Fryer Creek Beaver Impact Analysis and Alternatives Development Report

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1 Introduction

This report documents the findings by Prunuske Chatham, Inc. (PCI) for Sonoma Water's Fryer Creek Beaver Impact Analysis and Alternatives Development Project. Recently, American beavers (*Castor canadensis*) have constructed dams in the town of Sonoma, California, on a reach of Fryer Creek that is managed and maintained for flood control by Sonoma Water (**Figure 1**). Currently, there are four dams located within the reach, which has been channelized for flood control in the center of a highly developed area of Sonoma. Adjacent to a well-traveled pedestrian path, this reach of Fryer Creek has considerable value and visibility to the community. Much of the local community has expressed appreciation for the beavers and the ducks which are attracted to their ponds upstream of West MacArthur Street. Beavers are native to the region, but were nearly eradicated here and throughout much of their North American range by the late 1800s due to unregulated trapping and loss of habitat (Lundquist and Dolman, 2018). In recent decades, recognition of the value of beavers for biodiversity and riparian system function has increased, and many California land managers have been working to support the reestablishment of beaver populations (Lundquist and Dolman, 2018). One of Sonoma Water's guiding principles for stream maintenance is "to balance the goals of flood protection, permit compliance, and protecting and enhancing natural resources" (Sonoma Water, 2020). Sonoma Water is concerned that the beaver dams may affect flooding in the winter and inhibit access along maintenance roads during the summer.

PCI is supporting Sonoma Water to determine whether the beaver activities in Fryer Creek pose a flood risk in this urban setting, and to develop a design and recommendations for managing beaver activity in the flood control system that takes into consideration the ecological and community benefits of ongoing beaver presence. This work includes collaboration with Occidental Arts and Ecology Center (OAEC) and Swift Water Design. Representatives from OAEC's WATER Institute, Brock Dolman and Kate Lundquist, have been working with Sonoma Water, advising on beaver dam issues and responding to public questions and input. Kevin Swift of Swift Water Design has been supporting Sonoma Water with implementing non-lethal beaver management practices, such as installing flow control devices to manage ponded water levels. This report provides findings for the following work performed by PCI, OAEC, and Swift Water Design as part of the Fryer Creek Beaver Impact Analysis and Alternatives Development Project:

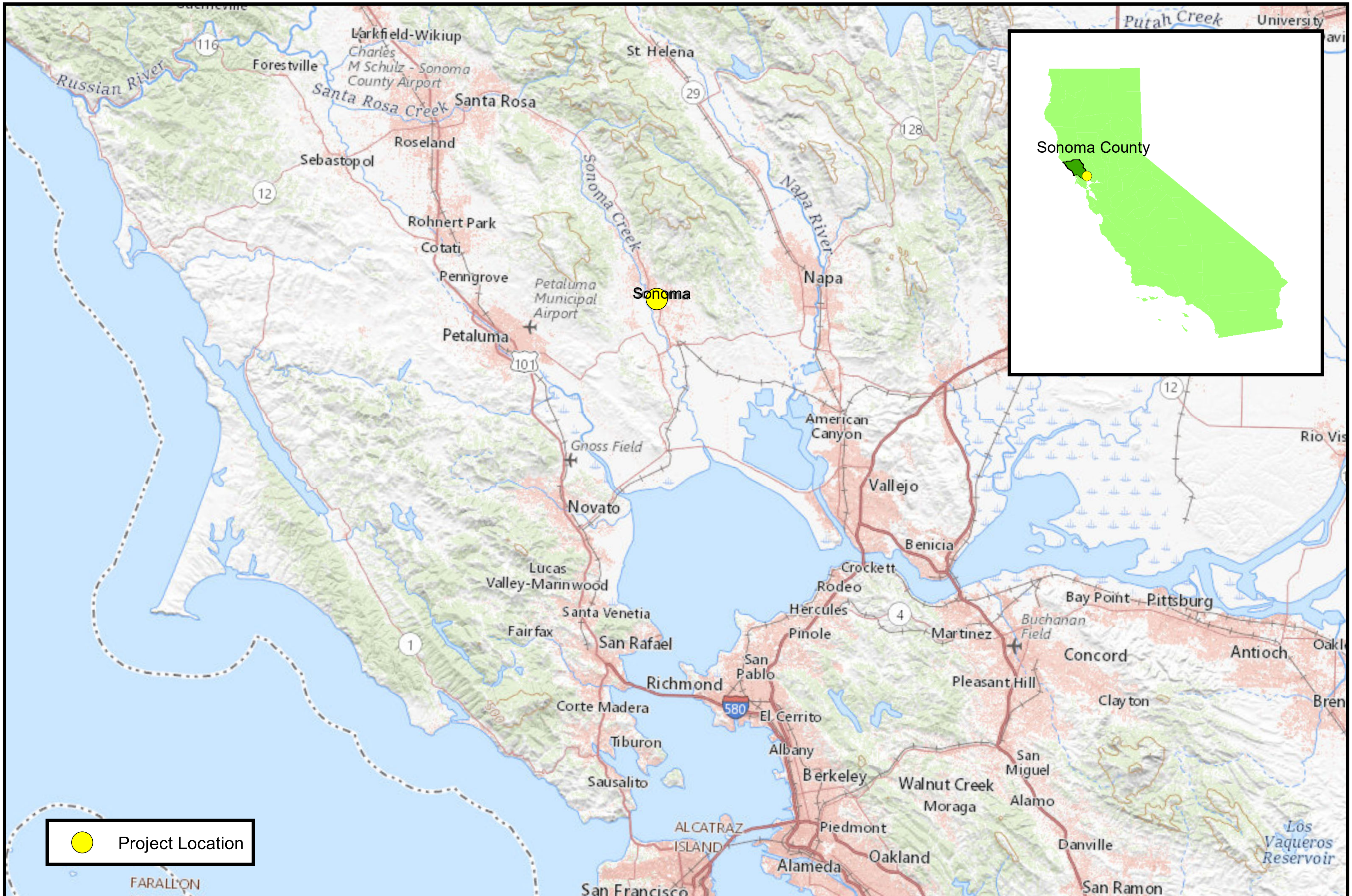
- Literature review on beaver habitation in urban settings
- Hydraulic modeling analysis of pre-dam and current dam conditions
- Hydraulic modeling analysis of future dam conditions
- Development, modeling, and selection of beaver dam area management alternatives
- Recommendations for beaver protection

Review of regulatory compliance considerations and costs of management alternatives, as needed, will be developed subsequently.

2 Literature Review of Beavers in Urban Settings

As a first step in this Project, PCI performed a literature review of beavers in urban settings, focusing on ecosystem benefits and flood impacts. Twenty-five beaver-specific documents were reviewed, synthesized, and referenced in this document. The following two key documents are referenced throughout the literature review:

- *Beaver in California: Creating a Culture of Stewardship* (Lundquist and Dolman, 2018)
- *The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains* (Pollock et al., 2018)



PRUNUSKE CHATHAM, INC.

Figure 1
Fryer Creek Beaver Impact Analysis and Alternatives Development Report
Project Location

0 2.5 5 10 Miles

4/16/2021
Source: USGS National Map

It should be noted the above two documents contain information sourced from a long list of beaver-related references. For more details regarding the sources of information cited in this report, see the reference sections of Lundquist and Dolman (2018) and Pollock et al. (2018).

The American beaver is a highly adaptable species with a range from northern Canada to northern Mexico, including California (Lundquist and Dolman, 2018). Recent research has found verifiable records that the American beaver is historically native to the watersheds of coastal California and the San Francisco Bay Area (Lanman, et al., 2013).

Beavers can establish anywhere there is water and food (Lundquist and Dolman, 2018). Beavers rely on deep water found in existing ponds, lakes, streams, and rivers to protect themselves from predators, such as mountain lion, wolf, coyote, bobcat, and even bear and river otters. Beavers create dwellings, where they eat, sleep, and raise kits (beaver young), by burrowing into banks and/or by building lodges made of mud and wood, with entrances that are underwater and protected from predators. Beavers typically feed on the bark of deciduous trees, including willow, poplar, cottonwood, and aspen, and on herbaceous matter, such as grasses, leaves, bulbs, and rhizomes. Beavers will build dams to create deeper pools that provide shelter from predators, and will often build multiple dams in a row along a waterway to extend sheltered access to food.

Generally, beaver dams need to last for two years to provide sufficient time before kits typically disperse and leave the care of their parents (Pollock et al., 2018). However, beavers can abandon dams and find new territories after resources (food and construction materials) have been depleted. Dams also can fail due to high flows during large storm events.

Beavers have commonly been found to colonize urban waterways, including creeks, ponds, and ditches, as long as the necessary resources are present (Pollock at al., 2018). However, beavers have historically been viewed as a nuisance in urban areas and are often perceived as posing a threat to infrastructure and private property through vegetation impacts and increased flood risk. As a result, the default land management response in the past has been to remove beavers from urban settings (Pollock at al., 2018). However, typically the removal of beavers is temporary, as they will return to areas that have the desired resources (Boyles and Savitzky, 2008). This has led to alternative methods for managing beavers, such as flow control devices (see Figure 1 below), that have been found to successfully mitigate the flood risk of beaver habitation (Boyles and Savitzky, 2008).

2.1 Ecosystem Effects

Dams built by beavers can have the benefit of increasing physical habitat quantity and quality in engineered urban channels that typically have poor habitat conditions (Pollock et al., 2018). Engineered urban channels often are uniform and lack the complexity that is beneficial to ecosystems. Ponding from beaver dams can deepen existing pools or create pools on streams that would typically go dry (Pollock, et al., 2003). This is can be particularly beneficial in the summer, especially during prolonged droughts that are increasingly common in California (Lundquist and Dolman, 2018). Beaver dams form a "step-pool" water surface profile, where flow pools behind beaver dams and steps down at each dam, which can increase hydraulic diversity and habitat complexity in otherwise uniform urban channels (Pollock et al., 2018; Lundquist and Dolman, 2018). Ponding of water by beaver dams can provide a range of improvements to habitat conditions in impacted urban streams, including increased storing of surface water and groundwater, regulating flow, storing fine sediment, and modifying nutrient cycling (Pollock et al., 2018; Lundquist and Dolman, 2018).

Sonoma Water staff have noted that one undesirable recent change at the Fryer Creek site, apparently a result of beaver-caused ponding and sediment accumulation, is an increase in invasive water primrose (*Ludwigia* sp.) establishment on the East Fork. Sonoma Water is also concerned that this may lead to an increase in mosquito activity in this area; water primrose cover can make insecticide treatment for mosquito control less effective. Water primrose is a highly invasive species throughout the region's waterways, but has not to date been prevalent on Sonoma Water channels, according to staff. Relatively shallow water, which may be exacerbated by current drought conditions, high nutrient loads from urban and agricultural runoff, and warming climate are also likely to facilitate water primrose establishment. Control of this species is challenging. Sonoma Water's main approaches to date have been using manual or mechanical removal methods, and attempting to gradually shade the species out by increasing tree canopy cover. Beaver are known to feed on water primrose, but not to an extent that suppresses it.

By increasing the quantity and quality of physical habitat, beaver dams support increased biodiversity (Lundquist and Dolman, 2018). Beaver dams create conditions capable of supporting a greater number of herbaceous plant species in the riparian zone (Wright et al., 2002). The microhabitats created by beaver dams and digging also significantly increase the diversity and abundance of aquatic invertebrate species (Rolauffs et al., 2001; Hood & Larson, 2014). This greater diversity in plant and invertebrate species in turn supports a greater abundance and diversity of animals that live in, or migrate through the riparian corridor (Pollock at al., 2018; Lundquist and Dolman, 2018). The constant source of water, especially during dry summers and prolonged droughts, along with abundant food and shelter from prey, results in an increased occupancy of fish and amphibian species (Pollock et al., 2003; Hossack et al., 2015; Pollock, 2018). Ponded water and wetland habitat from beaver dams also attracts a wide diversity of waterfowl and migratory songbird species (Cooke and Zach 2008; Lundquist and Dolman, 2018). Additionally, trees fallen by beaver or killed from beaver dam ponding provide foraging, refuge, and nesting habitat for various birds and mammals (Pollock, 2018; Lundquist and Dolman, 2018).

Beavers can even contribute to climate change resiliency (Pollock et al., 2018; Lundquist and Dolman, 2018). Elevated water levels from beaver dam ponding can help prevent drying of wetland sediment and soils and the associated releases of sequestered carbon into the atmosphere (Wohl, 2013; Lundquist and Dolman, 2018). Maintaining greater hydration of the soils and vegetation also helps reduce vegetation flammability, which can be a benefit especially where natural habitat abuts human infrastructure and wildfire is a concern, as it is on Fryer Creek. The ponding from beaver dams also slows runoff and increases groundwater recharge (Pollock et al., 2018; Lundquist and Dolman, 2018), an important function in places that experience more extreme variability in rainfall timing and quantity due to climate change such as California. Riparian zones inhabited by beavers have also been found to be resistant to fire and provide wildlife refuge during fires (Fairfax and Whittle, 2020), which are a much needed benefits as places like California continue to experience increased wildfire activity from climate change.

Since beaver dam complexes have been shown to enhance habitat quality and quantity, thus improving ecosystem benefits for a wide array of species (Lundquist and Dolman, 2018), interested stewards such as Sonoma Water are focusing on what they can do to support the existence of dams in systems that are managed for flood control. However, in order to realize these benefits and accommodate beaver occupancy of flood control systems, it is important to understand the impacts that beavers can have on flood conveyance and how those impacts can be managed.

2.2 Flood Impacts

In urban settings, areas of development and infrastructure are at risk of flooding when beavers colonize channels engineered for flood conveyance (Pollock et al., 2018; Lundquist and Dolman, 2018). Dams created by beavers that partially or fully span artificially narrowed urban channels can force flows out of the channel and onto adjacent areas constrained by developed (Pollock et al., 2018; Lundquist and Dolman, 2018). Beaver dams can also block culverts at roadways, railways, and other infrastructure, which can lead to flooding or washouts (Pollock et al., 2018; Lundquist and Dolman, 2018).

2.2.1 Hydraulic Modeling

Hydraulic models have been used to analyze the flood impacts of beaver dams. Stout (2017) developed a one-dimension (1-D) hydraulic model of a beaver-impacted reach that includes eight dams and a reach without dams to compare hydraulic response. The study found that a relatively low number of beaver dams resulted in significant increases in water depths and widths, as well as a decrease in flow velocities (Stout, 2017). Neumayer et al. (2020) developed 2D hydraulic models of 12 cascade scenarios in total in two catchments during eight different flood events to test flood retention benefits. Though the study did not find beaver dams had an effect on flood retention for flood events with return intervals of more than 2-year, it did find beaver dams resulted in larger (up to +300%) inundation areas (Neumayer et al., 2020).

2.2.2 Dam Failure Potential and Resilience

Though beaver dam failures may be common during flood events (Butler and Malanson, 2005), beaver dams have been shown to remain intact after even the largest flood events. Westbrook et al.'s (2020) study of dam failures across Kananaskis Country, Alberta, found only about a third of dams were breached during the largest flood on record. Typically, it was just the most upstream dam that failed in reaches where some dams failed and some remained intact (Westbrook et al., 2020).

Ultimately, the strength of dams can be variable depending on size, material, and age (Neumayer et al., 2020). New dams typically consist of recently chewed branches and an impermeable layer of mud on the upstream face. Mature dams will have both old and fresh branches, and may further stabilize over time as the willow and other riparian vegetation included in the dam sprouts and roots into the streambed. For abandoned dams the layer of mud is not maintained, which can lead to permeability and dam failure if the vegetation is not yet fully established.

For those dams that have failed, there is limited detailed information on failure thresholds (G. Müller and Watling, 2016; Neumayer, et al. 2020). Klimenko and Eponchintseva (2015) estimated that natural dam failure occurred during a 10-year peak flow event for active dams about 3-9 feet in height. However, the twig and mud construction of the dams prevented widening of breaches within the failed dams (Klimenko and Eponchintseva, 2015). Westbrook et al. (2006) report the failure (breaching) of a 3-foot-tall dam spanning 26 feet wide during a flow of 282 cubic feet per second (cfs). Levine and Meyers (2014) report a failure of a 32-foot-wide dam due to bank erosion during a flow of 247 cfs. These reported values indicate a unit discharge failure threshold of 8 to 11 square feet per second (sf/s) per foot width of the dam (Müller and Watling, 2016). Physical modeling (flume studies) by Müller and Watling (2016) found unit discharge failures of 9 to 17 sf/s. It should be noted this is very preliminary research. The models created in the experiments were much simpler than natural dams. The extreme variability in natural materials used and sites chosen by beavers, and streambed and bank composition, among other potential factors, all preclude a definitive understanding of beaver dam stability thresholds. In reality dams may be much more resilient to failure than expected.

2.3 Adaptive Management

Attempting to remove dams from urban flood control channels can be laborious, dangerous, and costly when beavers immediately and continuously return (Boyles and Savitzky, 2008). With a need to improve the efficacy of beaver management in flood control channels, and as beaver stewardship increases due to recognition of their ecosystem benefits in urban settings and a desire to support recovery of the species, improved adaptive management strategies are required to meet the goals of system stakeholders (Pollock et al., 2018). As stakeholder goals are identified, predictive models can be used to help develop management alternatives and a monitoring plan. Response and adjustments can be made if monitoring results indicate that thresholds established for the management alternatives are triggered. For example, rather than straightaway removing a beaver dam from a flood control channel within the urban setting, managers can monitor and assess the effect of the dam to take actions based on pre-established thresholds and management alternatives. If beavers increase the dam size, or build more dams, actions can again be taken based on pre-established thresholds and management alternatives.

