Lower Deer Creek Flood and Ecosystem Improvement Project
Geomorphology Analysis

DEER CREEK WATERSHED CONSERVANCY

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Prepared for
Deer Creek Watershed Conservancy

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April 20, 2021

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Introduction and Purpose

The Lower Deer Creek Flood and Ecosystem Improvement Project Geomorphology Analysis summarizes the geomorphic conditions in Lower Deer Creek and updates geomorphic analysis completed during previous studies on Lower Deer Creek. The analysis conducted in this report is intended to provide a summary of current channel and floodplain conditions in lower Deer Creek to help refine potential actions to improve anadromous fish habitat and flood control.

The Lower Deer Creek Flood and Ecosystem Improvement Project (Project) builds on monitoring work developed between 2001 and 2006 and documented in 2011 (DCWC et al., 2011). Updated analysis of Lower Deer Creek was required to characterize and quantify the current geomorphic and riparian vegetation conditions in the project area to better understand how the proposed project alternatives will impact the channel and floodplain. This analysis also provides supporting information for environmental documentation under CEQA and NEPA. Lastly, the baseline analysis conducted as part of the study will be used for future post-project evaluations related to habitat (channel, riparian, and floodplain) and flood management conditions. The purpose of this report is to summarize the geomorphic data collection, analysis, and conclusions.

Project Area

Lower Deer Creek is located in north-central California and is a tributary to the Sacramento River (Figure 1). Deer Creek has its headwaters in the high mountains near Lassen National Park and flows generally west to the Sacramento River near the town of Vina in Tehama County, California. Deer Creek flows into the Sacramento River about two miles west of the town of Vina. The geomorphic study extent includes Deer Creek and its floodplains and overflow channels between the confluence with the Sacramento River and the Deer Creek Irrigation District (DCID) diversion, approximately eleven miles upstream (see Figure 1). The Project vicinity extends from the confluence with the Sacramento River for approximately eight miles upstream, about two miles past Red Bridge (see Figure 2).

The Project objectives are to:

- Improve geomorphic function to increase the potential for more naturally-graded sediment composition and related channel form and the development of more diverse and ecologically complex riparian habitat.
- Increase rearing habitat for spring-run Chinook salmon.
- Increase flood conveyance capacity in the Deer Creek watershed and restore USACE levee freeboard conditions for a 21,000 cfs event.
- Minimize levee and channel flood control-related maintenance requirements, repairs, and costs.
- Minimize impacts to viable agricultural operations for landowners in the project area along Deer Creek.

Figure 2 is a summary of the elements included in the Project. These elements are described in detail in Chapter 3 of the Environmental Impact Report for the Project. The Project area includes (proceeding from downstream to upstream) the Abbey of New Clairvaux, the town of Vina, Highway 99, the Stanford-Vina Ranch Irrigation Company (SVRIC) Diversion Dam, Leininger Road Bridge (also known as the "Red Bridge"), and China Slough to the south of Deer Creek.

FIGURE 1: DEER CREEK WATERSHED IN NORTHERN CALIFORNIA AND THE STUDY REACH EXTENT FOR THE LOWER DEER CREEK FLOOD AND ECOSYSTEM IMPROVEMENT PROJECT.

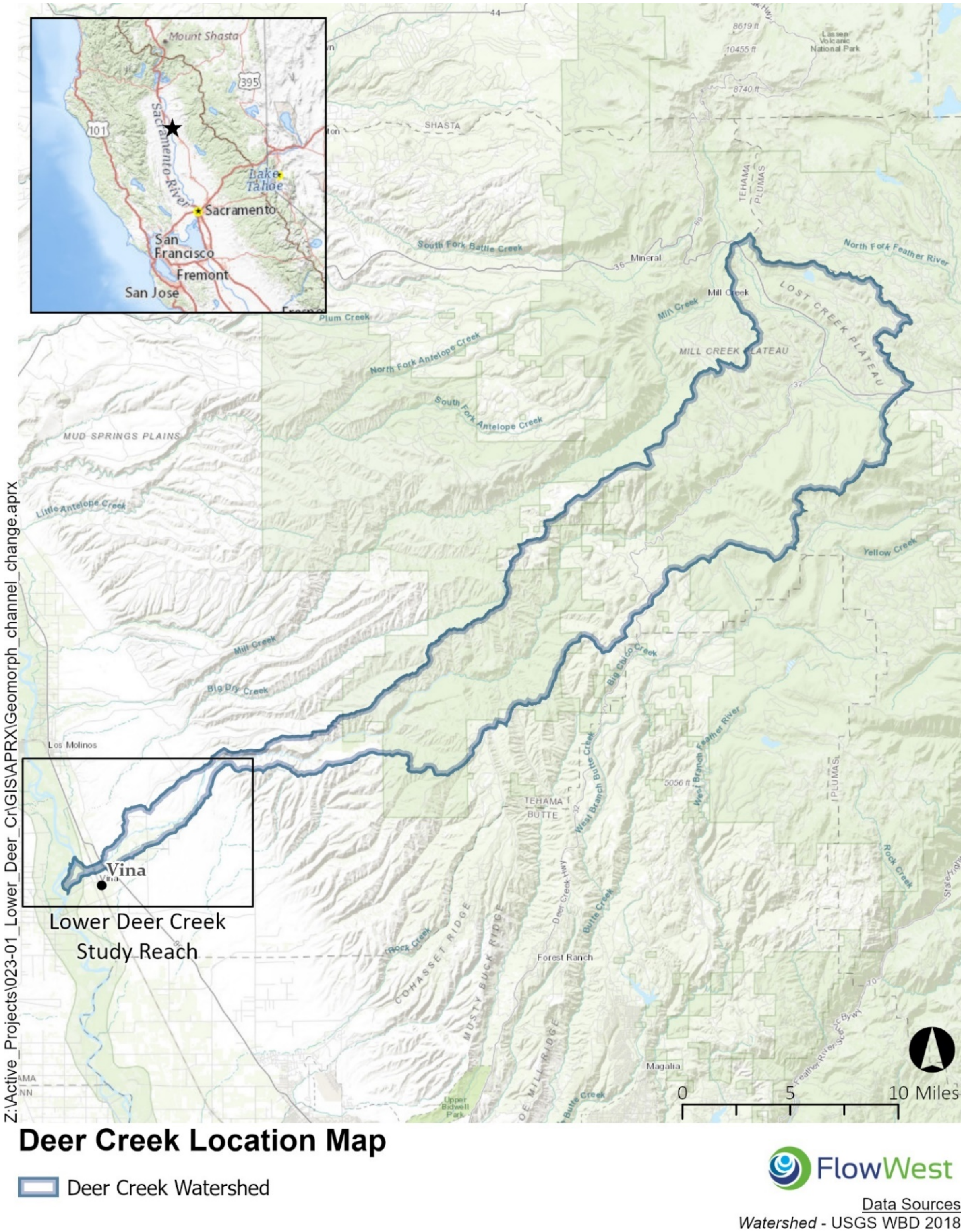
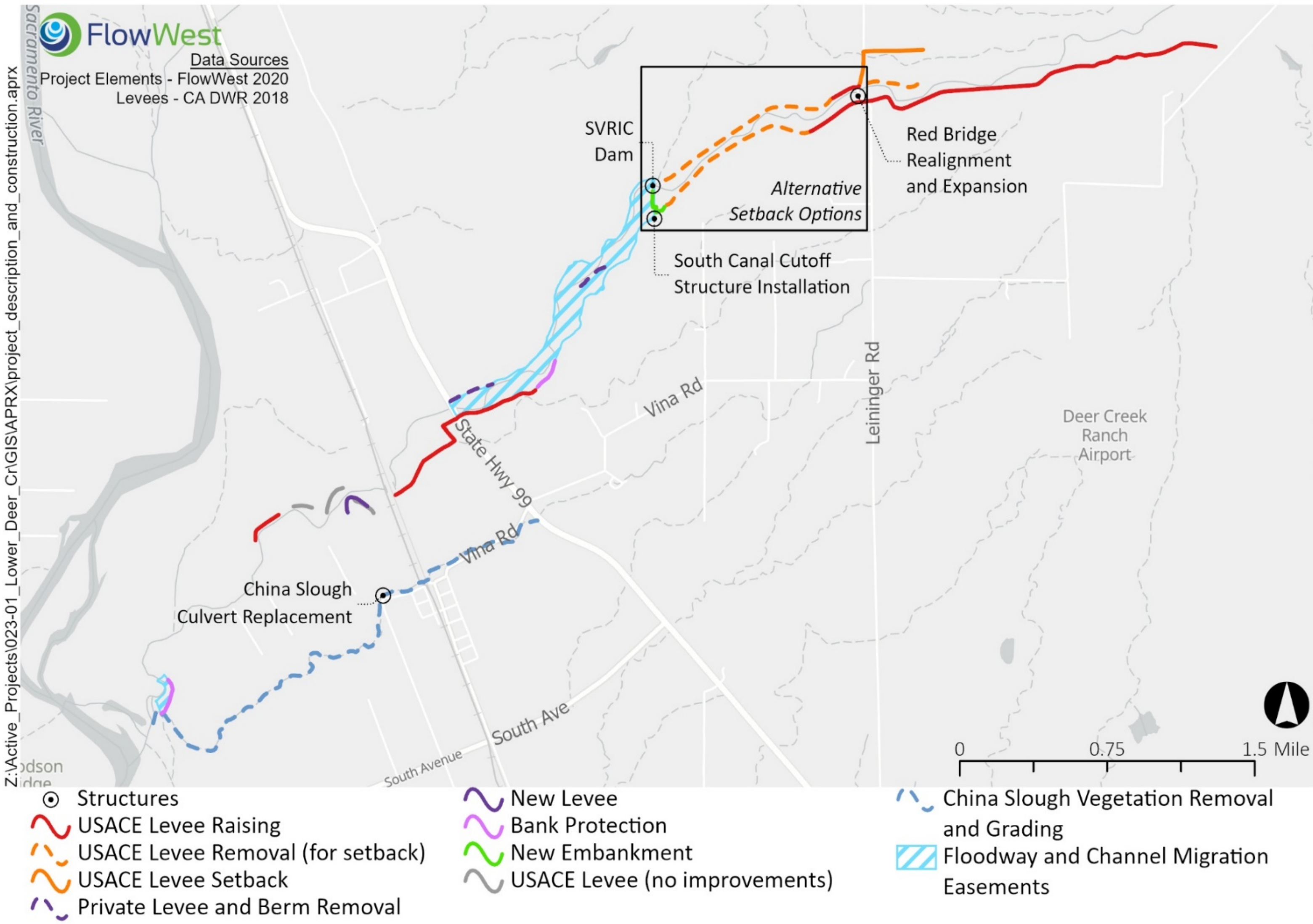


FIGURE 2: LOWER DEER CREEK FLOOD CONTROL AND RESTORATION PROJECT ELEMENTS AND EXISTING INFRASTRUCTURE.



Geomorphic Analysis

FlowWest conducted both hydrology and geomorphology assessments for this study and updated previous geomorphic analysis (CH2M Hill et al., 2005 and DCWC et al., 2011). FlowWest staff contributed to both previous analyses while working with other organizations. To complete this updated geomorphic analysis, FlowWest reviewed previous reports, conducted a site visit and topographic survey, and obtained additional aerial images for the project area. We obtained additional aerial imagery for 2006, 2009, 2014, 2016, and 2017. We also updated the hydrology analysis for the period of record from 1912 to 2017. This geomorphic analysis focuses on changes in channel form and riparian vegetation from comparisons of aerial images taken in 1938, 1985, 1999, 2006, and 2017. Using the most recent and historical aerial images, we conducted the following analyses:

- Channel Width Analysis - measured active Deer Creek channel width throughout the study area.
- Cumulative Channel Length Analysis - delineated the primary and secondary channels and summed lengths for each reach throughout the project area.
- Lateral Channel Migration Analysis - measured lateral migration at 3 locations (River Mile (RM) 2.5, 5.5, and 6.5).
- Flood Corridor Width Analysis – measured the width of the floodplain between bluffs, bedrock outcrops, terraces, levees, and other features throughout the project area.
- Riparian Vegetation Analysis - quantified the amount of riparian vegetation in proximity to Deer Creek throughout the project area.
- Shaded Riverine Aquatic (SRA) Analysis – measured the length of nearshore aquatic areas occurring at the interface between the creek channel and adjacent woody riparian habitat.

FlowWest utilized the same geomorphic reach (Figure 3) and levee (Figure 4) designations as previous studies (CH2M Hill et al., 2005 and DCWC et al., 2011) to facilitate comparisons of the results from this study with previous results.

FIGURE 3: GEOMORPHIC REACHES IN LOWER DEER CREEK AND THE LOCATION OF THE USGS GAGE USED FOR HYDROLOGIC ANALYSIS.

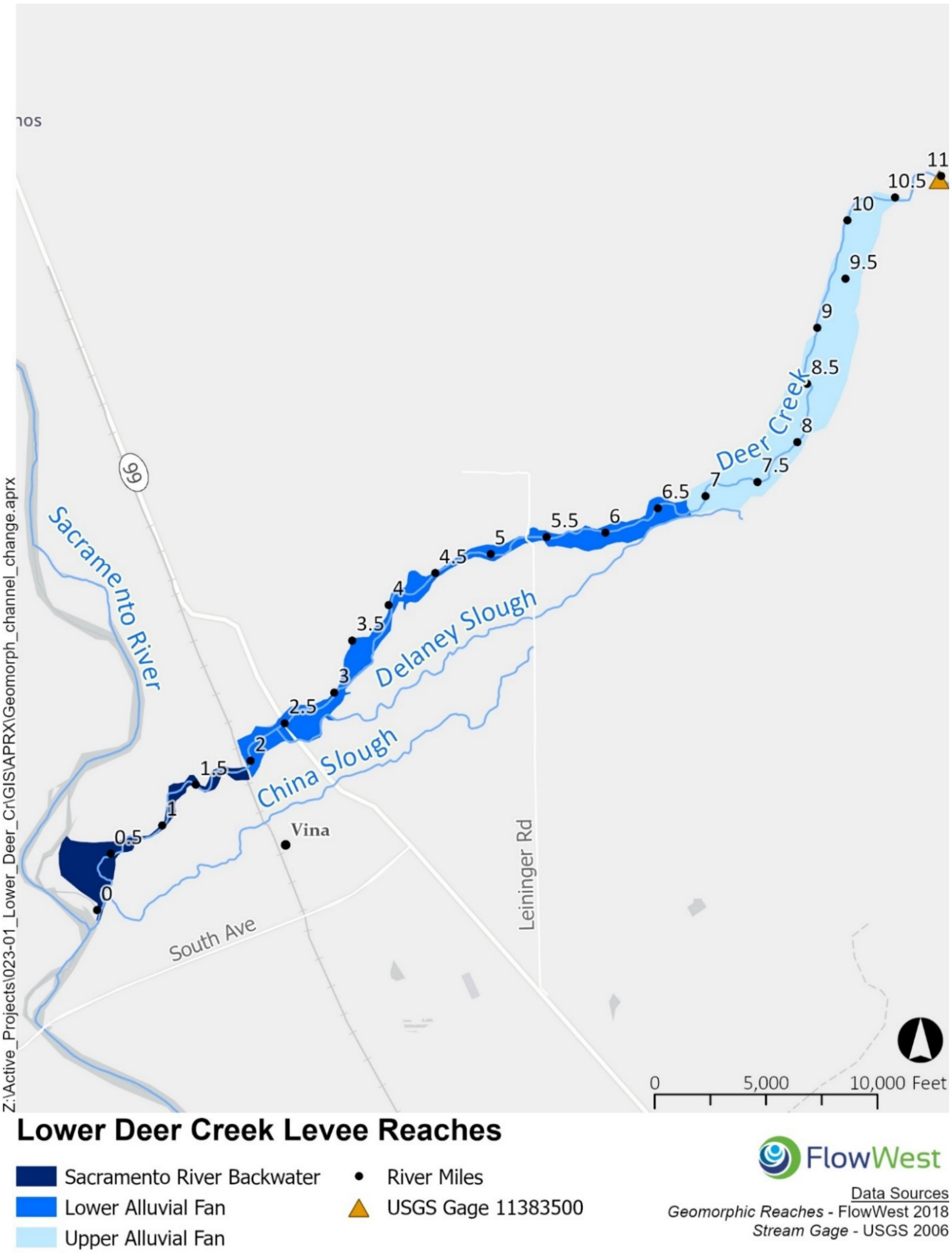
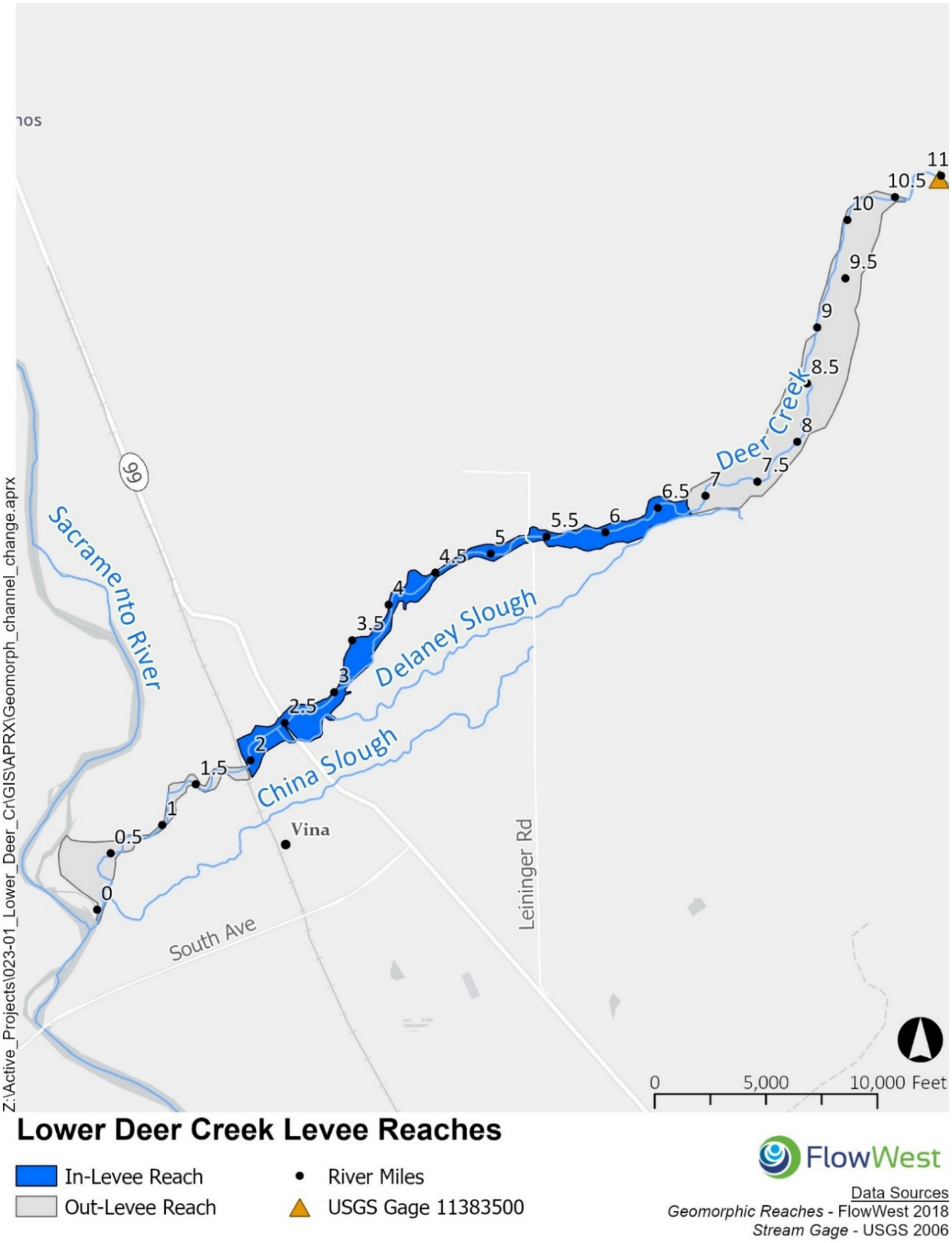


FIGURE 4: IN-LEVEE AND OUT-LEVEE REACHES AND THE LOCATION OF THE USGS GAGE USED FOR HYDROLOGIC ANALYSIS. THE IN LEVEE AND OUT-LEVEE REACHES COMBINE TO FORM LOWER DEER CREEK.



