MORMON SLOUGH:
Rediscovering a forgotten waterway IN STOCKTON, CA

Technical Appendix for the historical ecology, urban biodiversity, and urban heat analyses sections of the ArcGIS StoryMap



Prepared by the San Francisco Estuary Institute for Restore the Delta

August, 2026

SFEI
SAN FRANCISCO ESTUARY INSTITUTE

AUTHORS (SFEI):
Sacha Heath
Sean Baumgarten
Selena Pang
Ben Satzman
Evan Melendez
Mino Han
Kat Palermo
Alison Whipple

SFEI Contribution # 1315

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SUGGESTED CITATION

Heath, S. K., S. Baumgarten, S. Pang, B. Satzman, E. Melendez, M. Han, K. Palermo, A. Whipple. 2026. Technical Appendix for the historical ecology, urban biodiversity, and urban heat analyses sections of the ArcGIS StoryMap "Mormon Slough: Rediscovering a forgotten waterway in Stockton, CA". Prepared for Restore the Delta by the San Francisco Estuary Institute, Richmond, CA. SFEI contribution # 1315.

VERSION

Version 1.0 (August 2026)

REPORT AVAILABILITY

Report is available at sfei.org/projects/mormon-slough-restoration

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COVER IMAGE CREDIT

(top) Historical soil map (Lapham and Mackie 1905); (bottom left) patch size map by SFEI, generated from various land use and land cover data; (bottom right) urban heat map by SFEI, generated from EROS (2026) data.

Table of Contents

Introduction **1**
- Topic Selection 1
- Analysis Area 1
- Analysis Chapters 2

Chapter 1: Historical Ecology **4**
- Methods 4
  - Analysis Limitations 5
- Synthesis Results & Discussion 5
  - Slough Network 5
  - Hydrology 9
  - Wetland and Riparian Habitats 11
  - Terrestrial Habitats 14
  - Relevance to Mormon Slough restoration 17

Chapter 2: Urban Biodiversity **18**
- Methods 18
  - Patch Size 18
    - Analysis Limitations 20
  - Matrix Quality 20
    - Analysis Limitations 24
- Results & Discussion 24
  - Patch Size 24
    - Relevance to Mormon Slough restoration 25
  - Matrix Quality 27
    - Relevance to Mormon Slough restoration 27

Chapter 3: Urban Heat **29**
- Methods 29
  - Analysis Limitations 29
- Results & Discussion 30
  - Relevance to Mormon Slough restoration 31

Conclusion **35**

Acknowledgements **36**

Literature Cited **36**

Introduction

The Mormon Slough Restoration Association (MSRA) was formed in 2023 to lead the revitalization of a six-mile length of Mormon Slough in the city of Stockton, California (Figure 1). In support of this effort, Restore the Delta (RTD), a lead partner in the MSRA, contracted the San Francisco Estuary Institute (SFEI) to conduct three landscape-scale environmental analyses to inform community visioning for two pilot site designs in 2026, and to inform future phases of visioning and planning for Mormon Slough restoration. These technical analyses complement environmental assessments, site studies, and pilot sites selection performed by River Partners (River Partners 2025) and this technical appendix is a companion to the story map Mormon Slough: Rediscovering a forgotten waterway in Stockton, CA.

Topic Selection

In October-November 2025, Restore the Delta conducted a survey in communities around Mormon Slough to identify community priorities for near- and long-term restoration of Mormon Slough. Among these was one question to inform SFEI's selection of three topics for analyses; the question asked participants to rank topics on a scale of "very important" to "very unimportant." The results of this question were inconclusive, however, because there was a lack of consistency in how the scale of importance was interpreted by participants. In absence of reliable question results, SFEI proposed three analysis topics based on organizational expertise in multi-benefit urban greening planning (Spotswood et al. 2019, Stoneburner et al. 2025), community preferences articulated by RTD, and to complement previous work in the study area (Whipple et al. 2012, River Partners 2025). These topics were approved by RTD and the MSRA Technical Advisory Committee and are:

- Historical Ecology
- Urban Biodiversity
- Urban Heat

Analysis Area

The six-mile section of the Mormon Slough of interest to the MSRA is located between the Stockton Diverting Canal in the east and the Stockton Deep Water Channel to the west (hereafter referred to as Mormon Slough; Figure 1). Landscape-scale analyses were performed within an area that extended beyond Mormon Slough because of the

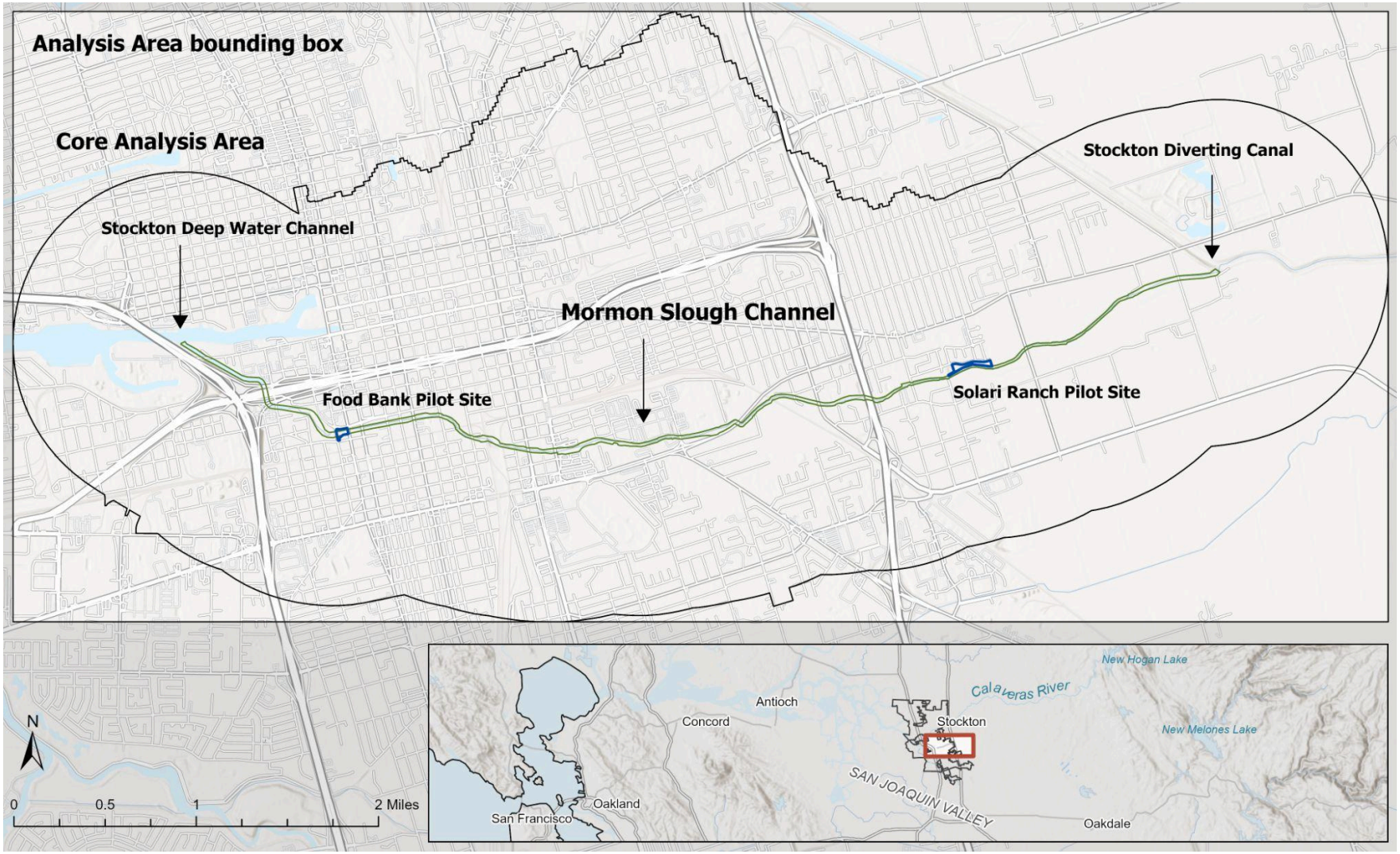
assumption that channel restoration will be affected by conditions in the surrounding landscape. The aim of these analyses was to characterize the historical ecology, urban biodiversity, and urban heat conditions in and around Mormon Slough to inform pilot site designs and potential future selection of sites where urban greening projects around the slough could complement in-channel restoration for additional community cooling and biodiversity benefits.

The analysis area bounding box encompassed five merged spatial components designating the core analysis area (Figure 1): 1) The area encompassing the historical network of sloughs connected to Mormon Slough (Whipple et al. 2012); 2) the combined stormwater drainage basin boundaries of Mormon Slough (City of Stockton MUD 2026); 3) the elevational drainage-basin boundary of the Mormon Slough and Stockton Deep Water Channel confluence (USGS 2025); 4) the 800 m (½ mile) or 10-minute walking distance within Mormon Slough, which is the distance benchmark used by the State of California to define healthy, walkable green spaces for community members (Zuniga-Teran et al. 2017, Logan et al. 2022, California State Parks 2026); and 5) a 1,500 m wildlife movement buffer surrounding the Mormon Slough channel, based on a literature review reporting urban dispersal distances of wildlife movement functional groups, and representing the longest distance the farthest-roaming group investigated is expected to disperse (see Table 1 in Chapter 2: Urban Biodiversity; Iknayan et al. 2026).

Analysis Chapters

Chapters for each of the three analysis topics include self-contained sections: introduction, methods, analysis limitations, results & discussion, and relevance to Mormon Slough restoration.

Figure 1. Mormon Slough, two pilot sites, core analysis area, analysis area bounding box, and locator map inset.



Chapter 1: Historical Ecology

The historical ecology analysis synthesized archival data to increase understanding of landscape patterns and processes that characterized Mormon Slough and surrounding areas in the early 1800s prior to major Euro-American modification. Historical ecology provides foundational information about the distribution and composition of local ecosystems, physical drivers, and the biophysical conditions to which native species are adapted. Information about historical conditions grounds restoration planning in an accurate understanding of how landscapes have changed over time, and helps identify restoration opportunities and targets (Jackson and Hobbs 2009, Beller et al. 2020, McClenachan et al. 2024).

The analysis relied primarily on research and mapping conducted for the Sacramento-San Joaquin Delta Historical Ecology Investigation (Whipple et al. 2012; referred to herein as Delta HE), which was supplemented with limited additional data collection, compilation, and synthesis. Historical mapping from the Delta HE study covers the western portion of the analysis area, though archival data collected for the study includes information about the broader region. Additional mapping was not conducted as part of this effort.

Methods

We reviewed all relevant archival data sources previously collected as part of the Delta HE study for information about landscape conditions within the analysis area. The dataset includes maps (e.g., Mexican land grant maps, General Land Office surveys, USGS topographic quads, USDA soil maps, irrigation and engineering maps), photos, drawings, surveys, and textual accounts (e.g., Spanish explorer accounts, Mexican land case files, surveyor field notes, newspaper articles, water resource reports, local and county histories) collected from a wide range of online databases and source institutions, as well as georeferenced historical maps and other geospatial data.

Additional data were collected from a subset of high-priority databases (e.g., California Digital Newspaper Collection, Biodiversity Heritage Library, Calisphere) using a list of keywords relevant to the analysis area. The keyword list was also used to search previously transcribed excerpts from textual data sources.

We synthesized the assembled data in conjunction with the Delta HE mapping to identify emerging findings related to channel configuration, habitat distribution and composition, hydrology, and other topics.

Analysis Limitations

The additional archival data collected as part of this effort to supplement the Delta HE mapping represents a subset of the available data, and thus findings presented here should be considered preliminary and subject to change with further research.