Flow control devices (**Figure 2**) have proven to be highly successful and cost-effective adaptive management solution to limiting the impact of beaver dams in flood control channels (Simon, 2006; Boyles and Savitzky, 2008; Pollock et al., 2018; Lundquist and Dolman, 2018). Flow control devices consist of a flexible PVC or HDPE pipe, sized to pass base flow, which is anchored in a notch in the dam. By diverting water through the dam with a flexible pipe, the water level upstream of the beaver dam is controlled by invert of the pipe over the crest of the beaver dam. The inlets of the flexible pipe are guarded by a heavy gauge wire cage to prevent beavers from hearing or feeling the water flow, and blocking the inflow with dam building material. The device inlet must always be completely submerged, preferably with a minimum freeboard of 12" to prevent formation of an audible whirlpool at the inlet. If the beavers can find the inlet, they will block it immediately. The outlet is hidden at the downstream edge of the dam to mimic the natural leakiness of all beaver dams, and avoid triggering the beaver's natural instinct to cover the outlet. Flow control devices limit how high the beavers can pond water upstream, thus reducing dam-building stimulus and related tree removal. Flow control devices can easily be raised and lowered as needed to allow for adaptive management of water levels heights during base flows and dam height impacts during flood flows. They also can slow down the impacts on woody vegetation as fewer materials are needed for building.

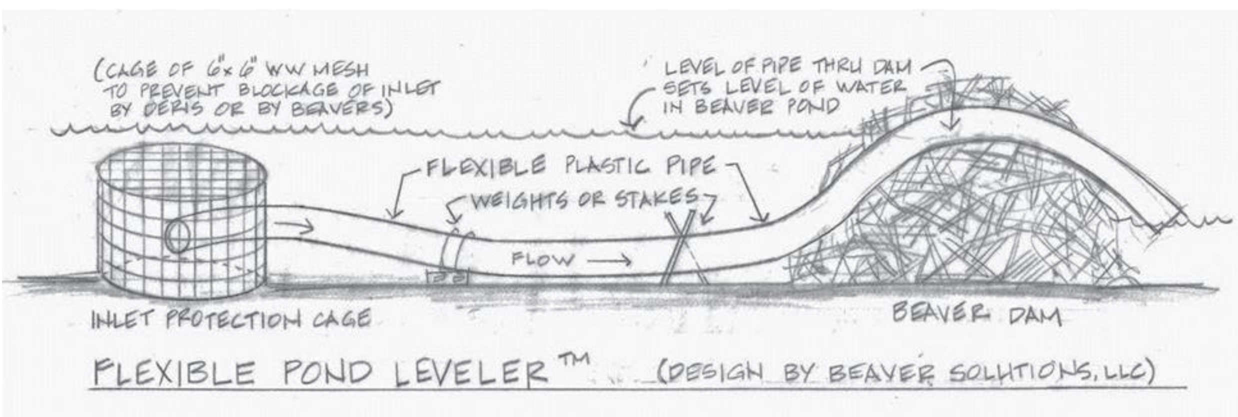


Diagram by Sherry Guzzi, Sierra Wildlife Coalition
(Source: Lundquist and Dolman, 2018)

Figure 2
Diagram of Beaver Dam Flow Control Device

3 Fryer Creek Beaver Impact Analysis

To support Sonoma Water with management and maintenance decisions regarding beaver activities, PCI used a hydraulic model to analyze the impact of current and future beaver dam conditions on flooding and access as compared to pre-dam conditions.

3.1 Project Area

The Project Area covers the reach of Fryer Creek owned and maintained by Sonoma Water within a ¼-mile radius of the current dams, which are located just upstream of the West MacArthur Street culvert, in the town of Sonoma, California (**Figure 3**). In addition, Sonoma Water has flood control easements on East Fork Fryer Creek upstream to Andrieux Street (**Figure 3**). Fryer Creek contains most of the engineered open channels in the Sonoma Creek watershed managed under Sonoma Water's Stream Maintenance Program (Sonoma Water, 2009). Sonoma Water maintains five reaches of Fryer Creek in the lower alluvial plain of the Sonoma Creek watershed as part of Flood Control Zone 3A Stream Maintenance Program activities, including the Project Area (**Figure 4**).

Fryer Creek flows south from the northern foothills through residential neighborhoods within the City of Sonoma (City) to the confluence with Nathanson Creek. At the downstream end of the Project Area, Fryer Creek has a watershed area of about 2 square miles (City of Sonoma, 2011; FEMA, 2017). There are two forks of Fryer Creek (**Figure 5**) that originate from small foothill watersheds just north of the City and enter a closed conduit system at the northern edge of the City limits (City of Sonoma, 2011). They flow underground across the City before daylighting just upstream of the Project Area near their confluence upstream of West MacArthur Street. The West Fork Fryer Creek daylights from under 4th Street West, and the East Fork Fryer Creek from beneath the Andrieux Street crossing. Fryer Creek then flows through engineered open channels, for which Sonoma Water owns and maintains easements, until the confluence with Nathanson Creek (Sonoma Water, 2009). Along the way, Fryer Creek receives flow from the storm drain pipe system with road-side ditches all maintained by the City of Sonoma (City of Sonoma, 2011).

The open channel reaches of Fryer Creek have typical engineered urban channel characteristics (Sonoma Water, 2009). Fryer Creek is a straightened and trapezoidal channel engineered to efficiently convey flow through a heavily confined corridor of development on both sides of the creek (Sonoma Water, 2009; City of Sonoma, 2011). The open channel profile gradient along the entire reach within the City has an average slope of 0.3% (City of Sonoma, 2011).

The East Fork of Fryer Creek maintains some semblance of a low flow channel, with a shallow bench that serves as an access road for stream maintenance (Sonoma Water, 2009). A paved pedestrian path, that also provides maintenance access, runs south along the West Fork, past the confluence and West MacArthur Street to the City limits. Currently, according to Sonoma Water Stream Maintenance Program staff, the reaches of Fryer Creek within the Project Area are cleared of excess deposited sediment periodically, most recently in 2013-2014. Within the Project Area, there are four culverts: one on the West Fork at Arroyo Way, two on the East Fork at 2nd Street and the pedestrian path, and one after the confluence on the main channel at West MacArthur Street. The invert of the West MacArthur Street culvert is perched 2 feet above the channel bottom on the upstream side and 4 feet above the channel bottom on the downstream side (City of Sonoma, 2011). Alternatively, the pedestrian path culvert opening, on the East Fork just upstream of the confluence with the West Fork, is relatively low in elevation. The pedestrian path culvert invert is over 2 feet below West MacArthur Street invert, and the soffit about 3 feet below the West MacArthur Street soffit. The paved pedestrian path across the culvert is 0.5 feet below the elevation of the lowest surrounding residential area, providing potential room for conveyance over the culvert without causing flooding to the surrounding residences.

Sonoma Water has established channel design criteria for the Fryer Creek flood control channel within the Project Area through their Flood Management Design Manual (Sonoma Water, 2020; City of Sonoma, 2011). Given the watershed area upstream of the modeled reach is less than 4 square miles, Fryer Creek is considered a secondary waterway with a design storm equal to the 25-year peak flow. Reportedly, there are several instances in which the creek has overtopped its banks and flooded the adjacent development (City of Sonoma, 2011).

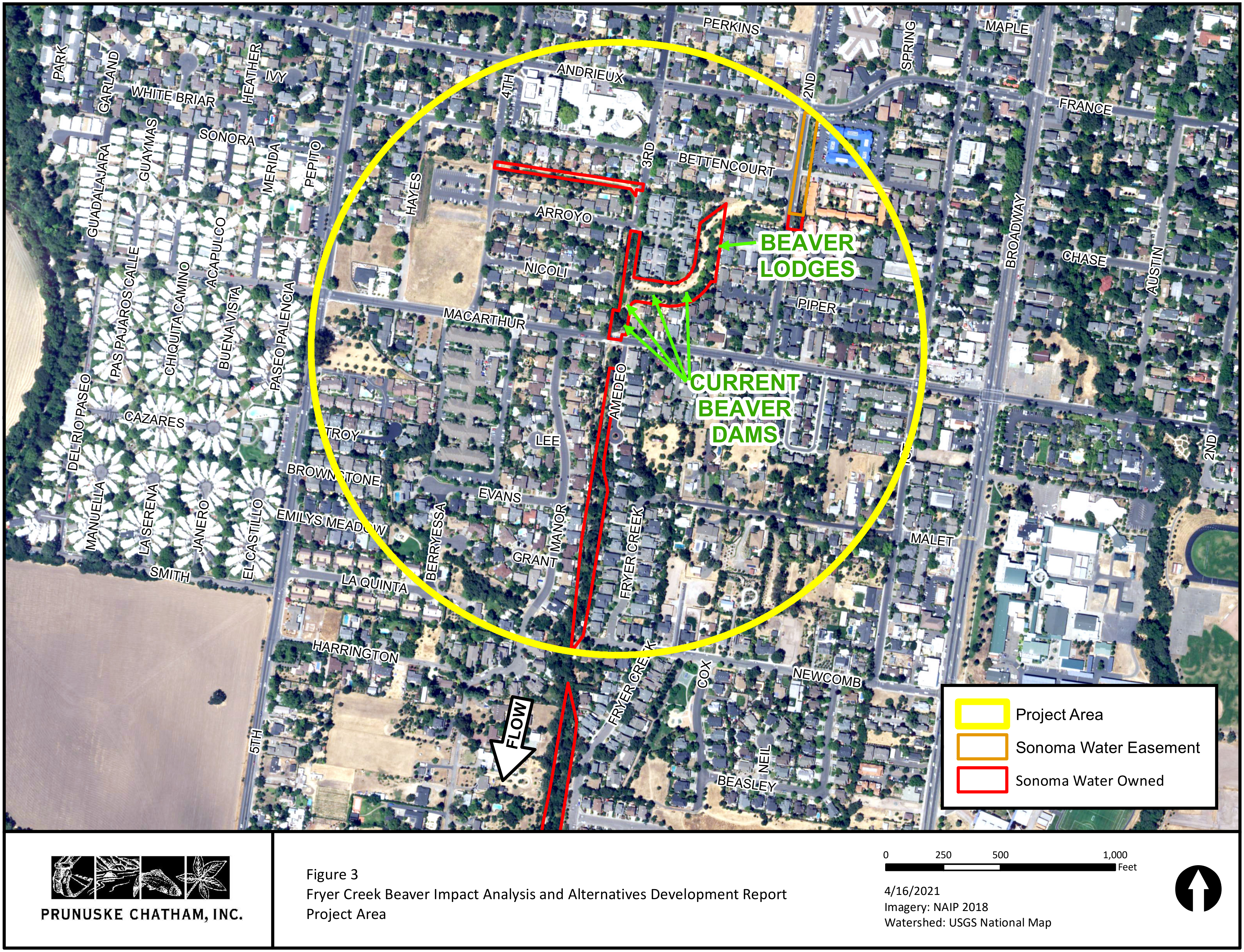


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Figure 3
Fryer Creek Beaver Impact Analysis and Alternatives Development Report
Project Area

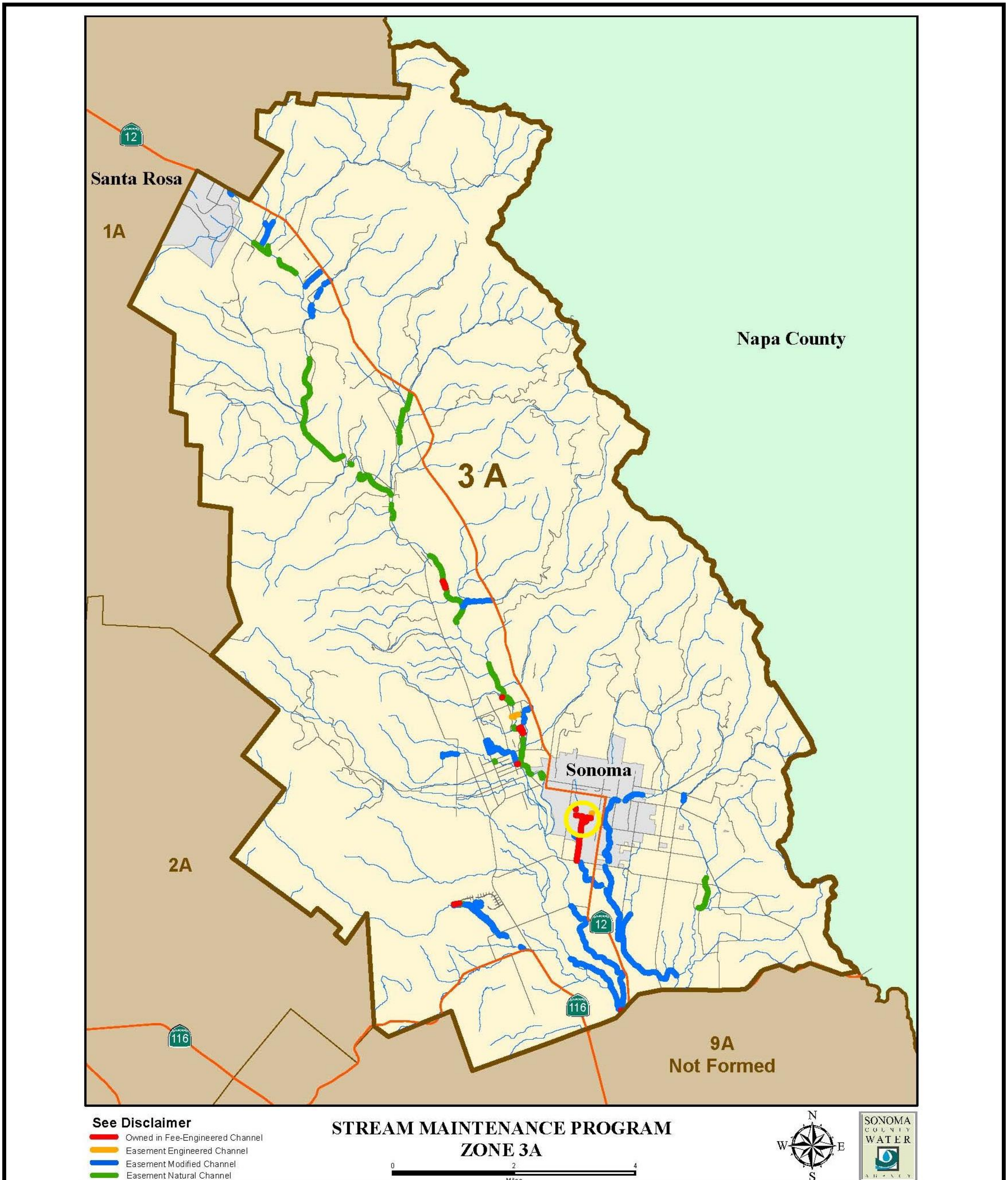

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Figure 4
Fryer Creek Beaver Impact Analysis and Alt. Development
Sonoma Water Stream Maintenance Program Zone 3A

4/16/2021
Source:https://evogov.s3.amazonaws.com/185/media/164728.pdf

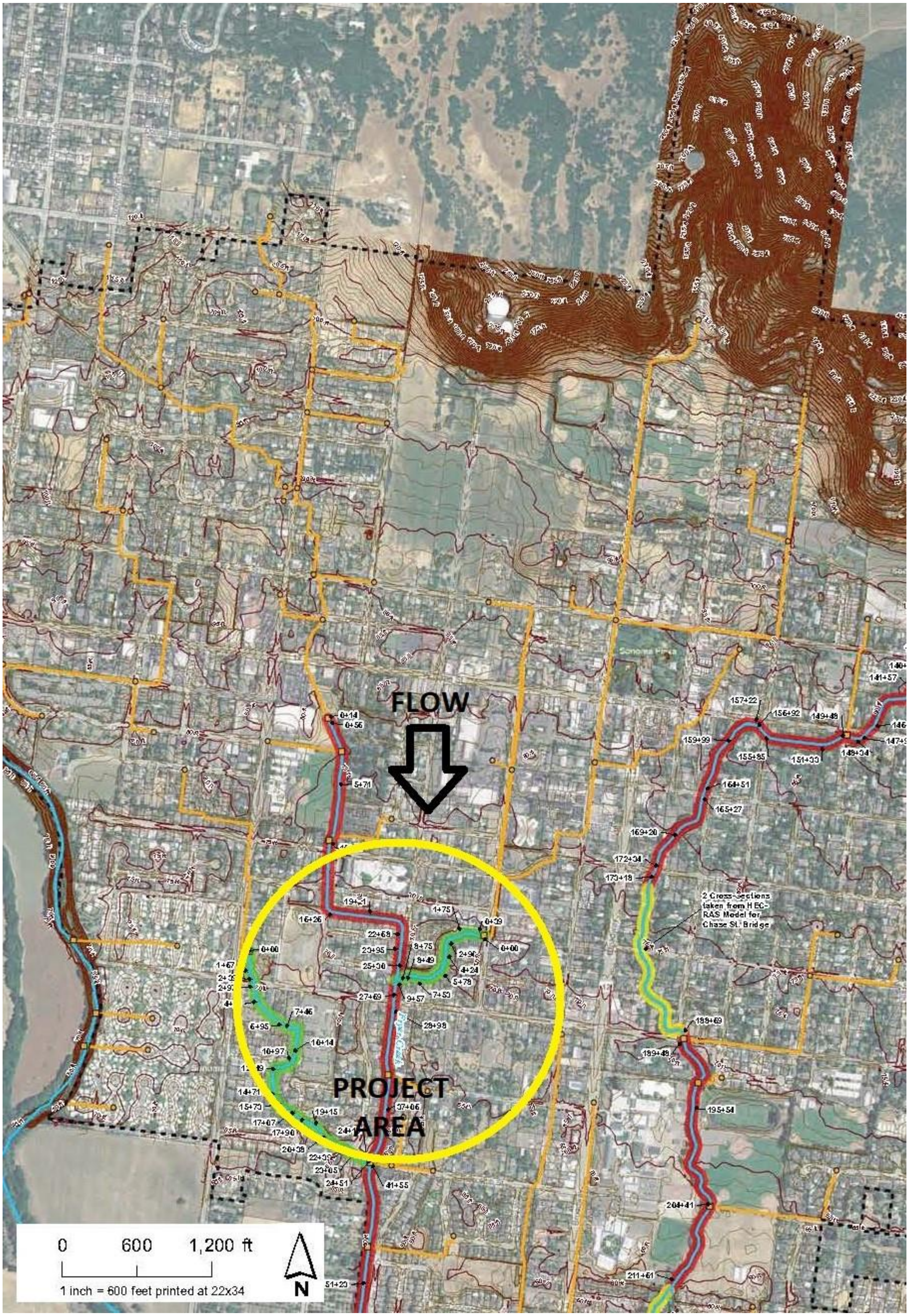

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Figure 5
Fryer Creek Beaver Impact Analysis and Alt. Development
Drainage Network Upstream of Project Area