Summary of Conclusions

FlowWest developed the following conclusions regarding geomorphic processes in Lower Deer Creek. Lower Deer Creek channel morphology has been and continues to actively evolve. Hydrologic analysis from 1912 to 2017 and aerial imagery analysis from 1938 to 2017 shows a pattern of channel change after high flood flows. Historically, large flood flows have scoured vegetation from the channel, eroded channel banks, breached levees (post-1949), and flooded land adjacent to the creek. Riparian vegetation typically encroaches back into the Deer Creek active channel gradually until the next large flood flow resets channel and vegetation conditions again. The pre-levee channel appeared to experience significantly more moderate flood flow impacts than the post-levee channel. Aerial imagery from 1938 (pre-levee) was taken immediately after the second largest flood flow on record for Deer Creek but shows much less channel disturbance than large flows after construction of the levees along Deer Creek.

This finding suggests that the setback levee Project elements should reduce the magnitude and frequency of high flow impacts on the channel and flood control system, thereby improving both flood control and habitat conditions along Lower Deer Creek over the long term. Without improvements to the existing flood control infrastructure, Deer Creek will likely continue to breach levees and flood adjacent land. Damaging flooding has occurred along Deer Creek in 1964, 1969, 1970, 1971, 1974, 1983, 1986, 1997, 2005, 2012, and 2017. While the large-scale and widespread damage experienced during the 1997 flood has not been repeated since, this analysis suggests that when a similar magnitude flood occurs again it will cause even greater damage because of the significant increases in vegetation density that have occurred in Deer Creek since 1997.

The following sections detail analyses conducted on a variety of geomorphic conditions Deer Creek. These analyses interpret geomorphic conditions evident in aerial photography and the flow conditions immediately before aerial photographs were taken. The analyses evaluate conditions in the following years, most of which represent conditions after relatively high flows have occurred in Deer Creek.

- 1938 (after 1937 high flow and pre-levee project)
- 1985 (after 1982 high flow)
- 1999 (after 1997 high flow)
- 2006 (intermediate flow)
- 2017 (after 2016 high flow)

Channel Width Change

This study measured active channel widths at regularly spaced transects along the Project area. Active channel width in this area has decreased approximately 18% from 1938 to 2017. The active channel shows a pattern of widening during high flow events followed by riparian vegetation encroachment until the next high flow. Between 1999 (after the 1997 flood of record) and 2017, the active channel width decreased by approximately 44% in the Project area. This reduction in channel width after the 1997 flood illustrates the general pattern of flood induced scour and erosion followed by vegetation encroachment that repeats cyclically in Deer Creek.

Channel Length Change

This study delineated the primary and secondary channels and summed lengths for each reach in the Project area. The cumulative channel length has generally decreased and the planform channel pattern has become straighter over time in Lower Deer Creek. The channel length from 1938 to 2017 decreased by 20% in the Project area, with a greater decrease in levee-confined reaches. This consistent decrease in channel length has reduced channel complexity, which has reduced suitable habitat for salmonids. Setback levees are expected to increase channel complexity for habitat and increase overall channel length.

Lateral Channel Migration

This study measured active channel migration at representative transects in the Project area. These measurements clearly show that Lower Deer Creek actively migrates within its riparian corridor. Lateral channel migration measurements from historical aerial imagery show migration of 493, 212, and 403 ft at three sites. Without sufficient space to accommodate this magnitude of channel migration, erosion and scour that would otherwise just shift the location of vegetation and geomorphic features instead damages adjacent infrastructure like levees and bridges.

Flood Corridor Width

This study measured the width of the available floodway for high flows in the Project area. While flood flows have historically overtopped or flanked levees, the measurements in this study were not carried beyond levees in leveed reaches. Flood corridor width decreased thousands of feet with the completion of the levee system. Since completion of the levee system there has been no significant increase in the flood corridor width between bluffs, bedrock outcrops, terraces, and levees.

Riparian Vegetation Change

This study digitized riparian vegetation in the Lower Deer Creek corridor to quantify the extent of contiguous riparian vegetation adjacent to the active channel. Riparian vegetation area decreased approximately 38% between 1938 and 2017. However, riparian vegetation area increased approximately 35% from 1999 to 2017 in the leveed reaches, demonstrating the typical vegetation encroachment pattern that occurs between high flows on Deer Creek. Overall, this study quantified a significant reduction in riparian vegetation area in the leveed reaches of Lower Deer Creek between 1938 and 2017, even with the increase in riparian vegetation between 1999 to 2017. The results of this study suggest that a significant portion of the riparian vegetation along Lower Deer Creek will be scoured out of the active channel during the next major flood in leveed reaches.

Shaded Riverine Aquatic Habitat Change

This study delineated Shaded Riverine Aquatic (SRA) habitat, defined as nearshore aquatic areas occurring at the interface between the river and adjacent woody riparian habitat. SRA decreased 21% in leveed reaches and increased 29% in non-leveed reaches between 1938 and 2017. These changes provide a rough quantification of the impacts of the existing flood control infrastructure on near-shore habitat that is important for salmonids. It also indicates the Project elements like levee setbacks could restore SRA while at the same time making flood control infrastructure more reliable and less dependent on maintenance.

Taken together, the results of this geomorphic analysis demonstrate the potential of setback levees, easements, remnant levee removal, and other Project elements to yield more natural geomorphic processes and increase habitat for salmonids and other species in the Lower Deer Creek corridor. Project elements (primarily setback levees) will also likely allow for the development of a riparian corridor that is more similar to non-leveed reaches of Lower Deer Creek, potentially resulting in development of a more extensive and diverse riparian corridor with more complex habitat for salmonids and an improved flood control system with limited maintenance needs.

Introduction and Purpose

Deer Creek is located on the East side of the Sacramento Valley north of Chico, California. Deer Creek flows through the rugged foothills of the Ishi Wilderness, onto the plains occupied by multi-generational family farms and ranches, and joins the Sacramento River near Vina, California. The project reach covers approximately 10.5 miles of Lower Deer Creek from the confluence with the Sacramento River to the Deer Creek Irrigation Company diversion dam (Figure 1). Deer Creek is one of California's last remaining native spring-run Chinook salmon streams.

The purpose of this report is to summarize the geomorphic data collection, analysis, and conclusions in support of environmental compliance documents to advance the implementation of multi-benefit improvements on Lower Deer Creek. The Lower Deer Creek Flood and Ecosystem Improvement Project Geomorphology Analysis summarizes the geomorphic conditions in Lower Deer Creek and provides the geomorphic basis for the project to improve habitat conditions and reduce maintenance of the existing levee project. This report updates geomorphic analysis completed in previous reports from 2001, 2005 (CH2M Hill et al., 2005), and 2011 (DCWC et al., 2011), and focuses on geomorphic processes that impact channel and floodplain conditions to improve anadromous fish habitat and flood control. An understanding of the current geomorphic condition of Lower Deer Creek is needed to characterize and quantify the current geomorphic and riparian vegetation conditions in the project area to better understand how the proposed project alternatives will impact the channel. The analysis completed for this report will support CEQA and NEPA environmental documentation, and the geomorphic baseline documented in this report will be used as a basis for comparison in future monitoring and post-project evaluations related to habitat and flood management improvements.

Geomorphic Setting

The geomorphic setting of Lower Deer Creek has been described in previous reports by the Deer Creek Watershed Conservancy (DCWC) (1998 and 2011) and CH2M Hill (2005). This analysis adds to the previous work and updates the documentation with new data reflecting current conditions. A detailed treatment of the geology of the Deer Creek Watershed is provided in USGS professional papers by Helley and Harwood (1985) and Harwood and Helley (1987), as cited in the Deer Creek Watershed Management Plan (DCWC 1998). FlowWest founder and principal engineering geomorphologist Mark Tompkins was a primary author of the CH2M Hill (2005) and DCWC (2011) reports summarized in this section. In addition, FlowWest principal Anthony Falzone was a primary author of the CH2M Hill (2005) report.

Deer Creek drains the slopes of Mount Lassen and originates south of Lost Creek Meadows at 6,200 feet. Tributaries in the upper watershed area include Lost Creek and Gurnsey Creek. Downstream of the meadows, Deer Creek flows into a deeply incised canyon underlain by the

Tuscan Formation that is comprised of ancient volcanic mudflows (Ely 1994 as cited in DCWC 1998). The channel form in the canyon is controlled by bedrock outcrops and channel width is controlled by the canyon walls (DCWC 1998). Immediately downstream of the incised canyon, Deer Creek flows out onto its alluvial fan. This reach of Deer Creek is referred to as Lower Deer Creek and extends from the mouth of the canyon at RM 10.5 to the confluence with the Sacramento River at RM 0.0. Lower Deer Creek is the focus of this analysis. Lower Deer Creek's natural, unconfined condition, is a high-energy, dynamic system that migrates across the available floodplain (CH2M Hill 2005).

In the upper section of the alluvial fan (from RM 10.5 to RM 6.5), Deer Creek is incised in cemented alluvium units (Riverbank Formation, Red Bluff Formation, and older terrace gravels). The alluvial fan is bounded by bluffs formed of older geologic units, and Deer Creek actively migrates across the fan. From approximately RM 6.5 to RM 2.0, Deer Creek flows through a more confined and stable corridor on the alluvial fan (CH2M Hill 2005). In the lower section of the alluvial fan (from RM 2.0 to RM 0.0) the channel morphology is strongly influenced by the backwater from the Sacramento River.

Historically, the primary Lower Deer Creek channel has shifted over centuries or millennia to alternate channels still visible on the alluvial fan topography and in historical aerial photographs and maps that show characteristic multiple channels radiating out across the alluvial fan (CH2M Hill 2005). Lower Deer Creek has occupied essentially the same flood channel in this area for the last 100 years. This analysis focuses on the existing channel alignment in the riparian corridor.

The existing flood control project on Deer Creek was completed in 1949, and the project includes levees on both banks of Deer Creek from the Delaney Slough overflow downstream to the Sacramento River (Figure 2). The flood control project has a design flow capacity of 21,000 cfs (approximately a 50-year flow) with three feet of freeboard (USACE 1957). Channel clearing during construction of the project and prescribed maintenance after construction appear to have significant impacts on channel morphology. Additionally, channel banks have been armored in some locations over the years. The floodplain area located approximately 2 miles upstream of the Stanford Vina diversion dam downstream to the Sacramento River are mostly designated as being in FEMA flood zone A (100-year flood areas where base flood elevations and flood hazard factors have not been determined). In addition to the 1949 flood control project infrastructure, private flood control infrastructure is also present on Lower Deer Creek. Private levees include, but are not limited to, the private levees constructed in 1970 approximately one-half mile upstream of the Red Bridge on the south bank along the Soske property, levees built of cobbles after the 1997 flood on the south bank along the Soske property, bank armoring along the north bank downstream of the Highway 99 bridge adjacent to the Rumiano property, and rock groins along the north bank adjacent to the Robinson property (CH2M Hill 2005).

There are three diversion dams located on Lower Deer Creek. The largest diversion dam is the Stanford Vina diversion dam, which is approximately 10 feet high. Gravel and cobble transported from upstream completely has aggraded to the crest of the dam and it is periodically excavated to maintain diversion operations. The dam locally controls channel gradient and impacts sediment transport during relatively low peak flows. Upstream, the Cone-Kimball diversion dam, a small seasonal structure composed of native creek cobble does not appear to significantly impact gradient or sediment transport characteristics. The upstream-most diversion dam is located at the mouth of the canyon. This dam was also a seasonal dam composed of flashboards and operated by the Deer Creek Irrigation District (DCID) until it was replaced by a roughened rock ramp diversion structure in 2019. The new dam moderately controls local gradient but has limited impact on sediment transport (CH2M Hill 2005).

Ongoing maintenance of the 1949 flood control project to maintain flood conveyance has impacted the Lower Deer Creek channel. Previous work (CH2M Hill 2005) documents the following significant maintenance projects:

- Sand and gravel removal project conducted by the Department of Water Resources (DWR) between 1984 and 1987. Approximately 60,000 cubic yards of bed material (mostly gravel) were removed in 1984 from the reach between Highway 99 and the Sacramento River.
- Low flow channel excavation and levee reinforcement downstream of Leininger Bridge in 1985.
- Removal of approximately 45,000 cubic yards of bed material between Stanford Vina Dam and Highway 99 in the summer of 1986.
- Rock weir construction downstream of SVID dam in 1986 to improve fish passage.
- Setback levee construction on the south bank downstream of Leininger Road Bridge after the original levee failed during the peak flow in February of 1986.
- Removal of approximately 30,000 cubic yards of riverbed material between Stanford Vina dam and Leininger Road Bridge and 8,000 cubic yards downstream of the dam in 1986.

Geomorphic Reaches

This study adopts the geomorphic reach designations proposed in previous reports (CH2M Hill 2005, DCWC 1998) for Lower Deer Creek (Figure 3). These reach designations were based on bed slope, average active channel width, average floodway width, bed particle material sizes, and riparian vegetation characteristics. The three geomorphic reaches of Lower Deer Creek include:

- Sacramento River Backwater (RM 0.0 to RM 2.0) where the channel is incised in Sacramento River floodplain deposits and influenced by backwater from the Sacramento River
- Lower Alluvial Fan (RM 2.0 to RM 6.5) where Deer Creek is confined by flood control infrastructure
- Upper Alluvial Fan (RM 6.5 to RM 10.5) where the Deer Creek corridor is bounded by bluffs and Deer Creek actively migrates across the floodplain

As geomorphic conditions change continuously throughout Lower Deer Creek, the geomorphic characteristics at the reach boundaries do not show an abrupt change from one reach to the next. The following sections briefly describe each geomorphic reach to illustrate the changes in channel conditions between geomorphic reaches and to provide a broad framework for the more detailed discussion of channel morphology in the following sections and a general guide for evaluating flood management and habitat restoration measures going forward.

Sacramento River Backwater (RM 0.0 to RM 2.0)
The Sacramento River Backwater Reach extends from the confluence with the Sacramento River to the Union Pacific Railroad (UPRR) bridge near RM 2.0 (Figure 3). The slope of the reach is 0.34% (CH2M Hill 2005), which is the flattest of the three geomorphic reaches. The Sacramento River Backwater geomorphic reach also has the narrowest average floodway width of 281 ft (CH2M Hill 2005) as the channel cuts through Sacramento River floodplain deposits. The Sacramento River Backwater reach also has the smallest median (D_{50}) bed material particle size range of 14-42 mm (CH2M Hill 2005) and the channel transitions from a sand bend to a gravel bed at approximately RM 1.5. Channel characteristics common to most locations in this reach include finer bed material, relatively high and steep banks, and a mature band of riparian vegetation in the riparian corridor (CH2M Hill 2005).

Lower Alluvial Fan (RM 2.0 to RM 6.5)
The Lower Alluvial Fan Reach extends from the Union Pacific Railroad (UPRR) bridge near RM 2.0 to RM 6.5 (Figure 3). The slope of the reach steepens to 0.48% (CH2M Hill 2005). This reach has an average floodway width of 401 ft (CH2M Hill 2005) as the channel is confined by flood control infrastructure. The Lower Alluvial Fan Reach has a median (D_{50}) bed material particle size range of 45-116 mm (CH2M Hill 2005). The reach is characterized by a relatively narrow band of mature riparian vegetation along the active channel, which is confined by the USACE levee project and reduces channel migration as compared to the Upper Alluvial Fan geomorphic reach. The Lower Alluvial Fan geomorphic reach is the most vulnerable to flooding in Lower Deer Creek. Construction of the USACE levees and maintenance of the project has resulted in an overall lack of complexity for channel morphology and riparian vegetation in this reach (CH2M Hill 2005).

The Leininger Road Bridge (Red Bridge) and the UPRR Bridge further confine the channel in the Lower Alluvial Fan Reach. The Highway 99 Bridge has a much wider span than the Leininger Road Bridge upstream and the UPRR Bridge downstream. The Highway 99 Bridge has less of an impact on upstream and downstream channel morphology than the UPRR and Leininger Road bridges. Wide-span bridges such as the Highway 99 Bridge with fewer piers in the active channel offer a good model for future river crossing improvements on Lower Deer Creek. The Stanford Vina Irrigation dam is located in the Lower Alluvial Fan Reach and acts as a local gradient control. Sediment upstream of the dam is periodically removed to maintain operation of irrigation diversions on both sides of Lower Deer Creek. Coarse and fine sediment and large woody debris (LWD) is transported to and over the dam during peak flows. Therefore, the downstream impacts of the dam on fluvial geomorphic process are relatively minor (CH2M Hill 2005) outside of the area immediately downstream of the dam where a large, deep scour pool has been formed and maintained by high flows over the dam. During high flows, the dam increases backwater elevations upstream and adversely affects the conveyance capacity of the upstream floodway and levee system (DCWC 2011).

Upper Alluvial Fan Reach (RM 6.5 to RM 10.5)

The Upper Alluvial Fan Reach extends from the RM 6.5 to RM 10.5 at the mouth of the Deer Creek Canyon (Figure 3). The slope of this reach steepens to 0.68% (CH2M Hill 2005), which is the steepest of the three geomorphic reaches. This reach also has the widest average floodway width of 1,122 ft (CH2M Hill 2005) as the channel has relatively shallow channel banks and overbank flow occurs quite regularly. The Lower Alluvial Fan Reach also has the largest median (D_{50}) bed material particle size range of 45-190 mm (CH2M Hill 2005). The bed of the reach is characterized by large cobble transported from the Deer Creek Canyon and deposited along this high gradient reach. Bluffs bound the wide flood corridor, but the channel is mostly unconfined except for private (non-USACE) levees. Unlike the USACE levees, the private levees are mostly constructed of native riverbed materials pushed up by heavy equipment. The private levees are vulnerable to failure during high flows. Riparian vegetation ranges from relatively sparse patches beyond the active channel where the channel frequently shifts and scours vegetation to dense, older, and extensive patches in more protected areas (CH2M Hill 2005).

Geomorphic Impacts

Modifications to Lower Deer Creek through alteration of the channel and banks, construction of levees, and disturbance of riparian vegetation for maintenance of the flood control project has degraded habitat diversity and complexity. Deer Creek provides habitat for endangered spring-run Chinook salmon (Oncorhynchus tshawytscha), fall-run Chinook salmon, and steelhead (O. mykiss). Fall-run Chinook salmon spawn in Lower Deer Creek. Spring-run Chinook and steelhead spawn further upstream. Degraded conditions in Lower Deer Creek affect passage of adult and juvenile spring-run Chinook and steelhead, limit in-watershed rearing of juvenile salmonids, and can affect the suitability of Lower Deer Creek as non-natal rearing habitat for winter-run Chinook and other species (DCWC 2011). Lower Deer Creek is one of three stream that still supports a viable, wild population of federally threatened spring-run Chinook salmon (Campbell and Moyle 1991 and National Marine Fisheries Service 2000, as cited in DCWC 2011). In addition to degradation of habitat, hydraulic analysis of the USACE flood control project indicated that the project does not have the capacity to convey the design flow of 21,000 cfs with three feet of freeboard for almost the entire length of the flood control project (DCWC 2011). This finding is consistent with updated two-dimensional hydraulic modeling conducted in support of the current Project.

