Appendix C

Bank Erosion Monitoring Report

July 2021

SAN JOAQUIN RIVER
RESTORATION PROGRAM

State of California
California Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
South Central Region Office

San Joaquin River Restoration Program

Bank Erosion Monitoring Report

July 2021

DRAFT

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Natural Resources Agency
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Division of Regional Assistance
South Central Region Office

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Acronyms and Abbreviations

cfs	cubic feet per second
DWR	California Department of Water Resources
ESRI	Environmental Systems Research Institute
LiDAR	light detection and ranging
Restoration Area	San Joaquin River between Friant Dam and the Merced River confluence
PEIS/R	program environmental impact statement/report
RM	river mile
Settlement	stipulation of settlement
SDP	San Joaquin River near Dos Palos
SJF	San Joaquin River below Friant
SJRRP	San Joaquin River Restoration Program
Reclamation	U.S. Bureau of Reclamation

1.0 Introduction

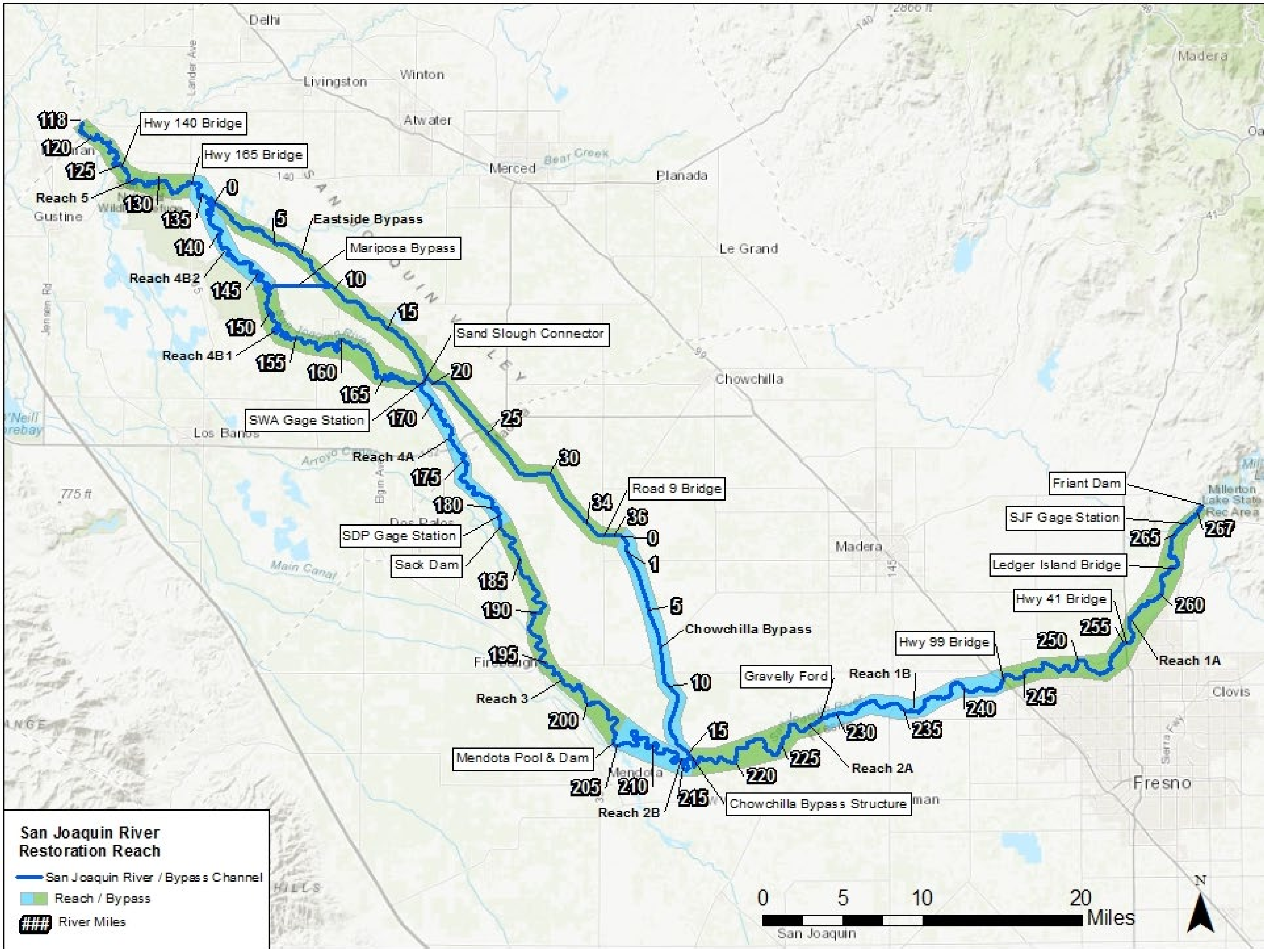
Completion of Friant Dam in 1942 permanently altered the hydrologic regime of the San Joaquin River. Although the dam provided for a reallocation of surface water supplies to more than 1 million acres of farmland in the San Joaquin Valley, it simultaneously ceased flow in some portions of the river and eliminated salmon runs above the Merced River-San Joaquin River confluence. This area above the confluence (i.e., the area along the San Joaquin River between Friant Dam and the Merced River confluence) is the San Joaquin River Restoration Program's (SJRRP) Restoration Area. In 2006, in the matter of *Natural Resource Defense Council, et al., v. Kirk Rodger, et al.,* a stipulation of settlement (Settlement) established multiple actions needed to return a self-sustaining, naturally reproducing salmon fishery back to the San Joaquin River. To accomplish this goal, additional flow releases from Friant Dam would be needed. These flows, termed Restoration Flows, would provide year-round flow in the San Joaquin River, except for the driest 5 percent of water years.

Restoration Flow releases identified in the Settlement range from a 350 cubic-feet-per-second (cfs) base flow to a spring pulse flow of 4,500 cfs. Over time, these flows could create geomorphic changes in some channels that have not seen flows in more than 60 years. Although these changes would provide significant benefit to the restored salmon fishery, they may contribute to channel erosion and depositional issues to the riverbed and banks. Eventually, lateral erosion can lead to channel migration, a natural condition where the streambed begins to alter its known course, as it had done prior to Friant Dam construction and is natural in river systems. With the channel banks heavily encroached, mostly with levees that provide flood protection, these changes need to be monitored to ensure they do not result in flood impacts to surrounding properties.

The SJRRP, a collaboration of five federal and State agencies commissioned to implement the Settlement, developed a Program Environmental Impact Statement/Report (PEIS/R) to ensure impacts of the program were identified and minimized. The PEIS/R described the need to "closely monitor erosion and perform maintenance and/or reduce Interim or Restoration Flows as necessary to avoid erosion-related impacts" (San Joaquin River Restoration Program 2012). The California Department of Water Resources (DWR), one of the SJRRP implementing agencies, is taking the lead to identify and monitor bank erosion within the Restoration Area (Figure 1). The goal of the monitoring effort is to identify the locations where erosion occurs and the threats of erosion on structures and farmland. The effort can also be developed to identify causal mechanisms of erosion at critical erosion sites. This report describes the initial step of the monitoring which is to develop a methodology to define critical erosion sites, and to develop a baseline for erosion for future evaluations. The results presented by DWR will assist the U.S. Bureau of Reclamation (Reclamation) with the erosion monitoring and reporting component of this commitment stated in the PEIS/R and allow for the development of advance measures to reduce erosion attributed to Restoration Flows. These measures are summarized in the SJRRP Physical Monitoring and Management Plan (2012).

In this initial report, DWR used aerial imagery from 2015 and 2017 to identify locations of bank erosion and provide baseline conditions for all future evaluations. DWR also identified the flows within this two-year period to provide an understanding of the source of erosion. During this period, flow releases included riparian flows, Restoration Flows, San Joaquin River Exchange Contractor flows, and a significant flood flow release. In all, DWR evaluated 268 locations along the San Joaquin River and flood bypass system for the presence of erosion. Results of this study identify vulnerable areas where monitoring for erosion should be continued to ensure the protection of nearby critical infrastructure and property. DWR will continue to monitor erosion in these areas to ensure that SJRRP actions avoid erosion-related impacts in these critical erosion areas. This report provides recommendations of necessary measures to include in a long-term erosion monitoring plan that can help identify causes of erosion. Periodic reports will provide an evaluation of erosion sensitive areas.

Figure 1 San Joaquin River Study Area by Reach



2.0 Background

Riverbank erosion is a common process of alluvial rivers that results in lateral changes in course through time and space (Yang et al. 1999). Through this process, channel geometry is altered to adjust for changes in hydrology and sediment supply (Leopold and Maddock 1953; Wolman 1955; Yang et al. 1999). Alluvial rivers, particularly those in lowland areas not confined laterally, are known to build, meander through, and reclaim floodplains through a redistribution of the sediment that they transport (Leopold et al. 1964). The ability of sediment within a river channel and floodplain to redistribute is controlled by hydrologic elements that include flow timing, magnitude, frequency, and duration (Wolman 1959; Wolman and Miller 1959) as well as the shear stress applied by the flow to sediment of specific sizes (Shields 1936). Studies in alluvial rivers show river channel geometry is primarily controlled by the flow magnitude that recurs about every 1.5 – 2 years, deemed as relatively moderate flows (Wolman and Miller 1959), and coincides approximately with the river stage that all but exceeds the channel's capacity, termed bankfull flow (Leopold et al. 1964). Dammed alluvial river channels have been shown to be controlled by both relatively low and high flow events, where fine sediment transport controls channel configuration at low flows and high flows are more effective at controlling channel morphology (Ma et al. 2012). The lower Reaches of the San Joaquin River are particularly susceptible to channel morphology changes at higher flows (McBain & Trush 2002).

The primary causes of bank erosion are tractive forces of shear stress applied by the river flow, and bank section failure (mass wasting) under gravitational forces. This shear stress mechanism can be exacerbated by higher flows that increase water surface area contact and shear stress against the bank that result in winnowing of bank material. This scenario is also worsened by a lack of vegetation and non-cohesive or unconsolidated soils. Gravitational bank failure is often preceded by rapid flow ramp-down in which river stage is reduced too quickly after a long duration of elevated flows. In this scenario, a combination of cohesive soil strength reduction from moisture saturation, a loss of hydrostatic lateral confining pressure (Rinaldi and Casagli 1999), and positive pore-water pressure (Dapporto et al. 2003) can lead to bank block detachment via planar, rotational, or cantilever failures (Rinaldi and Casagli 1999). Bank failures can be worsened by seasonal factors such as high temperatures leading to fissure development in cohesive or expansive soils (Rinaldi and Casagli 1999) and previous storms that moisten soils (Wolman 1959; Wolman and Miller 1959). Further issues arise in composite banks where soil properties vary stratigraphically within a bank (Rinaldi and Casagli 1999).

Although riverbank erosion and failure have multiple causes, each case is specific to the variables at individual sites and river systems, from which a thorough analysis can provide a sense of a river's evolution as it adjusts to changing hydrology, land use, and climate. Specifically, dams are known to cause downstream changes in channel geometry by altering the amount of sediment and water in the system (Willis and Griggs, 2003). The San Joaquin River has been altered by flow and sediment regulation from the operation of Friant Dam, as well as from other land and water use activities including gravel mining, flood control projects, water supply and transportation infrastructure, and land subsidence (McBain & Trush 2002). These cumulative effects include reduced floodway width and area, and simplified channel morphology, which have inhibited the river's ability to meander in some areas (McBain & Trush 2002). It is also likely that these activities increase the river's transport capacity immediately downstream of sediment impoundments, such that incision and bed coarsening occur due to a change in preferential sediment size transport (Kondolf, 1997), along with aggradation farther downstream (Ma et al. 2012).

In 2010, Tetra Tech performed a study to evaluate the erosion potential of the channel within the San Joaquin River Restoration Area. The study used the bank energy index (Mussetter et al. 1995) method to quantify the energy expenditure against the bank to predict the erosion potential around channel bends, accounting for magnitude and duration of flows and differences in bank material. The analysis was focused on the range of flows up to the target flow releases from Friant Dam of 4,500 cfs associated with the future capacity of all reaches under full project implementation, and the 1,600 cfs maximum Restoration Flow release that represents the then-estimated existing non-damaging capacity in Reach 2B. Study results indicate 52 high-priority sites and 94 uncertainty sites (sites where information was lacking to determine the erosion potential) between San Joaquin River Reaches 2B and 5 and the flood bypasses. The uncertain sites would require additional effort to identify and confirm the extent of erosion hazard.