4/16/2021
Source: City of Sonoma
Storm Drain Masterplan
(2011)

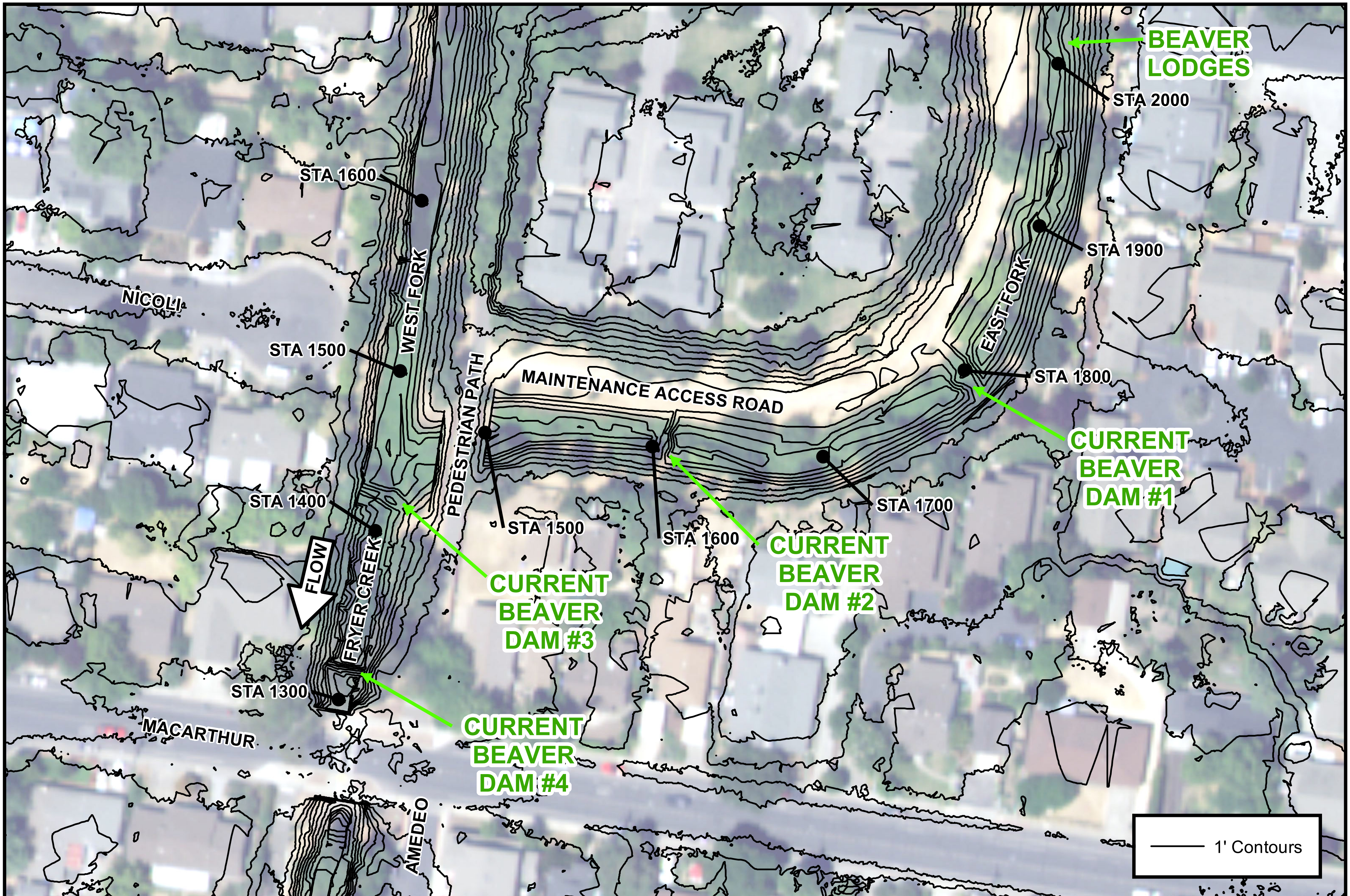

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Figure 6
Fryer Creek Beaver Impact Analysis and Alternatives Development Report
Current Beaver Dams and Lodges Locations

0 25 50 100 Feet

4/16/2021
Imagery NAIP 2018
Contours from Sonoma Veg Map 2013 LiDAR

3.2 Existing Conditions

In the mid-1990s, American beavers established in Sonoma Creek near the community of Glen Ellen (Bohemia, 2013). This was the first time beavers were documented in the watershed since they were extirpated decades earlier. Since then, though there has not been a concerted effort to monitor beaver population dynamics in this area, there is a common understanding beavers have expanded their range in the Sonoma Creek watershed, moved closer to the town of Sonoma, and continued their range expansion toward the Laguna de Santa Rosa and the Russian River. Starting in spring 2019, to date beavers have constructed four dams and two lodges in the Fryer Creek watershed within the Project Area (**Figure 6**). Currently, there are two beaver dams on the East Fork just upstream of the confluence and pedestrian bridge (**Figure 7a-b**), and two beaver dams on the main channel of Fryer Creek just upstream of West MacArthur Street (**Figure 7c-d**). The dams are constructed of mud and vegetation found in the vicinity of the dams, including the various trees, cattails, and even invasive *Ludwigia* found in the channel. Additionally, beavers have built their lodges on the East Fork, upstream of the two current dams (**Figure 8a-b**). Swift Water Design has installed flow control devices on all four dams. The level of the most upstream beaver dam was set low enough to dry out Sonoma Water's maintenance access road, yet high enough to conceal the entrance to the upstream lodges. Evidence of beaver activity, such as fallen trees, willow cuttings, and bark chips, have been observed on the West Fork upstream to where it daylights at 4th Street, and at a riffle crest near one of the few willows observed 400 feet downstream of the West MacArthur Street culvert (**Figure 9a-b**).

Upstream of the beaver dams, wetland vegetation is established throughout the low flow channel, including cattails and bulrush (see Photo 8a above). The slower flow, and resulting fine sediment deposits, above the dams provide favorable conditions for these emergent wetland species.

Several trees within wetland areas or immediately adjacent to them have either been felled by beavers, been eaten by them, or died from inundation. Willows and cattails, as the beavers' preferred food sources, are heavily used but readily re-sprout from beaver disturbance. Young native upland trees, including valley oaks, coast live oaks, and sycamores, which appear to have been planted, are present just upslope of the ponded areas. The trunks of some of these trees have been protected using either plastic tree wrap, which is deteriorating, or wire cages. The wire cages are often close against the tree trunk and may harm the tree if not expanded before the tree begins to grow around the wire.

Downstream of MacArthur Street, the creek corridor is narrower and banks are steeper. Vegetation is primarily limited to upland trees (including native oaks and planted species); there is little willow or wetland vegetation establishment and the understory is sparse.

The beaver ponds have also attracted a considerable amount of waterfowl. The dam upstream of West MacArthur Street has formed a long, deep pool extending several hundred feet upstream. The pond is home to a flock of resident mallards that can be found year-round within the Project Area. Other bird species also observed include great blue heron, green heron, and small songbirds, towhees, sparrows, finches, and others.

(Photo: PCI, 2021)

Figure 7a
Current Beaver Dam #1 with Flow Control Device (taken from right bank, flow from left to right)

(Photo: PCI, 2021)

Figure 7b
Current Beaver Dam #2 with Flow Control Device (taken from right bank, flow from left to right)

(Photo: PCI, 2021)

Figure 7c
Current Beaver Dam #3 with Flow Control Device (taken from left bank, flow from right to left)

(Photo: PCI, 2021)

Figure 7d
Current Beaver Dam #4 with Flow Control Device (taken from W. MacArthur St. looking upstream)

(Photo: PCI, 2021)

Figure 8a
Beaver Lodges on Left Bank (taken from right bank)

(Photo: PCI, 2021)

Figure 8b
Beaver Lodge Up-close (taken from left bank looking downstream)

(Photo: PCI, 2021)

Figure 9a

Beaver Dam Activity Downstream of West MacArthur Street (taken from channel looking downstream)

(Photo: PCI, 2021)

Figure 9b

Beaver Dam Activity Downstream of West MacArthur Street (taken from right bank looking upstream)

3.3 Hydraulic Analysis

To support beaver management decisions by Sonoma Water on Fryer Creek, PCI performed a hydraulic analysis of the Fryer Creek open flood control channel within the Project Area to assess the impacts of the four current beaver dams and potential future dams on designed flood conveyance. Details regarding the model input and development are provided in Appendix A: *Fryer Creek Beaver Impact Analysis Hydrology and Hydraulics Technical Memo*. The model domain of hydraulic analysis extends a ¼-mile from the existing beaver dams, which includes 1,300 feet of Fryer Creek downstream of West MacArthur Street, all of the West Fork of Fryer Creek from West MacArthur Street upstream to where it daylights beneath 4th Street West, and the East Fork of Fryer Creek from the confluence with the West Fork upstream to the 2nd Street West culvert (**Figure 3**). The modeling analysis was performed using the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS), version 6.0.0 Beta2, two-dimensional (2-D) hydraulic modeling software. A 2-D unsteady hydraulic model was used for this hydraulic analysis to account for the hydraulic complexity of the interaction of the flood control channel, the beaver dams, culverts, and overbank areas during large peak storm events. To support building terrains for the various model scenarios, PCI performed a survey of the existing channel, beaver dams, and culvert for the majority of the Project Area. Areas of terrain outside the limits of the survey were built with 2013 LiDAR topographic data available through Sonoma County Vegetation Mapping & LiDAR Program (http://sonomavegmap.org/). See Appendix A – Fryer Creek Beaver Impact Analysis Hydrology and Hydraulics Technical Memo for technical details on H&H analysis.

Sonoma Water has established channel design criteria through their recently updated Flood Management Design Manual (SCWA, 2020). Given that the watershed area at the project site is less than 4 square miles, this portion of Fryer Creek is considered a secondary waterway with a design storm equal to the 25-year event. For secondary waterways, a minimum freeboard of 1.5 feet must be maintained at this design storm for the 25-year event. Additionally, the 100-year event must be kept within the channel banks for secondary waterways. Thus the various beaver dam scenarios were analyzed at the 25-year and 100-year design storms. Additionally, the 2-year peak flow hydrograph was analyzed to examine the effects of the dams on smaller more frequent events. The 2-, 25-, and 100-year peak flow values for Fryer Creek West and East Forks just upstream of West MacArthur Street are provided in **Table 1** in cubic feet per second (cfs). Peak flows were extracted from hydrology data (hydrographs for the 2-, 5-, 10-, 25-, and 100-year recurrence intervals) provided by Sonoma Water.

Table 1. Peak flow hydrology for Fryer Creek at the upstream project boundaries and downstream of the confluence (Source: Sonoma Water)

Return Interval	Peak Flow (cfs)		
	West Fork Fryer Creek	East Fork Fryer Creek	Downstream of Confluence
2-year	163	123	265
25-year	287	292	538
100-year	377	324	636

The model simulation was run for the 2-, 25-, and 100-year flow events for the ¼-mile radius Project Area for the following model scenarios:

- Without Dam Condition
- Current Dam Condition

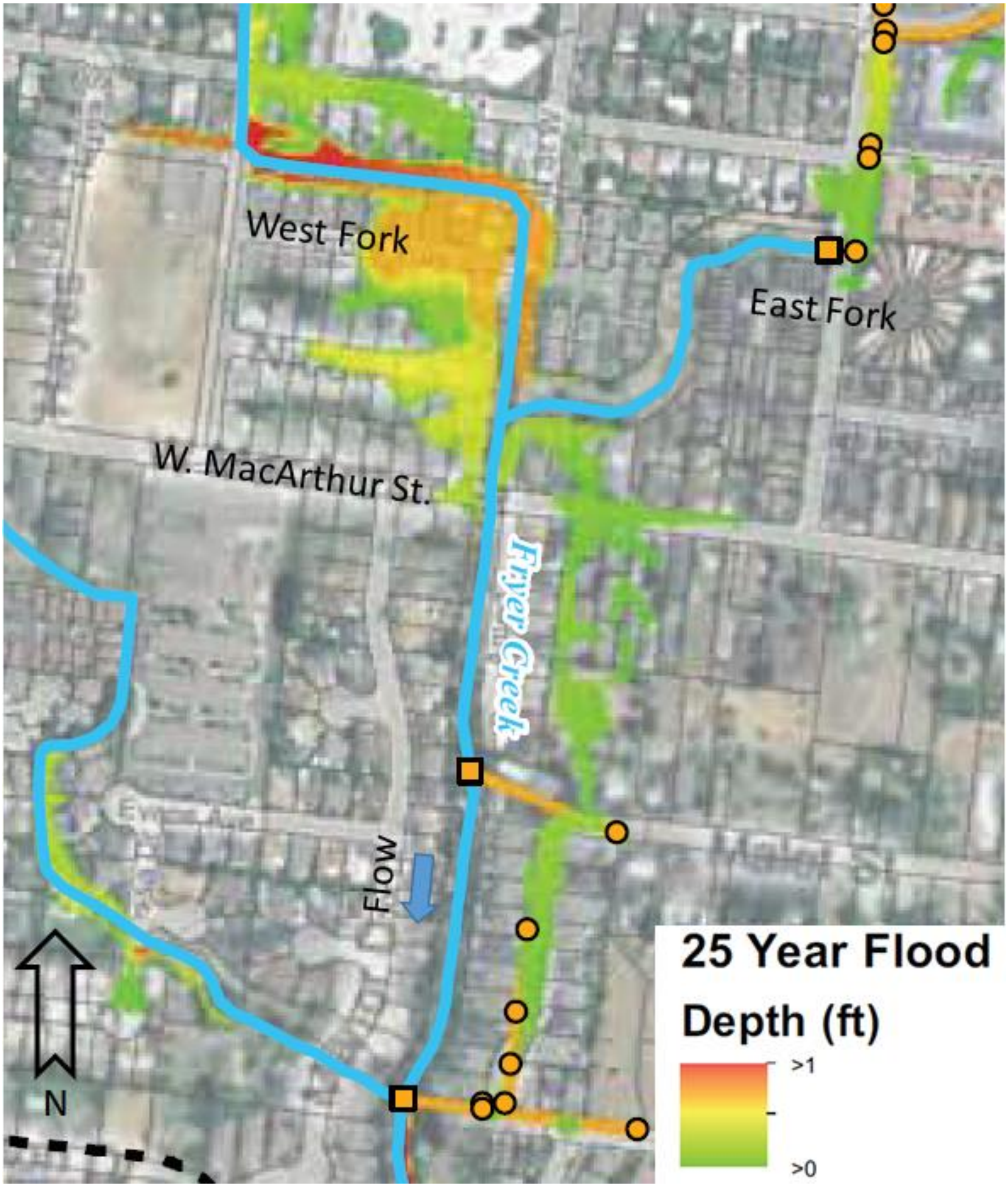
- Potential Future Dam Condition

Water surface elevation (WSE) profiles were extracted from the hydraulic model results at the peak of the hydrographs along the center of the channel for comparison.

3.3.1 Without Dam Condition

The “Without Dam” condition hydraulic model scenario was run with the terrain representing the channel prior to the established beaver dams. This Without Dam condition model terrain was built by adding all surveyed topo, except the beaver dams, to the 2013 LiDAR. This model terrain was run to establish baseline flow conditions for Fryer Creek within the Project Area without the beaver dams. Box culverts were entered into the model for three crossings: West MacArthur Street, Arroyo Way, and the pedestrian path at the confluence of the East and Main Forks of Fryer Creek.

Under the Without Dam condition, the West MacArthur Street culvert is controlling WSE upstream of the culvert. Modeling performed as part of the City of Sonoma Creek Storm Drain Master Plan (2011) shows overbank flow for the 25-year event upstream of the West MacArthur Street culvert (Figure 10). It’s clear this culvert is perched above the upstream and downstream channel profiles (Figure 11a-b, 12a-b). According to the City of Sonoma Creek Storm Drain Master Plan (2011), during the 25-year event the culvert creates a backwater effect that causes the WSE to exceed the channel banks upstream of West MacArthur Street. Modeled overbank flows then run through the development just to the east of Fryer Creek to end of the Project Area (Figure 10). The hydraulic modeling by PCI supports the results from the City of Sonoma Creek Storm Drain Master Plan (2011). Figure 10a and 10b show a 2.8, 2.5, and 2.5 feet rise across the West MacArthur Street culvert for the 2-, 25-, and 100-year flow events, respectively.