GEOMORPHIC ANALYSIS

FlowWest conducted both hydrology and geomorphology assessments for this assessment and updated previous geomorphic analysis (CH2M Hill et al 2005 and DCWC et al 2011). For this analysis we reviewed previous reports, completed a site visit and topographic survey, and obtained additional aerial images for the project area. We obtained additional aerial imagery for 2006, 2009, 2014, 2016, and 2017. We updated the hydrology analysis for a complete period of record from 1912 to 2017 and have aerial imagery that spans the period from 1938 to 2017. The geomorphic analysis focuses on changes in the channel form and riparian vegetation in 1938, 1985, 1999, 2006, and 2017. Using the most recent and historical aerial images (Table 1: Historical Aerial Photographs Used for this Project), we conducted the following analysis:

- Channel Width Analysis - measured active channel width along the study area
- Cumulative Channel Length Analysis - delineated the primary and secondary channels and summed lengths for each reach in the project area
- Lateral Channel Migration - measured lateral migration at 3 locations (RM 2.5, 5.5, and 6.5)
- Flood Corridor Width Analysis – measured the width of the floodplain between bluffs, bedrock outcrops, terraces, levees, and other features
- Riparian Vegetation Analysis - quantified the amount of riparian vegetation in proximity to Deer Creek in the project area
- Shaded Riparian Aquatic Analysis – measured the length of nearshore aquatic areas occurring at the interface between a river and adjacent woody riparian habitat

For each analysis, we summarized the purpose of the analysis, the methods we used, and the results.

TABLE 1: HISTORICAL AERIAL PHOTOGRAPHS USED FOR THIS PROJECT.

Year	Date	Scale	Discharge at Vina Gage (cfs)
1938	9/13	1:20,000	Approximately 100
1952	7/4 - 8/19	1:24,000	158 - 265
1966	5/16 - 6/15	1:20,000	118 - 187
1985	10/15	1:9,600	92
1998	8/11	1:144,000	97
1999	5/11	1 ft / pixel	399
2006	6/20	4 in / pixel	250
2009	7/3	1 m / pixel	98
2014	8/16	1 m / pixel	65
2016	7/10	2 ft / pixel	91
2017	10/31	6 in / pixel	125

Hydrology

The purpose of this section is to describe and set the context for the impact of hydrology on the interpretation of the existing geomorphic and riparian vegetation conditions and the changes observed over time.

Methods

We downloaded peak discharge data from the USGS gauge 11383500 (Deer Creek near Vina). We plotted the annual peak discharge for each water year for the period of record from 1912 to 2017. We also conducted a flood frequency analysis based on USGS Bulletin 17B (USGS 1982).

Results

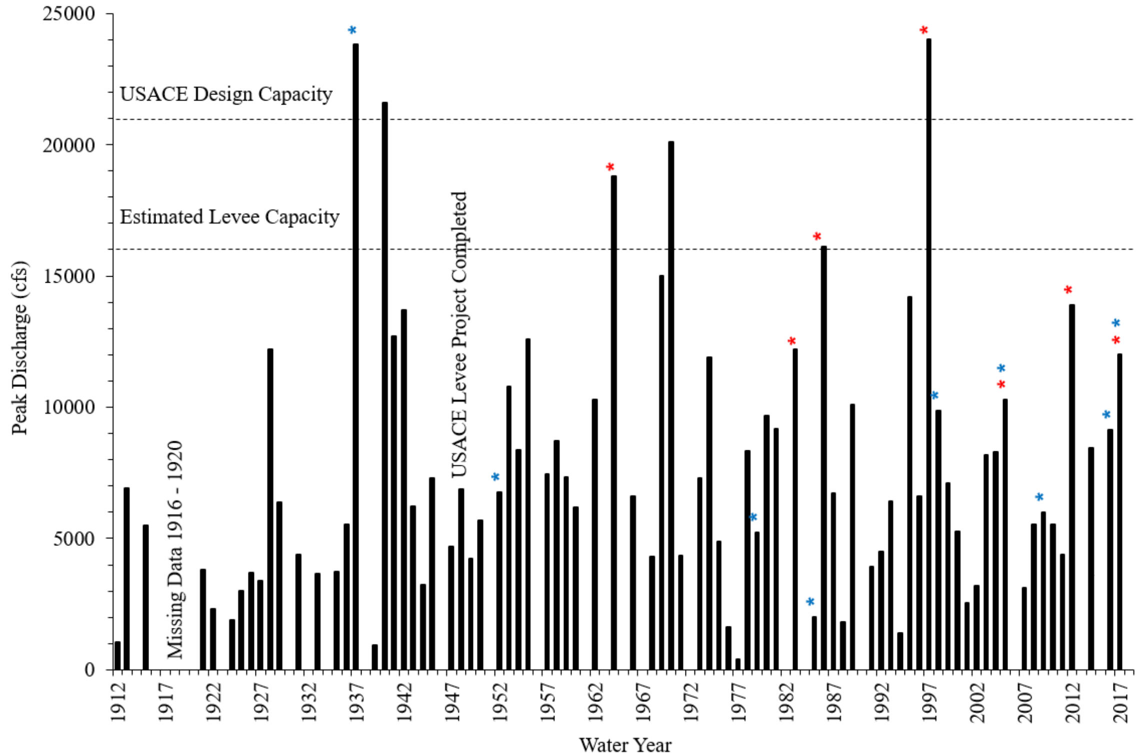
Flood flows have caused damages to property and flood control infrastructure along Lower Deer Creek since the completion of the USACE flood control project in 1949. Flows below the design capacity of 21,000 cfs have resulted in levee overtopping and damage to flood control infrastructure. Confined flood flows have scoured riparian vegetation and altered the channel form. These impacts have degraded habitat diversity and complexity, including habitat for spring-run Chinook salmon. The surrounding community in Tehama County is at risk of flooding, continued ecological impairment. Without improvements to the Lower Deer Creek corridor, levee overtopping and damage to flood-control structures will almost certainly continue to occur.

We downloaded the annual peak flow rates recorded at USGS gauge 11383500 (Deer Creek near Vina) and plotted the annual peak discharge by water year (Figure 5). We annotated Figure 5 to show the completion of the USACE levee project in 1949 and identified the design levee capacity of 21,000 cfs and the estimated levee capacity of 16,000 cfs. Figure 5 shows that 1938 and 1997 were the two largest flow events on record of 23,800 and 24,000 cfs, respectively. The 1997 flood caused numerous levee breaches, damaged bank protection, and resulted in costly damages to infrastructure (DCWC 2011).

We identified a pattern of large flows that significantly alter the channel and floodplain vegetation in Lower Deer Creek followed by a period of low flows that allows vegetation to encroach into the active channel, causing changes in channel geometry and roughness. These large flow events effectively “reset” geomorphic conditions. This dynamic is described in greater detail in the analysis sections below.

Since completion of the USACE Flood Control Project, peak flows that caused damage were documented in 1964 (18,800 cfs), 1969 (15,000 cfs), 1970 (20,100 cfs), 1974 (11,900 cfs), 1983 (12,200 cfs), 1986 (16,100 cfs), 1997 (24,000 cfs), 2006 (10,300 cfs), 2012 (13,900 cfs), and 2017 (12,000 cfs). The most recent period of relatively low flows between 1998 and 2017 has allowed riparian vegetation to encroach significantly into the Lower Deer Creek corridor.

FIGURE 5: DEER CREEK ANNUAL PEAK DISCHARGES RECORDED AT USGS GAGE #11383500 – DEER CREEK NEAR VINA, CA. THIS FIGURE IDENTIFIES THE YEAR (1949) THAT THE U.S. ARMY CORPS OF ENGINEERS LEVEE PROJECT WAS COMPLETED. LEVEE FAILURES DURING SUBSEQUENT FLOOD PEAKS ARE IDENTIFIED WITH RED ASTERISKS. BLUE ASTERISKS IDENTIFY WATER YEARS WITH AERIAL PHOTOGRAPHS.



FlowWest conducted a flood frequency analysis of Deer Creek (Table 2) using the annual peak flow rates recorded at USGS gauge 11383500 (Deer Creek near Vina) for the period of record from 1912 to 2017. These results were obtained using the USGS Bulletin 17B method using Hydrologic Engineering Center's Statistical Software Package (HEC-SSP, USACE 2016). Estimated flows with recurrence intervals of 2-, 5-, 10-, 25-, 50-, and 100-year events are summarized in Table 2. The 50-year flow has decreased slightly from calculations completed using the same method in 2005 (21,430 cfs in this study, 22,910 in 2005), a result of generally drier conditions and lower flows over the past 10 years.

TABLE 2: DEER CREEK FLOOD FREQUENCY ANALYSIS RESULTS.

Recurrence Interval (years)	Discharge (cfs)
2	5,540
5	9,890
10	13,200
25	17,880
50	21,430
100	25,260

Developed using the USGS Bulletin 17B Method

Channel Width Analysis

The purpose of this section is to quantify and compare the channel widths of Deer Creek for the years 1938, 1966, 1985, 1999, 2006, and 2017.

Methods

FlowWest measured the channel widths for Lower Deer Creek in GIS from aerial photographs for 1938, 1966, 1985, 1999, 2006, and 2017. Channel width measurements were taken only along the primary active channel. We took measurements at the same locations as the previous analysis (CH2M Hill, 2005). The flows associated with each set of aerial images is listed in Table 1, and flows range from 92 – 399 cfs. Images were taken during low flow conditions and the differences in width of the channel due to differences in discharge is low. Channel width measurements were averaged for each reach (i.e. In Levee, Out-Levee, and the entire Lower Deer Creek Reach) and these averages were used to calculate the percent change between 1938 and 1966, 1985, 1999, 2006, and 2017. Further, we compared the changes between 1999 and 2006 and 2017 to show the changes in the channel width since the last major high flow events in 1997.

Results

The results of the channel width analysis are summarized in Table 3 and Figure 6. The average channel width inside the project levee area has increased between 1938 and 1966, 1985, 1999, and 2006 by 19%, 9%, 63%, and 15%, respectively, and decreased between 1938 and 2017 by 7%. Outside the levee project area, the average channel width has increased between 1938 and 1966 and 1999 by 23% and 26%, respectively, decreased between 1938 and 1985 and 2017 by 3% and 26%, respectively, and did not change between 1938 and 2006. In its entirety, Lower Deer Creek's average channel width has increased between 1938 and 1966, 1985, 1999, and 2006 by 21%, 2%, 47%, and 6%, respectively, and decreased between 1938 and 2017 by 18%.

The average channel with inside the project levee area has decreased between 1999 and 2006 and 2017 by 30% and 43%, respectively. Outside the levee project area, the average channel with has decreased between 1999 and 2006 and 2017 by 26% and 46%, respectively. For all of Lower Deer Creek (leveed and non-leveed combined), the average channel width has decreased between 1999 and 2006 and 2017 by 28% and 44%, respectively.

We observed that the channel width of Deer Creek changes following a pattern of significant widening after high flows that scour riparian vegetation and erode channel banks, followed by narrowing from riparian vegetation encroachment that decreases the channel width until the next high flow. After the high flow in 1964, the channel width decreased in the aerial images from 1966 to 1985, showing vegetation encroachment in the active channel (Figure 7). After the 1997 high flow the channel again narrowed from the 1999 to 2006 and again from 2006 to 2017 (Figure 8). The data also shows that the 1938 high flows before the USACE levee project had a smaller impact on channel widening than the 1997 high flow (Figure 6). We believe that the confinement of the channel by the levees increases the scour of riparian vegetation in the in levee reach and this is why the 1997 high flow resulted in increased channel widening compared to the 1938 high flow.

TABLE 3: DEER CREEK CHANNEL WIDTH ANALYSIS RESULTS.

Attribute	1938 In Levee	1938 Out Levee	1938 Lower Deer Creek	1966 In Levee	1966 Out Levee	1966 Lower Deer Creek	1985 In Levee	1985 Out Levee	1985 Lower Deer Creek	1999 In Levee	1999 Out Levee	1999 Lower Deer Creek	2006 In Levee	2006 Out Levee	2006 Lower Deer Creek	2017 In Levee	2017 Out Levee	2017 Lower Deer Creek
Average Active Channel Width (ft)	62	69	66	73	85	80	67	67	67	101	94	97	71	69	70	58	51	54
% Change 1938-1966	NA	NA	NA	19	23	21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938-1985	NA	NA	NA	NA	NA	NA	9	-3	2	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938-1998	NA	NA	NA	NA	NA	NA	NA	NA	NA	63	36	47	NA	NA	NA	NA	NA	NA
% Change 1938-2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	15	0	6	NA	NA	NA
% Change 1938-2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-7	-26	-18
% Change 1999-2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-30	-26	-28	NA	NA	NA
% Change 1999-2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-43	-46	-44

FIGURE 6: DEER CREEK AVERAGE CHANNEL WIDTH RESULTS FOR THE IN-LEVEE REACH (BLUE), OUT-LEVEE REACH (ORANGE) AND THE ENTIRE LOWER DEER CREEK REACH (GREY).

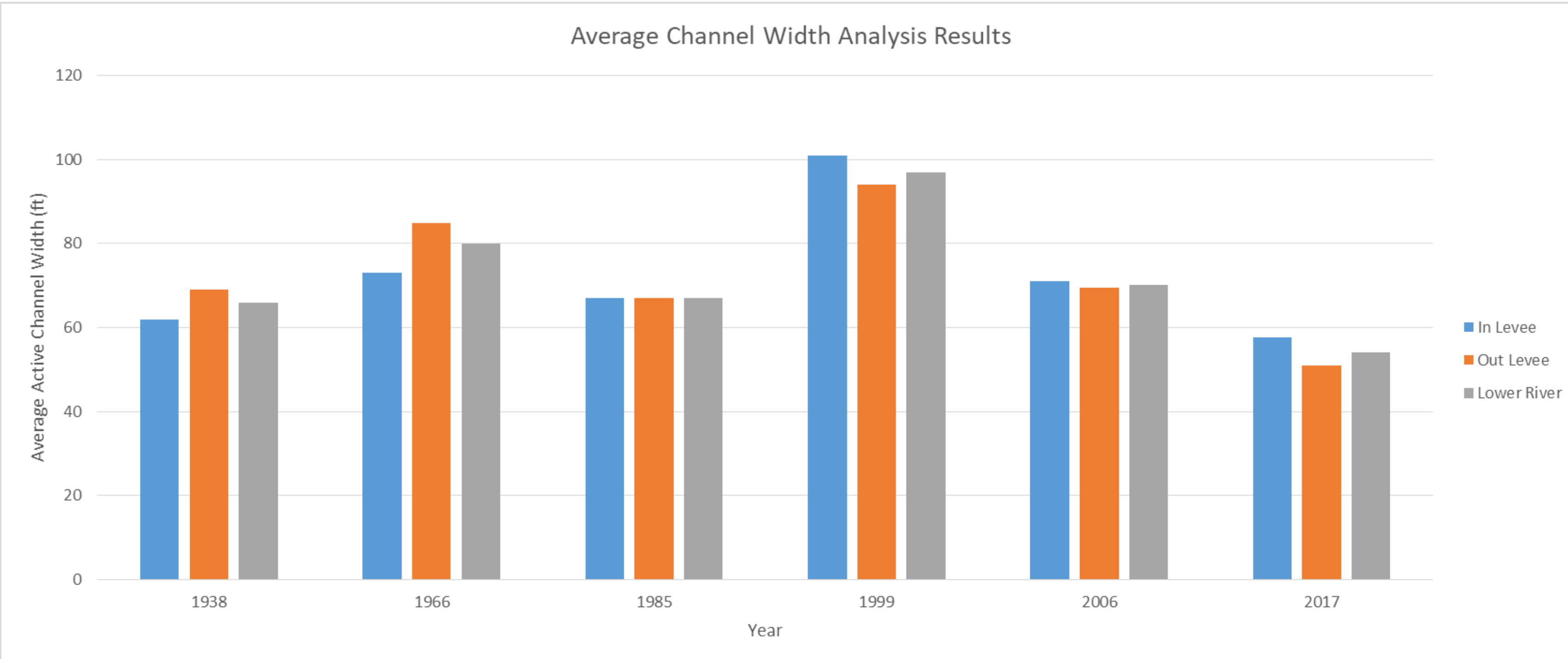


FIGURE 7: 1938 AND 1985 AERIAL IMAGES SHOWING THE CHANGE IN THE OUT-LEVEE ACTIVE CHANNEL WIDTH REACH AT RM 7.5.