Synthesis Results & Discussion

This section summarizes key findings and supporting evidence regarding historical landscape conditions within the analysis area, with a focus on the slough network, hydrologic patterns, wetland and riparian habitats, and terrestrial habitats. For more information, consult Whipple et al. (2012; see in particular pages 164-167 and 194-203).

Slough Network

Mormon Slough was one of many sloughs that were part of a larger distributary network across the alluvial fan formed by the Calaveras River to the north (Figure 2; Tinkham 1880). In addition to Mormon Slough, numerous other sloughs and tributaries drained into the analysis area from the east (Figure 3; Norris 1853, Beaumont 1858, Hall 1886).

Mormon Slough supported several multi-threaded reaches (Figure 4; Herron 1851, Unknown 1854, USDC 1859, California Secretary of State 1866, Henkknius 1894), including one near the location of present-day Solari Ranch (Hall 1886). An unnamed channel branched off of Mormon Slough just downstream of the present-day Stockton Diverting Canal, and flowed northwest before branching into Lindsay and Fremont's sloughs upstream of McCloud's (or McLeod's) Lake (Hall 1886, Henkknius 1894). Stockton Slough branched off Mormon Slough near present-day South Stanislaus St., and flowed northwest before connecting with Lindsay and Fremont sloughs at McCloud's Lake (Figure 5; Hammond 1849, Brown 1850). Mormon Slough and Stockton Slough reconnected further downstream, just west of present-day Highway 5, and then drained west into the San Joaquin River.

Figure 2. Conceptual diagram showing the historical alluvial fan and distributary network of the Calaveras River and its connections with the tidal wetlands of the Delta to the west.

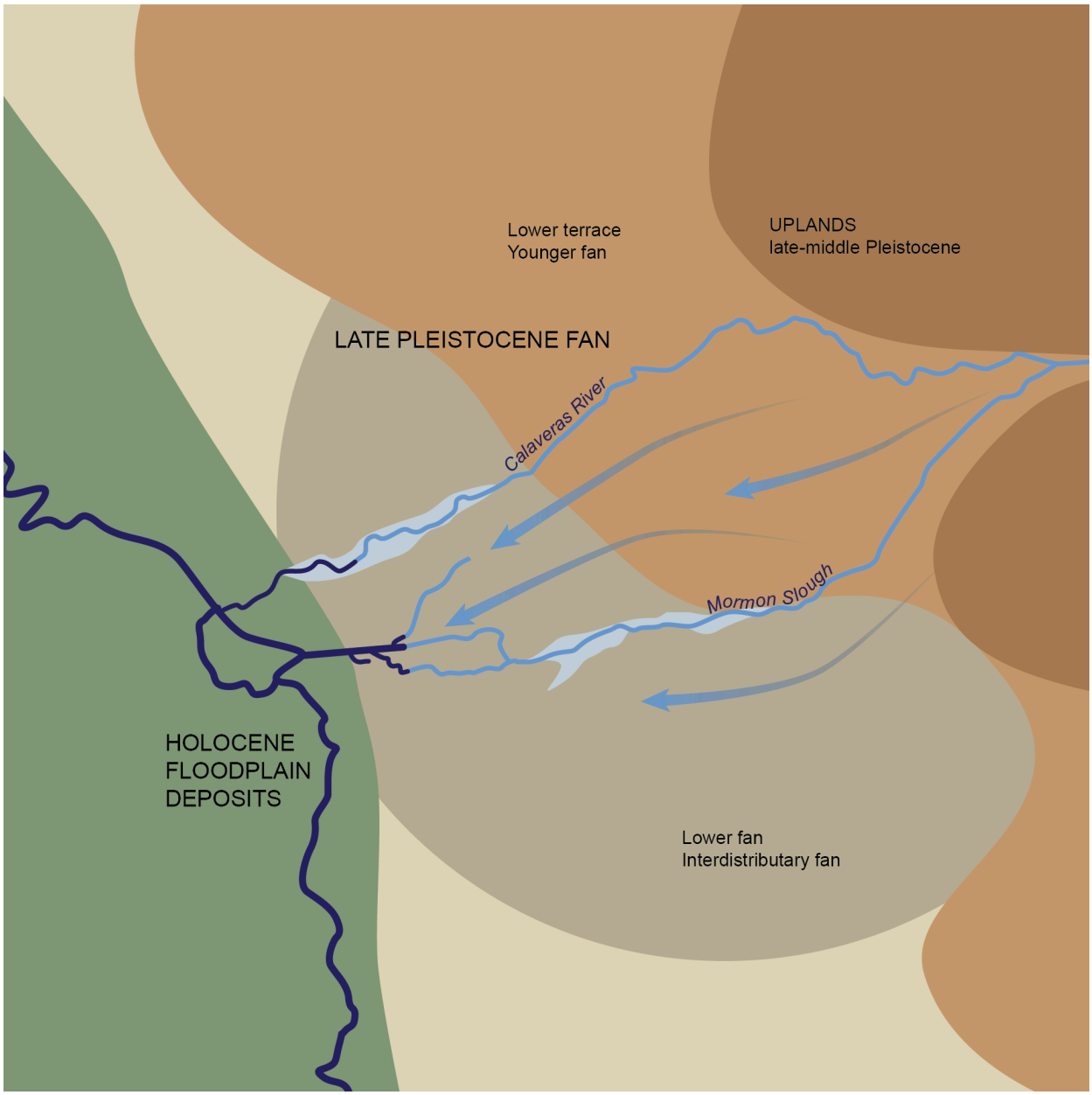


Figure 3. Delta HE mapping overlaid on an 1886 map showing the historical slough network within the analysis area. (Hall 1886, courtesy of David Rumsey Map Collection)

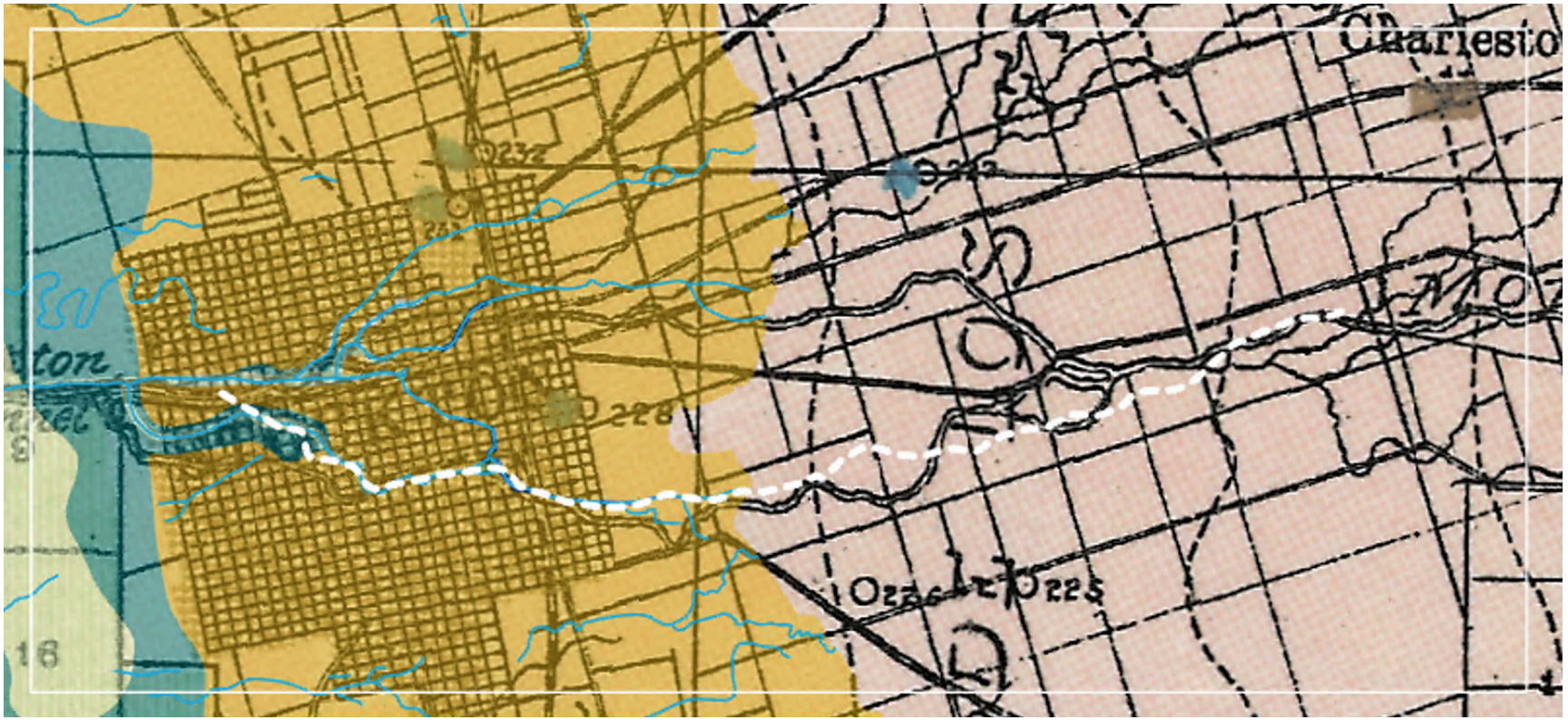


Figure 4. Map of Weber's Grant and Rancho del Campo de los Franceses, showing braided reaches of tributaries within the analysis area (Unknown 1854, courtesy of The Bancroft Library)