In 2016, DWR implemented a pilot study (San Joaquin River Restoration Program 2017) to confirm the results of the Tetra Tech study and explore other methods to detect erosion. The pilot study tested the ability of two remote sensing methods — light detection and ranging (LiDAR) and delineation of aerial imagery — to detect channel erosion in two sites: Reach 3 near the city of Firebaugh, and in Reach 1A near Ledger Island. The study illustrated that both methods were useful in identifying erosion, but delineation of the aerial photos was the best suited for the analysis. The method of delineation involves outlining the point where water meets the riverbank (waterlines) or the top of the bank escarpment (bank crest) of temporally spaced aerial photographs. The delineations are then compared across a time period to measure differences, which would indicate channel erosion or deposition. For the pilot study, high-resolution aerial photographs between 1998 and 2015 were delineated and compared (accounting for differences in flow and vegetation), then confirmed through ground-truthing at several sites to verify the remotely detected results.

Thirty sites were flagged within the Firebaugh reach by the combined methods of remote sensing and studies conducted by Tetra Tech (2010). But many of these sites experienced very little erosion, were in areas of low risk to infrastructure, or were determined uncertain. Only one of these sites appeared to have significant erosion and potential impact. A comparison of methods showed that the delineation method located erosion at 75 percent of the areas that Tetra Tech (2010) predicted erosion to occur within the study areas. The remaining 25 percent of sites still have potential to show future erosion.

Further analysis in the pilot study showed that LiDAR was effective at detecting erosion and deposition within the channel. Digital elevation surfaces of the floodplain dating between 2008 and 2015 were generated and compared, which showed agreement with the locations and trends presented by the delineation method. These surfaces also displayed LiDAR’s sensitivity to detect changes beyond river morphology, such as vegetation, bridge construction across the river, and inherent artifacts of data processing during procurement. Although LiDAR proved effective, it also required extensive verification by aerial imagery or site visits. Upon completion of the pilot study, DWR staff concluded that Tetra Tech study (2010) provided a useful prioritization of potential problem areas that can be assessed in a long-term monitoring plan to survey for new or continued erosion. The LiDAR method served to validate the results of the bank energy index and delineation methods, but was not deemed necessary to include in future surveys unless warranted for a specific purpose. Results from the Tetra Tech study (2010) and the DWR pilot study provide a foundation for long-term erosion monitoring consistent with objectives in the PEIS/R.

3.0 Methods

The remote sensing method of bank delineation was used to identify recent bank erosion that may be threatening levee stability, flow conveyance, infrastructure, or property. This study evaluated the 254 sites that Tetra Tech's levee stability evaluations predicted (Tetra Tech 2010), along with 14 additional sites where erosion was discovered since the Tetra Tech study (Tetra Tech 2010). Using high-resolution aerial imagery, DWR evaluated bank erosion using the methods described below, and presents the results in Section 4.0. Aerial photography surveys of all SJRRP reaches were performed on February 24, 25, and 26, 2015, and December 7, 2017.

3.1 Aerial Imagery Bank Delineations

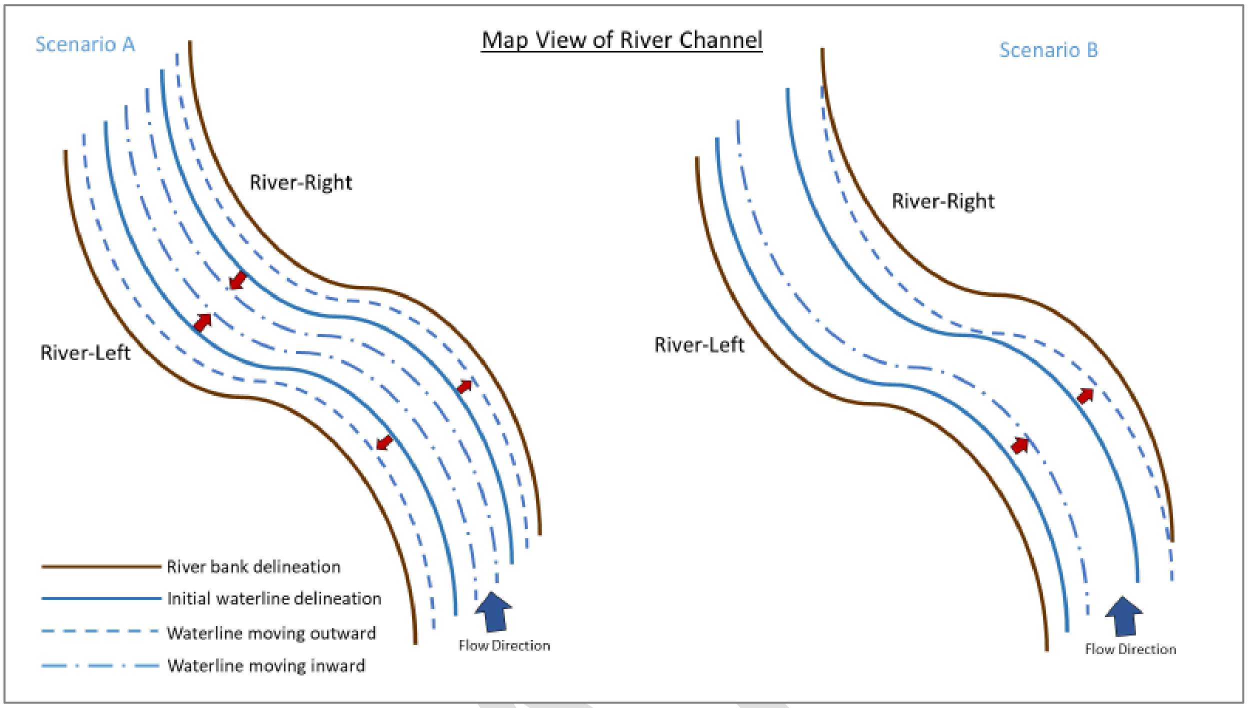
In general, the method of delineation is the process of outlining the bank crest or waterlines on aerial photographs. The bank crest is identified as the knick-point between escarpment and flat floodplain, and the waterline is where water's edge meets land; in some cases, these features coincide. After the delineations are recorded, they are compared by superimposing to identify any changes in location with time. Change suggests bank erosion or deposition. Additionally, some sense of river evolution is illustrated by comparing waterlines and bank crests, so this method creates a spatial record of the channel at specific dates and locations.

DWR made delineation maps using high-resolution aerial photographs dating from 2015 and 2017 for each site where Tetra Tech (2010) had predicted or identified potential erosion. Some additional areas were also delineated, in the case that new erosion sites were located. DWR made continuous outlines of the river channel by delineating waterlines that approximate the water's edge along the bank for each photoset (i.e., each point in time). The two years were compared using different colors to represent waterlines for each year. In a few areas of high erosion, additional information on erosion patterns were also gained from Google Earth imagery with dates not included by the aerial photography.

3.1.1 Limitations

It is possible that factors other than erosion and deposition can cause the appearance of bankline migration. In some instances, the waterline is obscured by overhanging vegetation or shadows, limiting the ability of the delineation to accurately identify erosion. Another challenge can arise from flow variability between photosets and its effect on the wetted width of the channel. In this case, flow variability can be determined by a change in the wetted width of the channel (see Figure 2, Scenario A). Conversely, channel geometry changes will typically show localized waterlines moving in the same direction (Figure 2, Scenario B). Also, an apparent change in the wetted channel width will be affected by the slope of the shore being delineated. For example, low-slope banks will show more lateral water movement than a vertical bank upon flow change. Analyzing multi-year bankline delineation sets contemporaneously can improve the accuracy of interpreting these conditions.

Figure 2 **Two Patterns Depicting Waterline Migration: Flow (Scenario A) and Erosion (Scenario B)**



The bankline delineation method effectively detects channel migration, but it does not reveal the causal mechanism. Although erosion and deposition are the principal causes of channel migration, erosion can manifest in multiple ways. For example, sediment can be winnowed away by shear stress from flowing water, and bank failure can occur from sudden decreases in discharge caused by loss of hydrostatic pressure (e.g. sloughing). Flow magnitude, frequency, duration, and timing have considerable effects on bank stability, especially when coupled with hydrogeologic variables (e.g., soil saturation, cohesion, compaction, composition). Waterline migration patterns provide insight to flow schedules that impose bank erosion risks, which can be identified with strategic timing of aerial imagery or field visits. (Note that this report does not focus on identifying the causal mechanisms of erosion.)

To build on the sites that Tetra Tech deemed threatening, a new form of stationing identification was created. Because Tetra Tech had labeled their sites sequentially from 1 to 254 working upstream, it would not be appropriate to add new sites in between these existing sites and number them sequentially. To resolve this issue, each Tetra Tech site and all additional sites were given a corresponding river or levee mile value as its new nomenclature. These values were estimated according to the site's position between the mile markers. River mile (RM) markers were obtained through Reclamation and levee mile indicators for the flood bypass system were acquired through the Reclamation's operation and maintenance maps.

RM designations were estimated starting at mile 118, located just before the Highway 140 bridge, and counted upstream to Friant Dam, which is just past mile 267. RMs start from zero in the Sacramento-San Joaquin Delta and end at Friant dam 267 miles upstream. The levee miles for the Eastside Bypass start at the downstream end of the Eastside Bypass at the confluence of the San Joaquin River and count upstream from zero to 36 on each side of the levee. The Eastside Bypass ends at the Fresno River confluence (near Road 9 bridge) where the Chowchilla Bypass levee miles begin at zero and count upstream towards the San Joaquin River. The erosion areas for the river and bypasses were identified as "L" and "R" to designate the left and right levees, respectively, on which the erosion was identified. The river and levee stationing are shown in Figure 1.

3.3 Threat Classification

To quantify the threat to each site showing erosion, a threat ratio was created. DWR developed this threat classification to quantify the risk of erosion to structures, where structures were defined as human-made additions within the study area. This ratio divides the distance to the nearest structure by the distance of lateral erosion measured between the photoset dates (in this case, between 2015 and 2017). A smaller threat-ratio value corresponds to a more significant threat from erosion at that site. Additionally, the denominator is the amount of erosion that occurred between photos. (In this analysis, the denominator shows the amount of erosion that most likely occurred during the flood event from January to July 2017.)

$$Threat\ Ratio = \frac{distance\ to\ nearest\ structure}{lateral\ erosion\ distance\ between\ photoset\ dates}$$

Sites with threat ratios lower than 3.0 were determined as critical and designated as a high threat. This is based on the prediction that it could take 3 or fewer similar erosion events to cause damage to the nearest structure. A threat ratio of 0.0 signifies that erosion is already present within a structure. Sites that showed erosion but had a threat ratio between 3 and 10 were designated as a medium threat. The sites that showed no perceptible erosion between 2015 and 2017 were designated as a low threat. Though these sites showed no erosion between 2015 and 2017, DWR will continue to monitor them for future erosion as funds are available.

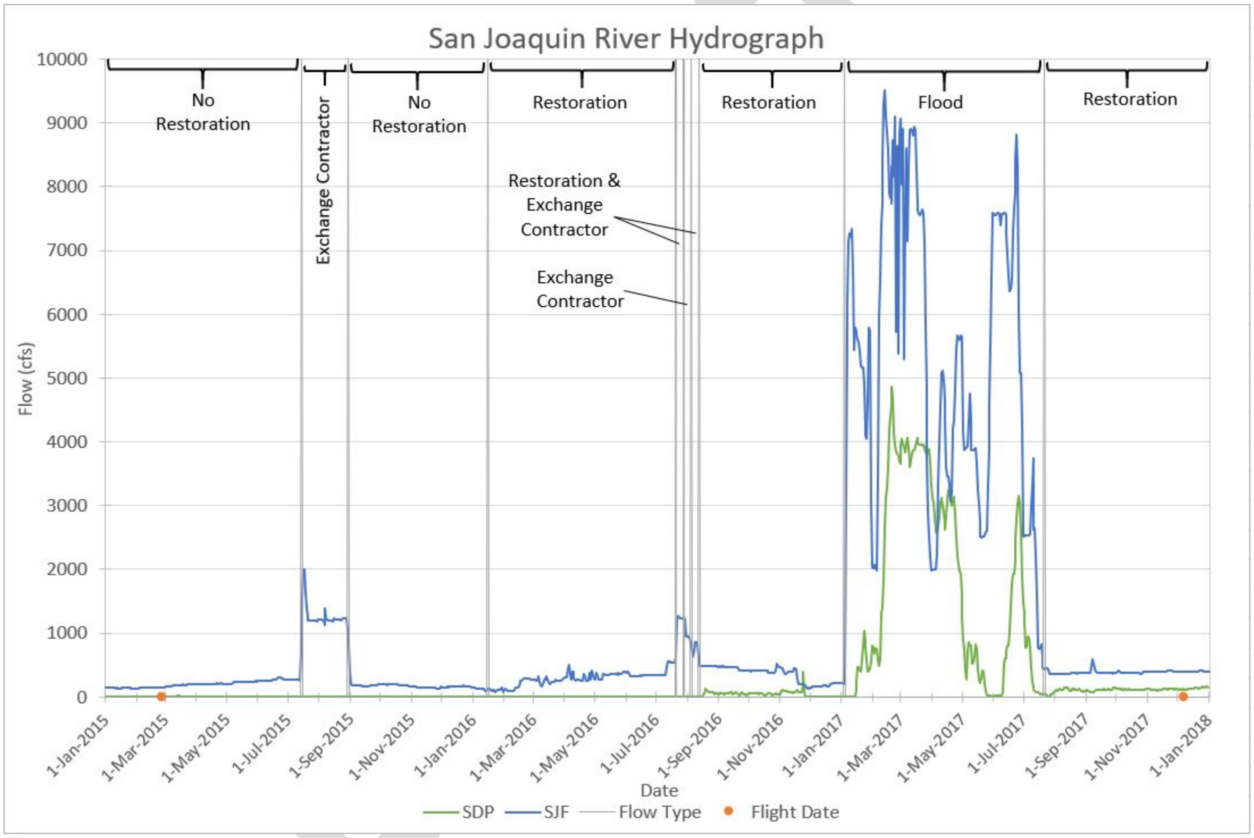
3.4 Flow-Type Comparison

Flow types were identified to provide a basis for understanding the relative flow magnitudes present between the aerial photoset dates. DWR identified the timing and discharge of Restoration Flows, San Joaquin River Exchange Contractor (Contractor) deliveries, and flood flows. Flow-type information was gathered from SJRRP (www.restoreSJR.net) and compared to discharge information gathered from the California Data Exchange Center (CDEC) (www.CDEC.water.ca.gov) and DWR's direct measurements. Flow-type release intervals and total discharge were compared at two stream gauges shown in Figure 1: San Joaquin Friant (SJF) and San Joaquin River near Dos Palos (SDP). Discharge data from CDEC is available in 15-minute intervals. From this information, DWR created daily averages spanning January 1, 2015, to January 1, 2018. The mean daily discharge was then compared for each flow type between the aerial photoset dates, February 26, 2015, and December 7, 2017. Daily averages were calculated to include the effect of zero flow days and considered all 1016 days between aerial photoset dates (including the first and last day). Flow lag time and groundwater interactions were not accounted for.