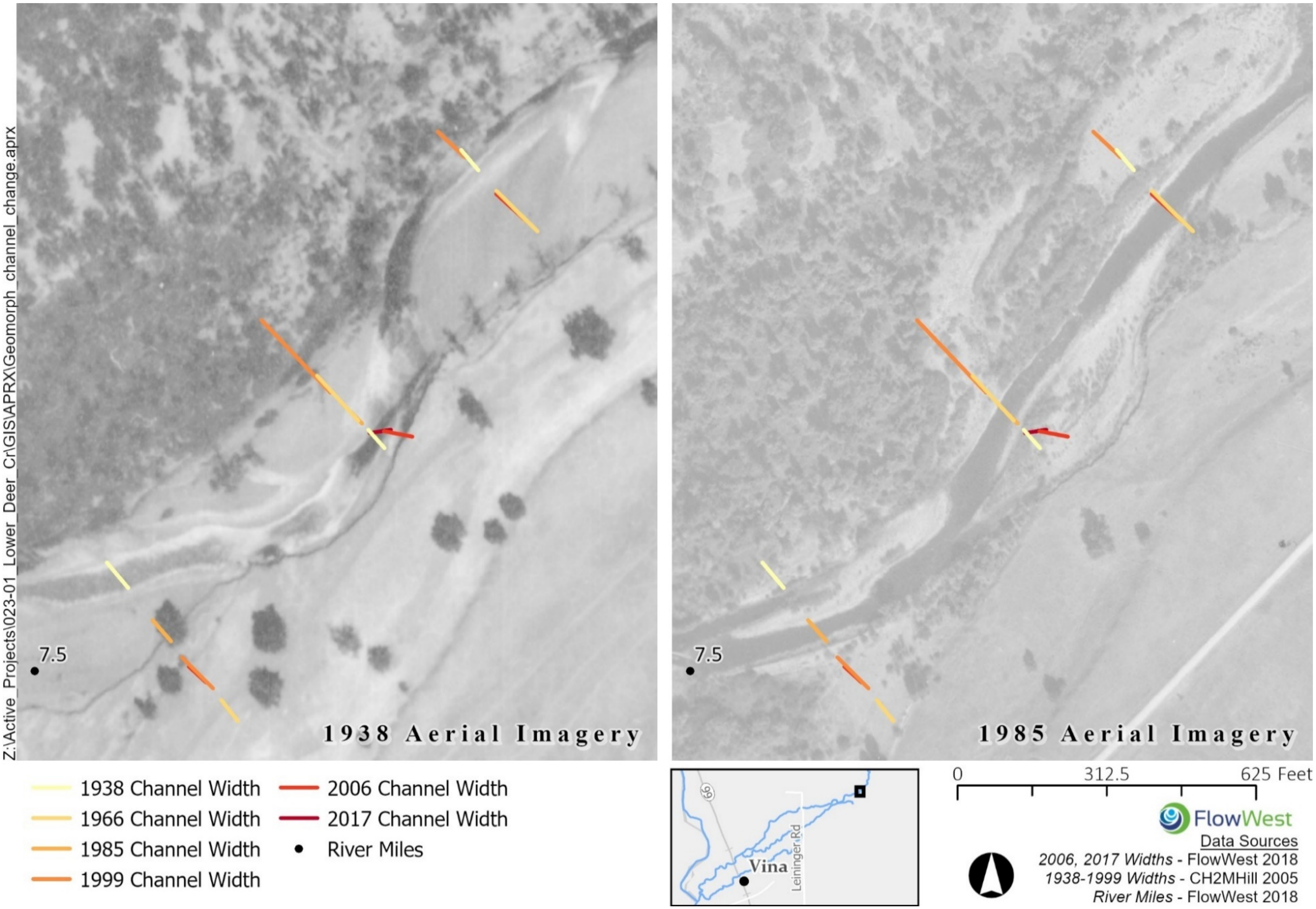
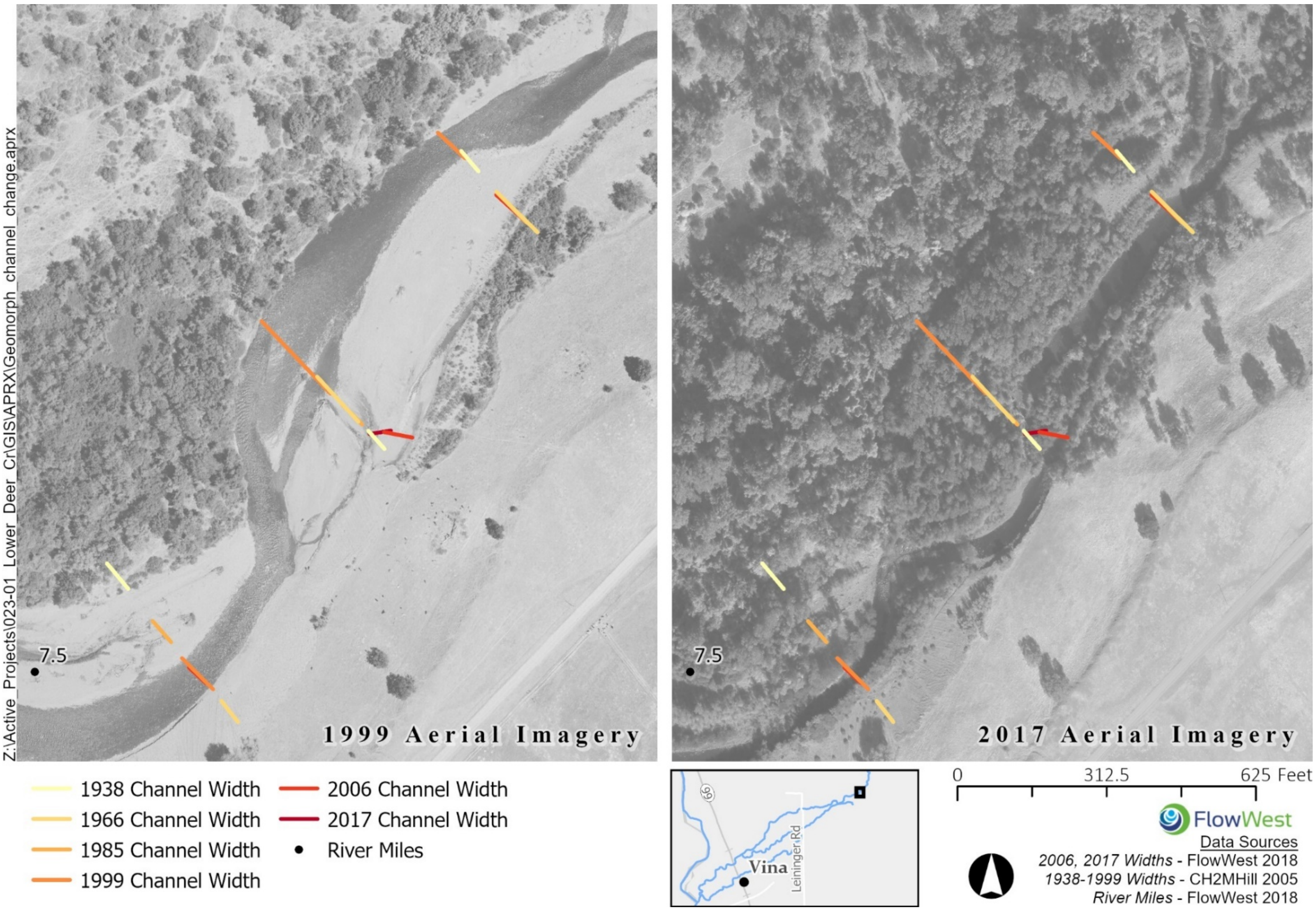


FIGURE 7: 1999 AND 2017 AERIAL IMAGES SHOWING CHANGES IN OUT-LEVEE ACTIVE CHANNEL WIDTH REACH AT RM 7.5.



Cumulative Channel Length Analysis

In this section we quantify and compare the total channel length of Deer Creek for the years 1938, 1966, 1985, 1999, 2006, and 2017 (existing condition). We use channel length as a proxy for channel complexity.

Methods

Channel lengths were measured in GIS from aerial photographs for the years 1938, 1966, 1985, 1999, 2006, and 2017 (existing condition). We digitized the primary and secondary channels and summed the segments to calculate cumulative channel length for each reach (In Levee, Out-Levee, Lower Deer Creek). High flow channels were not included in the cumulative channel length calculation. We define primary and secondary channels as clearly visible channels on the aerial images that have water in them or are directly connected to the mainstem. High flow channels are only accessed during high flows and do not have water in them in the aerial images. We calculated the percent change in total channel length between 1938 and 1966, 1985, 1999, 2006, and 2017 and 1999 and 2006 and 2017.

Results

Cumulative channel length results are summarized in Table 4 and Figure 9. The cumulative channel length has decreased in the project levee area between 1938 and 1966, 1985, 1999, and 2017 by 14%, 15%, 10%, 16%, and 23% respectively. Outside the project levee area, the cumulative channel length increased between 1938 and 1999 by 2% and decreased between 1938 and 1966, 1985, 2006, and 2017 by 5%, 7%, 21%, and 18%, respectively. The cumulative channel length for Lower Deer Creek as a whole, has experienced a decrease from 1938 and 1966, 1985, 1999, 2006, and 2017 by 9%, 11%, 3%, 18%, and 20%, respectively.

There has been a reduction in cumulative channel length in the project levee area between 1999 and 2006 and 2017 by 6% and 15%, respectively. Outside the project levee area, the cumulative channel length decreased between 1999 and 2006 and 2017 by 22% and 20%, respectively. Lower Deer Creek’s cumulative channel length has decreased between 1999 and 2006 and 2017 by 15% and 17%, respectively.

The cumulative channel length follows a similar trend as the channel width results. We observe a reduction in channel length after the years following large flow events (Figure 10 to Figure 13), and an increase in cumulative channel length in years where there were large flows. During periods without high flows, vegetation encroaches into the secondary channels. Vegetation encroachment also causes sediment deposition at moderate flows, which results in sediment plugging secondary channels. Secondary channels then dry out and vegetation begins to grow where water once flowed. During peak flows, the secondary channels are scoured of vegetation and the cumulative channel length increases. We determined that the decrease in cumulative channel length is greater in the In-Levee Reach (Table 4). A decrease in the cumulative channel length results in a decrease in channel complexity that reduces the quality and quality of habitat for salmonids. Comparison of the increase in channel simplification in the In-Levee

Reach (Figure 10 and Figure 11) to the Out-Levee Reach (Figure 12 and Figure 13) shows the decrease in channel complexity and habitat for the In-Levee Reach.

TABLE 4: LOWER DEER CREEK CUMULATIVE CHANNEL LENGTH ANALYSIS RESULTS.

Attribute	**1938 In Levee**	**1938 Out Levee**	**1938 Lower Deer Creek**	**1966 In Levee**	**1966 Out Levee**	**1966 Lower Deer Creek**	**1985 In Levee**	**1985 Out Levee**	**1985 Lower Deer Creek**	**1999 In Levee**	**1999 Out Levee**	**1999 Lower Deer Creek**	**2006 In Levee**	**2006 Out Levee**	**2006 Lower Deer Creek**	**2017 In Levee**	**2017 Out Levee**	**2017 Lower Deer Creek**
Cumulative Active Channel Length (ft)	41,102	46,157	87,259	35,485	43,664	79,149	34,863	42,681	77,544	37,020	47,238	84,258	34,652	36,676	71,329	31,593	37,991	69,584
% Change 1938 - 1966	NA	NA	NA	-14	-5	-9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938 - 1985	NA	NA	NA	NA	NA	NA	-15	-8	-11	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938 - 1998	NA	NA	NA	NA	NA	NA	NA	NA	NA	-10	2	-3	NA	NA	NA	NA	NA	NA
% Change 1938 - 2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-16	-21	-18	NA	NA	NA
% Change 1938 - 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-23	-18	-20
% Change 1999 – 2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-6	-22	-15	NA	NA	NA
% Change 1999 – 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-15	-20	-17

FIGURE 8: DEER CREEK CUMMULATIVE CHANNEL LENGTH RESULTS FOR THE IN-LEVEE REACH (BLUE), OUT-LEVEE REACH (ORANGE) AND THE ENTIRE LOWER DEER CREEK (GREY).

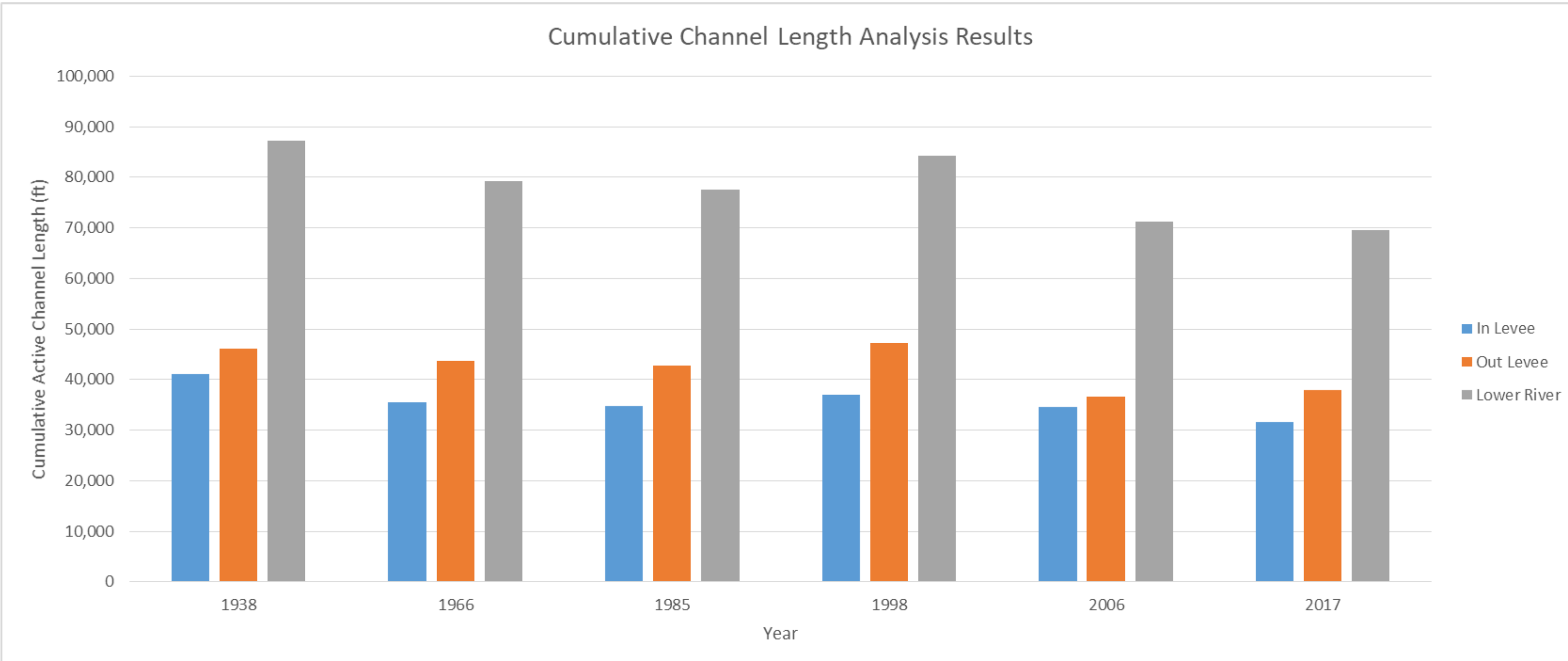


FIGURE 9: 1938 AND 1985 AERIAL IMAGES SHOWING CHANGE IN CHANNEL LENGTH IN-LEVEE REACH BETWEEN RM 2.5 AND RM 3.

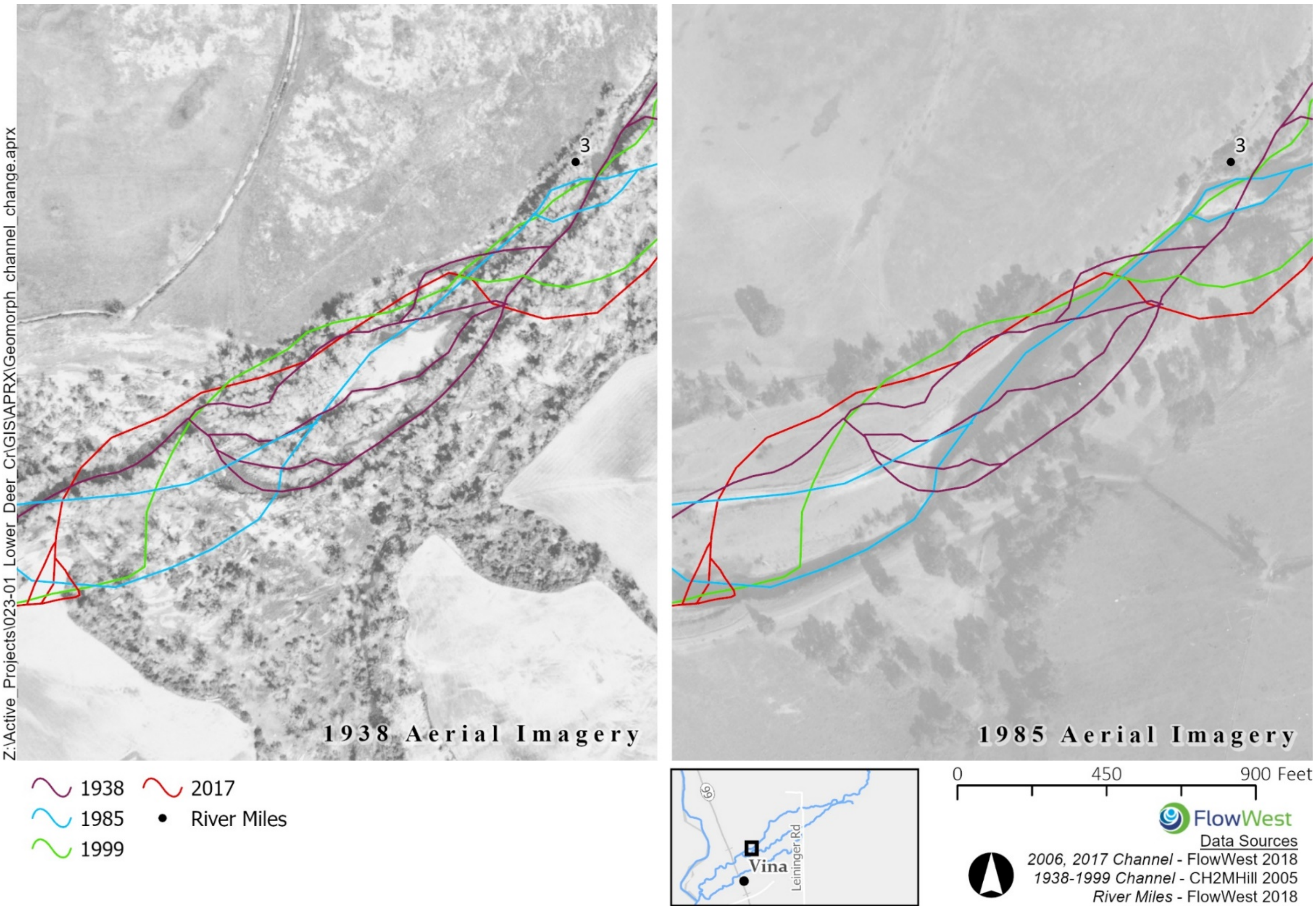


FIGURE 10: 1999 AND 2017 AERIAL IMAGES SHOWING CHANGE IN CHANNEL LENGTH FOR THE IN-LEVEE REACH BETWEEN RM 2.5 AND RM 3.

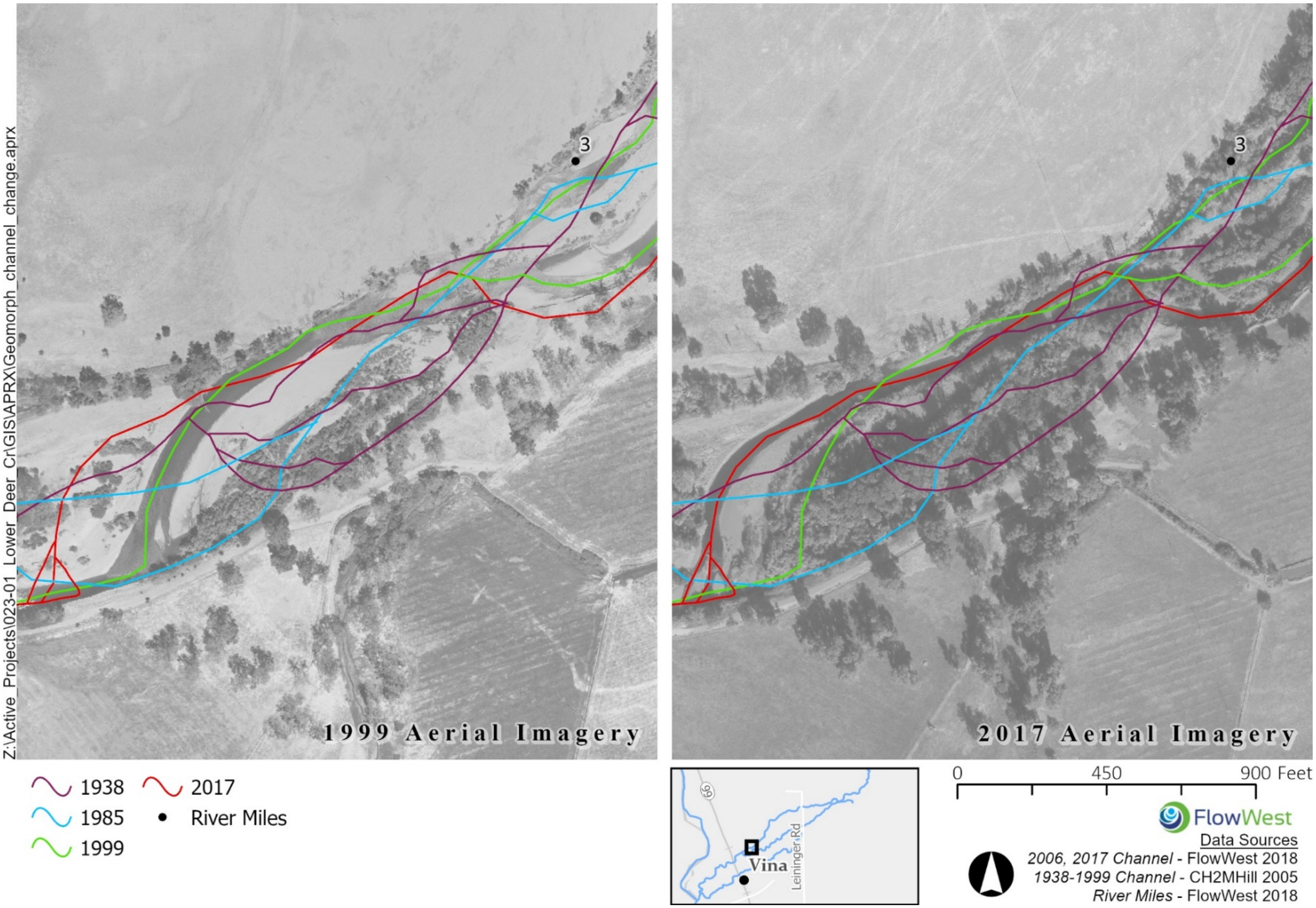


FIGURE 11: 1938 AND 1985 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL LENGTH IN THE OUT-LEVEE REACH AT RM 8.

