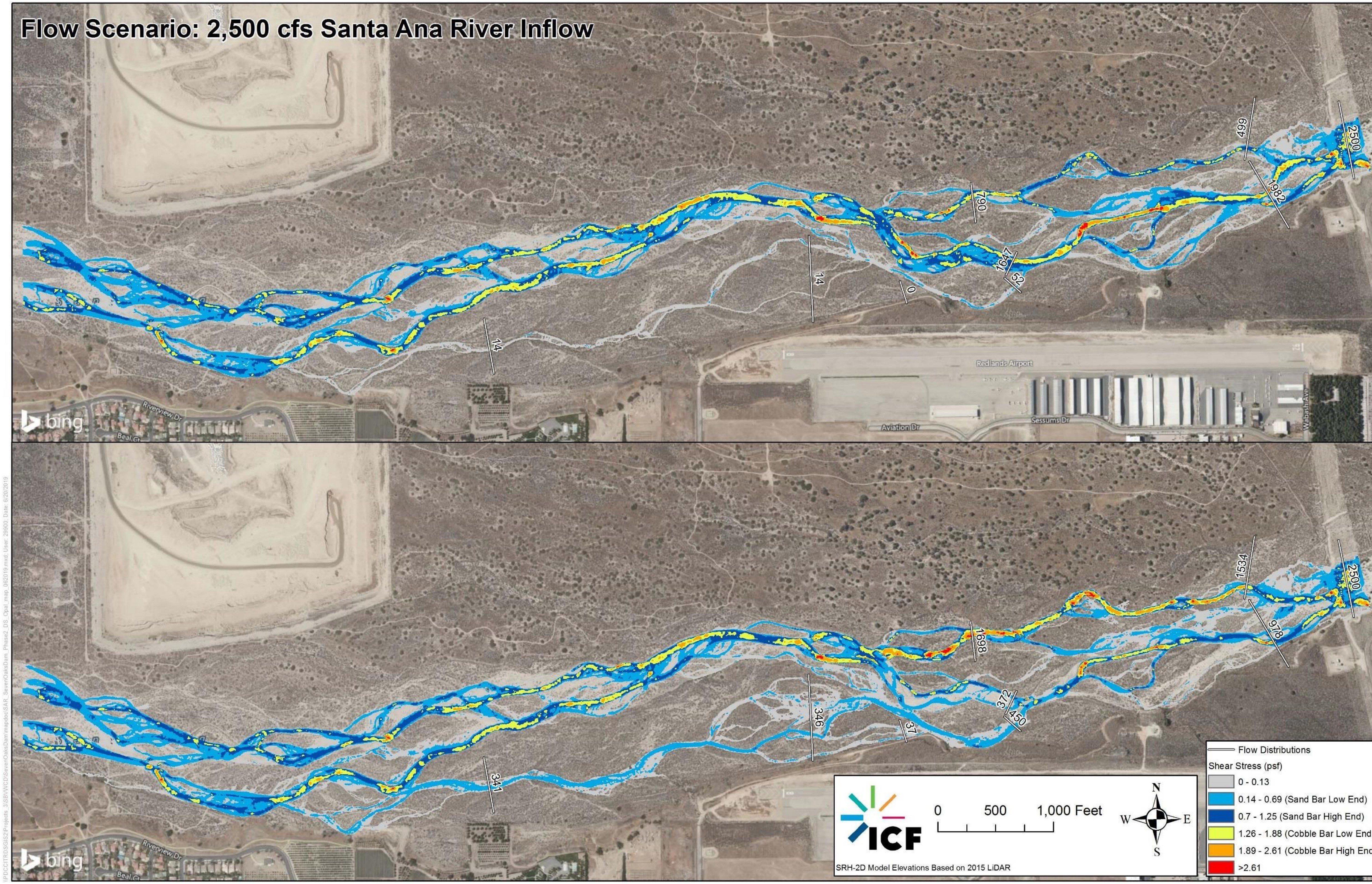


Figure 4-62. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 2,500 cfs (Existing Condition top; with Enhancement Measures bottom)

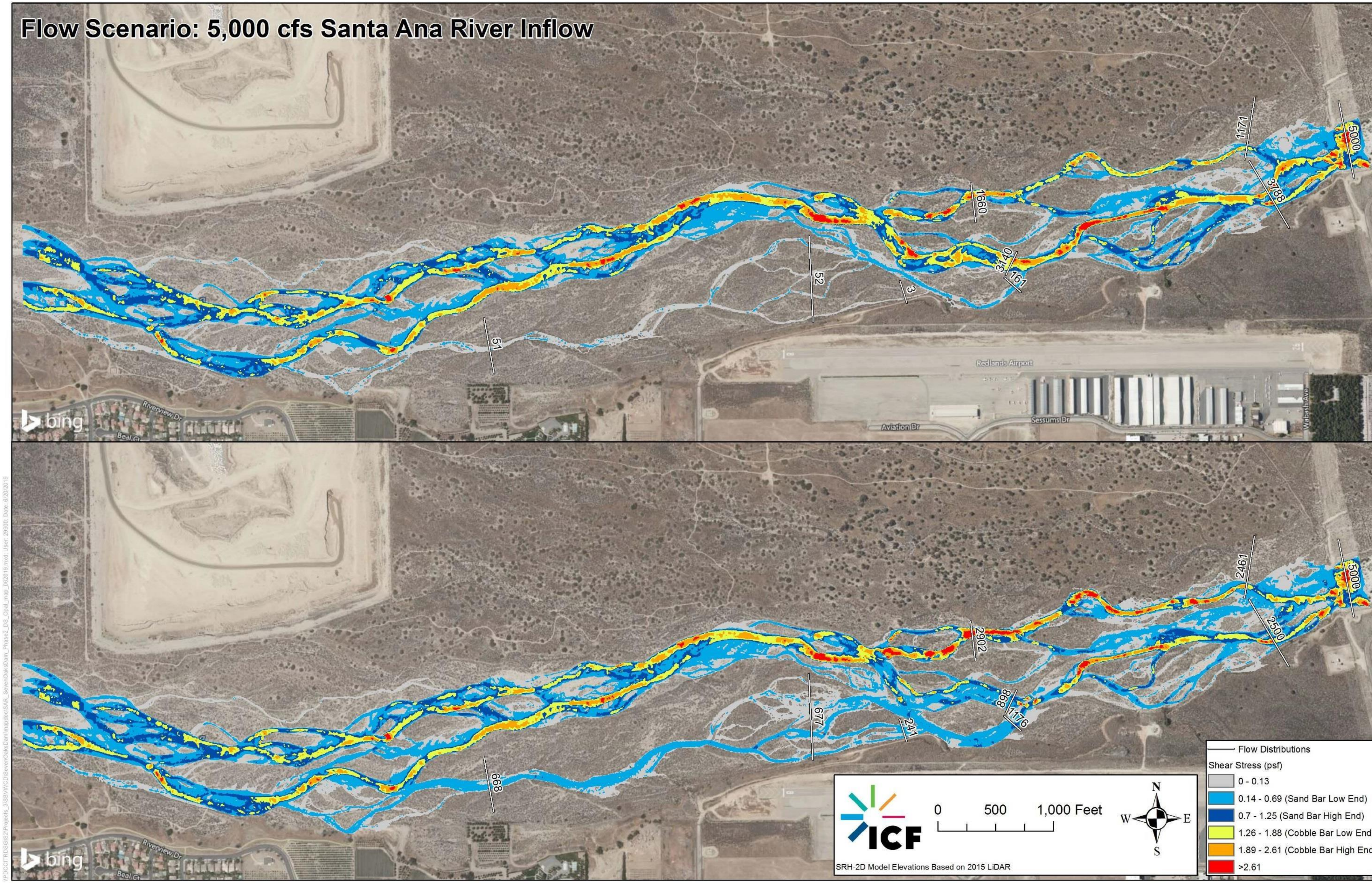


Figure 4-63. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 5,000 cfs (Existing Condition top; with Enhancement Measures bottom)

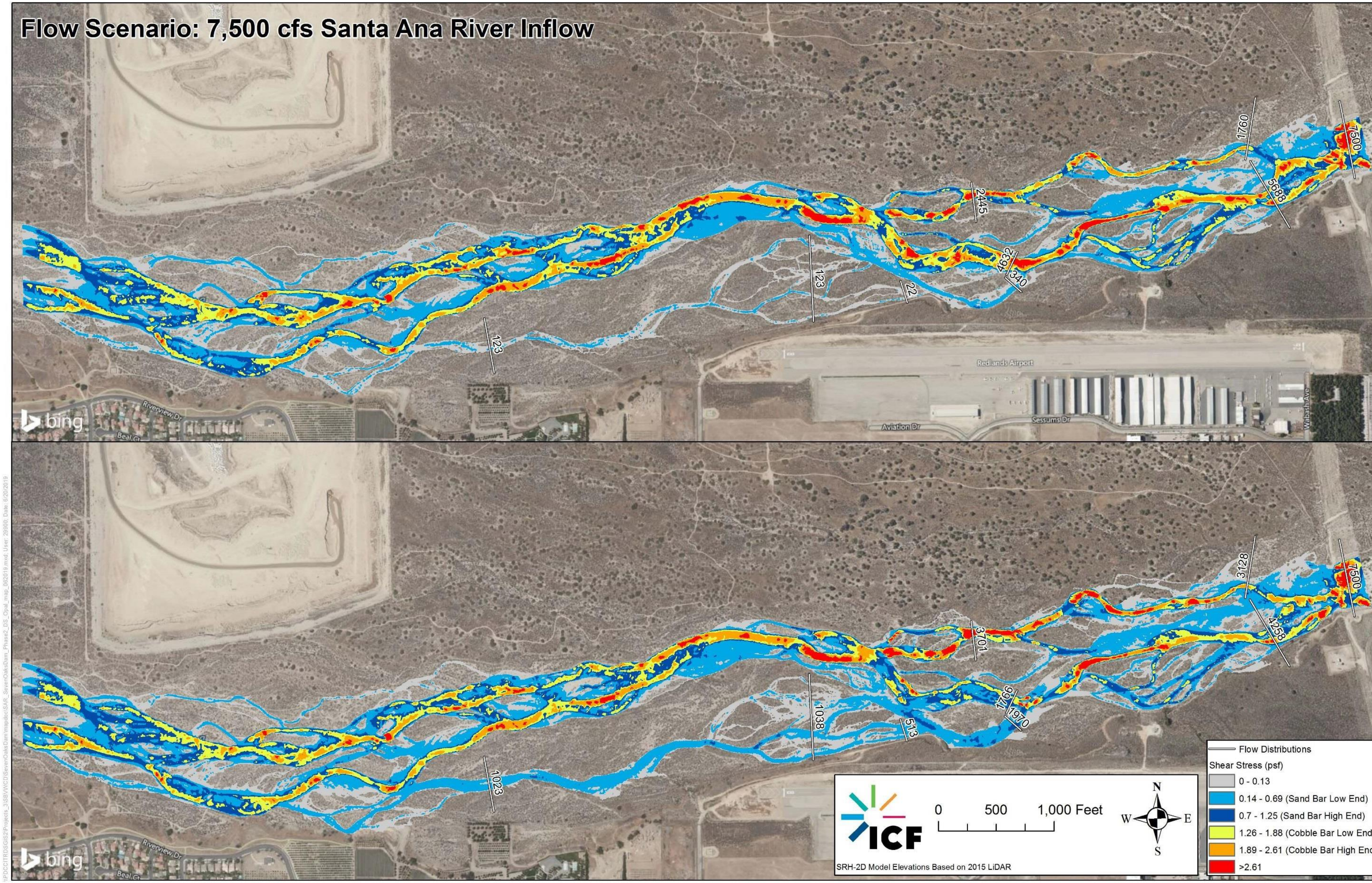


Figure 4-64. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 7,500 cfs (Existing Condition top; with Enhancement Measures bottom)

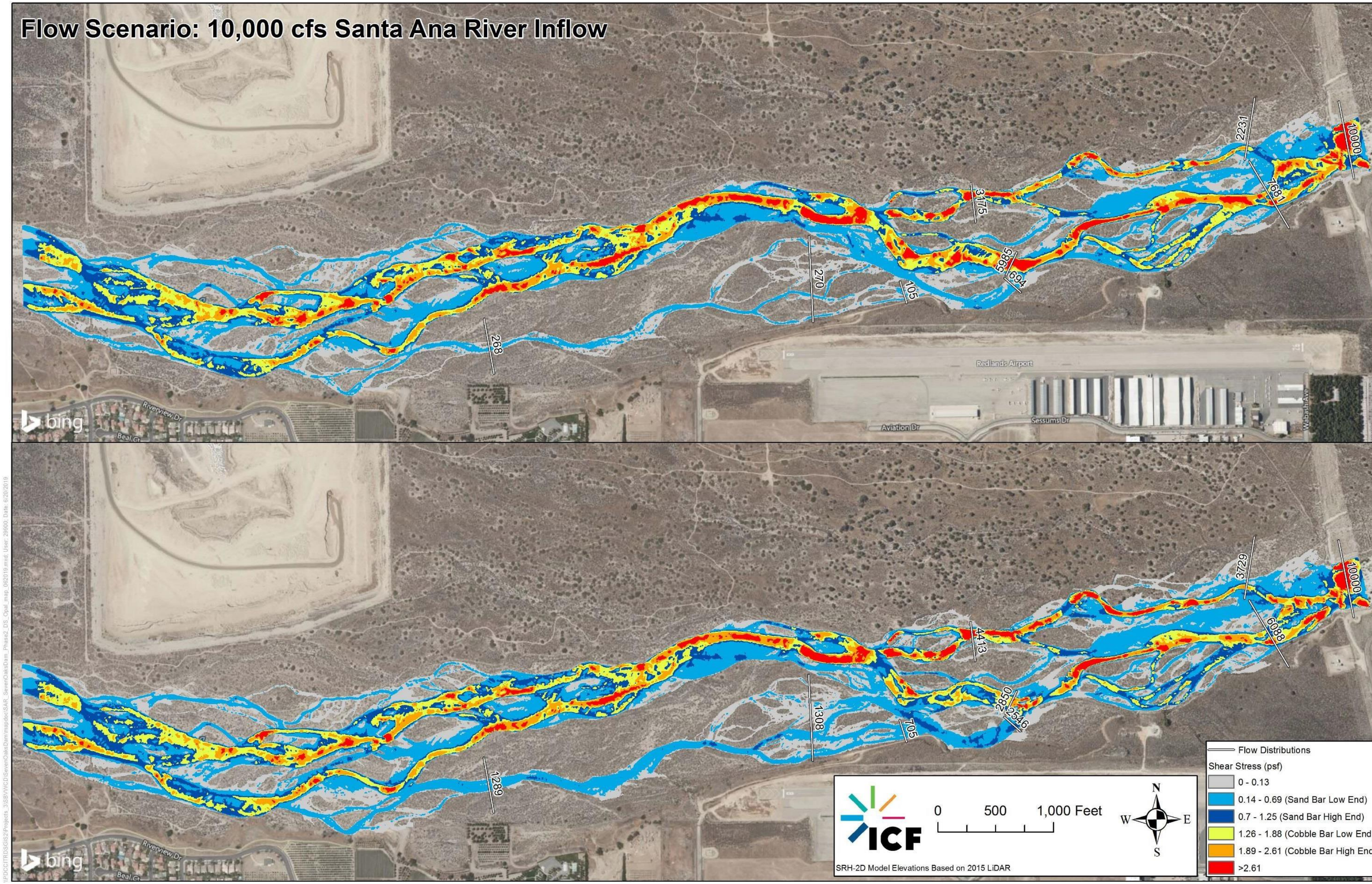


Figure 4-65. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 10,000 cfs (Existing Condition top; with Enhancement Measures bottom)

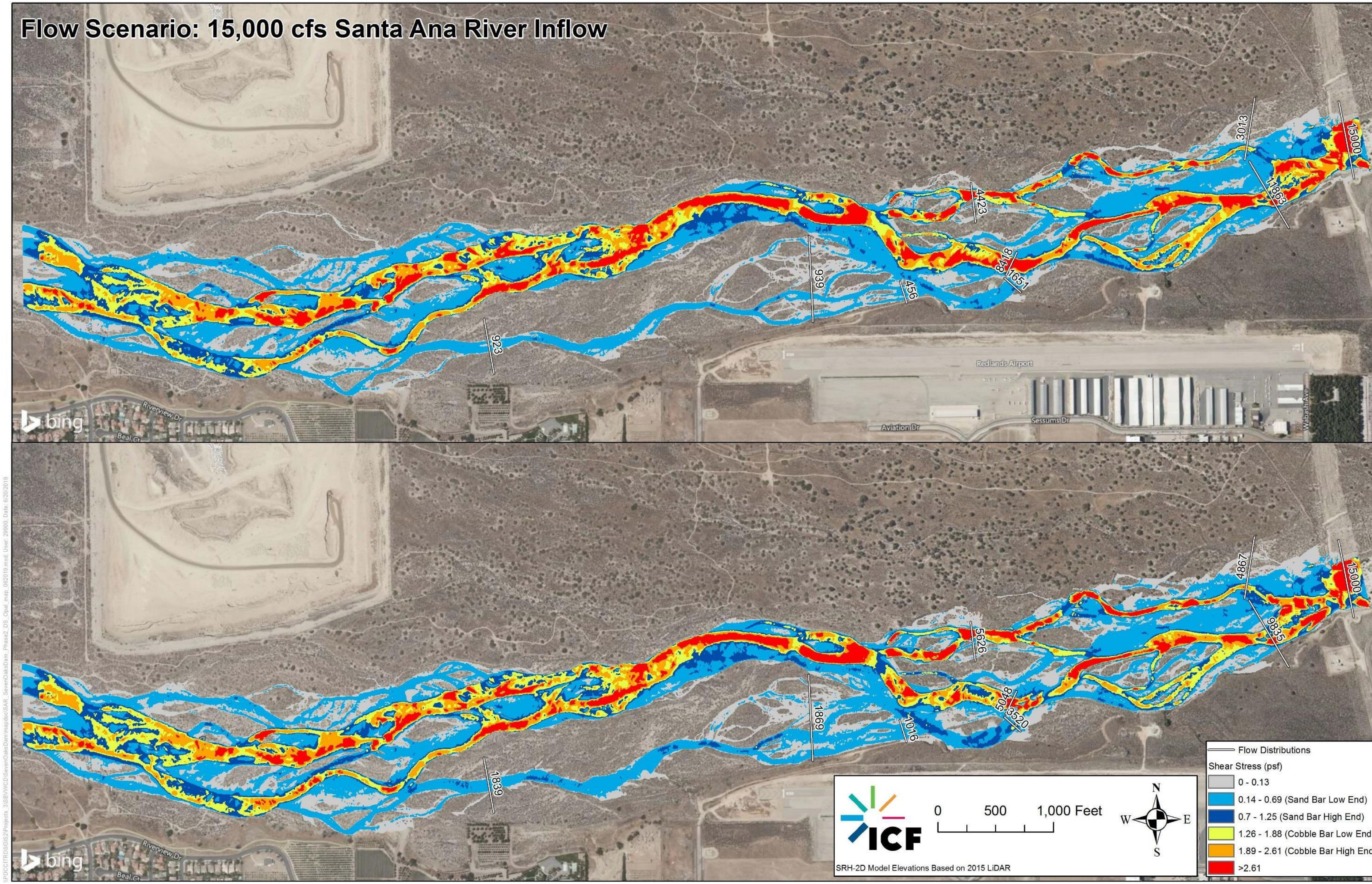


Figure 4-66. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 15,000 cfs (Existing Condition top; with Enhancement Measures bottom)

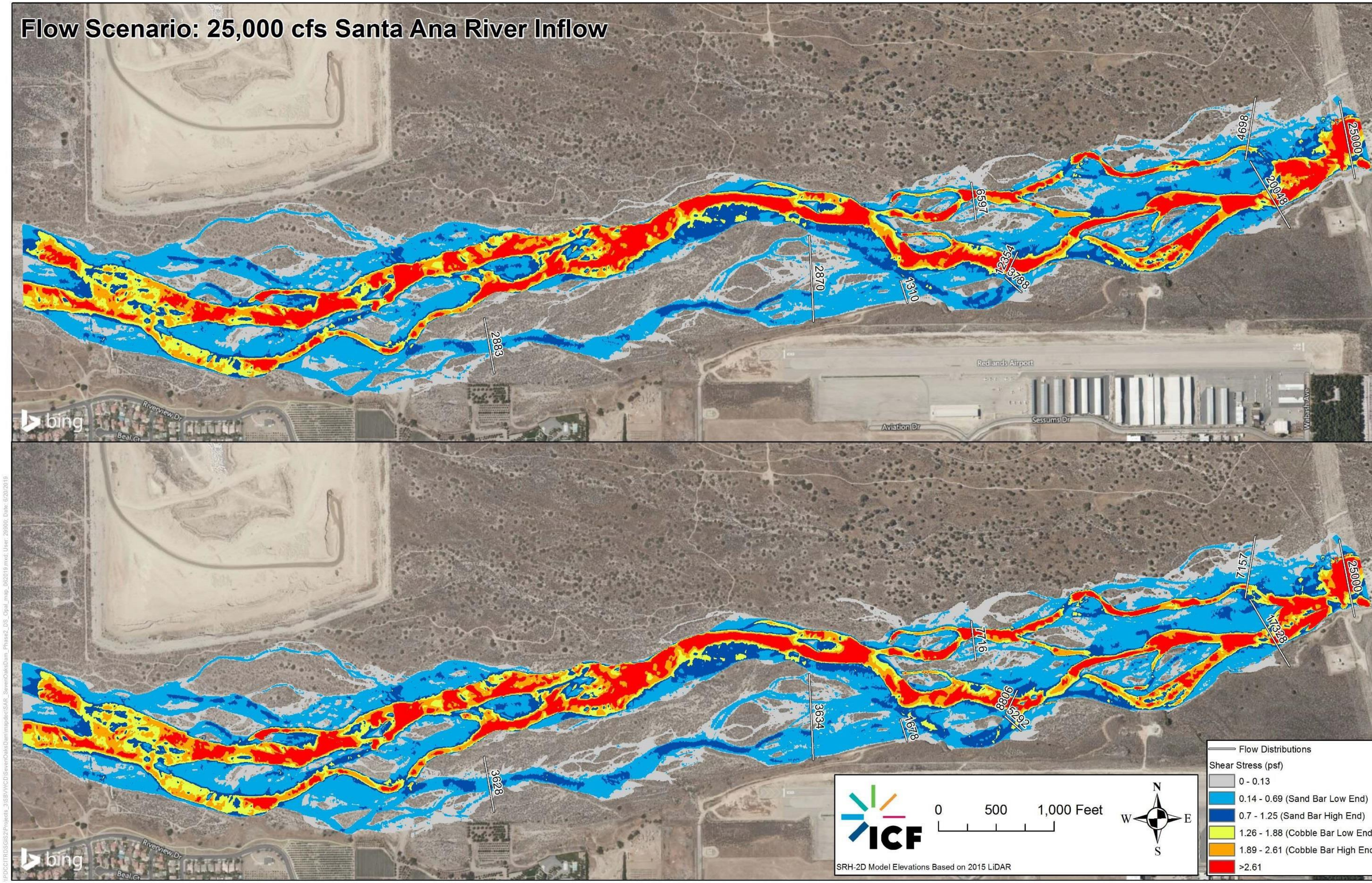


Figure 4-67. Predicted Types of Bar Migration in the Santa Ana River Near the Redlands Airport at 25,000 cfs (Existing Condition top; with Enhancement Measures bottom)

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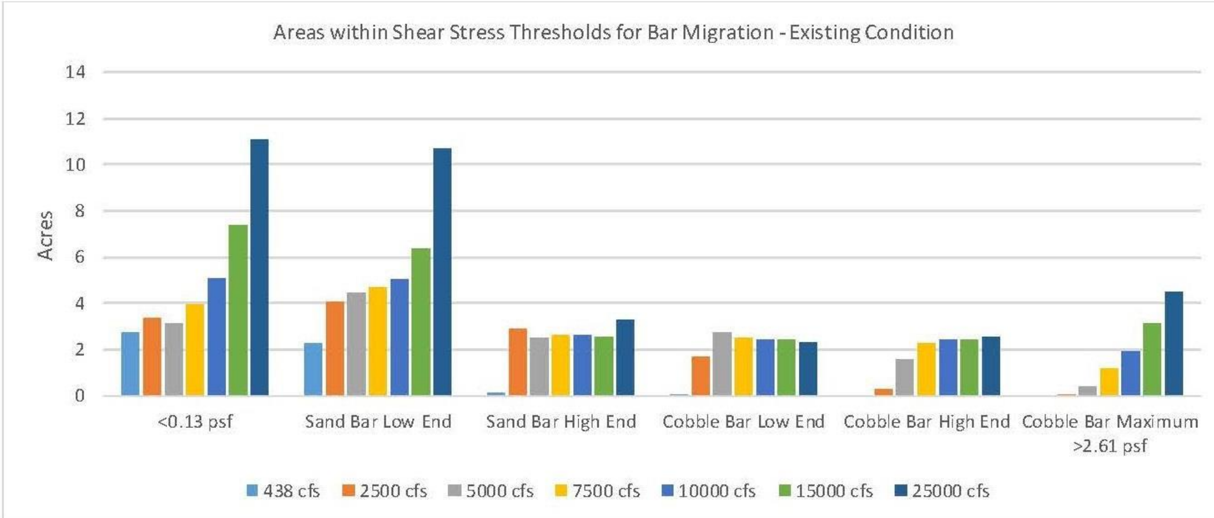


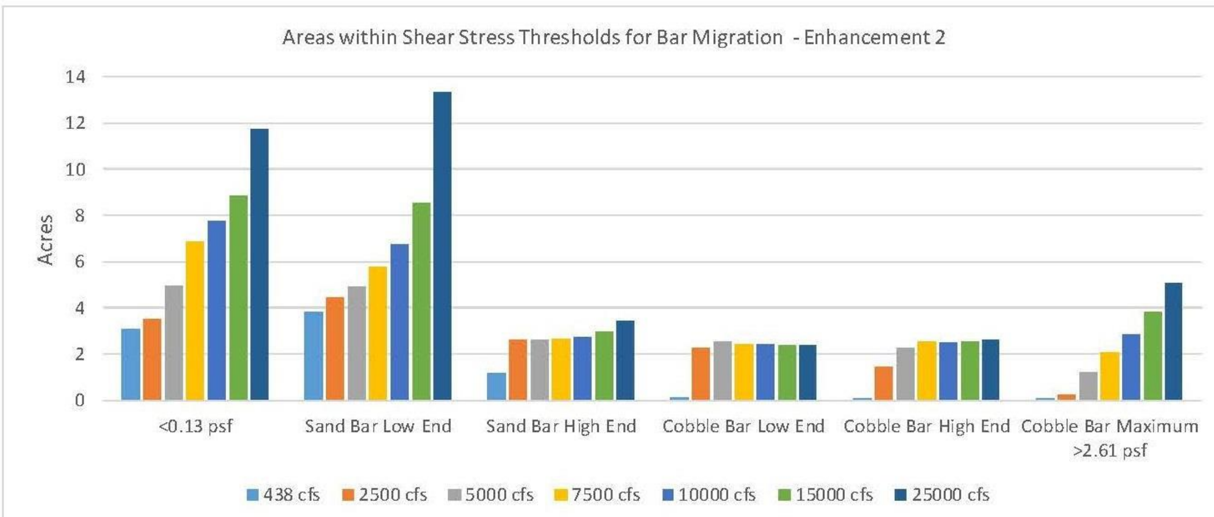
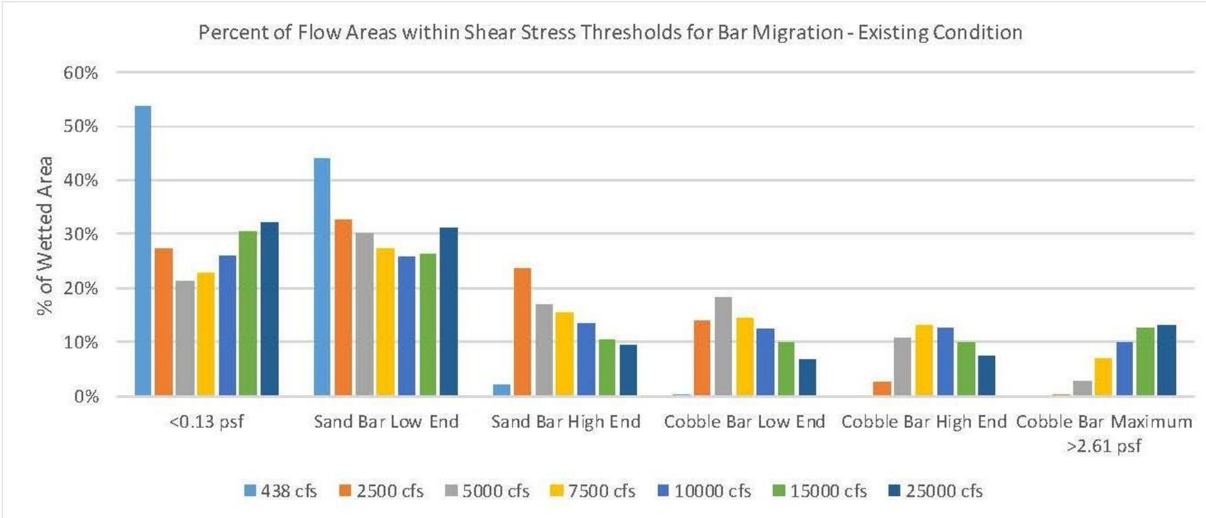


Figure 4-68. Acreages within Shear Stress Thresholds for Bar Migration Under Existing Condition (top) and with Enhancement 2 (bottom)



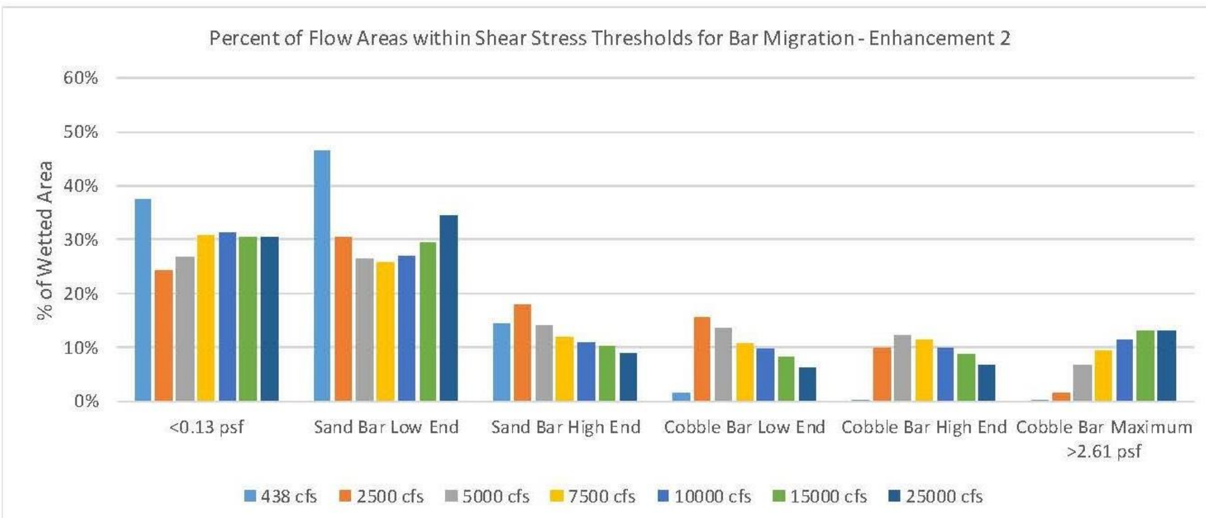


Figure 4-69. Percent of Flow Areas within Shear Stress Thresholds for Bar Migration Under Existing Condition (top) and with Enhancement 2 (bottom)

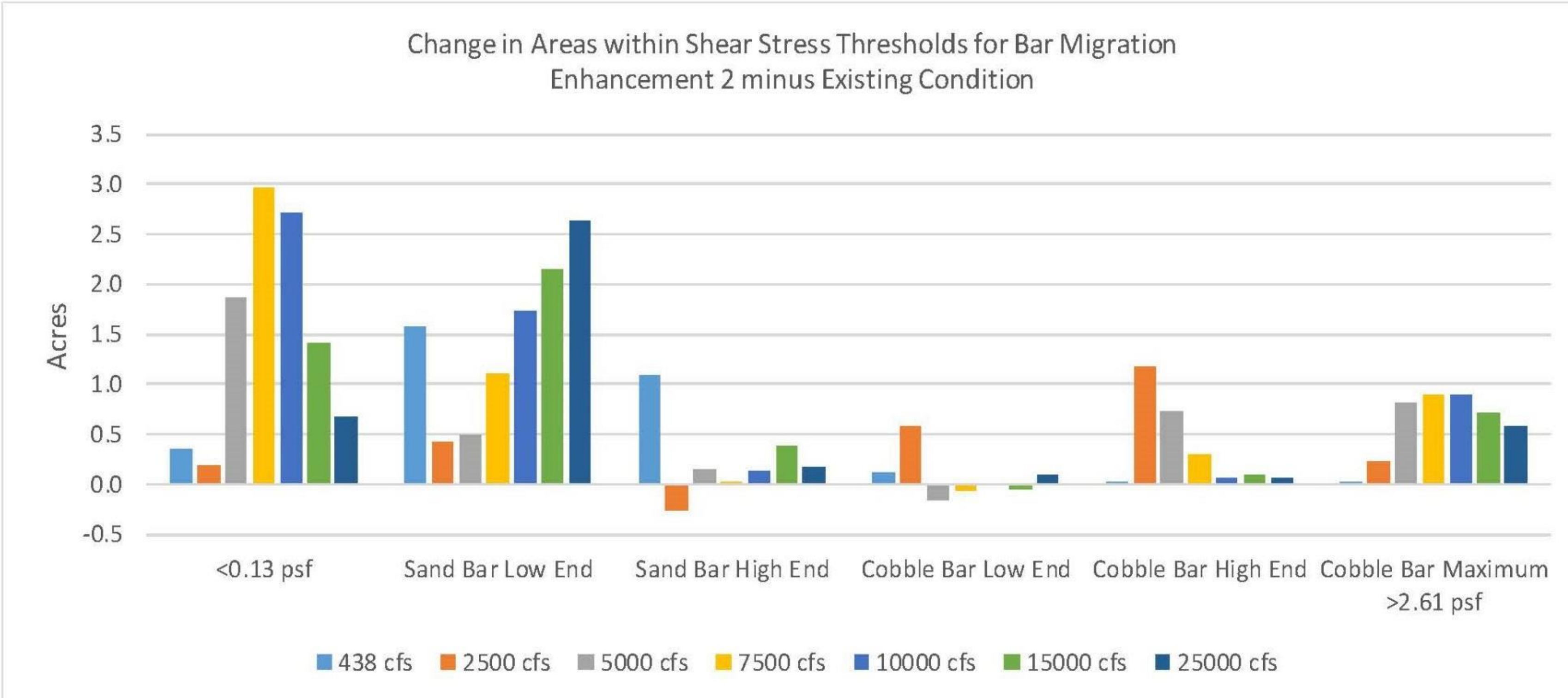


Figure 4-70. Increase in Acreage within Shear Stress Thresholds for bar Migration from the Existing Condition to Enhancement 2 Condition

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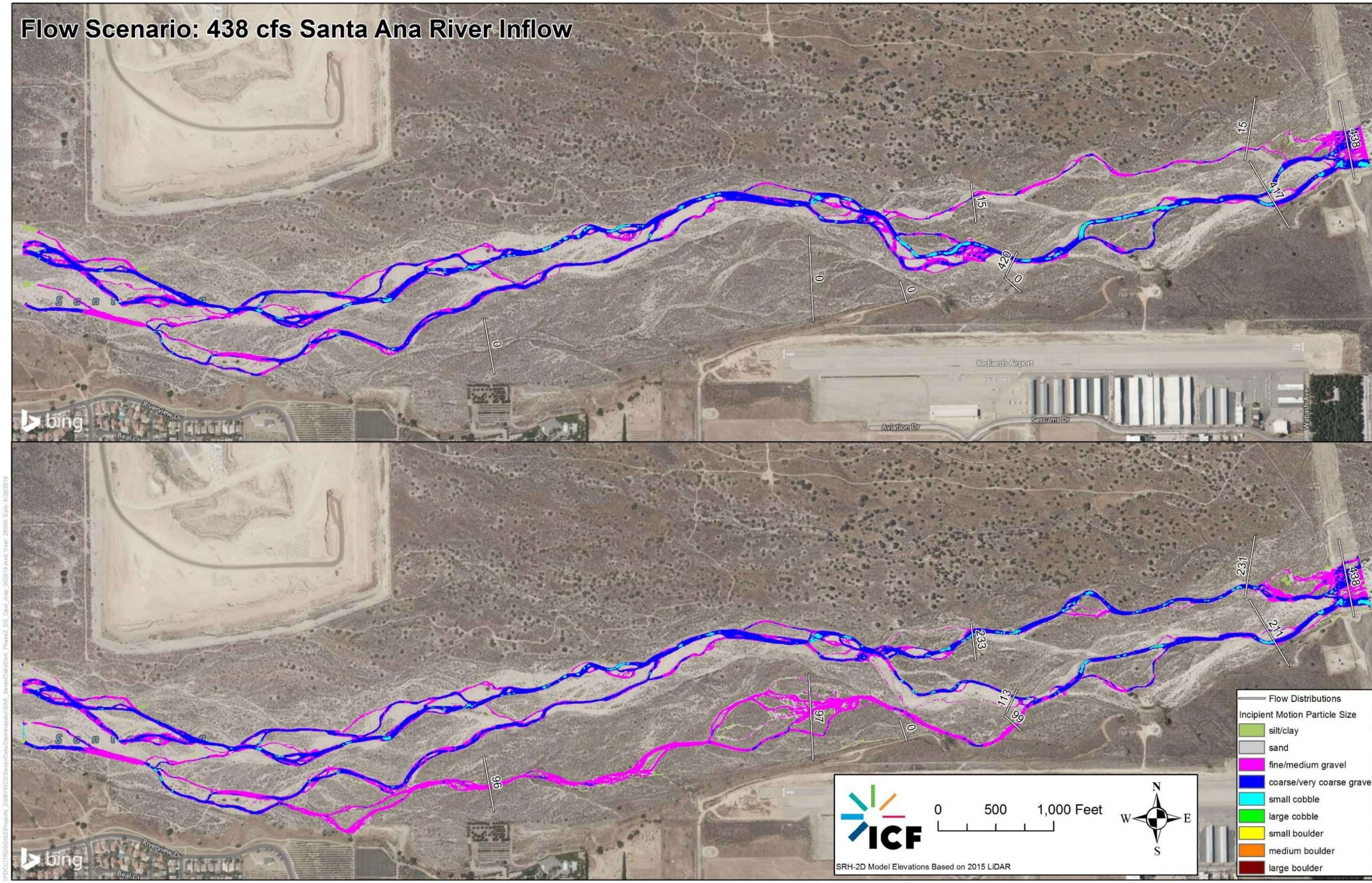

Figure 4-71. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 438 cfs (Existing Condition top; with Enhancement Measures bottom)

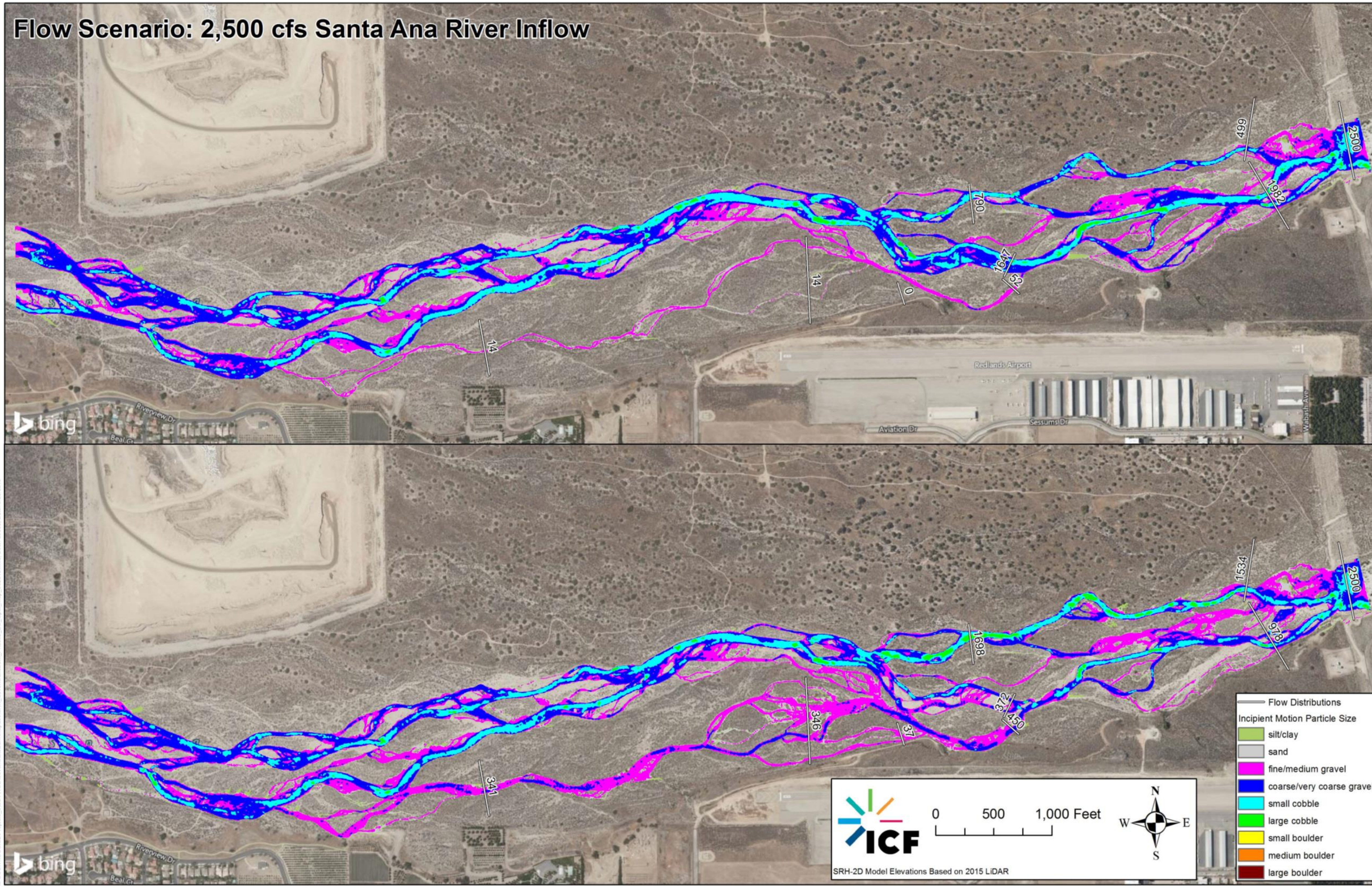

Figure 4-72. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 2,500 cfs (Existing Condition top; with Enhancement Measures bottom)

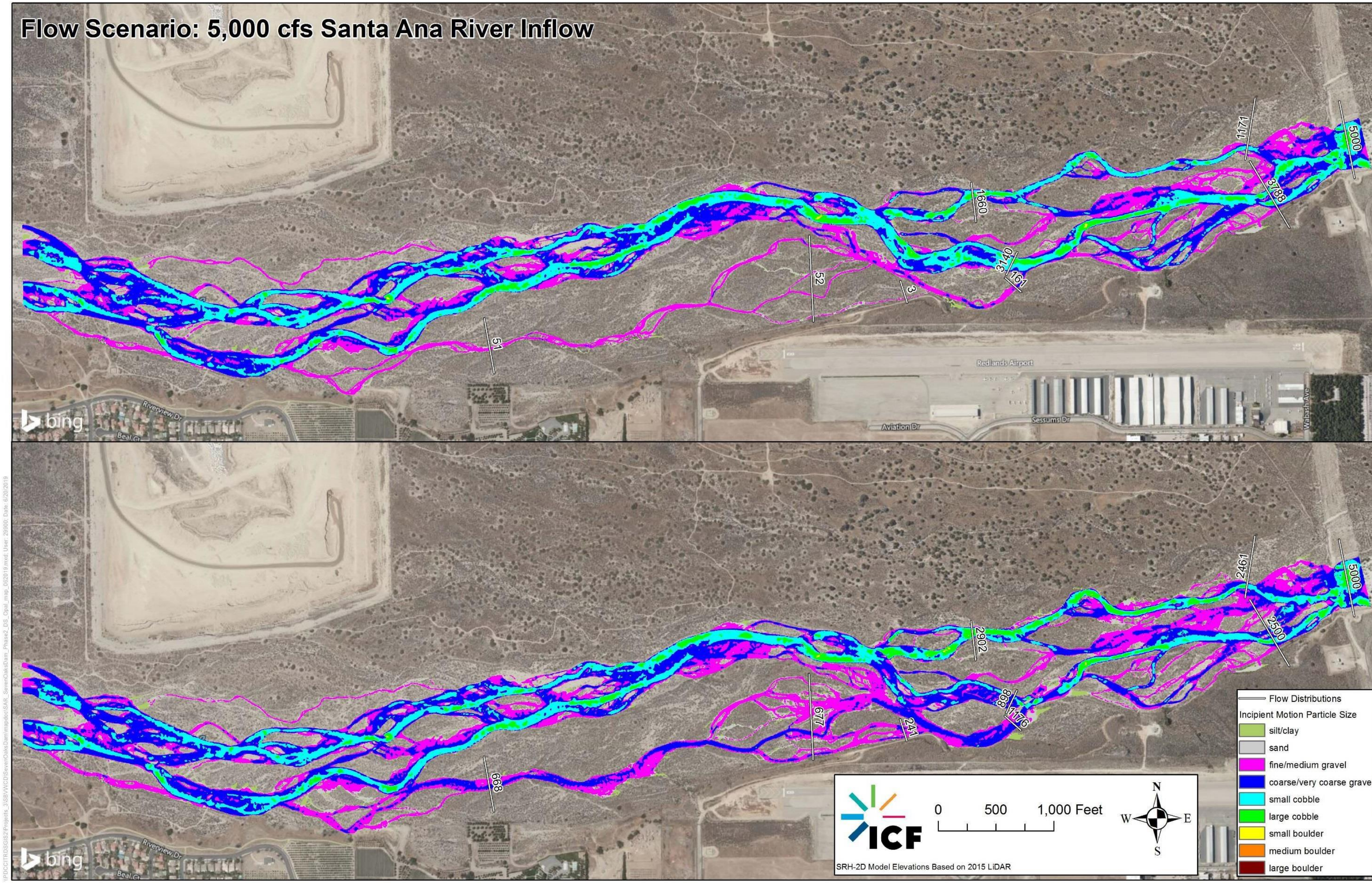

Figure 4-73. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 5,000 cfs (Existing Condition top; with Enhancement Measures bottom)