During the January 1, 2015 to January 1, 2018 period, the hydrograph created in this analysis (see Figure 3) shows that significant flood control releases occurred between January 4, 2017, and July 20, 2017 (198 days). Within the aerial photoset time period, daily average flood flows were 1027 cfs at SJF and 337 cfs at SDP. Daily average Contractor releases were 74 cfs at SJF and 0 cfs at SDP. Daily average Restoration Flows were 165 cfs and 21 cfs at SJF and SDP, respectively. No restoration or flood flows were released in 2015 because it was listed as a critical-low restoration year type.

The daily average of all flows within the aerial photoset time period were 1,318 cfs at SJF and 358 cfs at SDP. Based on the daily averages listed above, flood flows were 78 and 94 percent of total flows at SJF and SDP, respectively. Contractor flows at SJF were 6 percent of the total average flow and were diverted at the end of Reach 2B/Mendota Pool and therefore not detected at the SDP stream gauge. Restoration Flows were 13 and 6 percent of the total flows at SJF and SDP, respectively. Within that time span, flood flows were released for 198 days, Contractor flows were released for 70 days, and Restoration flows were released for 488 days. While these flow characteristics provide an understanding of relative flow type release rates that cause erosion, they are not an exclusive indicator of erosion cause and more data and analyses would be needed to determine the exact causes of the erosion during this period.

Figure 3 San Joaquin River Hydrograph of Mean Daily Discharge calculated at SJF and SDP Stream Gauges (Vertical gray lines indicate when flow type changes occurred; flow types are labeled at top of chart.)



4.0 Results

The SJRRP PEIS/R recommends that Reclamation monitor bank erosion to reduce the effect of Restoration Flows on flood impacts on levees and other infrastructure along the river and flood bypasses. DWR used bankline delineation of aerial imagery to identify bank erosion within the SJRRP Restoration Area of the San Joaquin River to support Reclamation in this effort. The work was performed using bank delineations of aerial images taken in 2015 and 2017. This period will act as a baseline for future erosion efforts and will show the potential for erosion in the Restoration Area from a high flood event similar to what occurred in early 2017.

Initially, Tetra Tech identified 254 locations throughout Reaches 1 through 5 and the bypasses (Tetra Tech 2010), and DWR delineated and reviewed each site along with 14 additional sites of potential erosion. The study area shown in Figure 4 is divided into 12 index maps to display each site of potential erosion. The index maps are provided in Appendix A and show each of the 268 sites labeled by RM and threat classification. Each figure has the 2017 aerial flight photography superimposed over a 2018 Environmental Systems Research Institute (ESRI) ArcMap base map. The base maps were included with the 2017 aerial photography to show areas of the valley not covered in the study flight path.

After delineating each of the 268 sites, DWR determined that 50 show signs of erosion. Of these 50 sites, eight exhibited the highest risk to infrastructure based on a threat ratio below 3.0. This threat ratio is based on the prediction that it could take 3 or fewer erosion events to cause damage to the nearest structure if conditions are similar. Two of the eroding sites, RM 258.5, RM 131.3, are currently experiencing erosion into a nearby structure and have a threat ratio of 0.0 (a threat ratio of 0.0 signifies that erosion is already present within a structure). These 8 high-threat classification sites are discussed below (listed by RM location) and illustrated in Figures 5 through 12. All are located in the main stem of the San Joaquin River. There are also 22 medium sites that have a threat ratio of between 3.0 and 10.0. The high- and medium-risk sites are displayed in Table 1.

RM 258.50
This site is in Reach 1A near Owl Hollow and depicts a bare bank with no bank protection. The nearest structure threatened is an embankment road that separates a gravel mining pit from the river, the bank of which is currently being eroded. Up to 12 feet of lateral erosion occurred over a longitudinal distance of 136 feet on the river-left side. From Google Earth imagery, most of the erosion appears to have occurred between March 18, 2015, and March 31, 2017. During that time frame, a dirt berm was built on top of the embankment road. Threat ratio is 0.0; threat level is high; see Figure 5 and Index Map 12.

RM 131.30
This site is in Reach 5 and depicts a barren bank with no bank protection. A 430-foot-long stretch of bank is actively eroding and encroaches a flood control levee on the river-left side. Up to 20 feet of lateral erosion occurred here. As seen by the bend in the road, motorists must drive off of the eroding levee as a detour to continue on their way. This levee is part of the State Plan of Flood Control levees that protect adjacent lands. As high flows overtop a bank and bypass the river bend, they then encounter and erode the outside bank; continual high flows may establish this path until it becomes the main channel and cuts off the outer bend. Threat ratio is 0.0; threat level is high; see Figure 6 and Index Map 2.

RM 200.30
This site is in Reach 3 and depicts vegetation loss and no bank protection. The nearest structure threatened is a service road and row crops 3 feet from the bank crest. Imagery comparison shows a multi-stage terrace with possible 55 feet of lateral bank erosion along 270 feet of bankline. Waterline migration pattern supports channel migration evidence. Deposition is apparent on opposite side of channel. Threat ratio is 0.1; threat level is high; see Figure 7 and Index Map 9.

RM 222.50
This site is in Reach 2A and depicts sparse vegetation with no bank protection. The nearest threatened structure is a levee 45 feet away, with farm buildings and an orchard beyond it. There is a maximum of 140 feet of lateral erosion along 1,270 feet of bankline on the river-left side. The river is single-threaded

during low flow and becomes braided and shallow with increased flow. Most of the erosion occurred during flood flows between March 31, 2017, and August 7, 2017, as depicted by Google Earth imagery. This site likely contributes significant amounts of sand downstream. Threat ratio is 0.3; threat level is high; see Figure 8 and Index Map 11.

RM 262.20
This site is in Reach 1A at the southern end of Ledger Island and depicts a bare bank with no bank protection. The nearest structure threatened is a gravel mining pit 85 feet from the river, separated by an eroding bank. This site shows up to 55 feet of lateral erosion along 420 feet of bankline on the river-right side. This erosion provides a significant amount of sand to the spawning reach, and connectivity with the pond would have other adverse impacts to salmonids. Threat ratio is 1.5; threat level is high; see Figure 9 and Index Map 12.

RM 202.60
This site is in Reach 3 and depicts a sparsely vegetated bank with no bank protection. The nearest threatened structure is a service road and canal 20 feet from the bank crest. Evidence of 12 feet of lateral erosion is apparent from a missing tree and scalloped bank for 112 feet longitudinally on the river-right side. The bank scarp is noticeably encroaching on the service road and canal embankment. Threat ratio 1.6; threat level high; see Figure 10 and Index Map 9.

RM 194.40
This site is in Reach 3 within the city of Firebaugh and depicts light vegetation with riprap serving as bank protection. The nearest threatened structure is a residential neighborhood 24 feet away. There is evidence of 12 feet of lateral erosion along 40 feet of river-left bankline at the downstream end. Large woody vegetation loss at this site increases its vulnerability to erosion. Threat ratio 2.0; threat level high; see Figure 11 and Index Map 8.

RM 220.60
This site is in Reach 2A and depicts sparse vegetation with no bank protection. The nearest threatened structure is a levee 75 feet away and row crops beyond. This is a shallow braided channel where the riverbed was dry in 2015. There is a maximum of 37 feet of lateral erosion along 900 feet of river-right bankline. As shown in Figure 12, the area is between the two high risk sites RM 220.5 and RM 220.7. Although this site endured similar flows and durations in 2011, the flood releases from 2017 appear to have caused most of the erosion. Threat ratio is 2.0; threat level is high; see Figure 12 and Index Map 11.

Figure 4 **Bank Erosion Study Area**

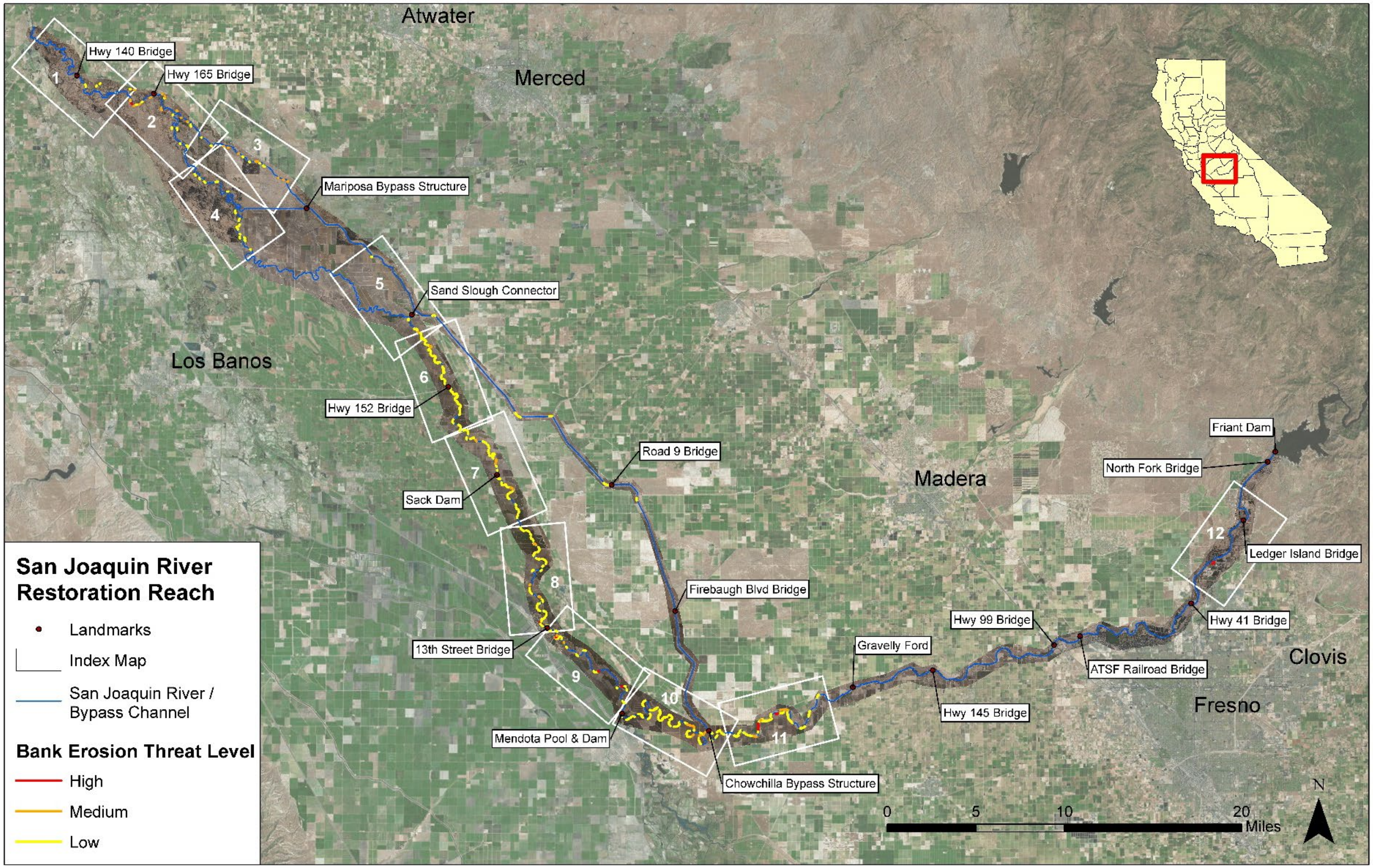


Table 1 Top 30 of 50 Sites with Detected Erosion

River Mile/ Levee Mile	Channel	Threat Level	Lateral Erosion (feet)	Distance from Structure (feet)	Threat Ratio
258.50	SJR	High	10	0	0.0
131.30	SJR	High	11	0	0.0
200.30	SJR	High	55	3	0.1
222.50	SJR	High	140	45	0.3
262.20	SJR	High	55	85	1.5
202.60	SJR	High	20	33	1.6
194.40	SJR	High	12	24	2.0
220.60	SJR	High	37	75	2.0
215.90	SJR	Medium	17	58	3.4
0.20	ESB	Medium	8	33	4.1
170.80	SJR	Medium	24	100	4.2
5.30	ESB	Medium	15	65	4.3
3.60	ESB	Medium	12	54	4.5
0.65	ESB	Medium	11	50	4.5
133.40	SJR	Medium	9	48	5.3
131.80	SJR	Medium	12	67	5.6
214.50	SJR	Medium	20	115	5.8
181.20	SJR	Medium	12	71	5.9
196.10	SJR	Medium	10	60	6.0
212.30	SJR	Medium	10	64	6.4
178.60	SJR	Medium	13	85	6.5
196.00	SJR	Medium	19	130	6.8
181.10	SJR	Medium	9	71	7.9
130.60	SJR	Medium	10	80	8.0
132.50	SJR	Medium	13	109	8.4
191.30	SJR	Medium	15	130	8.7
3.40	ESB	Medium	11	96	8.7
131.00	SJR	Medium	9	80	8.9
212.60	SJR	Medium	11	102	9.3
7.30	ESB	Medium	9	88	9.8