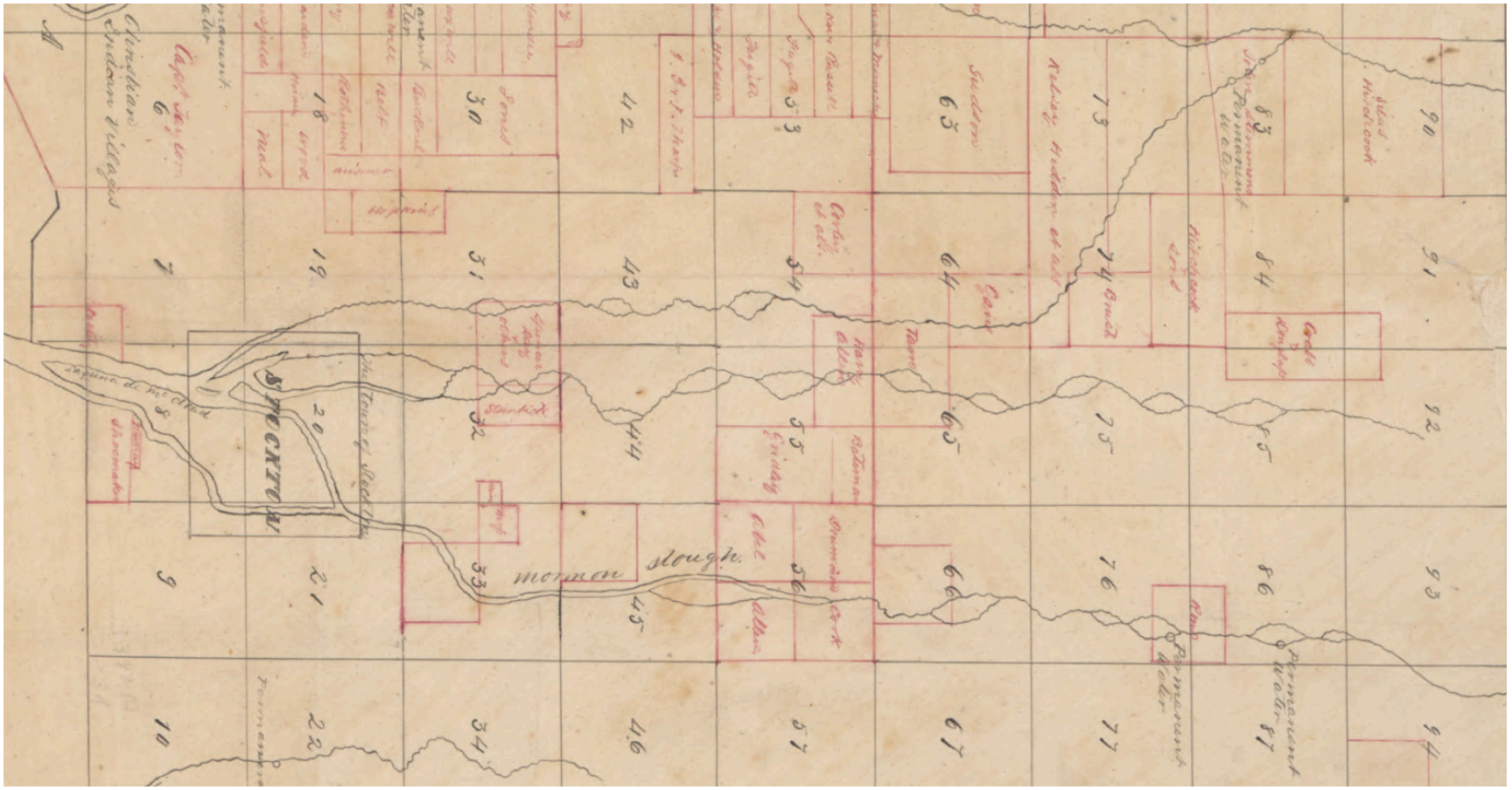


Figure 5. 1849 map showing Mormon, Stockton, Lindsay, and Fremont sloughs in downtown Stockton (Hammond 1849, courtesy of San Joaquin County Surveyor's Office).



Hydrology

Mormon Slough and neighboring sloughs regularly conveyed floodwater from the Calaveras River and other upstream areas during the winter and spring snowmelt season, often flooding portions of Stockton and surrounding areas (Figure 6). A December 1851 newspaper article, for instance, reported, "There has been an immense rush of water into the sloughs, and they are now bank high. A ferry has been established on the Mormon channel" (San Joaquin Republican 1851), while an article the following year stated that a "flood was all over the city" of Stockton, which "looked like a vast lake" (Daily Alta California 1852). An article in February 1857 reported that the "banks of the Calaveras

are overflowed… [and] Mormon Slough afforded the outlet of a large volume of water," and noted that Mormon Slough "effectually conveys the great body of water that comes from the plains south of [Stockton]" (Sacramento Daily Union 1857).

Early Stockton resident Carl Edward Grunsky offered a vivid account of flooding in Mormon Slough during the mid-19th century:

> "[Mormon] *slough… received a considerable increment from the flood waters of the Calaveras River, and as the floods of this stream usually occurred in advance of the rise in the San Joaquin River, the flood water of the slough had a gradient or drop of from fifteen or twenty feet in its short course through Stockton. The rough bed over which it flowed created rapids. The water at such times was in wild motion and it was no exaggeration to speak of the 'roaring' of the slough"*
> (Grunsky and Taylor 1959)

Figure 6. Circa 1895 photograph showing a flood in Stockton (Unknown 1895, courtesy of University of the Pacific Library)



In contrast, the Calaveras River and Mormon Slough rarely sustained streamflow through the dry season (Hilgard 1884, Tinkham 1923, Whipple et al. 2012). Moerenhout (1849), for instance, wrote, "We covered six leagues, from French Camp to the Arroyo de las Calaveras, without encountering any water, and even the [Arroyo de las Calaveras], which is an impassable torrent during the season of rains and of the first melting snows, today

showed water only here and there." Testimony from the Campo de los Franceses land grant case similarly affirms that the "bed of the [Calaveras] river is dry at all times except during the rainy season" (Beaumont 1859). An 1868 article noted that "1868 saw the water flows from the Calaveras River in the Mormon Slough channel continue through the summer, something that had not occurred since 1849" (Stockton Independent 1868).

Freshwater tidal influence extended upstream along Mormon Slough as far east as present-day California Street (Grunsky and Taylor 1959). Grunsky, for instance, wrote:

> *"The lower section of* [Mormon Slough], *from its junction with Stockton Slough, upstream as far as California Street, was a tidal channel. The rise and fall of the tide at low stages of the San Joaquin River was about two feet this far upstream. The lower reaches of the slough had a width, based on my recollection, of from 100 to 150 feet…*
>
> *Just west of where the California Street bridge now crosses the slough was the 'Rosebush'… The Rosebush marked the extreme upper level of tidal effect. A few hundred yards further west we often watched and even ran from a small-scale tidal bore, perhaps ten to twelve inches high, which would form under certain conditions of wind and rising tide"* (Grunsky and Taylor 1959)

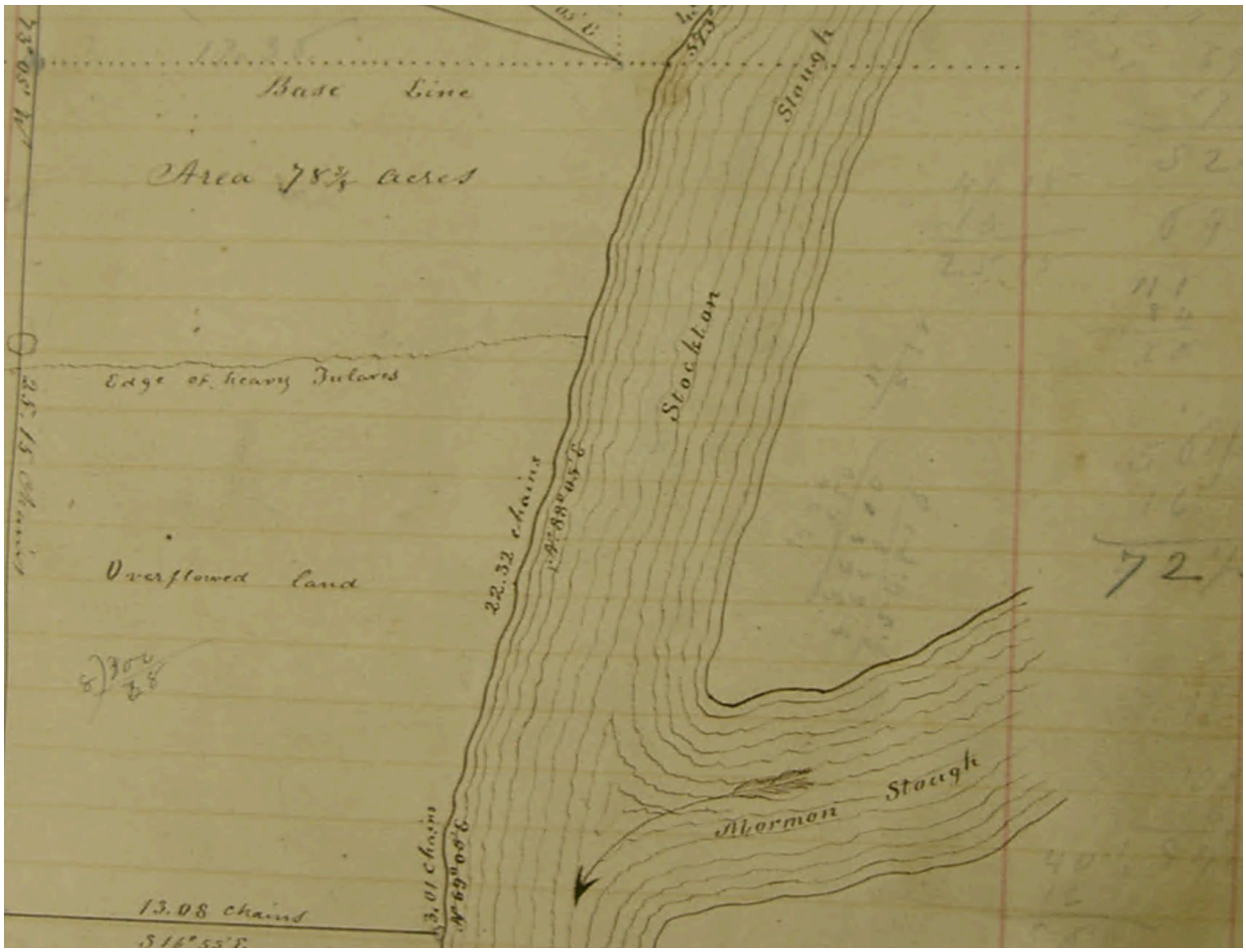
Grunsky goes on to describe a "mud bar [in Mormon Slough] just to the east of Center Street" that was "bare at low tide," where freshwater clams were collected (Grunsky and Taylor 1959). Records from 1913 indicate that the extreme tidal range at Stockton was about three feet (Allen 1920).

Wetland and Riparian Habitats

Outside the slough network, the valley on the western portion of the analysis area—west of the confluence of Mormon Slough and Stockton Slough—was characterized by non-tidal freshwater emergent wetlands (see Figure 3; Gibbes 1850, Beaumont 1858, Grunsky and Taylor 1959, Whipple et al. 2012). An 1850 survey, for instance, indicates the "edge of heavy tulares" just to the east of this confluence, with "overflowed land" to the west (Figure 7; Gibbes 1850). Grunsky recalled that the "tule country extended to the western limits of Stockton as the city was originally laid out, their eastern margin being fully a mile up the slough, extending thence north and south" (Grunsky and Taylor 1959). An 1873 account reported that "the low lands between Mormon Slough and French Camp Slough… are subject to overflow, at times of high water, from one to four feet in depth" (San Joaquin and Tulare Railroad Company 1873).

A narrow swath of wetlands extended further east along Mormon Slough to near present-day South Van Buren St, and patches of wetland vegetation also occurred within and immediately adjacent to sloughs. While camped near McCloud's Lake in 1833, for instance, trapper John Work observed "bulrushes along the edge of the bay" (Work and Maloney 1945). On the western side of the analysis area, this border of non-tidal wetlands transitioned into the tidal freshwater emergent wetland (also tule-dominated; *Schoenoplectus* spp.) that extended throughout the Delta to the west of Stockton (see Figure 3; Lapham and Mackie 1905, CDWR 2008).

Figure 7. 1850 survey showing "edge of heavy tulares" near the confluence of Mormon and Stockton sloughs. (Gibbes 1850 courtesy of San Joaquin County Surveyor's Office)



Both tidal and non-tidal freshwater emergent wetland were dominated by tule. For instance, while surveying approximately 1 mile north of Stockton Channel in June 1853, General Land Office surveyor Ralph Norris reported, "Edge of tule… Could proceed no farther west" (Norris 1853). A witness in the Campo de los Franceses land grant case in 1856 testified that "the land between the [San Joaquin] river and the East line of the Tule is swampy, wet, marshy land. Its width varies from 1 to 3 miles" (Beaumont 1859). Bayard

Taylor, traveling near the Calaveras River in August 1849, described heavy smoke from "burning tule" (Taylor 1854).

In addition to the extensive wetlands on the western side of the analysis area, Mormon Slough, along with other waterways such as Stockton Slough and Lindsey Slough, supported sparse to dense corridors of riparian forest dominated by oaks and willows (Lapham and Mackie 1905, Grunsky and Taylor 1959). These riparian corridors were not likely very wide and there is a lack of accurate early spatial data showing the extent of riparian forest laterally and longitudinally prior to major modifications in the 1800s, and thus riparian forest along these sloughs is not depicted in the Delta HE mapping, with the exception of a patch on Park Island.