(Source: City of Sonoma, 2011; Figure 6-2)

Figure 10
City of Sonoma Creek Storm Drain Master Plan - 25 Year Baseline Flood Map

(Photo: PCI, 2021)

Figure 11a
Upstream of West MacArthur Street Culvert looking Downstream

(Photo: PCI, 2021)

Figure 11b
Downstream of West MacArthur Street Culvert looking Upstream

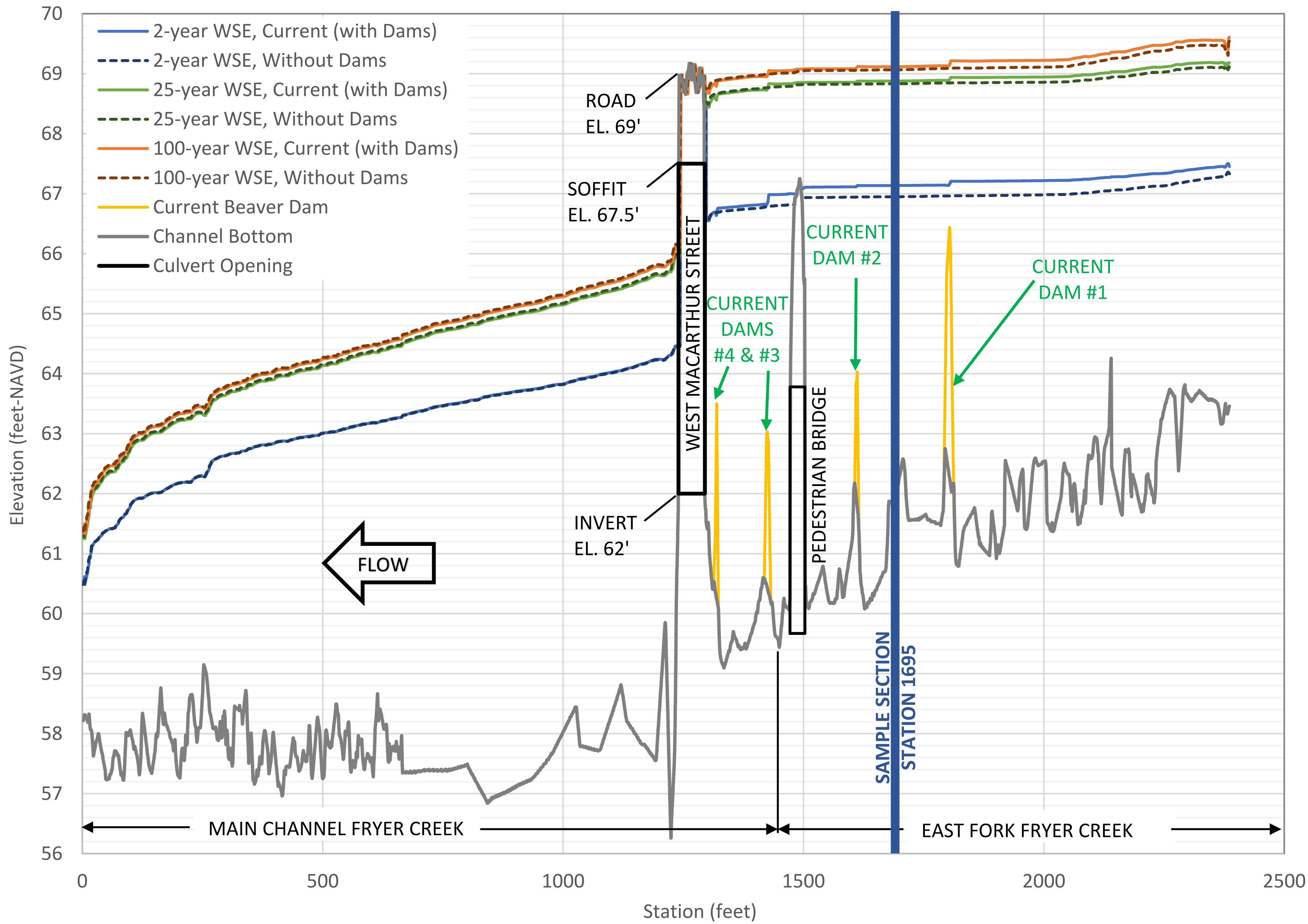


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Figure 12a

Fryer Creek Beaver Impact Analysis and Alternatives Development

Without Dam and Current (with Dam) Model Water Surf. Prof. for M. Channel and E. Fork

4/16/2021

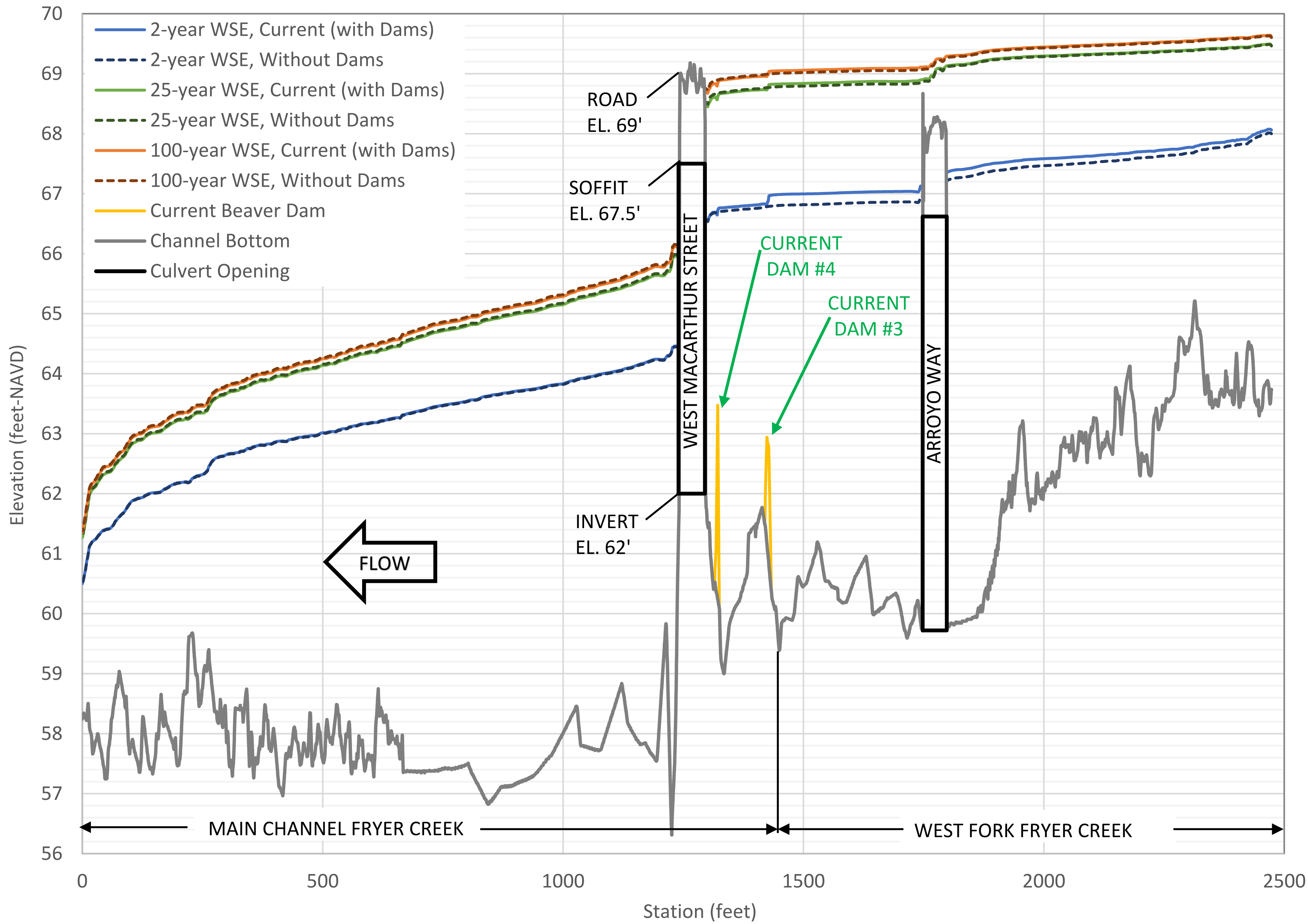

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Figure 12b
Fryer Creek Beaver Impact Analysis and Alternatives Development
Without Dam and Current (with Dam) Model Water Surf. Prof. for M. Channel and W. Fork

4/16/2021

The next hydraulic model scenario run was the "Current Dam" condition. The two beaver dams in the East Fork and two in the main channel downstream of the confluence (**Figure 13**) were added to the Without Dam condition terrain to create the Current Dam terrain. The flow control devices installed by Swift Water Designs were represented in the model terrain by adding one-foot diameter culverts across Current Dams #1-3. A flow control device was not included for Dam #4 because it was not present at the time of survey.

As compared to the Without Dam scenario, the Current Dam condition creates a 0-0.2ft rise in the water surface profile across the Project Area for the 2-, 25-, and 100-year peak flow events. During the 25-year peak flow event, which is the design flow, the Current Dams cause a rise in WSE that is less than 0.1 feet at each dam, with the cumulative rise upstream of Current Dam #1 of less than 0.1 feet (**Figures 12a-b**). The same is true for the 100-year peak flow, with each dam causing a rise in WSE of less than 0.1 feet, and a cumulative rise of just slightly above 0.1 feet (**Figures 12a-b**). For the 2-year peak flow event, there is a rise of about 0.2 feet at Current Dam #3, which results in a cumulative effect of just above 0.2 feet upstream of Current Dam #1.

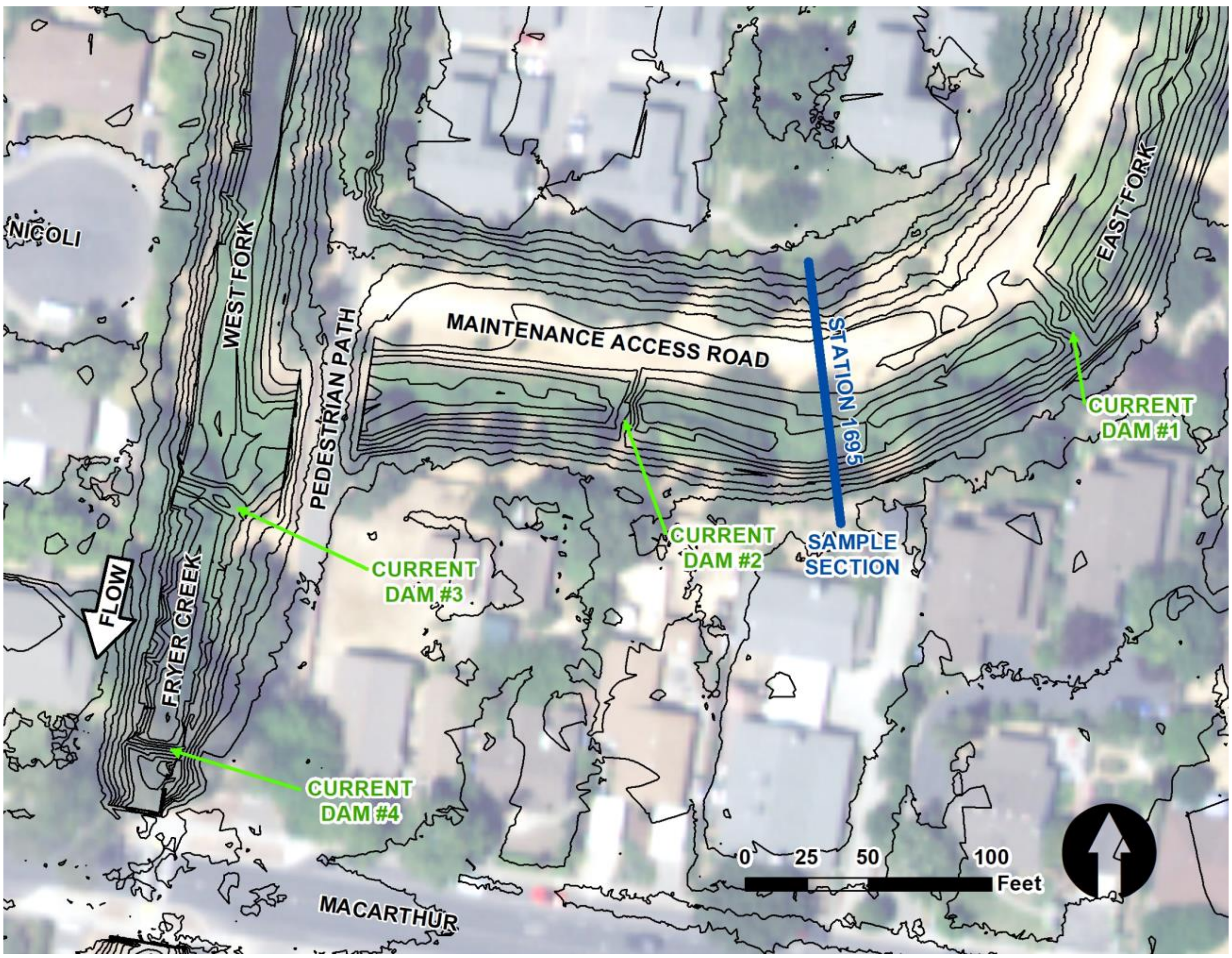

Figure 13
Sample Section at Station 1695 of the Fry Creek East Fork

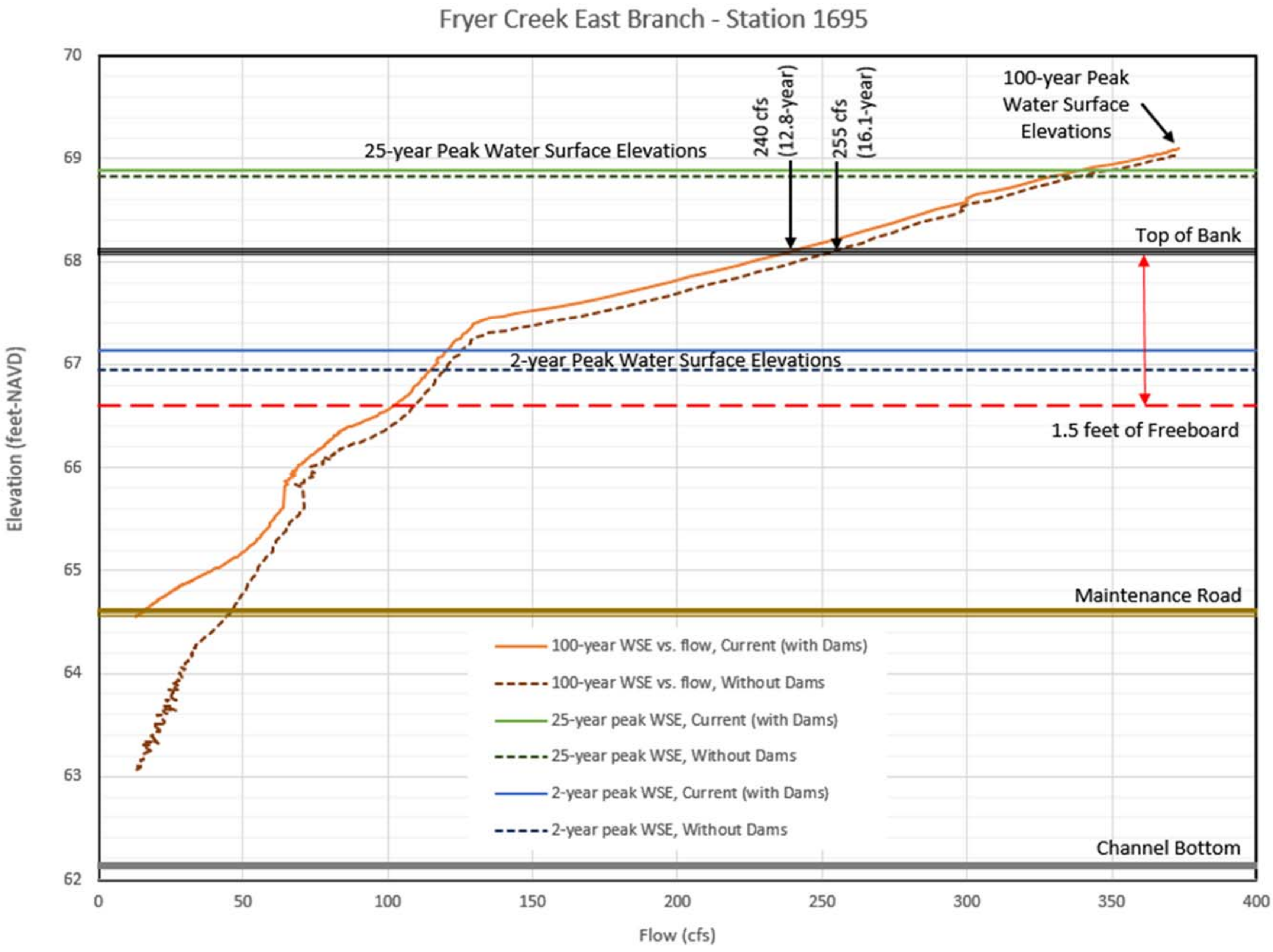

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Figure 14
Fryer Creek Beaver Impact Analysis and Alternatives Development
Without Dams and Current (with Dams) Model Water Surf. Elev. vs. Flow at E. Fork Sta. 1695

4/16/2021

The impact that the current dams have on flooding was explored across the full range of flows up to the 100-year return interval event between Current Dams #1 and #2 (Station 1695). Just upstream of Current Dam #2 is where the top of bank is the lowest in elevation, and overbank flows leave the channel and flow across West MacArthur Street and down the development to the east of Fryer Creek (**Figure 10**). At a cross section between Current Dams #1 and #2 just upstream of where flows break out of the channel (**Figure 13**), water surface elevations were extracted from the model across the full 100-year hydrograph to develop a stage-discharge curve (**Figure 14**). Stage-discharge values were also extracted for the peaks of the 2- and 25-year hydrographs. These were plotted in comparison to the elevations of the channel bottom, maintenance road, elevation for 1.5-feet of freeboard, and lowest top of bank elevation just downstream.