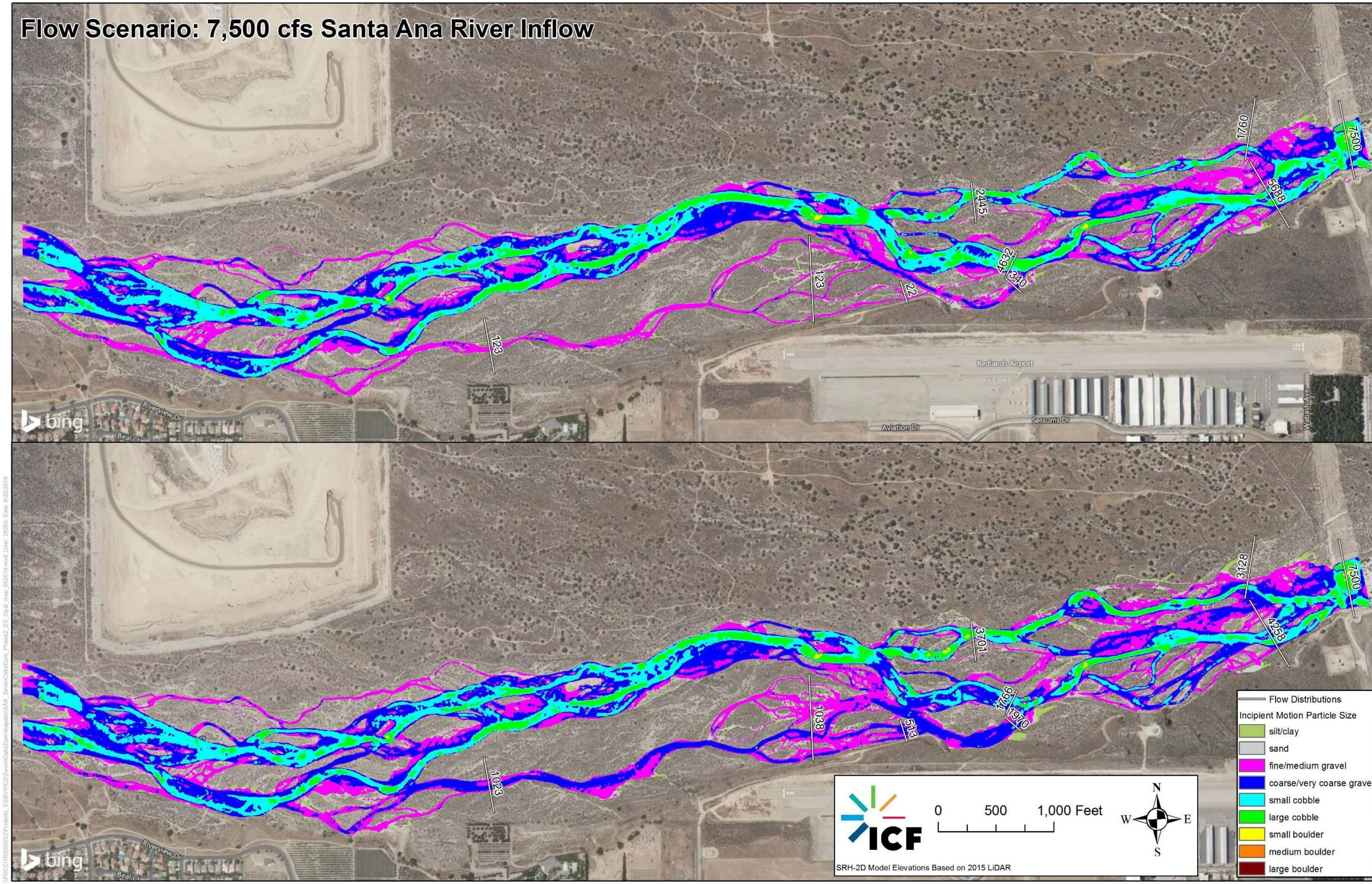

Figure 4-74. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 7,500 cfs (Existing Condition top; with Enhancement Measures bottom)

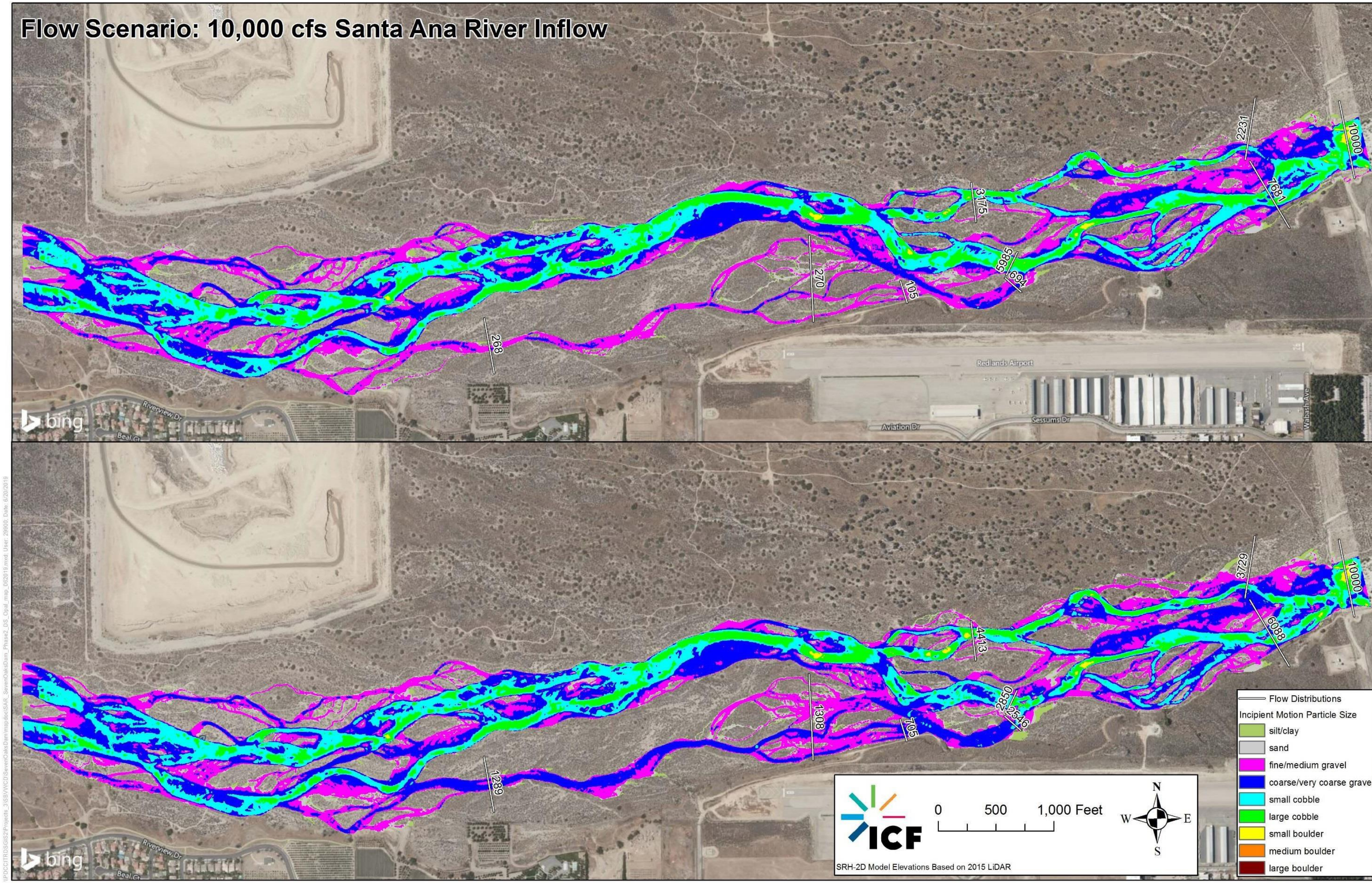

Figure 4-75. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 10,000 cfs (Existing Condition top; with Enhancement Measures bottom)

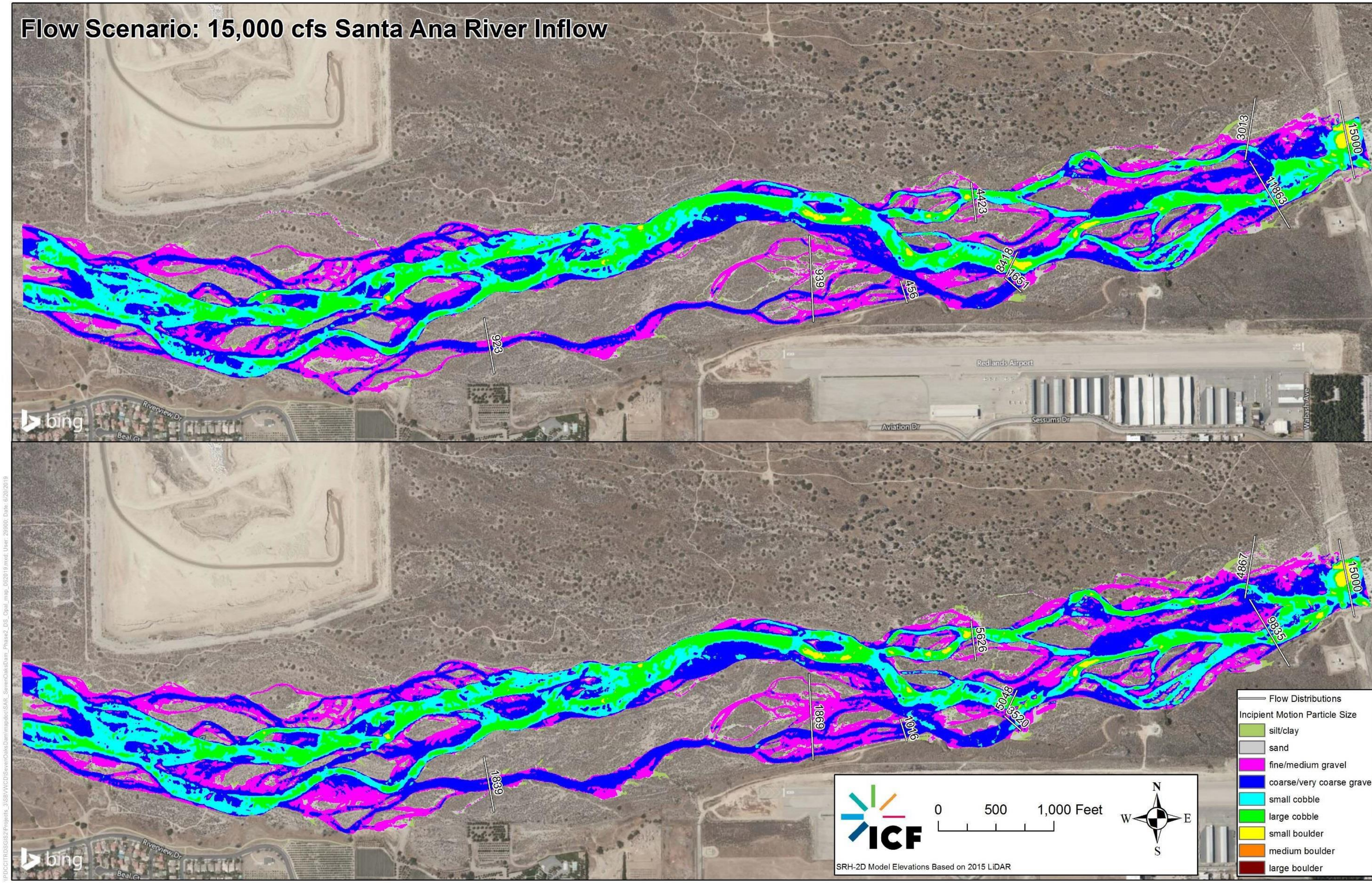

Figure 4-76. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 15,000 cfs (Existing Condition top; with Enhancement Measures bottom)

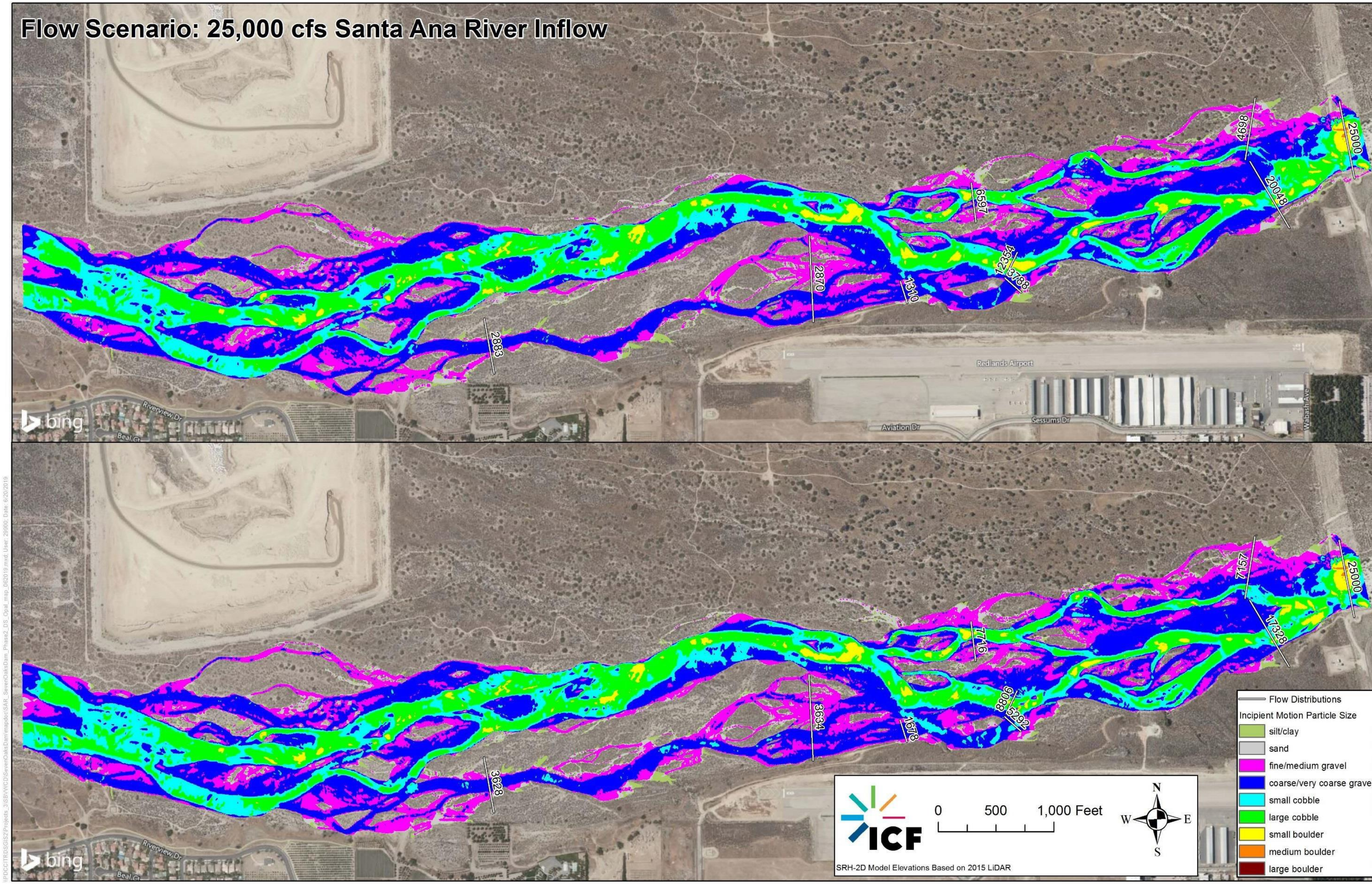

Figure 4-77. Predicted Types of Sediment Incipient Motion in the Santa Ana River Near the Redlands Airport at 25,000 cfs (Existing Condition top; with Enhancement Measures bottom)

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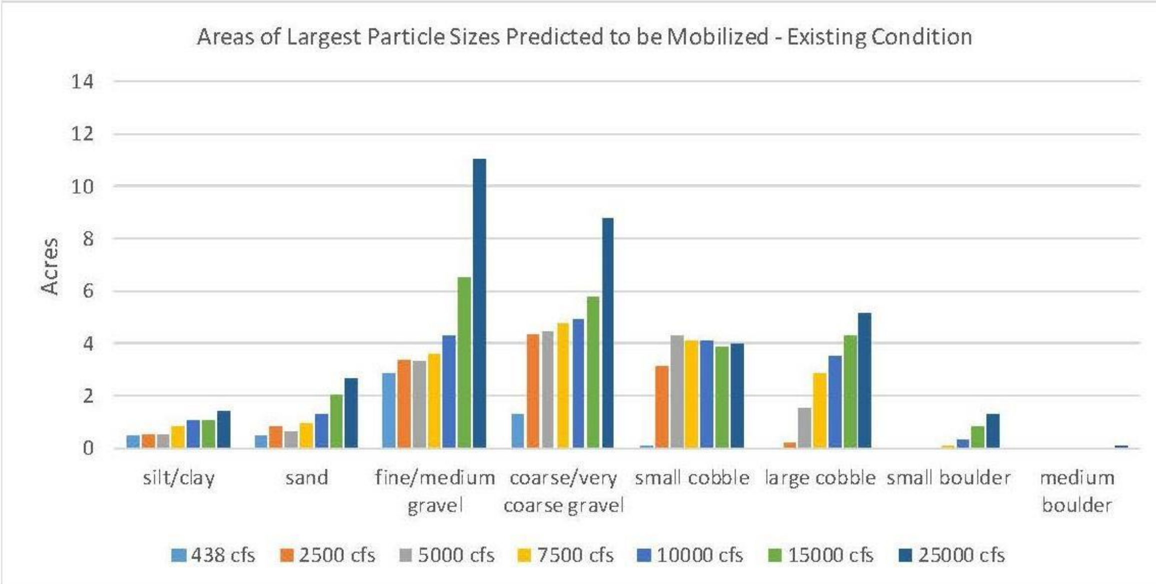


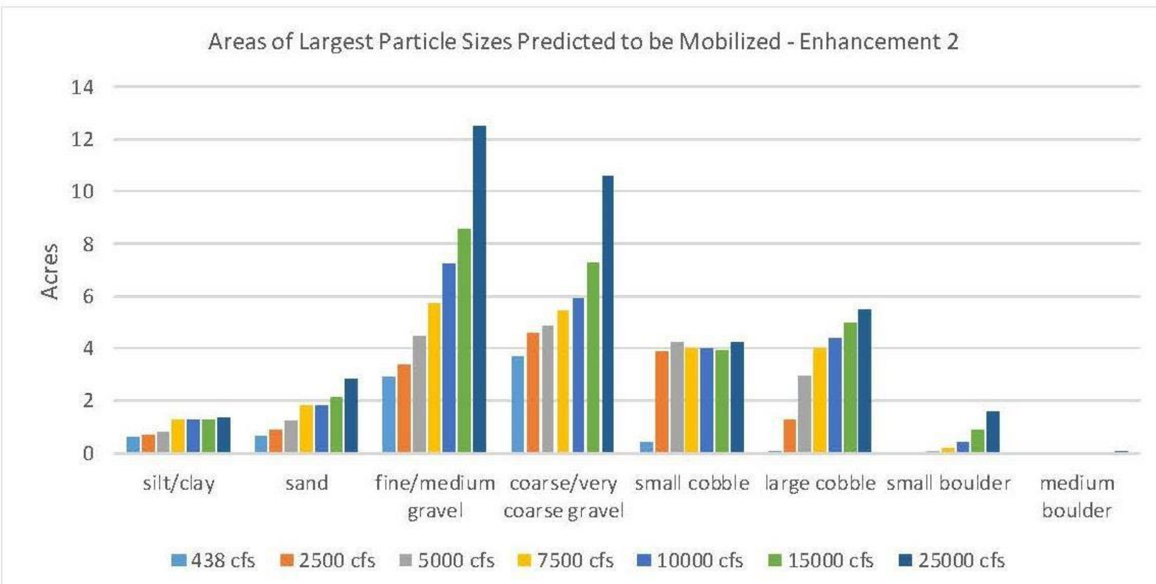
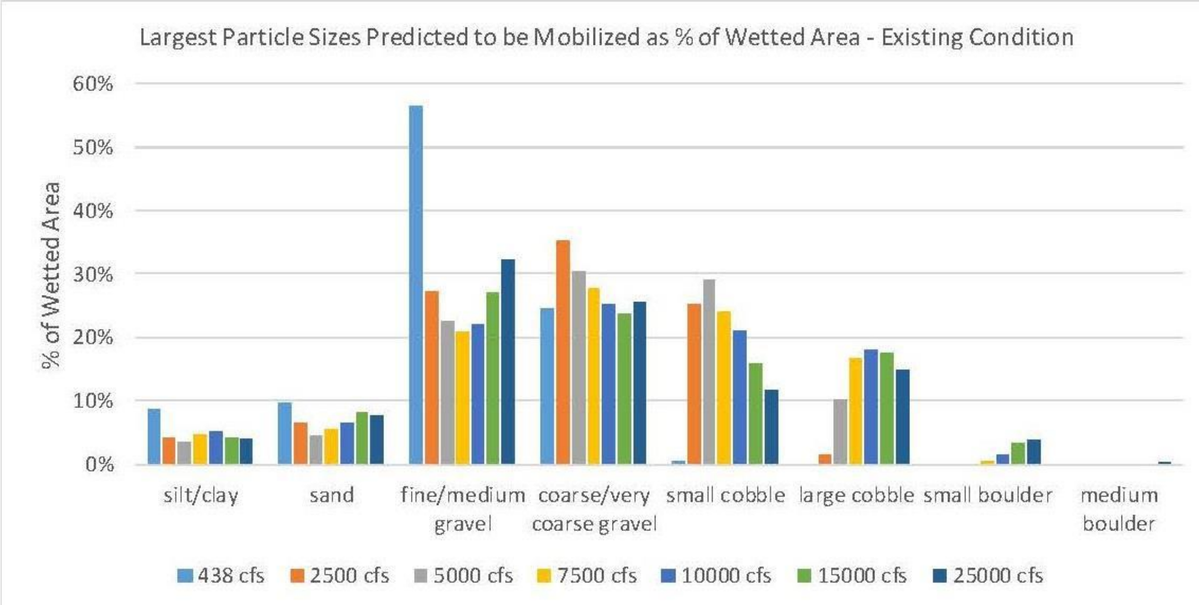


Figure 4-78. Acreages with Incipient Motion of Sediment Size Classes for Existing Condition (top) and with Enhancement 2 (bottom)



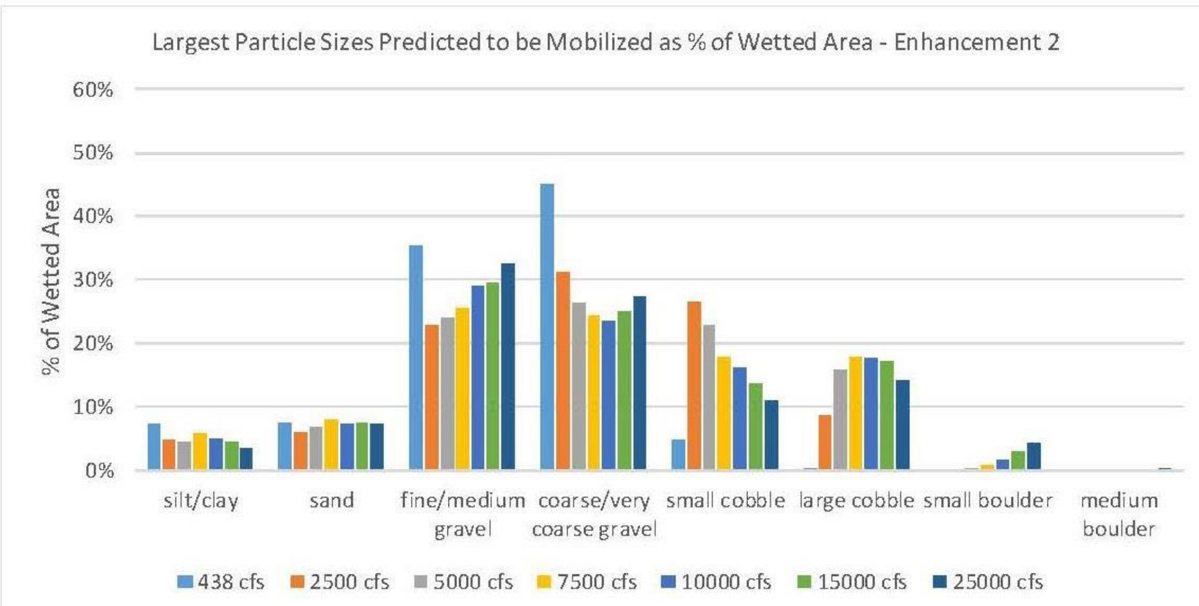


Figure 4-79. Percent of Flow Areas with Incipient Motion of Sediment Size Classes for Existing Condition (top) and with Enhancement 2 (bottom)

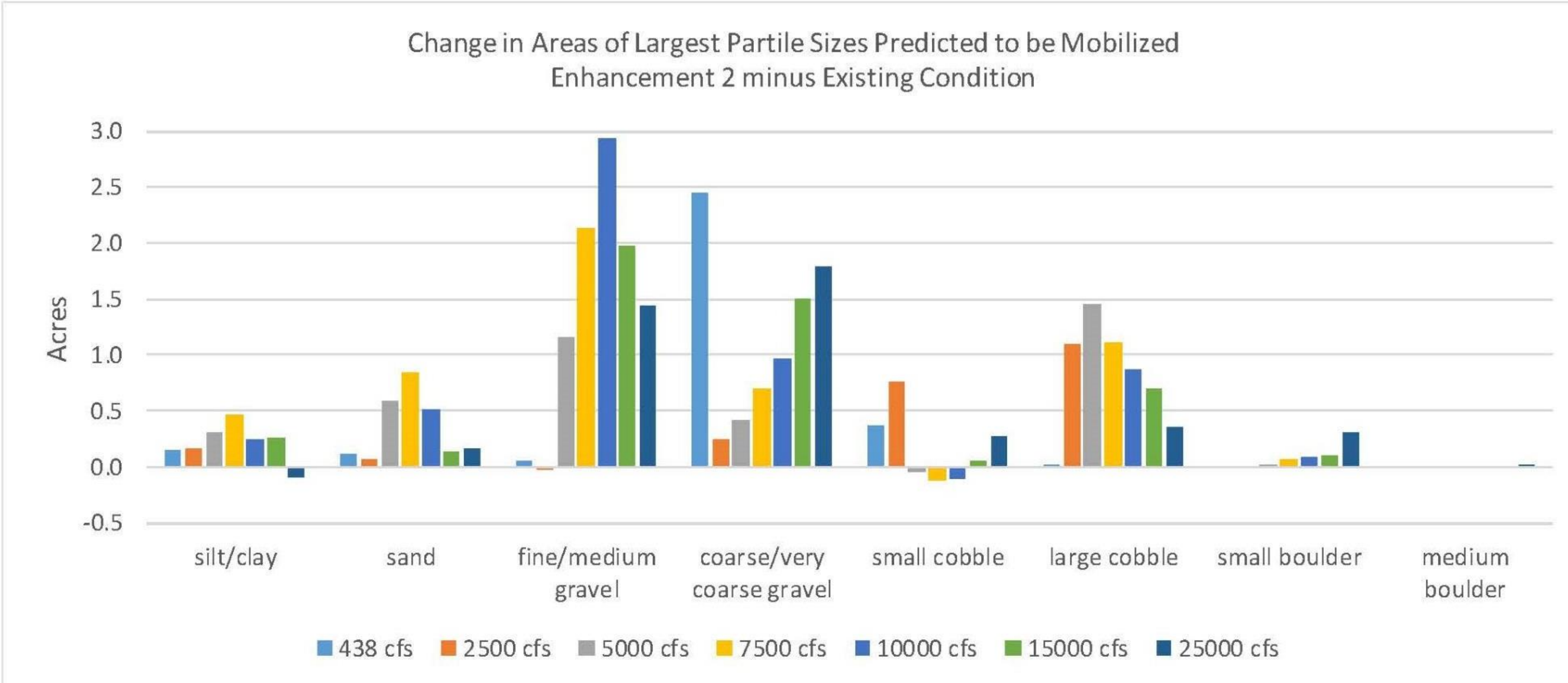


Figure 4-80. Increase in Acreage of Incipient Motion of Sediment Size Classes from the Existing Condition to Enhancement 2 Condition.

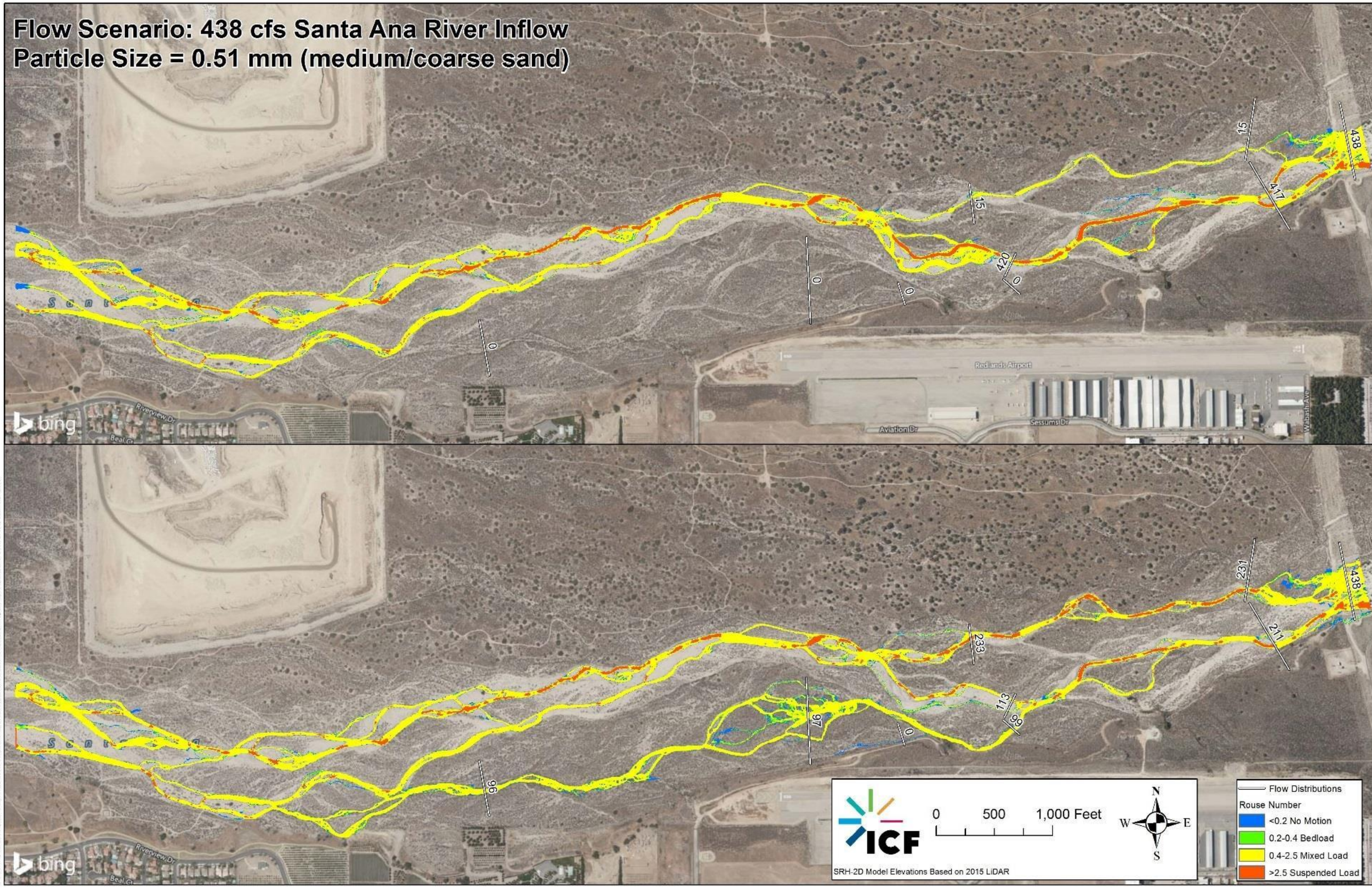


Figure 4-81. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 438 cfs (Existing Condition top; with Enhancement Measures bottom)

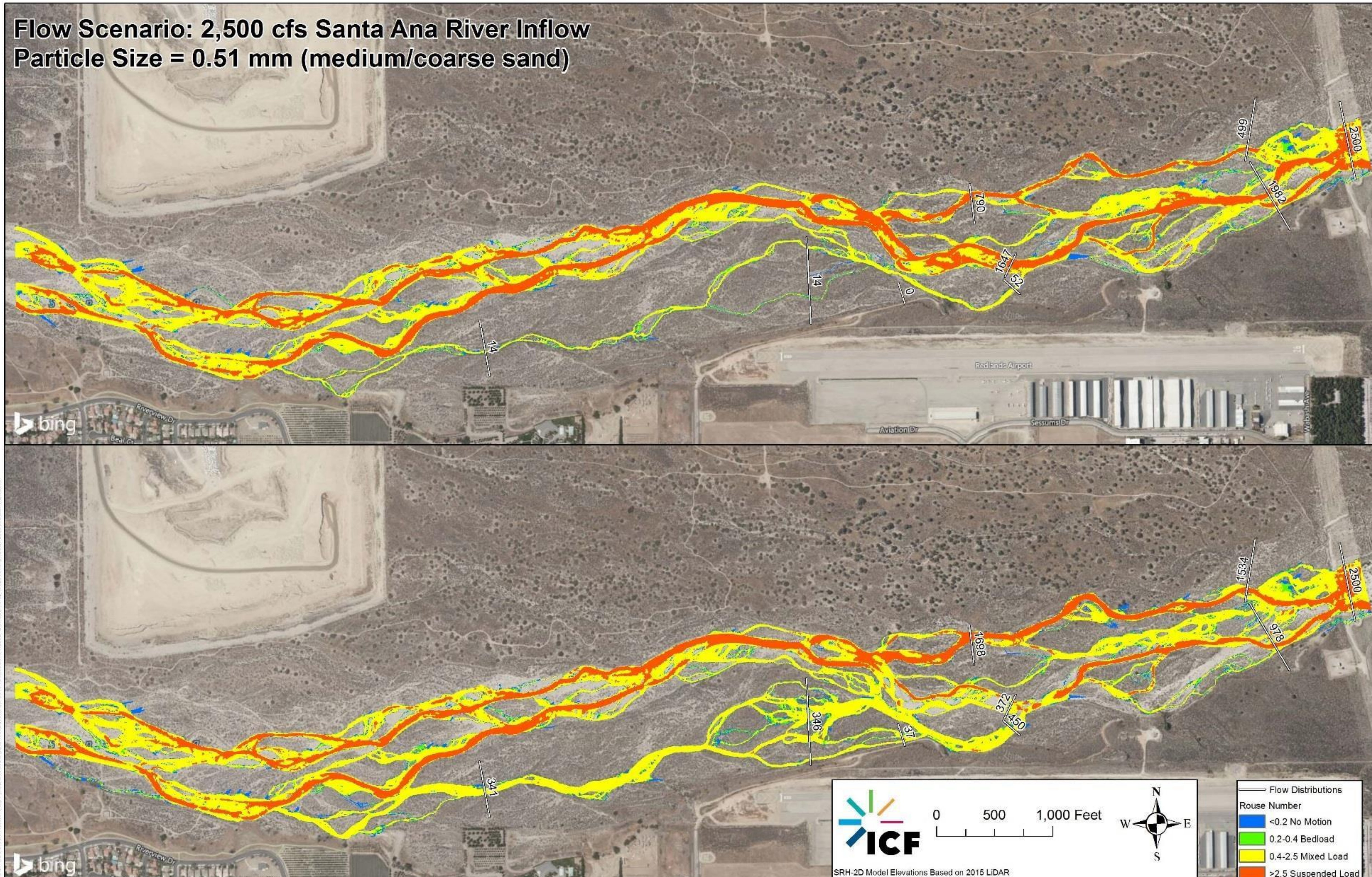


Figure 4-82. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 2,500 cfs (Existing Condition top; with Enhancement Measures bottom)

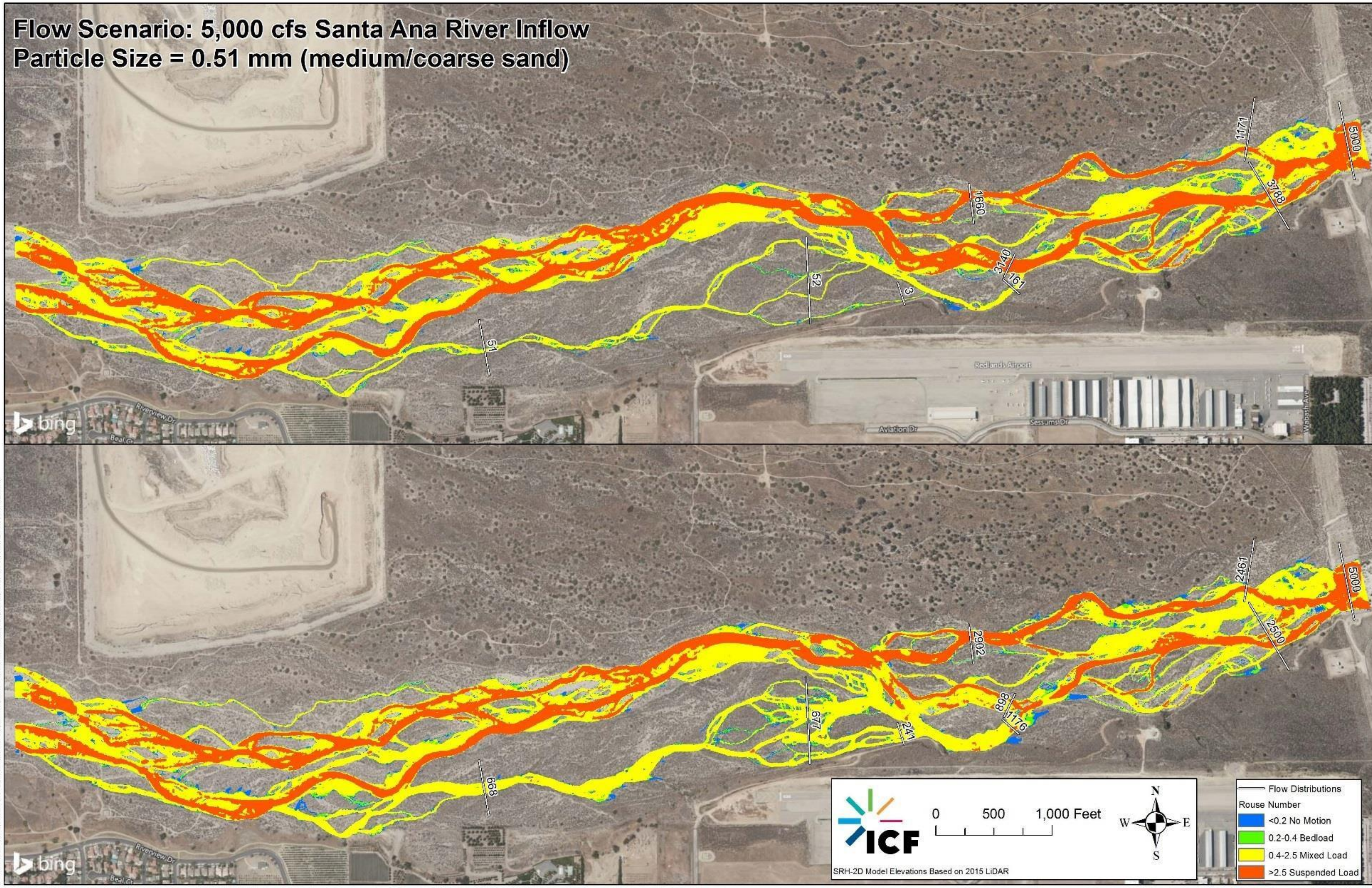


Figure 4-83. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 5,000 cfs (Existing Condition top; with Enhancement Measures bottom)

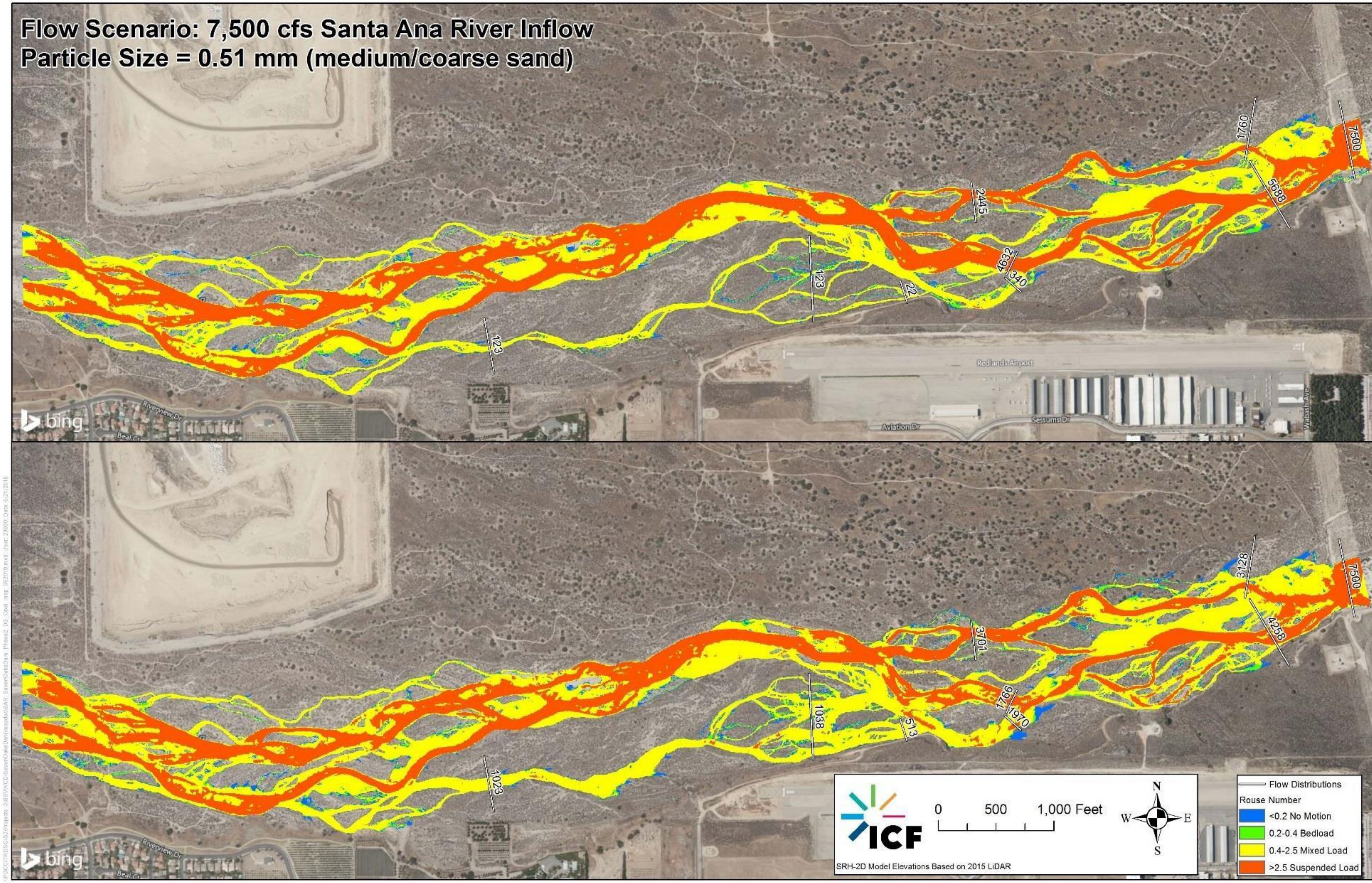


Figure 4-84. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 7,500 cfs (Existing Condition top; with Enhancement Measures bottom)

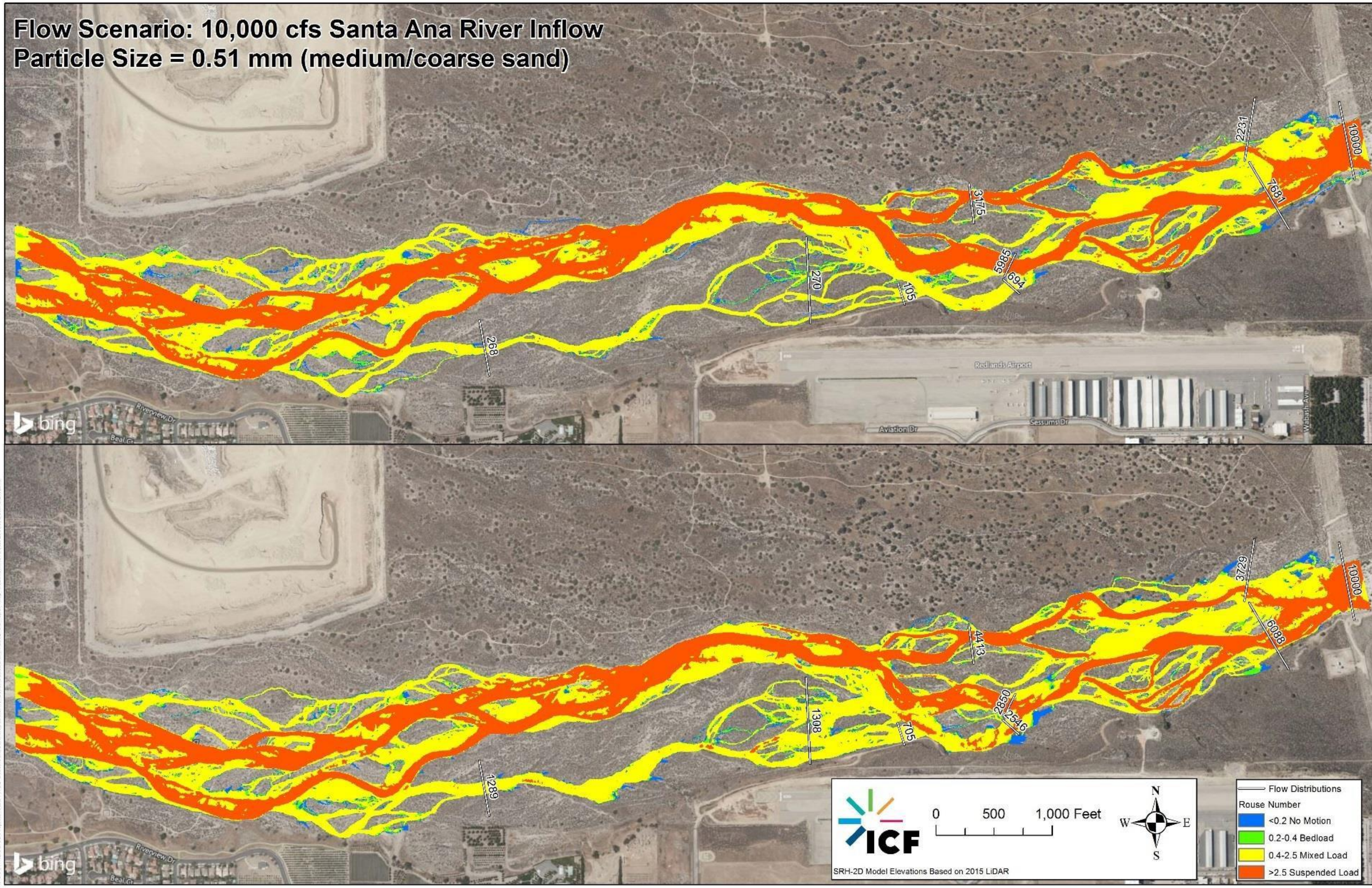


Figure 4-85. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 10,000 cfs (Existing Condition top; with Enhancement Measures bottom)