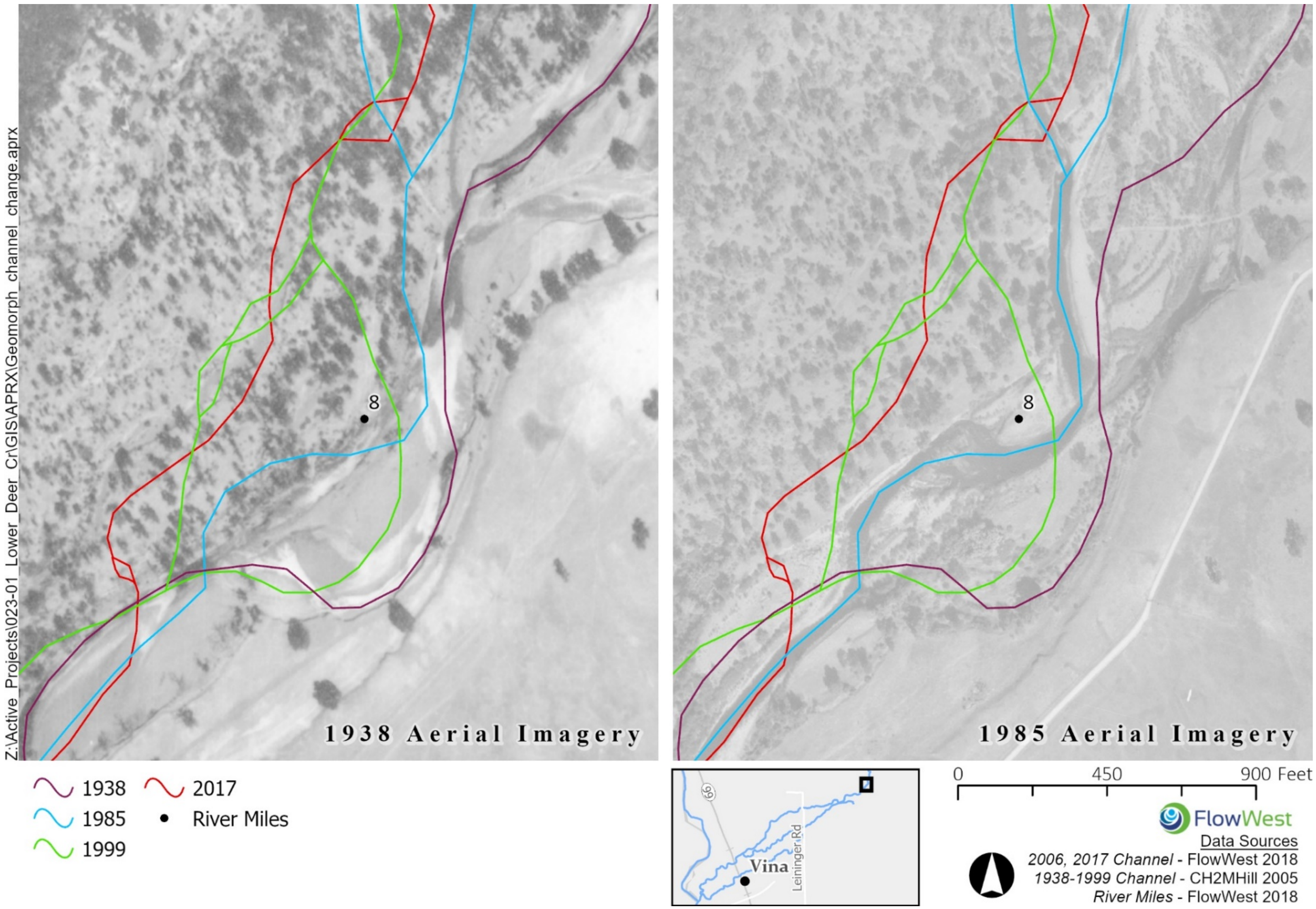
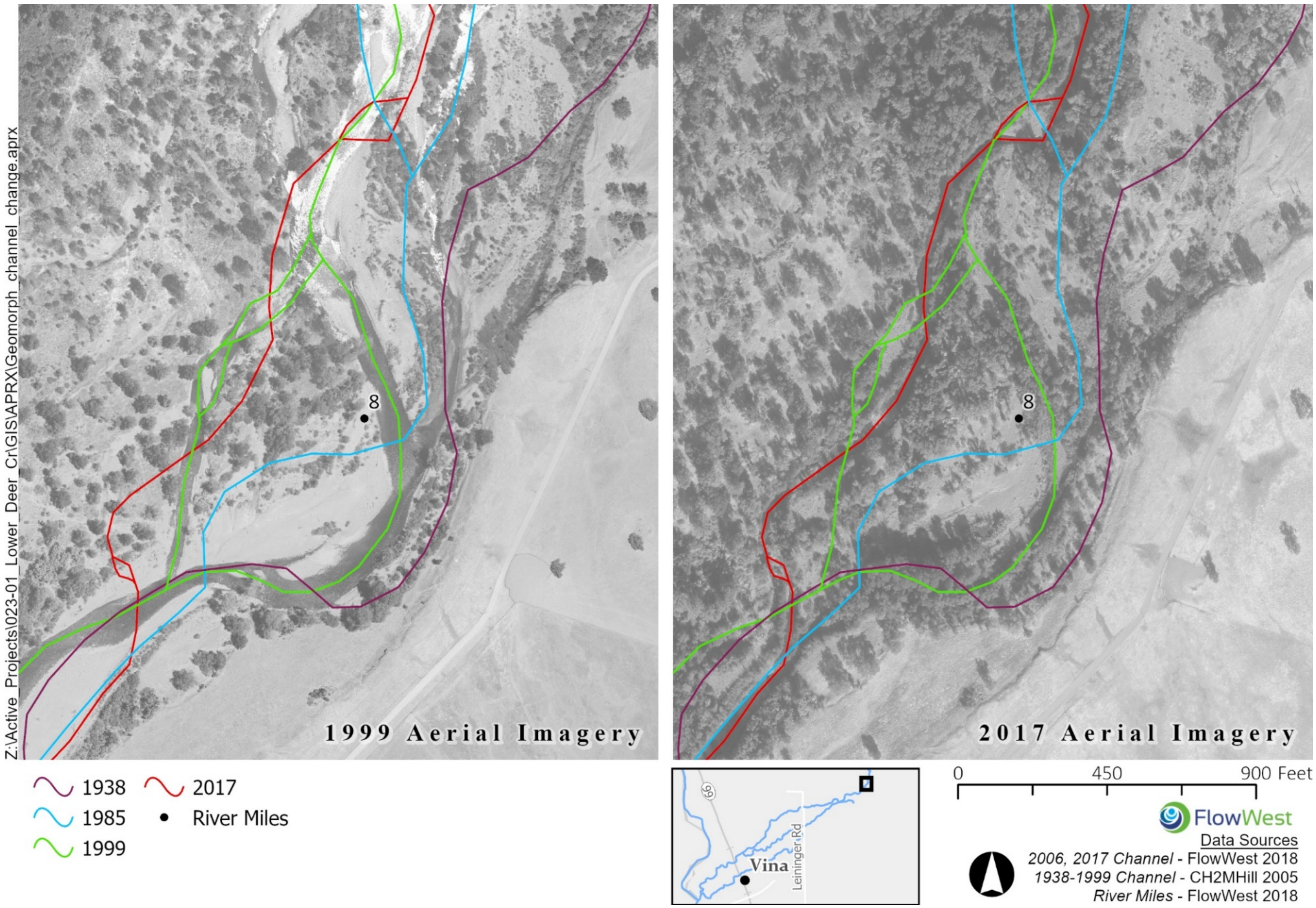


FIGURE 12: 1999 AND 2017 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL LENGTH IN THE OUT-LEVEE REACH AT RM 8.



Lateral Channel Migration

We assessed the lateral channel migration of Deer Creek between 1938, 1985, 1999, and 2017 by delineating the channel bank at three locations.

Methods

The three locations chosen to measure channel migration included: 1) the north bank downstream of Highway 99 at RM 2.5; 2) the south bank upstream of Red Bridge at RM 5.5; and 3) the north bank upstream of Red Bridge at RM 6.5. At each measurement location, we digitized the channel bank from aerial images from 1938, 1985, 1985, 1999, and 2017. We digitized a transect at the apex of the bend in each bank perpendicular to the direction of flow in the channel and measured the distance of bank retreat or repair from 1938 to 1985, 1985 to 1999, and 1999 to 2017.

Results

The lateral migration and channel migration rates at RM 2.5, RM 5.5, and RM 6.5 for the period from 1938 to 1985, 1985 to 1999, and 1999 to 2017 are summarized in Table 5. Lower Deer Creek is actively migrating across the floodplain (Figure 14, Figure 15, Figure 16, and Figure 17). Migration rates for the period of record range from -2.1 (bank accretion) to 21.4 (bank erosion) feet per year for the three sites. The greatest change in channel migration occurred between 1985 (a low flow year) and 1999 (after the highest flow on record) where the channel migrated 300 feet at the North Bank Downstream of Highway 99 site in the Levee Reach. Between 1999 and 2017 there have been no extreme high flows, which explains the lower rate of migration. We also observed bank accretion at the South Bank Upstream of Red Bridge site and the North Bank Upstream of Red Bridge site. Confinement of Lower Deer Creek in the Levee Reach has not stopped the channel from migrating during large flow events. Without modifications (i.e. setbacks) to the existing flood control project, the channel will likely continue this pattern of migration that damages levees close to the active channel. Where levees are not threatened by channel migration, these levees have directed flow at the adjacent bank. Levees have resulted in erosion of agricultural land in the floodplain (Figure 14 and Figure 15).

TABLE 5: LOWER DEER CREEK CHANNEL MIGRATION 1938 - 1985, 1985 - 1999, AND 1999 – 2017 AT RM 2.5, 5.5 AND 6.5.

Site	River Mile	1938 – 1985 Migration (ft)	1938 – 1985 Period (yr)	1938 – 1985 Rate (ft/yr)	1985 – 1999 Migration (ft)	1985 – 1999 Period (yr)	1985 – 1999 Rate (ft/yr)	1999 – 2017 Migration (ft)	1999 – 2017 Period (yr)	1999 – 2017 Rate (ft/yr)
North Bank Downstream of Highway 99	2.5	121	47	2.6	300	14	21.4	72	18	4.0
South Bank Upstream of Red Bridge	5.5	122	47	2.6	-30	14	-2.1	60	18	3.3
North Bank Upstream of Red Bridge	6.5	274	47	5.8	107	14	7.6	-22	18	-1.2

FIGURE 13: 1938 AND 1985 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL BANKS FOR THE IN-LEVEE REACH AT RM 2.5 FROM 1938 TO 2017.

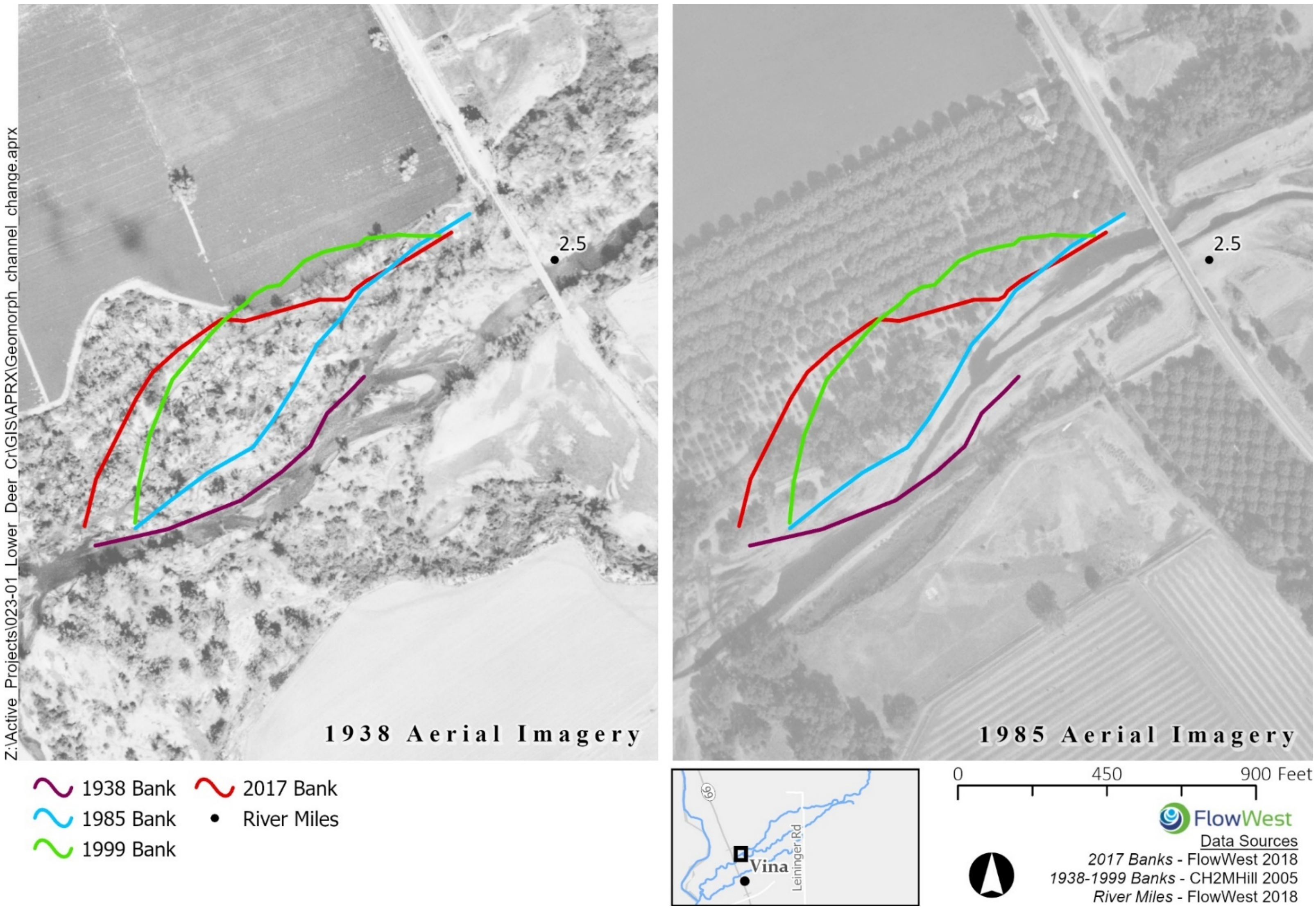


FIGURE 14: 1999 AND 2017 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL BANKS FOR THE IN-LEVEE REACH AT RM 2.5 FROM 1938 TO 2017.

FIGURE 15: 1938 AND 1985 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL MIGRATION (RM 6.5) AT THE UPSTREAM EXTENT OF THE IN-LEVEE REACH.