During the lowest flow, 13 cfs, there is a large increase (approximately 1.5-feet) in water surface elevation (WSE) due to the Current Dams (#2-4) as compared to the Without Dam condition. At this flow, the Current Dam condition WSE is set by the downstream flow control device and is at the elevation of the maintenance road. However, the increase in WSE caused by the Current Dams diminishes rapidly to about 0.2 feet by 80 cfs. As stage approaches the top of bank, the difference in WSE between Current Dams and Without Dam condition is reduced to approximately 0.1 feet.

At the location where flows first begin to exit the channel, the Current Dam conditions result in approximately a 6% reduction of the channel's maximum flow capacity before flooding begins, as compared to the Without Dam condition. Under Current Dam conditions, the WSE exceeds the top of bank elevation at a slightly lower flow, 240 cfs (12.8-year peak flow event), versus 255 cfs (16.1-year peak flow event) for the Without Dam condition. Under either scenario, as a result of the backwater effect of the W. MacArthur St. culvert, flows are overtopping fairly frequently and not meeting the 25-year, 1.5 feet of freeboard or containment of the 100-year design criteria. This result is also reflected in the modelling performed for the SDMP.

Note that recurrence intervals estimated above are interpolated from hydrology data from the City's SDMP and are meant only to provide temporal context to their associated flow values in relation to pre- vs post-beaver dam conditions. This study was not scoped to certify the accuracy of peak flow hydraulics and return intervals of specific flood events. As such, these results may vary somewhat from the hydraulics results in the SDMP.

3.3.3 Potential Future Dam Condition

A "Future Dam" condition model scenario was run to examine the potential impact on flooding if beavers continue to build dams on Fryer Creek in the future. For the potential Future Dam condition model scenario, dams were added to the Current Dam Conditions terrain in areas identified collectively by Swift Water Design, Occidental Arts & Ecology Center (OAEC), and PCI. OAEC and Swift Water Design indicated that any new dams were most likely to be built downstream of the current dams. In part, this determination was based on extrapolating the current trend of the beavers moving downstream. Also, above the existing dams, the East Fork is tightly constrained by urban development for the short distance where it is daylighted, offering no significant resources for beavers. On the West Fork, the extent of riparian habitat is limited above the existing dams, but there is evidence of beavers feeding there; dam building cannot be entirely ruled out there. Overall, though food and dam building resources are currently scarce, it was determined the most likely place for beavers to continue to build was downstream of West MacArthur Street. According to the OAEC and Swift Water Design, beavers typically build dams at riffles and stream confluences. There are no major confluences within the ¼-mile Project Area, however there are several small riffles just downstream of the West MacArthur Street

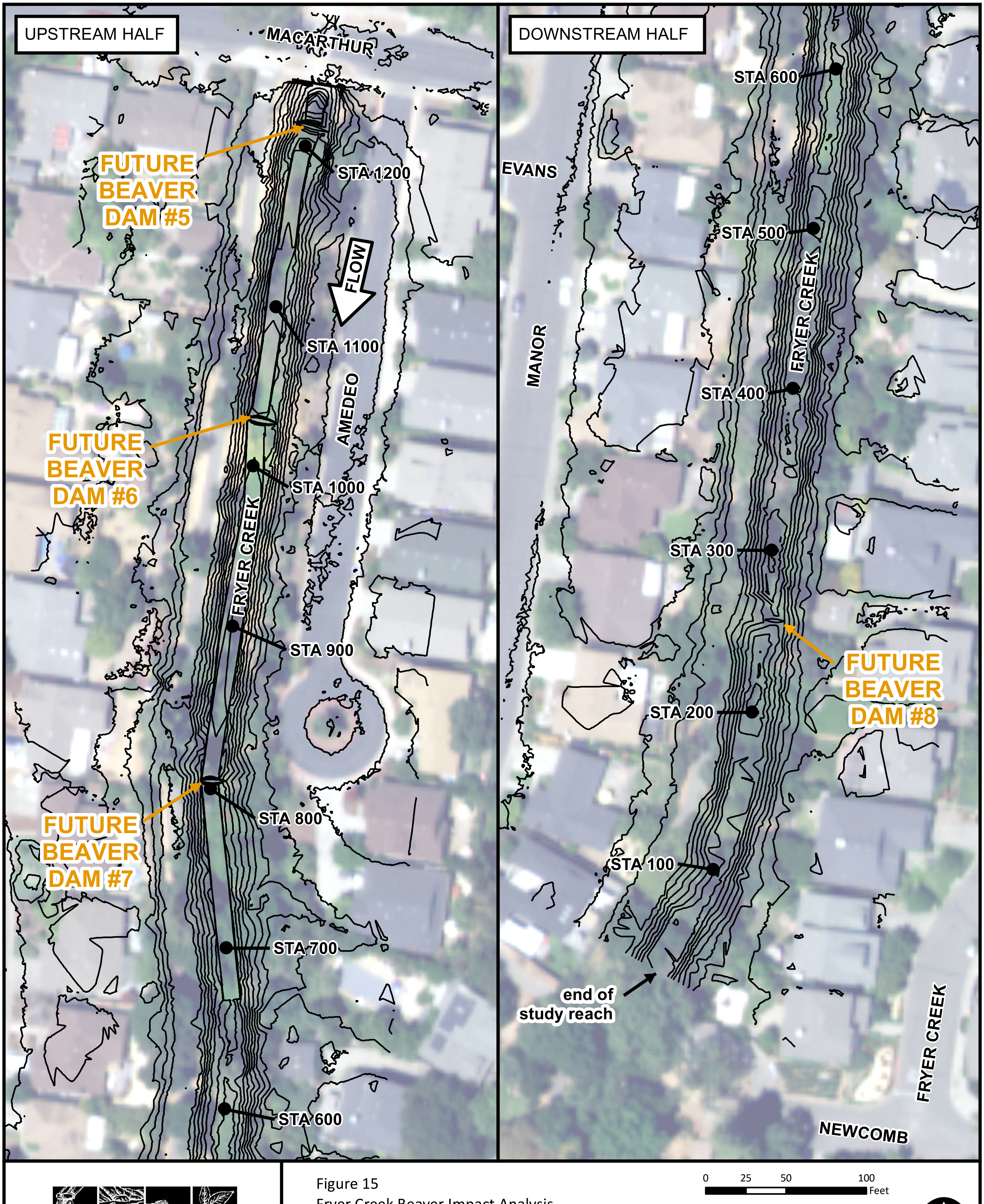

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Figure 15
Fryer Creek Beaver Impact Analysis
and Alternatives Development Report
Sonoma Water Stream Maintenance Program
Future Dam Locations

4/16/2021
Imagery: NAIP 2018
Contours: Sonoma Veg Map 2013

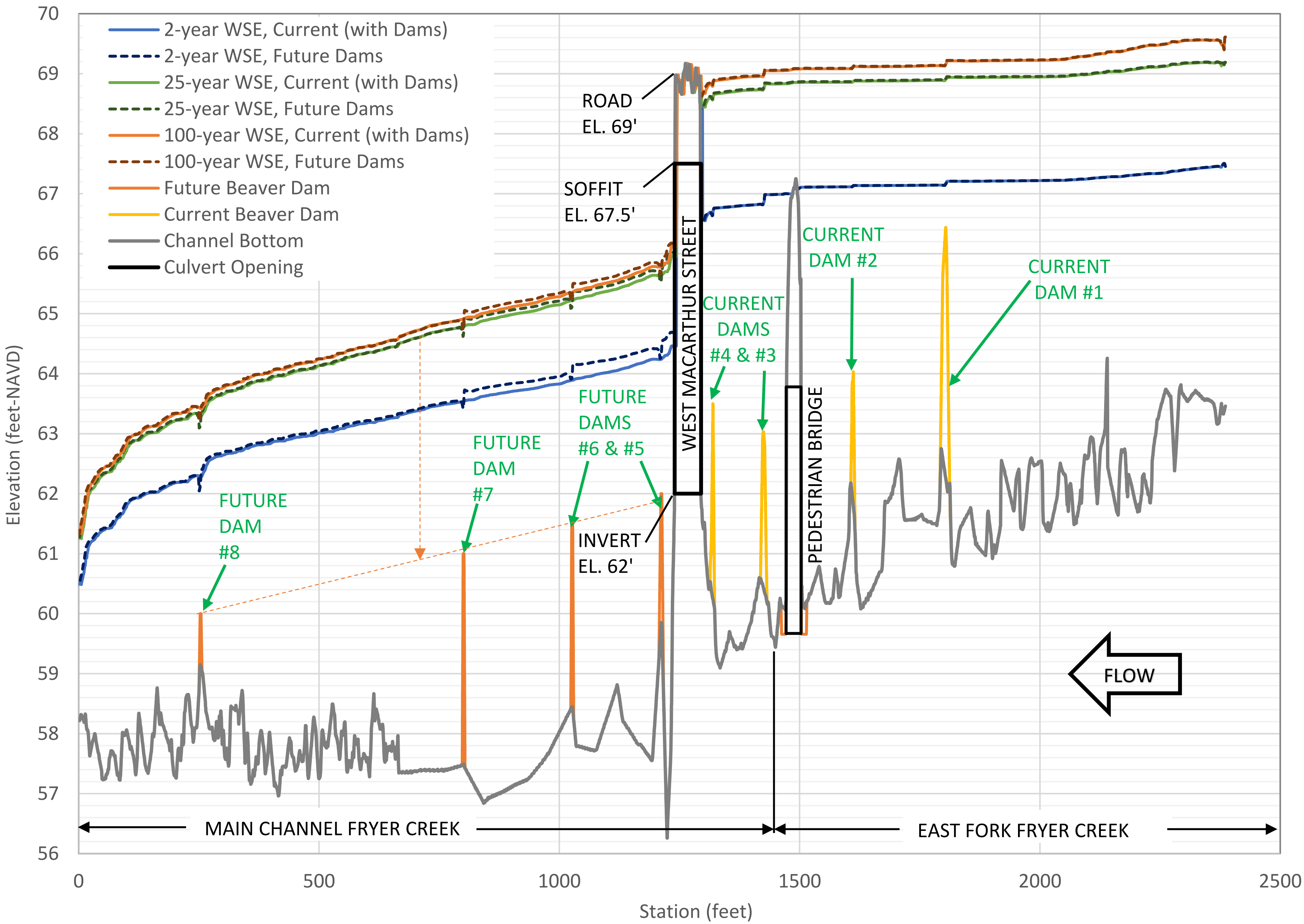

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Figure 16a
Fryer Creek Beaver Impact Analysis and Alternatives Development
Future Dam and Current Dam Model Water Surf. Prof. for M. Channel and E. Fork

4/16/2021

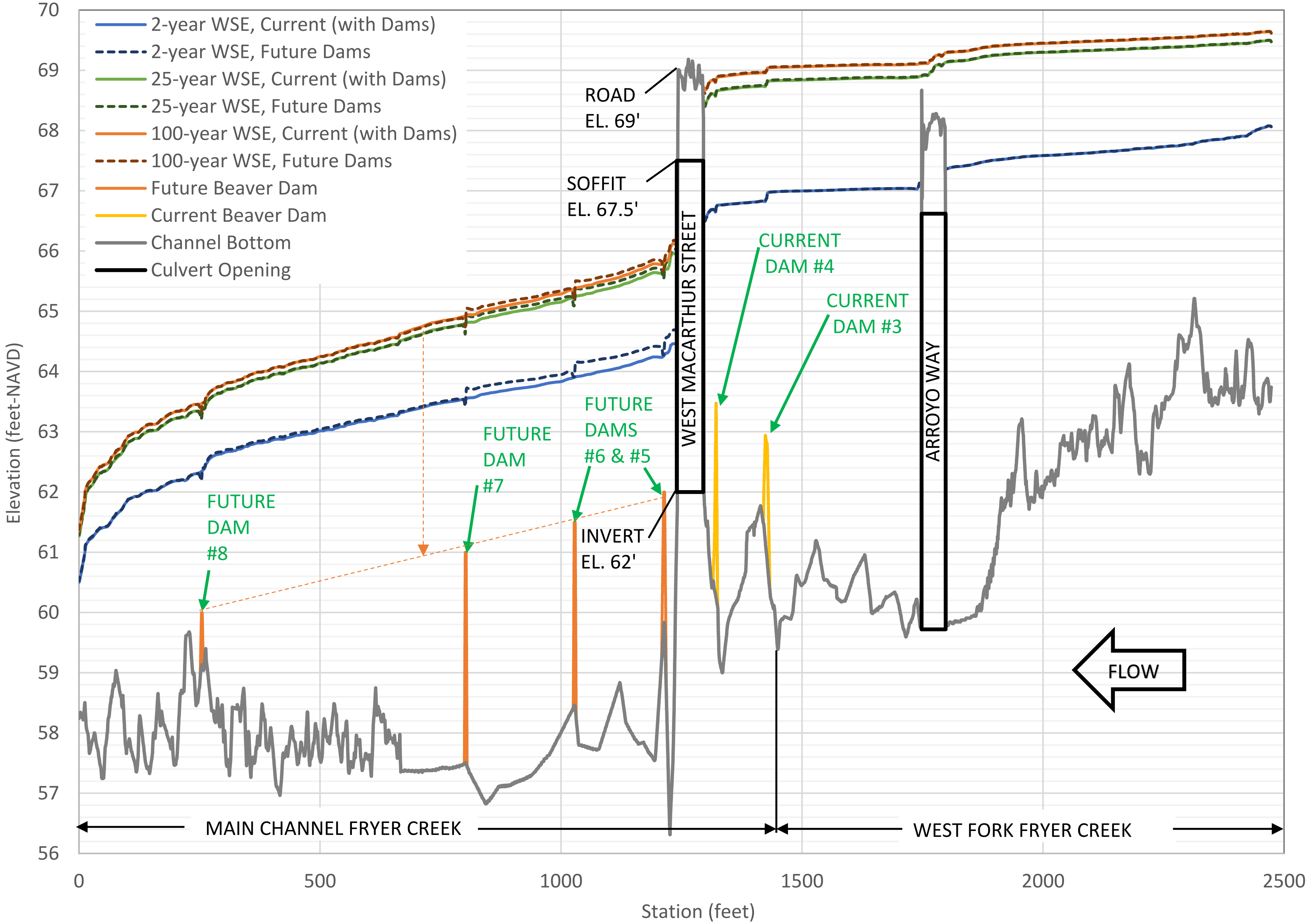

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Figure 16b
Fryer Creek Beaver Impact Analysis and Alternatives Development
Future Dam and Current Dam Model Water Surf. Prof. for M. Channel and W. Fork

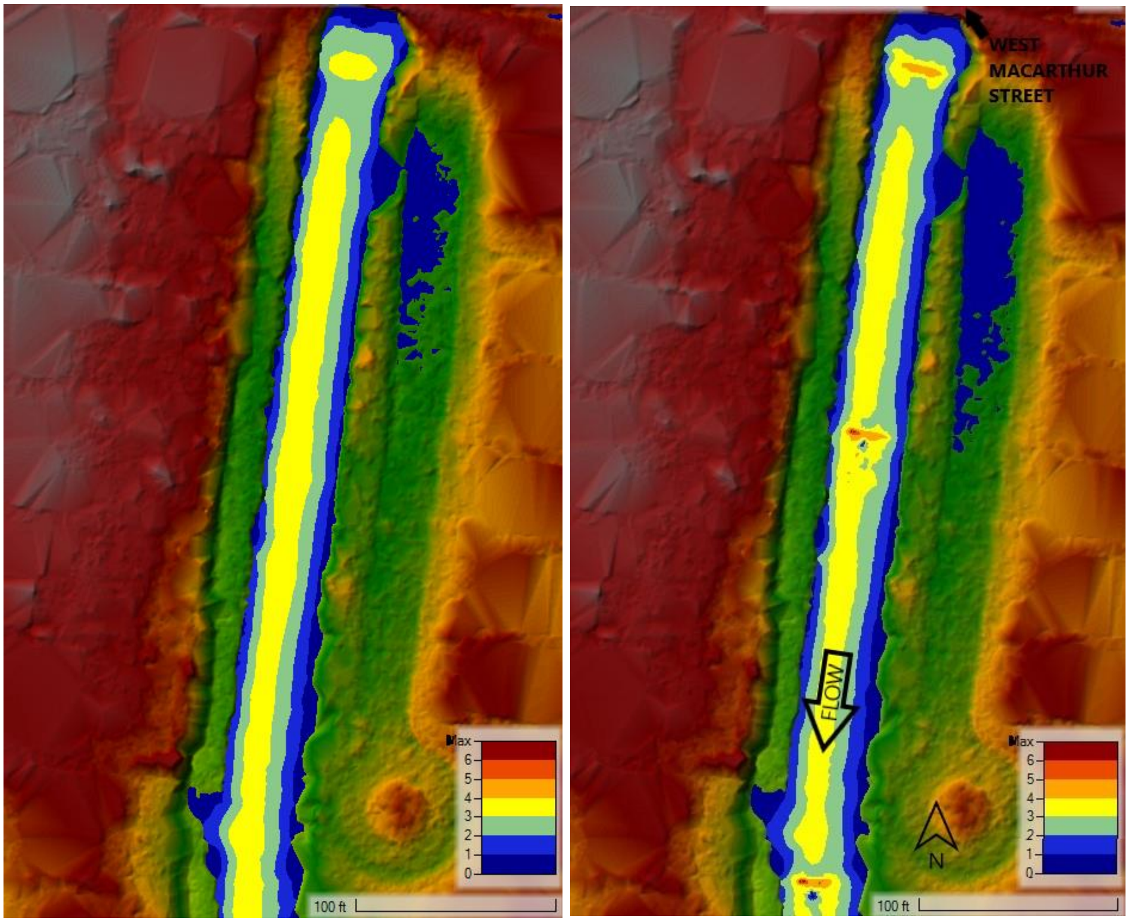
4/16/2021

culvert. Future Dams (#5-7) were added to riffles in the Current Dam condition terrain 30-, 210-, 440-, and 1000-feet downstream of the West MacArthur Street culvert (**Figure 15**).