Late 19th and early 20th century photos show trees bordering Mormon Slough, Lindsay Slough, Stockton Slough, and McCloud's Lake (Figure 8; Lawrence & Houseworth Collection 1866, Martin 1890, Covello ca. 1900). "Low scrub willows" were described along Mormon Slough in 1870 (Lester 1887), and Grunsky reported oaks on the banks of Stockton Slough east of the confluence with Mormon Slough (Grunsky and Taylor 1959). Apparently describing riparian vegetation on Park Island, Grunsky wrote, "Quite a grove of fair-sized oaks grew here within the area that was part of the slough at its high stages. These trees were all cut down for stove wood early in the '60s" (Grunsky and Taylor 1959, Whipple et al. 2012).

Figure 8. Mormon Slough is bordered by oaks in this undated ca. 1900 photograph. (Covello ca. 1900, courtesy of Bank of Stockton Historical Photograph Collection)



Terrestrial Habitats

The plains surrounding Mormon Slough and Stockton were dominated by oak woodland/savanna (Whipple et al. 2012). This pattern, compared to the more open plains to the north and south, was likely attributable to the area's position on the alluvial fan of

the Calaveras River, likely with comparatively better-drained inorganic soils. Within the portion of the analysis area covered by the Delta HE mapping, oak woodland/savanna extends from the eastern edge of the freshwater emergent wetland to the eastern boundary of the mapping (see Figure 3). Beyond the extent of the Delta HE mapping, the reviewed evidence suggests that the eastern portion of the analysis area was likewise dominated by oak savanna (USDC ca. 1840, Norris 1853, Fisher 1854, Snow and Roos 1870, Lapham and Mackie 1905, Grunsky and Taylor 1959), and may also have supported patches of seasonal wet meadow (Lapham and Mackie 1905).

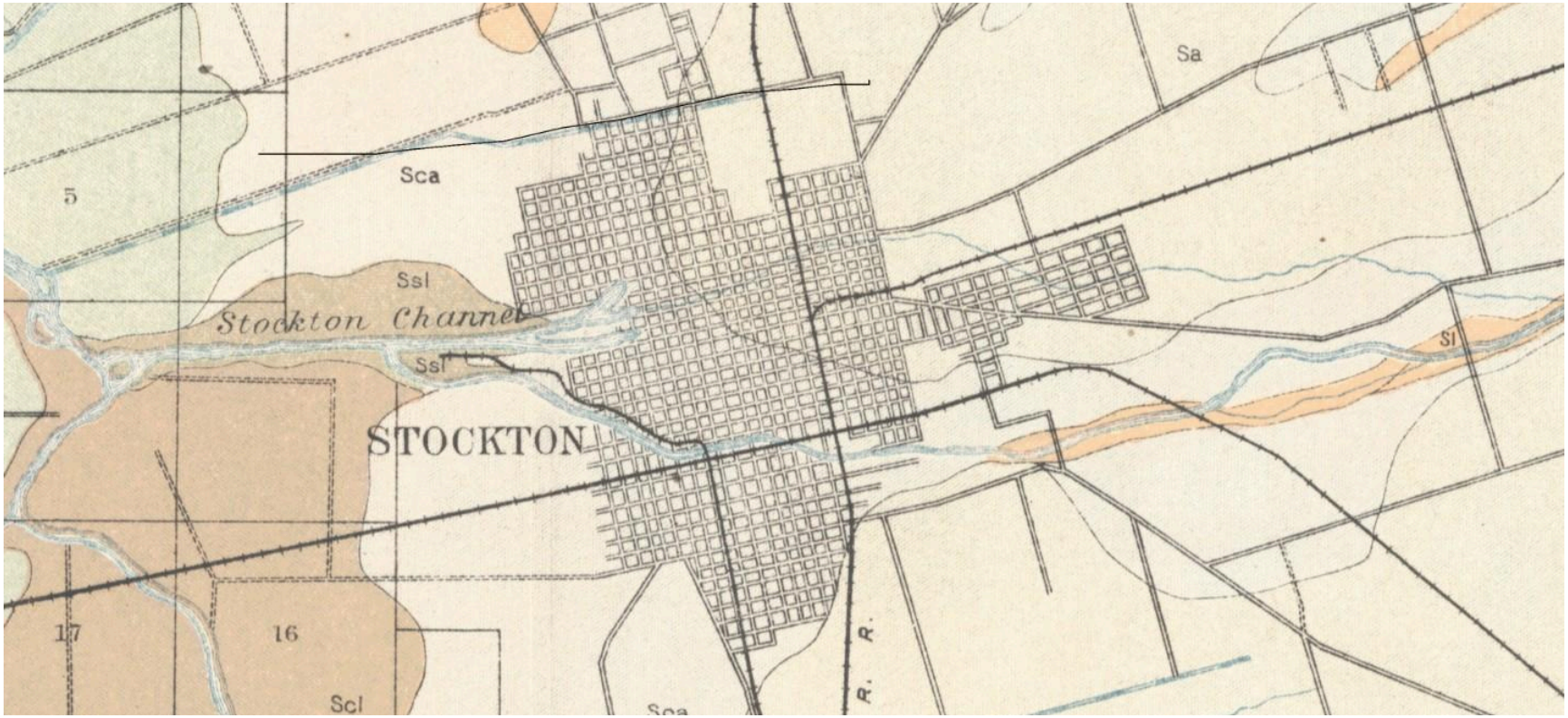
Oak savanna was likely characterized by scattered valley oak (*Quercus lobata*), with an understory of grasses and forbs (Lapham and Mackie 1905, Tinkham 1923). Numerous early observers described the park-like nature of these habitats. Moerenhout (1849), for instance, described "magnificent country, covered with beautiful oaks and grass and absolutely like a park" in the vicinity of Rancho Campo de los Franceses (around present-day Stockton). Approaching Stockton, McCollum (1960) wrote that in 1849 "oak-openings and glades of timber, begin to approach the [San Joaquin] river." GLO surveyor Ralph Norris described oaks and "scattering timber" at a number of locations throughout the analysis area in 1853 (Norris 1853).

Grunsky described wildflowers and oak savanna in the region during the mid-19th century as follows:

> *"In the spring there was an abundance of wild flowers, so that for great stretches one saw only the carpet of their bloom, with the green of grass and foliage hidden under the riot of color. There were many pinks and whites among them, but the blue of ground lupine and larkspur and the gold of buttercups and California poppies and the many other yellow species predominated…*
>
> *Oaks covered the site of the city* [Stockton] *and extended far to the north, south and east. They were wonderfully graceful, giving a parklike character to the landscape… They did not stand in compact forest, but were isolated or in small picturesque groups and were of goodly size, generally from two to four feet in diameter and from sixty to a hundred feet high. There was no underbrush on the plains—just the iridescent green of grass interspersed with flowers"* (Grunsky and Taylor 1959)

While oak woodland/savanna dominated the plains and alluvial fan areas, the extensive and poorly drained clay adobe soils that occupied much of the region—including Stockton clay adobe and Stockton clay loam adobe—may also have supported patches of seasonal wet meadow (Figure 9; Lapham and Mackie 1905). Investigation of historical botanical records may help confirm the presence of seasonal wetlands in the analysis area.

Figure 9. 1905 soil map showing Stockton clay adobe (Sca) and Stockton clay loam adobe (Sa) on the plains surrounding Mormon Slough. These soil types were characterized by sparse oak savanna, and may have supported patches of seasonal wet meadow as well (Lapham and Mackie 1905)



Relevance to Mormon Slough restoration

Findings from the historical ecology analysis can be used in conjunction with other landscape assessments and analyses to identify opportunities, set restoration targets, prioritize restoration sites, and inform site design. The MSRA can use this information to pursue no-regrets habitat improvements in the near term while maintaining opportunities for landscape-scale, process-based restoration over the long term (SFEI-ASC 2016).

- Historical ecology can be used to identify target habitat zones for different parts of the slough where existing physical conditions and processes may be most suitable for particular habitat types (Spotswood et al. 2019, Baumgarten et al. 2023).
- Designing site-level plant palettes based on historical habitat composition can provide support for native pollinators and wildlife that share long evolutionary histories with native plant species (Spotswood et al. 2019, Berthon et al. 2021).
- Restoration of tidal influence to the lower reaches of Mormon Slough could restore aquatic and perennial wetland habitat and provide support for healthier aquatic food webs.
- Restoration of adjacent tidal and non-tidal wetlands around the lower reaches of Mormon Slough could provide benefits such as habitat, carbon sequestration, flood storage, and provision of materials for cultural uses.
- Restoration of more natural streamflow patterns in Mormon Slough primarily via hydrologic connectivity upstream could support aquatic and riparian habitats and associated fish and wildlife.
- Restoration of riparian forests could provide multiple benefits such as shading, wildlife habitat, allochthonous inputs, runoff filtration, and access to greenspace.
- Levee setbacks could provide benefits such as flood storage, primary productivity and habitat enhancement.
- Restoration of native oak ecosystems could provide numerous benefits including wildlife habitat, carbon storage, shading/temperature regulation, and reduction in stormwater runoff. It could also help connect Mormon Slough to its surrounding landscape. “Re-oaking” strategies provide guidance for reintegration of oak ecosystems into urban and agricultural landscapes (Spotswood et al. 2017, Baumgarten et al. 2020).

Chapter 2: Urban Biodiversity

This analysis focused on two of the seven Urban Biodiversity Framework elements recommended in the Making Nature's City report (Spotswood et al. 2019; SFEI 2026a). The seven elements are features of the landscape expected to support higher levels of biodiversity in urban settings (see global literature review in Spotswood et al. 2019): Patch Size, Connections, Matrix Quality, Habitat Diversity, Native Plant Vegetation, Special Resources, and Management. Elements are analyzed with geospatial layers and landscape-scale data, and results can help identify and prioritize areas for management, restoration, or urban greening actions to better support urban biodiversity.

The scope of this project was limited to three types of landscape analyses. Thus, to accommodate a wider variety of topics (i.e., historical ecology and urban heat), the two interdependent Urban Biodiversity elements expected to best complement the other topics and to inform restoration, urban greening, and pilot site design visioning were selected: Patch Size and Matrix Quality.

- **Patch Size**: the size of a contiguous patch of vegetation, permeable surface, or water within the analysis area, where a patch is defined as at least 2 acres.
- **Matrix Quality**: habitat features that support ecological processes and animal and plant movement in the urban matrix. The urban matrix is defined in this exercise as the urban space between patches, water features, and agricultural crops.