Notes: Table does not include sites designated as low risk.
SJR = San Joaquin River
ESB = Eastside Bypass

Figure 5 San Joaquin River Reach 1, RM 258.5; Threat Ratio 0.0, Threat Level: High; Index Map 12

Figure 6 San Joaquin River Reach 5, RM 131.3; Threat Ratio 0.0, Threat Level: High; Index Map 2

Figure 7 **San Joaquin River Reach 3, RM 200.3; Threat Ratio 0.1, Threat Level: High; Index Map 9**

Figure 8 **San Joaquin River Reach 2A, RM 222.5; Threat Ratio 0.3, Threat Level: High; Index Map 11**

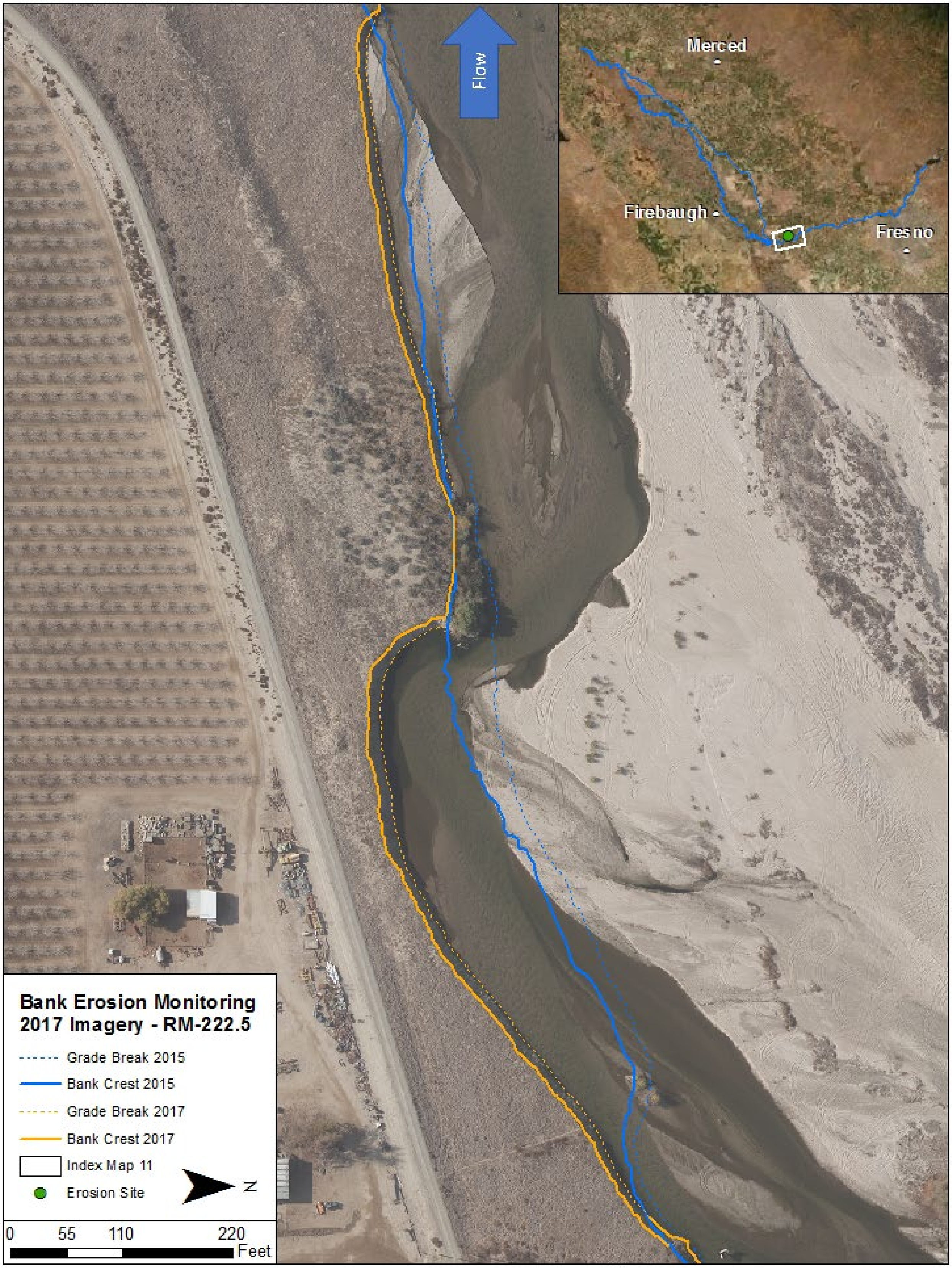


Figure 9 **San Joaquin River Reach 1, RM 262.2; Threat Ratio 1.5, Threat Level: High; Index Map 12**

Figure 10 **San Joaquin River Reach 3, RM 202.6; Threat Ratio 1.6, Threat Level: High; Index Map 9**

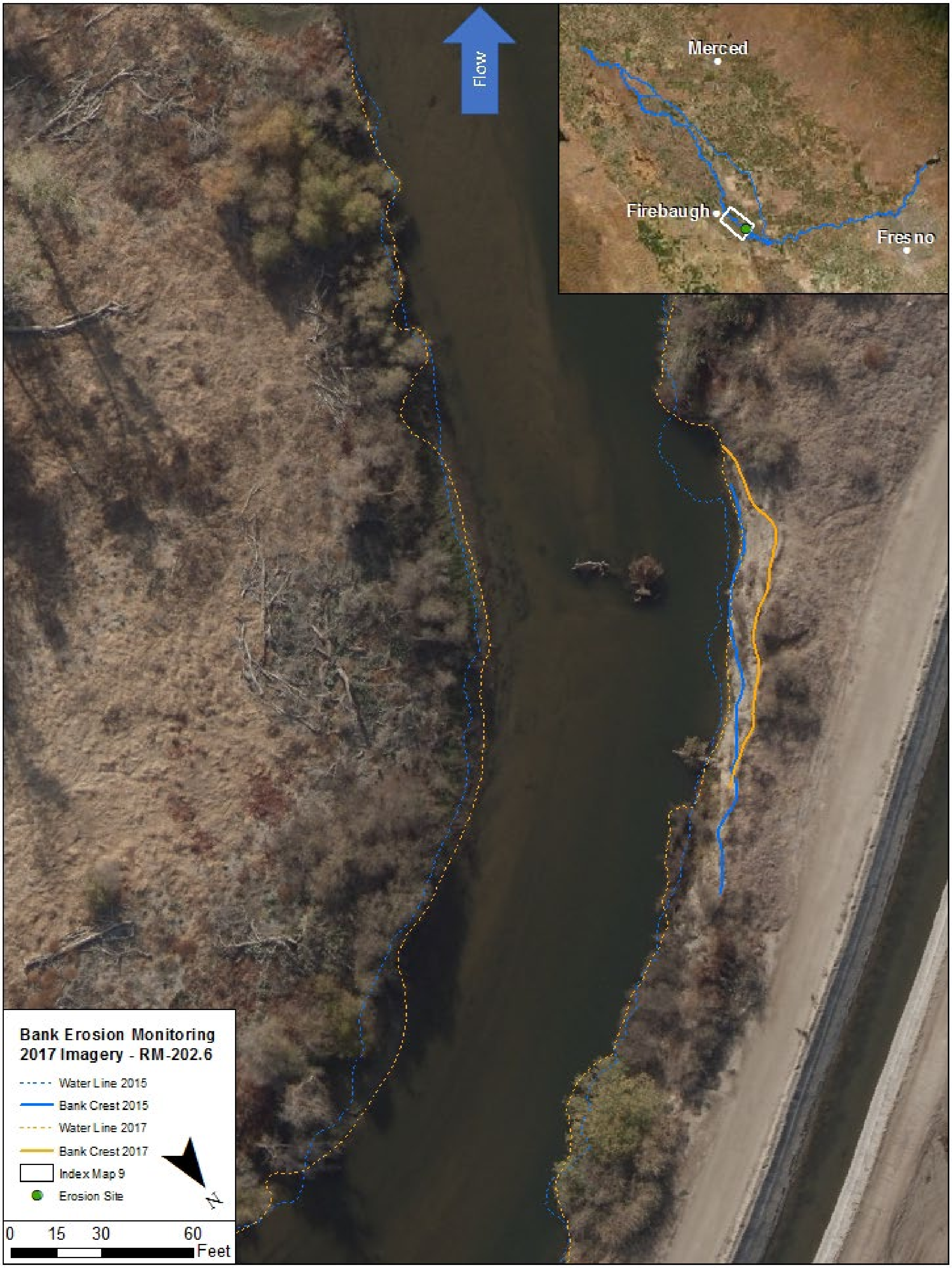


Figure 11 San Joaquin River Reach 3, RM 194.4, Threat Ratio 2.0, Threat Level: High, Index Map 8

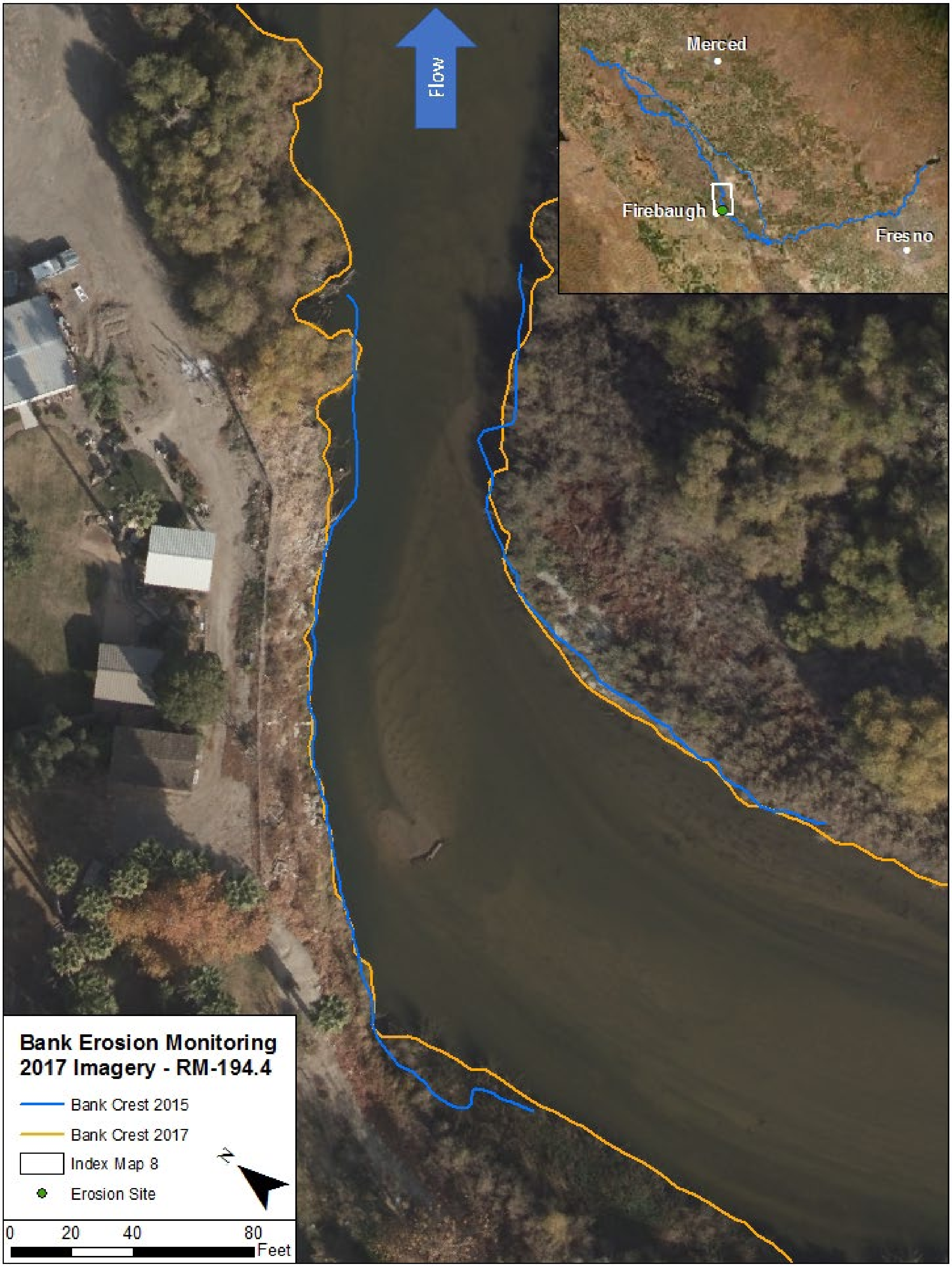


Figure 12 **San Joaquin River Reach 2A, RM 220.6; Threat Ratio 2.0, Threat Level: High; Index Map 11**