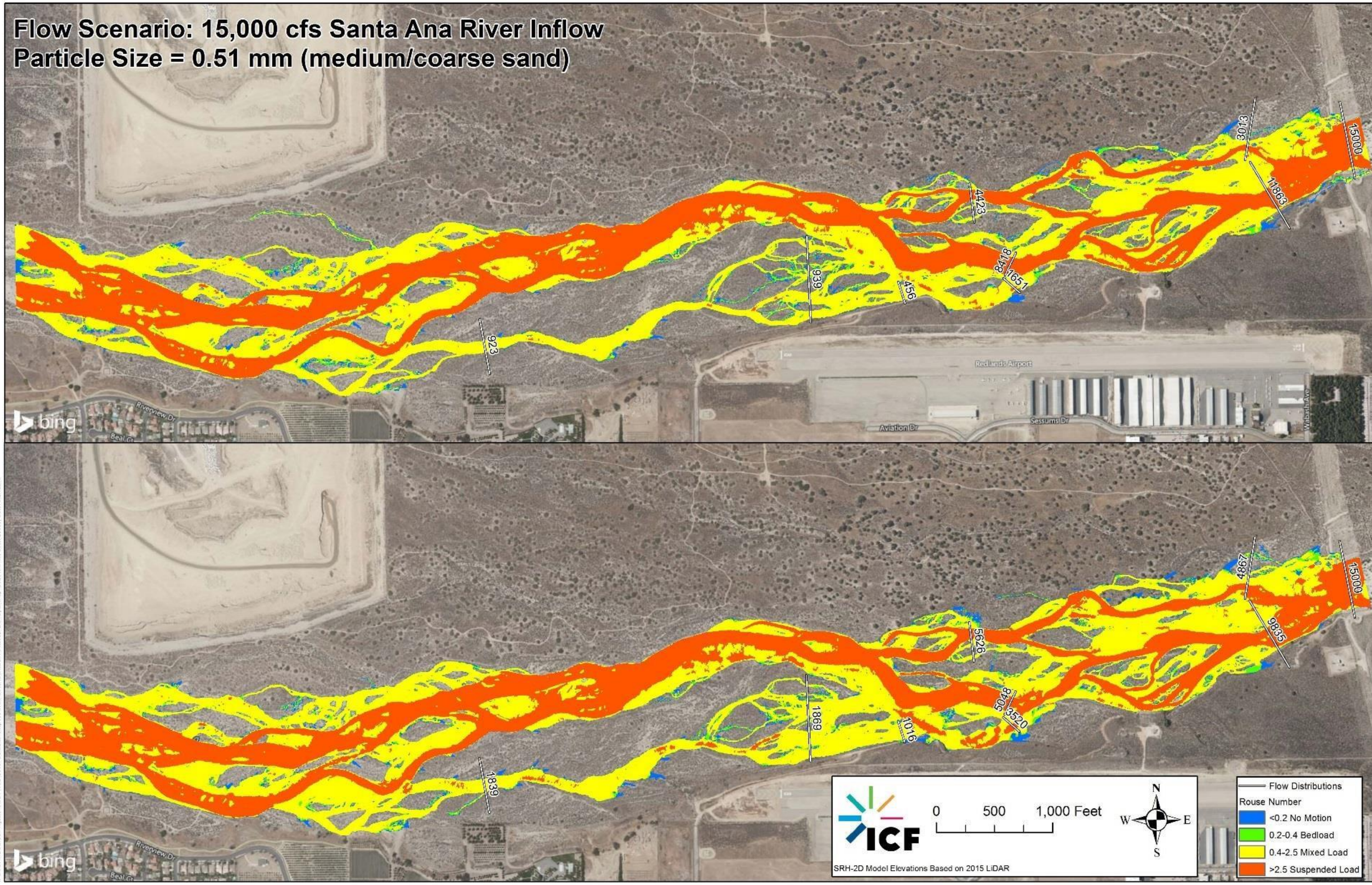


Figure 4-86. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 15,000 cfs (Existing Condition top; with Enhancement Measures bottom)

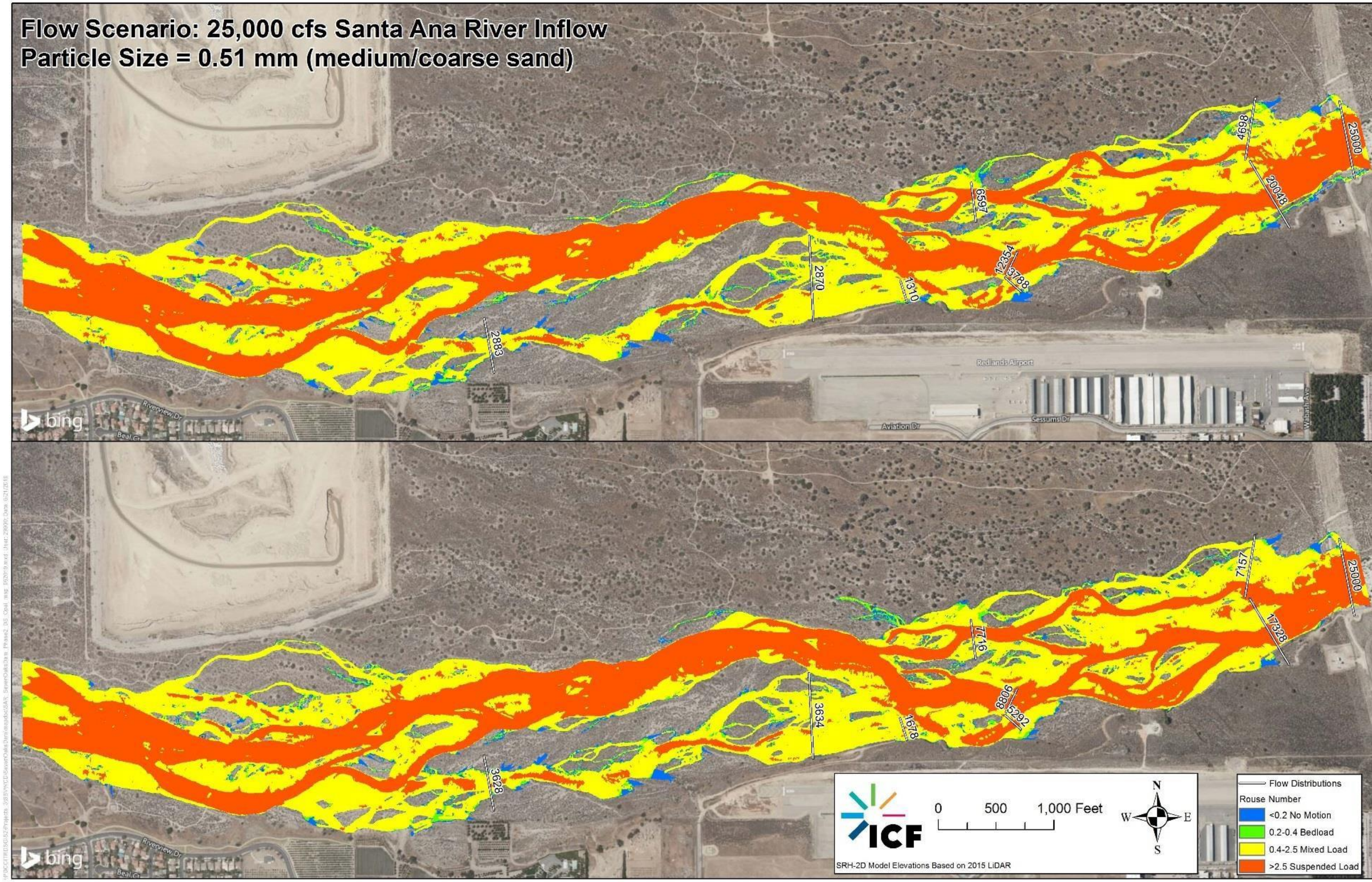


Figure 4-87. Predicted Mode of Sediment Transport in the Santa Ana River Near the Redlands Airport at 25,000 cfs (Existing Condition top; with Enhancement Measures bottom)

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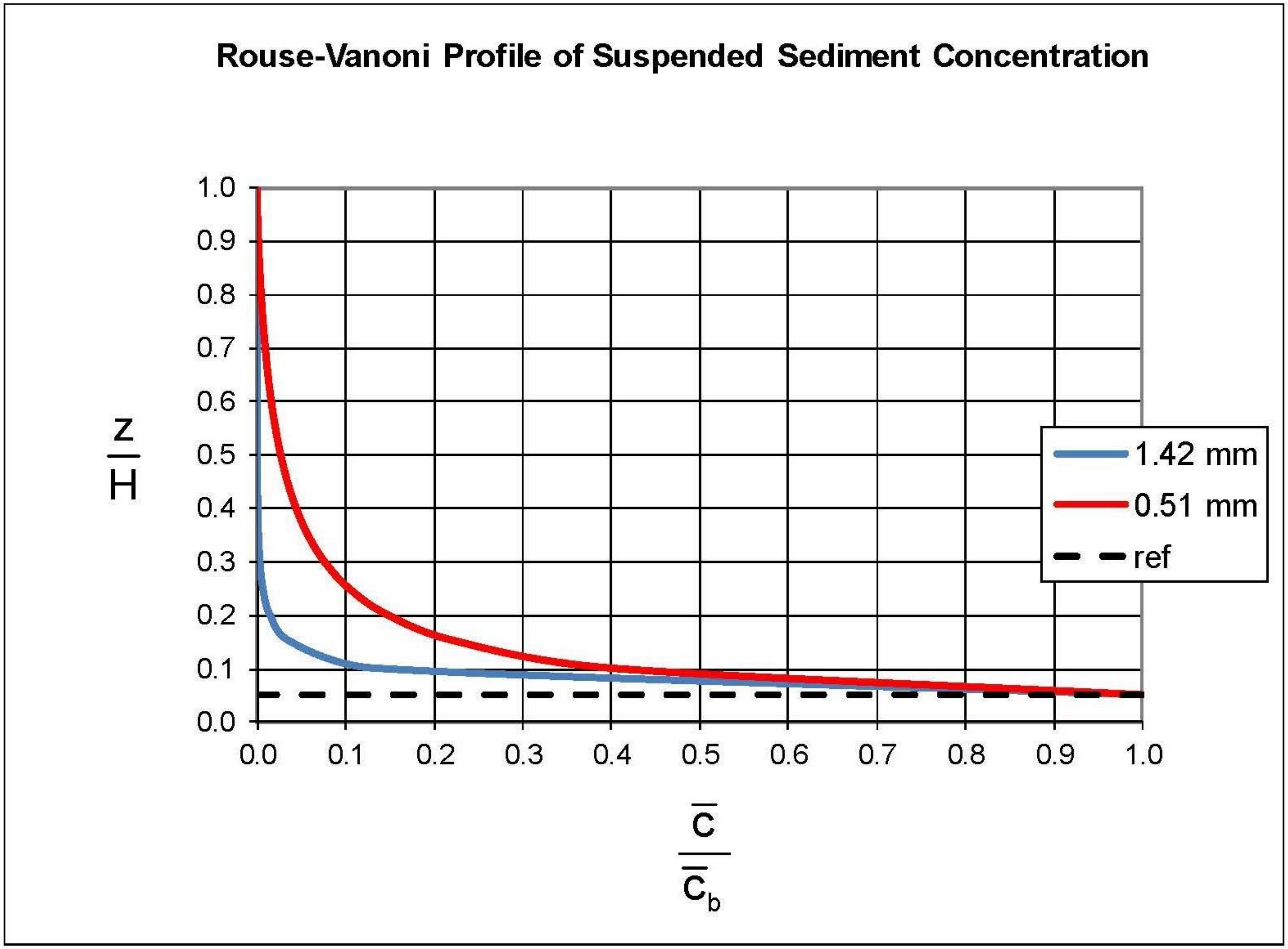
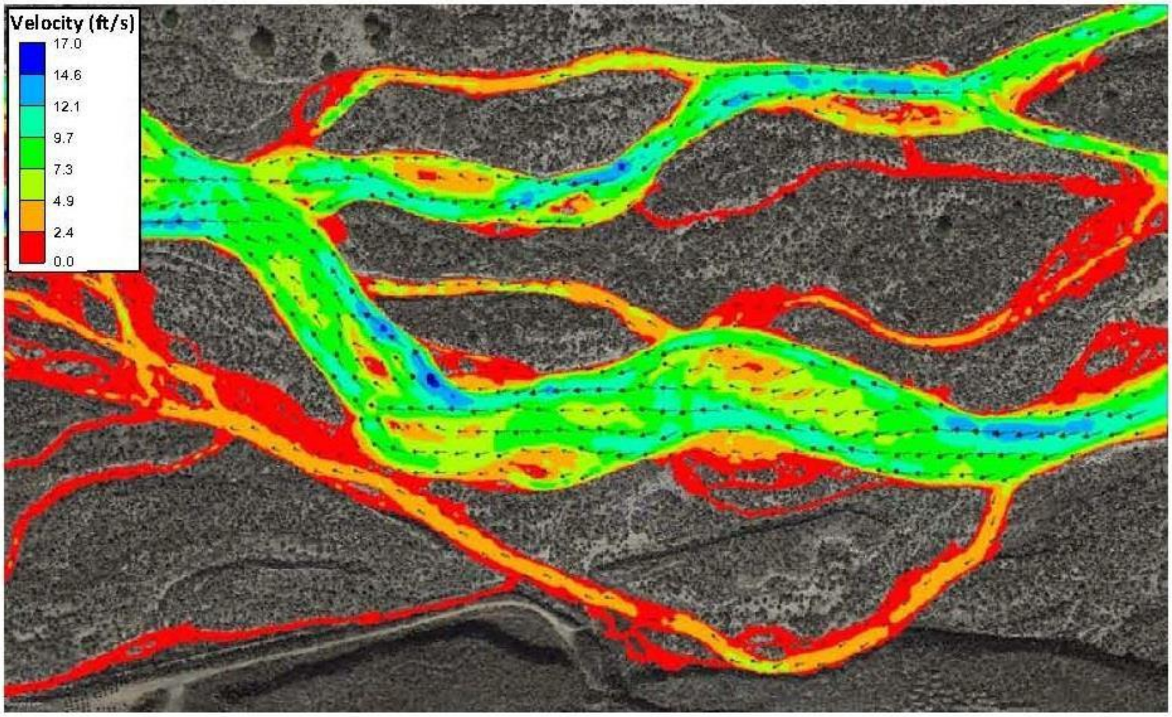


Figure 4-88. Rouse-Vanoni Profile Averaged Over the Total Inundation Area Downstream of the Mentone Pipeline with Enhancement Measures 2 and 3 for the San Diego Zoo D_{50} and D_{90} Particle Sizes



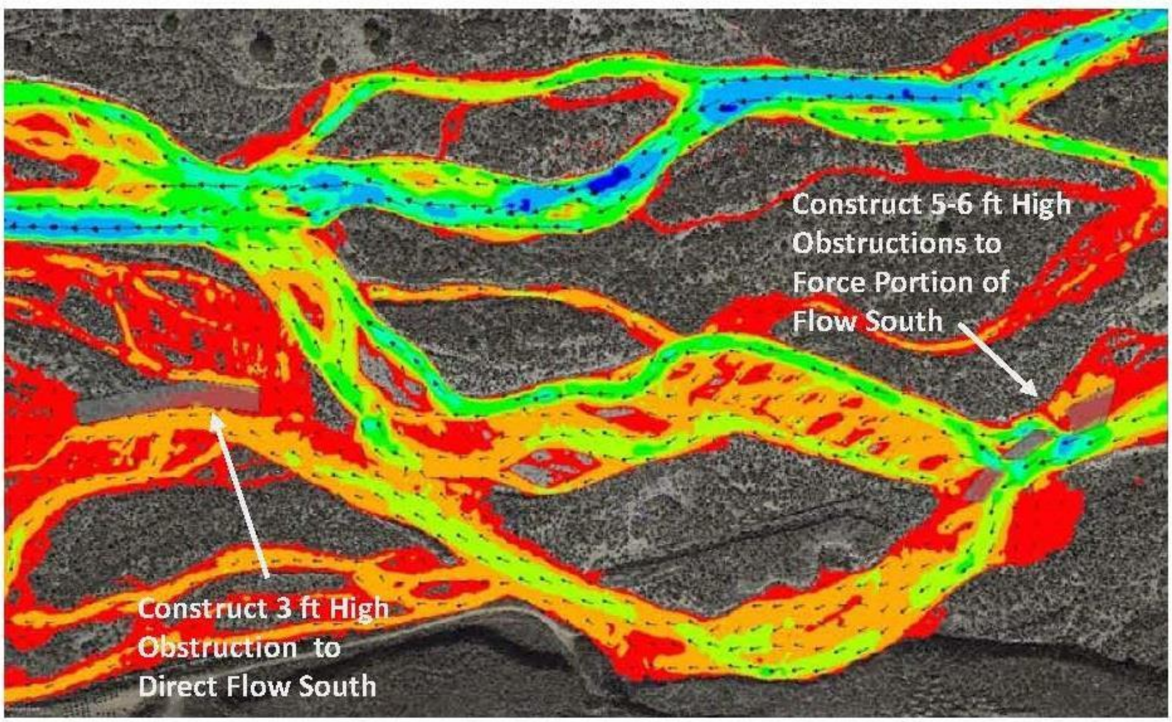
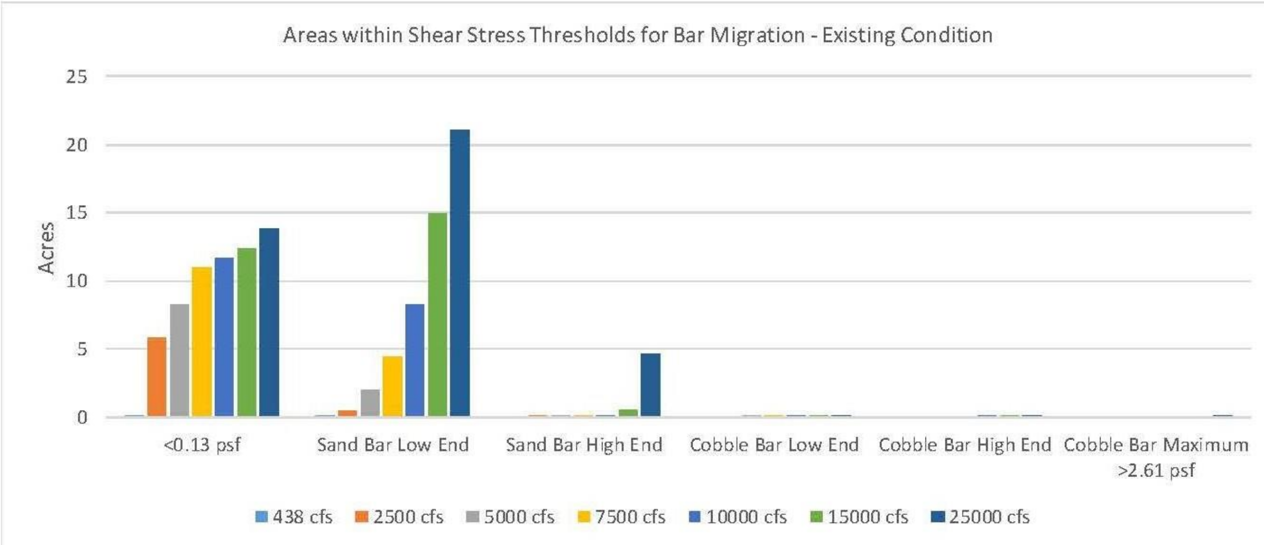


Figure 4-89. Flow Velocity Magnitudes and Vectors at 5,000 cfs for the Existing Condition (top) and with Enhancement Measure 3 (bottom)



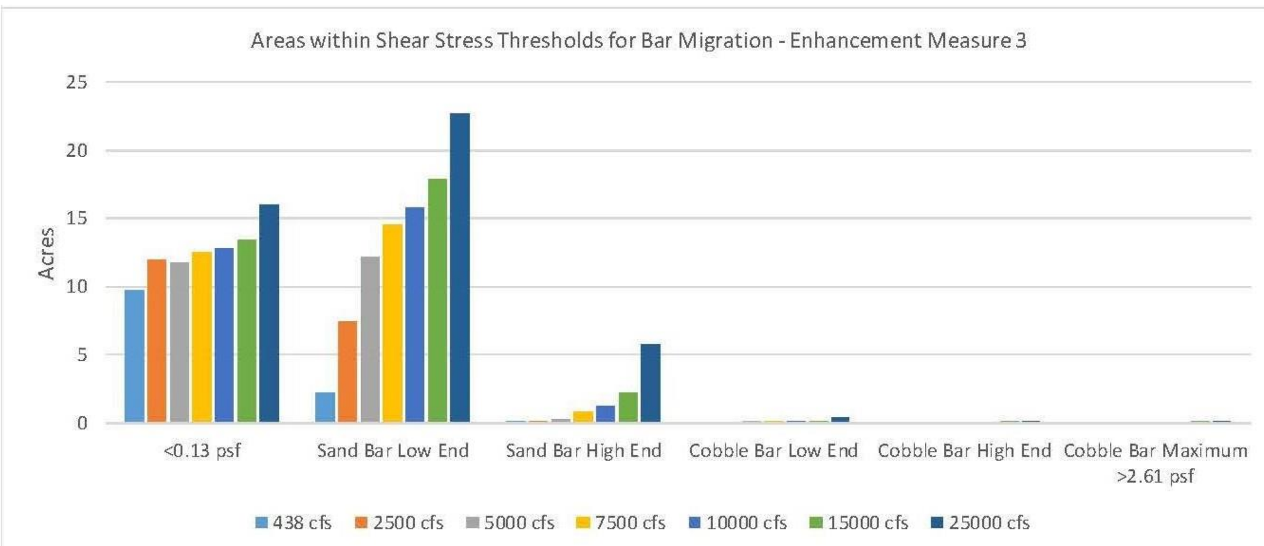
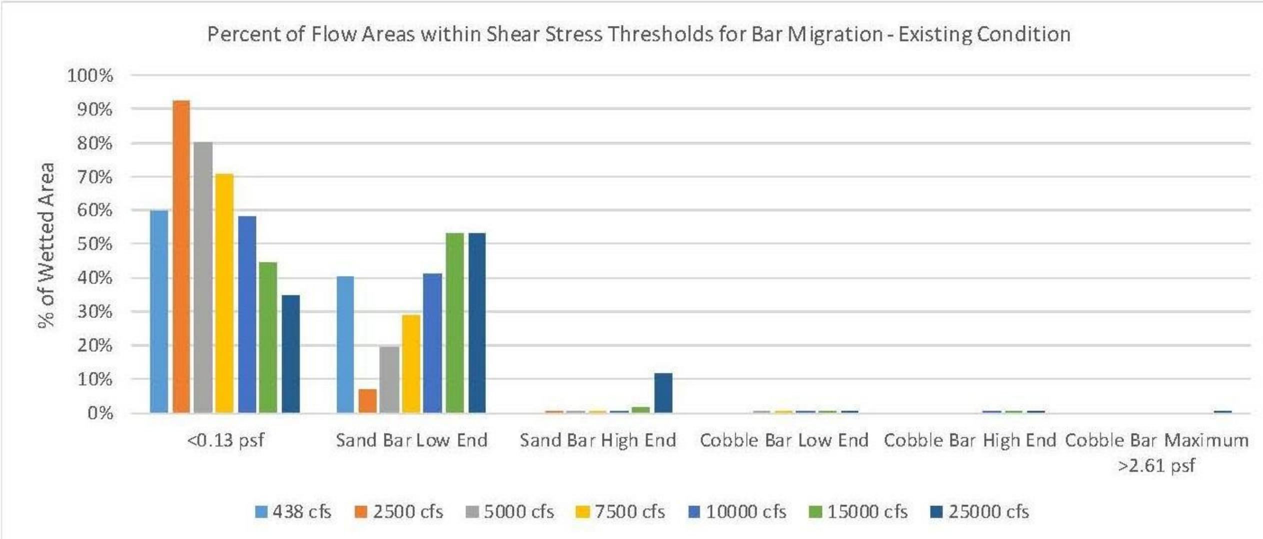


Figure 4-90. Acreages within Shear Stress Thresholds for Bar Migration Under Existing Condition (top) and with Enhancement 3 (bottom)



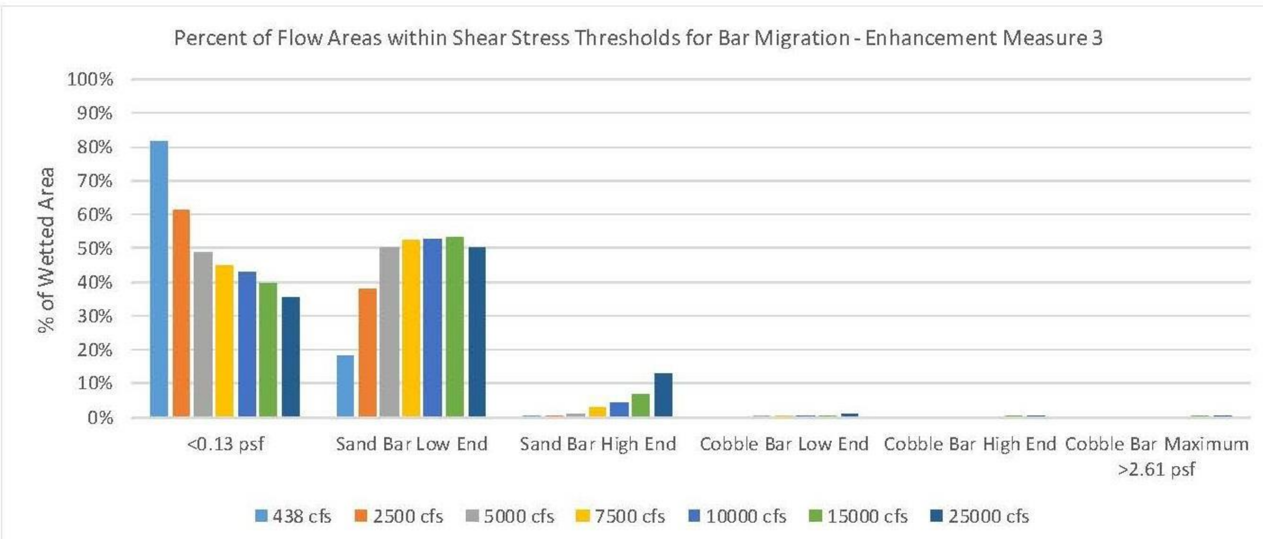


Figure 4-91. Percent of Flow Areas within Shear Stress Thresholds for Bar Migration Under Existing Condition (top) and with Enhancement 3 (bottom)

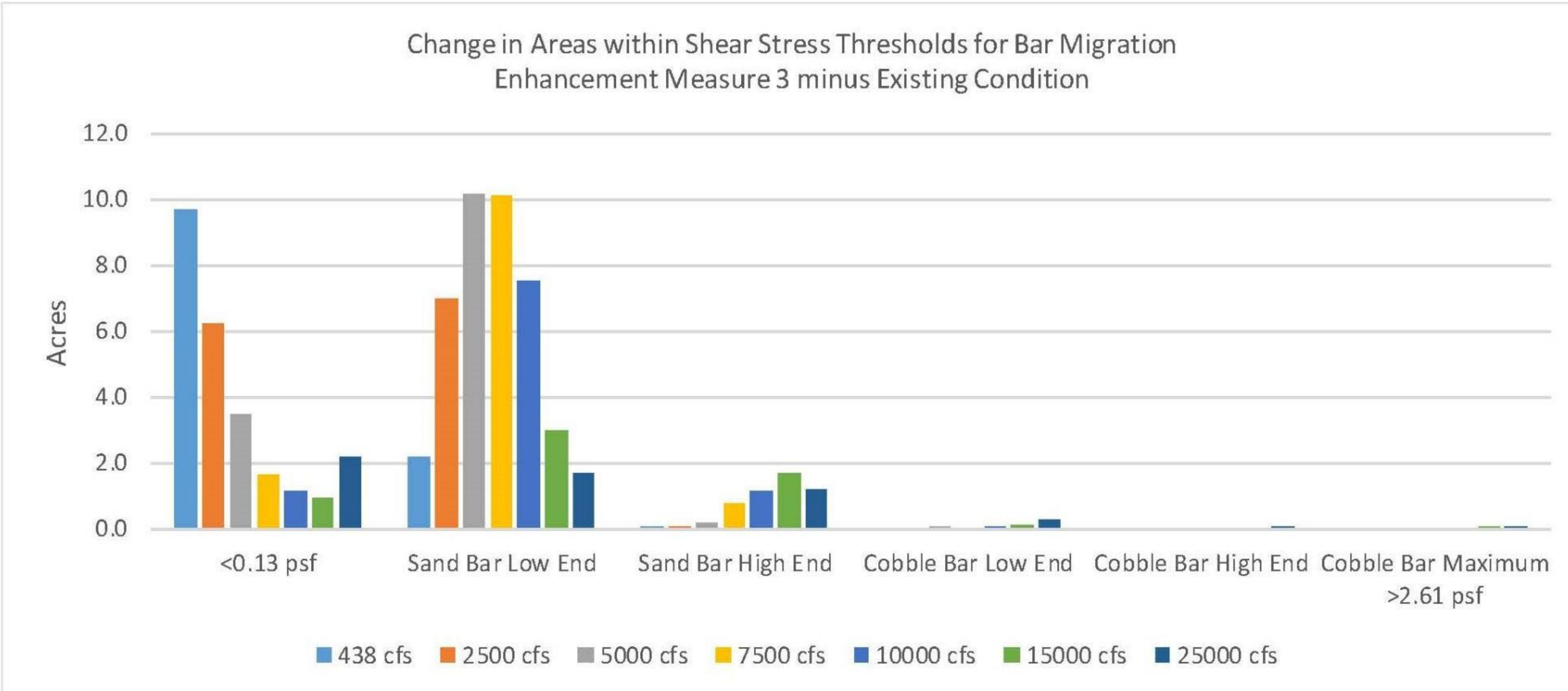
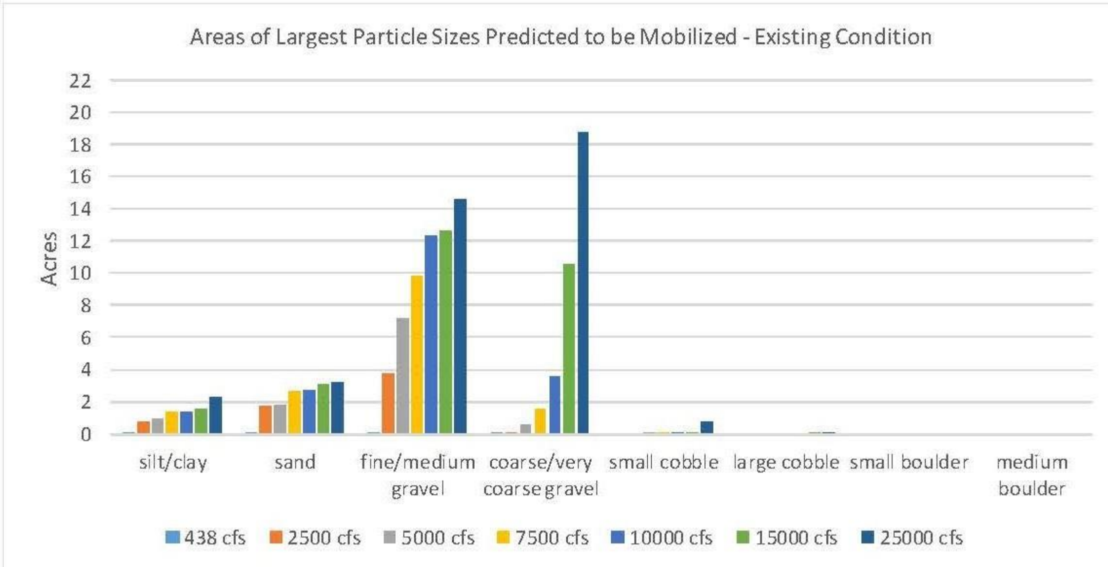


Figure 4-92. Increase in Acreage within Shear Stress Thresholds for Bar Migration from the Existing Condition to Enhancement 3 Condition



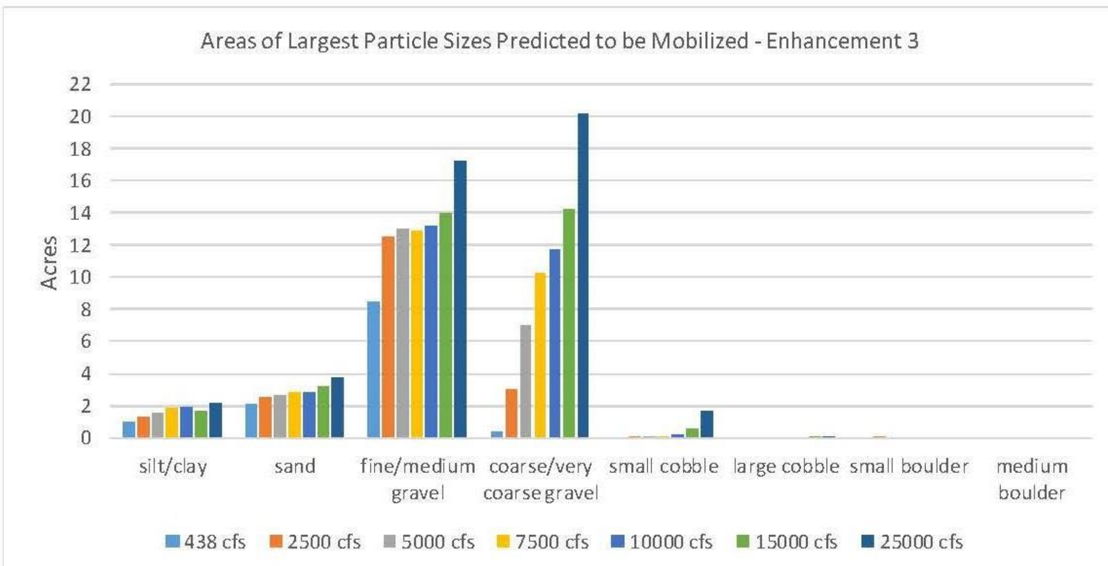
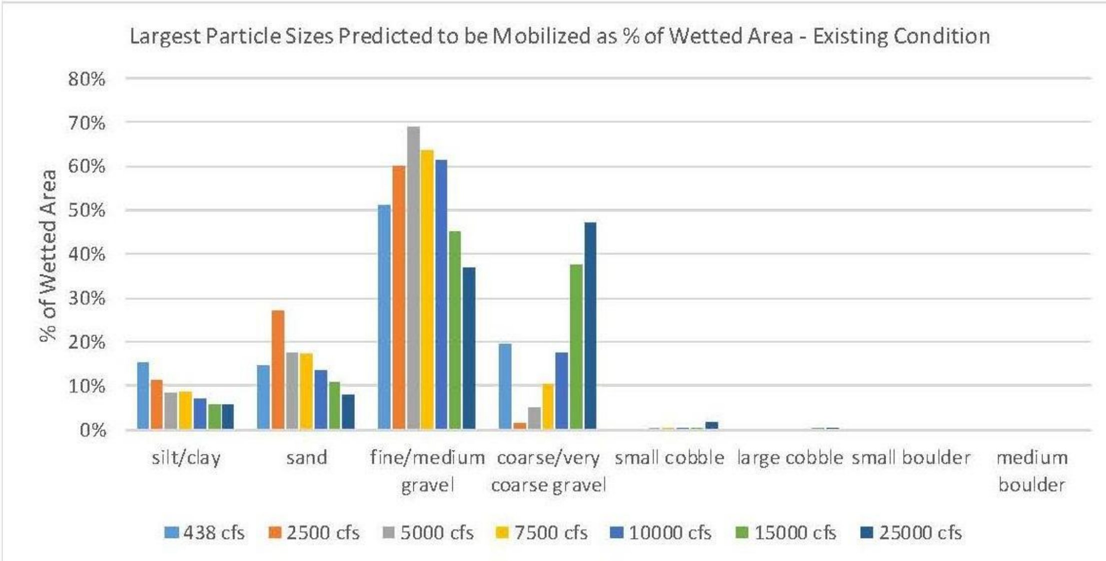


Figure 4-93. Acreages with Incipient Motion of Sediment Size Classes for Existing Condition (top) and with Enhancement 3 (bottom)



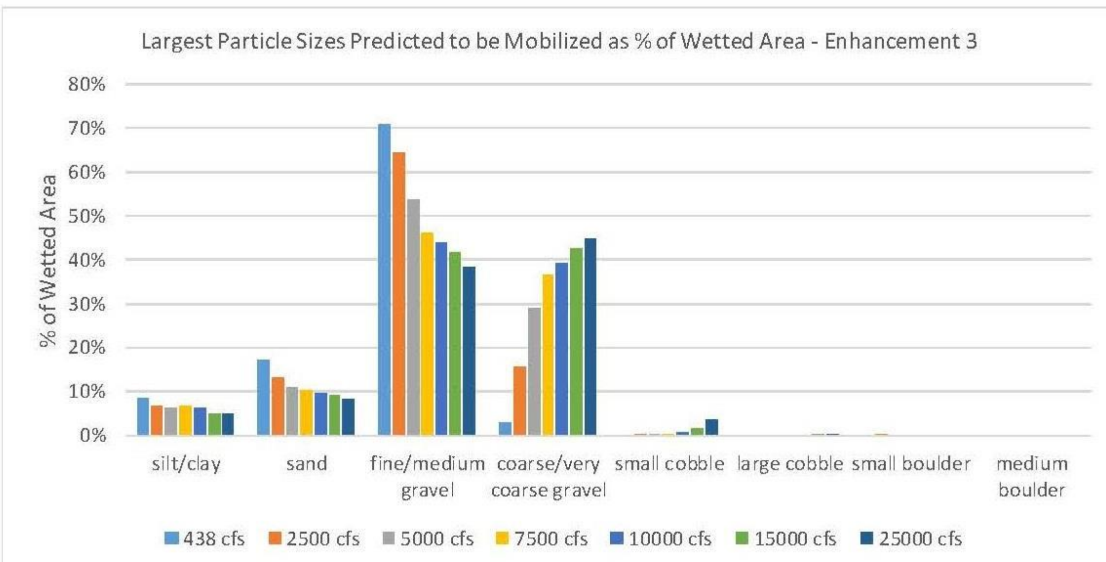


Figure 4-94. Percent of Flow Areas with Incipient Motion of Sediment Size Classes for Existing Condition (top) and with Enhancement 3 (bottom)

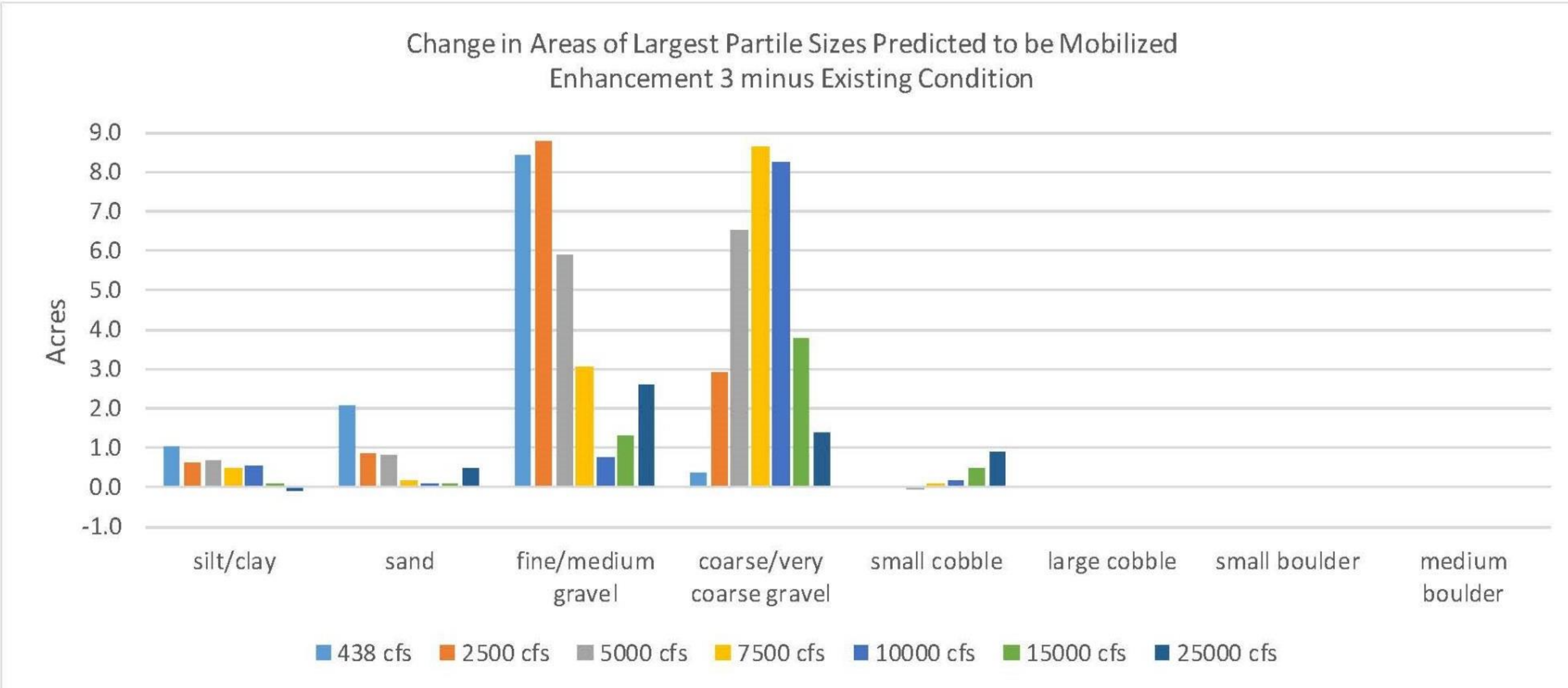


Figure 4-95. Increase in Acreage of Incipient Motion of Sediment Size Classes from the Existing Condition to Enhancement 3 Condition

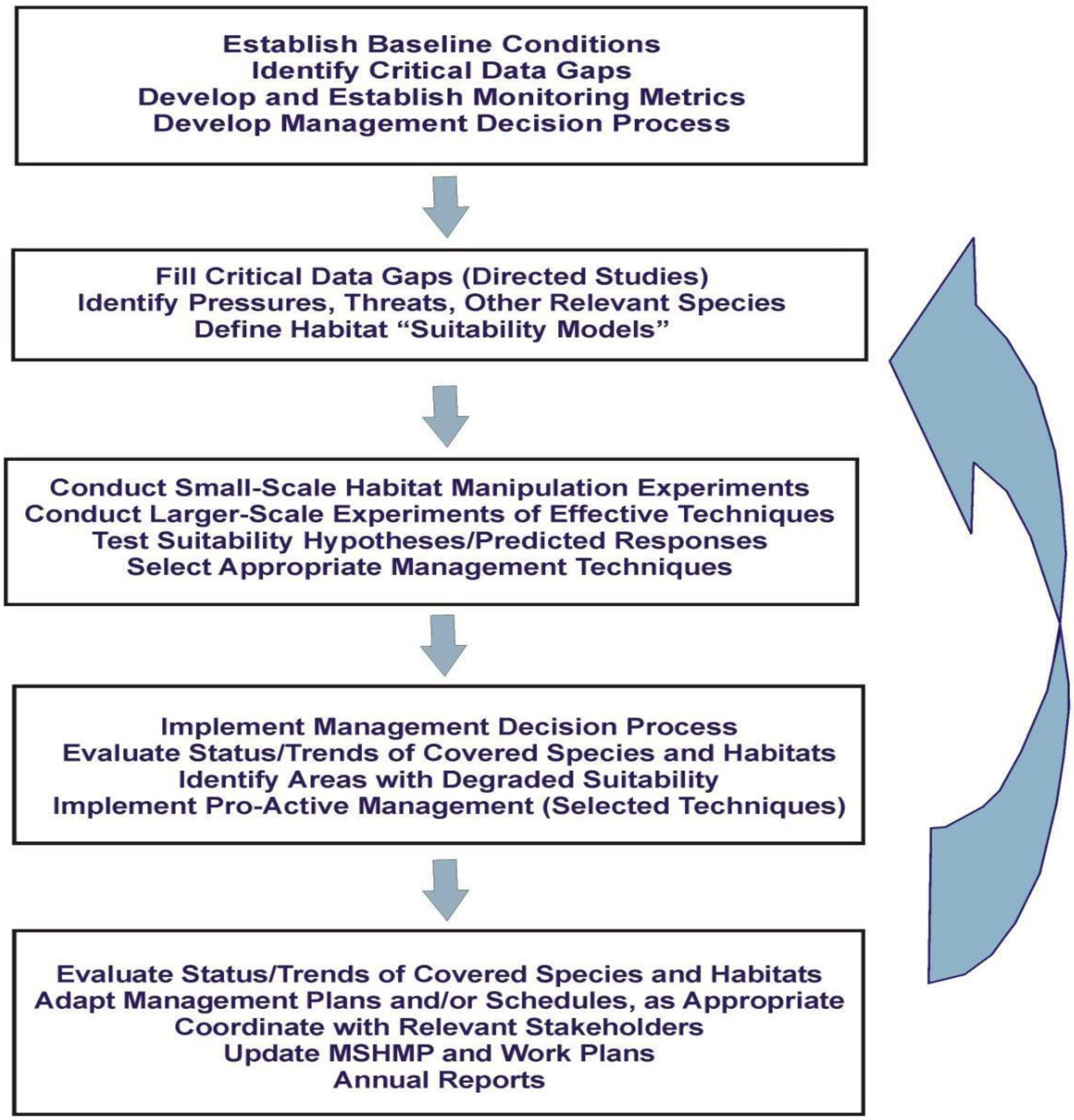


Figure 7-1. Diagram of the MSHMP Adaptive Management Program Elements

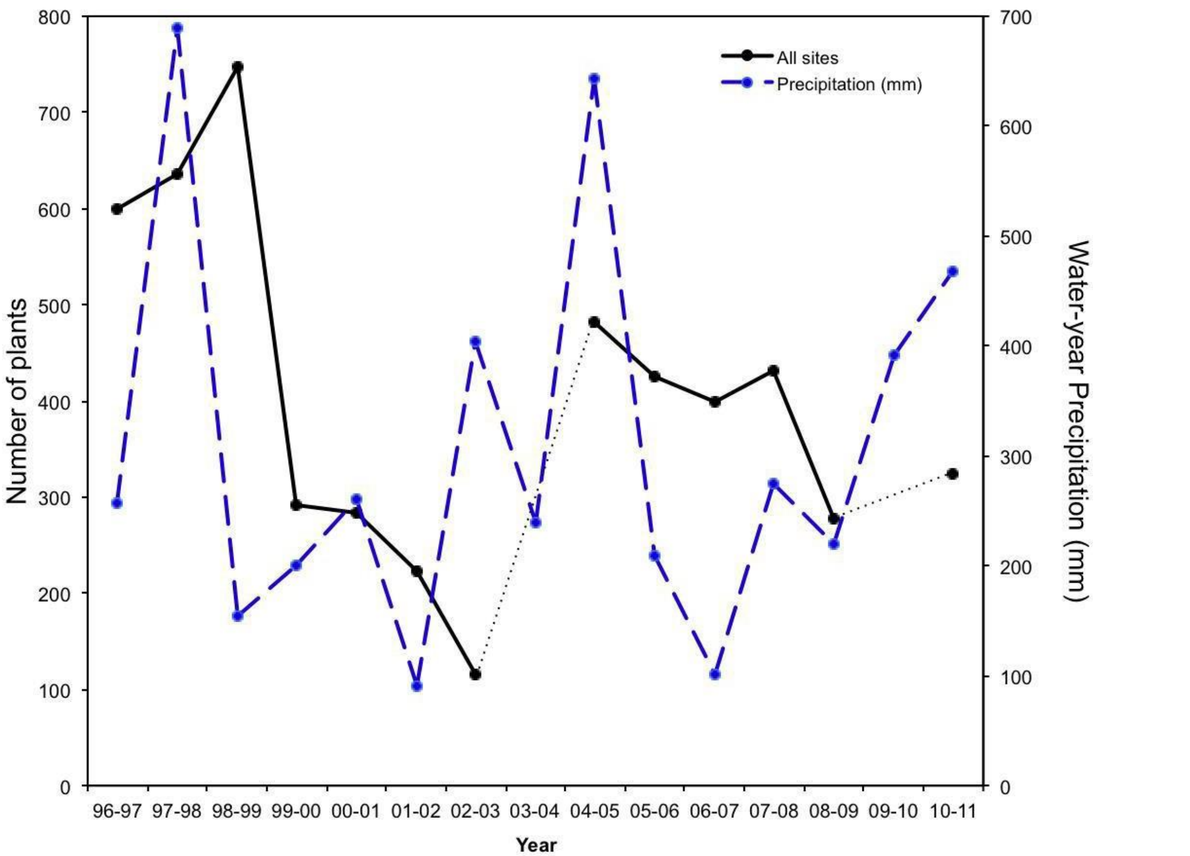


Figure 7-2. Number of Woolly Star Plants at All Sites and Annual Water Year Precipitation in mm