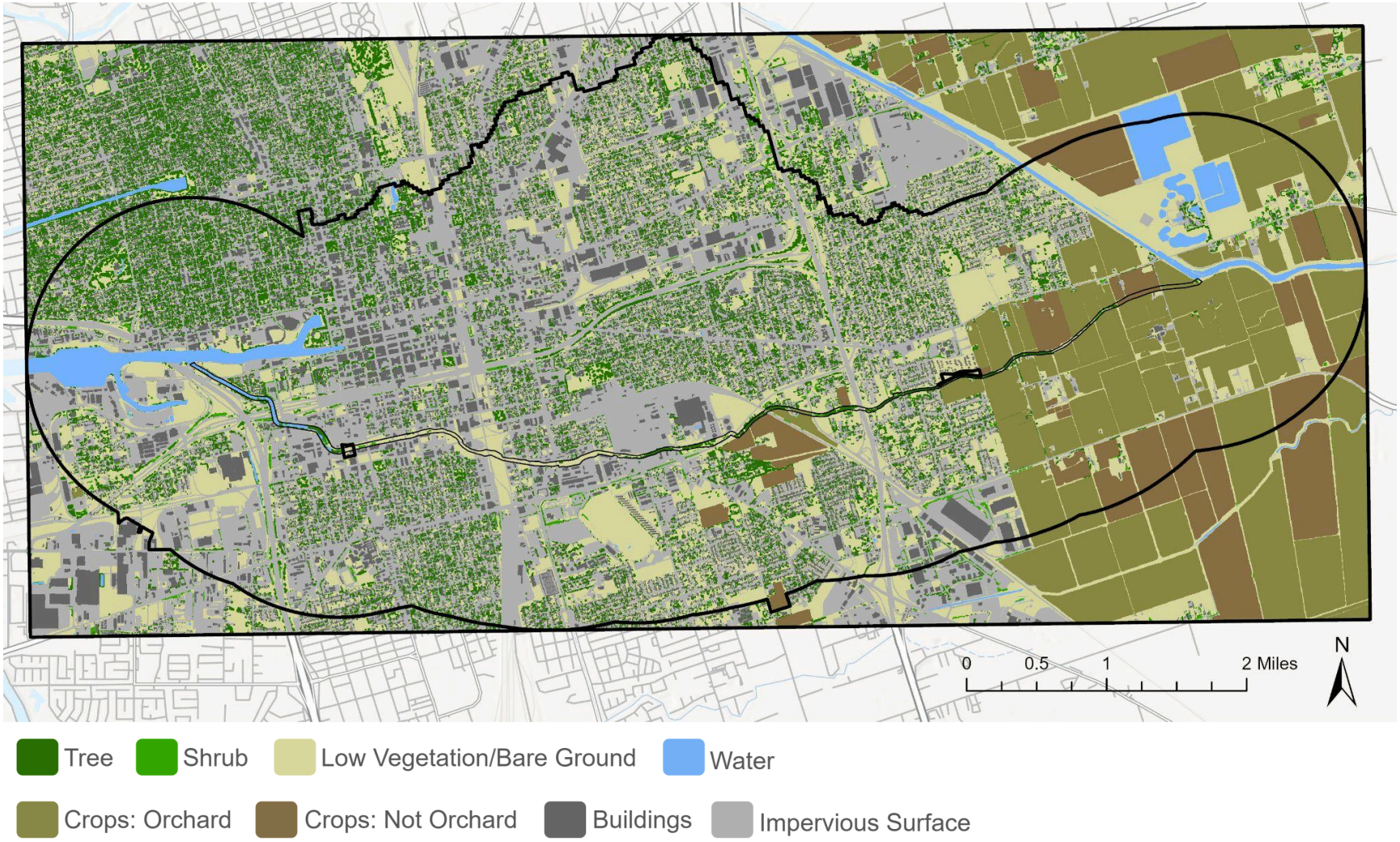
Methods

Patch Size

The goal of the Patch Size analysis was to identify and quantify patches of different sizes within the analysis area and use the output of this analysis as an input layer for the Matrix Quality element.

We first established a land use and land cover layer (LULC) for the analysis area (Figure 10) by compiling available data layers from several different sources and time periods using ArcGIS Pro: impervious cover and shrub canopy (NOAA and OCM 2021a, 2021b), tree canopy (USDA 2018, NOAA and OCM 2021b), building footprints (Microsoft 2025, City of Stockton 2026), agricultural crops (CNRA 2024), and water resources (NOAA and OCM 2021c, SFEI 2026b). We filled in the remaining land cover as the bare ground/low vegetation cover class because it was difficult to reliably differentiate these two cover types from available satellite data.

Figure 10. Land use and land cover data in the analysis area. Note that the layer was generated from data ranging from 2018-2026 and therefore might differ from contemporary conditions.



We defined the following LULC classes eligible for patch analysis: tree, shrub, low vegetation/bare ground, and water. We used the R Core Team (2025) software environment and Sciaini et al. (2018) to identify all contiguous patches of these land and water cover types totalling at least 2 acres. We then summarized patch types by size, according to patch size types recommended in Spotswood et al. (2019): small patches (2-10 acres), medium patches (>10-130 acres), and large patches (>130 acres).

Analysis Limitations

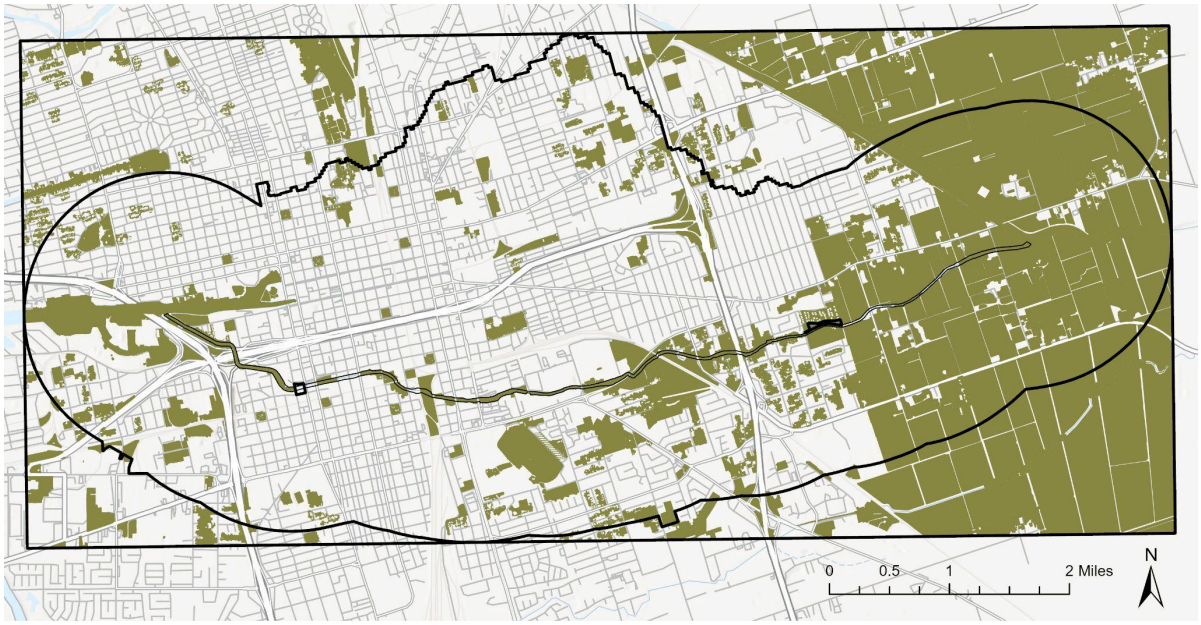
It is important to note that the Patch Size element uses size as a proxy for quality and does not summarize the types of microhabitat types within patches, nor prioritize the different types of land cover within patches. There are a few examples where large patches are identified because the continuous land cover type was bare ground/low vegetation (e.g., the Stockton Dirt Track). In reality, we would expect these patches to be of lower quality habitat for wildlife than, for example, a park with native vegetation of multiple canopy heights, but there is no difference in quality assigned to the patches in our analysis. Nonetheless, we suggest that all patches identified in this analysis represent opportunities to enhance and protect habitat throughout the analysis area, either through land acquisition, management agreements, community-led habitat enhancement programs, or other creative ventures to improve support for biodiversity at both small and large scales.

Matrix Quality

The goal of the Matrix Quality analysis was to produce a map identifying areas that should be prioritized for smaller scale habitat enhancements within the analysis area, with the goal of improving conditions in the urban matrix in support of higher biodiversity. The expectation is that improving the urban matrix within the analysis area around Mormon Slough will improve the quality of restored habitats for biodiversity within the slough. Four steps were followed to create the final Matrix Quality prioritization map. All steps were performed in ArcGIS Pro Version 3.6.1 (ESRI 2026):

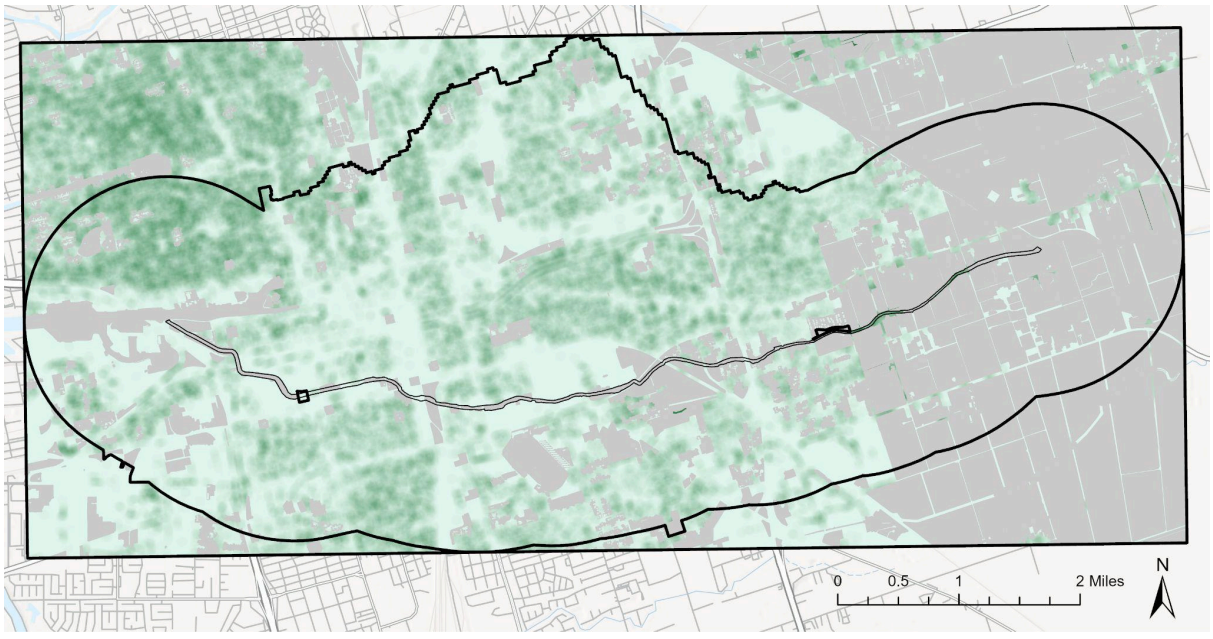
Step 1. We created a vector geospatial layer to be used as a masking layer in future steps that merged 1) the patch layer output from the Patch Size analysis, 2) all water feature classes from the LULC layer regardless of size, and 3) the Crops: Orchard and Crops: Not Orchard classes from the LULC layer (Figure 11). Crop areas were included in the masking feature alongside patches and water because agricultural lands also support wildlife, and—similar to the urban matrix—uncultivated areas around crops can be enhanced to support biodiversity (e.g., hedgerows and pollinator strips; Heath et al. 2017, Froidevaux et al. 2019, Ponisio et al. 2019).

Figure 11. Output vector layer from Step 1 of the Matrix Quality analysis; merged classes of patches from the patch analysis output, water bodies, and orchard/not orchard crop areas.



Step 2. We used the output vector geospatial layer from Step 1 to mask patches greater than 2 acres, water features, and cropland. In the remaining unmasked matrix in the analysis area we took the mean of the percentage of tree and shrub cover (identified from the LULC layer) within 50 m of each of the 1 m raster cells using the Focal Statistic geoprocessing tool (Figure 12). The 50 m radius buffer was selected because this area

Figure 12. Initial output raster layer from Step 2 of the Matrix Quality analysis. Darker green areas are those with a higher percentage of shrub and tree cover within a 50 m radius of raster cells, after masking out the vector layer in Step 1.



(1.94 acres) is near but less than the 2 acre minimum cutoff we used to designate a Patch of continuous vegetation, bare ground, or water cover in Step 1. Because the Matrix Quality analysis is intended to quantify the habitat available for biodiversity between patches, this buffer distance quantifies the amount of vegetation within an area smaller than and between patches.