5.0 Conclusions and Recommendations

The purpose of bank erosion monitoring within the Restoration Area of the San Joaquin River as described in the PEIS/R is to avoid erosion related impacts from Restoration Flows. The purpose of this bank erosion monitoring report is to present results of the first step of erosion monitoring to define baseline erosion and critical erosion sites at the start of continuous Restoration Flows. From the 2015 and 2017 imagery studied in this report, the erosion shown is most likely a response to flood flows occurring between January and July 2017. It is less likely that Restoration Flows caused erosion because those average daily discharges were small in comparison to the flood flows. The results shown are the most severe examples of erosion found in this study. These high-threat sites need to be closely monitored to protect the surrounding infrastructure. Continual monitoring will improve the understanding of how Restoration Flows, Contractor deliveries, and flood flows effect the erodible perimeter of the river and bypasses. And further study will be required to understand the causal mechanisms of erosion in the Restoration Area and confirm that Restoration Flows are not causing erosion-related impacts.

The SJRRP needs an effective and efficient method to identify and monitor bank erosion within the Restoration Area. The remote sensing of bank delineation method can be used to identify and monitor potential bank erosion sites with minimal expense. The number of monitoring sites may need to be adjusted in the interest of time and usefulness. Future monitoring sites should include all high-threat locations and consider medium- and low-threat locations at DWR's discretion. Sites should be removed or added according to their individual threat classification, with the lowest threat (highest ratio) removed first. If low-threat sites still require monitoring, a geographic information system swipe tool or Google Earth imagery can be used for quick analysis; however, these are less-detailed evaluations compared to delineation methods. Continued monitoring will be necessary to (1) track erosion progress at high- and medium-risk sites, and (2) identify erosion caused by Restoration Flows and implement measures to avoid erosion-related impacts. This monitoring effort will help to protect the safety of surrounding structures.

The remote sensing method of delineation has some limitations in detecting bank erosion. For example, overhanging vegetation can hide or obscure the waterline. Care must be taken to distinguish between bank erosion and changes in vegetation growth or seasonal patterns. Also, because discharge affects the appearance of the river planform, aerial photograph dates are important for comparison with local hydrograph records. Despite these challenges, the remote sensing method of delineation is an efficient and effective method of detecting bank erosion.

DWR recommends implementing a long-term erosion monitoring plan that would evaluate the causal mechanisms by reach throughout the Restoration Area to reduce or avoid erosion-related Restoration Flow impacts in the Restoration Area. This plan would apply the methods outlined in this study by using remote sensing technology to monitor and detect erosion. When deemed necessary, future studies may include separate investigations of the processes and flow schedules that cause bank erosion. The necessary actions to continue bankline delineation are listed below.

Monitoring Locations

The monitoring plan will include San Joaquin River Reaches 1 through 5 and the bypasses that receive Restoration Flows. Because of the large distance of the combined reaches and high number of possible sites, prioritization is necessary. Initial monitoring will consist of the highest threat sites identified in this report. Medium-threat sites may be monitored less frequently, and low-threat sites monitored at DWR's discretion. As time and funding allows, other sites identified by Tetra Tech (2010) might be evaluated. As DWR is made aware of other occurrences, the monitoring plan may incorporate those occurrences into the monitoring site list. The list of the bank protection sites — those lined with riprap or other armoring — identified by Tetra Tech (2010) should also be updated as new sites are identified to reduce the number of sites that need monitoring.

Monitoring Types

A baseline was created for the 268 sites within the Restoration Area using bankline delineations from 2015 and 2017 aerial photography. As sites are further determined to impose bank erosion risks, remote sensing methods will be used to monitor their banklines over time. When the banklines are ambiguous, topographic surveys may be employed to examine for evidence of recent bank erosion and to provide surveyed locations of the bank. Other types of monitoring that may be useful for clarifying bank change and causal mechanisms could include drone surveys, LiDAR, erosion pins, planimetric surveys, or repeated cross profiling (Lawler 1993). Use of these technologies will be determined by the cost, usefulness, and erosion risk priority.

Monitoring Frequency and Timing

Monitoring should help determine if bank erosion was caused by Restoration Flows. This may require, at a minimum, that surveys occur before and after the less-frequently occurring flood flows. In so doing, the surveys would capture the bank erosion that occurred as a result of the flood as well as erosion that occurred between floods (i.e., presumably as a result of Restoration Flows or Contractor releases). Post-flood aerial photographs would ideally be obtained following flood-water recession. Because flood flows are difficult to predict with sufficient lead time, other sources of aerial imagery can be used to provide pre-flood banklines (e.g., ESRI, California GeoDatabases, Google Earth).

Aerial Photography Dates

Aerial photography flight dates should avoid times when shadows are long, such as in winter. When possible, surveys should capture consistent seasonal effects from vegetation (e.g., deciduous leaf loss) that otherwise will convolute waterline interpretations. The most advantageous aerial surveys would occur late fall after leaf loss and during low flows. Annual frequency will depend on flood events and should occur before and after floods to isolate erosion-related impacts from floods and Restoration Flows. Future assessments might reflect a need to monitor only high-threat sites, depending on threat level and available funding.

Erosion Response

Response to erosion found through monitoring should be considered on a case-by-case basis. This report outlines some examples of noticeable erosion that may require a response such as bank stabilizing actions or enhanced monitoring. Creating and maintaining relationships with stakeholders will be beneficial to allow proactive erosion-event responses.

Flow Evaluations

The San Joaquin River flow regime becomes increasingly complicated in Reaches 2B through 5 in conjunction with the bypass systems. Flows are affected by tributaries, bifurcation structures, land subsidence, seepage losses, channel capacity loss, low channel slope, and backwater effects. Evaluating Restoration Flows, Contractor flows, and flood-flow routing through this system is imperative to quantify risk from each flow type. DWR recommends that flow is evaluated at several stream gauges throughout the river and bypasses to help identify flow type, magnitude, duration, and routing in conjunction with Friant Dam releases. Groundwater elevation can also be considered to distinguish soil saturation from causes other than river flow, such as agricultural irrigation.

Furthermore, future studies could investigate the effects of accumulated discharge for each flow type. Specifically, a flow analysis should compare flow frequency, magnitude, duration, timing, and ramp-down rate. Geomorphic and hydrologic variables, including soil types and groundwater interactions, will affect the river's ability to alter the channel and should be considered. For example, it is possible for long-duration or frequent short-duration moderate flows to alter a channel more than a short-lived high flow. Similarly, if river stage falls too quickly after elevated flows, bank-collapse can occur where steep channel walls are no longer supported by hydrostatic pressure. Because geologic and hydrologic conditions vary from site to site, each should be evaluated individually where warranted by the erosion threat. Aerial imagery from multiple sources (e.g., Google Earth) should be considered even if not delineated.

Communication System

A communication system should be considered that would allow relevant stakeholders to be notified of potential and current erosion that could have future flood impacts. A communication system could resemble or potentially be joined with the SJRRP Seepage Hotline to also provide a means for stakeholders to report bank erosion to the SJRRP. The SJRRP representatives should work with local flood agencies to determine the need for such a system.

6.0 References

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Appendix A. Index Maps

The figures in this appendix utilize the 2017 flight imagery with a lighter-shaded 2018 basemap. Because the flightpath covered only the area of interest, the surrounding area was completed with a 2018 basemap to show context of the valley; the shading color difference is arbitrary. The following maps show an overview of all 268 sites and label them by station identification and threat level designated by the California Department of Water Resources. Sites in the Chowchilla and Upper Eastside Bypass were excluded from the index maps because these sites were not affected by river Restoration Flows.