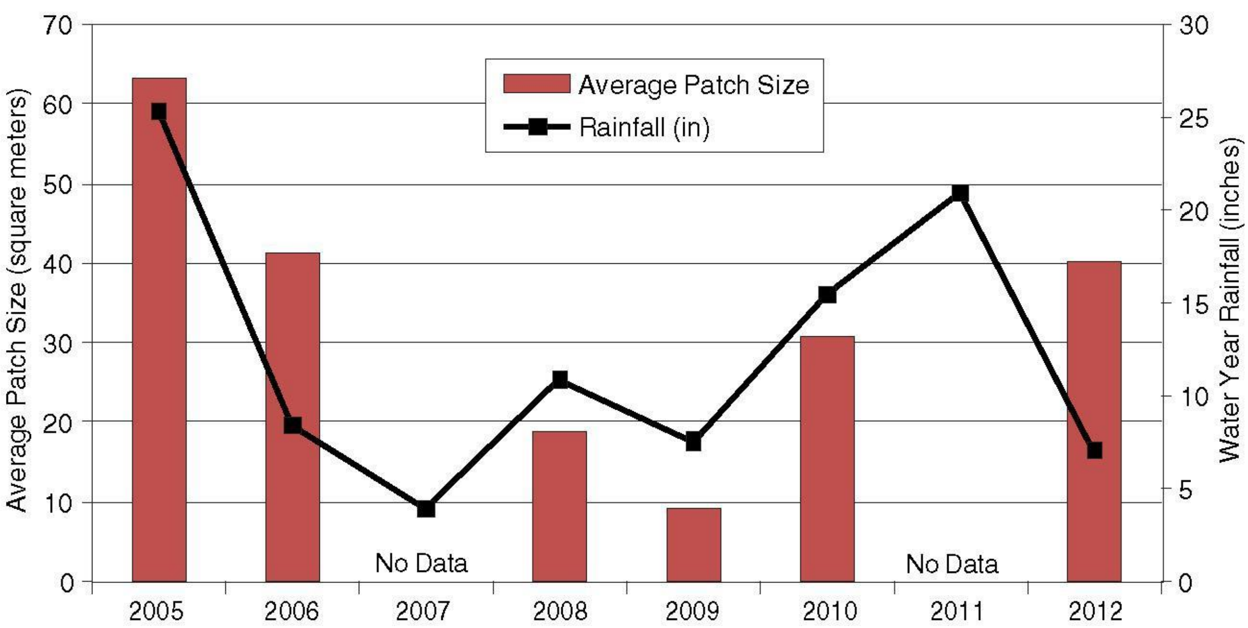


Figure 7-3. Comparison of Average Spineflower Patch Size with Annual Rainfall, 2005 to 2012

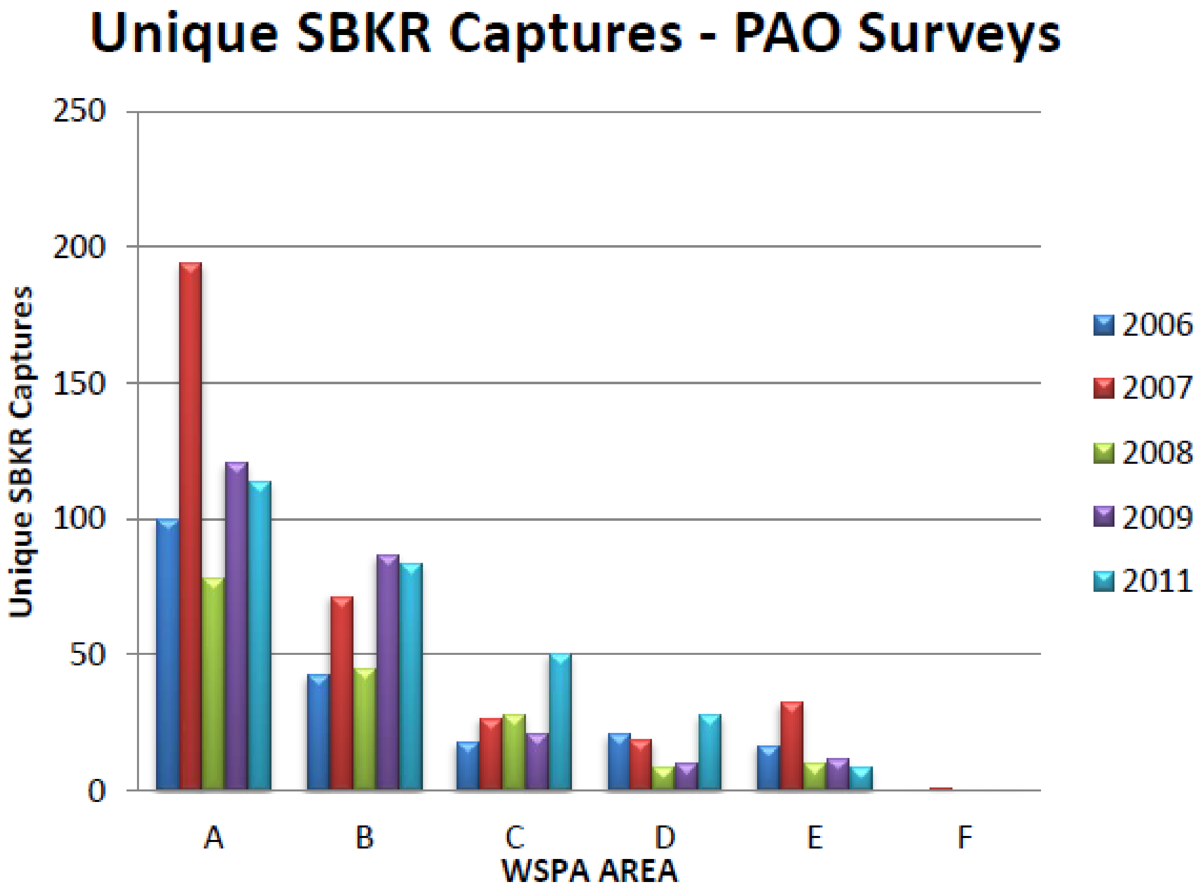


Figure 7-4. Unique SBKR Capture - PAO Surveys

Chapter 11
Tables

Table 2-1. Shear Stress Thresholds for Sand and Cobble Bar Migration as Reported in Blue Octal (2019)

Bar Migration Type	Shear Stress (Pa)[1]	Shear Stress (lb/ft^2)	Particle Size Class[2]
Sand Bar (low end)	6-33	0.13-0.69	medium gravel to very coarse gravel
Sand Bar (high end)	33-60	0.69-1.25	very coarse gravel to small cobble
Cobble Bar (low end)	60-90	1.25-1.88	small cobble
Cobble Bar (high end)	90-125	1.88-2.61	small cobble to large cobble
Cobble Bar (maximum)	190	3.97	large cobble

[1] Shear stress thresholds from Blue Octal 2019.

[2] Corresponding particle size classes by ICF and based on Shields curve that flattens out at a τ^*_c of 0.47 (Buffington and Montgomery 1997).

Table 3-1. Dimensions and Cut and Fill Volumes of the Enhancement Measures

Location	Length (ft)	Width (ft)	Average Height [Cut (-) / Fill (+)](ft)	Maximum Height [Cut (-) / Fill (+)]	Area (acres)	Cut (yd³)	Fill (yd³)
Enhancement Measure 1 Construct Flow Splitter on SAR North Bank	70	58	2.6	6.0	0.09		396
Enhancement Measure 1 Lower SAR North Bank Berm at Splitter	~220	~25	-2.2	-6.0	0.14	-498	
Enhancement Measure 1 Excavate Fill	~45	~20	-1.0	-2.0	0.02	-24	
Enhancement Measure 1 Raise Ground at Rock Wall Channel Plug	~90	~40	0.7	2.0	0.06		76
Enhancement Measure 1 Construct Bank to Direct Flow into 1969 Channel	~220	~15	3.1	6.0	0.06		320
Enhancement Measure 1 Excavate 1969 Channel Rock Wall Channel Plug	~100	~24	-2.1	-5.0	0.08	-262	
Enhancement Measure 1 Lower Canal's West Bank at 1969 Channel Intersection	~55	~25	-2.3	-5.0	0.04	-132	
Enhancement Measure 1 Construct Canal Plug at 1969 Channel Intersection	~30	~30	3.7	6.0	0.02		104
Enhancement Measure 1 Excavate Basin 18 Spillway	~150	~40	-1.0	-3.0	0.15	-251	
				subtotal	**0.66**	**-1,166**	**896**
Enhancement Measure 2 Construct Flow Splitter	138	66	3.2	5.0	0.21		1,077
Enhancement Measure 2 Construct Bank to Plug Channel	155	40	2.5	5.0	0.14		574
Enhancement Measure 2 Excavate Channel Deepening	~200	~70	-1.0	-3.0	0.31	-470	
				subtotal	**0.65**	**-470**	**1,650**
Enhancement Measure 3 Construct Active Channel Obstruction 1	80	48	3.8	8.0	0.09		548
Enhancement Measure 3 Construct Active Channel Obstruction 2	72	31	4.6	8.0	0.05		373

Location	Length (ft)	Width (ft)	Average Height [Cut (-) / Fill (+)](ft)	Maximum Height [Cut (-) / Fill (+)]	Area (acres)	Cut (yd^3)	Fill (yd^3)
Enhancement Measure 3 Construct Active Channel Obstruction 3	70	35	3.5	6.0	0.06		324
Enhancement Measure 3 Excavate Channel Deepening	~180	~32	-0.5	-1.7	0.13	-102	
Enhancement Measure 3 Construct Inactive Channel Obstruction	320	42	2.2	5.0	0.31		1,097
				subtotal	**0.63**	**-102**	**2,341**
				Total	**1.94**	**-1,738**	**4,887**

Table 4-1. Analysis of Seven Oaks Dam Release Flows in Relation to Tributary Flood Events

Location	Drainage Area (mi²)	January 2005 Event Peak Flow (cfs)	January 2005 Event Date of Peak Flow	January 2005 Event Recurrence Interval (years)	December 2010 Event Peak Flow (cfs)	December 2010 Event Date of Peak Flow	December 2010 Event Recurrence Interval (years)	February 2019 Event Peak Flow (cfs)[4]	February 2019 Event Date of Peak Flow	February 2019 Event Recurrence Interval (years)
Santa Ana River near E Street (11059300)	541	35,700	1/11/2005	59	27,800	12/22/2010	30	6,250	2/14/2019	3
Gaged Inputs to Santa Ana River E Street Gage										
City Creek (11055800)	19.6	9,900	1/10/2005	83	7,250	12/22/2010	50	2,690	2/14/2019	11
Plunge Creek (11055500)	16.9	3,920	1/10/2005	30	5,740	12/22/2010	63	1,400	2/14/2019	7
San Timoteo Creek (11057500)	125	3,950	1/9/2005	26	4,150	12/22/2010	28	1,920	2/14/2019	10
East Twin Creek (11058500)	8.8	>600[1]	1/9/2005	--	2,120	12/22/2010	28	290	2/14/2019	3
Seven Oaks Dam Release[2]	210	670	1/9/2005	14[3]	50.1	12/22/2010	<1	121	2/14/2019	1.5
Total for Gaged Inputs	380.3	19,040	--	--	19,310	--	--	6,421	--	--
Difference Between SAR E St. and Total Inputs	160.7	16,660			8,490			-167		
Estimated Mill Creek Flow										
Lower Estimate	42.4	8,200	1/9/2005 or 1/10/2005	26	8,300	12/22/2010	28	630	2/14/2019	3
Upper Estimate	42.4	20,000	1/9/2005 or 1/10/2005	83	16,000	12/22/2010	63	3,400	2/14/2019	11

[1] The 2005 water year peak flow occurred on 10/20/2004. No 15-minute data available online for January 2005. Mean daily flow reached maximum of 600 cfs on 1/9/2005.
[2] Combined 15-minute records of USGS gages 11051499 and 11051502 represent SOD release.
[3] Per SOD outflow frequency curve in Plate 8-03 in USACE 2003.
[4] Peak flows for the February 2019 based on provisional 15-minute gaging records.

Table 4-2. Particle Size Analysis of Channel Bed Sediment Samples

Source	Site	D_5 (mm)	D_{10} (mm)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{90} (mm)	D_{95} (mm)	Folk & Ward Sorting (S_o)	Dominant Class Size (mm)	Percent in Dominant Class (%)	Finer than Sand (%)	Sand (%)	Gravel (%)	Cobble (%)	Boulder (%)
Blue Octal	XS 1 in 1969 Channel	0.22	0.27	0.31	0.77	161.27	228.07	362.04	very poor	0.5	34.0	0.0	66.0	6.0	20.0	8.0
Blue Octal	XS 2 in 1969 Channel	0.15	0.19	0.25	0.69	87.31	219.79	376.43	very poor	0.5	27.9	0.9	64.9	16.2	9.0	9.0
Blue Octal	XS 3 in SAR Active Channel Upstream Opal Avenue	0.16	0.19	0.25	0.67	81.86	157.59	235.69	very poor	0.5	24.5	0.0	66.2	15.9	13.9	4.0
Blue Octal	XS 4 in SAR Active Channel Downstream Opal Avenue	0.14	0.18	0.23	0.97	180.26	238.14	357.50	extremely poor	0.5	20.1	0.7	54.5	10.4	26.0	8.4
Blue Octal	XS 5 in SAR Inactive Channel Downstream Airport	0.16	0.23	0.29	0.76	205.33	302.49	403.77	extremely poor	0.5	24.4	0.0	63.5	8.4	15.1	12.9
Blue Octal	XS 6 in SAR Active Channel Downstream Airport	0.27	0.29	0.31	0.56	98.63	127.12	213.41	very poor	0.5	49.2	0.0	57.4	16.4	23.0	3.3
USGS	SAR near Greenspot Road	0.64	2.93	7.75	102.24	328.11	408.12	489.51	very poor	128.00	21.41	0.90	7.80	26.82	41.65	22.82
USGS	SAR near Orange Street	0.11	0.16	0.22	0.67	42.84	103.66	190.56	very poor	0.50	24.00	2.05	67.07	17.33	11.11	2.44
USGS	Mill Creek near Greenspot Road	0.19	0.30	0.44	16.62	96.32	125.75	190.68	very poor	128.00	15.60	0.02	23.18	51.60	23.60	1.60

Sources: Blue Octal 2019; Wright and Minear 2019 (USGS)

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Table 4-3. Primary Modes of Sediment Transport

Transport Mode	U_*/v_s	Rouse Number (P)
No Motion	<0.2	>12.5
Bedload	0.2-0.4	6.25-12.5
Mixed Load	0.4-2.5	1-6.25
suspended	>2.5	<1

Source: Julien 2009

Table 5-1. Summary of Additional Bar Migration Created by the Three Enhancement Measures for a 5,000 cfs Total Flow

	Enhancement Measure 1[a]		Enhancement Measure 2		Enhancement Measure 3[b]	
	Total Acres	Increase from Existing Acres	Total Acres	Increase from Existing Acres	Total Acres	Increase from Existing Acres
<0.13 lb/ft^2	6.5	6.5	5.0	1.9	11.8	3.5
Sand Bar Low End	9.9	9.9	4.9	0.5	12.2	10.2
Sand Bar High End	2.0	2.0	2.6	0.2	0.2	0.2
Cobble Bar Low End	0.1	0.1	2.5	-0.2	0.0	0.0
Cobble Bar High End	0.0	0.0	2.3	0.7	0.0	0.0
Cobble Bar Maximum >2.61 lb/ft^2	0.0	0.0	1.2	0.8	0.0	0.0
sum of >= 0.13 lb/ft^2	12.0	12.0	13.6	2.0	12.4	10.4

[a] For time-step 16 hours on the hydrograph with a peak of 646 cfs in the 1969 Channel

[b] Enhancement Measures 2 and 3 were modeled together. Diversion of flow at Enhancement Measure 2 reduces the amount of flow at Measure 3. Without diversion of water at Measure 2, more flow would be available at Measure 3 and for a total flow of 5,000 cfs approximately 13 acres of bar migration >= 0.13 lb/ft^2 would be created.

Table 6-1. Summary of Habitat Requirements for the Species of Interest

Habitat Requirements/Species	San Bernardino Woolly Star	San Bernardino Kangaroo Rat	Slender-horned Spineflower
Substrate texture	Gravel, sand, rock mounds, boulder fields.	Sand and gravel with low silt content.	Generally prefer silt and sand, scattered river cobble. Within the WSPA, all occurrences are on unconsolidated coarse sand with biological soil crusts.
RAFSS successional stage	Early to intermediate (to a lesser extent in mature/later succession).	Early to intermediate stages show highest population densities, mature stage may be occupied, but at lower density.	Areas of low relief within Juniper seral stage. Also, may occur in intermediate and non-juniper seral stage.
Vegetative cover	<50% perennial, <19% annual.	Low to moderate (30-50%) perennial, low shrub (6-15%),	Open canopy.

Habitat Requirements/Species	San Bernardino Woolly Star	San Bernardino Kangaroo Rat	Slender-horned Spineflower
		low to medium grass cover (<28%).	
Habitat size	Minimum 385 acres needed to support a minimum viable population.	1- acre range comprised of a “home area’ and many satellite burrows. may make quick bursts up to 100 m for brief periods.	5-20 m patches.
Inverse relationship with annual grass cover?	Yes	Yes	Likely
Germination requirements	Increased after floods, diminished after fire.	---	Germination appears most closely linked to sufficient amount and duration of rain.
Landform	Sandy sediments on flood-influenced alluvial fans.	River, creek, stream, and wash channels, associated alluvial fans, floodplains, floodplain benches and terraces, and historic braided channels. These areas may include a mosaic of suitable and unsuitable habitat patches.	Low relief, Floodplain terrace, 0-2% slopes.
Other	Highly associated with historic flood signatures (Chambers Group 1993, Psomas and CSUF 2010 from MSHMP).	Diet consists of seeds, preferring *Erodium circutarrium*.	Sufficient rainfall is the most important indicator of occurrences in any given year. Does not appear to co-occur with woolly star. Low nutrient, salinity, and exchange capacity.

Table 6-2. Disturbance Techniques and Likely Effects on the Species of Interest

Method/Species	SBKR	Woolly Star	Spineflower
Non-Native Invasive Grass Control (Herbicides)	Beneficial (short-term)	Beneficial (short-term)	Beneficial (short-term)
Mechanical De-vegetation	Beneficial (long-term)	Beneficial (long-term)	Beneficial (long-term)
Fire	Detrimental (short-term) Beneficial (long-term)	Detrimental	Detrimental (due to expected effect on juniper)
Cut	Detrimental (short-term) Beneficial (long-term)	Beneficial (long-term, highest benefit)	Detrimental

Method/Species	SBKR	Woolly Star	Spineflower
Sand Deposition	Detrimental (short-term) Beneficial (long-term)	Beneficial (long-term, nearly as beneficial as cut)	Detrimental
Hydraulic Sand Spreading	Detrimental (short-term) Beneficial (long-term)	Beneficial (long-term, may aid in germination)	Detrimental

Table 7-1. Comparison of Acreages Associated with Different Fluvial Surfaces. (From Ch7)

Surface	1993 Acres	2003 Acres	2003 Acres Revised to 2009 WSPA Boundary	2009 Acres Revised to 2009 WSPA boundary
Early	239	301	298.9	458.2
Intermediate	208	173	208.9	91.2
Total Suitable Habitat Acreage	447	474	507.8	549.4
Late	317	225	233.1	233.5
Disturbed		66	40.0	N/A
Total Acreage	764*	765	782.9	782.9

*The total acreage for late and disturbed habitat was determined by subtracting the early and intermediate surface acreages specified in the 1993 Plan from the total acquisition acreage of the WSPA

Note: The last two columns of the table include total acreage revised to the 2009 updated WSPA boundary; minor differences between this total and that in Table 2-1 were due to rounding differences (J. Campbell-Young, Psomas, personal communication).

Table 7-2. Results from Generalized Linear Models with One Variable at a Time Classified as Categorical with Low, Medium, or High Values to Test for Intermediate Selection.

Model	Variable Set	Low	Medium	High
1. Vegetation	Shrub Cover	6-15%	23-35%	40-65%
	Grass Cover	1-17%	22-28%	45-81%
	Forb Cover	0-4%	5-9%	10-19%
2. Surface	Duff Cover	2-9%	15-18%	25-30%
	Sand/bare ground	5-19%	35-40%	59-71%
	Gravel	1-8%	12-19%	27-40%
	Woody Debris	0-4%	6-13%	16-25%
3. Species	SD pocket mouse	0	<5	5-25
	Dulzura kangaroo rat	0	1-5	6-49
	Cactus mouse	0	1-6	9-32
	Deer mouse	0-10	10-30	30-90
	LA pocket mouse	0-01	3-9	10-22

Table 7-3. Sediment Particle Size Fraction vs. SBKR Density

SBKR Density	Clay% (less than 0.0002 mm)	Silt% (0.002 mm to 0.05 mm)	Sand% (0.05 mm to 2 mm)	Gravel% (2 mm to 75 mm)
No SBKR	2.7-12.4	2.0-21.2	70.3-92.8	1.4-45.0
Low SBKR (0.9-3/unit effort)	2.5-6.6	0.5-17.5	76.7-97.0	2.7-50.3
High SBKR (4-9.2/unit effort)	2.4-6.6	1.2-14.6	81.9-95.6	1.0-54.9

Table 7-4. Treatment Trade-Offs

Method	Experimental Manipulation	Habitat Manipulation	Potential Downstream Effects
Non-Native Invasive Grass Control (Herbicides)	Evaluation complete[1,2]	None	Avoidance
Mechanical De-vegetation	Evaluation complete[1]	None	Avoidance, SBKR clearance
Fire	Not evaluated	Potential increased sedimentation rates	Avoidance, SBKR clearance
Cut	Evaluation complete[1]	None	Avoidance, SBKR clearance
Sand Deposition	Evaluation complete[1]	None	Avoidance, SBKR clearance
Hydraulic Sand Spreading	Not evaluated	Yes, depending on release volumes	Avoidance, SBKR clearance

[1]Woolly star
[2]SBKR
[3]Spineflower

Appendix 1

Stillwater Sciences’ 2019 report Seven Oaks Dam Scour Analysis

Stillwater Sciences
2855 Telegraph Ave, Suite 400, Berkeley, CA 94705
phone 510.848.8098

TECHNICAL MEMORANDUM

DATE: June 17, 2019

TO: Heather Dyer, San Bernardino Valley Municipal Water District

FROM: Stillwater Sciences

SUBJECT: Seven Oaks Dam scour analysis

1 BACKGROUND

Phase 2 of the Seven Oaks Dam high flows study is designed to assess potential restoration approaches to improve habitat for three listed species between Seven Oaks Dam and the Santa Ana confluence with City Creek: slender-horned spineflower (*Dodecahema leptoceras*), Santa Ana River woolly-star (*Eriastrum densifolium* ssp. *sanctorum*), and San Bernardino Kangaroo Rat (*Dipodomys merriami parvus*, SBKR). Stillwater Sciences was asked to assess the degree of lateral erosion along the Santa Ana River from the confluence with Mill Creek downstream to the confluence with City Creek in order to assess the potential for restoration actions designed to widen the active channel in the study reach. We were also asked to assess the degree to which vegetation is uprooted during high flows

Braided rivers in arid environments, such as the Santa Ana, have a vegetation and erosion cycle tied to floods. During high flows, much of the vegetation in the active channel corridor is uprooted or buried by sediment deposition. The uprooting occurs through sediment erosion around the roots or direct uprooting. From the aerial photography differentiating uprooting from deposition can be difficult, but both result in vegetation mortality and creation of fresh surfaces. For convenience, we refer to these surfaces as scoured, but they could potentially be depositional surfaces. Subsequently, during years with smaller floods, vegetation becomes re-established within at least part of the scour zone, with vegetation density increasing gradually through time until it is uprooted during the next large flood. This pattern has implications for pioneer species such as SBKR, spineflower, and woolly-star which thrive in relatively fresh sandy deposits following large floods. In particular, SBKR prefers habitats ranging from recent sand deposits without grasses and sparse shrubbery. To create and maintain SBKR habitat therefore requires periodically creating new sand deposits through scour and/or burial of vegetation more frequently than dense vegetation (particularly grasses) can become established in these deposits, but not so frequently that SBKR populations cannot maintain their population. Prior to human modification of the basin, large floods every 30 years or so likely created new surfaces for the SBKR to establish on that were unlikely to be inundated during the next 30 years. As described in Phase 1 of this project (ICF, 2019), the potential for high flow releases from Seven Oaks Dam to help create new habitat may be limited. As part of the Phase 2 exploration, Stillwater Sciences examined (1) the degree to which lateral erosion into older surfaces occurs and (2) vegetation scour under the current high flow regime.

2 METHODS

For each aerial photograph we investigated, we categorized the landscape into four vegetation types based on the aerial imagery. The relative vegetation density was assigned a value from (1) very low (2) sparse (3) moderate, and (4) high. We have also coded areas with large human interventions (quarry pits, large roads, etc.). The range of vegetation densities was defined using the 2016 NAIP photography and the minimum mapping unit for this exercise was ~0.5 acres. We also identified anthropogenically altered areas. The total mapped area was 2,990 acres and is outlined in Figure 1. We have divided the mapped area into 4 regions:

- Santa Ana River between Seven Oaks Dam and Mill Creek (reach length = 1.8 miles);
- Santa Ana from Mill Creek to City Creek (reach length = 5.9 miles);
- Santa Ana downstream of City Creek (reach length = 0.3 mile, included to account for any adjustments to the confluence position); and
- Mill Creek upstream of the confluence with the Santa Ana River (reach length = 1.8 miles).

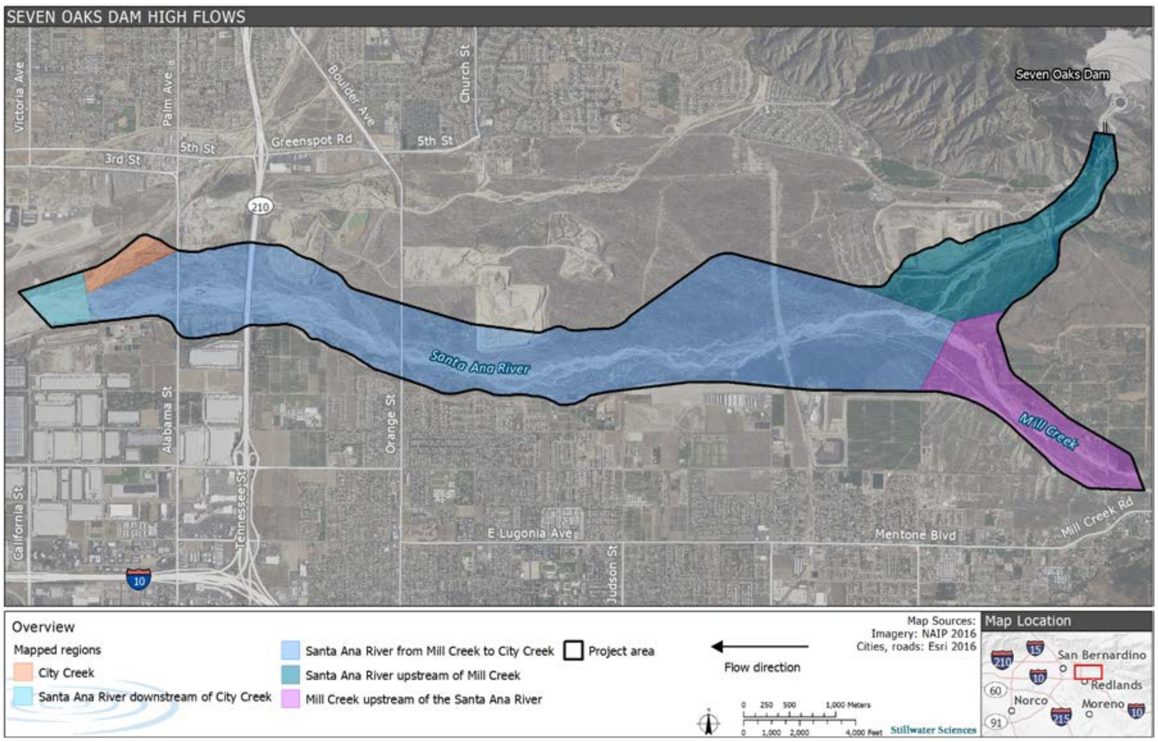

Figure 1. Vegetation mapping area boundary.

We mapped vegetation using aerial imagery from for different years:

1. 1970 (provided by ICF) to represent the channel state following the 1969 flood.
2. 2008 (NAIP imagery) to represent the channel prior to the 2010 floods
3. 2012 (NAIP imagery) to represent the channel following the 2010 floods
4. 2016 (NAIP imagery) to represent the recent state of the channel, including changes since 2012.

Additional photographs are available that could be analyzed and mapped in the future, depending on the needs of the group. To save time we could map a limited area of the channel to emphasize the number of years of analysis at the expense of spatial variation.

We assessed the degree of bank erosion by comparing the vegetation classification in the 1970 (post-1969 flood) and 2016 vegetation classification maps. Areas were marked as scoured if they were vegetation class 3 or 4 (moderate or high density) in 1970 and vegetation class 1 or 2 in 2016. Once the scoured areas were mapped, we then classified each scoured area polygon as being primarily created by lateral erosion, potential lateral erosion (mapped scour that could be due to shadows or photo distortion), mid-channel island erosion, erosion on Mill Creek, erosion on the Santa Ana River upstream of the confluence with Mill Creek, and anthropogenic changes.

We assessed in-channel vegetation scour from floods using the vegetation maps described above. Vegetation scour was mapped where the vegetation class was 2, 3, or 4 prior to the flood and was vegetation class 1 after the flood.

3 FLOOD HISTORY

Our goal was to tie lateral erosion and vegetation scour to discharge. Unfortunately, flows in the study reach are poorly understood due to the lack of a gage in Mill Creek (Blue Octal 2018, ICF 2019). The best proxy for discharge in the study reach, the USGS gage at E street near San Bernardino gage (number 11059300), is downstream of the confluence with City Creek, which drains an extensive urban area as well as the mountains upstream. Moreover, the discharge during the two 1969 floods (1/25/1969 and 2/25/1969) is not clear and discharge estimates range from 25,700-40,495 cfs (ICF, 2019). The peak flow measured at the USGS Santa Ana River at E Street gage (11059300) had a peak discharge of 28,000 cfs. The three largest floods since 1969 measured at the E Street gage are 1998 (21,100 cfs), 2005 (35,700 cfs), and 2010 (27,800 cfs). ICF (2019) estimates that the discharge from Mill Creek ranged from 8,300 -16,000 cfs during the 2010 flood. The highest discharge measured at the E Street gage between folders is shown in Table 1. The 1998 flood occurred during dam construction and the 2005 and 2010 floods post-date Seven Oaks Dam. ICF (2019) documented four tests conducted by the Seven Oaks Dam operators that released significant amounts of water from Seven Oaks dam in March 9, 2005 (4,179 cfs), July 15, 2010 (3,159 cfs), February 15, 2011 (4,648 cfs), and March 1, 2011 (5,003 cfs). The first two tests were during high water years, but the release flows occurred well after the measured downstream peak discharges.

Table 1. Highest flows between photographs.

Photo year	Highest discharge at E Street gage prior to photo (cfs)	Date of highest discharge
1970*	~25,700-40,495*	1/25/1969-2/25/1969
2008	35,700	1/11/2005
2012	27,800	12/22/2010
2016	6,150	11/21/2013

*The 1970 photo represents conditions following the 1969 flood. Reported discharges for the 1969 flood vary (see ICF 2019).

4 RESULTS AND DISCUSSION

The vegetation maps for each year are shown in Appendix A. Below we first discuss the results of the lateral erosion analysis and then the vegetation scour analysis.

4.1 Lateral bank erosion 1970-2016

Overall, we mapped 18.4 acres of scour into Moderate and High vegetation density surfaces from 1970 into 2016 for the 2,990 acres mapped in Figure 1 (i.e., 0.6 % of the mapped area was scoured relative to 1970) (Table 2, Figures 2-6). Downstream of the Mill Creek confluence, there was 10.7 acres of scour of Moderate and High vegetation density surfaces despite having a much larger surface area than Mill Creek and the Santa Ana upstream of the Mill Creek confluence. Our results showed that scour of vegetated surface between the confluence with Mill Creek and City Creek was relatively limited, with only 3 acres of lateral scour into the higher floodplain surfaces. Downstream of the confluence with Mill Creek, the channel is lined by older terraces comprised of boulders and cobbles, many of which were likely transported as debris flows (Mussetter, 1999, Figure 7).

Bank erosion was higher upstream of the confluence with Mill Creek than downstream (Table 2) even though the reach length is only 1.8 miles for the Santa Ana upstream of the confluence versus the 5.9 miles for the reach from the Mill Creek confluence downstream to City Creek. This is partially due to the morphology of the fan and wash. The morphology of the Santa Ana is very different downstream of the confluence with Mill Creek. While the channel is braided throughout the study area, it is confined by older terraces that extend across the valley flood downstream of Mill Creek. Upstream of the confluence with Mill Creek, the 1970 Santa Ana River flowed through multiple channels across a wide fan (Figure 5). A levee south of the channel near Greenspot Road and the levee along the borrow pit used to build the dam have constrained the width of the channel along the upper part of the fan and limited the available space for multiple channels, leading to fewer channel threads and a widening of the primary channel (Figure 8). Erosion is focused on the main thread of the channel beginning where levees constrain both sides of the channel near the upstream end of the borrow pit (Figure 8). While some levees have been constructed/enlarged downstream of the confluence with Mill Creek, these levees have constrained the flow less than on the upper part of the fan.

Lateral erosion of Mill Creek was higher than the other reaches, particularly the Santa Ana downstream of the confluence with Mill Creek (Table 2, Figure 6). The erosion focused on the southeast channel bank (Figure 6). The construction of Seven Oaks Dam has not altered flow in Mill Creek, and thus lateral erosion has not been limited by low discharge as it has been on the Santa Ana. Anthropogenic influence on the erosion in Mill Creek is unknown.

Our analysis may underestimate the extent of lateral erosion, if surfaces were scoured soon after the 1970 photographs and had sufficient time to develop moderate or high vegetation density before the next photographs were taken in 2008. During the data processing we did not observe dense vegetation patches along the channel margin that were lower elevation than the terrace, but it is possible that our lateral erosion measurements were an underestimate.

Table 2. Scour Area by reach and erosion type 1970-2016.

Scour Type	Reach length (miles)	Area (acres)	Erosion (acres/mile)
Lateral Erosion	5.9	3.0	0.5
Potential lateral erosion	n/a	0.5	n/a
Mid channel island scour	5.9	4.5	0.8
Mill Creek	1.8	6.0	3.3
Upper Santa Ana	1.8	4.7	2.6
total	**9.5**	**18.2***	**1.9**

*total does not include potential erosion

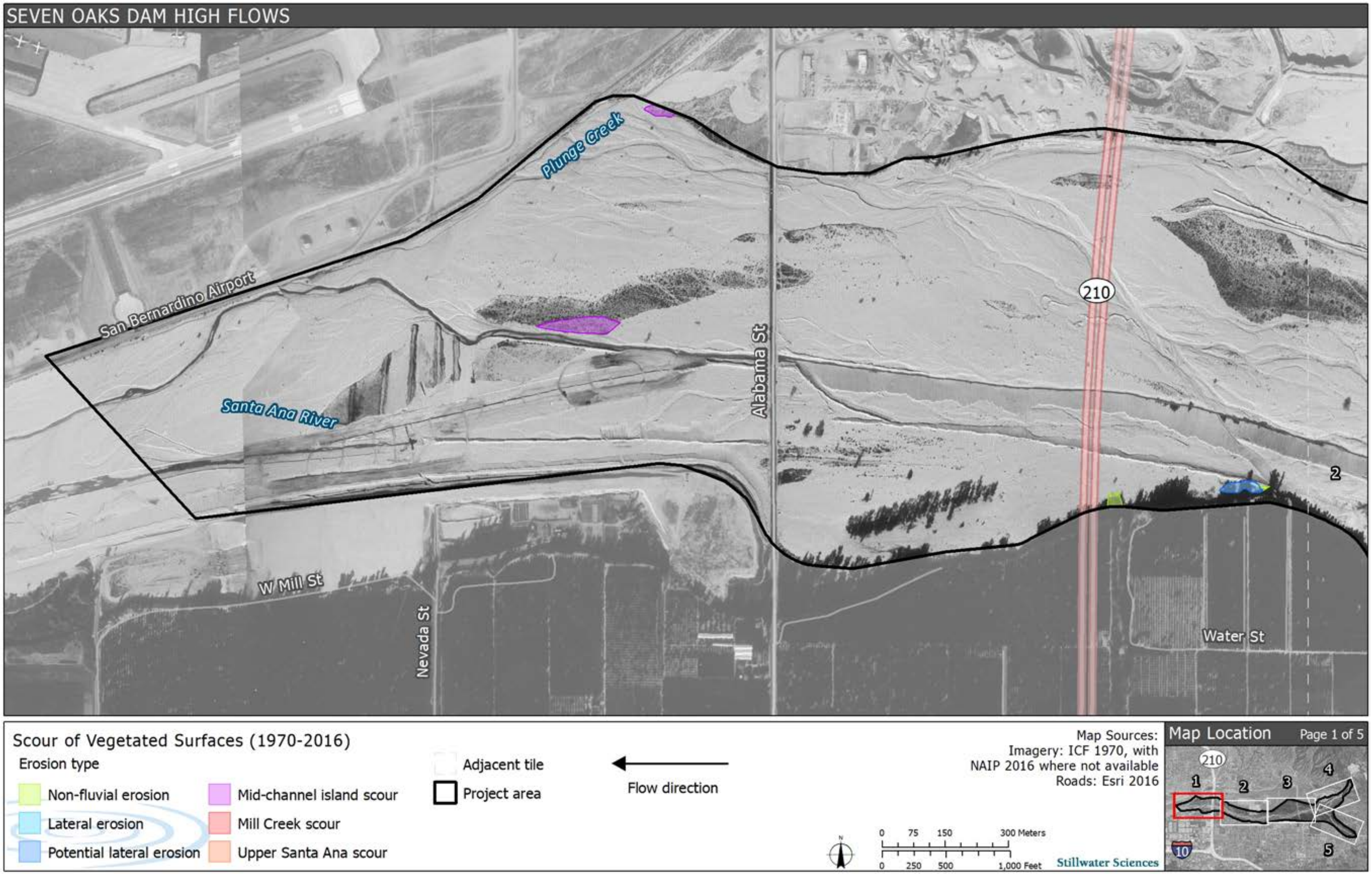

Figure 2. 1970-2016 scour map of the Santa Ana River near the City Creek confluence on the 1970 image.

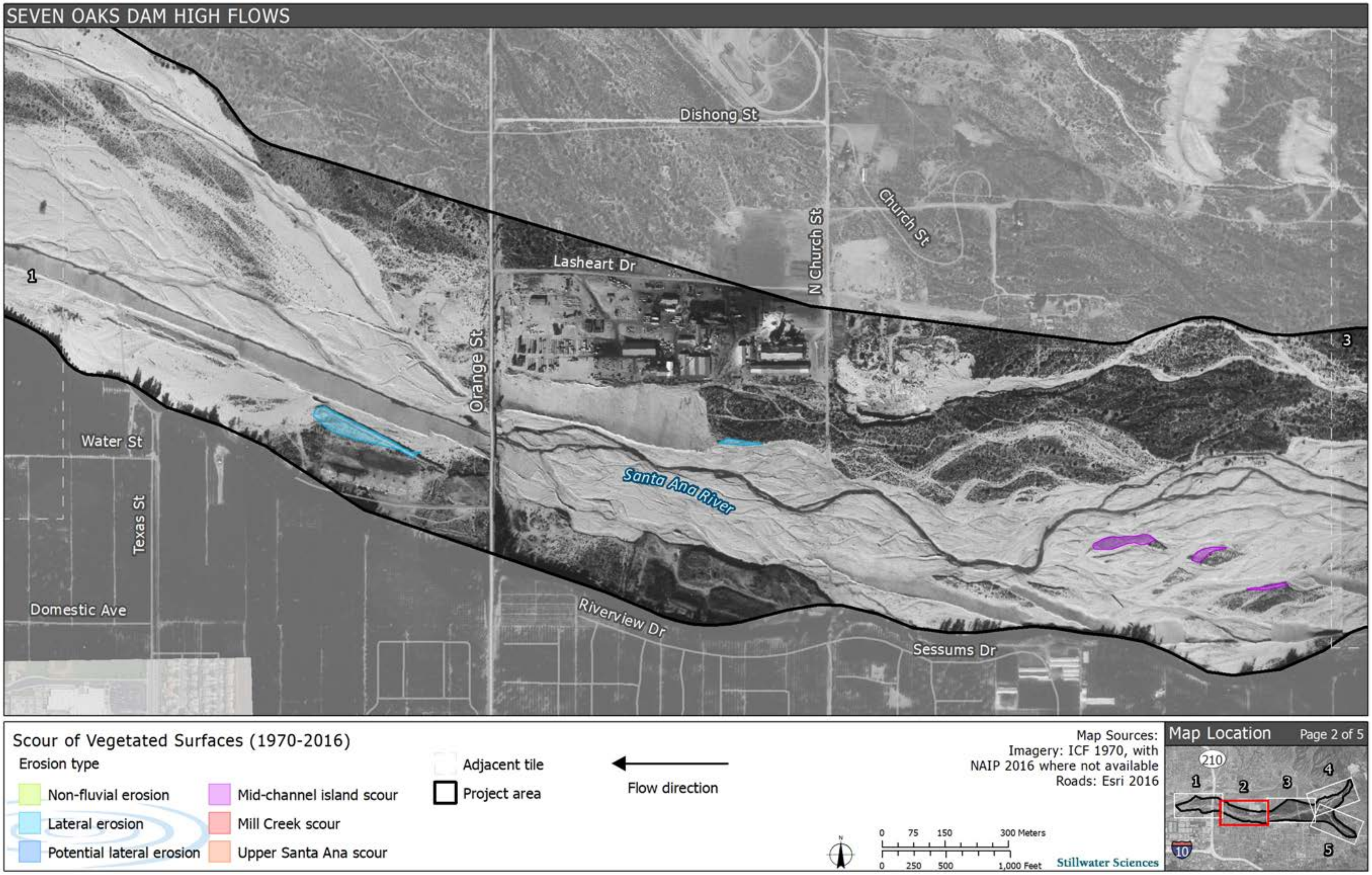

Figure 3. 1970-2016 scour map of the Santa Ana near the Orange Street Bridge on 1970 image.

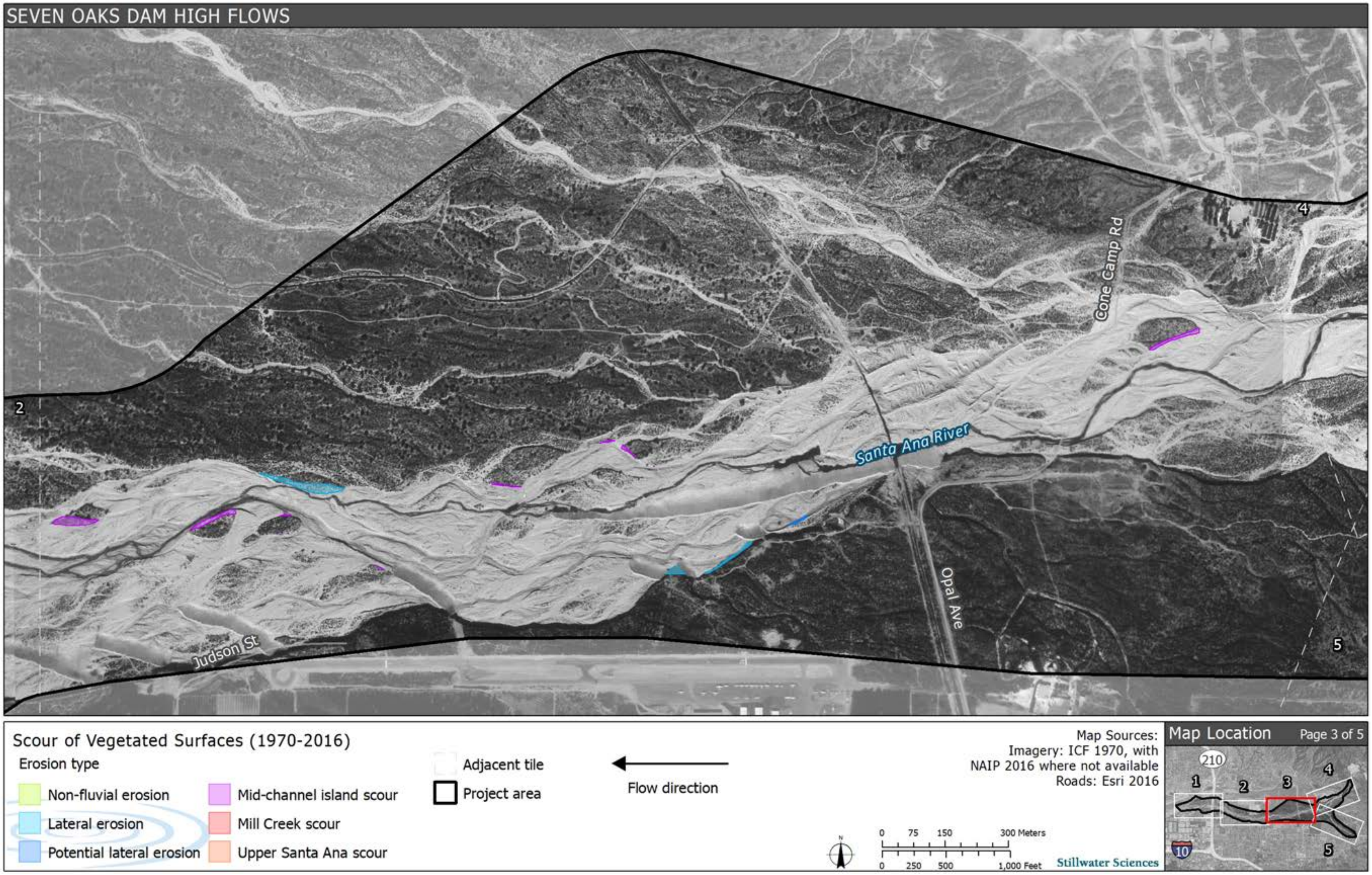

Figure 4. 1970-2016 scour map of the Santa Ana near Opal Avenue on 1970 image.