We then inverted the focal statistics values presented in Figure 12 to create an output raster representing areas with lower tree and shrub cover where urban greening activities are needed most (Figure 13).

Figure 13. Final output raster for Step 2 in which higher scores (dark brown) represent areas where urban greening is needed most because they have a relatively low percentage of tree and shrub cover within a 50 m radius of raster cells, based on the inverted values from Figure 12.



Step 3. We scored raster cells in the urban matrix based on their proximity to existing patches greater than 2 acres, water features, and orchard/not orchard crop areas (i.e., the masked layer developed in Step 1; Figure 11), where Proximity Scores were higher in areas closest to these features.

Proximity Scores were informed by literature-reported animal movement distances in urban areas (Table 1; literature reviewed by Iknayan et al. 2026). We first assigned landscape resistance scores to animal movement guilds, where higher resistance scores represented a lower likelihood of an animal's movement between urban habitat patches. Resistance scores increased stepwise with distance, with different increase-thresholds among animal groups based on reported distances across which groups were more or less likely to move (literature reviewed by Iknayan et al. 2026). For example, among the animal

movement groups examined, reptiles were the shortest distance dispersers and were reportedly most likely to move up to 10 m (resistance score = 0), somewhat likely to move between 10 - 100 m (resistance score = 10), and least likely to move across distances greater than 100m (resistance score = 40). We then calculated Proximity Scores by averaging resistance scores across the six animal movement groups for each dispersal distance range, and inverted and rescaled the scores (Table 1). Finally, Proximity Scores were assigned to each raster cell in the urban matrix based on its distance from the patch, water, and crop masking layer (Figure 11). For example, raster cells that fell within 0-10 m of patches, water, or crops were assigned a Proximity Score of 100, representing the distance across which all animal groups were expected to meet the least resistance to movement.

Table 1. Dispersal distance ranges and associated resistance and proximity scores were informed by a literature review summarizing the movement distances of animal groups representing different movement types in urban areas (Iknayan et al. 2026).

Dispersal Distance Range (m)	**Animal movement-guild landscape Resistance Scores**						**Proximity Score**
	Reptile	**Amphibian**	**Birds & Bats**	**Invertebrate Pollinators**	**Medium-sized mammals**	**Small-sized Mammals**	
0-10	0	0	0	0	0	0	100
10-20	10	0	0	0	0	0	95
20-30	10	20	0	0	0	0	84
30-45	10	20	10	0	0	0	79
45-80	10	20	20	0	0	0	74
80-100	10	40	20	0	0	0	63
100-115	40	40	20	0	0	0	47
115-250	40	40	20	20	0	0	37
250-500	40	40	20	20	10	0	32
500-700	40	40	20	20	10	20	21
700-750	40	40	20	20	20	20	16
750-1500	40	40	20	30	20	20	11
> 1500	40	40	20	30	20	40	0

Step 4. We calculated final Urban Greening Priority scores for each raster cell in the analysis area outside of the Step 1 masking layer by averaging the inverted focal statistics values for tree and shrub cover (final output from Step 2; Figure 13) and the Proximity Scores (Step 3; Table 1). The map produced from those scores are presented in the Matrix Quality results section.

Analysis Limitations

The Matrix Quality analysis prioritizes the greening of impervious areas nearest existing habitat patches, waterways, and crops because these are the areas most likely to be occupied by wildlife. Nonetheless, urban greening projects placed in areas ranked lower for their potential biodiversity support can provide many other benefits to communities, including stormwater management and water quality improvements, cooling, and access to natural spaces (Burg et al. 2023, Stoneburner et al. 2025). Additionally, if greening projects in these areas are coordinated and grouped they can form "habitat complexes" that might also provide resources for diet generalists and aerial species that are more tolerant of urban areas (Spotswood et al. 2019).

Results & Discussion

Patch Size

Patches of continuous vegetation, water, and permeable ground were present in a variety of forms in the analysis area, including residential yards, roadside vegetation, street trees, and city parks (Figure 14). Patches spanned both public (i.e., city parks, roadsides) and private ownership. Of these, patches located in public parks are likely the most protected and thus have added value for biodiversity, but residential gardens and other patches located outside of parks can also be refuges for wildlife and native plants (Lerman and Warren 2011, Tallamy 2020, Smallwood and Wood 2023, Stanford et al. 2026).

The analysis area contained patches of all sizes, and several regions lacked defined patches greater than 2 acres. The Mormon Slough channel contained patches of small (2-10 acres) and medium size (>10-130 acres) and some segments with no defined patches greater than 2 acres. Because larger patches tend to have larger, more, and different microhabitats, they tend to support more species and individuals (Ayers and Rehan 2021, Sari and Bayraktar 2023, Ye et al. 2025) and are the highest priority areas for conservation and restoration in cities (literature reviewed in Spotswood et al. 2019).

Relevance to Mormon Slough restoration

The total acreage of the Mormon Slough channel downstream of the Diverting Canal is about 84 acres, where the channel is defined by the highest elevation point of the bank or levee directly adjacent to the channel. If the entire acreage of the Mormon Slough channel were to be restored, it would represent a “local hub” for biodiversity in the City of Stockton, which is expected to support urban-tolerant species (Spotswood et al. 2019). Restoration and urban greening adjacent to the slough, or connected to the slough via habitat corridors, could boost Mormon Slough into the category of a “regional hub” of greater than 130 acres, where urban- and area-sensitive species could be supported (Spotswood et al. 2019).

Figure 14. Patches of contiguous tree, shrub, low vegetation/bare ground and water cover in the analysis area color-coded by size group. City of Stockton parks, the Mormon Slough channel, and the pilot sites (blue outlines) are also depicted.



Matrix Quality

The Matrix Quality prioritization map identifies areas where urban greening in the matrix is expected to have the greatest benefit for boosting urban biodiversity (Figure 15). Highest priority areas are those that are near patches, water features, or agricultural crops and also have low tree and shrub canopy cover.

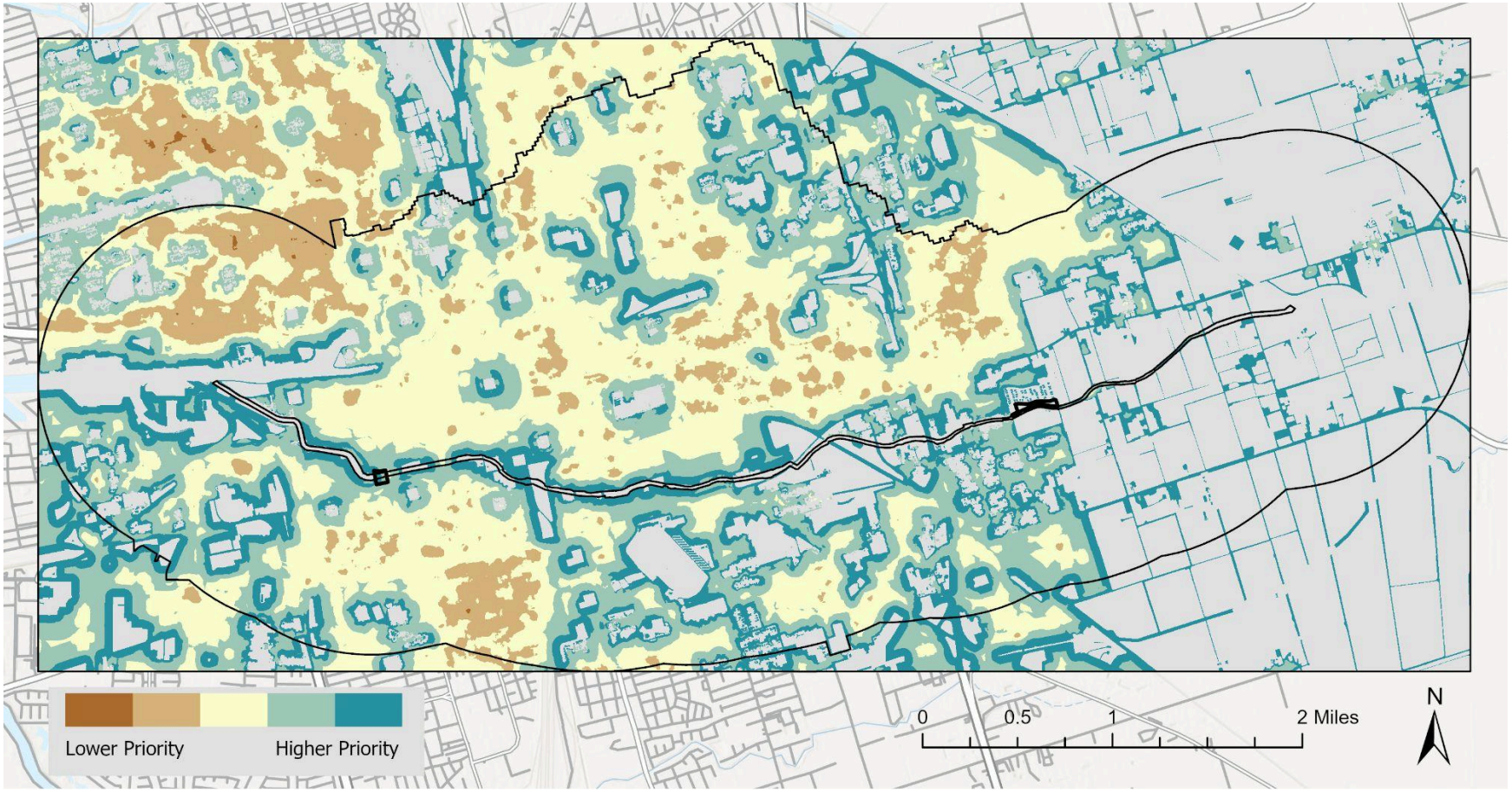
Even small scale greening projects in the urban matrix can boost the quality of the matrix to support biodiversity (see literature reviewed in Spotswood 2019). Cumulatively, these small projects can add up to provide stepping stones of habitat for aerial wildlife like pollinators, other insects, and migrating birds through an otherwise inhospitable environment. Greening activities that increase vegetation cover in the matrix can also improve the habitat quality of nearby patches for biodiversity (Spotswood 2019, Oertli and Parris 2019, Guo et al. 2025) by improving connectivity between them or increasing their effective size. Enhancements that can improve the quality of the matrix include street trees, pollinator gardens, native plants in residential yards, green roofs and walls, greening projects in the road right-of-way, and green stormwater infrastructure projects, such as bioswales and rain gardens that incorporate native plants.

Relevance to Mormon Slough restoration

Areas adjacent to most of the length of Mormon Slough are among the highest priority areas for greening. The expectation is that improving the urban matrix within the analysis area around Mormon Slough will improve the quality of restored habitats within the slough for biodiversity, either by increasing the effective patch size or corridor width of a restored Mormon Slough, or by "softening" the contrast between the restored Mormon Slough and the urban matrix around the slough.

Several areas within the slough channel are also higher priority areas. Restoration of these more impacted parts of the slough could be prioritized in segments that 1) connect the ≥ 2 acres patches, or 2) are adjacent to an existing patch.

Figure 15. Priority areas for urban greening and restoration in the analysis area. Higher priority areas are those that are both 1) lower in tree and shrub cover, and 2) closer to patches greater than 2 acres, water features, and orchard/not orchard crop areas (masked layer in gray).