Figure 13 Index Map 1 with Overview of Footprint Identified in Figure 4

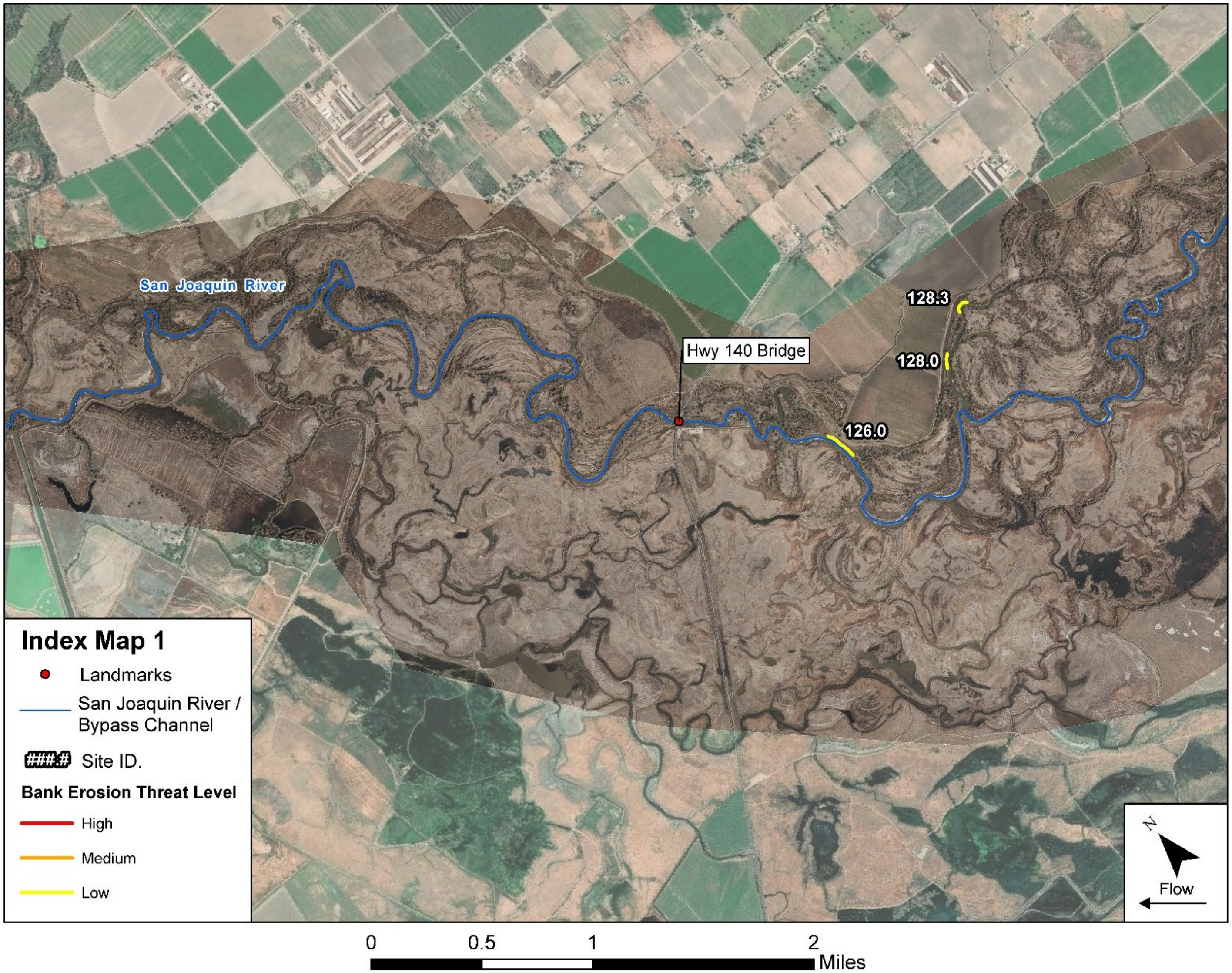

Figure 14 Index Map 2 with Overview of Footprint Identified in Figure 4

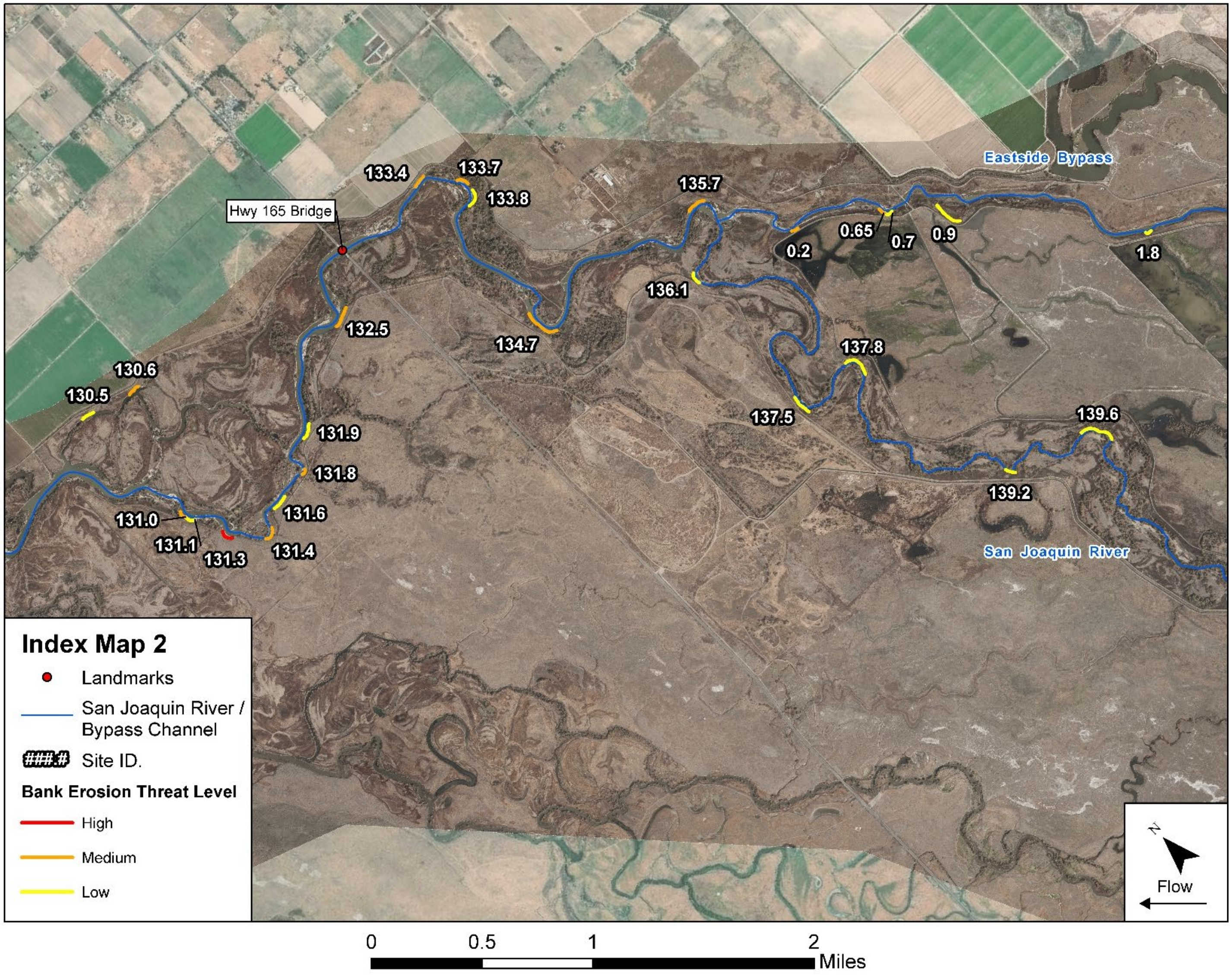

Figure 15 Index Map 3 with Overview of Footprint Identified in Figure 4

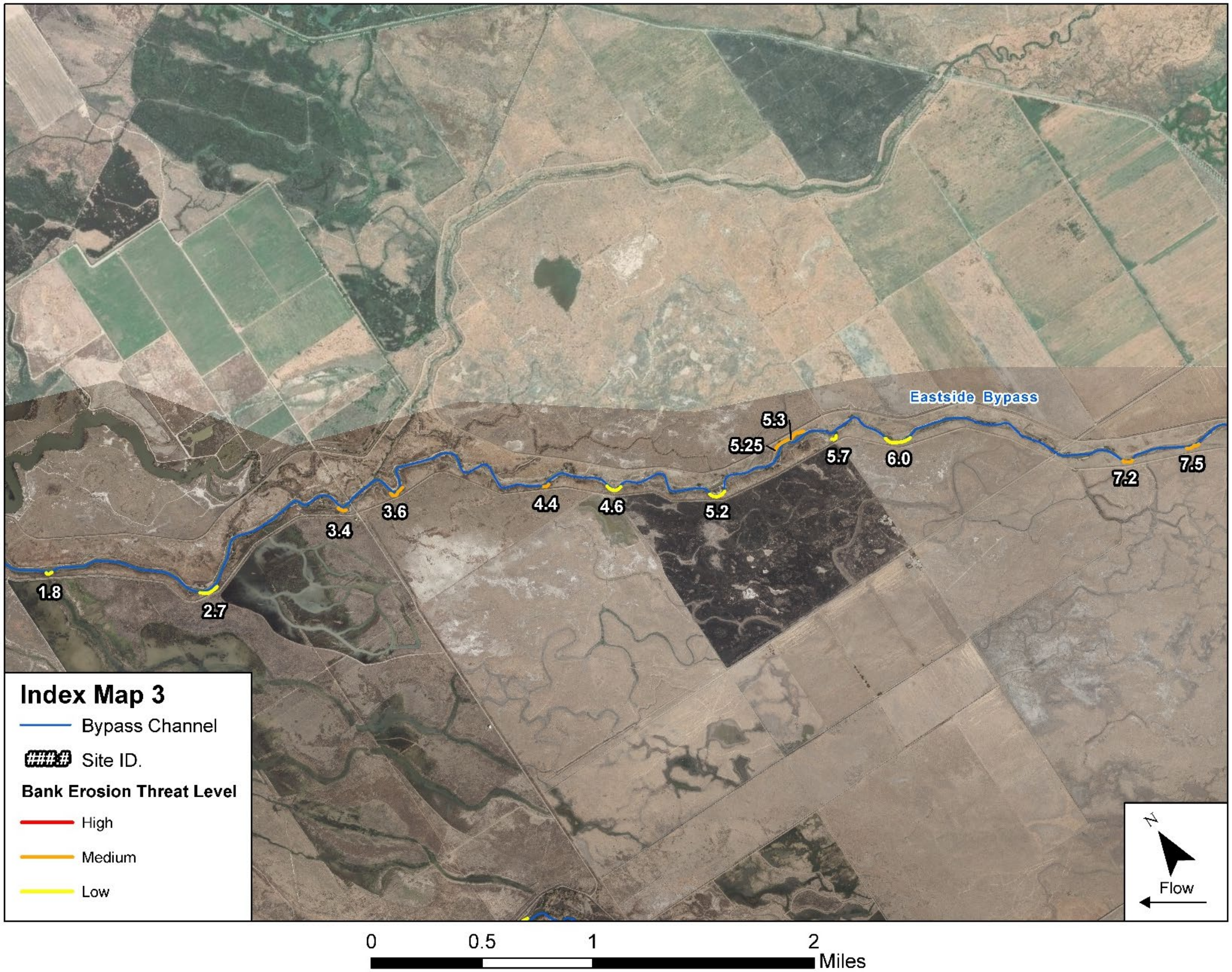

Figure 16 Index Map 4 with Overview of Footprint Identified in Figure 4

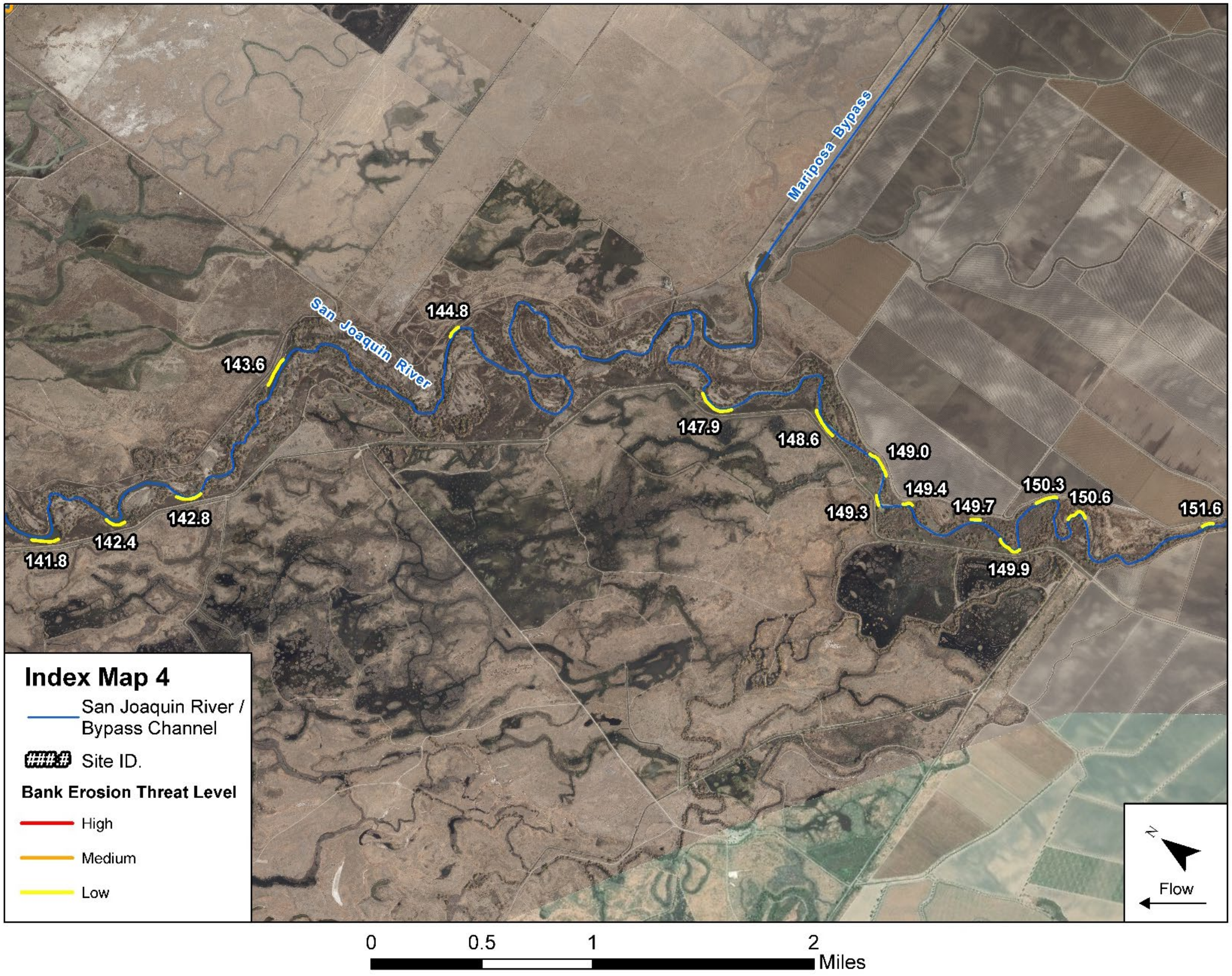