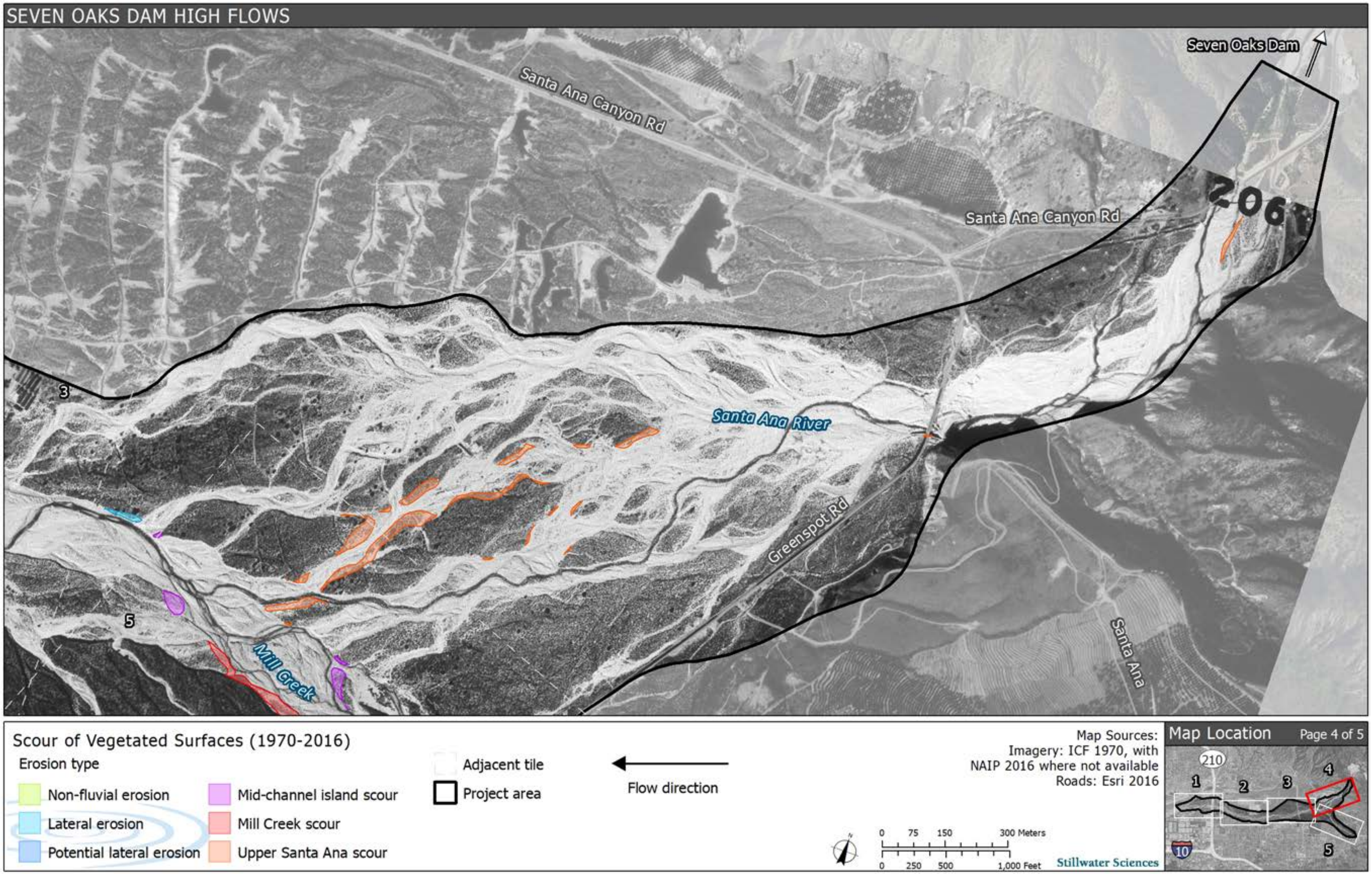

Figure 5. 1970-2016 scour map of the Santa Ana River upstream of the confluence with Mill Creek.

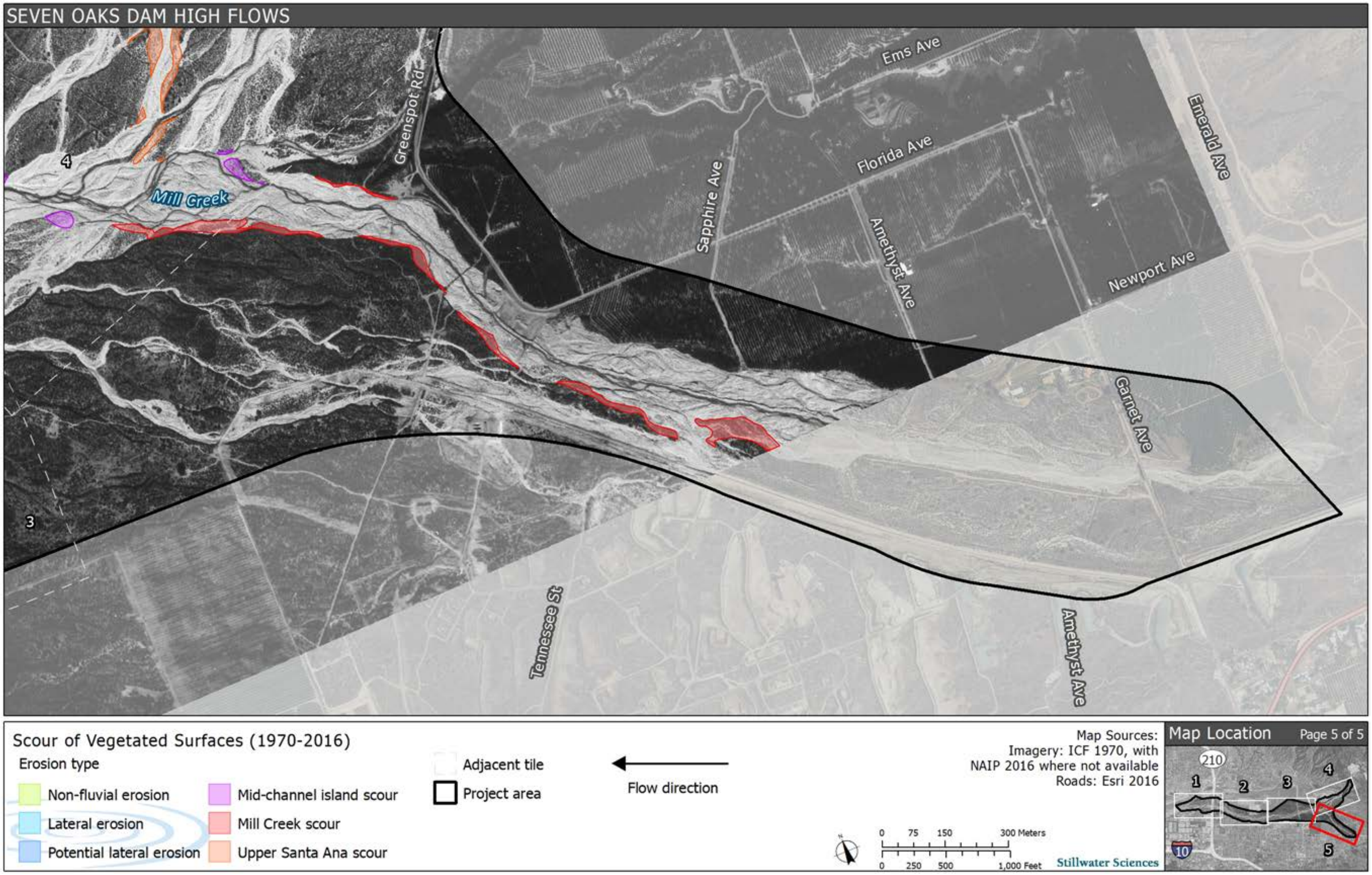

Figure 6. 1970-2016 scour map of Mill Creek upstream of the Santa Ana River confluence on 1970 image.

Figure 7. Boulders making up the right bank of the Santa Ana River just downstream of the confluence with Mill Creek.

4.2 In-channel vegetation scour

Our three primary study reaches showed a similar pattern in the extent of unvegetated channel through time. Unvegetated channel extent was largest in 1970 and decreased considerably by 2009 (Table 3). The extent of unvegetated channel surface increased by 2012 following the 2010 floods and then decreased again by 2016 (Table 3).

2009-2102

During 2009-2012, the peak discharge recorded for the E street gage was 27,800 cfs. Although the discharge in the study reach is unknown, there were three test flows released from Seven Oaks Dam ranging from 3,159 to 5,003 cfs. These test flows were (and remain) the highest discharges upstream of the confluence with Mill Creek since the dam was constructed in 2000. Our vegetation scour analysis shows that between 2009 and 2012, approximately 488 acres of vegetated surfaces were scoured between Mill Creek and City Creek on the Santa Ana (Table 4, Figure 9 – Figure 11). About 88 percent of the scour was into surfaces mapped as sparse vegetation density, with most of the remainder into surfaces with moderate vegetation density. This scour represents about 54% of the total unvegetated channel area in 2009 and the extent of low vegetation density (channel) expanded from 890 to 1415 acres. Scour included erosion of vegetation along the active channel margin, reactivation of secondary channels, and was continuous throughout the entire reach (Figure 9 – Figure 11). Similar trends occurred in the Santa Ana upstream of Mill Creek (Table 3, Figure 12). In Mill Creek, the extent of low density vegetation changed much less between 2009 and 2012 than the other two reaches.

Table 3. Extent (acres) of low vegetation density surfaces by year.

Year	Reach		
	Santa Ana downstream of Mill Creek	Santa Ana upstream of Mill Creek	Mill Creek
1970	2638	438	163
2009	697	115	82
2012	1125	202	88
2016	934	179	46

2012-2016

By 2016, the extent of low vegetation density surfaces had contracted to 934 acres between the Mill Creek confluence and City Creek, a decrease of about 191 acres (17%) (Figure 14 – 16). Scoured vegetation patches tended to be sparsely vegetated (85% of total) with lesser scour on moderately vegetated surfaces. Similar trends occurred in the Santa Ana upstream of Mill Creek (Figure 17, Table 3). The extent of low vegetation density decreased much more in Mill Creek than the other two reaches between 2012 and 2016 (Table 3) with the widespread increase of sparse vegetation surfaces (Figure 18). However, it is possible that the difference in the mapped extent of sparse vegetation between 2012 and 2016 could be due to differences in brightness of the images (See Appendix A for the maps).

From 2012-2016, 191 acres of low vegetation density surfaces became sparse to high vegetation density in the Santa Ana downstream of Mill Creek. This included:

- 177 acres that were scoured/buried from 2009-2012 (i.e., they were sparse to high vegetation density in 2009, low vegetation density in 2012, and sparse to moderate vegetation density in 2016);
- 48 acres that were low density in 2009 and 2012 and sparse to moderate vegetation density by 2016 (i.e., active channel surfaces in 2009 and 2012 that were vegetated in 2016); and
- 34 acres that were sparse to high density surfaces in 2009 and 2012 and scoured in 2016.

If we assume that vegetation density is primarily tied to scour frequency and relative elevation, these results indicate that the decrease in extent of low density vegetation from 2012 to 2016 shown in Table 1 primarily occurred in intermediate relative elevation surfaces that were scoured/buried during the 2010 floods, rather than in lower relative elevation areas (low vegetation density in 2009 and 2012), or high relative elevation surfaces (sparse to high vegetation density in 2009 and 2012).

Table 4. The initial vegetation density of scoured/buried surfaces for 2009-2012 and 2012-2016 for three study reaches.

Vegetation density	Santa Ana from Mill Creek-City Creek		Santa Ana from Seven Oaks Dam to Mill Creek		Mill Creek	
	2009-2012 (acres)	2012-2016 (acres)	2009-2012 (acres)	2012-2016 (acres)	2009-2012 (acres)	2012-2016 (acres)
Sparse	429.6	29.2	60.3	0.2	26.8	4.5
Moderate	57	4.9	29.4	0.3	2.4	0.1
High	1.3	0.1	1.3	0.7	1.8	0
Total	**487.9**	**40.1**	**90.9**	**1.2**	**31.0**	**4.5**

5 KEY FINDINGS AND NEXT STEPS

This study suggests that bank erosion is rare since the 1969 flood and that channel widening due to high flows alone is unlikely to occur. Structures could be placed in the channel to increase stress on the bank, but given the absence of recent bank erosion and the coarse size of material on the banks, the structures would have to be very large.

We found that for the Santa Ana River bed scour (and transition from denser vegetation to low density vegetation) was much greater during the 2010 floods (discharge =27800 cfs at the USGS E Street gage) than during the 2012-2016 period (maximum discharge = 6,180 cfs at the E Street gage). This is a wide range in discharge, but even during 2012-2016 some scour occurred, although it was less than the rate of revegetation. These studies also point to the role of antecedent floods in determining the resistance to scour of vegetated surfaces, particularly given that surfaces with sparse vegetation were the most likely to scour.

The results suggest that surfaces with sparse to high vegetation density that scoured during the observed floods were more likely to revegetate than surfaces that maintained a low vegetation density through the flood. This is likely because higher relative elevation surfaces were only scoured during the larger floods (i.e., 2010) and could revegetated during periods with lower flows (i.e., 2012-2016). Because most of the surfaces scoured/buried in 2010 transformed from low vegetation density to sparse vegetation density, the surfaces may still be suitable for SBKR habitat, provided that non-native grasses are absent.

This study could be extended to include more aerial photographs to better assess the degree to which vegetation scour is tied to flow. Such an analysis would be complicated by the time since the last flood and the relative elevation of the surfaces that could be scoured. Linkages between stress and vegetation scour would be most accurate when the vegetation map and topography are linked, hence focusing on periods with topographic data could be helpful.

6 REFERENCES

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ICF. 2019. High-Flow Study Phase 1 Report. Final. March. (ICF 00190.16.) San Diego. Prepared for CBD/EHL/SBVMWD/SBVWCD, California.

Mussetter Engineering Inc. 1999. Geomorphic evaluation of Santa Ana River alluvial fan and San Bernardino kangaroo rat habitat, CA. Prepared for USAC

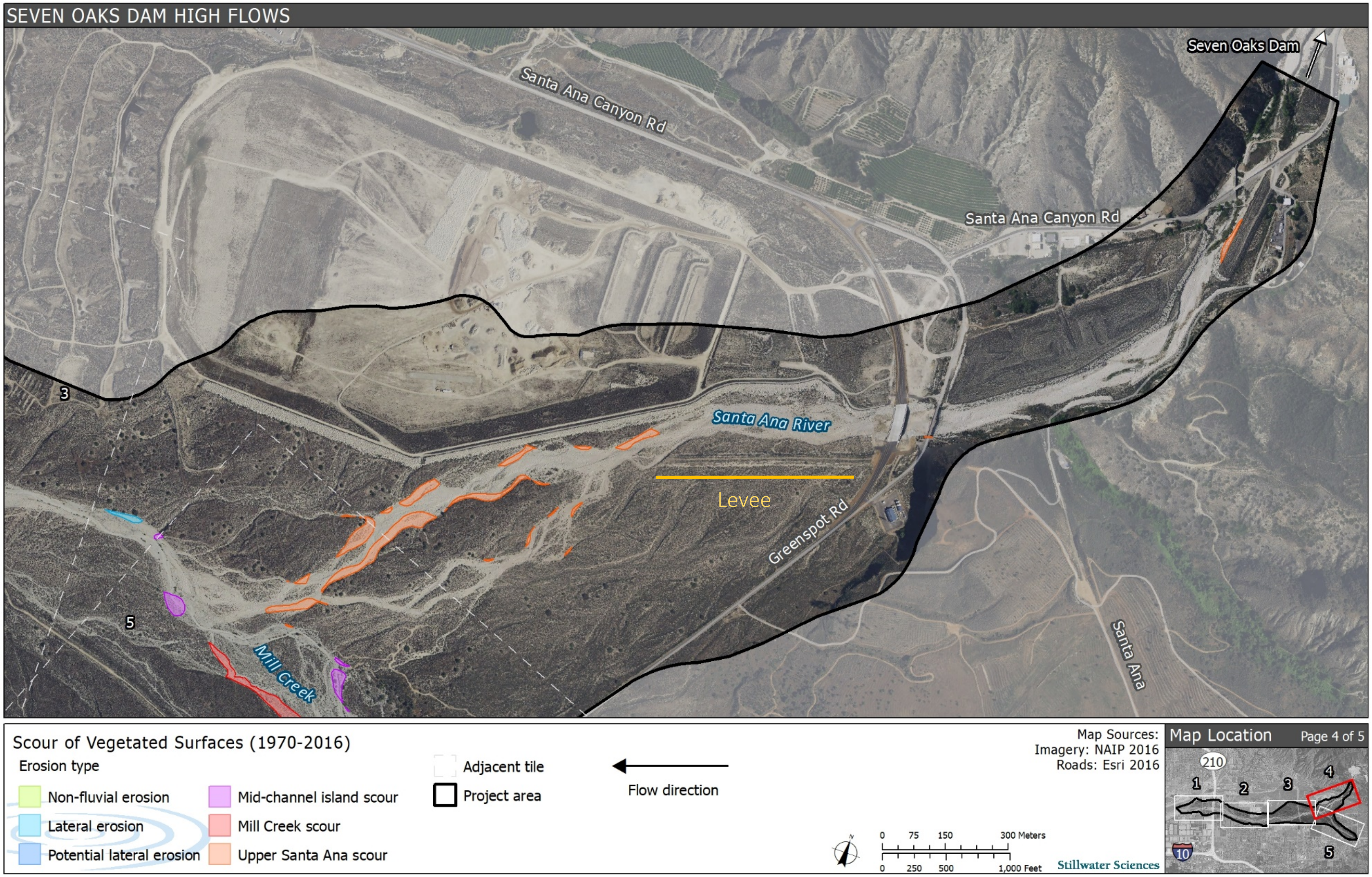


Figure 8. 1970-2016 scour map of the Santa Ana River upstream of the confluence with Mill Creek on the 2016 imagery. The levee near Greenspot Road is highlighted in gold.

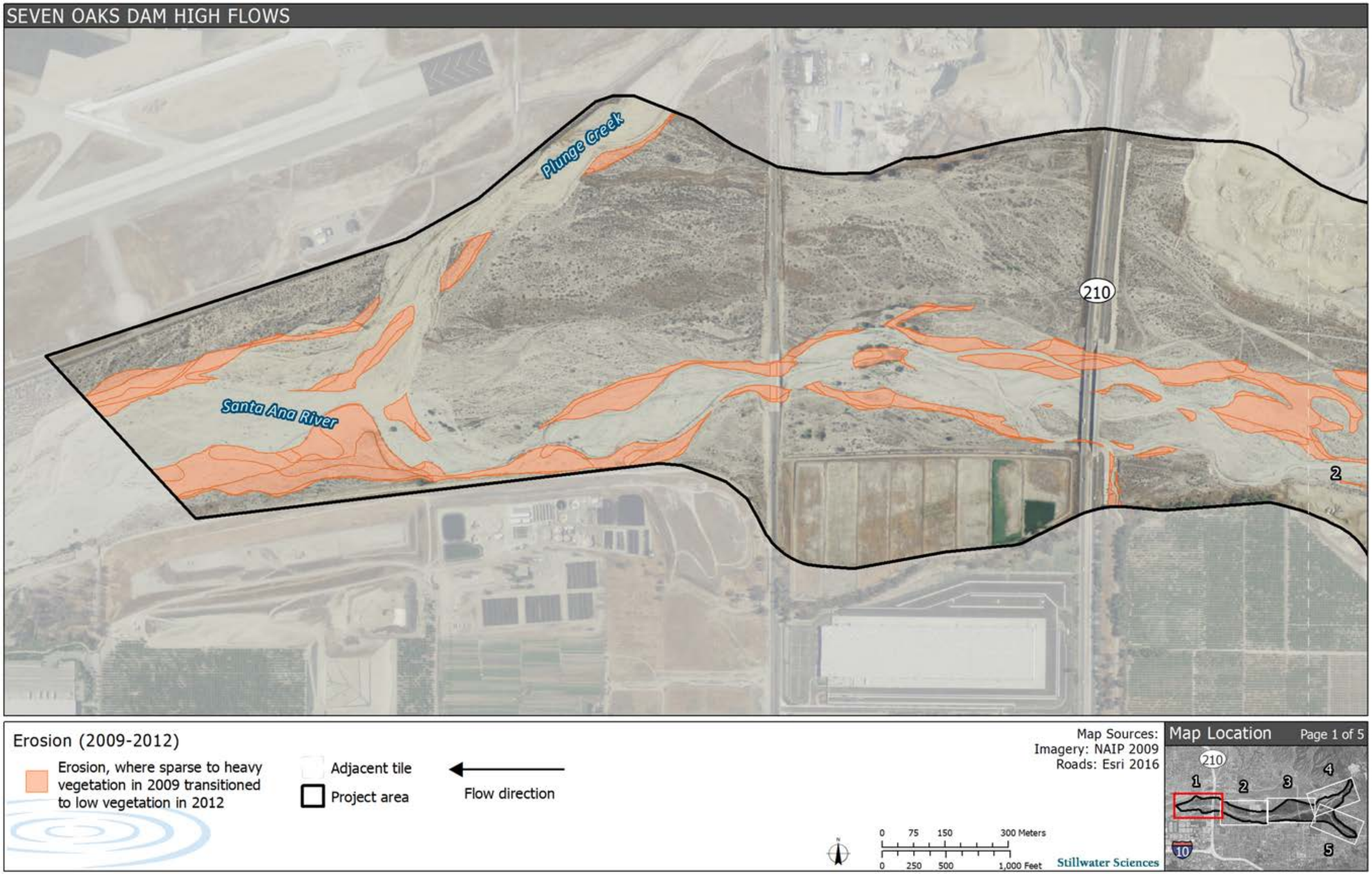


Figure 9. Vegetation scour 2009-2012 for the Santa Ana River near the City Creek confluence.

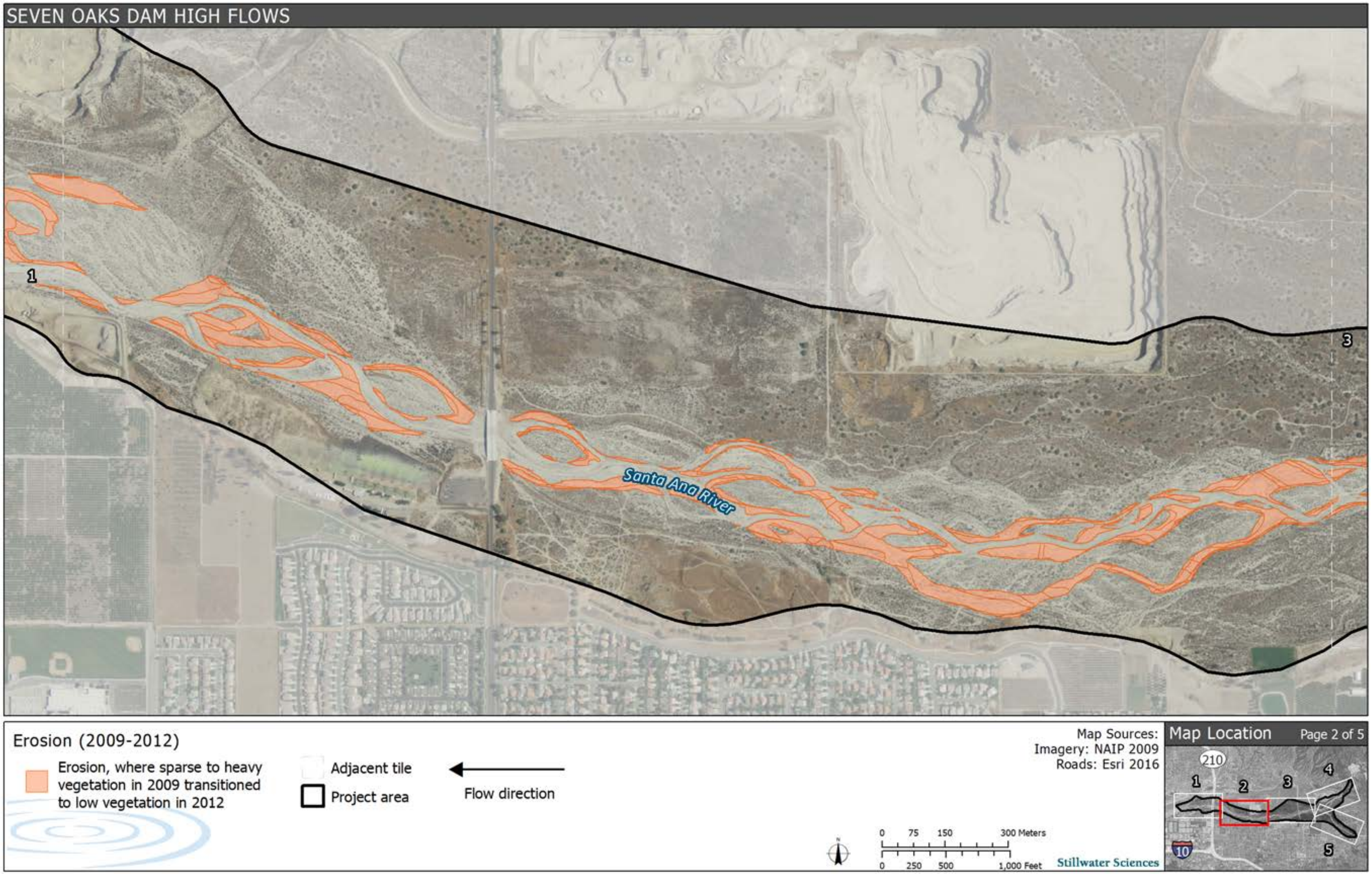


Figure 10. Vegetation scour 2009-2012 for the Santa Ana River near the Orange Street Bridge.

Figure 11. Vegetation scour 2009-2012 for the Santa Ana River near reach near Opal Avenue.

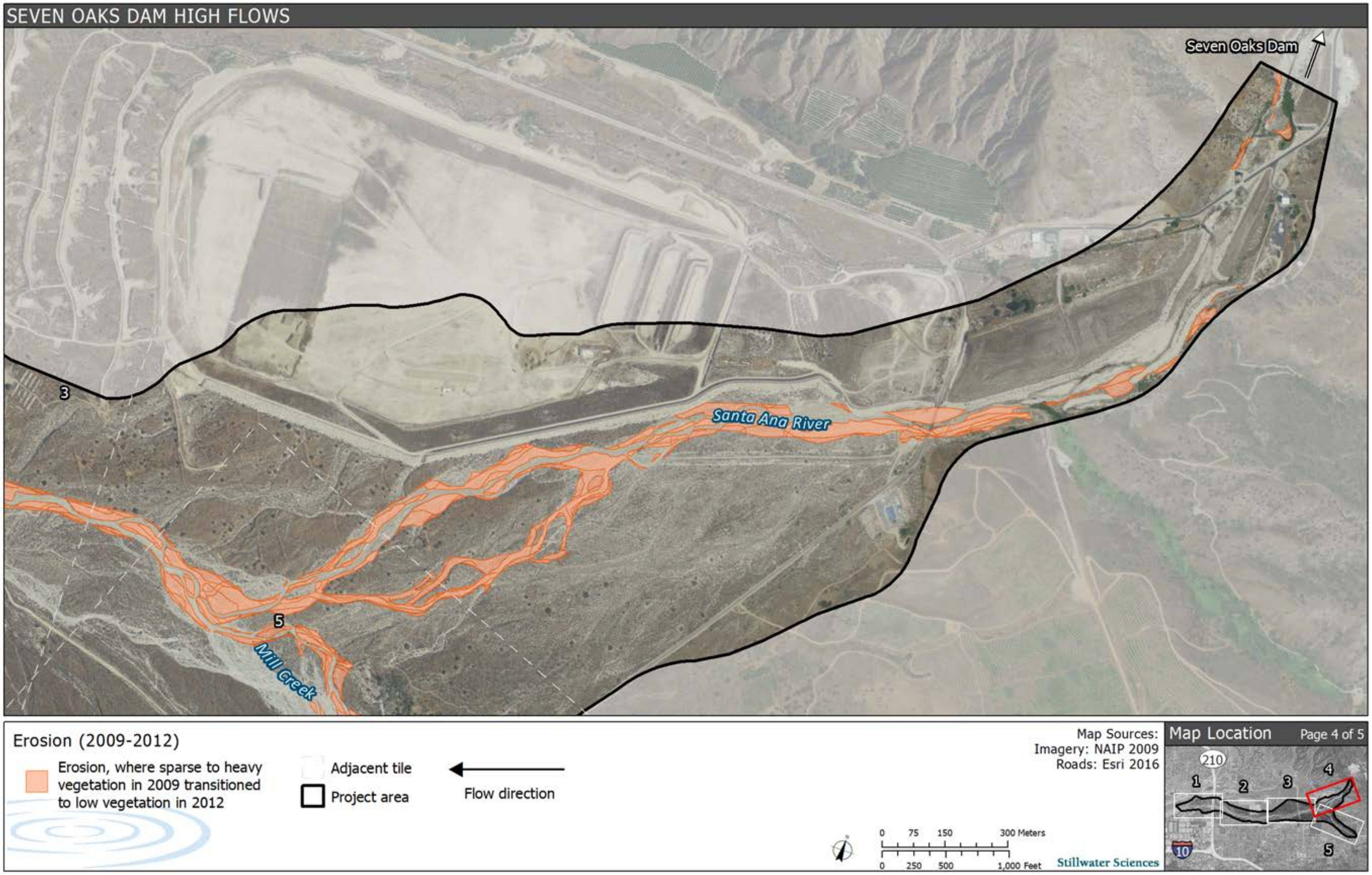


Figure 12. Vegetation scour 2009-2012 for the Santa Ana River upstream of the Mill Creek confluence.

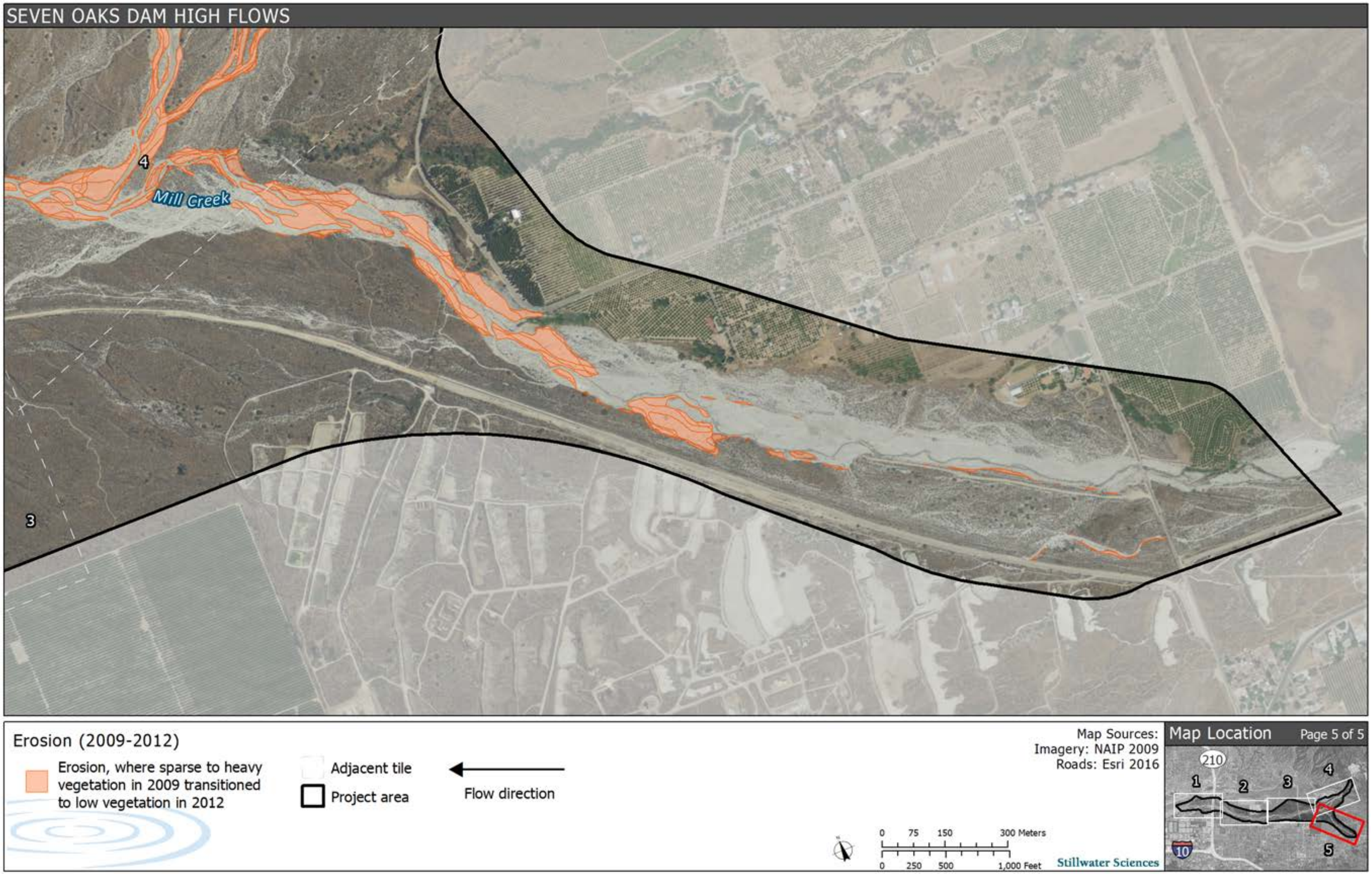


Figure 13. Vegetation scour 2009-2012 for Mill Creek.

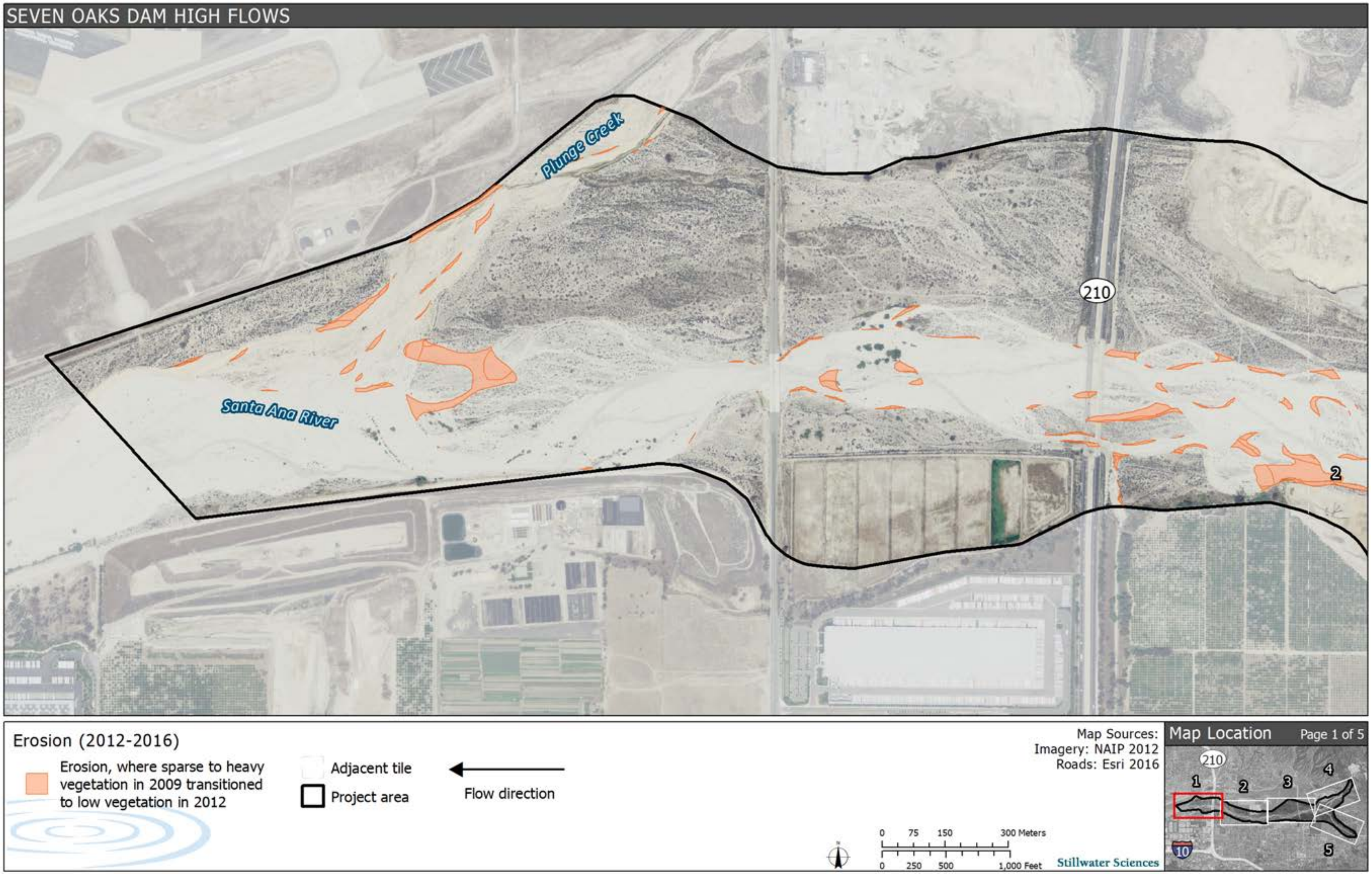


Figure 14. Vegetation scour 2012-2016 for the Santa Ana River near the City Creek confluence.

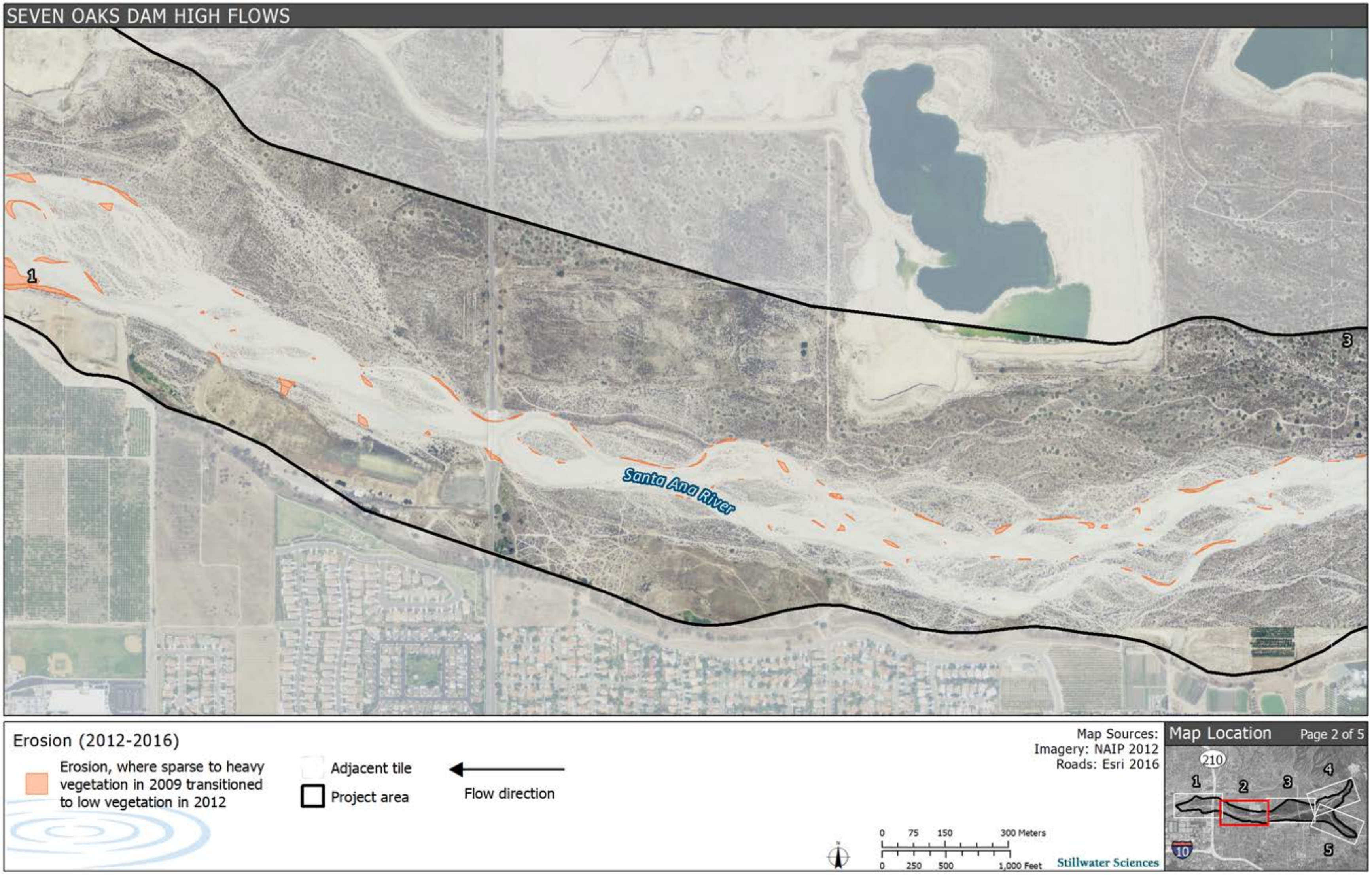


Figure 15. Vegetation scour 2012-2016 for the Santa Ana River near the Orange Street Bridge.

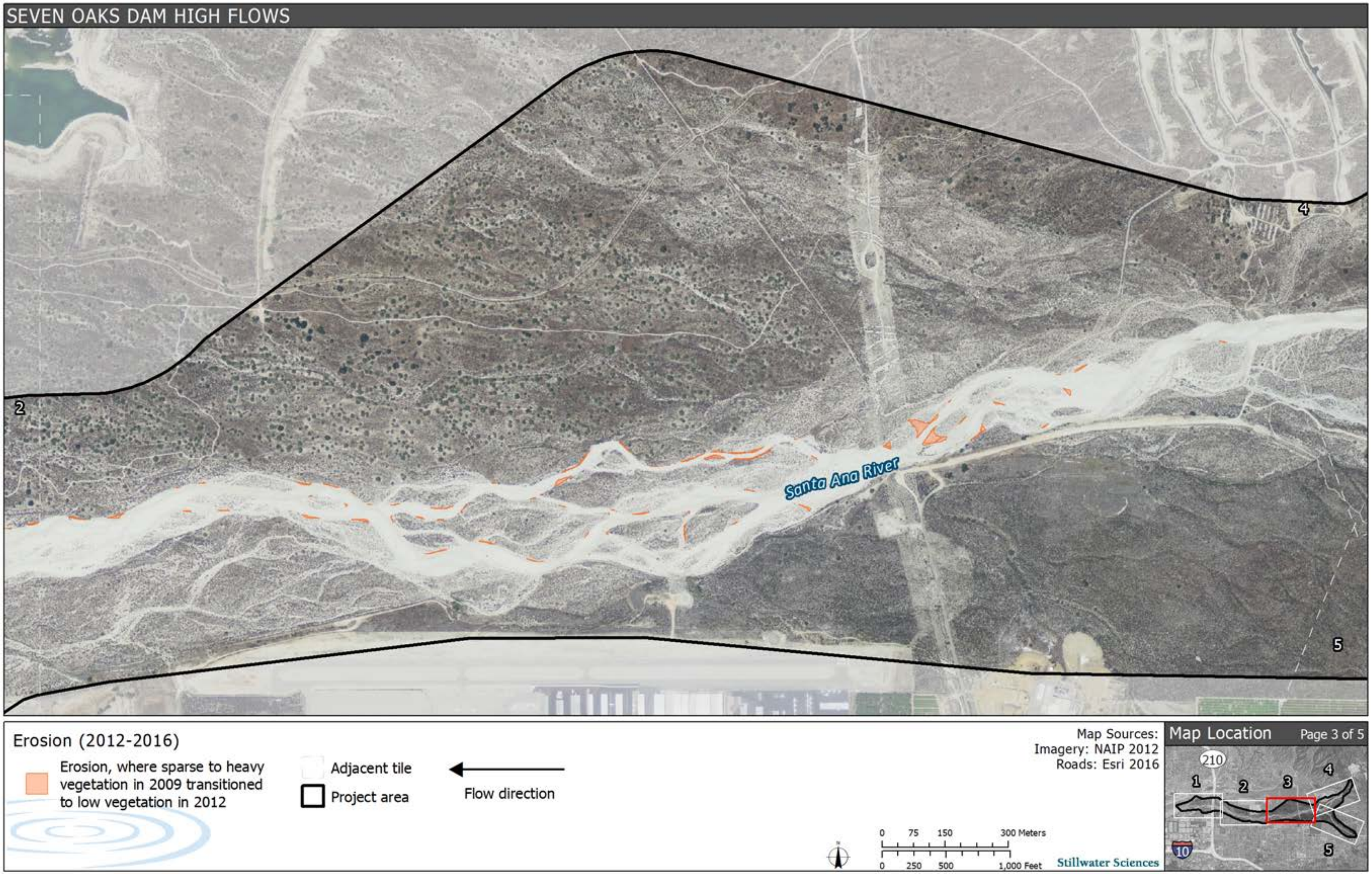


Figure 16. Vegetation scour 2012-2016 for the Santa Ana River near reach near Opal Avenue.

Figure 17. Vegetation scour 2012-2016 for the Santa Ana River upstream of the Mill Creek confluence.

Figure 18. Vegetation scour 2012-2016 for Mill Creek.