Chapter 3: Urban Heat

Like many cities, Stockton's community faces heat-related risk during the warm season and heat waves. Climate change and continued urbanization will increase this risk, and Stockton has been identified as especially vulnerable to extreme heat (Delta Stewardship Council 2021). High heat conditions tend to impact urban landscapes in particular, as industrial uses and vehicles generate heat, buildings and pavement retain heat. Green and blue spaces in cities, such as parks and waterways, can therefore provide an important refuge from heat by providing access to shade, water bodies, and moist, vegetated areas.

For this assessment, we mapped land surface temperature (LST) in the analysis area. LST is a measure of thermal infrared energy (heat) radiating off the earth's surface, and in that regard it is different from air temperature or a heat index. LST is a useful metric for assessing heat in our analysis area because it can be measured at the landscape scale via remote sensing to quickly identify variation (relatively warmer and cooler areas) across a large area.

Methods

We first identified Stockton's warm season, defined as the hottest consecutive 60 days of the year, determined from daily records spanning 01/01/1995-12/31/2025. We evaluated air temperature data availability from weather stations in Stockton from the Daily Global Historical Climatology Network (NOAA 2026). Stockton Airport's weather station (USW00023237) was selected due to its long time series (over 30 years) and completeness of data collection at that station (Figure 16). The warm season for the analysis area was determined to be June 30 - August 28 (Figure 16).

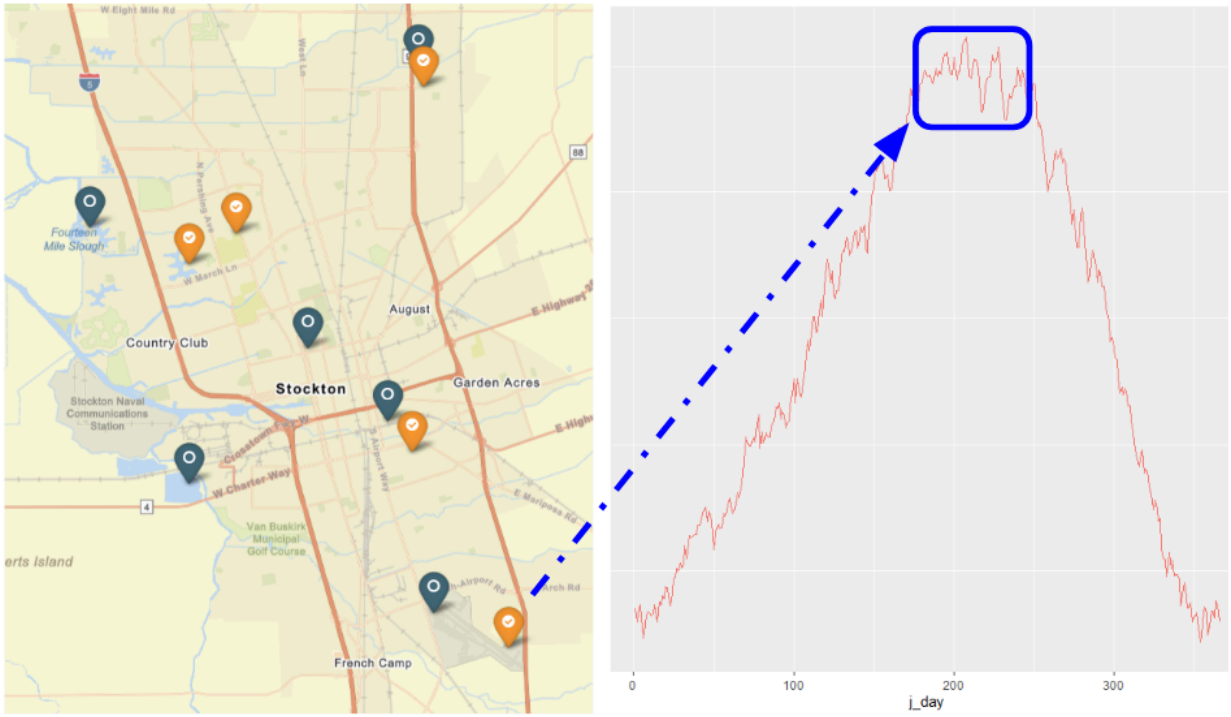
We then averaged LST data from the USGS Landsat satellite (EROS 2026) for the analysis area during the warm season of June 30-August 28. This dataset is high resolution (1 m) and has good coverage for the analysis area. This analysis used 13 landsat "scenes" collected during the day during the 2025 warm season. For each cell of the analysis area we averaged the LST value, and mapped it as standard deviations above and below the analysis area average LST.

Analysis Limitations

LST was selected for this analysis due to its appropriateness for the project's schedule, budget, and available data for the analysis area. LST correlates spatially with other metrics of human thermal comfort, such as mean radiant temperature (MRT; Li et al. 2023). The

difference is that while LST describes the heat radiating off the earth's surface, MRT factors in other influences on the human experience of heat such as shade, wind, and humidity. MRT estimates, therefore, better capture the way people experience heat, compared to LST. However, MRT estimates for urban environments require modeling that incorporates multiple types of climate data as well as data on physical structures like trees and buildings. It is therefore generally more time-intensive and costly to model MRT compared to LST, and the results are limited by the quality of data available.

Figure 16. Map of weather stations in the Global Historical Climatology Network integrated database, and a graph of daily air temperature averages at Stockton Airport weather station, located in the lower right hand corner of the map, from 01/01/1995 to 12/31/2025. The hottest 60 consecutive days of the year were determined to be June 30 - August 28, highlighted by the blue box.



Results & Discussion

The following output maps display the relative difference (i.e., standard deviations) above (red) or below (yellow) the average analysis area LST during the warm period. Orange indicates cells where LST is about average for the analysis area (Figure 17, 18, 19).

The center portion of Mormon Slough is more built out and urbanized compared to upper reaches of the slough, and the color ramp shows that this area is generally warmer compared to the upper portions of the slough which have more agricultural uses and less development (Figure 17). Although also urbanized, watered portions of the slough near

Stockton Harbor also are generally cooler. Within the upper reaches of Mormon Slough (in the east side of the analysis area), certain farm practices (e.g., perhaps irrigation or certain crop types) appear to create a relative cooling effect.

We superimposed the boundaries of city parks over the heat map to visually assess their potential cooling effects. Figure 18 shows park boundaries (green) and summer heat; it appears that parks—large parks in particular—confer some cooling benefits relative to surrounding areas.

Relevance to Mormon Slough restoration

The apparent cooling effects at and adjacent to city park locations (Figure 18) suggest that similarly-sized restoration projects along Mormon Slough could provide a cooling benefit that is measurable at the landscape scale. Restoration plantings that encourage cooling at the Emergency Food Bank pilot site (which had above average temperature; Figure 19) could provide a noticeable cooling service in the urbanized portion of the analysis area. Restoration, enhancement, and preservation of green space and tree canopy at the Solari Ranch site (where temperatures were closer to the analysis area average) could provide preemptive protection from heat in the developing upper portion of the analysis area.

Regarding design implications, the assessment reveals landscape-scale heat patterns which could help identify restoration areas that should particularly consider plants' heat tolerance when selecting a plant palette. While shade structures and water features would provide immediate relief, it is noted that restoration planners should expect a ramping-up period as plant communities mature, before the full cooling benefits could be enjoyed. While mature tree canopy and shade structures stand to provide valuable cooling at restoration sites in and around the slough, future site uses should be considered. When designing sites that may undergo future/further restoration, it should be considered whether rewatering plans are expected to inundate portions of the slough that are currently dewatered. If that may be the case, placing permanent and/or expensive structures is not recommended.

Figure 17. Map of 2025 warm season land surface temperature in the analysis area. Watered areas in the lower reaches of the slough, near Stockton Harbor, are generally cooler compared to immediately surrounding areas. The center (de-watered) portion of the slough is more built out and urbanized compared to upper, agricultural reaches of the slough, and is warmer. The upper portion of the slough is dominated by agricultural uses, and is generally the coolest part of the analysis area . Relatively higher land surface temperatures in or around the slough should be considered during planning and design of restoration sites, and suggest that shade or water features may be a priority for proposed improvements to these areas.

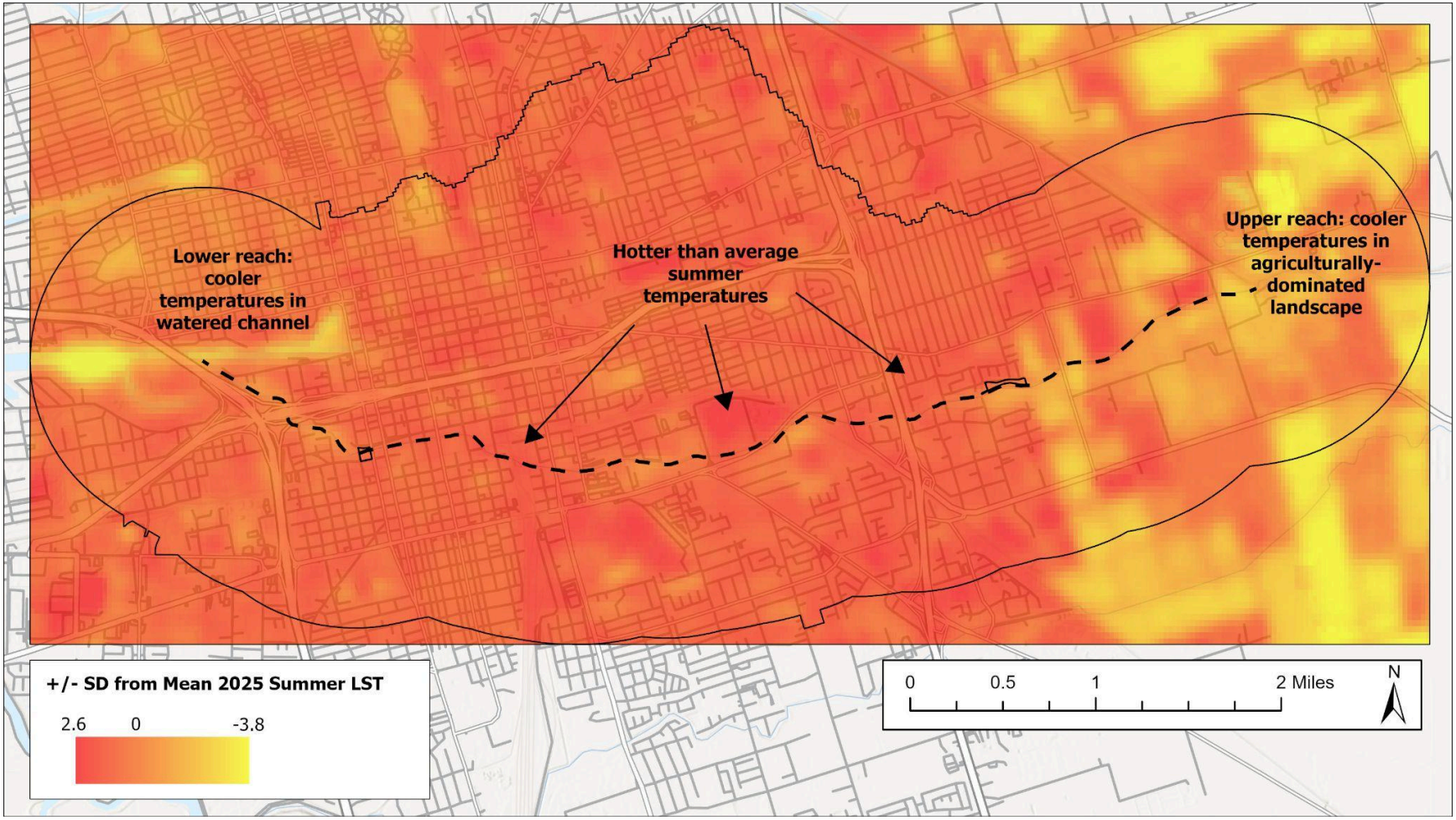


Figure 18. Map of 2025 warm season land surface temperature in the analysis area with parks delineated. Parks–large parks in particular–are associated with a generally lower temperature, compared to immediately surrounding areas. The cooler temperatures associated with parks suggest that similarly-sized restoration projects along Mormon Slough could potentially provide a cooling effect that is noticeable at the scale of this assessment.