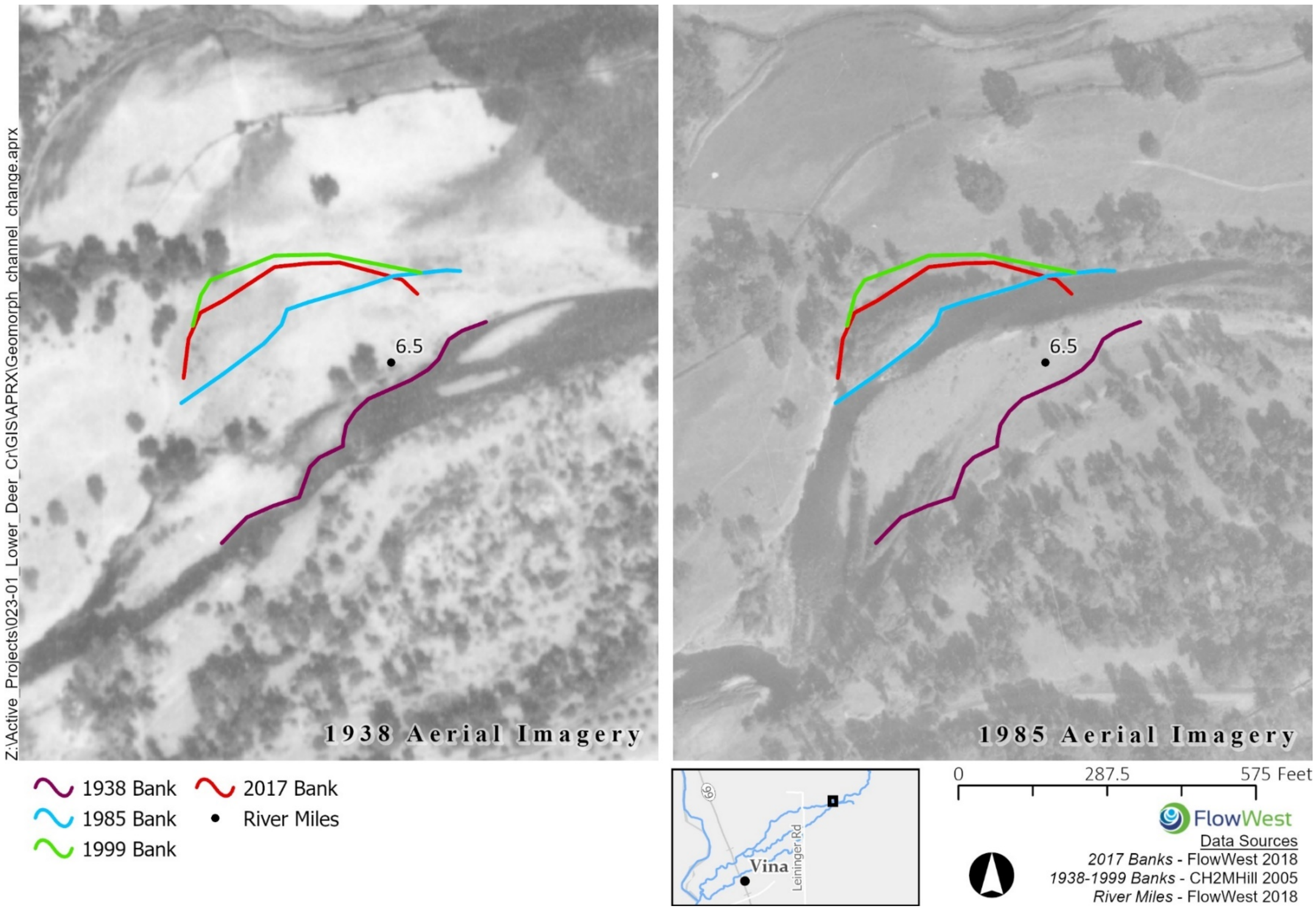
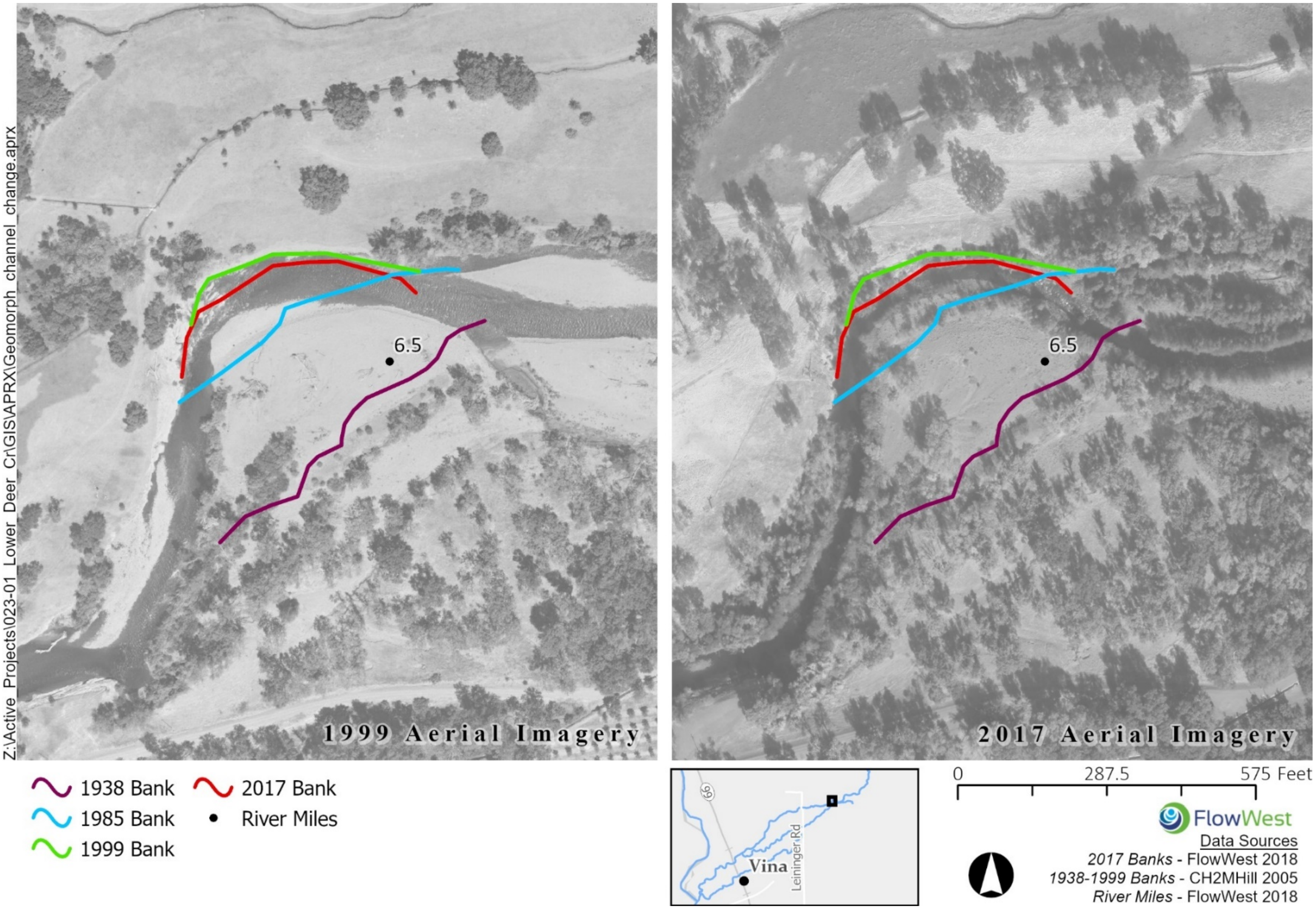


FIGURE 16: 1999 AND 2017 AERIAL IMAGES SHOWING THE CHANGE IN CHANNEL MIGRATION (RM 6.5) AT THE UPSTREAM EXTENT OF THE IN-LEVEE REACH.



Flood Corridor Width Analysis

We verified that the flood corridor width has not changed since the previous analysis (CH2M Hill 2005). We defined the flood corridor for this study as the stream corridor bounded by bluffs, bedrock outcrops, or terraces in the natural portion Lower Deer Creek and bound by flood control infrastructure including levees, dams, and floodwalls in regulated portion of the system.

Methods

FlowWest overlaid flood corridor boundary data from the 1999 rectified aerial images (CH2M Hill 2005) on the 2017 aerial images in GIS and looked for changes in the flood control infrastructure and natural flood corridor boundaries.

Results

The flood corridor was found to be unchanged since 1999 when compared to the aerial imagery from 2017 in GIS. No change in flood corridor width was expected as there has been no change to the flood control infrastructure. The flows since 1997 have been relatively low and mostly confined to the area between levees and channel banks. Previous analysis found that the average flood corridor width was reduced by 42% throughout Lower Deer Creek between 1938 and 1999. The confined nature of the flood corridor contributes to flood control problems and decreases habitat by increasing velocities and shear stress during high flow events (CH2M Hill, 2005). This finding suggests that levee setbacks will improve both flood control and habitat in Lower Deer Creek.

Riparian Vegetation Analysis

We quantified the area of riparian vegetation in proximity to Deer Creek from 1938 to 2017 and the changes in riparian vegetation between 1938, 1999, 2006, and 2017.

Methods

FlowWest digitized riparian vegetation along Lower Deer Creek from 1999 and 2017 using aerial imagery. We reviewed the riparian vegetation delineation completed in previous analysis (CH2M Hill 2005) and used the same methods to compare the results between the 2006 and 2017 aerial imagery with the 1938 and 1999 aerial imagery. The vegetation was measured within two “bands” defined by a distance from the channel banks; the northern channel bank band is 450 feet wide extending parallel from the channel bank, and the southern band is 300 feet wide extending parallel from the southern channel bank. We digitized riparian vegetation within these bands to be consistent with the previous analysis. We used the results to calculate the percent change in riparian vegetation area between 1938 and 1999, 1938 and 2006, and 1938 and 2017. We also compared the changes between 1999 and 2006 and 1999 and 2017.

Results

The results of the riparian vegetation area analysis for In-Levee Reach, Out-Levee Reach, and entire Lower Deer Creek study area are summarized in Table 6. We used two base years in our comparison of pre-levee construction (1938) and post-levee construction (1999) after high flow events (Table 6).

For the pre-levee condition after a large flow event, we used 1938 as a baseline for calculating percent change in area of riparian vegetation in the In-levee, Out-Levee, and Lower Deer Creek Reaches (Table 6). Inside the project levee area, the riparian vegetation has decreased between 1938 and 1999, 2006, and 2017 by 54%, 43%, and 38%, respectively (Figure 18 and Figure 19). Outside the project levee area, the riparian vegetation has increased between 1938 and 1999 and 2006 and 2017 by 12% and 27%, respectively (Figure 20 and Figure 21). For the entire Lower Deer Creek study area, the riparian vegetation area has decreased between 1938 and 1999, 2006, and 2017 by 24%, 11%, and 8%, respectively.

For the post-levee condition after a large flow event, we used 1999 as a baseline for calculating percent change of riparian vegetation in the In-Levee Reach, Out-Levee Reach, and entire Lower Deer Creek study area (Table 6). We determined that for the In-Levee Reach riparian vegetation has increased between 1999 and 2006 and 1999 and 2017 by 24% and 35%, respectively (Figure 18 and Figure 19). In the Out-Levee Reach, riparian vegetation has increased by 14% and 13%, respectively (Figure 20 and Figure 21). For the entire Lower Deer Creek study area, riparian vegetation has increased between 1999 and 2006 and 1999 and 2017 by 17% and 20%, respectively.

We summarized the total amount of riparian vegetation in the In-Levee Reach, Out-Levee Reach, and for the Lower Deer Creek in Figure 22 and Table 6. The total area of riparian vegetation in the In-Levee Reach decreased from 206 acres in 1938 to 94 acres in 1999. This illustrates that both the area of riparian vegetation decreased after the levee project was constructed and that high flow events in the In-Levee Reach have a greater impact on scouring riparian vegetation post-levee construction. Figure 22 and Table 6 also show that there has been an increase in riparian vegetation in the Out-Levee Reach. Additionally, the 1997 high flow event had a smaller reduction in the riparian vegetation in the Out-Levee Reach than the In-Levee Reach. The results suggest that high flow events have a greater impact on scour of riparian vegetation in the In-Levee Reach than the Out-Levee Reach, supporting the potential for setback levees to yield improved habitat conditions along Lower Deer Creek.

TABLE 6: COMPARISON OF RIPARIAN VEGETATION IN LOWER DEER CREEK, 1938 TO 2017.

Attribute	1938 In Levee	1938 Out Levee	1938 Lower Deer Creek	1999 In Levee	1999 Out Levee	1999 Lower Deer Creek	2006 In Levee	2006 Out Levee	2006 Lower Deer Creek	2017 In Levee	2017 Out Levee	2017 Lower Deer Creek
Total Riparian Vegetation Area (acres)	206	176	381	94	196	291	117	224	341	127	223	350
% Change 1938 – 1999	NA	NA	NA	-54	12	-24	NA	NA	NA	NA	NA	NA
% Change 1938 – 2006	NA	NA	NA	NA	NA	NA	-43	27	-11	NA	NA	NA
% Change 1938 – 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	-38	27	-8
% Change 1999 – 2006	NA	NA	NA	NA	NA	NA	24	14	17	NA	NA	NA
% Change 1999 – 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	35	13	20

FIGURE 17: 1938 AND 1999 AERIAL IMAGES SHOWING THE CHANGE IN RIPARIAN VEGETATION FOR THE IN-LEVEE REACH AT RM 3.

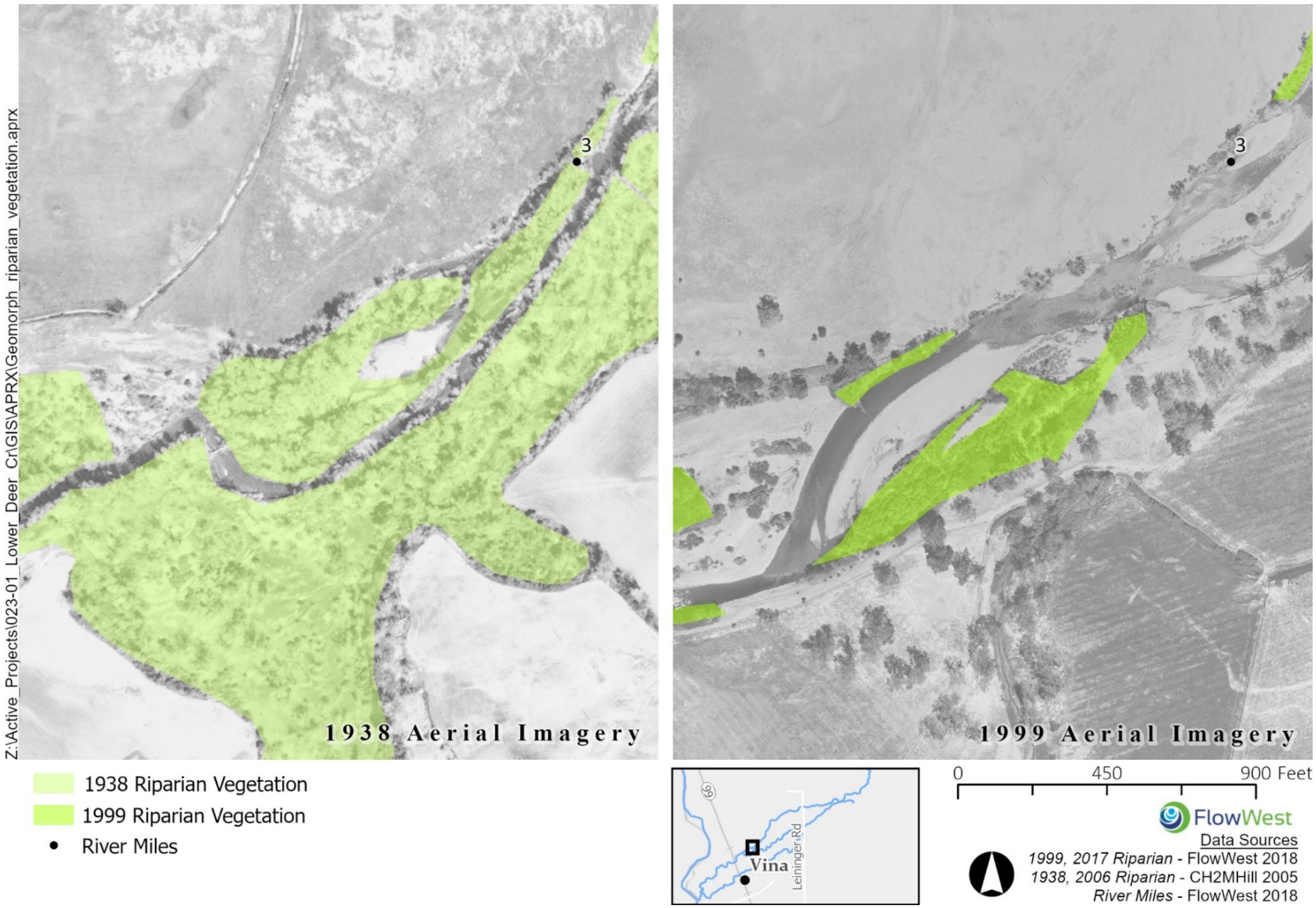


FIGURE 18: 2006 AND 2017 AERIAL IMAGES SHOWING THE CHANGE IN RIPARIAN VEGETATION FOR THE IN-LEVEE REACH AT RM 3. THE APPARENTLY VEGETATED AREA IN 2017 THAT WAS NOT DIGITIZED IS A RESULT OF A BUFFER FROM THE ACTIVE CHANNEL.

FIGURE 19: 1938 AND 1999 AERIAL IMAGES SHOWING THE CHANGE IN RIPARIAN VEGETATION FOR THE OUT-LEVEE REACH AT RM 8.

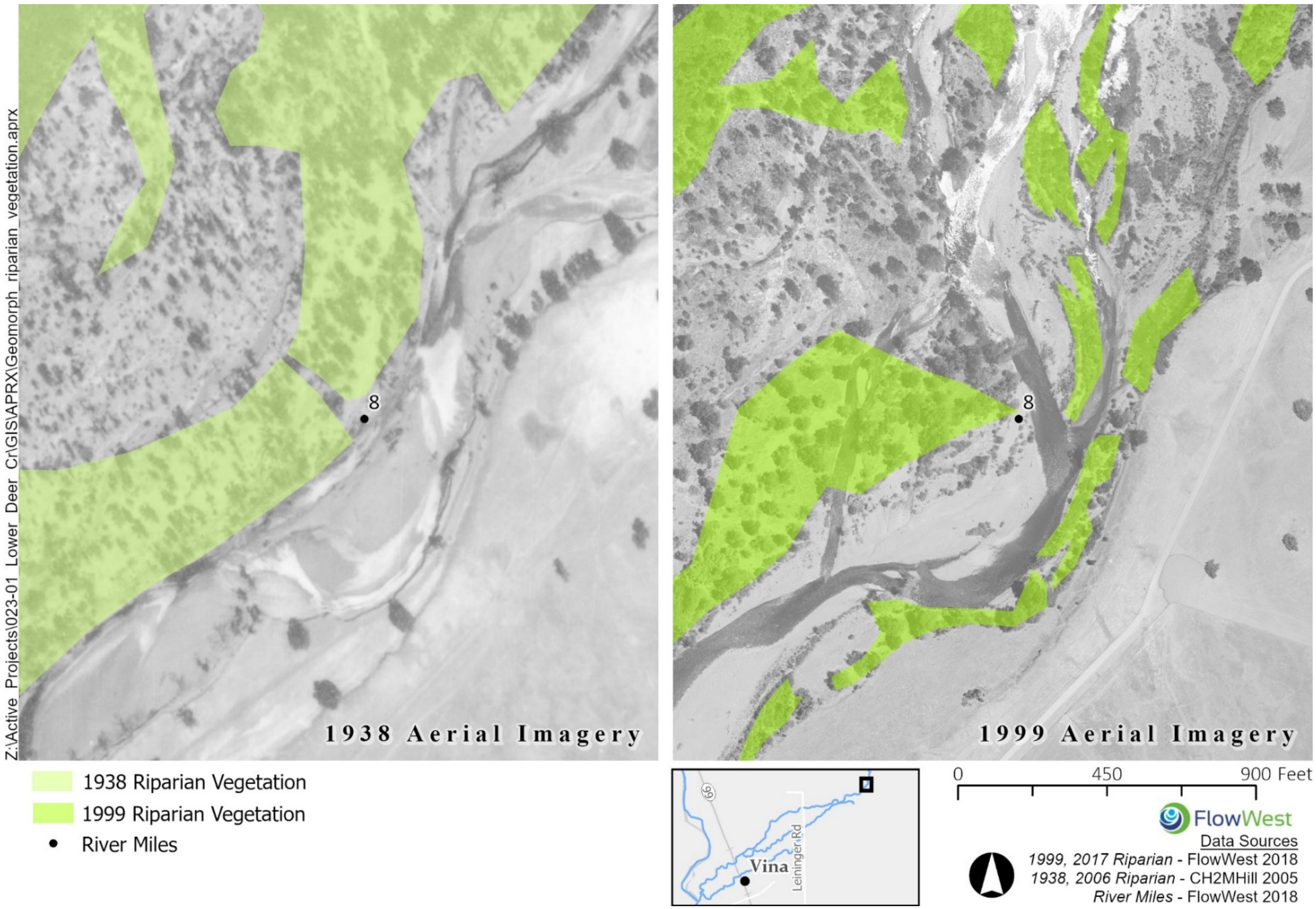


FIGURE 20: 2006 AND 2017 AERIAL IMAGES SHOWING THE CHANGE IN RIPARIAN VEGETATION FOR THE OUT-LEVEE REACH AT RM 8.