Figure 17 Index Map 5 with Overview of Footprint Identified in Figure 4

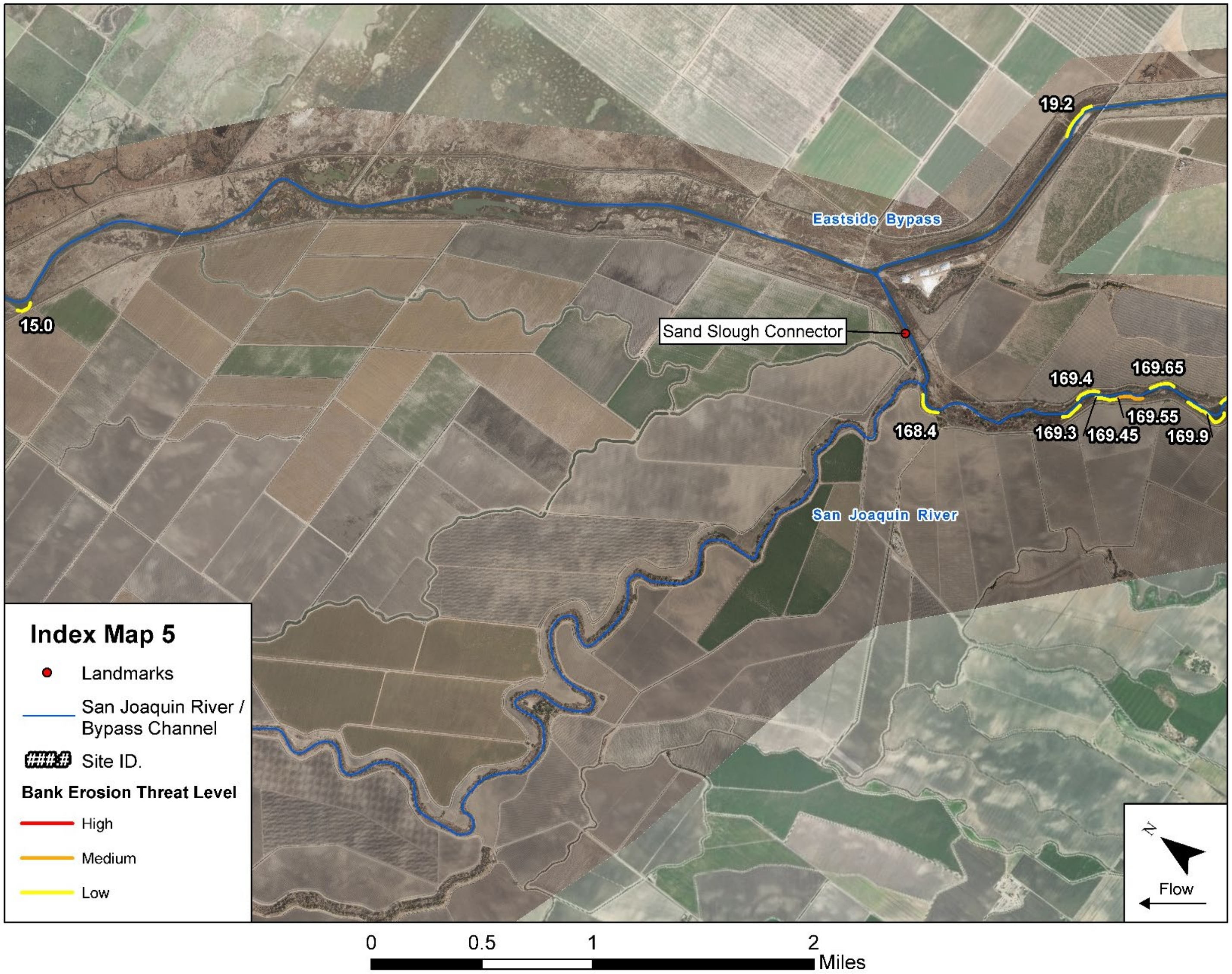

Figure 18 **Index Map 6 with Overview of Footprint Identified in Figure 4**

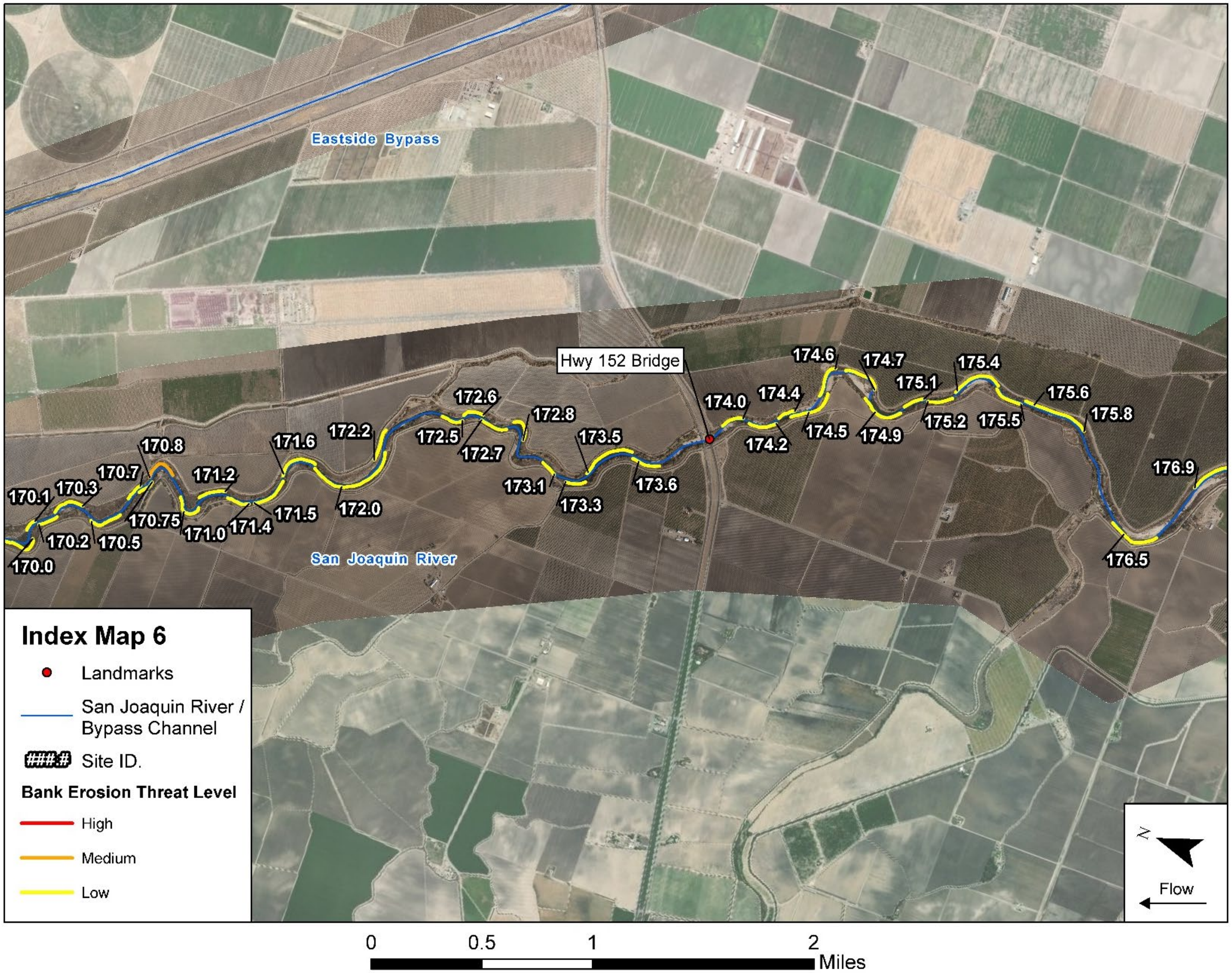

Figure 19 Index Map 7 with Overview of Footprint Identified in Figure 4

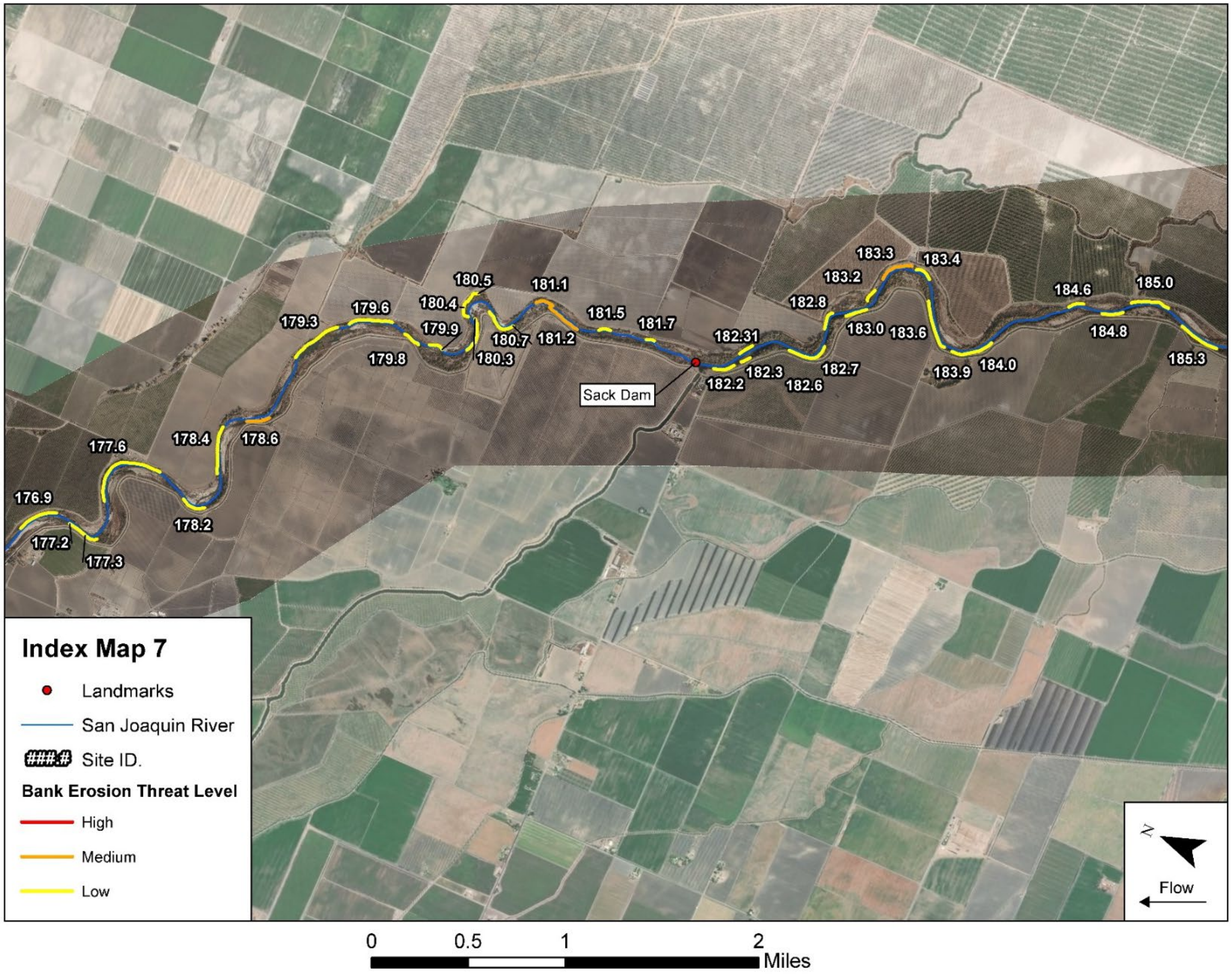

Figure 20 **Index Map 8 with Overview of Footprint Identified in Figure 4**