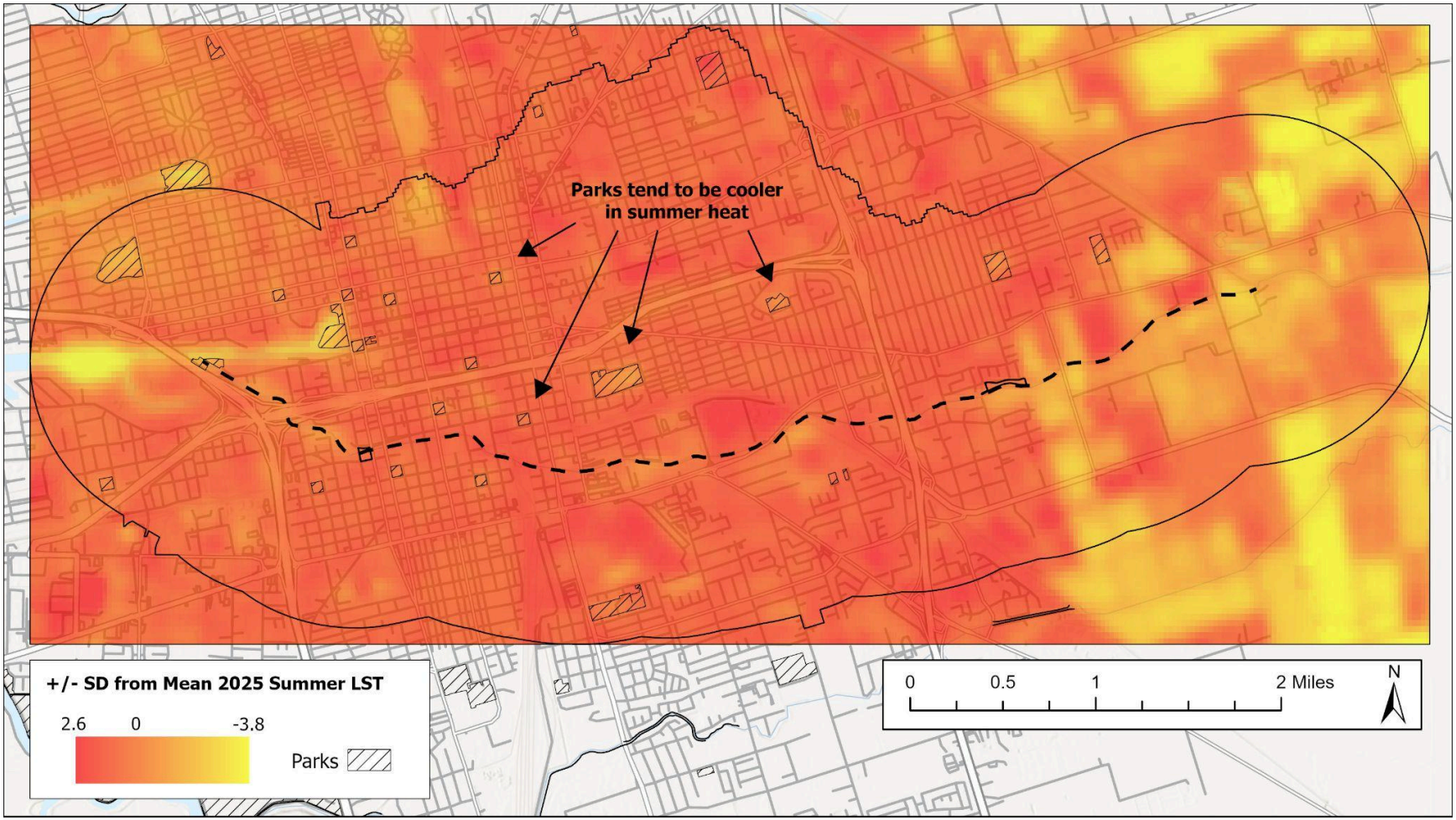
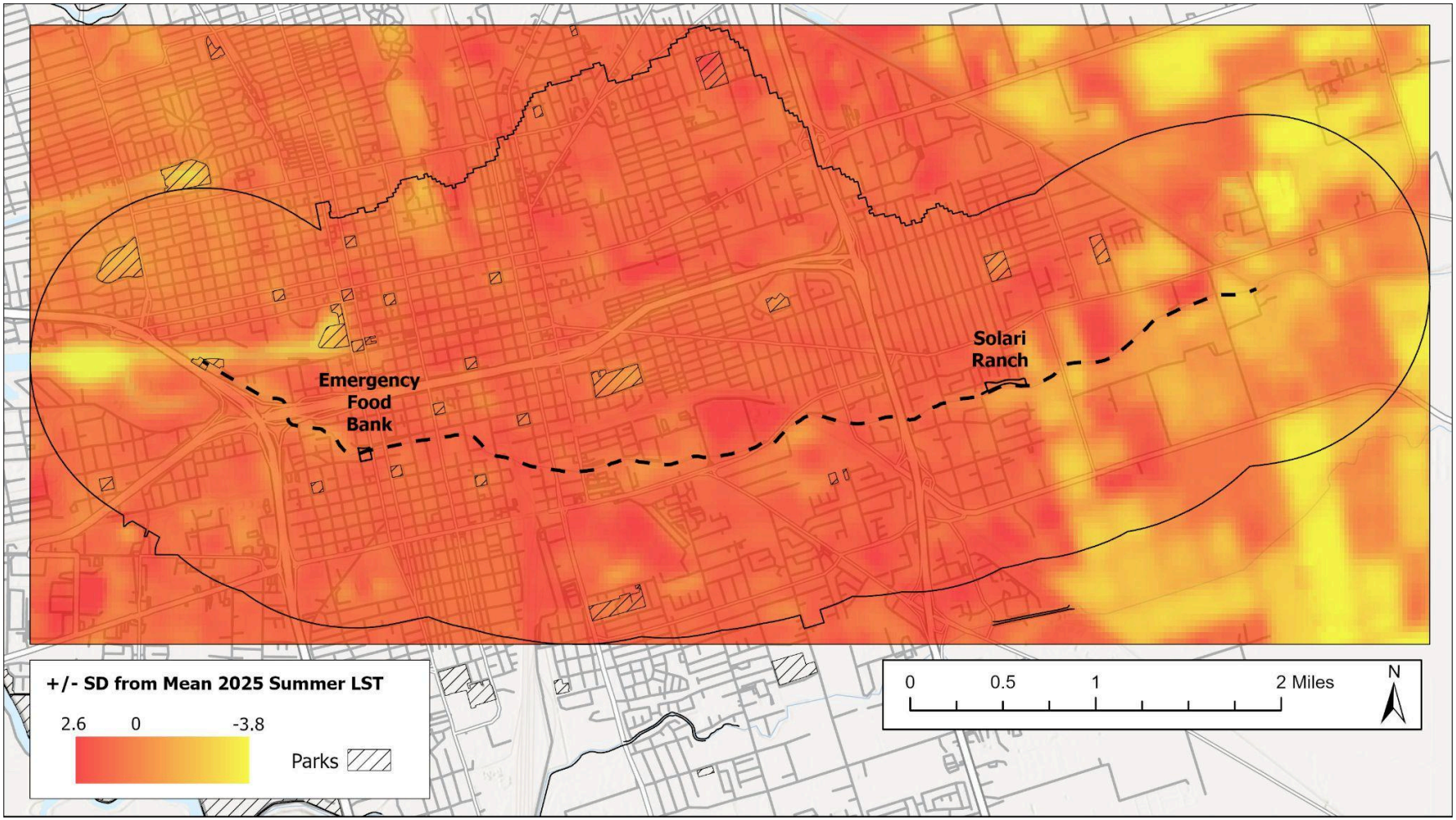


Figure 19. Map of 2025 warm season land surface temperature in the analysis area with pilot sites delineated. The Emergency Food Bank pilot site is hotter than average for the analysis area, indicating the potential to provide a dramatic cooling benefit through restoration (greening and/or re-watering). The Solari Ranch site abuts the cooler agricultural portion of the slough, highlighting a potential opportunity to expand the cooling benefit into this pilot site through restoration.



Conclusion

The three analyses presented in this Technical Appendix, coupled with the environmental assessment and pilot site selection performed by River Partners (River Partners 2025), represent important first steps in assessing the historical and current ecological conditions and priorities for restoration and urban greening in and around Mormon Slough. Here we offer next steps to build on these efforts, and highlight additional topics and knowledge gaps that could be explored to further inform restoration in and around Mormon Slough.

Findings from the historical ecology investigation can be used alongside other landscape assessments and analyses to identify opportunities, set restoration targets, prioritize restoration sites, and inform site design. Restoration could be further informed by continued research into historical datasets. For example, compilation of historical botanical and wildlife records could inform restoration plant palettes and site design. Revisiting historical records referenced in this Technical Appendix could also inform design themes or interpretive signage placed at individual restoration sites.

The urban biodiversity analysis was limited to two of the seven recommended Urban Biodiversity Framework elements (Spotswood et al. 2019; SFEI 2026a). The remaining five elements could be analyzed to complement the current analysis and provide guidance for additional aspects of urban biodiversity support. These include investigations into connectivity for wildlife movement, native plant vegetation, habitat diversity, special resources, and management that affects biodiversity. Additionally, field-based biodiversity surveys that estimate the number of species and individuals that currently occupy the slough could be conducted to establish a baseline from which to monitor changes over time, serving as one gauge by which to monitor the success of restoration.

A recommended next step to build on the heat analysis is continued consultation to gauge perceived heat exposure by community members, and to identify areas along the slough where perceived “hotspots” align with, or diverge from, the results of this assessment. For example, active transportation areas such as bike or walking paths could be prioritized for cooling to protect cyclists and pedestrians. Future analytical work could include MRT modeling, especially if the priority is to understand how much (or little) heat along Mormon Slough is influenced by existing shade or weather factors. MRT modeling may also be helpful to quantify the impacts of significant proposed landscaping changes, such as a large-scale tree planting plan.

While biodiversity support and heat mitigation are important benefits expected to result from restoration and urban greening, there are additional potential benefits that could be assessed and monitored. As of the writing of this Technical Appendix, the economic benefits of Mormon Slough restoration are being analyzed by project partners (Holly Michael personal communication). Examples of other benefits that remain to be explored include nature-based stormwater and sea-level rise solutions to address flooding, community access to the slough, carbon sequestration, human physical and mental health, and recreational activities such as hiking, fishing, and kayaking. We urge the MSRA to consider the findings of this Technical Appendix and other benefits and impacts that may result, as they continue to lead in the restoration of Mormon Slough.

Acknowledgements

Restore the Delta, through a grant from North Valley Thrive, supported this work. Bruce Fayler and Jonathan Nicholas from the City of Stockton shared geospatial data used in these analyses. SFEI's Lauren Stoneburner, Kelly Iknayan, and Pedro Avellaneda provided analysis advice and Melissa Foley provided review of the analyses and writing. SFEI's Vanessa Lee and Jennifer Symonds helped gather geospatial data and inspired the interpretation of results in ways that were relevant to pilot site design visioning. The Mormon Slough Restoration Association Technical Advisory Committee provided review and feedback on the early stages of these analyses. This is SFEI contribution # 1315.

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