In determining dam height, it was assumed the dams would include flow control devices and the dam heights would be limited to similar heights as the Current Dams (#1-4), which is about 2-3 feet above the existing channel bed. It was also assumed that the Future Dam (#5) just downstream of West MacArthur Street would not be allowed to extend in height above the culvert invert. Ultimately, elevations for the Future Dams (#5-8) were set at the longitudinal profile slope that approximated the same slope as the 25-year and 100-year WSE profiles (**Figures 16a-b**).

A comparison of the results for the Future Dam condition to the Current Dam condition shows that adding Future Dams downstream of West MacArthur Street only effects WSE downstream of the culvert. For the 25- and 100-year peak flow events, the increase in WSE is less than 0.1 feet across each Future Dam with a cumulative increase in WSE of about 0.1 feet just downstream of West MacArthur Street (Figures 16a-b). For the 2-year event, there is about a 0.1-foot increase across Future Dam #6 & 7, which provides a cumulative increase of about 0.2 feet just downstream of West MacArthur Street (Figure 16a-b). For all events modeled, Figures 16a and 16b show the increase in WSE as result of the Future Dams downstream of West MacArthur Street does not affect the WSE upstream of the crossing.

The model shows an increase in velocity across the dams to account for the discrepancy between bed heights versus WSE rise between the Future Dam condition to the Current Dam condition. Though the channel beds were raised by about 2-3 feet for the Future Dam condition, there is only about a 0-0.2 feet rise in WSE. In order to account for flow continuity, this means velocity must increase across the Future Dams. Spikes in velocity for Future Dam conditions at Future Dams #5-7 are shown in **Figure 17**. The increase in velocity at the Future Dams for the various modeled flows ranges between 1.5 and 2.7 feet/second (**Table 2**).



Current Conditions Future Conditions

Figure 17. *Model Velocity Results for 25-year Peak Flow for Future Dams #5-7.*

Table 2. Velocity Results at Future Dams #5, 6, and 7 for Current and Future Dam Condition

	Current Dam Condition Peak Velocity (ft/s)	**Future Dam Condition Peak Velocity (ft/s)**
2-year		
Dam #5	2.8	4.8
Dam #6	3.2	4.7
Dam #7	3.3	4.7
25-year		
Dam #5	3.2	4.7
Dam #6	3.5	6.2
Dam #7	3.4	6.0
100-year		
Dam #5	3.3	4.7
Dam #6	3.6	6.0
Dam #7	3.5	6.1

Given the rise in velocity across the Future Dams, it was worth examining whether the dams might be susceptible to failure during the peak flows modeled. Though very little information exists on the threshold for failure, the unit discharges at each dam were compared to the few reported values of 8-17 square feet per second by Westbrook et al. (2006), Levine and Meyers (2014), and Müller and Watling 2016). **Table 3** presents the unit discharges estimated for the Current Dams (#1-4) and Future Dams (#5-8). For the 2-year event, the Current Dam #4 and all Future Dams' (#5-8) unit discharges are within the reported range of failure. For the 25- and 100-year event, all Future Dams' (#5-8) unit discharges exceed the reported range of failure, while Current Dam #4 is within the range.

Downstream of West MacArthur Street, the channel is particularly narrow and straight. It stands to reason that in such a confined channel, dams built by beavers in this location could fail. Building materials here are limited as well, and may consist of less-resistant grass, mud and small sticks. At Current Dam #4 just upstream of the West MacArthur Street culvert, the channel also begins to narrow creating a potential dam failure scenario. It's possible that the backwater caused by West MacArthur Street may prevent a failure of Current Dam #4 from happening. However, a failure of Current Dam #4 may result in the West MacArthur Street culvert getting clogged with debris, reducing flow conveyance capacity and exacerbating the backwater and flooding upstream of West MacArthur Street. For Current Dam #1 and #2, because of the added width from the maintenance road, there was less flow across the dams resulting in lower unit discharges.

Table 3. Velocity Results at Future Dams #5, 6, and 7 for Current and Future Dam Condition

Dam	Dam Width (ft)	Unit Discharge (sf/s)		
		2-year	25-year	100-year
Current Dam #1	40	2	3	4
Current Dam #2	31	2	3	4
Current Dam #3	29	6	7	7
Current Dam #4	24	10	15	16
Future Dam #5	21	11	18	18
Future Dam #6	19	11	19	20
Future Dam #7	16	12	19	20
Future Dam #8	12	12	18	18
Note: Orange values are in the range of, and red values exceed reported dam failure thresholds of 8-17 sf/s (Westbrook et al.2006; Levine and Meyers, 2014; Müller and Watling; 2016).				

4 Fryer Creek Beaver Alternatives Development

Various possible beaver dam/management scenarios were explored in the development of three beaver management alternatives that were then hydraulically modelled:

- Beaver dams go undiscovered or a flow leveler fails, allowing beavers to build as high as they want (Alternatives 1a and 1b). Typical beaver dam height can get up to 6 feet tall (Pollock et al., 2018).
- Beaver dams enable cattails to establish and completely fill the low flow channel (Alternative 2). Cattails grow up to 9 feet tall and the surrounding topography is about 5 to 9 feet above the channel bed, so it is possible under this scenario that the cattails do not lay over, which would drastically obstruct flow.

The following scenarios were considered but not pursued for modelling:

- The maintenance road is raised to dry it out for improved summer access. This was not considered a viable management approach because relatively simple flow control devices can be used to adjust summer pond water levels until the road is dry. Raising the road would be a much higher cost approach, and could potentially reduce the capacity of the channel.
- A flood control wall is built to contain flows within Fryer Creek. This was ultimately determined not likely to be a feasible scenario because a wall would be required for a significantly large portion of Fryer Creek upstream of W. MacArthur St, and other engineering would need to be considered for drainage to the creek from the community. Based on the likely high expense of these items, this option was not pursued for modelling.

4.1 Alternatives 1a and 1b

The first two alternatives developed and modeled pertained to the scenario in which beavers are able to build the dams as tall as they want. This scenario assumes either a flow control device has not been installed to limit dam height, or that the flow control device is not properly functioning. This alternative assumes that without the flow control device to deceive beavers from continuing to build, beavers will increase dam heights up to the typical maximum height of 6 feet above the bed (commonly at a riffle crest). Under this assumption the following alternatives were developed and modeled:

- Alternative 1a: Select beaver dams are increased by 1.5 feet to about 4.5 feet above the channel bed

- Alternative 1b: Select beaver dams are increased by 3 feet to about 6 feet above the channel bed

Given the difference in hydraulic affect from the backwater of the W. MacArthur St. culvert, a single dam was chosen to be elevated for each reach, downstream and upstream of the culvert. The most hydraulically influential dam for each reach was selected to be raised. This was Current Dam #3 for the reach upstream of W. MacArthur St., and Future Dam #7 for the downstream reach. These dams were increased in height by 1.5 feet and 3 feet in the “Future Dam” condition hydraulic model terrain for Alternatives 1a and 1b respectively. The 25-year event design storm was run for each of the two alternatives and compared to the “Without Dam” and “Future Dam” condition model results (**Figure 18**).

Increasing the dam heights by 1.5 feet (Alt. 1a) caused an increase in WSE of about 0.1 feet from the “Without Dam” condition at Current Dam #3 and 0.3 feet at Future Dam #7. A 3-foot increase in dam height (Alt. 1b) resulted in an increase in WSE of about 0.2 feet at Current Dam #3 and 1.1 feet at Future Dam #7. By contrast, the “Future Dam” condition model which included both Current Dam #3 and Future Dam #7 at the original 3-foot height had only a 0.1-foot increase in WSE at each dam when compared to the “Without Dam” condition.

Ultimately, it’s only at the maximum expected beaver dam height outside the influence of other hydraulically controlling features that there appears to be a significant increase in the water surface profile. Upstream of the W. MacArthur St. culvert the hydraulic backwater effect drowns out even the maximum beaver height of 6 feet at Current Dam #3. In that location, flood conditions are much more controlled by the undersized crossing at MacArthur Street than they are by beaver dam conditions. However, downstream of W. MacArthur St., where the channel is confined and outside the effect of any hydraulic controls, an increase of 3 feet in dam height at Future Dam #7 creates a significant increase in WSE (1.1 feet) as compared to without dams.

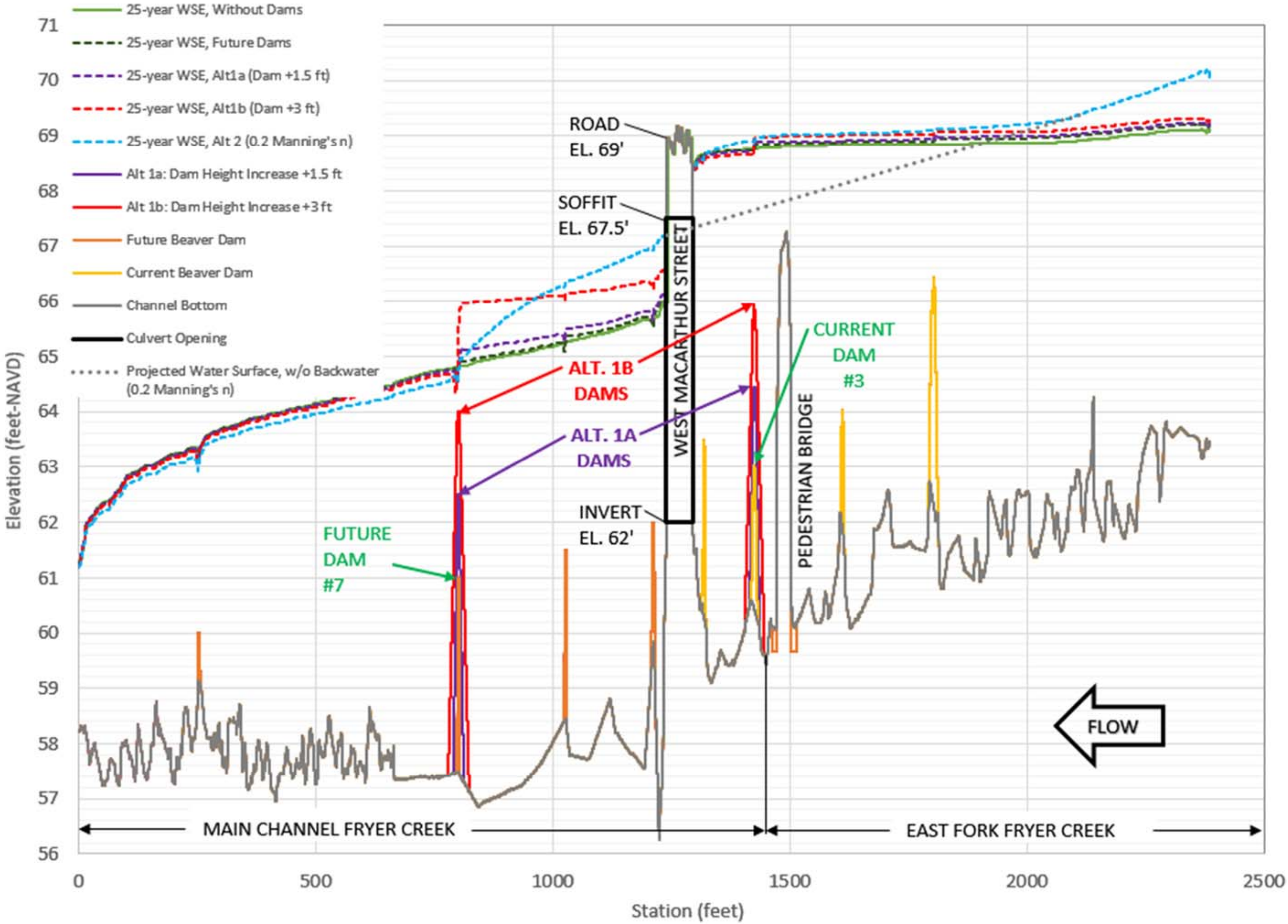


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Figure 18
Fryer Creek Beaver Impact Analysis and Alternatives Development
Comparison of Dam Alternatives Water Surf. Prof. for M. Channel and E. Fork

5/28/2021

4.2 Alternative 2

Alternative 2 analyzed the impact that full cattail establishment within the low flow channel would have on hydraulics. (Note that this is not a recommended condition, but rather a theoretical condition for analysis purposes; see Section 5 for management recommendations relating to cattail.) Beaver dams have been shown to facilitate the establishment of wetland vegetation upstream of the dams in areas experiencing increased ponding (Pollock et al., 2018; Lundquist and Dolman, 2018). Currently, cattails have become established at various locations in the low flow channel upstream of W. MacArthur St. (**Figure 19**). Cattails can grow up to 9 feet tall which is well above the surrounding topography. This alternative assumes the worst case scenario in which the cattails do not lay over, causing a drastic increase in flow roughness or obstruction of flow. Research by the U.S. Army Corp of Engineers' Wetlands Research Program found that Manning's n roughness values level off between 0.18 (observed) and 0.27 (calculated) at the highest velocities (Hall and Freeman, 1994). Thus for Alternative 2, a Manning's roughness value of 0.2 was used in the hydraulic model below the elevations of the beaver dams for the entire active channel (not including culverts) in both forks of Fryer Creek upstream of Future Dam #7.

(Source: PCI, 2021)

Figure 19
Established cattails in the Fryer Creek East Fork low flow channel

The 25-year peak water surface profile for Alternative 2 is included in **Figure 18** to compare with the "Without Dam" and "Future Dam" condition as well as Alternatives 1a and 1b model results. The water surface profile for Alternative 2 shows the high roughness begins to elevate the water surface upstream of Future Dam #7 to a maximum of 1.1 feet above the "Without Dam" condition just downstream of W. MacArthur St. Immediately upstream of W. MacArthur St., once again the backwater effect of the culvert drowns out the influence of the high roughness. However, this influence appears to diminish approximately 750 feet upstream of the culvert, with the water surface once again elevating to approximately 1.1 feet above the "Without Dam" condition at the very upstream end of the model. Interpolating from just downstream of W. MacArthur St. culvert upstream to the end of the model, it appears the effect of the high roughness would be about 1.1 feet across the reach if it were not for the backwater effect of the culvert (see grey dotted line, **Figure 18**).

5 Fryer Creek Beaver Adaptive Management Findings

This study examined whether current and future beaver activities in Fryer Creek may affect flooding in the winter and inhibit access along maintenance roads during the summer. The four beaver dams currently provide valuable ecological benefits along this engineered flood control channel within the urbanized Sonoma community. This study will be used to better understand flood risk and develop guidance for more general beaver management of 89 miles of engineered channels maintained as part of Sonoma Water's Stream Maintenance Program.

Flow control devices are used to ensure the maintenance road is dry for use in the summer. Flow control devices have been installed over the four current beaver dams by Swift Water Design to set water levels below Sonoma Water's maintenance access road. Water levels should be monitored in the summer to determine if adjustments must be made to support drying of the maintenance road.

The current beaver dams, with heights limited by the flow control devices, appear to have a minimal effect on flooding. Flow control devices discourage the beavers from increasing the height of the dams, in this case limiting dam heights to about 2-3 feet above the original channel bed elevation. Though the dams modeled had heights of 2-3 feet above the channel bed, the modeled rise in water surface elevations is only about 0-0.2 feet. Upstream of West MacArthur Street, the backwater of the culvert may be drowning out any hydraulic effect of the dams. This suggests management of beaver establishment should account for flood impacts of other features such as culverts and grade control structures in the vicinity of the dams. Downstream of West MacArthur Street, it is possible that the relatively small dams as compared to tall banks of the channel limited the dam's impact on flood water surface elevations. However, due to flow continuity, they did result in localized increases in velocity across the dams. The modeling also showed that dams are less likely to persist in narrow, confined flood control channels that force all the flow across the beaver dam. If the dams persist during high flow events, it may be possible the dam will experience end-cutting and bank erosion depending on the resistance of the existing banks. Where individual beaver dam sites are found, the adjacent streambanks should be evaluated for potential erosion concerns to adjacent infrastructure. Some bank erosion might be acceptable in many locations while in some cases further engineering considerations for bank protection may be required.