A. APPENDIX A-VEGETATION MAPS

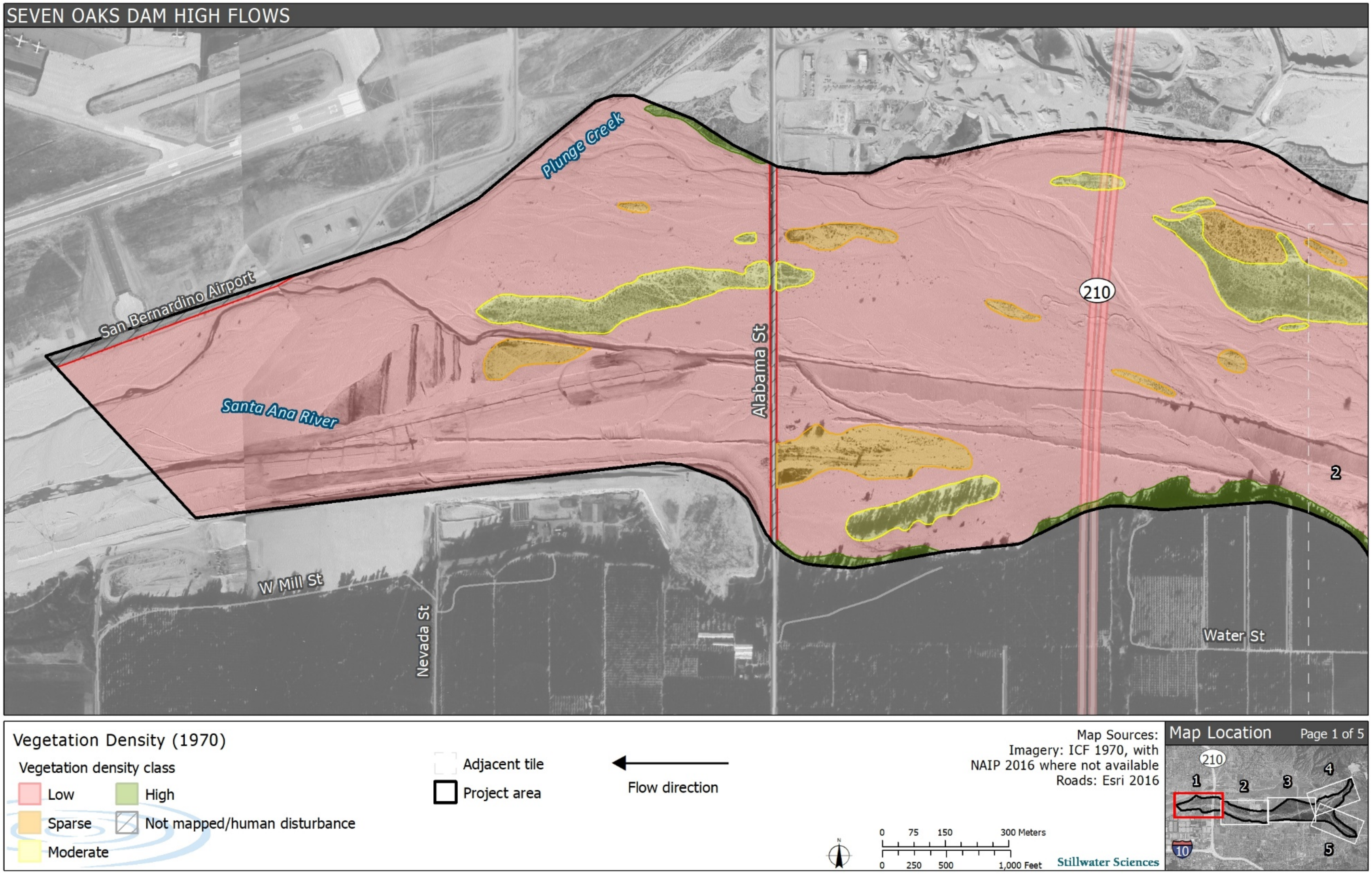


Figure A1. 1970 vegetation density map for the reach near the Plunge Creek confluence.

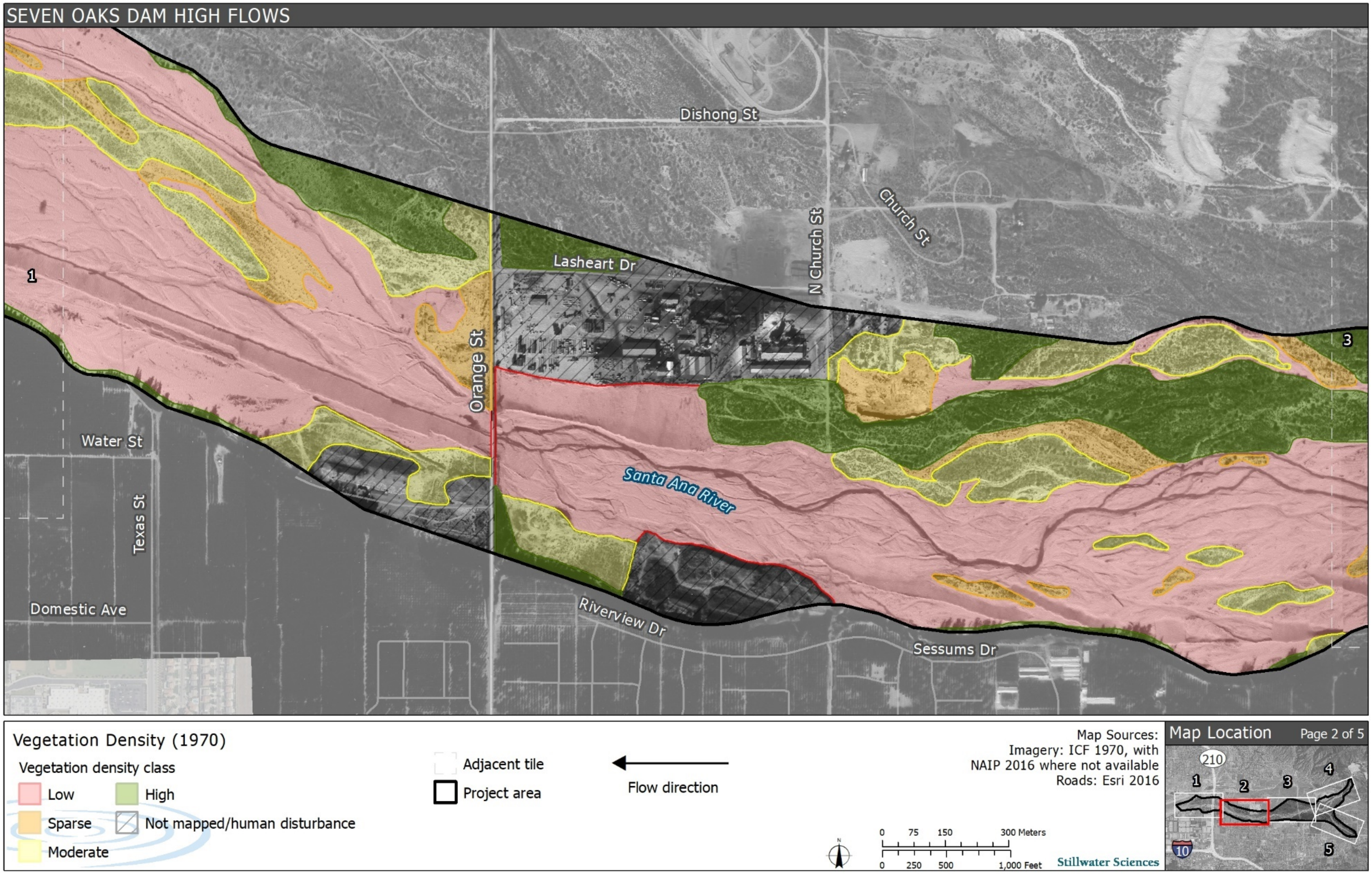


Figure A2. 1970 vegetation density map for the Santa River Ana reach near the Orange Street Bridge.

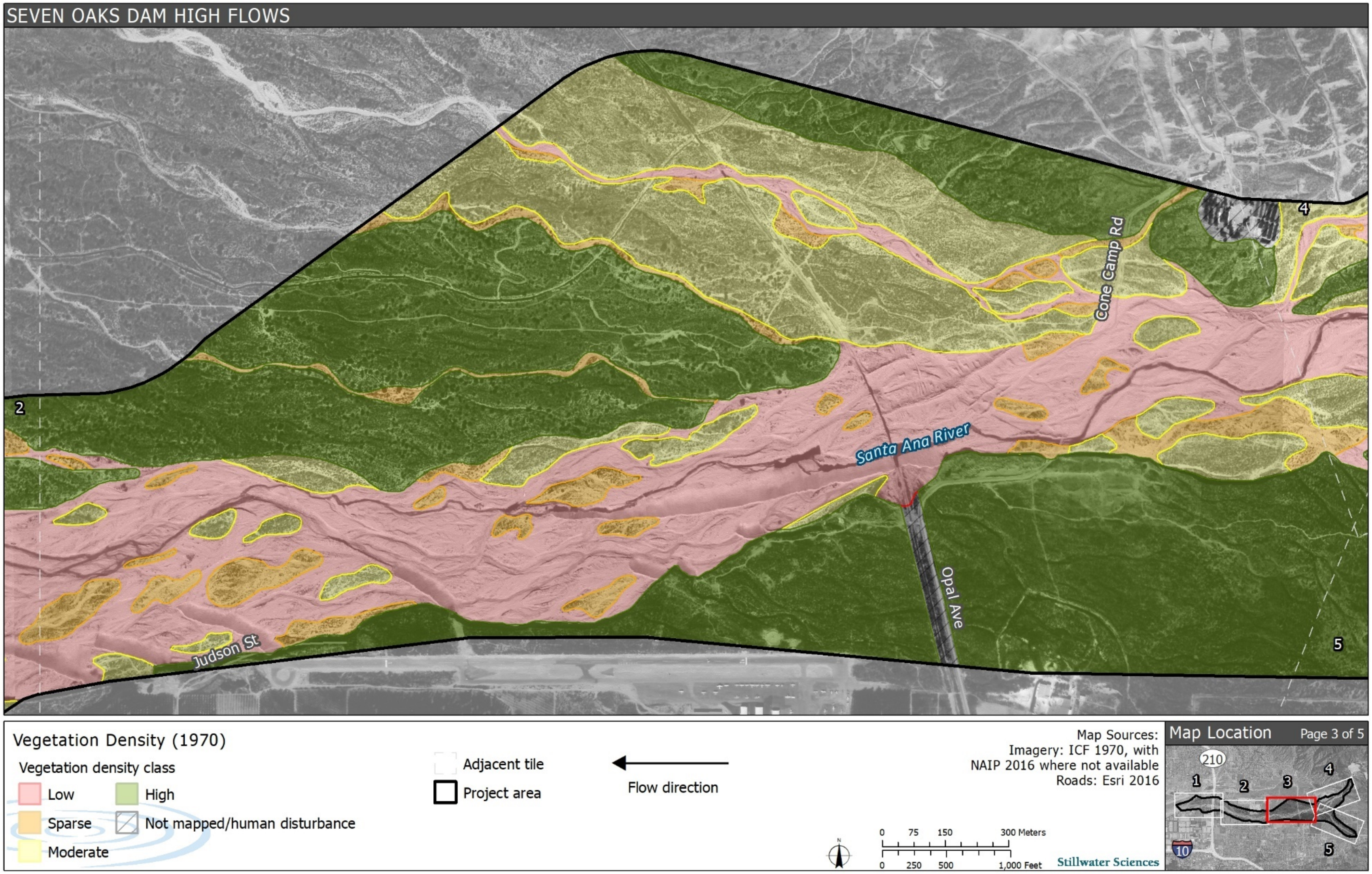


Figure A3. 1970 vegetation density map for the Santa River Ana reach near Opal Avenue.

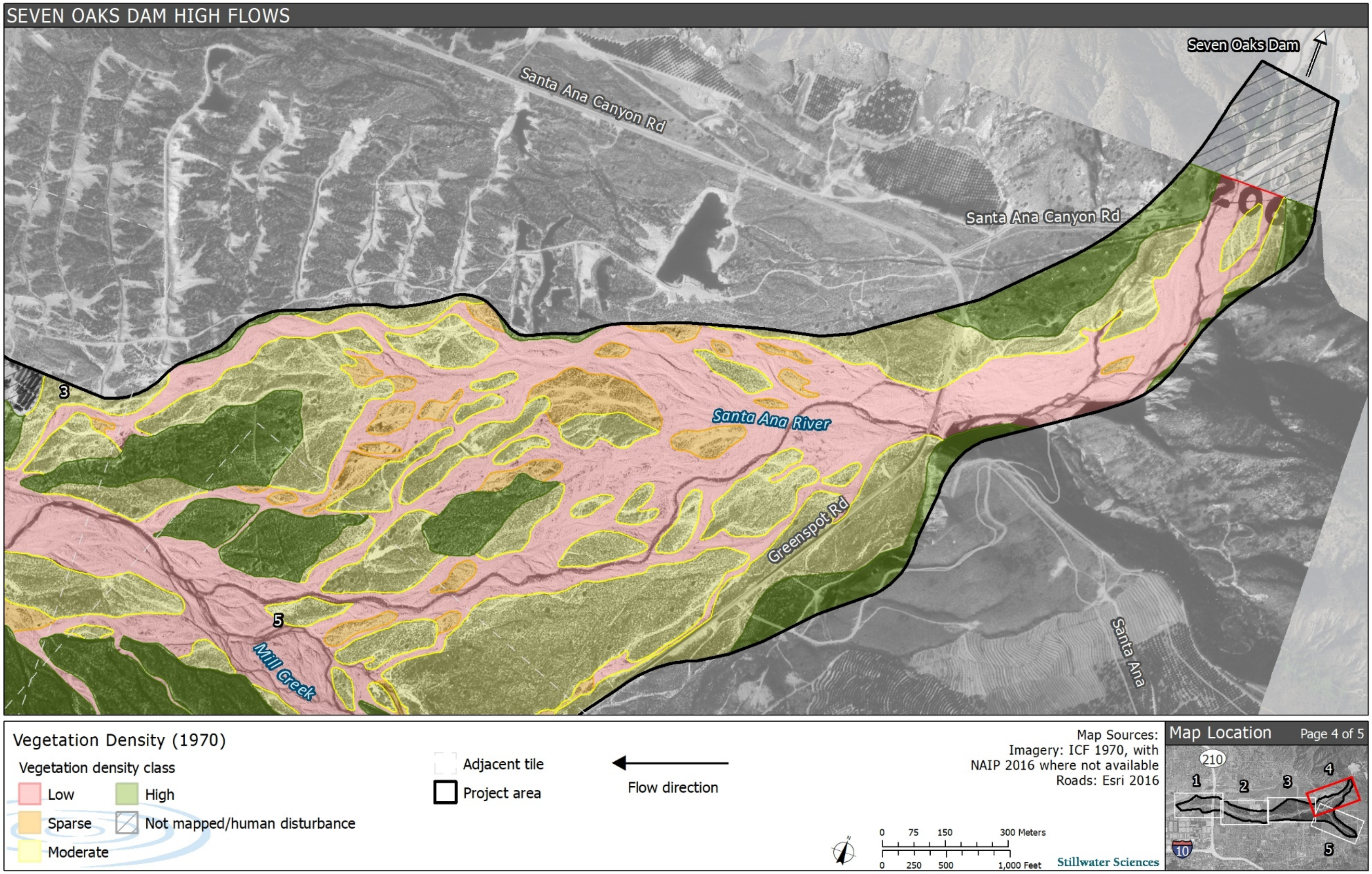


Figure A4. 1970 vegetation density map for the Santa Ana reach upstream of the Mill Creek confluence

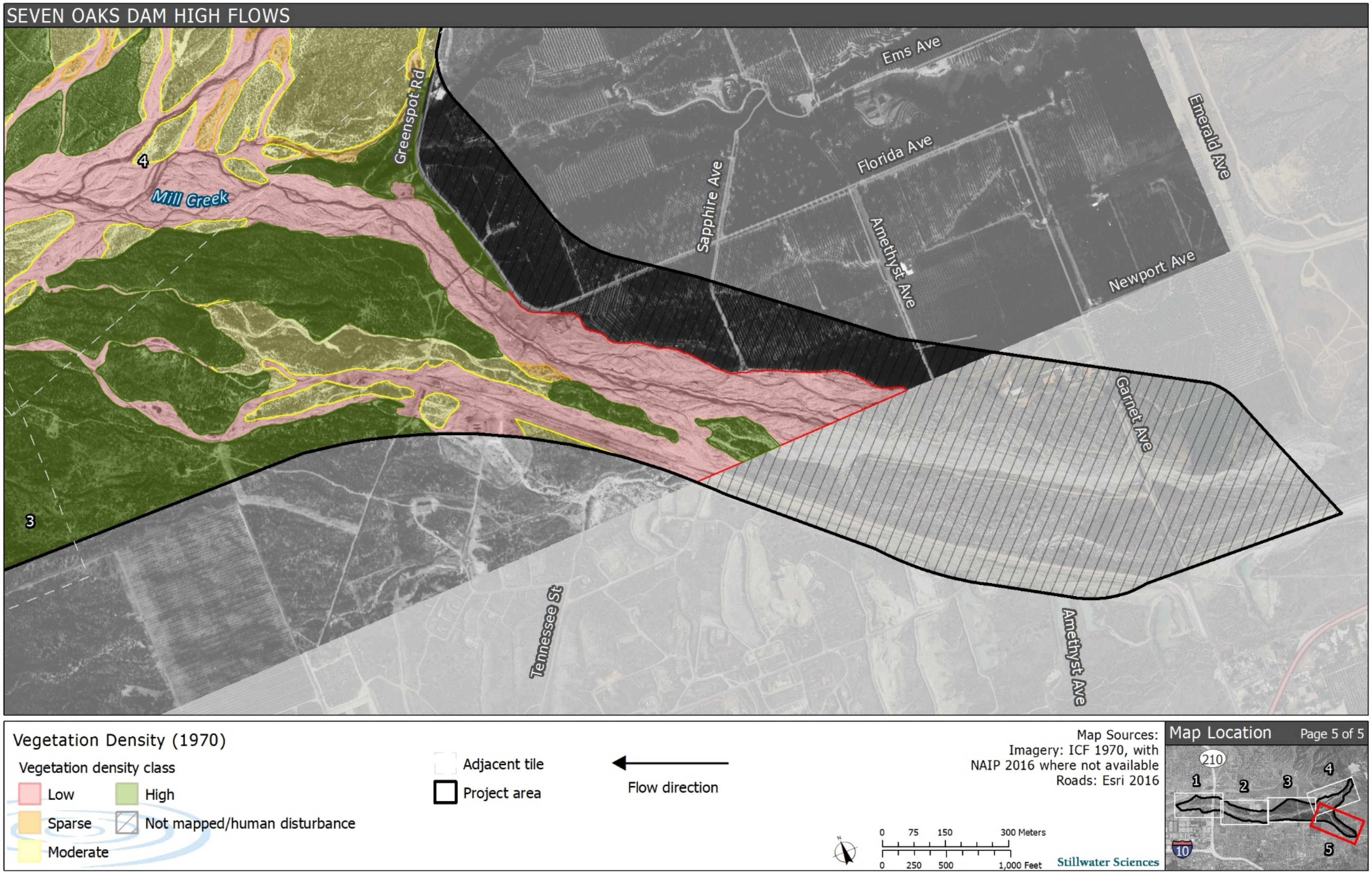


Figure A5. 1970 vegetation density map for Mill Creek.

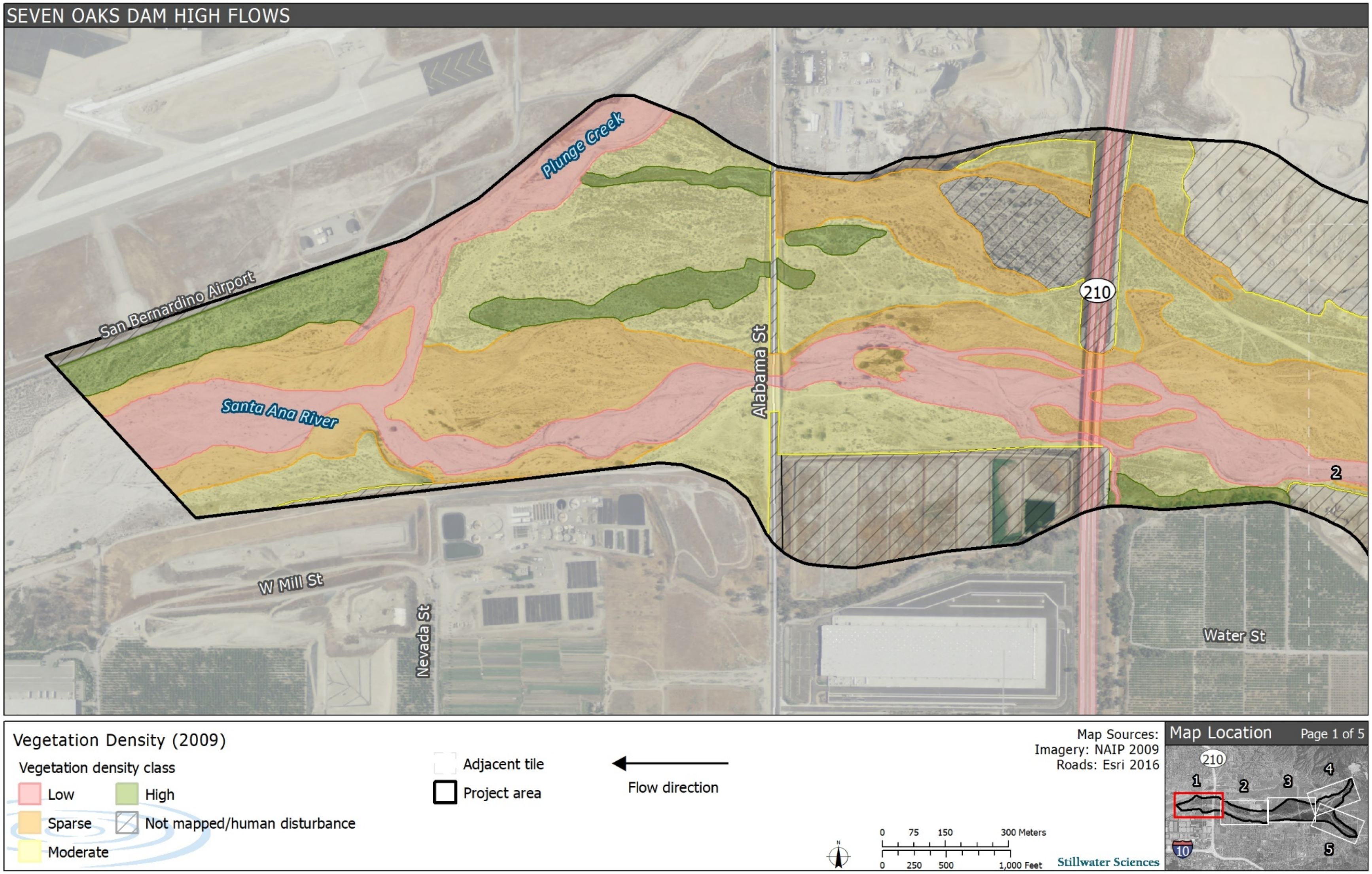


Figure A6. 2009 vegetation density map for the reach near the Plunge Creek confluence.

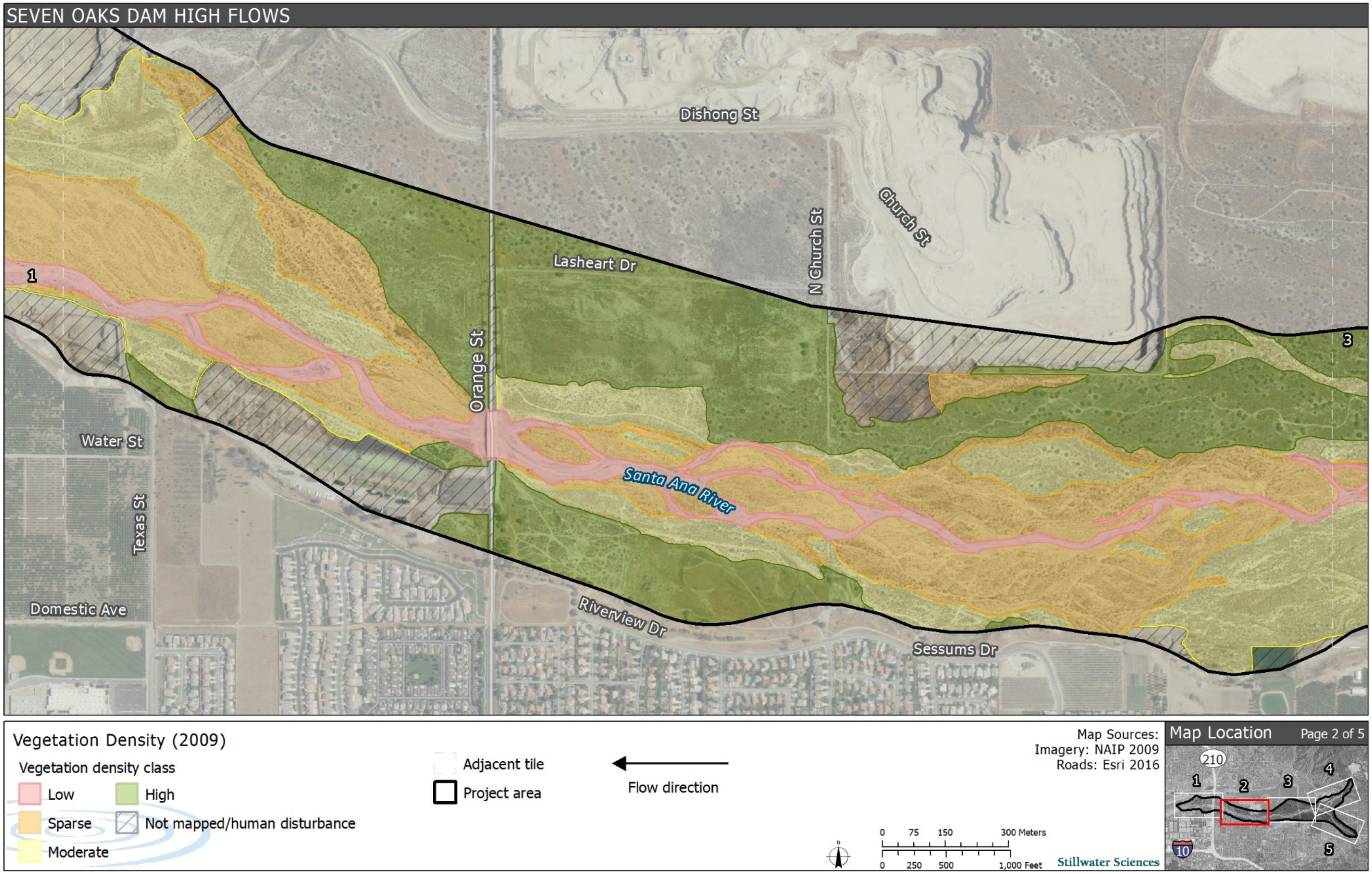


Figure A7. 2009 vegetation density map for the Santa River Ana reach near the Orange Street Bridge.

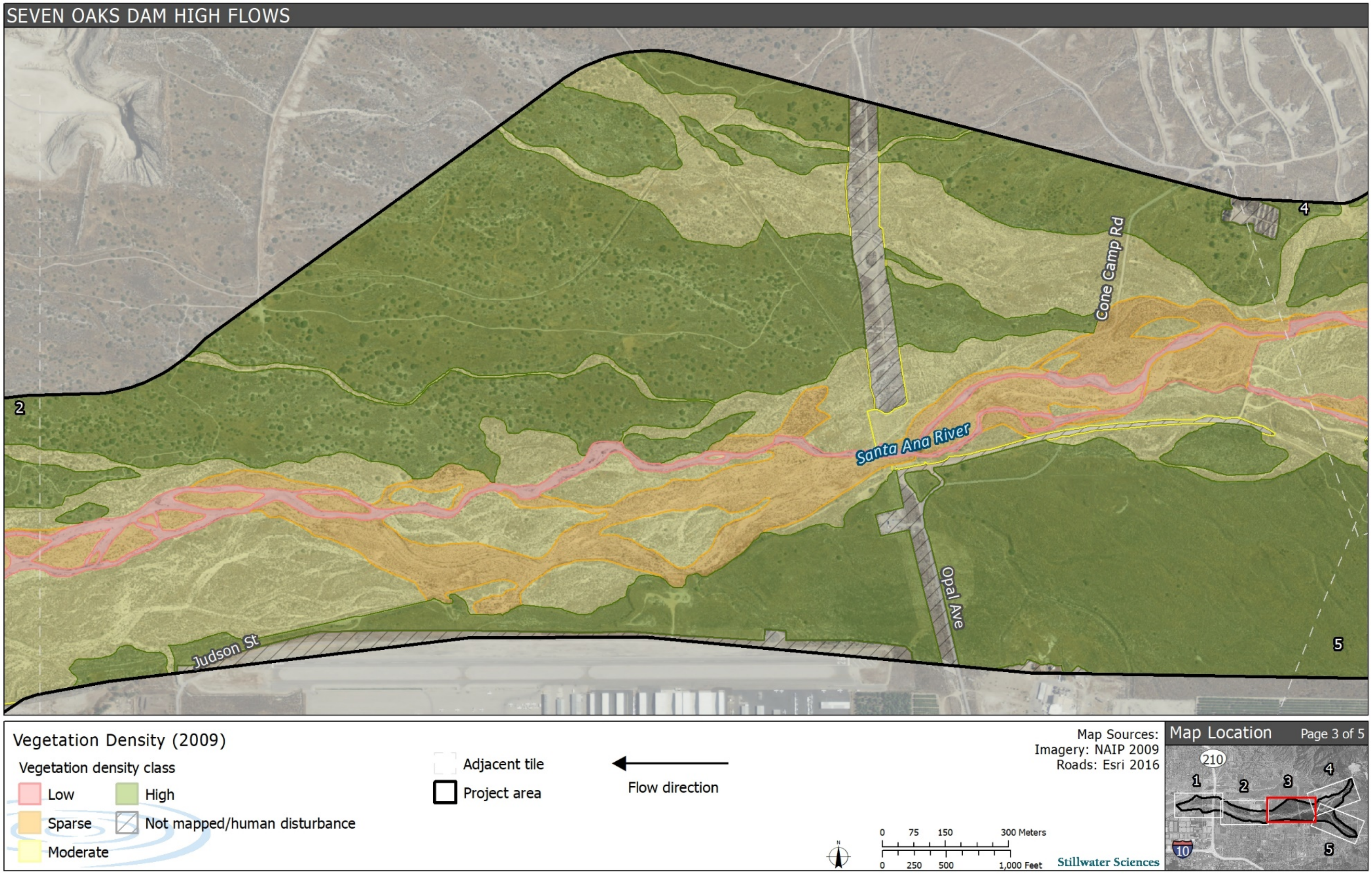


Figure A8. 2009 vegetation density map for the Santa River Ana reach near Opal Avenue.

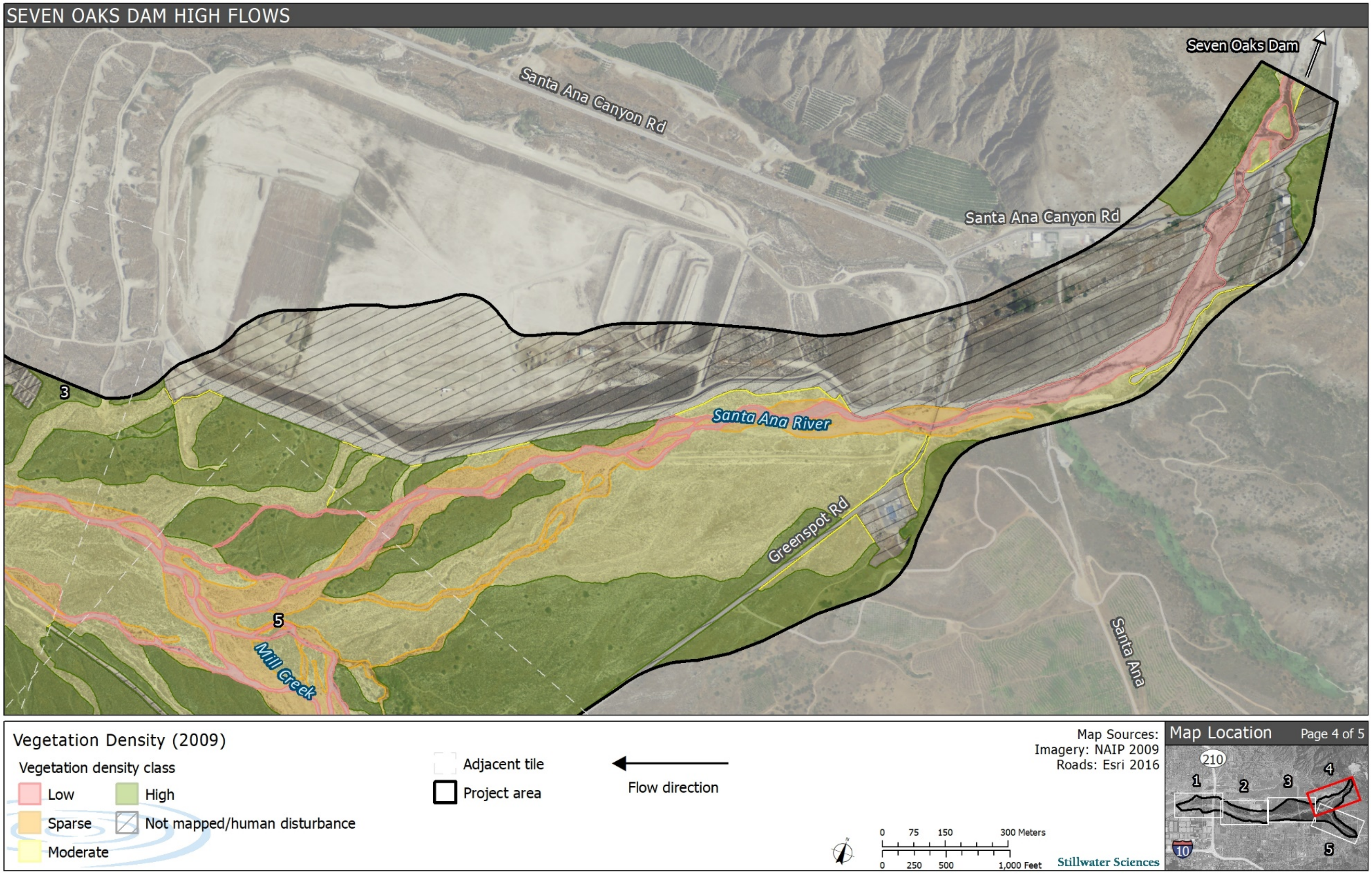


Figure A9. 2009 vegetation density map for the Santa Ana reach upstream of the Mill Creek confluence.

Figure A10. 2009 vegetation density map for Mill Creek.

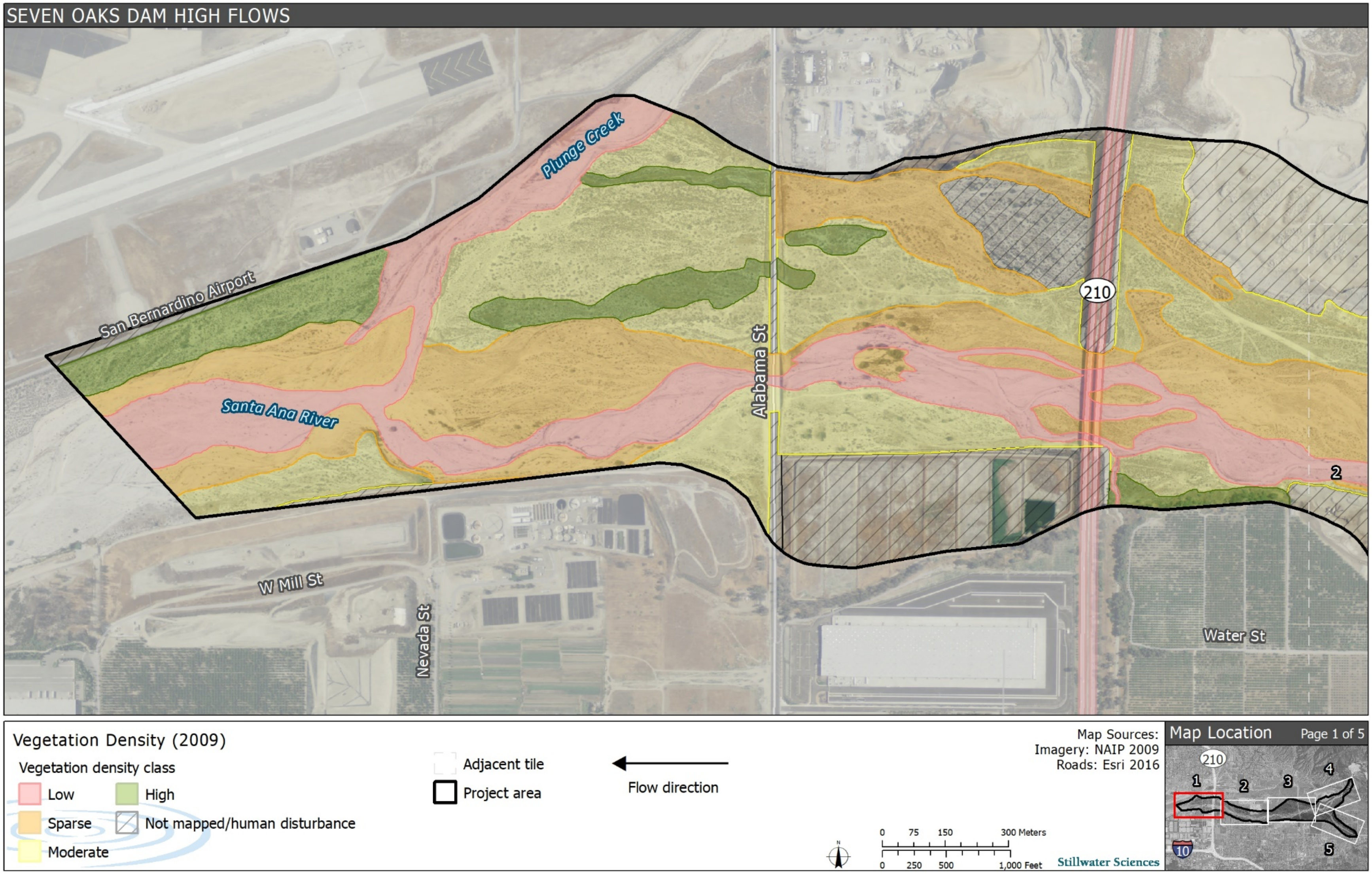


Figure A11. 2012 Vegetation density map for the Santa River Ana near the City Creek confluence.

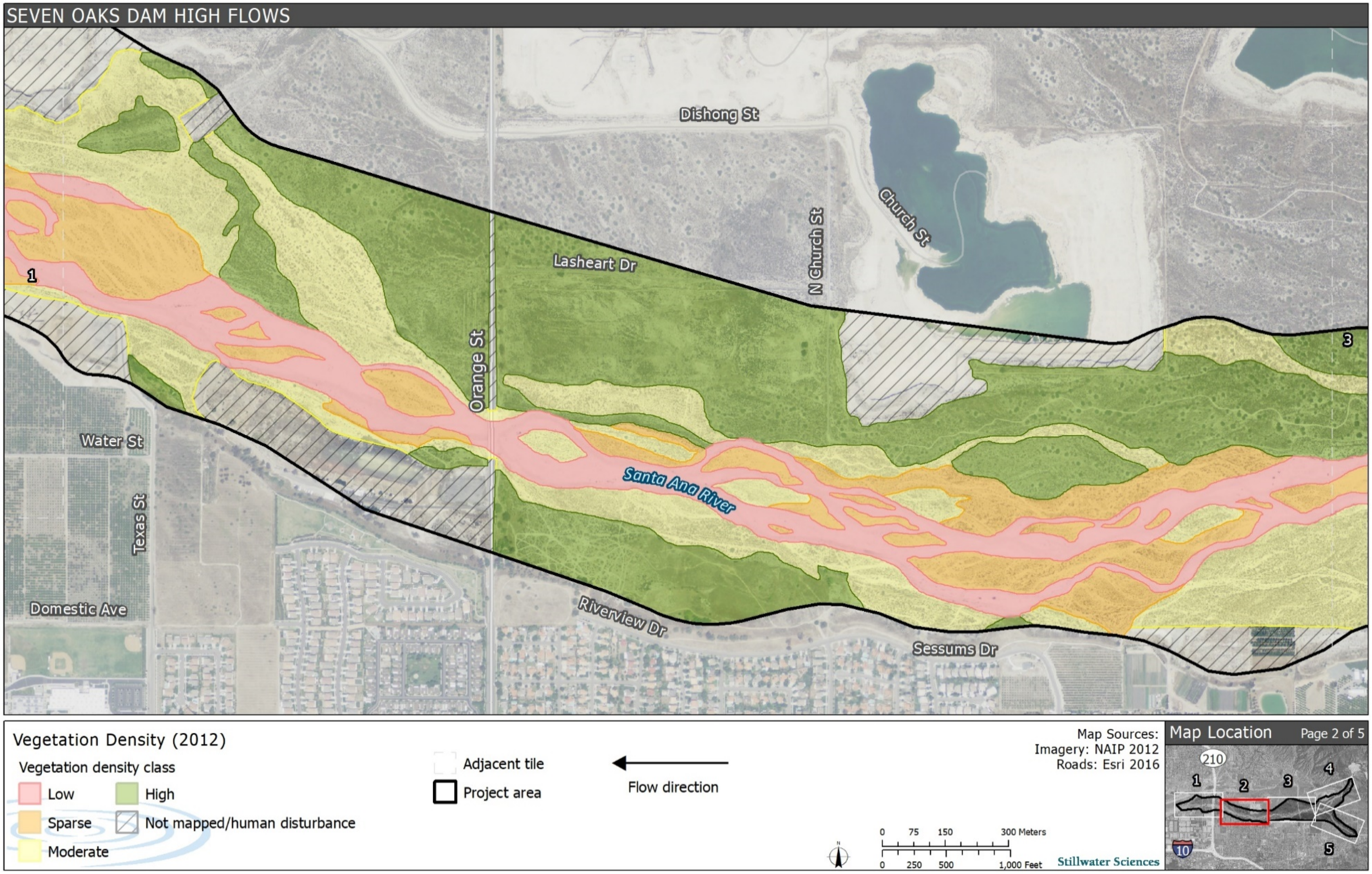


Figure A12. 2012 vegetation density map for the Santa River Ana reach near the Orange Street Bridge.

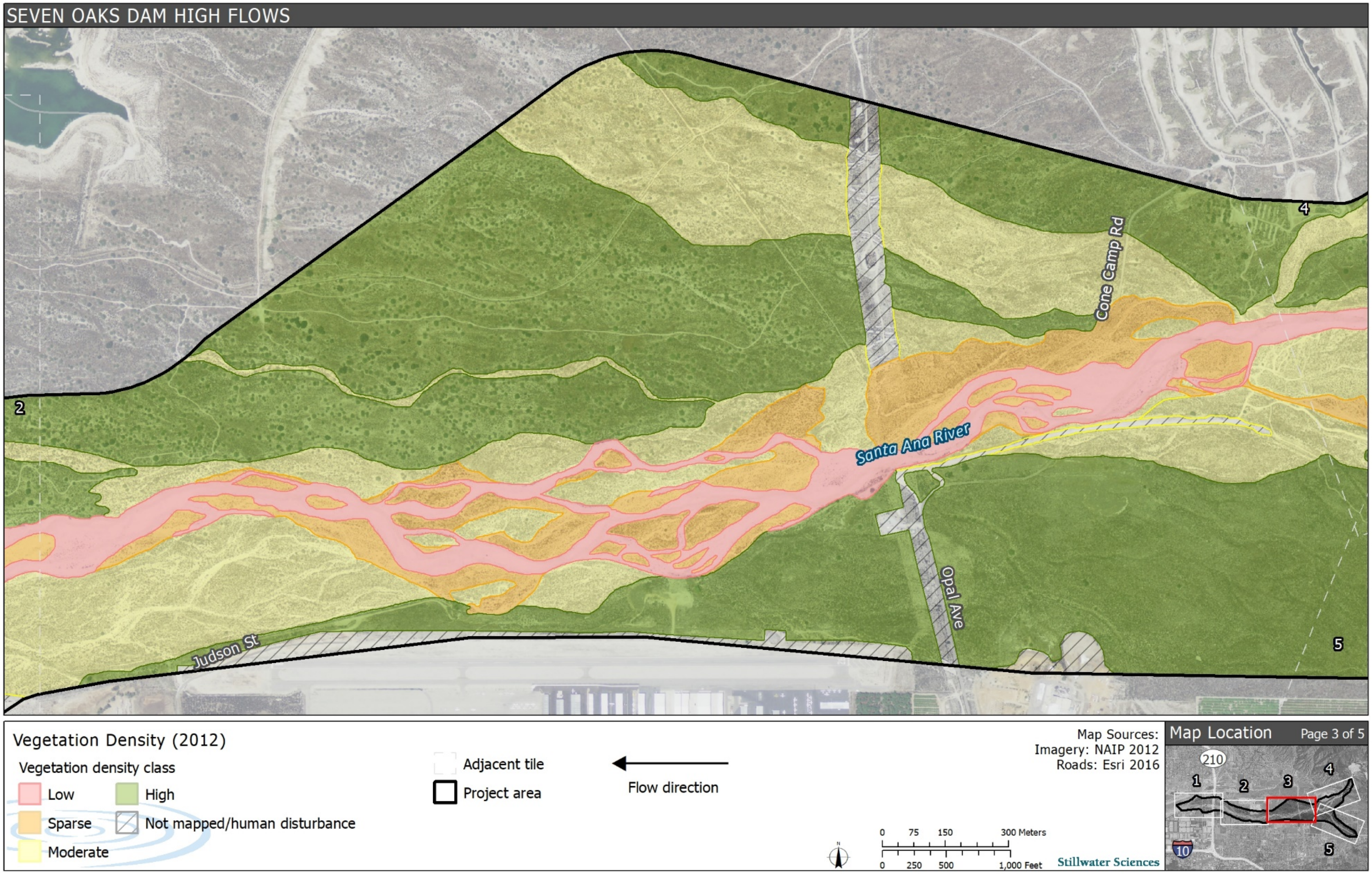


Figure A13. 2012 Vegetation density map for the Santa River Ana reach near Opal Avenue.

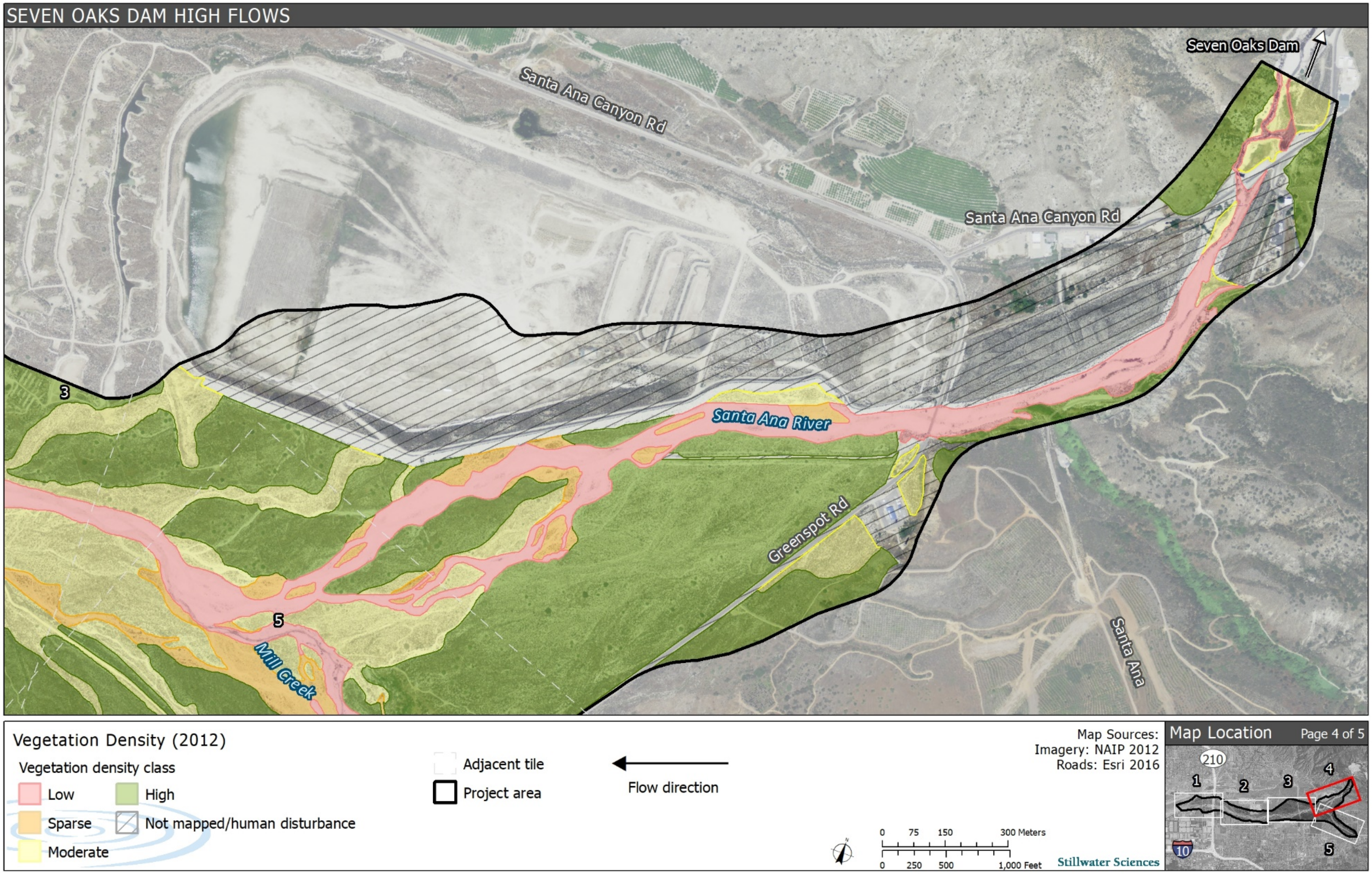


Figure A14. 2012 vegetation density map for the Santa Ana reach upstream of the Mill Creek confluence.