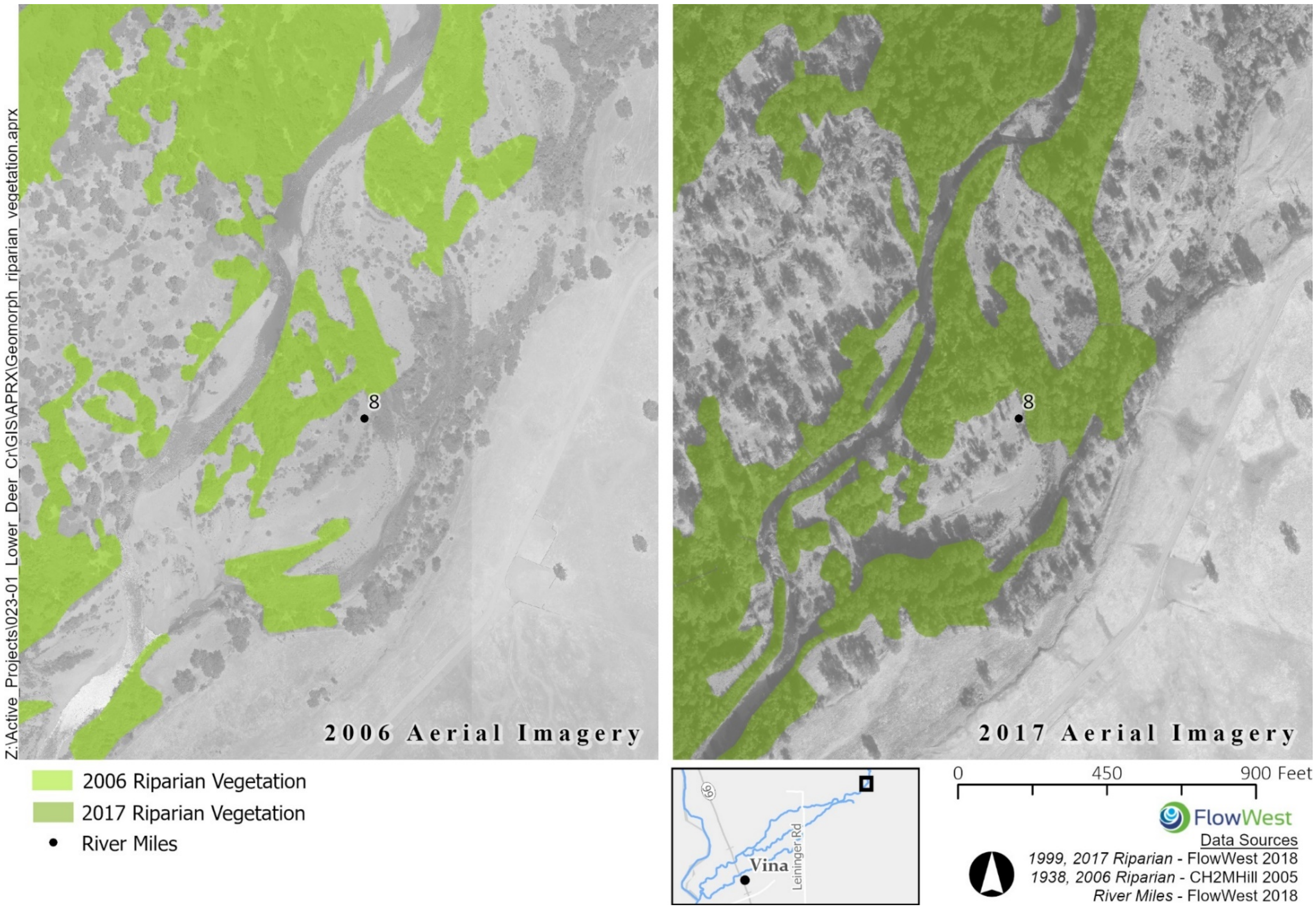
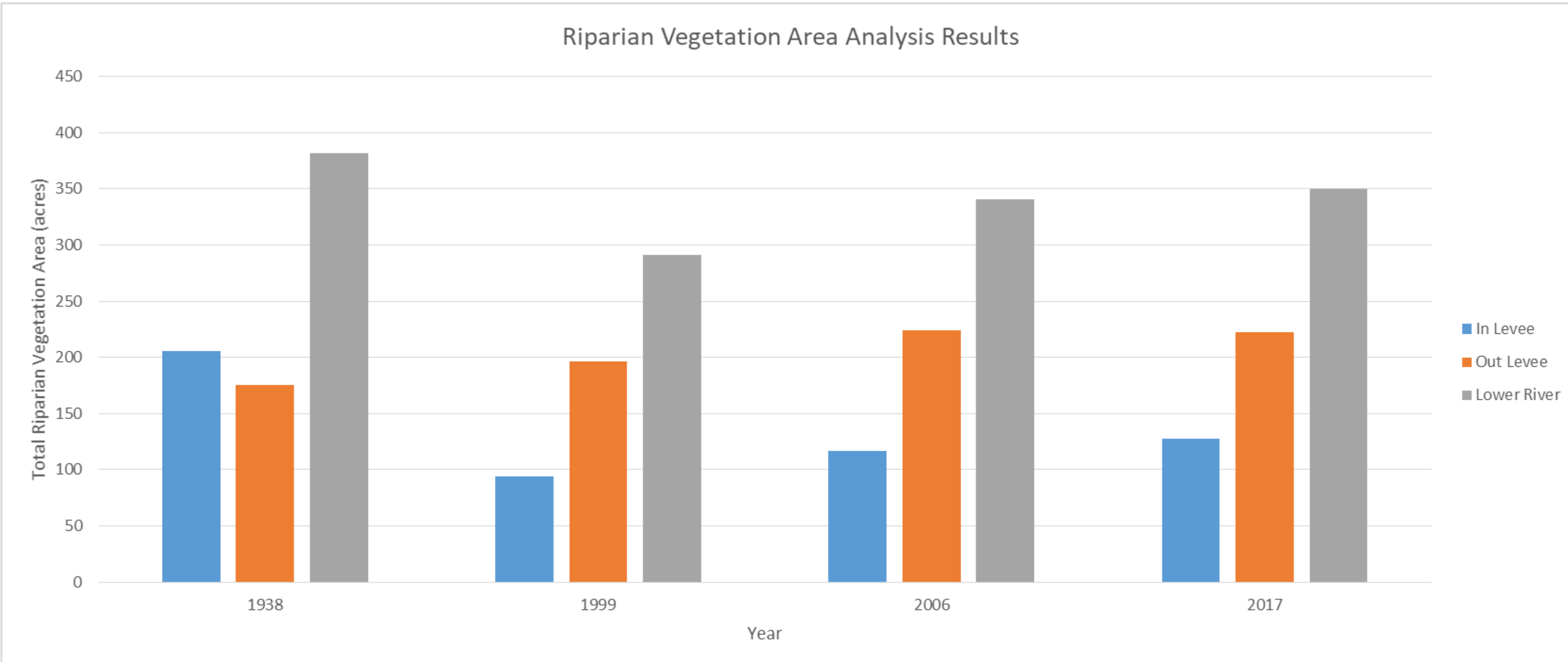


FIGURE 21: AREA OF RIPARIAN VEGETATION IN ACREAS IN-LEVEE REACH (BLUE), OUT-LEVEE REACH (ORANGE), AND THE ENTIRE STUDY AREA (LOWER DEER CREEK, GREY) IN 1938, 1999, 2006, AND 2017.



SHADED RIVERINE AQUATIC ANALYSIS

We quantified the length of banks on Deer Creek that are considered shaded riverine aquatic (SRA) habitat. SRA is a measurement of the area of river channel at the interface of woody riparian vegetation and is used as a metric to quantify salmonid habitat in many salmon-bearing systems like Deer Creek (CH2M Hill 2005).

Methods

SRA habitat is defined as nearshore aquatic areas occurring at the interface between a river and adjacent woody riparian habitat with characteristics such as natural, eroding adjacent banks supporting riparian vegetation that either overhangs or protrudes into the water, and aquatic areas containing variable amounts of woody debris (CH2M Hill 2005). FlowWest reviewed the previous analysis of aerial imagery from 1938, 1966, 1985, and 1999 (CH2M Hill 2005) and then digitized segments of Deer Creek in the 2006 and 2017 aerial images that fit this definition. Lastly, we calculated the percent change between each set of aerial images.

Results

The results of this analysis are summarized in Table 7 below. In the In-Levee Reach, SRA length decreased from 1938 to 1966, 1938 to 1985, 1938 to 1999, 1938 to 2006, and 1938 to 2017 by 70%, 66%, 55%, 40%, and 21%, respectively. In the Out-Levee Reach, SRA length decreased between 1938 to 1966 and 1938 to 1985 by 26% and 11%, respectively, and increased between 1938 to 1999, 1938 to 2006, and 1938 to 2017 by 2%, 7%, and 29%, respectively. As a whole, SRA length for Lower Deer Creek Reach has decreased between 1938 to 1966, 1938 to 1985, 1938 to 1999, and 1938 to 2006 by 50%, 41%, 29%, and 18%, respectively, and increased between 1938 to 2017 by 2%.

There has been an overall increase when comparing the results between 1999 and 2006 and 2017. Inside the levee project area, the SRA length has increased between 1999 and 2005 and 2017 by 35 and 77 %, respectively. Outside the project levee area, the SRA length has increased between 1999 and 2005 and 2017 by 5 and 27 %, respectively. Total SRA length for all of Lower Deer Creek has increased between 1999 and 2006 and 2017 by 16 and 45 %, respectively.

The changes in SRA length can be attributed to the lack of extreme high flows scouring the channel banks of riparian vegetation since 1997. Also, the results show that the total SRA length in the In-Levee Reach is less than the Out-Levee Reach. This finding supports the potential for setback levees to increase the length of SRA in leveed reaches of Lower Deer Creek, thereby improving habitat for salmonids and other species.

TABLE 7: LOWER DEER CREEK SHADED RIVERINE AQUATIC (SRA) HABITAT ANALYSIS RESULTS.

Attribute	1938 In Levee	1938 Out Levee	1938 Lower Deer Creek	1966 In Levee	1966 Out Levee	1966 Lower Deer Creek	1985 In Levee	1985 Out Levee	1985 Lower Deer Creek	1999 In Levee	1999 Out Levee	1999 Lower Deer Creek	2006 In Levee	2006 Out Levee	2006 Lower Deer Creek	2017 In Levee	2017 Out Levee	2017 Lower Deer Creek
SRA Length (ft)	22,144	18,347	40,491	6,646	13,665	20,311	7,445	16,328	23,773	9,913	18,649	28,562	13,383	19,658	33,040	17,525	23,758	41,283
% Change 1938 – 1966	NA	NA	NA	-70	-26	-50	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938 – 1985	NA	NA	NA	NA	NA	NA	-66	-11	-41	NA	NA	NA	NA	NA	NA	NA	NA	NA
% Change 1938 – 1998	NA	NA	NA	NA	NA	NA	NA	NA	NA	-55	2	-29	NA	NA	NA	NA	NA	NA
% Change 1938 – 2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-40	7	-18	NA	NA	NA
% Change 1938 – 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-21	29	2
% Change 1999 – 2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	35	5	16	NA	NA	NA
% Change 1999 – 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	77	27	45

FIGURE 22: SHADED RIVERINE AQUATIC (SRA) VEGETATION CUMULATIVE LENGTH FOR THE IN-LEVEE REACH (BLUE), OUT-LEVEE REACH (ORANGE), AND THE ENTIRE STUDY AREA (LOWER DEER CREEK, GREY).

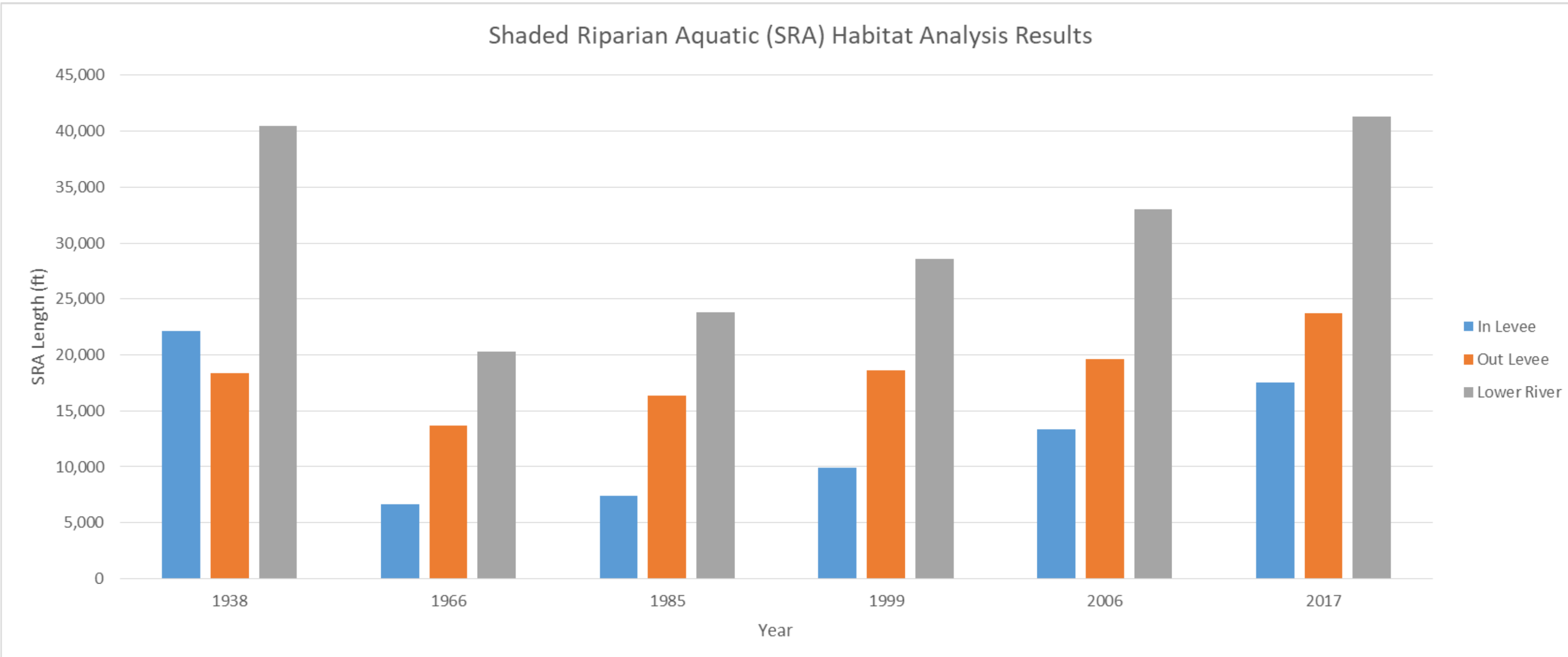


FIGURE 23: 1938 AND 1999 AERIAL IMAGES SHOWING THE EXTENT OF SHADED RIVERINE AQUATIC (SRA) VEGETATION FOR THE IN-LEVEE REACH.

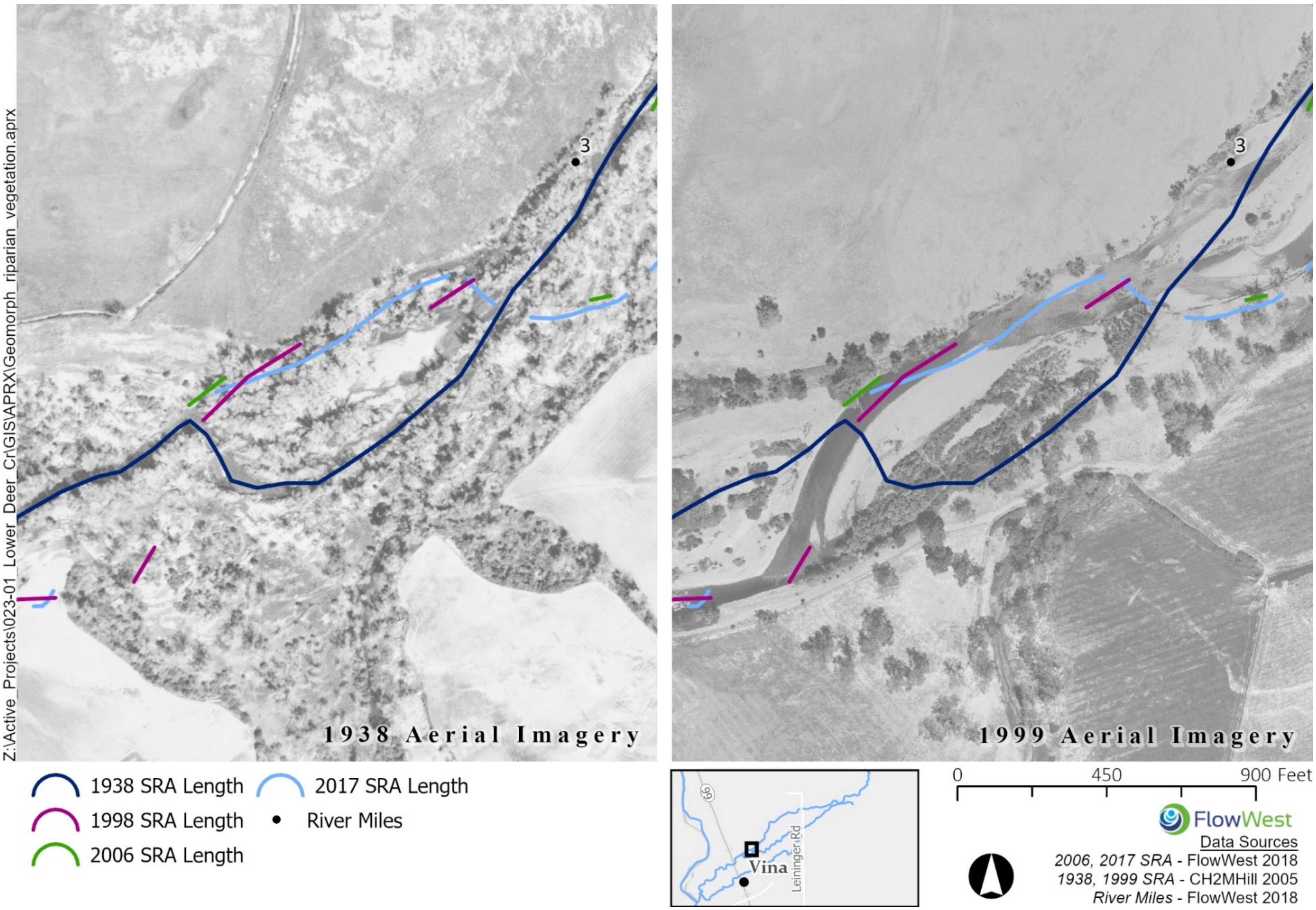


FIGURE 24: 2006 AND 2017 AERIAL IMAGES SHOWING THE EXTENT OF SHADED RIVERINE AQUATIC (SRA) VEGETATION FOR THE IN-LEVEE REACH.