The main management implication of the analysis of Alternatives 1a, 1b, and 2 for Sonoma Water is the possible need for increased monitoring and maintenance. The findings for Alternatives 1a and 1b suggest an increased need for monitoring to ensure new dams are identified early. Flow control devices should be monitored regularly, including after large storm events, to ensure that they are clear and in proper working order. In particular, inlet protection cages need to be inspected for potential damage or plugging after larger storms where bedload or vegetative debris have been transported by the stream. It appears there is some room for the dams to go undiscovered, but once the dams reach a typical maximum height of 6 feet they may prove to be problematic for meeting designed flood freeboard requirements. The analysis of Alternative 2 indicates the potential need to perform more regular vegetation clearing in the channel. Cattails are a source of food for beavers so some balance will need to be considered between vegetation clearing and maintaining resources for beavers.

This study did not undertake hydraulic modeling to assess the risk that larger trees felled by beavers may mobilize during storm events and lodge in downstream culverts. PCI's findings indicate that the

MacArthur St crossing is undersized and, even without any blockage, significantly controls the peak flow water surface elevations upstream. Any reduction in flow capacity of the crossing will only worsen this condition. However, for material from a failed beaver dam to have a significant effect on flooding, the material would have to be capable of spanning the culvert opening while resisting a relatively large stream force. As most of the material in the beaver dams is relatively small, it would likely pass through the crossings, or potentially create a small partial blockage that would then be forced through during high flow events as velocity increases. PCI recommends taking steps to prevent blockages. Currently, the Project Area beavers have felled a red willow upstream of the McArthur St. crossing, which is a possible concern. Felled trees provide essential resources for beaver (for feeding on cambium, and sharpening teeth) while the trees are relatively fresh. However, Sonoma Water is concerned that if these are left in place they could block culverts in a storm, and prefers to remove them promptly. Sonoma Water has determined that it is not feasible to cut felled trees to smaller sizes (which could pass through the culvert) and leave them in place.

Selected living trees can be protected, either individually or in groups. It is recommended to wrap trees that are large enough to be a threat to downstream culverts with 3-foot-high galvanized welded wire (Lundquist and Dolman, 2018). Chicken wire is not strong enough to withstand beaver chewing. The wire should completely surround the tree, while leaving a 12-inch space to allow for growth. A single pole culvert inlet trash rack could help prevent dam debris from getting hung up in the culverts but Sonoma Water has determined that this is not practical in this setting.

To summarize, the following management steps are recommended to support the goals of flood protection and natural resource protection where beavers are active on Fryer Creek:

- Monitor the channel regularly to identify new beaver dams early. Monitor culverts regularly to ensure that they are clear of debris.
- Continue the use of pond leveler devices. In general, maintain water levels at the highest level that still supports infrastructure protection.
    - Monitor water levels in the summer to determine whether adjustments in pond levelers are needed to allow the maintenance road to dry.
    - Monitor to ensure that flow control devices are clear and working as intended. Using flow control devices, ensure that dams do not reach 6' in height, or are maintained to acceptable heights for a given stream reach.
- Assess the site annually for sediment accumulation and vegetation establishment within the channel. If seasonal flows do not control vegetation establishment in the low-flow channel, perform vegetation clearing as needed for public safety. Balance the vegetation's value for beaver and other habitat benefits with the need to reduce flood risk. Undertake the clearing with as light a touch as possible, minimizing the area of disturbance and retaining patches of each native vegetation type. See next section for additional beaver and habitat protection guidance.
- For dead trees felled by beavers: Sonoma Water plans to monitor for these regularly throughout the year and remove them from the site. A final clearance of downed material in late summer, prior to fall rains, will be part of this routine. However, recently downed trees provide essential resources for beaver, so if any trees can be safely left on site temporarily while they are still fresh (e.g., trees felled early in the dry season), these may be retained, at Sonoma Water's discretion. Note that, if all felled trees are immediately removed, beavers are likely to cut down additional trees, may cause damage to nearby residential infrastructure, or may leave the area. Consider anchoring selected fallen logs in place near the den to provide the beavers with woody vegetation without potentially causing culvert blockage.
- To protect living trees that Sonoma Water wants to retain (which may include those that are large enough to block the culvert, if felled), wrap trees with 3'-high galvanized welded wire, leaving a 1' space between the wire and trunk to allow for growth. Recommended fence

material is 14-gauge with 2”x4” openings. Monitor and replace cages as needed. Alternatively, groups of trees may be protected together.

- To help suppress water primrose establishment and generally enhance riparian habitat, consider planting of additional native trees with the goal of shading the creek, pond and wetlands over time. Manual or mechanical removal of water primrose will likely also be needed in the short term. See the Stream Maintenance Program Manual for additional information on water primrose management and tree planting guidelines.

See the seasonal calendar below for an overview of key maintenance activities in relation to beaver activity on the site.

6 Beaver Protective Measures During Vegetation and Sediment Management in Fryer Creek

The following recommendations were developed by OAEC and Swift Water Design (SWD), with input from PCI.

The beaver-occupied area of Fryer Creek will still require ongoing maintenance by Sonoma Water. The vegetation will need to be managed annually for public safety and fire fuel reduction and will include such activities as mowing, downed tree removal, tree pruning, invasive plant removal and hazard tree removal. The sediment build-up in the creek itself will also need management. This will require periodic sediment removal in the area occupied by the beaver. This sediment removal could help the beaver persist, since they need 1-meter pool depths to ensure escape cover from predators. Maintenance activities can be conducted in a way that minimizes negative impacts to beavers.

The following measures are recommended to help protect beavers during sediment and vegetation removal activities. These should be overseen by a qualified biologist who is familiar with beaver behavior, or beaver specialist.

1. Designate the area within a 100-foot radius of the beaver’s bank burrow (lodge) as “sensitive” (Figure 20, below).

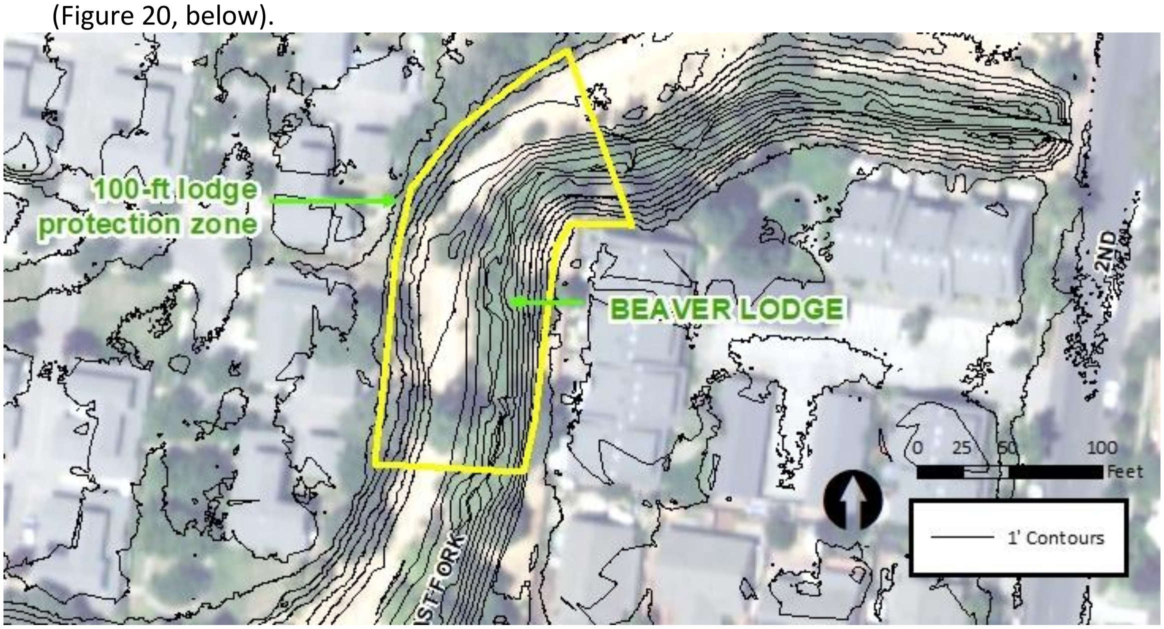

Figure 20. *100-foot zone around current Fryer Creek beaver lodge, for protection of beaver from stream maintenance activities*

2. Use landscaping flags on the banks to help work crews identify where this area begins and ends.

3. Use camera traps to monitor beaver presence before and after maintenance, especially when conducting larger projects such as sediment removal. Use camera monitoring observations to confirm den location(s), kit season (typically mid-April to mid-June; generally prior to sediment removal work), and activity patterns to support avoidance. Also use camera monitoring to compare beaver activity patterns before and after work on site, to determine whether work appears to affect beaver persistence or activity. If camera monitoring indicates disruption of beavers by maintenance activities, confer with biologist to identify any changes needed in management practices.
4. Other than to address emergencies, do not work in the sensitive area during kit season (generally mid-April to mid-June) to the extent possible. Mowing or weed abatement to reduce fire hazard may need to be performed in this area in this time frame.
5. Use hand tools alone to conduct work in the sensitive area. If heavy equipment use cannot be avoided within the 100-foot sensitive area:
    a. Keep heavy equipment at least 50 feet from the burrow entrance. Use the smallest equipment practical.
    b. At the current Fryer Creek burrow location, keep heavy equipment on the opposite bank from the burrow to minimize ground vibration, using the excavator's arm and bucket to reach towards the burrow.
    c. Minimize the length of time equipment is in use.
6. Within the sensitive area, minimize the removal of favored food species (willow, cattail, green grasses) to the extent possible. Where Sonoma Water determines this is necessary for flood or fire protection, consult with a biologist familiar with beaver ecology to identify how much vegetation, which plant species, and which locations, can be cleared with the least impact on beavers. Retaining approximately 100 stems of woody vegetation suitable for beaver forage in this sensitive area is likely needed for beaver persistence; having many hundreds of stems is preferable. If possible, undertake an adaptive management process in which a minimal amount of vegetation is removed the first year; observe beaver responses; and slowly increase the amount removed annually (if needed) to determine what this site's minimum beaver food resource threshold is. Focusing vegetation removal work in the midday hours will reduce likelihood of direct interactions with beavers, who are most active from dusk to early morning.
7. Currently, there is no significant willow establishment within the sensitive zone, but it is present immediately upstream and downstream. Willow is a key resource for beaver. To the extent feasible, retain willow cover near the sensitive area.
8. When favored beaver food sources are cut or pulled for maintenance outside of the sensitive area, consider leaving them on the bank near the lodge for beaver to utilize.
9. Sonoma Water typically undertakes temporary dewatering to facilitate channel sediment removal. Dewatering in the sensitive area of Fryer Creek, around the den, could cause beavers to abandon the site. Sonoma Water plans to investigate the feasibility of putting up a temporary dam that would keep the den area watered during this process, or of doing sediment removal without dewatering. The latter may require installation of a turbidity curtain to protect water quality and aquatic species. Changes to sediment removal practices will require review of Sonoma Water's permits for instream work to ensure the new approaches are acceptable to regulatory agencies.

See the seasonal calendar below for an overview of typical timing for key beaver protection and maintenance activities on the site.

7 Seasonal Calendar of Beaver-related Activities at Fryer Creek

The monthly calendar below shows typical timing for key beaver activity, monitoring, and maintenance tasks on the Fryer Creek site.

<table>
<tr><th></th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td rowspan="2">Key beaver activity and monitoring</td><td></td><td></td><td></td><td colspan="3">Kit season</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="12">Ongoing: camera monitoring to confirm den location(s), kit season, activity patterns</td></tr>
<tr><td rowspan="8">Key maintenance activities</td><td></td><td></td><td></td><td colspan="3">Flag sensitive area around den for avoidance. No work in sensitive zone at this time if possible.</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="3">Mowing/trimming for fuel reduction</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="5">Vegetation pruning or removal as needed - for public safety and invasive species management</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Sediment removal as needed</td><td></td><td></td></tr>
<tr><td colspan="5">Ongoing: Monitor for downed wood to remove or other debris that may clog culvert</td><td></td><td></td><td colspan="2">Final check for downed wood prior to rains</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Ongoing: Maintain flow control devices</td><td colspan="3">Monitor levels to support drying of maintenance road</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Ongoing: Monitor for new dams</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Ongoing: Protect selected living trees from beaver damage by caging. Monitor existing cages to ensure adequate space around trunk is maintained.</td><td></td><td></td><td></td><td></td><td colspan="2">Plant native trees for habitat and shading of Ludwigia</td></tr>
</table>

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Appendix A:
Fryer Creek Beaver Impact Analysis
Hydrology and Hydraulics Technical Memo

MEMO

Date: May 28, 2021, revised June 15, 2021

To: Dave Cook (Sonoma Water)

From: Brian Schlosstein, E.I.T; Luke Walton, P.E.

Subject: Fryer Creek Beaver Impact Analysis Hydrology and Hydraulics Technical Memo

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1 Introduction

Prunuske Chatham, Inc. (PCI) performed a hydrology and hydraulic analysis to assess the impact that recently built beaver dams have on flood conditions in Fryer Creek near West MacArthur Street in Sonoma, California. This analysis is in support of Sonoma Water's Fryer Creek Beaver Impact Analysis and Alternatives Development Project (White, 2021). Currently, there are four beaver dams located within a channelized reach of Fryer Creek in the center of a highly developed area of Sonoma. Beavers began construction of the dams in 2019. The most recent dam was completed in February of 2021. This portion of Fryer Creek is owned by Sonoma Water and maintained for flood control. The main goals of this analysis are to:

- Assess the impacts of the four beaver dams on flood conveyance through the reach.
- Assess the flood conveyance impacts that additional beaver dams could potentially have in a "future conditions" scenario.
- Develop management alternatives that support beaver habitation in this reach of Fryer Creek while maintaining designed flood conveyance and maintenance access.

This technical appendix to the Fryer Creek Beaver Impact Analysis and Alternatives Development Report documents the hydraulic analysis conducted for the project, including model input data, model parameters, model runs, and model results. Findings from this hydraulic analysis are discussed in the Fryer Creek Beaver Impact Analysis and Alternatives Development Report.

2 Hydraulic Analysis Methods

A two-dimensional (2D) hydraulic model was developed for the open channel reach of Fryer Creek near West MacArthur Street. The model domain includes the West Fork of Fryer Creek from the 4th St. W. storm drain outlet, to approximately 1400-feet downstream of the West MacArthur St. crossing; and upstream along the East Fork of Fryer Creek to the 2nd St. crossing (**Figure 1**). The modeling analysis was performed using the US Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS), version 6.0.0 Beta2, 2D hydraulic modeling software (USACE, 2020). Components of the hydraulic analysis model development are described below.

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Stormdrain outlet
4th St W
West Fork Fryer Creek
3rd St W
Bettencourt St
Culvert outlet
2nd St W
Arroyo Way
Arroyo Way Culvert
Fryer Creek
Nicoli Ln
East Fork
Pedestrian Path Culvert
Beaver Dam #1
Beaver Dam #2
Beaver Dam #3
Beaver Dam #4
West MacArthur St
MacArthur St Culvert
Main Fork Fryer Creek
Amedeo Ct
Manor Dr
Hydraulic Model Extents
FLOW
0
60
120
240
N

2.2 Model Input Data

Data used for the hydraulic model were obtained through a variety of methods and sources. These are described below.

2.2.1 Terrain

The base terrain used in the hydraulic model was based on 2013 LiDAR data from the Sonoma County Vegetation and Habitat Mapping Program (Veg Map, 2020). Supplemental surveys by PCI were conducted in February of 2021 to capture the beaver dam topography as well as other differences that were not reflected in the LiDAR data. Points surveyed include channel toes and breaklines below the water surface, culvert geometry, and beaver dam geometry. Culvert geometry was surveyed at W. MacArthur St., Arroyo Way, and under the pedestrian path at the confluence of the East and main Fryer Creeks.

2.2.2 Stream Crossings

The model was built with 3 box culverts to represent the crossings at: West MacArthur Street., Arroyo Way, and the pedestrian path at the confluence of the East and West Forks of Fryer Creek. Geometry data for the culverts at W. MacArthur St., and the pedestrian crossing were provided by Sonoma Water from the City of Sonoma's Storm Drain Master Plan (SDMP) (Winzler & Kelly, 2011). The data for the culvert under Arroyo Way was gathered by PCI during the topographical survey of the channel (Table 1.)

Table 1. Box Culvert parameters

Location	Length (ft)	Span (ft)	Rise (ft)
MacArthur	54	12.5	5.5
Arroyo	50.2	8.7	6.9
Pedestrian Path*	26.1	8	4.1

* A double box culvert. Both barrels equal.

The LiDAR based channel terrain around the inlet and outlet of the pedestrian path was slightly higher than the surveyed culvert inverts. Occurrences where adjacent terrain is higher than a culvert invert often result in runtime errors in the HEC-RAS model. In order to avoid these runtime errors, the terrain around the inlet and outlet of the pedestrian path was adjusted to be lower than the surveyed culvert inverts (Figure 2). This is not expected to affect the modelling results.