Figure A15. 2012 vegetation density map for Mill Creek.

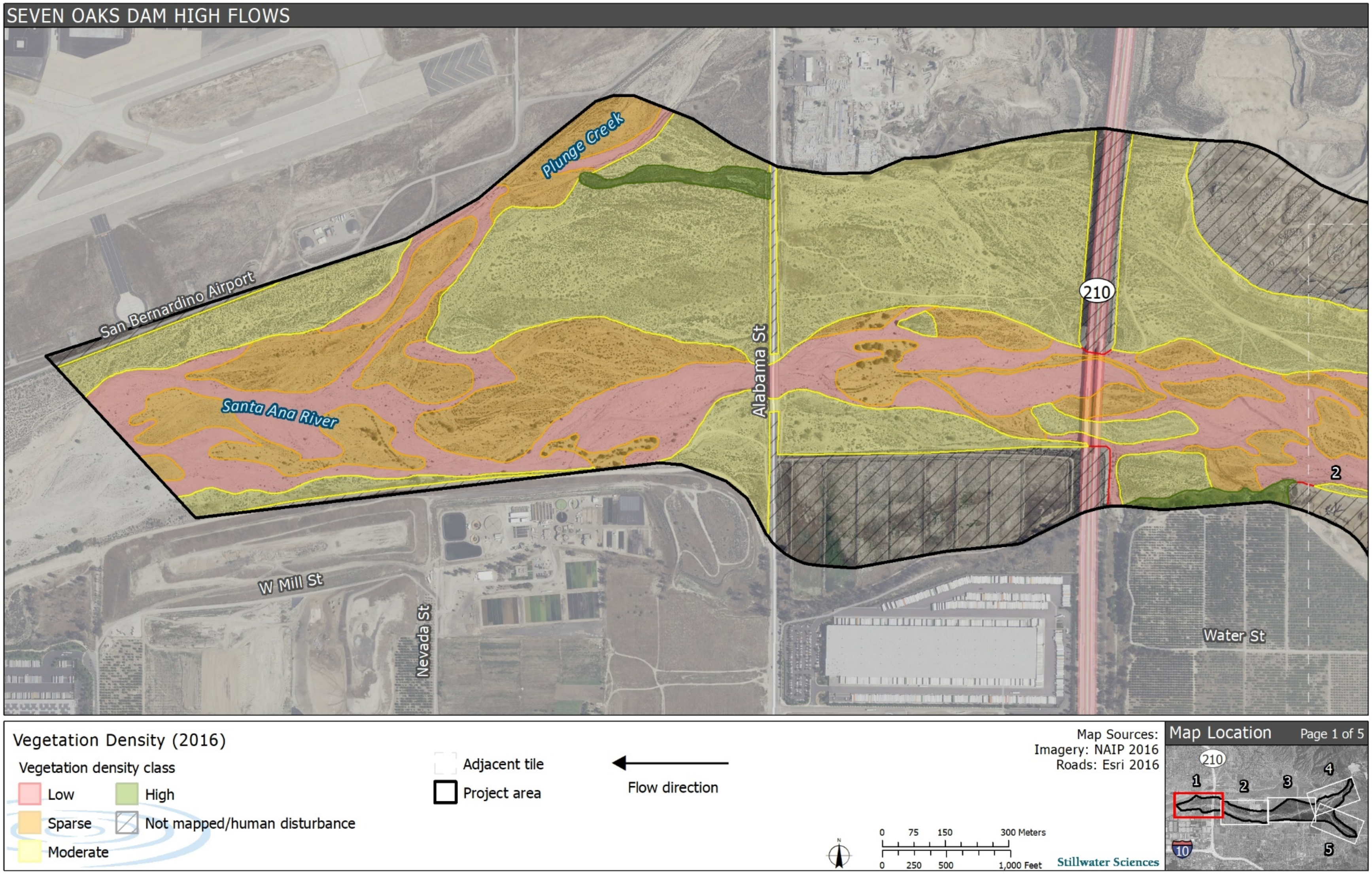


Figure A16. 2016 vegetation density map for the reach near the Plunge Creek confluence.

Figure A17. 2016 vegetation density map for the Santa River Ana reach near the Orange Street Bridge.

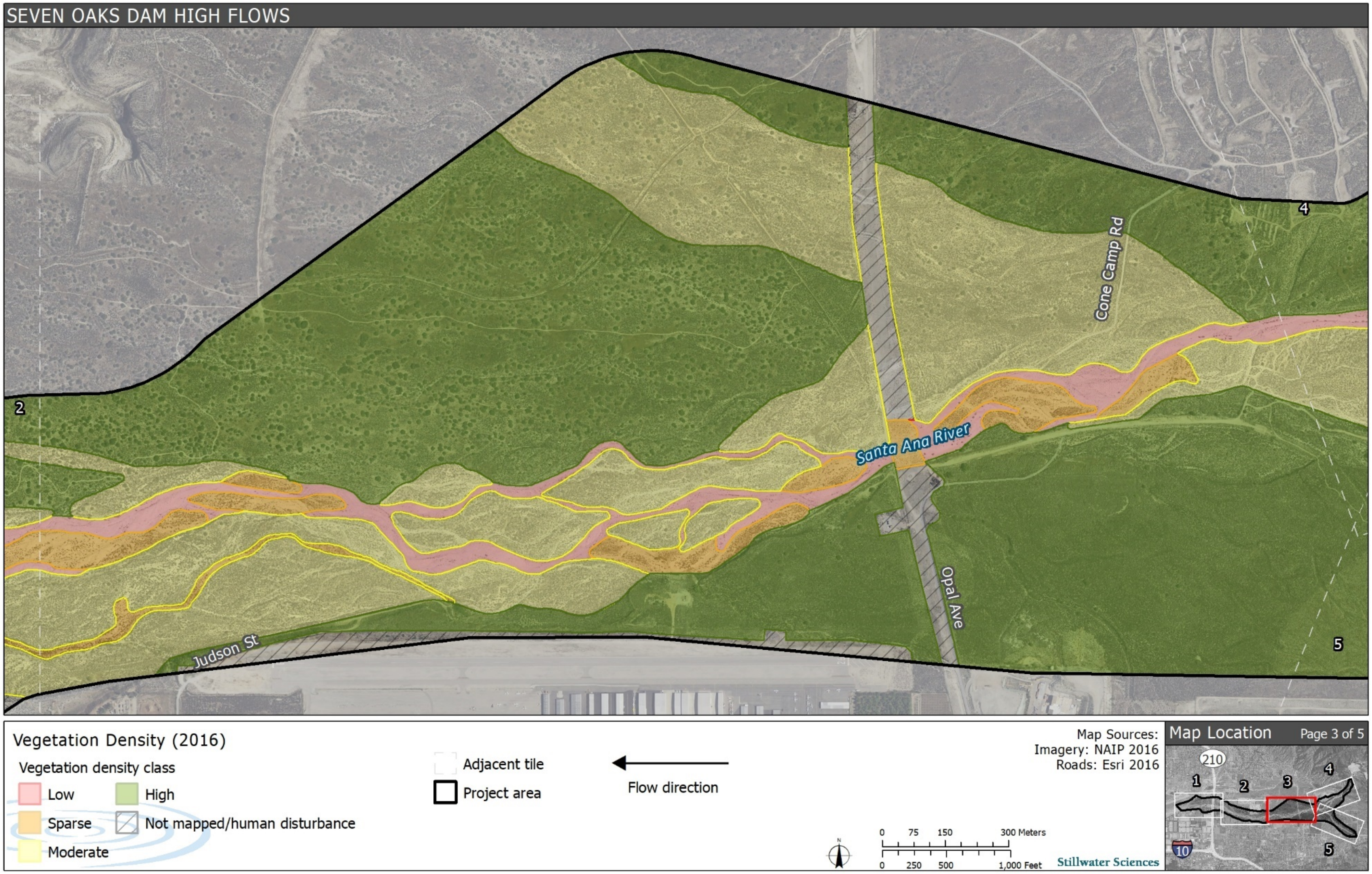


Figure A18. 2016 vegetation density map for the Santa River Ana reach near Opal Avenue.

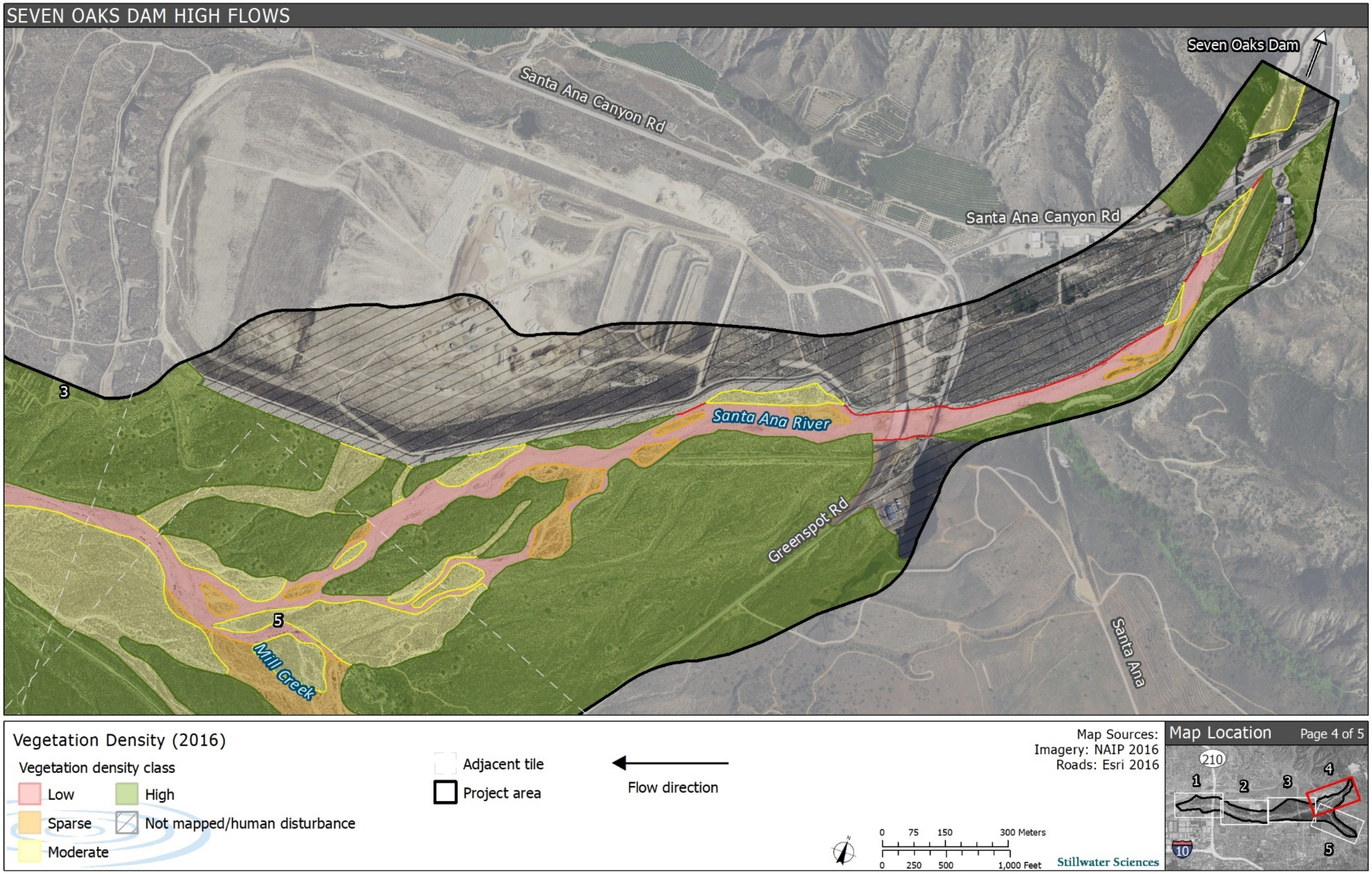


Figure A19. 2009 vegetation density map for the Santa Ana reach upstream of the Mill Creek confluence.

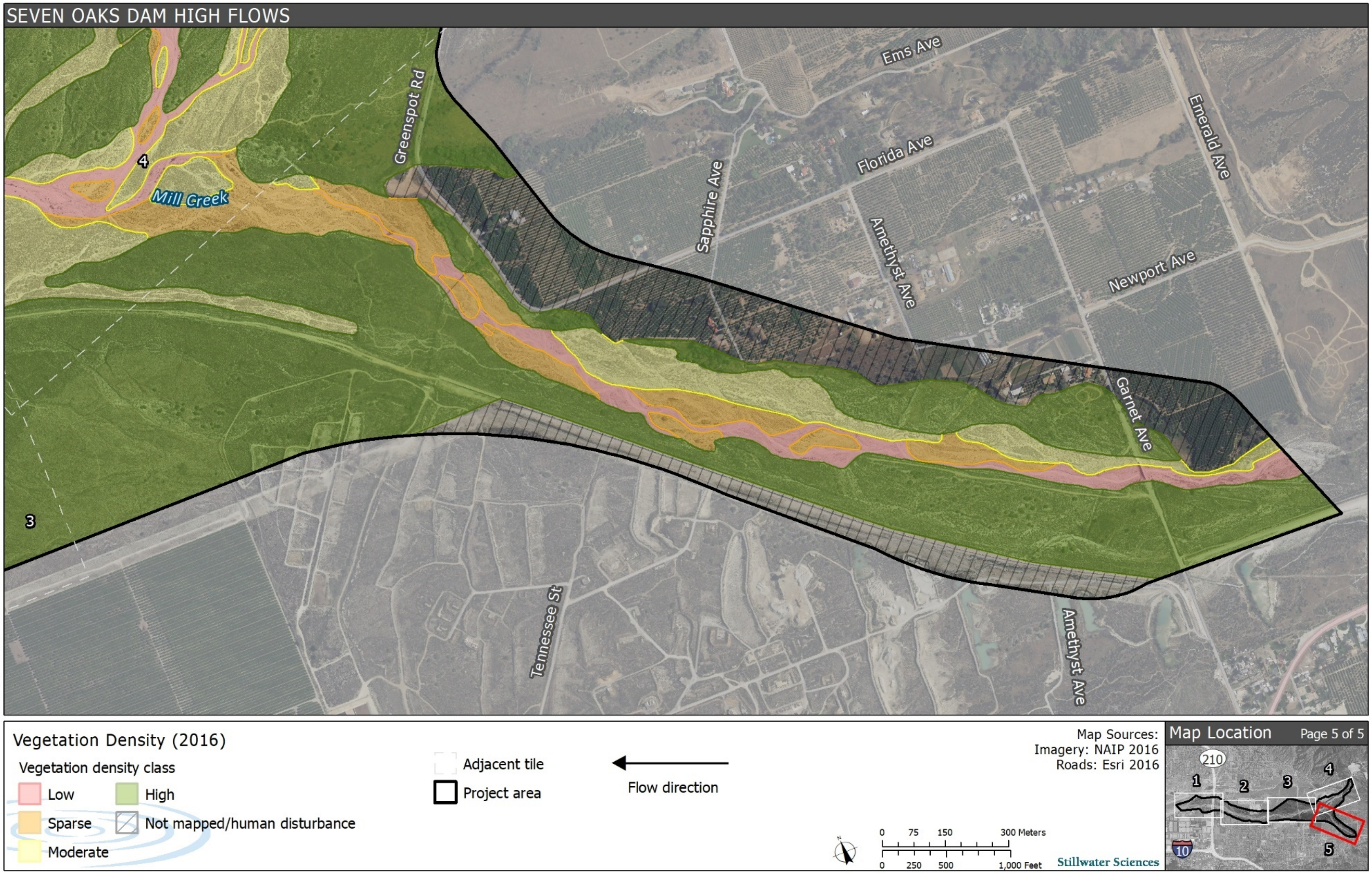


Figure A20. 2016 vegetation density map for Mill Creek.

Appendix 2

Blue Octal Solution's 2019 Report Thresholds for Vegetation Removal and Sediment Transport: Literature Review, Field Measurements and Analysis to Improve San Bernardino Kangaroo Rat Habitat in the Upper Santa Ana River, California

DRAFT Thresholds for vegetation removal and sediment transport: Literature review, field measurements and analysis to improve San Bernardino Kangaroo Rat habitat in the upper Santa Ana River, California

Report prepared by:

Michael Lamb, Tom Ulizio, & J. Toby Minear,

Blue Octal Solutions, LLC

May 31, 2019

Report submitted to:

San Bernardino Valley Municipal Water District

San Bernardino, California

DRAFT Thresholds for vegetation removal and sediment transport: Literature review, field measurements and analysis to improve San Bernardino Kangaroo Rat habitat in the upper Santa Ana River, California

Michael Lamb, Tom Ulizio, & J. Toby Minear, Blue Octal Solutions, LLC

1. Motivation and Scope

One of the objectives of the high-flow study on the upper Santa Ana River is to investigate the size of floods necessary to improve SBKR habitat. Based on data compilations in the ICF Phase 1 Report and previous work (Mussetter, 1999; Burk et al., 2007), high quality SBKR habitat currently exists in former flood pathways on the alluvial fan, such as the 1969 breakout zone. Based on historical air photos, these floodways experienced significant disturbance when they were flooded including channel incision (likely up to few meters), removal of vegetation, and sediment transport and sorting of sediment into sand and gravel bars. Disturbance of this magnitude may be necessary to improve habitat by thinning vegetation and grass cover, resetting the vegetation succession and depositing pockets of sand that are suitable for burrowing. Therefore, an effective flood design should achieve flow discharges sufficient to mobilize sediment and remove vegetation. This report compiles work by Blue Octal Solutions, LLC aimed at giving a preliminary and first-order assessment of flood requirements to this end. The report includes a summary of peer-reviewed scientific literature on removal of vegetation by floods (Section 2), summary of criteria to assess sediment transport (Section 3), field observations and measurements of plant sizes and sediment sizes in the 1969 breakout channel and the currently active channel belt in the study reach (Section 4), and recommendation for future work (Section 5).

2. Literature Review: Vegetation Scour by Flood Flows

Floods engineered to transport sediment or remove vegetation are known as *flushing flows* in river restoration science (Kondolf and Wilcock, 1996; Whiting, 2002). Flushing flows as they relate to vegetation are designed to counteract the reduced range of floods due to dams and land use. The reduced flood range causes a decline in the areal extent of different successional species that are needed to maintain diverse habitat. Diverse stands of riparian vegetation requires dynamic channel change (Kondolf and Wilcock, 1996). Dynamic channels that adjust their topography through sediment erosion and deposition create

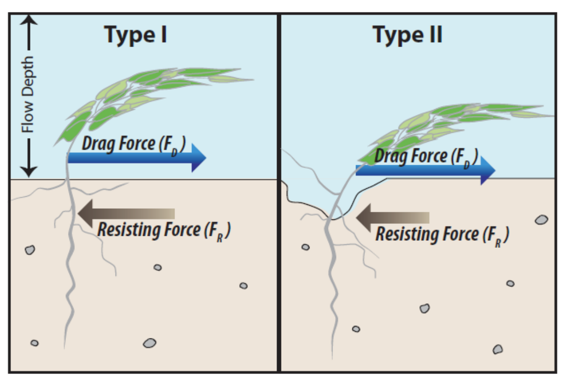


Figure 1. Schematic showing drag and resisting forces on plants, and the two types of vegetation removal following Edmaier et al. (2011). Schematic from Bywater-Reyes et al. (2015).

a diversity of terrain with different timescales of flood disturbance.

Vegetation removal by flowing water is typically classified into two mechanisms (Edmaier et al., 2011). Type 1 is uprooting, which occurs when the drag force exerted by flowing water is sufficient to overcome the resisting forces of the plant roots (Fig. 1). Type 2 occurs when sediment around the plant rootball are scoured, which exposes the roots and weakens the plant. Type 2 can be classified further into the type of scour: whether from flow disturbances due to the presence of the plant itself, or some other cause of bed scour such as bar migration, channel-bend migration or channel-reach incision due to a lack of sediment supply (Bywater-Reyes et al., 2015).

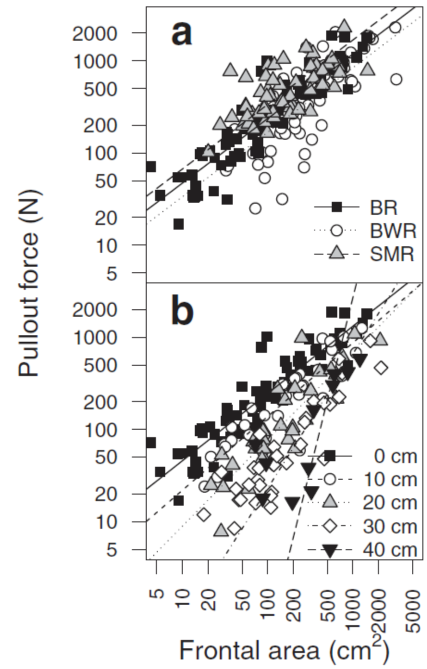


Figure 2. Forces required to pull out vegetation as a function of plant frontal area from Bywater-Reyes et al. (2015).

2.1 Drag Forces on Vegetation

Drag forces on submerged and emergent vegetation have been relatively well characterized (Nepf and Vivoni, 2000; Nepf, 2012), and so are only briefly summarized here. The drag force is typically calculated as

$$F_D = \frac{1}{2}\rho C_D U^2 A_x \qquad (1)$$

where ρ = 1000 kg/m^3 is the density of water, C_D is a drag coefficient, U is the local average flow velocity near the plant, and A_x is the cross sectional area of the plant perpendicular to the flow. The drag coefficient tends to be approximately one ($C_D \approx 1$), although it can vary as a function of plant size (Nepf and Vivoni, 2000; White and Nepf, 2008).

The local flow velocity can be calculated from a 2-D flow simulation. In dense vegetation, the effect of the vegetation on the flow field should be considered (van Rooijen et al., 2018), but for relatively sparse vegetation the influence may be minor. Lightbody and Nepf (2006) proposed a photographic method to estimate A_x for plants in the field, since the effective cross sectional area depends strongly on the stem and leaf structure of the plant, as well as its flexibility in the flow.

2.2. Resisting Forces of Vegetation

Compared to drag forces on a vegetation canopy, less is known about the resisting forces of plant roots to uprooting. Bywater-Reyes et al. (2015) conducted systematic measurements on 1-5 year pioneer saplings (Pupulus and Tamarix) on the Bill Williams River, AZ, the Santa Maria River, AZ, and the Bitterroot River, MT. The study was conducted by pulling on plants with a hand winch and measuring the force at uprooting with a load cell. They measured pullout forces that range from ~20 – 2000 N for relatively small plants with 0.5 – 4 cm stem diameters and rooting depths that ranged from 0.2 – 0.8 m. They found that the best correlate with the pullout force was with the above-ground fontal area of the plant (A_x ; Fig. 2), because the frontal area scales with the size of the root mass. Equating the resisting force to the drag force (Eq. 1), they found that the onset of uprooting in the absence of bed scour would require unrealistically high flow velocities of ~3 – 20 m/s.

Bankhead et al. (2017) conducted a similar study of manually pulling out plants on a river bar on the Platte River, NB. They found that the pullout or root-breaking occurred at 139 $\pm$ 96 N, 58 $\pm$ 31 N, and 255 $\pm$ 151 N for 2-yr old cottonwood saplings, reed canary grass, and Phragmites, respectively (Table 1). Cottonwood had stem diameters typically of 0.05 – 0.5 cm, Phragmites had stem diameters of ~0.3-1.3 cm, and reed canary grass had stem diameters of < 5 mm. They did not report plant frontal area, and so their data cannot be placed on Figure 2.

Bankhead et al. (2017) also used their data to calculate the resistance to uprooting for patches of vegetation using the model RipRoot. This model predicts 2 to 10 fold larger forces (~10^3 - 10^4 N) needed to uproot patches of vegetation as compared to individual plants (Table 1). The model RipRoot is based on the forces required to break a fiber bundle (Pollen and Simon, 2005; Thomas and Pollen-Bankhead, 2010), in which failure occurs by progressive breaking of individual fibers in the bundle. They placed in a flume similar plants as they measured on the Platte River, and found that the driving forces for a 1.5 m/s flow was insufficient to pull out individual plants, and far insufficient to pullout patches of plants (Table 1).

Table 1. Summary of data from Bankhead et al. (2017).

	Maximum forces from 1.5 m/s water flow	Plant pullout/break force measurements	Pullout/break force for veg. patches (calculation)
Cottonwood (2 yr. old)	156 N	139 $\pm$ 96 N	315 N
Reed canary grass	248 N	58 $\pm$ 31 N	4,560 N
Phragmites	218 N	255 $\pm$ 151 N	28,000 N

Another similar study by Pollen-Bankhead et al. (2011) analyzed uprooting resistance of *Sparganium Erectum*, with rooting depths of ~0.5-1 m using the RipRoot model. Individual plant removal forces range from ~50 – 150 N with plant patches estimated to be 10^3- 10^4 N. Drag forces from water flow in their environment of interest are less than 1 N, far too small for uprooting.

2.3. Bed Scour around Vegetation

Given the large resisting forces to uprooting, several studies have concluded that sediment scour into the bed is necessary for plant removal. Scour exposes the roots, decreasing the resisting force while increasing the above-ground area exposed to the flow thereby increasing the driving force (Eq. 1). Several studies have calculated potential scour depths based on formulas established for river scour around bridge piers (Bankhead et al., 2017; Bywater-Reyes et al., 2015). Bridge-pier scour depths, however, scale approximately with the bridge pier diameter (Sheppard and Miller, 2006). Since plant rooting depths tend to be far deeper than the plant stem diameter, local scour due to disturbance of the plant around the flow is unlikely to create a scour hole of any significance (Bankhead et al., 2017; Bywater-Reyes et al., 2015).

Direct force measurements on plants from Bywater-Reyes et al. (2015) showed that uprooting forces can be reduced by a factor of 10 or more given scour depths of tens of centimeters (Fig. 2) – i.e., a significant fraction of the plant rooting depth. In flume experiments, scour has been induced by limiting sediment supply. For example, Edamier et al. (2015) found that 56% of roots (Avena sativa) were exposed prior to uprooting. In an experiment with live cottonwood and tamarisk (2-10 mm stem diameters, 0.5 – 1 m tall), little to no uprooting occurred in a coarse sand bed flume (0.5 mm) at 0.6% slope and a discharge per unit width of 0.32 m^2/s (Kui et al., 2019). However, when the upstream sediment supply was ceased, the bed scoured and 64% of the plants uprooted when planted sparsely and 35% of the plants uprooted when planted in patches (Kui et al., 2019). Plant removal occurred when scour exposed > 20% of the rooting depth. Thus, in Type 2 plant removal by bed scour, not only must there be erosion, but the erosive flows must last for a sufficient duration to scour down to a significant fraction of the rooting depth (Perona and Crouzy, 2018).

Wilcox et al. (2013) analyzed the effect of engineered floods on vegetation removal below a dam on the Bill Williams River, AZ. They found that a significant fraction of 0.5 – 2 m high, 3-20 mm stem diameter willow and tamarisk saplings were removed from river bars after floods. Flood flow velocities were around 0.5-0.8 m/s near the vegetation, and 1.3 m/s in the channel thalweg. Unfortunately they do not quantify bed stress or hydraulic forces. The bed grain sizes in different reaches they analyzed ranged from D_{50} = 0.8 to 2 mm. They attributed the removal of vegetation to river incision in the reach immediately below the dam due to the lack of sediment supply. Repeat field surveys also showed ~ 1m channel elevation changes locally due to bar migration. Farther downstream plant mortality rates also were high, but there they observed deposition and plant burial, rather than scour. Plant damage and mortality from burial also has been noted elsewhere (Polzin and Rood, 2007; Burylo et al., 2012; Kui et al., 2014).

Jourdain et al. (2017) also observed that vegetation was removed during a 5-year flood on a gravel-bed river in the French Alps. Historical imagery showed that vegetation was preferentially removed on the upstream end of bars due to lateral bar migration. Similar observations were made on the Cache la Poudre River, CO, where vegetation removal coincided with active sediment transport (Milhous, 2016). Finally, Caponi & Siviglia (2018) used a model to show a runaway positive feedback: vegetation uprooting occurs when scour reaches some fraction of the root depth, which increases flow velocities locally and causes rapid removal of all neighboring plants.

3. Vegetation Uprooting Analysis in 1969 Breakout Flood Zone

On May 1, 2019, we made observations of vegetation in the 1969 breakout flood zone in the study area of the upper Santa Ana floodplain. Along a 116 m transect (CS_2 on Fig. 4), we photographed and measured the height and approximate width of 21 individual plants, or clusters of grass, with an emphasis on capturing examples of different species and morphologies (Appendix 1; Table 2). Although rooting depths vary with species, depth to groundwater table, and other variables, to first order the resisting force to uprooting scales with above-ground plant area (Bywater-Reyes et al., 2015; Fig. 2). We found that plants in our transect on average had widths and heights of ~0.9 m (Table 2) with relatively dense branching structures as compared to tree saplings analyzed in previous studies. Assuming a triangular shape, we find an approximate area of $A_x = 0.4$ m^2 (or 4000 cm^2 on Fig. 2). These plant areas are near the upper limit of those measured by Bywater-Reyes et al. (2015) suggesting that drag forces of $F_D \approx$ 2000 N would be required for plant uprooting in the absence of bed scour (Fig. 2). Rearranging Eq. (1) for flow velocity, and inserting $F_D \approx$ 2000 N and $A_x = 0.4$ m^2, suggests that the necessary flow velocity for uprooting is $U \approx$ 3.2 m/s.

Future work should conduct a more careful analysis, in line with Bywater-Reyes et al. (2015), for example, to measure plant rooting depths, root biomass, uprooting forces, and quantify plant area exposed to the flow using the method of Lightbody and Nepf (2006). Our estimates here should be seen as approximate. Nonetheless, the analysis is in line with previous work reviewed in Section 2 that large flow velocities are likely necessary to achieve uprooting in the absence of bed scour. We suspect that plant removal due to bar migration and riverbed scour would occur prior to reaching these flow velocities, as was the case in previous studies (Wilcox et al., 2013; Jourdain et al., 2017). Importantly, our flow velocity estimates are for sparse vegetation, which appears to be the case currently in the 1969 breakout zone. However, vegetation is denser in the higher, older surfaces in the study area, and for these areas the RipRoot model for vegetation patches should be used (Pollen and Simon, 2005; Thomas and Pollen-Bankhead, 2010). Based on previous work (e.g., Table 1), accounting for vegetation patches may increase resisting forces by a factor of ten, which would translate into necessary flow velocities that would be unrealistic ($U \approx$ 10 m/s).

Table 2. Observations of plant sizes within the 1969 breakout zone, cross section CS_2 (Fig. 4)

Plant	Height (cm)	Width (cm)	Transect location (m)
1	70	120	-1
2	35	5	1
3	100	30	10
4	70	70	12
5	100	110	19
6	60	60	38
7	150	250	44.5
8	80	90	46
9	150	Cluster	52
10	100	50	63
11	110	180	67
12	110	110	71
13	120	Cluster	74
14	20	Cluster	75.5
15	100	55	81
16	60	80	91
17	70	80	94
18	60	140	98
19	100	60	109
20	80	80	116
21	150	Cluster	Edge of water

4. Sediment Transport Analysis in Santa Ana River

The preceding literature review and our preliminary field analysis makes clear that removing plants by direct uprooting or breaking roots is difficult to achieve in the absence of bed scour. Plant roots are strong compared to typical hydraulic drag forces – even for small plants and saplings. Instead, vegetation removal is most likely to occur through river bed scour when scour depths are a large fraction of the rooting depth. To remove vegetation by bed scour in a braided river like the Santa Ana, a designed flood should develop bars and cause them to migrate laterally or downstream. Migrating bars create local scour due to the migration of their associated pools. If the bar-pool forms are of sufficient relief so that they expose a significant fraction of the root depth, plant removal is likely to occur.

4.1. Field observations

On May 1, 2019, we made observations of bar morphology, plant stability and conducted Wolman-style pebble counts along two cross-section transects in the 1969 breakout channel (CS_1 & CS_2; Fig. 4) and one across the currently active channel (CS_3). In addition, on May 22, 2019, we surveyed three additional cross sections further downstream in or near the active channel belt in sites of interest to the high flow study team (CS_4, CS_5 and CS_6; Fig. 4). CS_5 is located in an area that is more densely vegetated and is largely abandoned by active

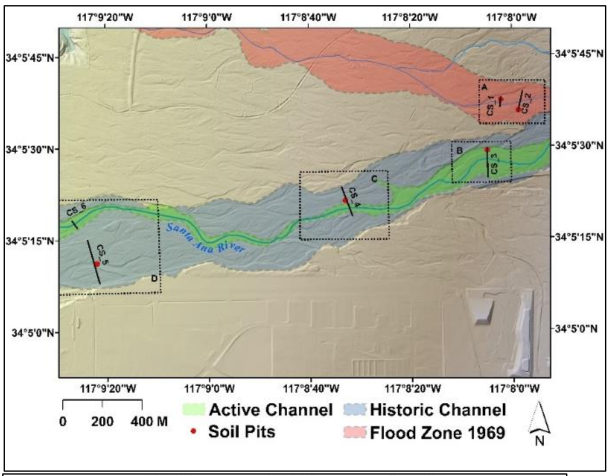
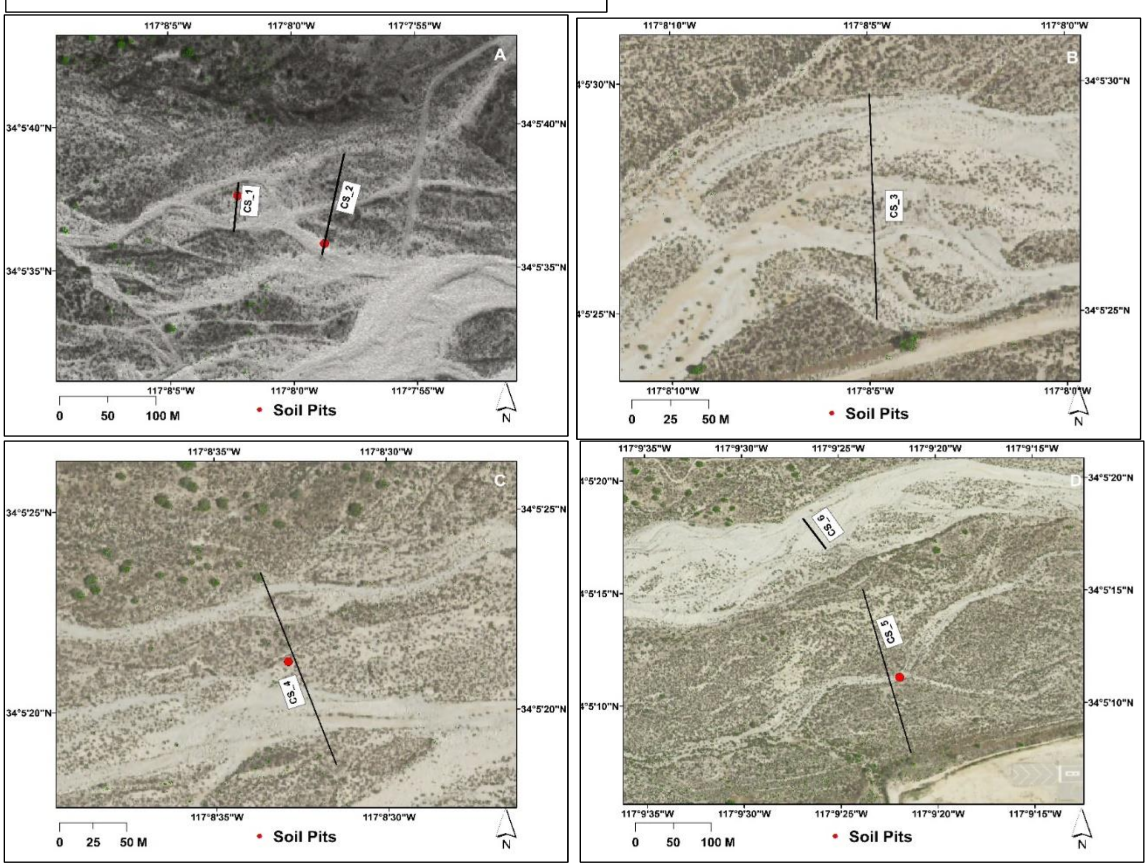


Figure 4: Overview map of study area with cross section and soil pit locations indicated. Transects CS_1 & CS_2 mapped over aerial image from 1970 showing the scoured areas from the 1969 flood. Transect CS_3, CS_4, CS_5 and CS_6 are mapped over aerial image from 2016. Aerial images acquired from USGS National Map Viewer historical photos archive.



flows except for a small channel that receives some flow during floods. Grainsize of a single particle was measured every 1 m along a transect perpendicular to main flow direction (Appendix 2). Sand sizes were assessed visually with a sand card and the intermediate diameter of coarser particles were measured directly with a ruler. Sandy substrates on older surfaces were generally coarser in the top few grain layers, likely due to winnowing of fines by wind, and therefore we made measurements a few centimeters below the land surface.

The location of CS_3 was chosen specifically because it was relatively devoid of vegetation and appeared to have active sediment transport and bar migration during the 2018-2019 winter-flood season. Of the little vegetation that remained in at CS_3, most of it was partially buried or partially undercut and damaged due to cobble impacts (Fig. 5). Significant amounts of vegetation also were uprooted and deposited as a lag at high-water levels. Our observations are similar further downstream in the active channel belt at CS_4 and CS_6. In addition, the small active channel in CS_5 appeared to have been active during the 2018/2019 season including active sediment transport, bar migration and vegetation removal (Fig. 5). Thus, the active channel, the channel thread that goes through CS_5, and the winter floods of 2018-2019 are important points of comparison for designing floods. The 2018/2019 floods at these locations produced sufficient bed stresses to transport significant quantities of bed sediment, remove vegetation, and thus created a disturbed floodway that is similar to the desired outcomes of the engineered floods, and similar to what occurred in the1969 breakout zone (Fig. 4) that produced desirable habitat.

Grain size distributions are similar between the 1969 breakout zone (CS_1 & CS_2) and the neighboring active channel (CS_3) (Fig. 6). Grain size distributions also are similar at the two downstream locations in the active channel belt (CS_4 and CS_6), and on the mostly abandoned surface at CS_5. All distributions are bi-modal, with the majority of sediment being

Figure 5. Observations of scoured and damaged vegetation from 2018-2019 floods along transect CS_3 (top) and CS_5 (bottom).

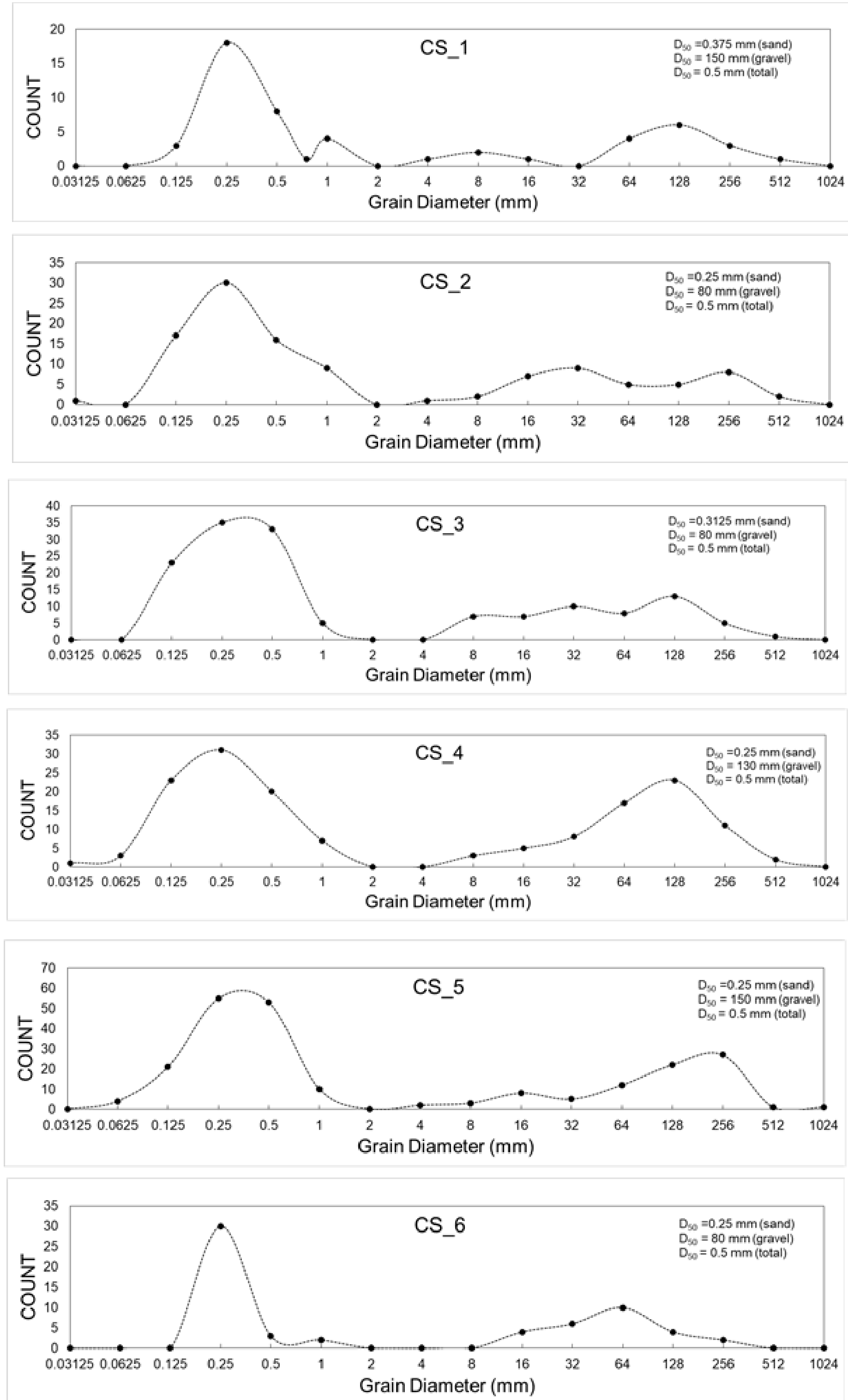


Figure 6. Grain size distributions from our 6 transects (see Fig. 4 for location) based on a Wolman pebble count. Data were binned and plotted according to the lower bin boundary to be comparable to sieve measurements. Sand sizes were estimated visually with a sand card, and coarser particles were measured with a ruler. Median sizes (D_{50}) are reported for the sand mode, the gravel model, and all sediment combined (total).

sand sized and with less abundant, but still significant population of gravel, cobbles and boulders. The median size of the sand fraction is typically medium sand ($0.25 < D_{50} < 0.5$ mm), and the median size of the coarser mode ranges from $D_{50} = 80 – 150$ mm (Fig. 6).

Our transects crossed multiple braid bars and channel threads, as shown by lidar-extracted topographic profiles along our transects (Fig. 7). Some bars were active and devoid of vegetation, whereas others were vegetated and appeared to be inactive recently. At all cross sections, inactive bar tops and sides tended to have a higher abundance of cobbles, whereas channel bottoms and active bars tended to be sandy with sparse patches of mobile, imbricated gravel and cobbles. For example, there is a large, active sand bar on the river-right portion of CS_3. Bar-pool relief is in the range of ~1 m (Fig. 7). All active channel belts are inset by > 2 meters, bounded by higher, older terraces with more dense vegetation. Observations of bank sediment in the terrace risers show that they are coarse grained compared to the channel bed, and

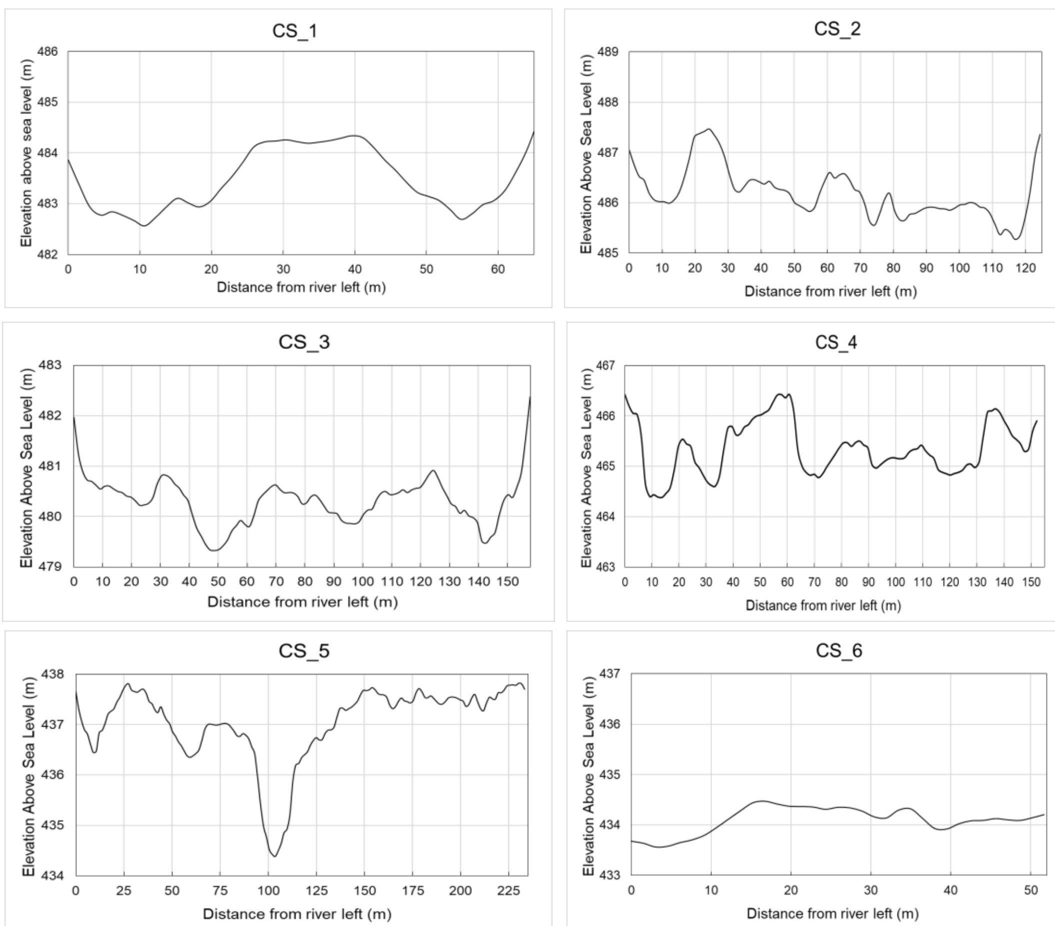


Figure 7. Topographic profiles extracted from lidar along the grainsize transects (See Fig. 4 for location). The coordinates at the start and end points of the cross sections are: (A) Cross section 1: Start (34.09342 N, 117.13400 W), End (34.09390 N, 117.13394 W). (B) Cross section 2: Start (34.09319 N , 117.13301 W), End (34.09417 N, 117.13275 W). (C) Cross section 3: Start (34.09023 N, 117.13471 W), End (34.0916 N, 117.13471 W). (D) Cross section 4: Start (34.08986 N, 117.14268 W), End (34.08851 N, 117.14208 W). (E) Cross section 5: Start (34.08753 N, 117.15661 N), End (34.08551 N, 117.15594 W). (F) Cross section 6: Start (34.08803 N, 117.15713 W), End (34.08841 N, 117.15746 W). Topographic lidar data from the USGS National Map Viewer.

often poorly sorted and matrix supported indicating likely debris flow deposits. These older debris flow deposits might be a main source of cobbles and boulders to the modern system.