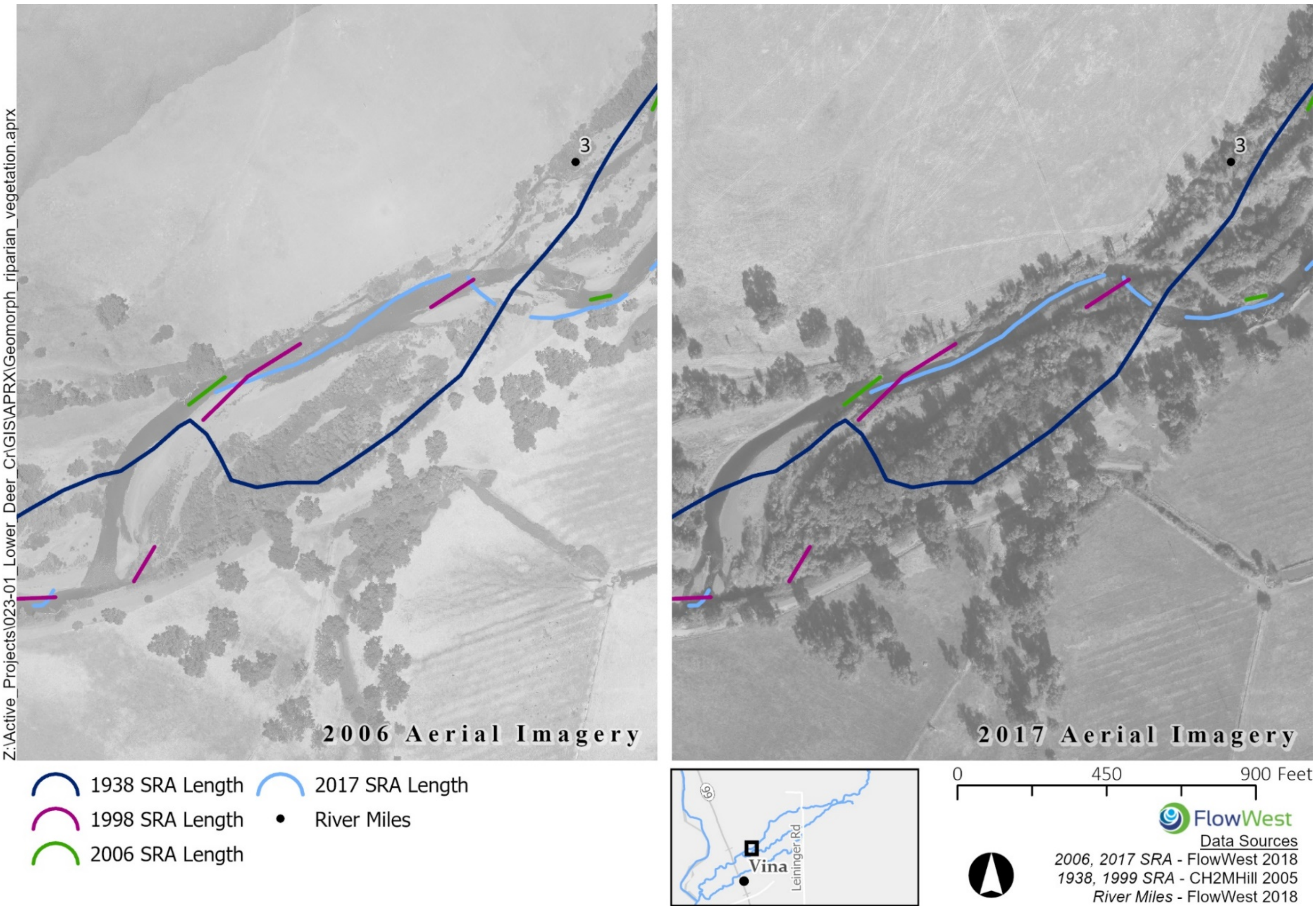


FIGURE 25: 1938 AND 1999 AERIAL IMAGES SHOWING THE EXTENT OF SHADED RIVERINE AQUATIC (SRA) VEGETATION FOR THE OUT-LEVEE REACH.

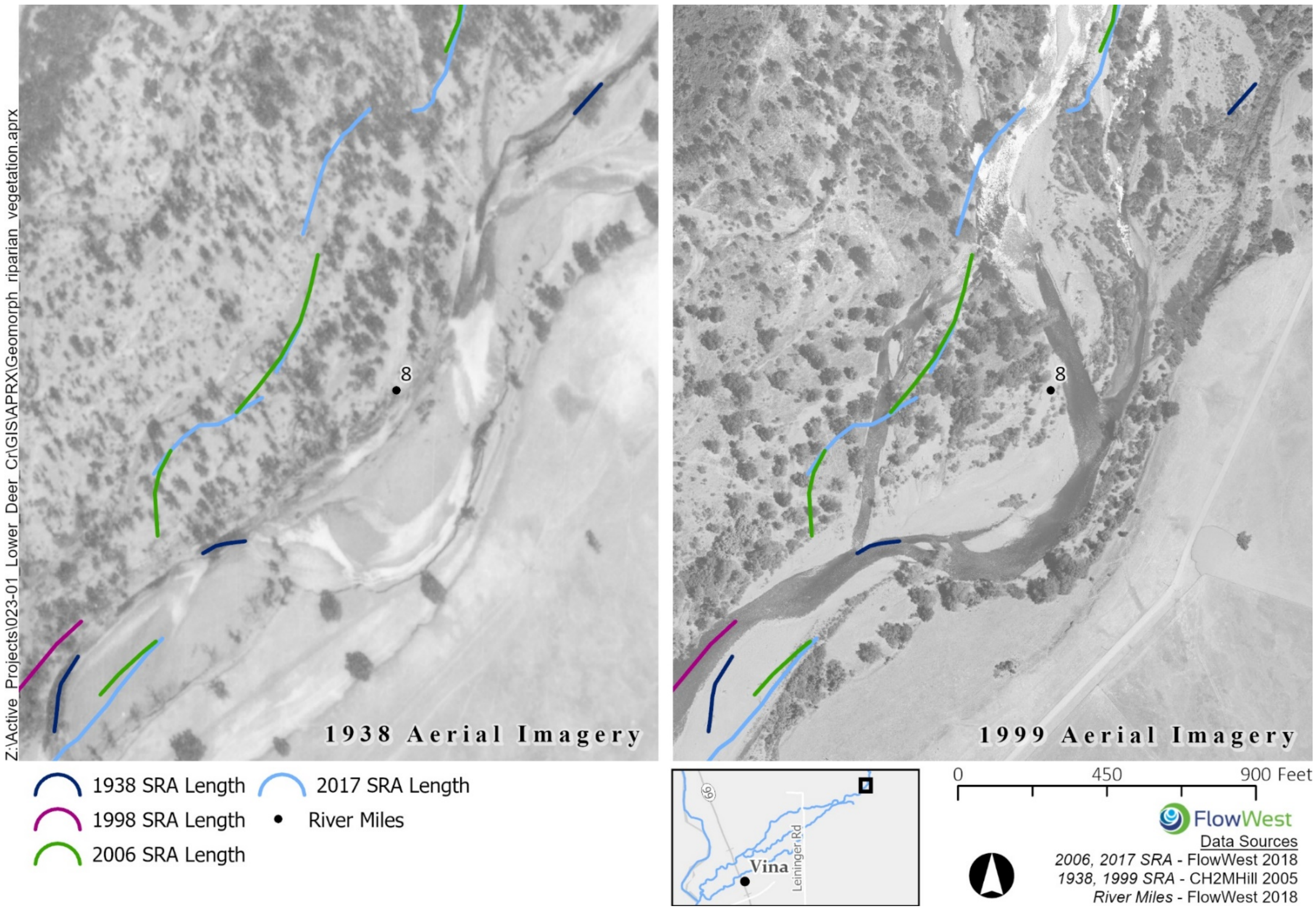
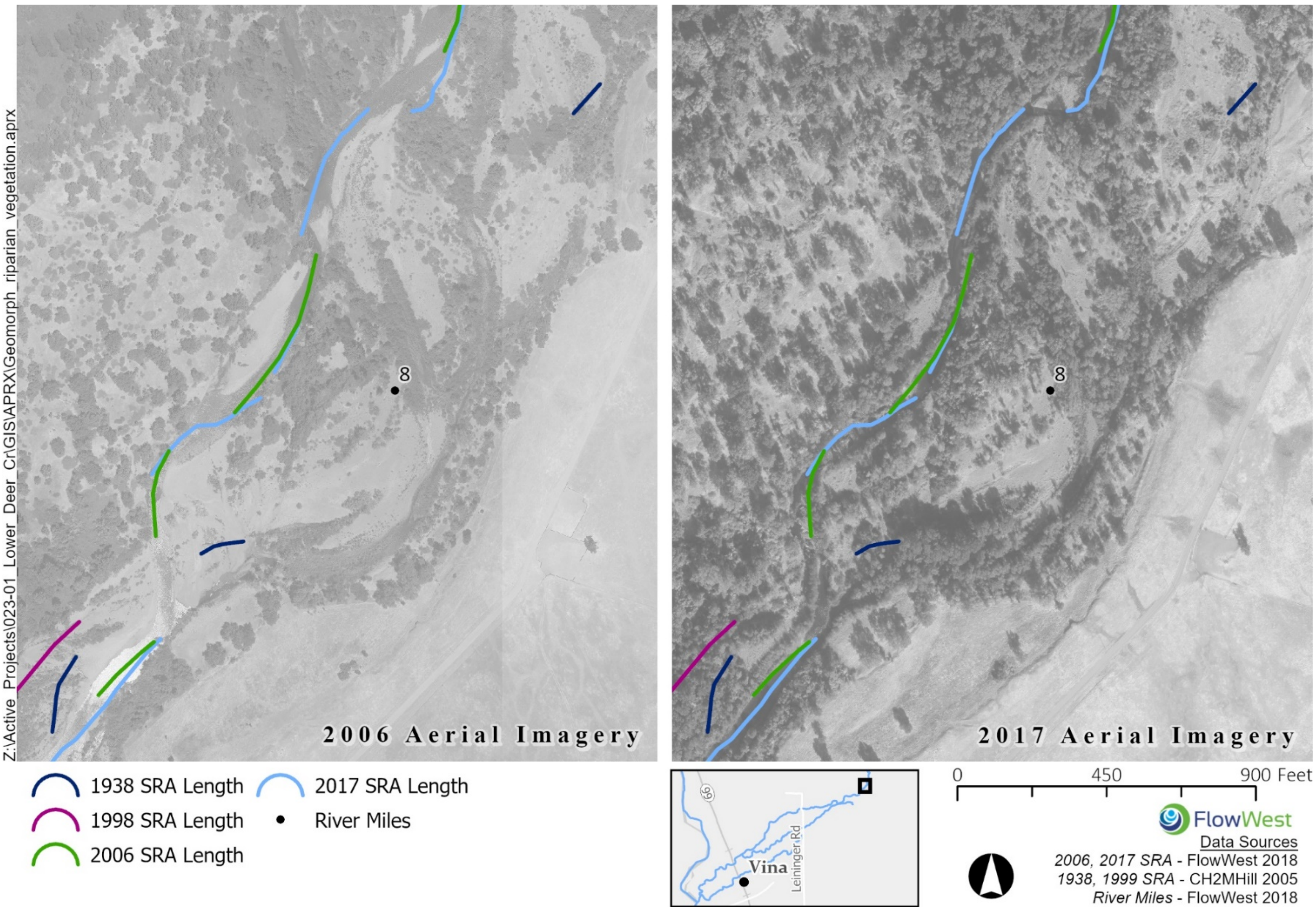


FIGURE 26: 2006 AND 2017 AERIAL IMAGES SHOWING THE EXTENT OF SHADED RIVERINE AQUATIC (SRA) VEGETATION FOR THE OUT-LEVEE REACH.



Conclusions and Recommendations

Geomorphic Conditions
Lower Deer Creek is an active channel that is not regulated by an upstream dam or storage reservoir and will continue to experience natural flows, sediment transport, large woody debris supply, and vegetation recruitment that will drive geomorphic change and threaten existing flood control levees, bridges, and other infrastructure. Without intervention, Lower Deer Creek will continue to breach the levees adjacent to the channel during high flow events. Encroachment of vegetation in the active channel during periods of low flows will decrease the conveyance capacity of the channel during high flows and result in damage to flood control infrastructure and private property. Confinement of the channel by the levees will also reduce habitat for salmonids by simplifying the channel form and scouring riparian vegetation during peak flows. This analysis strongly suggests that modification of the flood control project that incorporates setback levees will likely reduce the effects of the levee system on channel morphology and lead to more natural geomorphic conditions with less levee failure and improved habitat conditions.

Summary of Changes from 1938 to 2017
In this study we compared channel conditions from the earliest aerial photograph from 1938 to the most current imagery collected in 2017. We also reviewed Deer Creek hydrology for the period of record from 1912 to 2017. Based on this analysis, we developed the following summaries of channel and vegetation change that generally support the ability of the Project elements to improve both flood control and habitat conditions along Lower Deer Creek.

Hydrology
Deer Creek is unregulated by upstream storage or flood control reservoirs and maintains a natural hydrograph that is characteristic of Mediterranean climates with low flows in the summer and high flow during the mild winters. Flood flows have caused damages to Lower Deer Creek property and infrastructure since the completion of the USACE flood control project in 1949. Flows below the design capacity of 21,000 cfs of the USACE Levee Project result in levee overtopping and damage to flood control infrastructure.

Analysis of annual peak flows recorded at USGS gauge 11383500 (Deer Creek near Vina) shows a pattern of large flows that significantly alter the channel and floodplain vegetation in Lower Deer Creek followed by a period of low flows that allows vegetation to encroach into the active channel. These large events define “resets” in geomorphic conditions. Since completion of the USACE Project, peak flows that caused damage to levees and/or private property were observed in 1964, 1969, 1970, 1971, 1974, 1983, 1986, 1997, 2005, 2012, and 2017. The flood frequency analysis of Deer Creek for the period of record from 1912 to 2017 determined that the recurrence intervals of the 2-, 5-, 10-, 25-, 50-, and 100-year events are 5,540 cfs, 9,890 cfs, 13,200 cfs, 17,880 cfs, 21,430 cfs, and 25,260 cfs, respectively.

Channel Width Analysis

FlowWest measured the active channel width of Lower Deer Creek from aerial photographs taken in 1938, 1966, 1985, 1999, 2006, and 2017. Channel width measurements were taken only along the primary active channel and were taken at the same locations as previous measurements (CH2M Hill 2005). The active channel width has decreased from 1938 to 2017 by 7% in the levee reach, 26% outside of the levee reach, and 18% for the entire Lower Deer Creek Reach. Between 1999 and 2017 the active channel width decreased by 43% in the levee reach, 46% outside of the levee reach, and 4% for the entire Lower Deer Creek Reach. Our review of the historical aerial photographs shows a pattern of flood induced scour of riparian vegetation and associated channel widening, followed by vegetation encroachment and associated channel narrowing. Channel widening is more severe and lasts longer in leveed reaches, creating conditions with less suitable salmonid habitat as depths decrease and temperature increases over longer durations.

Cumulative Channel Length Analysis

FlowWest delineated the primary and secondary channels and summed lengths for each reach to understand how levee confinement may have simplified the channel by reducing meanders. We found that the channel length from 1938 to 2017 has decreased by 23% in the levee reach, 18% outside of the levee reach, and 20% for the entire Lower Deer Creek Reach. For the recent period between 1999 and 2017 the channel length has decreased by 15% in the levee reach, 20% outside of the levee reach, and 17% for Lower Deer Creek as a whole. These results suggest that narrowly confined leveed reaches have more significantly reduced complexity and therefore less suitable habitat for salmonids and other species.

Lateral Channel Migration

To better understand lateral channel migration in Lower Deer Creek, we delineated the channel bank at three locations and calculate the channel change between 1938 and 2017. We found that the channel has migrated 493 feet at the River Mile 2.5 site in the In-Levee Reach. Further upstream the channel migrated 212 feet within the In-Levee Reach at the River Mile 5.5 site. Lastly, upstream of the levee reach we found that the channel has migrated 403 feet at River Mile 6.5. These measurements confirmed the characterization of Lower Deer Creek as actively migrating across the floodplain. Without setback levees, migration will erode existing flood control infrastructure. It is likely that a wider riparian and floodplain corridor along Lower Deer Creek will better accommodate natural channel migration and reduce or even eliminate the need for maintenance of flood control infrastructure.

Flood Corridor Width Analysis

FlowWest determined that there was no change in the flood corridor width, which we define as the valley width controlling features such as bluffs, bedrock outcrops, and terraces.

Riparian Vegetation Analysis

FlowWest quantified the amount of riparian vegetation in proximity to Deer Creek by digitizing riparian vegetation from aerial imagery from 1999 to 2017. We determined that riparian vegetation decreased by 38% for the In-Levee Reach, increased 27% in the Out-Levee Reach, and decrease 8% for the entire Lower Deer Creek Reach. Over the period from 1999 to 2017 riparian vegetation increased by 35% for the In-Levee Reach, by 13% for the Out-Levee Reach, and by 20% for the entire Lower Deer Creek. Riparian vegetation decreased between 1938 and 2017, but for the period from 1999 to 2017 riparian vegetation encroached in the active channel. Riparian vegetation likely will be scoured by the next high flood flow.

Shaded Riparian Aquatic Analysis

FlowWest quantified shaded riparian aquatic (SRA) habitat, which we defined as nearshore areas occurring at the interface between a river and adjacent riparian habitat. By mapping SRA habitat from 1938 to 2017 we determine that SRA decreased 21% for the In-Levee Reach, increased 29% for the Out-Levee Reach, and increased 2% for the entire Lower Deer Creek. From 1999 to 2017 SRA habitat increased 77% for the In-Levee Reach, increased 27% for the Out-Levee Reach, and increased 45% for the entire Lower Deer Creek. Significant reduction in SRA habitat for the In-Levee Reach from 1938-2017 compared to the Out-Levee Reach illustrates the reduction in SRA habitat caused by levees that narrowly confine the creek corridor. The 1999 to 2017 period shows increase in SRA as expected during periods of lower to moderate flows on Deer Creek. Vegetation will likely be scoured during the next extreme flood flow and SRA habitat will decrease more significantly in leveed reaches than in non-leveed reaches.

RECOMMENDATIONS

This analysis strongly indicates that setting back flood control infrastructure will convey flood flows more efficiently, provide the active channel with room to migrate without causing damage, increase habitat complexity for salmonids, and eliminate the need for riparian vegetation management to maintain flood conveyance capacity. Deer Creek is unregulated by storage dams and the hydrology of the watershed includes frequent channel forming flows that should naturally improve channel, riparian, and floodplain habitat conditions suitable for salmonids when more room is provided for natural geomorphic processes to occur.

REFERENCES

Deer Creek Watershed Conservancy (DCWC). 2011. Lower Deer Creek Restoration and Flood Management: Feasibility Study and Conceptual Design. Phase I Final Report. Prepared for CALFED Bay-Delta Authority under project #ERP-02D-P53 Prepared by Mussetter Engineering, Inc. (MEI),
M. MacWilliams, M. Tompkins, M. Kondolf, and McBain & Trush. Vina, CA. 171 Pages + Appendices

Deer Creek Watershed Conservancy (DCWC). 1998. Deer Creek Watershed Management Plan. Prepared for the Deer Creek Watershed Conservancy, prepared by The Habitat Restoration Group, Aquatic Systems Research, Meadowbrook Conservation Associates, CSU Chico, M. Kondolf. June.

CH2M Hill. 2005. Lower Deer Creek 2017: Hydrology and Geomorphology. Prepared by M. Tompkins, A. Falzone, M. Kondolf, M. Hall, M. MacWilliams, K. Iceman). January 31.

Harwood, D.S. and E.J. Helley. 1987. Late Cenozoic tectonism of the Sacramento Valley, California. USGS Professional Paper 1359.

Helley E.J. and D. S. Harwood. 1985. Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California. USGS Miscellaneous Field Studies, Map MF-1790.

United States Army Corps of Engineers (USACE). 1957. Operation and Maintenance Manual for Deer Creek, Tehama County, California. Sacramento District. March.

United States Army Corps of Engineers (USACE). 2016. HEC-SSP Statistical Software Package, Version 2.1. Institute for Water Resources, Hydrologic Engineering Center (HEC). Davis. July. http://www.hec.usace.army.mil/software/hec-ssp/documentation.aspx

United States Geological Survey (USGS). 1982. Guidelines for Determining Flood Flow Frequency. Bulletin #17B. Interagency Advisory Committee on Water Data. Reston, Virginia. March. https://water.usgs.gov/osw/bulletin17b/dl_flow.pdf