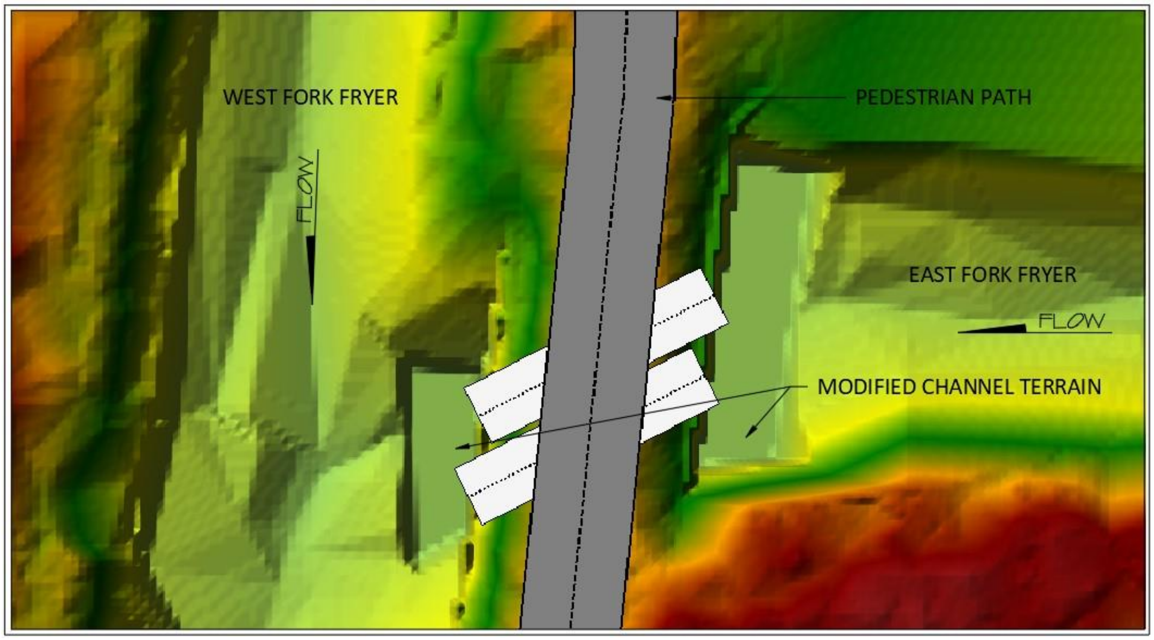

Figure 2. Channel terrain modified to fix culvert invert runtime error.

2.2.3 Boundary Conditions and Peak Flow Hydrographs

Boundary conditions represent locations in the model where water flows into or out of the region being modelled. For this study, upstream boundary conditions are required to define inflow from both East Fork Fryer Creek and West Fork Fryer Creek (**Figure 3**). A normal depth boundary condition was used at all downstream boundaries to simulate water free flowing out of the model domain (**Figure 3**).

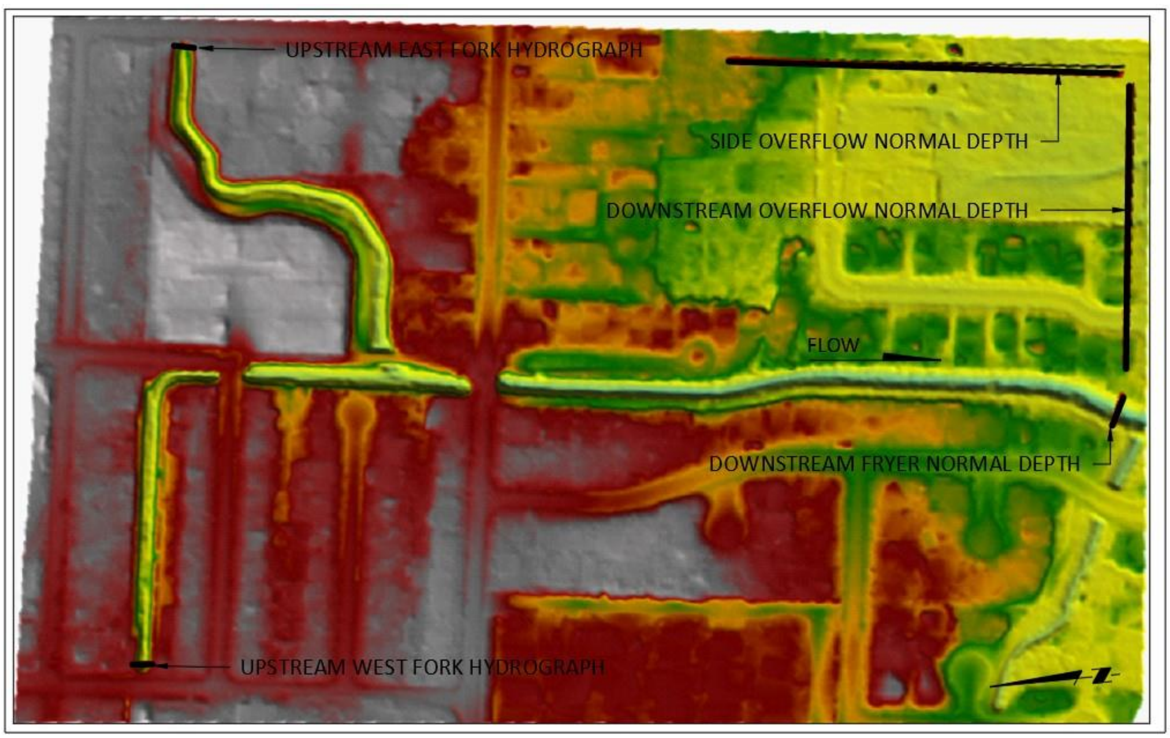

Figure 3. Hydraulic model terrain and inflow and outflow boundaries indicated by black lines.

Design storm hydrographs for West and East Fork Fryer Creek were provided by Sonoma Water, at the 2nd St. W. culvert crossing (East Fork) and at the Arroyo Way crossing. The hydrograph for the Arroyo Way crossing was used as the West Fork input hydrograph at the 4th St. W. storm drain outlet. The peak of each design storm hydrograph was used in the analysis to reference flows during a given return interval event (**Table 2**).

Table 2. Peak flow hydrology for Fryer Creek at the upstream boundaries and downstream of the confluence.

Return Interval	Peak Flow (cfs)		
	West Fork Fryer Creek	East Fork Fryer Creek	Downstream of Confluence
2-year	163	123	265
25-year	287	292	538
100-year	377	324	636

Note that these flows were extracted from City Watersheds modeling Sonoma Water conducted in years following the SDMP. Values may differ slightly compared to SDMP values due to model version updates.

2.2.4 Roughness

Hydraulic roughness (Manning's n) values and areas were generally set to match those from the City's SDMP (**Table 3**). Roughness values for RCP, Concrete Trench Drain, and Concrete Swale were excluded as these surfaces were not present within the HEC-RAS model domain.

Table 3. Manning's n values used for analysis (Winzler & Kelly, 2011).

Type of Channel and Description	n
RCP	0.014
Concrete Trench Drain	0.014
Concrete Swale	0.015
Earth: Short grass, few weeds	0.035
Earth: Light brush on banks	0.05
Earth: Dense weeds	0.08
Natural Channel	0.07

2.3 Model Parameters

The HEC-RAS model was run using the Shallow Water Equations (full Saint Venant equations), as this method is generally assumed to be more accurate and produces better results in areas with abrupt contractions and expansions as occur around the beaver dams (USACE, 2020). For grid spacing, a base grid with 30'x30' cells was used throughout the extent of the model. Refinements were made to this base grid in areas with more topographic relief to accurately represent the existing ground surface or to align cell faces perpendicular to flow. Active channel areas were refined to have 5'x5' cells. Breaklines with 2-foot cell spacing were used at the beaver dams to align cell faces with high points and to prevent flow from falsely "leaking" through elevated ridges (**Table 4**).

Table 4. Summary of 2D grid cell spacing.

Region	Cell Spacing (ft)
Channel	5
Overbank	30
Dams	2

An initial modelling time step of 1 second was chosen with the adaptive time step option selected to adjust the value based on maintaining a Courant number of less than or equal to 1 as determined by the Courant-Friedrich-Lewy condition:

$$C = \frac{V * \Delta T}{\Delta X} \leq 1.0\ (with\ a \max C = 3.0)$$

Where:

C = Courant number
V = Velocity of the flood wave (feet/second)
ΔT = Computational time step (second)
ΔX = The average cell size (feet)

2.4 Model Runs

Three different beaver dam scenarios were modelled:

1. Without Dam Conditions
2. Current Dam Condition
3. Potential Future Dam Condition

Additionally three management alternatives were developed and modeled:

1. Alternative 1a: Beaver Dam Increase by 1.5 feet
2. Alternative 1b: Beaver Dam Increase by 3.0 feet
3. Increase roughness (Manning's n) due to established wetland vegetation

2.4.1 Without Dam Condition

The "Without Dam" condition model was run with the terrain representing the channel prior to the established beaver dams. The surface includes the surveyed channel and culvert data surrounded by LiDAR data, minus the beaver dams. This scenario was run to establish baseline flow conditions for the project site without any impact from the beaver dams.

2.4.2 Current Dam Condition

The "Current Dam" condition model was run with the terrain representing the current state, with the two beaver dams in the East Fork and two in the channel downstream of the confluence but upstream of MacAurther St. The terrain includes the same terrain as the Without Dam condition, but with the surveyed dams pasted into the channel. This scenario was modeled to assess the impacts of the newly established beaver dams on flooding and represents the existing conditions at the time of this report.

2.4.3 Potential Future Dam Condition

The potential "Future Dam" condition model was constructed with the current condition terrain as a base, but with four additional "future" dams located downstream of MacArthur St. This simulation was run to examine the potential impact on flooding if beavers continued to build additional dams on Fryer Creek. The OAEC and Swift Water Design were consulted to determine the locations and elevations of the potential future dams. Four dams were pasted over the current conditions terrain at riffle crests downstream of MacArthur Street. The elevation of the dam crests were set to match the slope of the water surface profiles in the current condition model results (**Figure 4**).

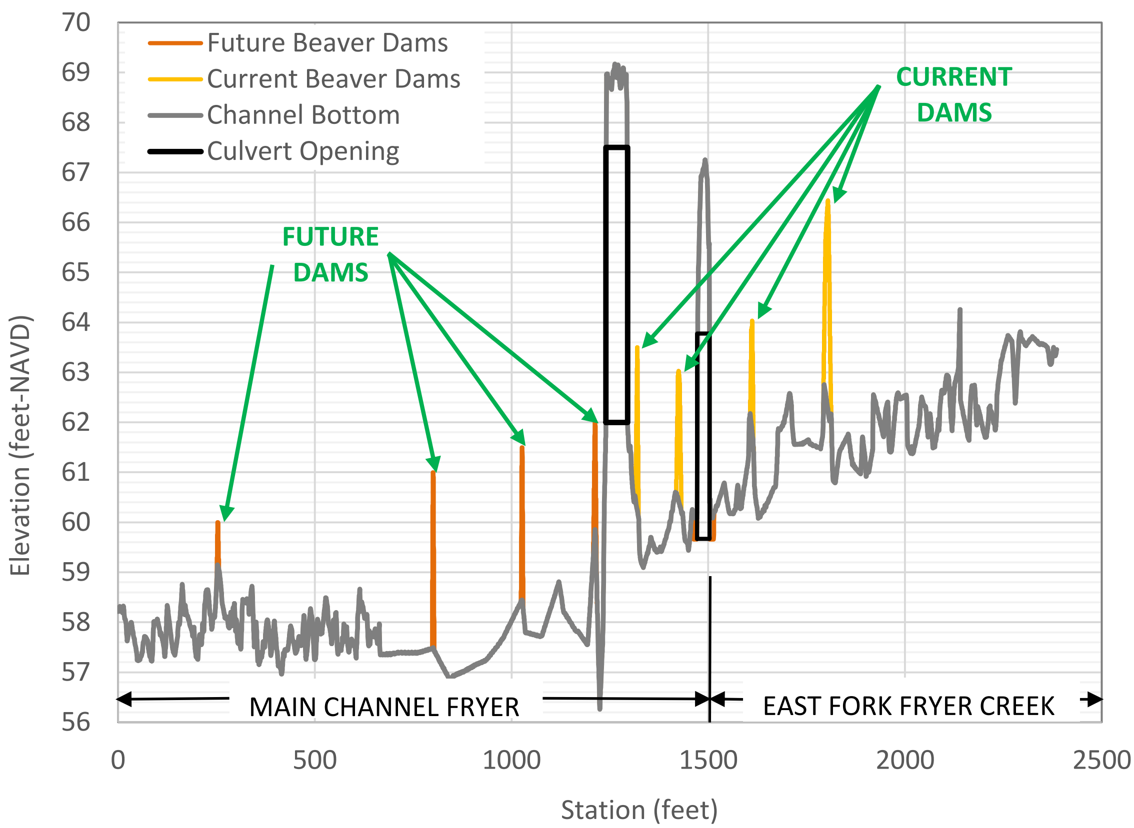

Figure 4. Main and East Fork of Fryer Creek with Potential Future Beaver Dam locations.

2.4.4 Beaver Management Alternatives

Three beaver management alternatives were explored, developed, and modeled. Two different scenarios were considered in regards to how Sonoma Water might manage beaver in Fryer Creek. The first scenario that was explored is the potential for beavers to increase the height of the dams. For this scenario two alternatives were modeled: Alternative 1a, Beaver Dam Height Increased by 1.5 feet; and Alternative 1b, Beaver Dam Height Increased by 3.0 feet. The second scenario explored is the potential for wetland vegetation (i.e. cattails) establishment in the channel. A third alternative for this scenario was modeled with a high Manning's n roughness value. For each of the three beaver management alternatives, only the 25-year design flow hydrograph was run.

2.4.4.1 Alternatives 1a and 1b: Increased Dam Height Conditions

This alternative looks at the impact on maximum water surface elevations if the beavers were allowed to build their dams higher. Two alternatives, Alt. 1a and 1b were modeled: an increase of 1.5 and 3 feet, respectively, of Dams 3 and 7. A dam was selected downstream and upstream of W. MacArthur St. because the two reaches appear to be hydraulically disconnected due to the backwater effect of the W. MacArthur St. culvert. Dams 3 and 7 were chosen from these to separate reaches because they appear to have the highest impact on the water surface profile in Current and Future Condition model runs. These “Increased Dam Height” condition models were constructed with the “Future Dam” condition model as a base. (**Figure 5**).

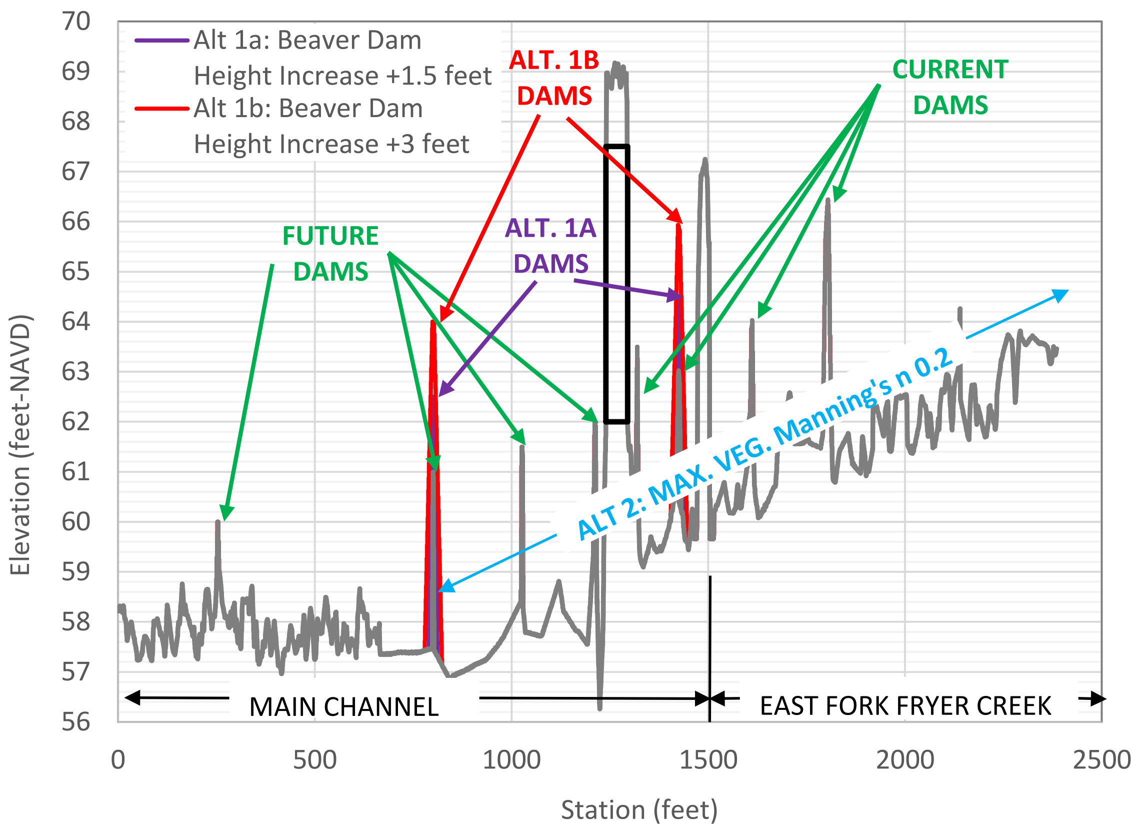

Figure 5. Main and East Fork of Fryer Creek Alternatives 1a and 1b, increased dam heights of 1.5 and 3 feet, and Alternative 2, max. veg. Manning’s n of 0.2.

2.4.4.2 Alternative 2: Maximum Channel Vegetation Roughness Condition

The “Maximum Channel Vegetation Roughness” condition model simulates the effects on the flow in the event that the vegetation upstream of the existing and future dams is allowed to grow in the active channel upstream to its maximum potential. Cattails were assumed for their ability to completely fill the channel and grow above the surrounding development. Research by the USACE Wetland Research Program found that cattail roughness was observed to be about 0.18, and calculated to be 0.27 at the highest recorded velocities (Hall and Freeman, 1994). To simulate the “Maximum Channel Vegetation Roughness” condition, the Manning’s n was set to 0.2 in the active channel up to the elevation of the top of the dams upstream of Future Dam #7 (approx. Station 800). The Future Conditions model terrain was used as the base.

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