At five of the more sandy locations along the transects we excavated ~0.5 m deep pits with a shovel to verify if the sand layer was thick, or whether it was a thin cover on top of a cobble substrate. The vertical profiles of sediment sizes from these pits are shown in Figure 8. Sand beds were generally about 0.5 m thick, sometimes with thin lenses of pebbles or cobbles (pit at CS_1), and often with cobbles at their base. In one case (CS_3), we found a buried soil horizon with root mats and buried plant stems at 0.55 m depth, suggesting significant recent local bed aggradation, likely due to bar migration.

To verify our visual estimates of sand sizes using a sand card, we took two samples of sand from soil pits at CS_4 and CS_5 and analyzed that sediment using a Camsizer Instrument, which optically measures hundreds of thousands of grains in a sample. Figure 9 shows these grain size distributions, and verify our visual estimates.

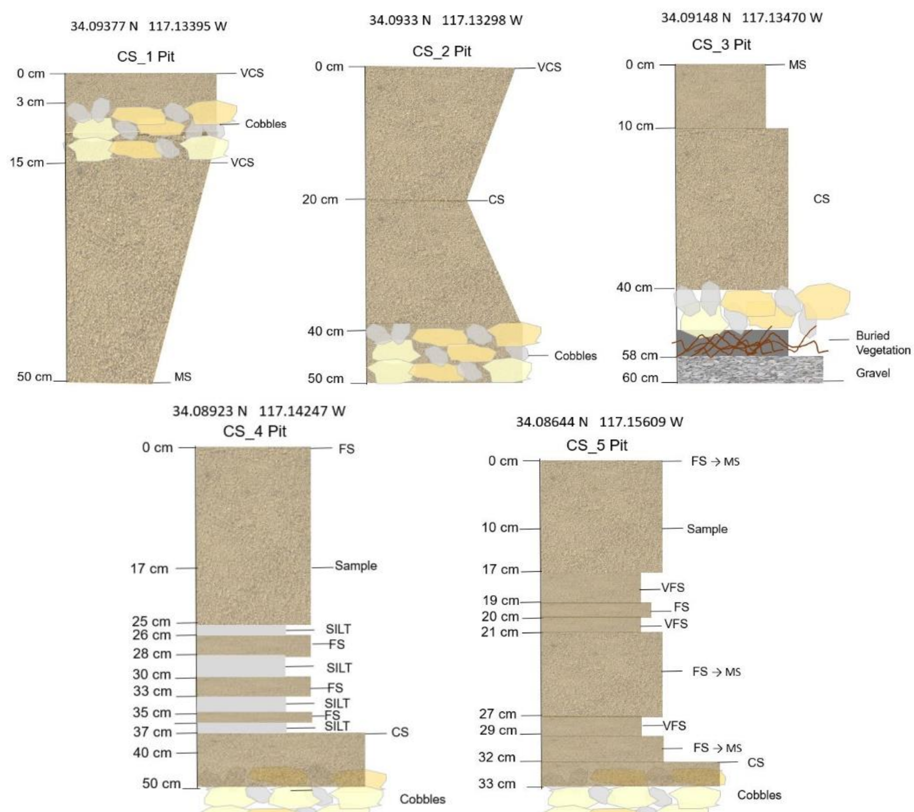


Figure 8. Sediment layers observed in pits dug at certain points along transects CS_1, CS_2, CS_3, CS_4, and CS_5. The coordinates of each pit are given at the top of the graphics, and are also shown as red dots on Fig. 4.The side walls of pits CS_4 and CS_5 were sampled at the locations indicated by “Sample” for grainsize analysis with the Camsizer (see Figure 9).

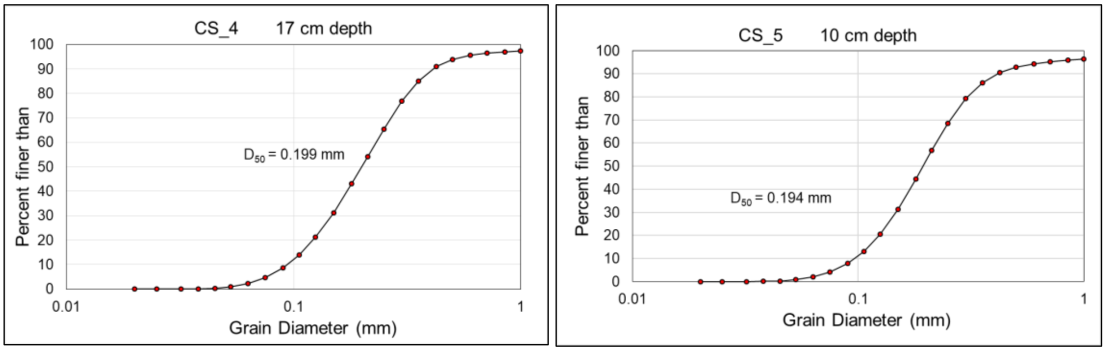


Figure 9. Cumulative particle size distributions for sand samples measured by the Camsizer Instrument. Samples were taken at 17 cm depth from the pit along transect CS_4 (Fig. 4 & 8) and at 10 cm depth in the pit along transect CS_5 (Fig. 4 & 8).

4.2. Threshold for sediment transport and bar development

Bars form when there is bedload transport and a large channel width-to-depth ratio (Parker, 1976). The criteria for transport is often assessed using a Shields number (Buffington and Montgomery, 1997)

$$\tau_* = \frac{\tau_b}{(\rho_s - \rho) g D_{50}} \qquad (2)$$

where τ_b is the shear stress on the bed from the flow, ρ_s is the sediment density, ρ is the water density, g is the acceleration due to gravity and D_{50} is the median bed grain size. The critical Shields number for initial sediment motion (τ_{*c}) has been found empirically to be about 0.03 for sand and 0.045 for gravel, and it increases from these values for river gradients greater than ~1% (Lamb et al., 2008). However, bed stresses greater than the threshold of motion are needed to move a substantial amount of sediment and form and migrate bars. A large compilation of alluvial rivers shows that the Shields number during bankfull flood conditions (when bars form and move), τ_{*bf}, is typically $1 < \tau_{*bf} < 10$ for rivers with medium sand beds and $0.05 < \tau_{*bf} < 0.1$ for cobble beds (Trampush et al., 2014).

Given these bounds on Shields number and measurements of D_{50}, Eq. (2) can be rearranged to solve for τ_b, which can then be compared to designed flood scenarios. Despite the common occurrence of beds with strongly bimodal size distributions (Lamb and Venditti, 2016), there is not a well-established framework to calculate bankfull Shields numbers for these cases. Instead we calculate shear stresses for the sand patches and cobble patches separately. For sand patches, we find that stresses during floods should be in the range of 6 – 60 Pa, whereas mobilizing cobble patches require stresses 90 - 190 Pa (Table 3). Given a typical channel-bed gradient in the study reach of ~2%, these shear stresses likely require flow depths of ~1 m, consistent with our observations of the relief of active bars (Fig. 7). A 2-D model that accounts for non-uniform flow should be used to better estimate the depths and discharges necessary to achieve these bed stresses.

Table 3: Calculation of bed stresses necessary for bar formation and migration for the sand and cobble patches using Eq. (2).

	Grain size, D_{50} (mm)	Bankfull Shields number, τ_{*bf}	Bed stress, τ_b (Pa)
Sand	0.375	1 - 10	6 - 60
Cobbles	115	0.05 – 0.1	90 - 190

4.3 Expected bar height and scour depths

Bars typically grow to a height that is a large fraction of the flow depth during bankfull conditions. Flood flow depth that will be required to achieve the necessary Shields numbers in the Santa Ana River are likely to be ~1 m. Thus, we can likely expect bars (and scour depths) of meter height. These estimates are consistent with our observations of bar relief in the active channel and the 1969 breakout zone of bar heights of ~1 m (Fig. 7). Bar heights are similar to the expected plant rooting depths, given plants are typically ~1 m tall. Thus, bars should be capable of undermining vegetation, which appears to have happened during recent winter floods (Fig. 5).

4.4. Bar mobility

Flood flows will need to have a long enough duration to cause significant bar mobility. The timescale for a bar to shift downstream by its wavelength can be estimated from mass balance as

$$T_b = \frac{H_b L_b}{q_b} \qquad (3)$$

where H_b is bar height, L_b is bar length, and q_b is the volumetric sediment transport capacity per unit width. The bedload sediment transport capacity can be estimated from (Luque et al., 1976)

$$q_b = 5.7\left(\frac{\rho_s - \rho}{\rho} g D_{50}^3\right)^{0.5} \left(\tau_{*bf} - \tau_{*c}\right)^{1.5} \quad (4)$$

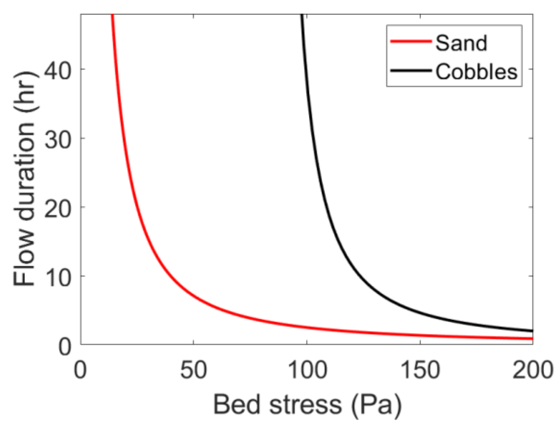


Figure 10. Flow duration and bed stress combinations necessary for bar migration of 100 m using Eq (3) and (4).

As an example calculation, assuming H_b = 1 m, L_b = 100 m, D_{50} = 115 mm, the flood would need to persist for hours to tens of hours, depending on the bed stress, to achieve meaningful amounts of bar migration (Fig. 10). For example, floods with bed stresses of ~125 Pa that persisted for ~10 hrs would cause significant migration of both sand and gravel bars.

Equation (4) does not account for the binding effect that plant roots have on stabilizing sediment (Pasquale and Perona, 2014; Lightbody et al., 2019). In densely vegetated areas, flood durations may need to be significantly longer than indicated in Figure 10 due to reduced sediment fluxes until plants begin to be removed. Once some plant removal occurs, further sediment transport and plant removal is expected to occur rapidly (Caponi & Siviglia, 2018).

5. Summary and Recommendations for Future Work

- Uprooting is difficult, and most likely happens by undermining or burying plants through bar migration.
- Bar migration likely requires bed stresses of 6 - 60 Pa to form and mobilize sand bars, and 90 -190 Pa to form and mobilize cobble bars. These floods would need to persist for hours to tens of hours, depending on the bed stress, to achieve significant bar migration and plant removal. An ideal condition for both sand and cobble bars would be bed stresses of ~125 Pa that persisted for ~ 10 hours. For a given discharge, bed stresses are a function of channel width and slope and 2-D models are needed to assess whether these bed stresses can be achieved by the designed floods.
- Due to the bimodal sediment size distribution, calculated bed stresses needed to produce the desired channel disturbances are uncertain. These should be cross checked through analysis of historical events that produced the desired channel change. For example, the active channel belt appears to have migrated bars and removed and buried vegetation during the 2018/2019 floods. Bed stresses for these events could be constrained using a 2-D model flood model combined with a water routing model to estimate the discharge on the ungauged Mill Creek, which is the biggest contributor to the study area below Seven Oaks Dam.
- The current flood regime appears to be capable of creating the desired disturbances (vegetation removal, bar migration, sand deposition) in the active channel belt that are favorable for SBKR habitat. However, a major problem is that the active channel-belt is flooded too often to develop favorable habitat, whereas the neighboring terrain is not flooded often enough. One solution that would not require a contribution from Seven Oaks Dam would be to divert the entire river away from the currently active channel belt. This would allow the then-abandoned channel-belt to be colonized by SBKR. At the same time, the new flood pathway would likely scour vegetation, migrate bars and deposit sand. In 30 years the flood routing could be shifted again, allowing colonization again of the once active channel belt. These ideas are described in detail, along with a quantitative framework to evaluate the benefits of different flood scenarios, in a presentation included as Appendix 3: *The optimal flooded area hypothesis*.
- There is some risk that high flows without sediment supply from Seven Oaks Dam will cause channel incision. While channel incision will aid in vegetation removal, it may cause narrowing of the active channel belt and further isolate the neighboring terrain, such as the 1969 breakout area, from flood disturbance. The reduced width of the active channel belt would reduce the diversity of flooded terrain, habitat, and timescales of flood disturbance within the channel belt.

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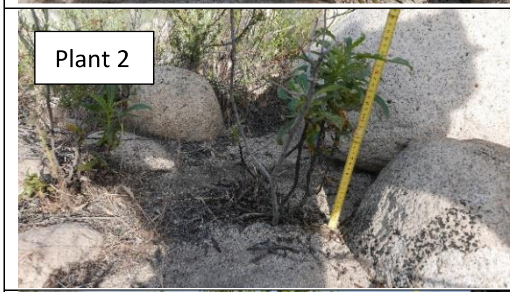
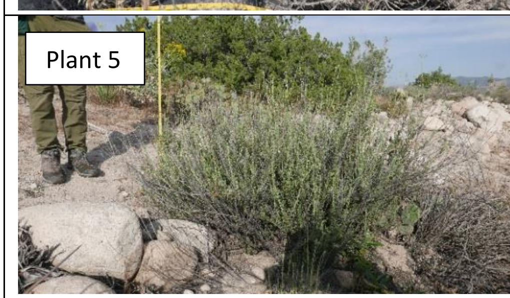
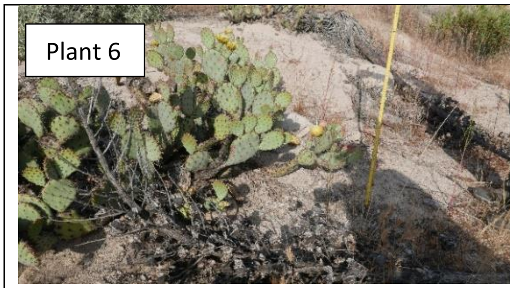
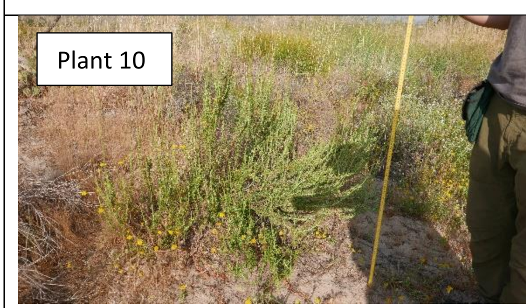
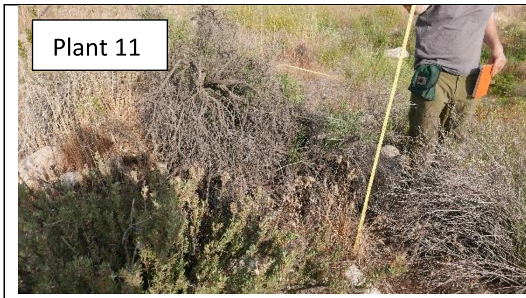
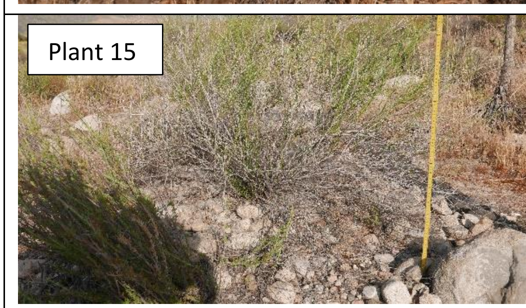
Whiting, P.J., 2002, Streamflow Necessary for Environmental Maintenance: Annual Review of Earth and Planetary Sciences, v. 30, p. 181–206, doi:10.1146/annurev.earth.30.083001.161748.

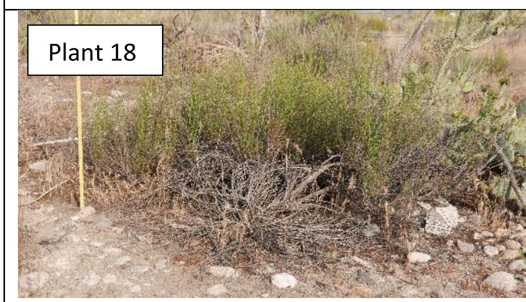
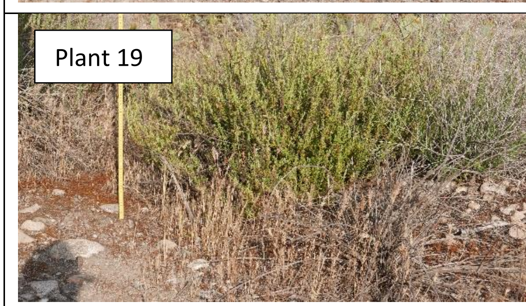
Wilcox, A.C., and Shafroth, P.B., 2013, Coupled hydrogeomorphic and woody-seedling responses to controlled flood releases in a dryland river: Water Resources Research, v. 49, p. 2843–2860, doi:10.1002/wrcr.20256.

Appendix 1 – Photographs of plants reported in Table 2 from Cross section CS_2 (Figure 4).

	Height = 70cm Width= 120cm Position = -1 meter along CS_2 transect
	Height= 35cm Width = 5cm Position = 1 meter
	Height= 100cm Width= 30cm Position= 10 meters
	Height= 70cm Width=70cm Position= 12 meters
	Height= 100cm Width= 110cm Position= 19 meters

	Height= 60cm Width= 60cm Position= 38 meters
	Height=150cm Width=250cm Position=44.5 meters
	Height=80cm Width=90cm Position=46 meters
	Height= 150cm Width= Cluster of grasses; 2mm wide stalks in a cluster of 50 stalks. Position=52 meters
	Height= 100cm Width=50cm Position=63 meters

	Height= 110cm Width= 180cm Position= 67 meters
	Height= 110cm Width= 110cm Position= 71 meters
	Height= 120 Width= 4 mm clusters in a cluster of 9 stalks Position= 74 meters
	Height= 20 cm Width= 1 mm stalks in a cluster of 30 stalks Position= 75.5 meters
	Height= 100 cm Width= 55 cm Position= 81 meters

	Height= 60 cm Width= 80 cm Position= 91 meters
	Height= 70 cm Width= 80 cm Position= 94 meters
	Height= 60 cm Width= 140 cm Position= 98 meters
	Height= 100 cm Width= 60 cm Position= 109 meters
	Height= 80cm Width= 80 cm Position= 116 meters

	Height= 150cm Width= 4 mm stalks in a cluster of 9 stalks Position= Edge of active channel

Appendix 2 – Data from Woman pebble count transects that is reported in Figure 6. Cross section locations are shown on Figure. 4.

Silt/Sand	Diameter range (cm)
SILT	0.003125 – 0.00625
VFS (very fine sand)	0.00625 – 0.0125
FS (fine sand)	0.0125 – 0.025
MS (medium sand)	0.025 – 0.05
MS→CS (medium to coarse sand)	≈0.0375 (binned with MS in plots)
CS (coarse sand)	0.05 - 0.1
VCS (very coarse sand)	0.1 – 0.2

APPENDIX 2: Grain size data; cross section 1		
Transect Distance	$D_{x\ (cm)}$	Comments
1	58	34.09342 N 117.13400 W. Edge of a small ridge in the 1969 breakout flood zone, ~3 meters relief. Meter spacing measured with tape
2	20	Begin trough, possibly a relict channel from 1969 flood
3	33	Relict channel trough
4	MS→VC	Relict channel trough
5	1	BSC on surface, Relict channel trough
6	MS	Relict channel trough
7	15	Relict channel trough, ≈ location of soil along cross section. 34.09346 N 117.13398 W
8	25	Relict channel trough
9	CS	Relict channel trough
10	CS	BSC on surface, Relict channel trough
11	30	Relict channel trough
12	VC	Relict channel trough
13	MS	Approximate end of relict channel trough
14	FS	
15	MS→CS	
16	MS→CS	
17	CS	
18	MS→CS	
19	VCS	3-4 cm gravel included in sand
20	20	
21	MS	
22	FS	Very coarse sand on surface
23	0.5	
24	40	
25	CS	
26	MS→CS	
27	CS	
28	VCS	
29	8	
30	MS→CS	
31	13	
32	MS	
33	23	
34	MS	
35	FS	
36	COVERED	
37	MS	

38	MS	
39	MS	
40	MS	
41	CS→VCS	Approximate location of soil pit, 34.09377 N 117.13395 W
42	MS	
43	12	
44	7	
45	CS	
46	10	
47	MS	
48	3	
49	CS	
50	VCS	
51	MS	
52	COVERED	
53	COVERED	
54	EDGE	Small steam 34.09390 N 117.13394 W

APPENDIX 2: Grain size data, cross section 2		
Transect Distance	**$D_{x\ (cm)}$**	**Comments**
2	VCS	Marker 243. Ridge, approximately 2 meters of relief. Meter spacing measure with tape.
3	45	
4	FS	
5	50	
6	75	swale begins
7	MS	Swale
8	MS→CS	Swale
9	CS	Swale
10	CS	Swale
11	VCS	Swale
12	40	Swale
13	MS→CS	Swale, approximate location of soil pit along cross section 34.0933 N 117.13298 W
14	VCS	Swale
15	CS	Swale
16	CS	Swale
17	CS	Swale
18	VCS	Swale
19	CS	Swale
20	CS	swale ends
21	23	
22	CS	
23	VCS	Elevated, ridge like topography. Poorly sorted sands
24	VCS	Poorly sorted sands
25	MS	Poorly sorted sands
26	MS	Poorly sorted sands
27	FS	
28	FS	
29	CS	
30	13	
31	FS	Biological soil crust on surface
32	25	
33	CS	

34	CS	
35	FS	
36	MS	
37	MS	
38	MS	
39	VCS	
40	VCS	Very coarse sand mixed with 1-2 cm pebbles
41	MS	
42	MS	
43	FS	
44	55	
45	40	
46	FS	
47	MS	
48	8	
49	10	
50	MS	
51	FS	
52	CS	
53	CS	
54	CS	
55	CS	
56	COVERED	
57	COVERED	
58	MS	
59	MS	
60	MS	
61	MS→CS	
62	MS	
63	FS	
64	FS	
65	FS	
66	VCS	
67	5	
68	5	
69	6	
70	2	
71	2	
72	30	
73	25	
74	30	
75	SILT	
76	MS	
77	MS	
78	MS	
79	2.5	
80	27	
81	5	
82	15	
83	FS	
84	34	
85	MS	
86	FS→MS	
87	MS	
88	MS	
89	1	
90	MS	
91	3	

92	MS	
93	MS	
94	1	
95	FS	
96	CS	
97	3	
98	10	
99	8	
100	FS	
101	4	
102	4	
103	MS	
104	2	
105	MS	
106	FS	
107	FS	
108	6	
109	6	
110	MS	
111	12	
112	5	
113	MS	
114	2	
115	WATER	34.09417 N 117.13275 W.The edge of CS_2 is the same creek encountered to end CS_1

APPENDIX 2: Grain size data, cross section 3		
Transect Distance	**$D_{x\ (cm)}$**	**Comments**
1	FS	Starting point is heavily vegetated, appears to be a debris flow deposit. Boulders up to 75 cm in diameter in a sandy matrix. ≈ Meter spacing by pace. 34.09023 N 117.16467 W
2	23	
3	8	
4	12	
5	25	
6	FS	
7	4	
8	FS	
9	FS	
10	FS	
11	FS	
12	FS	
13	18	
14	24	
15	FS	
16	FS	
17	FS	
18	FS	
19	FS	
20	FS	
21	FS	
22	7	
23	14	
24	FS	

25	FS	
26	6	
27	12	
28	50	
29	12	
30	FS	
31	FS	
32	FS	
33	FS	
34	30	
35	CS	
36	1	
37	0.8	
38	2.4	
39	VCS	
40	CS	
41	1.5	
42	0.8	
43	CS	
44	VCS	
45	2.3	
46	5.5	
47	19	
48	MS	
49	MS	
50	MS	
51	CS	
52	1	
53	3.5	
54	15	
55	2	
56	3	
57	4	
58	2.8	
59	2.9	
60	CS	
61	CS	
62	CS	
63	4	
64	6	
65	6.2	
66	8	
67	20	
68	MS	
69	17	
70	11	
71	MS	
72	5.3	
73	MS	
74	FS	
75	4.5	
76	VCS	
77	CS	
78	CS	
79	9	
80	15	
81	MS	
82	1	
83	MS→CS	

84	VCS	
85	MS	
86	25	
87	MS	
88	MS	
89	MS	
90	CS	
91	VCS	
92	CS	
93	MS	
94	MS	
95	CS	Begin mid channel bar, un-vegetated
96	CS	Mid channel bar
97	CS	Mid channel bar
98	CS	Mid channel bar
99	CS	Mid channel bar
100	CS	Mid channel bar
101	CS	Mid channel bar
102	CS	Mid channel bar
103	CS	Mid channel bar
104	CS	Mid channel bar
105	CS	Mid channel bar
106	CS	Mid channel bar
107	CS	Mid channel bar
108	CS	Mid channel bar
109	MS→CS	Mid channel bar
110	CS	Mid channel bar
111	CS	Mid channel bar
112	CS	Mid channel bar
113	CS	Mid channel bar
114	CS	Mid channel bar
115	CS	Mid channel bar
116	MS	Mid channel bar
117	MS	Mid channel bar
118	MS	Mid channel bar
119	CS	Mid channel bar
120	MS	Mid channel bar
121	2.5	Seasonally active channel
122	1.2	Seasonally active channel
123	28	Seasonally active channel
124	18	Seasonally active channel
125	42	Seasonally active channel
126	22	Seasonally active channel
127	MS	Seasonally active channel
128	MS	Seasonally active channel
129	55	Seasonally active channel
130	MS→CS	River right thalweg
131	FS	River right thalweg
132	FS	River right thalweg
133	MS→CS	River right thalweg
134	MS	Seasonally active channel
135	MS→CS	Seasonally active channel
136	MS→CS	Seasonally active channel
137	MS→CS	Seasonally active channel
138	MS→CS	Seasonally active channel
139	MS	Seasonally active channel
140	CS	Seasonally active channel
141	MS→CS	Seasonally active channel
142	MS	Seasonally active channel

143	MS	Seasonally active channel
144	MS	Seasonally active channel
145	MS→CS	Seasonally active channel
146	30	Seasonally active channel
147	MS	Seasonally active channel
148	MS	Seasonally active channel
149	CS	Seasonally active channel
150	FS	Seasonally active channel
151	MS	Seasonally active channel
152	EDGE	End of cross section, end of active channel. 34.09160 N 117.13471 W

APPENDIX 2: Grain size data, cross section 4

Transect Distance	D_x (cm)	Comments
0	CS	Starting on river right, moving to river left. Starting on an approximately 2 meter high terrace. Meter spacing by pace. 34.08986 N 117.14268 W
1	CS	
2	16	
3	21	
4	10	
5	42	
6	MS	
7	6	
8	12	
9	CS	
10	16	
11	40	
12	MS	Medium sand in an active side channel
13	MS	
14	MS	
15	12	
16	2.5	
17	4	
18	2.5	
19	VCS	
20	2.5	
21	CS	
22	MS	
23	MS	Start of approximately 1 meter high vegetated island bar.
24	MS	
25	CS	
26	MS	
27	MS	
28	17	
29	MS	
30	MS	
31	20	
32	MS	
33	MS	
34	5	
35	10	

36	VFS	
37	15	
38	30	
39	50	
40	80	
41	MS	
42	20	
43	8	
44	20	Ridge like form in the middle of the vegetated island bar.
45	15	Island bar
46	8	Island bar
47	30	Island bar
48	MS	Island bar
49	CS	Island bar
50	15	Island bar
51	CS	Island bar
52	21	Island bar
53	FS	Island bar
54	MS	Island bar
55	20	Island bar
56	5	Island bar
57	20	Island bar
58	FS	Island bar
59	MS	Island bar
60	FS	Island bar
61	VCS	Island bar
62	5	Island bar
63	MS	Island bar
64	13	Island bar
65	4	Island bar
66	10	Island bar
67	VCS	End of island bar.
68	1	Seasonally active channel
69	15	Seasonally active channel
70	VFS	Seasonally active channel
71	VFS	Seasonally active channel
72	FS	Seasonally active channel
73	FS	Seasonally active channel
74	FS	Seasonally active channel
75	FS	Seasonally active channel
76	FS	Seasonally active channel
77	FS	Seasonally active channel
78	FS	Seasonally active channel
79	FS	Seasonally active channel
80	FS	Seasonally active channel
81	FS	Seasonally active channel
82	FS	Seasonally active channel
83	FS	Seasonally active channel
84	100	Seasonally active channel
85	FS	Seasonally active channel
86	FS	Seasonally active channel
87	FS	Seasonally active channel
88	MS	Seasonally active channel
89	FS	Seasonally active channel
90	FS	Seasonally active channel
91	FS	Seasonally active channel
92	FS	Seasonally active channel
93	10	Seasonally active channel

94	6	
95	CS	
96	CS	
97	1.5	
98	2	
99	VCS	
100	10	
101	MS	
102	6	
103	CS	
104	MS	
105	42	
106	2.5	
107	MS	
108	MS	
109	13	
110	34	
111	CS	
112	CS	Active channel, with estimated discharge of 150 cfs. Water released from dam. 34.08889 N 117.14243 W. This portion of the cross section was conducted in the part of the actively flowing channel that was safest for crossing. Flow depth of ≈ 55 cm
113	silt	Active Channel, 150 cfs
114	7	Active Channel, 150 cfs
115	16	Active Channel, 150 cfs
116	10	Active Channel, 150 cfs
117	13	Active Channel, 150 cfs
118	1	Active Channel, 150 cfs
119	30	Active Channel, 150 cfs
120	15	Active Channel, 150 cfs
121	40	Active Channel, 150 cfs
122	15	Active Channel, 150 cfs
123	12	Active Channel, 150 cfs
124	VCS	Active Channel, 150 cfs
125	12	Active Channel, 150 cfs
126	7	
127	11	
128	CS	
129	MS	
130	30	
131	MS	
132	MS	
133	CS	
134	CS	
135	VCS	
136	MS	
137	CS	
138	CS	
139	VCS	
140	CS	
141	FS	
142	MS	
143	18	
144	20	
145	21	
146	CS	
147	CS	

148	30	
149	MS	
150	MS	
151	MS	
152	10	
153	7	34.08851 N 117.14208 W

APPENDIX 2: Grain size data, cross section 5		
Transect Distance	**$D_{x\ (cm)}$**	**Comments**
0	MS	Start of cross section is on the edge of a moderately vegetated terrace, 3-4 meters above seasonally active channel. Cross section done by ≈ meter pace. Started on river right moving to river left. 34.08753 N 117.15661 N
1	20	
2	MS	
3	VCS	
4	CS	
5	MS	
6	CS	
7	23	
8	CS	
9	30	
10	MS	
11	MS	
12	5	
13	MS	
14	35	
15	50	
16	CS	
17	CS	
18	CS	
19	MS	
20	CS	
21	MS	
22	20	
23	15	
24	15	
25	VCS	
26	VCS	
27	CS	
28	CS	
29	CS	
30	CS	
31	CS	
32	CS	
33	CS	
34	CS	

35	CS	
36	CS	
37	0.5	
38	CS	
39	CS	
40	50	
41	3	
42	MS	
43	MS	
44	MS	
45	MS	
46	CS	
47	CS	
48	CS	
49	CS	
50	30	
51	VCS	
52	CS	
53	CS	
54	MS	
55	MS→CS	
56	15	
57	CS	
58	CS	
59	CS	
60	10	
61	MS	
62	MS→CS	
63	MS	
64	25	
65	MS	
66	CS	
67	MS→CS	
68	30	
69	FS	
70	FS	
71	VCS	
72	CS	
73	CS	
74	MS	
75	MS	
76	MS	
77	30	
78	MS→CS	
79	MS	
80	50	
81	40	
82	140	
83	7	

84	37	
85	CS	
86	MS	
87	VCS	
88	CS	
89	60	
90	MS	
91	CS	
92	MS	
93	30	
94	FS	
95	FS	
96	25	
97	25	
98	CS	
99	FS	
100	FS	
101	35	
102	FS	
103	FS	
104	FS	
105	FS	
106	CS	
107	MS→CS	
108	10	
109	35	
110	VCS	
111	15	
112	15	Start of seasonally active channel
113	VFS	Seasonally active channel
114	VFS	Seasonally active channel
115	CS	Seasonally active channel
116	MS	Seasonally active channel
117	MS	Seasonally active channel
118	FS	Seasonally active channel
119	FS	Seasonally active channel
120	MS	Seasonally active channel
121	FS	Seasonally active channel
122	2	Seasonally active channel
123	MS	Seasonally active channel
124	FS	Seasonally active channel
125	VCS	Seasonally active channel
126	30	Seasonally active channel
127	28	Seasonally active channel, approximate pace location of soil pit and sediment sample. 34.08644 N 117.15609 W
128	5	Seasonally active channel
129	MS	Top of a bank, vegetated terrace
130	MS	Vegetated terrace
131	MS	Vegetated terrace

132	MS	Vegetated terrace
133	MS	Vegetated terrace
134	MS	Vegetated terrace
135	MS	Vegetated terrace
136	MS	Vegetated terrace
137	FS	Vegetated terrace
138	FS	Vegetated terrace
139	FS	Vegetated terrace
140	10	Vegetated terrace
141	MS	Vegetated terrace
142	CS	Vegetated terrace
143	3	Vegetated terrace
144	MS→CS	Vegetated terrace
145	MS	Vegetated terrace
146	MS	Vegetated terrace
147	10	Vegetated terrace
148	VCS	Vegetated terrace
149	28	Vegetated terrace
150	30	Vegetated terrace
151	CS	Vegetated terrace
152	MS→CS	Vegetated terrace
153	CS	Vegetated terrace
154	16	
155	VFS	
156	15	
157	CS	
158	CS	
159	CS	
160	15	
161	MS→CS	
162	1	
163	1	
164	15	
165	VFS	
166	CS	
167	12	
168	CS	
169	CS	
170	25	
171	CS	
172	CS	
173	25	
174	30	
175	30	
176	MS	
177	MS	
178	CS	
179	MS	
180	30	

181	CS	
182	50	
183	MS	
184	2	
185	MS	
186	MS	
187	MS	
188	30	
189	32	
190	18	
191	40	
192	8	
193	45	
194	14	
195	43	
196	25	
197	2	
198	1.5	
199	0.5	
200	8	
201	4	
202	CS	
203	14	
204	VCS	
205	10	
206	2	
207	2	
208	2	
209	14	
210	4	
211	6	
212	FS	
213	8	
214	FS	
215	CS	
216	MS	
217	MS	
218	FS	
219	FS	
220	8	
221	4	
222	10	
223	CS	
224	30	End of cross section is a fence at the base of a ≈6-7 meter tall berm. 34.08551 N 117.15594 W

APPENDIX 2: Grain size data, cross section 6

Transect Distance	$D_{x\ (cm)}$	Comments
0	MS	Un-vegetated active channel, ≈ meter pace. Moving from river left to river right approaching 150 cfs active channel. Starting on a ≈ 1 meter high densely vegetated terrace. 34.08803 N 117.15713 W
1	3	
2	MS	
3	6	
4	8	
5	4	
6	MS	
7	MS	
8	2	
9	VCS	
10	MS	
11	MS	
12	6	
13	MS	
14	10	
15	CS	
16	MS→CS	
17	VCS	
18	CS	
19	CS	
20	3.5	
21	MS	
22	MS	
23	MS	
24	10	
25	MS	
26	MS	
27	MS	
28	MS	
29	MS	
30	MS	
31	MS	
32	MS	
33	MS	
34	MS	
35	MS	
36	MS	
37	MS→CS	
38	MS	
39	MS	
40	MS	
41	MS	
42	MS	
43	MS	
44	35	
45	2.5	
46	8	
47	18	
48	3	
49	15	
50	10	

51	15	
52	11	
53	4	
54	30	
55	15	
56	10	
57	5	
58	7	
59	7	
60	10	Stopping prior to entering 150 cfs active channel. ≈10 meters shy of ≈2 meter high vegetated river right bank. Wetted channel looks similar to the cobbles and boulders previously counted in the 150 cfs active channel of cross section 4. Noted active transport of silts and very fine sand. 34.08841 N 117.15746 W

Appendix 3. The Optimal Flooded Area Hypothesis

Optimal Flooded Area Hypothesis for SBKR Habitat

Based on our work so far, SBKR ideal habitat appears to be in areas that flood every ~ 30 years to reset the vegetation succession and replenish sand, but do not flood for intervals of 5+ years allow some plants to grow and a stable surface. This then leads to the hypothesis that to improve SBKR habitat, we need to optimize the area of land that floods less frequently than ~5 years but more frequently than every ~30 years. I will refer to this as the "optimal flooded area."

The schematics in Figure 1 show what might have been the effect of the dam. Before the dam, there was a significant area, including the breakout channel area, that was flooded every ~20-30 years. By lowering flood levels due to the dam, the optimal flood area was reduced significantly. It now takes more than a 30-yr flood to activate the floodplain and breakout channels, so these habitats are declining due to over vegetation. At the same time, there is little new habitat created within the main channel because the geometry forces it to be flooded too often.

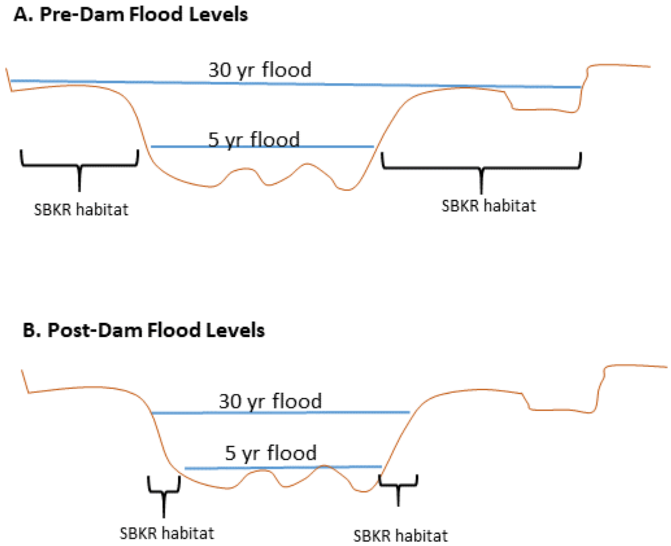


Figure 1.

Possible Solution 1. Make higher flood levels

The first possible sets of solutions have been the focus to date: to attempt to recreate the pre-dam 30-yr flood levels.

This could be accomplished by:

a) Timing flood releases in concert with floods on Mill Creek during 30-yr floods (Fig. 2A). This would restore habitat, but this option seems unlikely due to the amount of water needed and the downstream hazards of making a large flood even larger.

b) Designing a structure to force water to higher elevations in key locations (Fig. 2B). This would improve habitat in areas of diversions, but diversions would need to be active only at certain ~30 yr intervals.

c) Releases from borrow pits directly onto floodplain with recurrence of ~ 30 years (Fig. 2C). This could restore habitat if flows (~500 cfs) are large enough reset vegetation succession and transport sand.

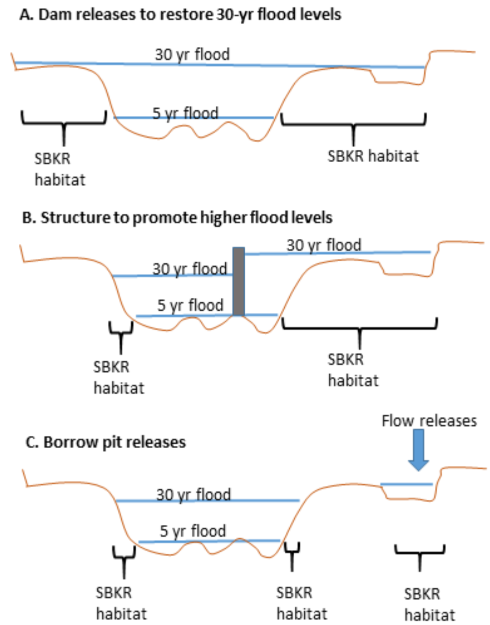


Figure 2.

Possible Solution 2. Create new floodplain within active valley

A second possible line of solutions is to modify the shape of the active inner valley/channel to create a floodplain region that floods less often.

This could be accomplished by:

a) Widen the active channel (or lower the neighboring high elevation floodplain) to create an area that is flooded at the optimum reoccurrence (Fig. 3A). This would restore habitat, and allow the channel to shift laterally and create more natural habitat. Requires earth moving.

b) Designing an engineering structure to force water into the bank at high velocity (Fig. 3B). The dry side of the structure would create habitat immediately since it would be an area that was recently flooded, but now will not be dry due to the structure. The wet side of the structure would ideally promote bank erosion and widen the channel naturally creating eventually something similar to Fig. 3A. Major issue is that erosion of boulder banks may not be possible.

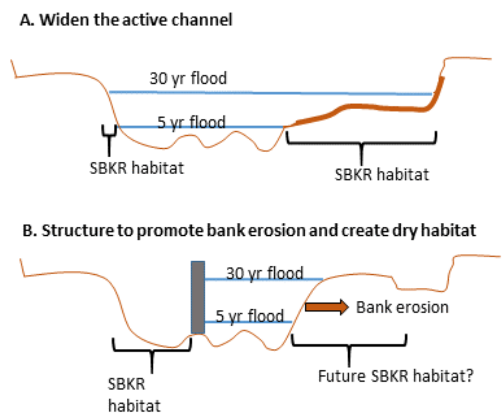


Figure 3.

Possible Solution 3. Divert entire river into a breakout channel.

A third possible solution is to divert the entire channel from its current course into one of the breakout channels and hold it there for the next 30 years (Fig. 3). This then would create a large area of new habitat in the current, now abandoned channel. To achieve the 30-yr flood recurrence, the river would need to be diverted back to the current channel in 30 years, and then the newly abandoned channel would become the new habitat zone for the next 30 years. The breakout channel would likely naturally widen and deepen after the entire flow is diverted in that direction. This would create a large area of usable habitat. We know that the current flow conditions are suitable to remove vegetation and transport sand (as observed in the active channel). Issue is finding a safe alternative route for the new channel.

Divert channel into a breakout channel for next 30 years.

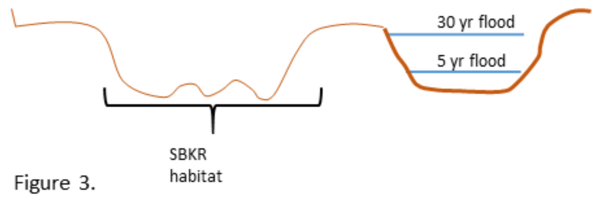


Figure 3.

Possible Solution 4. Supply the channel sand so it fills.

A fourth possible solution is to supply the active channel with ample sand (Fig. 4). Then it will aggrade, allowing the new, lower discharge 30-year events to flood a larger area. Would be a more natural process, but would require a continuous feed of sand.

Feed channel ample upstream sediment supply

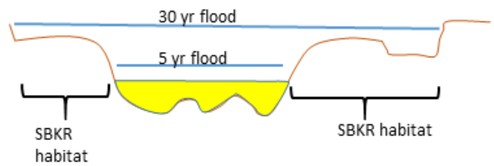


Figure 4.

Suggested Tasks to Investigate Proposed Solutions

1. First task is to assess the amount of optimal flooded area under the pre-dam and post-dam scenarios, and to quantify my cartoons. Using the topography and the flood models (1-D is fine) for pre- and post-dam floods of a given recurrence, something like Figure 5 can be generated. This will give a quantitative metric on how the ideal SBKR habitat has changed due to the dam. It shows the area of terrain that is flooded for a given recurrence interval, and the optimum flooding area (if between 5-yr and 30-yr flood intervals) can be defined.
2. For each of the proposed solution scenarios a similar diagram like Fig. 5 can be generated from the flood models to quantify the land area that will be improved. The solutions will either change the flood heights for a given recurrence interval (x-axis) or the shape of the valley (shape of curves). This figure gives a way to compare the outcome of the different scenarios.
3. To assess Solution 1b and 1c, we need to calculate whether the overspill flood from the diversion or 500 cfs from borrow pit releases will be sufficient to remove plants and reset the vegetation succession. This requires 1) flood models across the landscape with output grids of boundary shear stress, and 2) review of studies to find the critical stress needed for plant removal. As discussed, field tests should also be conducted to verify plants can be removed.
4. To assess Solution 2a, we determine the degree that the floodplain should be widened by trying different geometries and computing the new curves for Figure 5, to find the largest optimal flooded area. We should also put the results in the context of theoretical river braiding stability, which requires inputs of flow depths, widths, slopes and bed sediment sizes for different flood discharges. These inputs can then be used to determine the likelihood the channel will braid and the number of braid threads and islands. Ideally we want a braided system because it creates non-uniformity in the area that is flooded since the channel will naturally shift around.
5. For Solution 2B, we need to assess the likelihood and magnitude of bank erosion. This requires model outputs of bed and near bank shear stresses. Field measurements of sediment sizes in banks. And incorporation of this information into a bank erosion theory.
6. Solution 3 requires a flood simulation as to whether it's possible to divert the entire channel without causing other problems.
7. Solution 4 requires a morphodynamic model, if even 1-D, to model sediment aggradation as a function of upstream sand supply. The goal would be to determine how much sand is needed to force the channel to aggrade enough to alter the curve in Fig. 5 and promote more optimal flooded area.

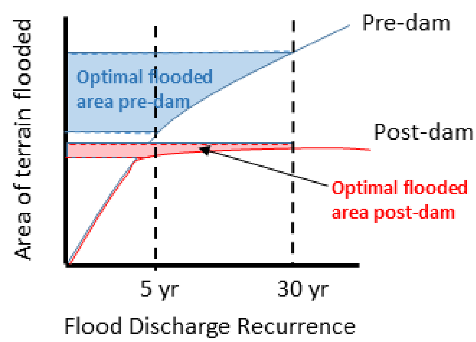


Figure 5.

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