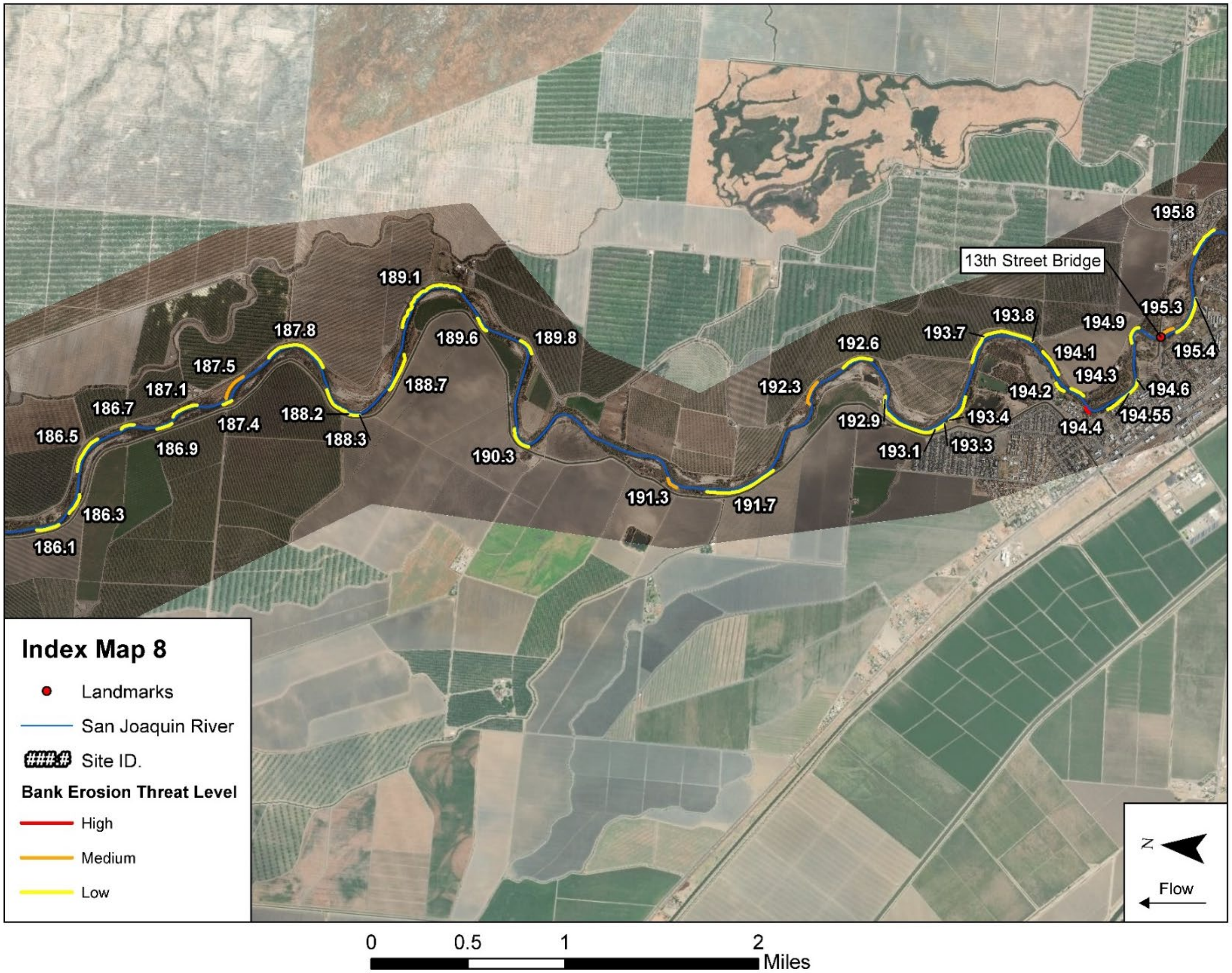

Figure 21 Index Map 9 with Overview of Footprint Identified in Figure 4

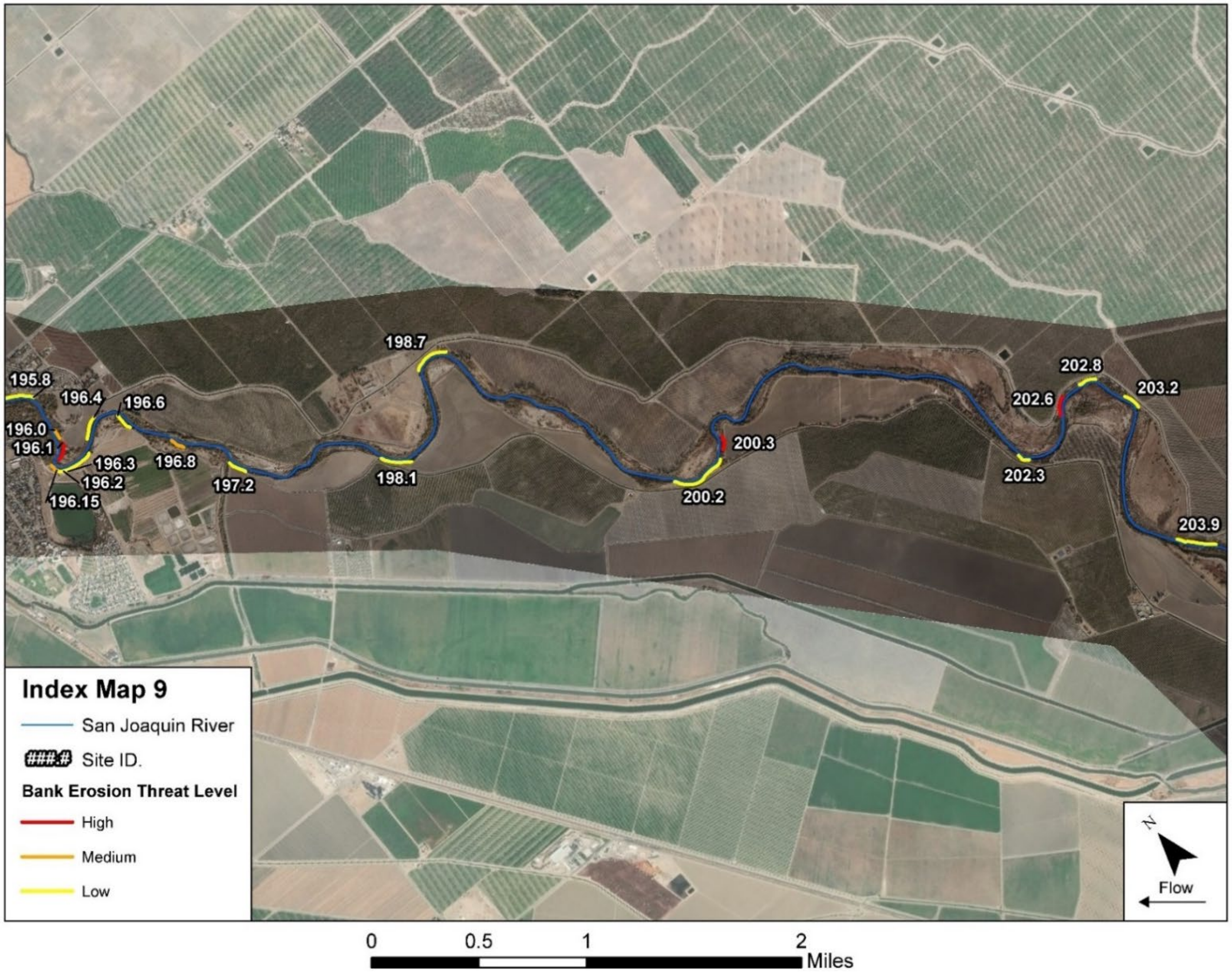

Figure 22 Index Map 10 with Overview of Footprint Identified in Figure 4

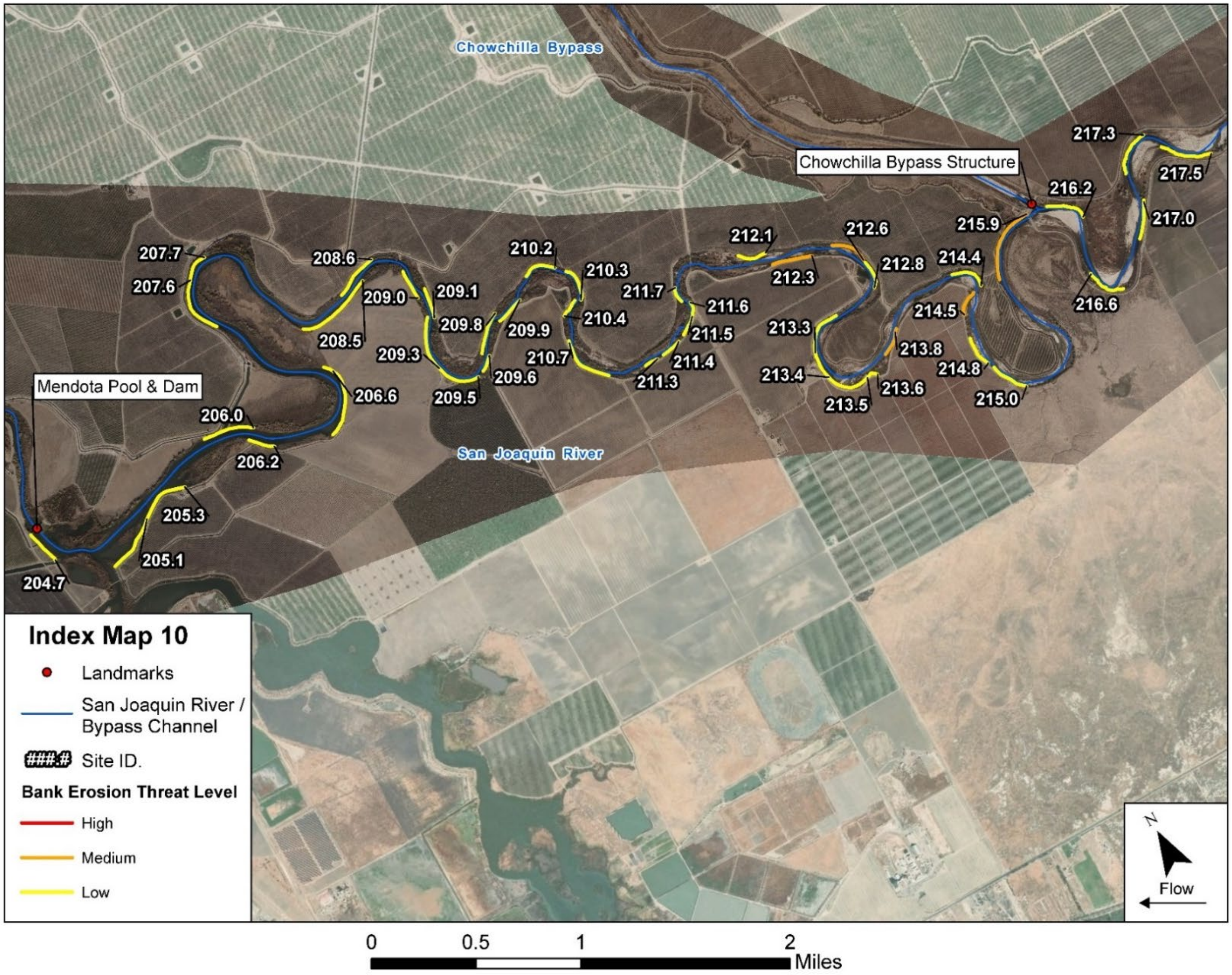

Figure 23 **Index Map 11 with Overview of Footprint Identified in Figure 4**

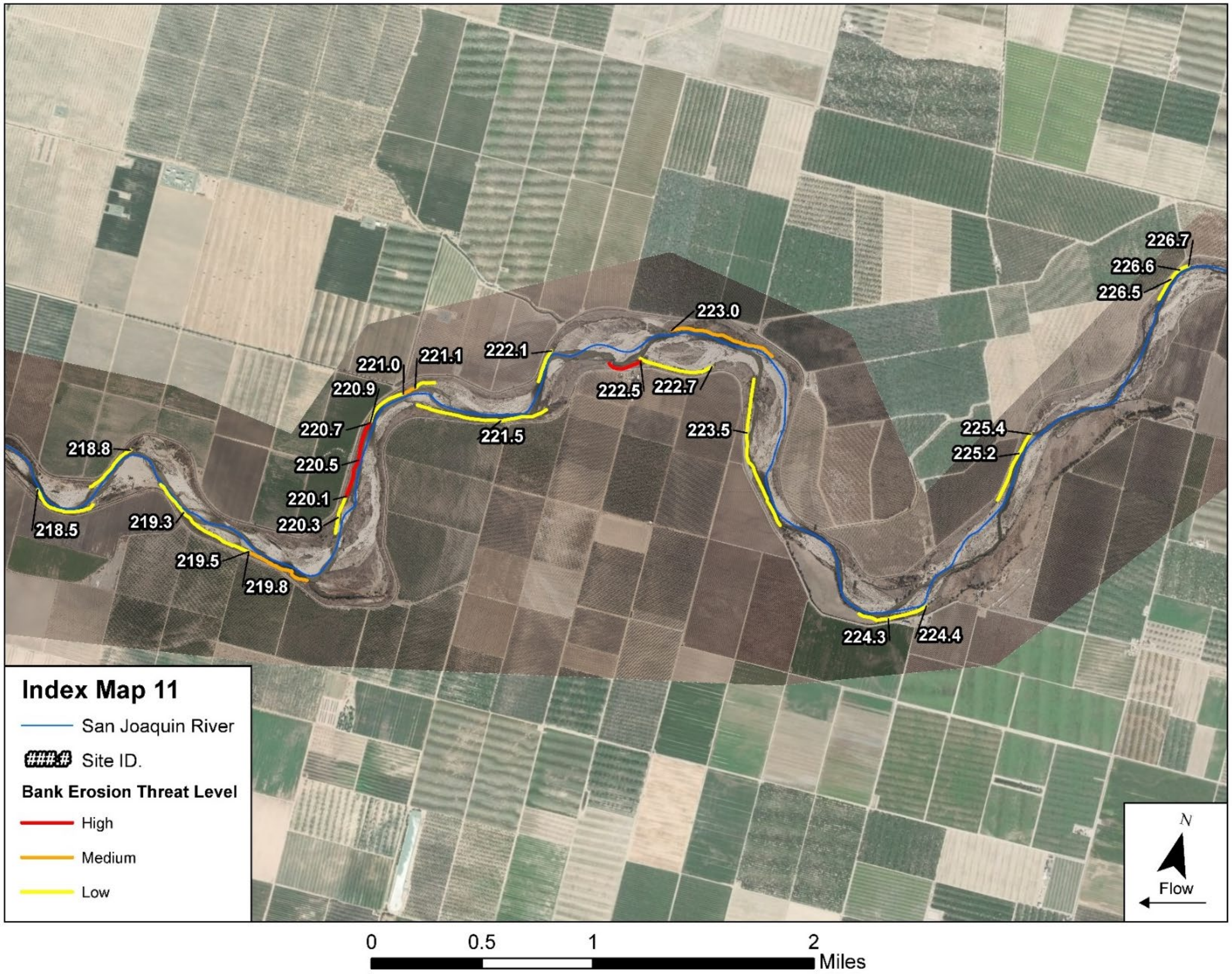

Figure 24 Index Map 12 with Overview of Footprint Identified in Figure 4