Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning, Mill Creek Watershed, Sonoma County, CA

Prepared for:

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and

State of California, Wildlife Conservation Board
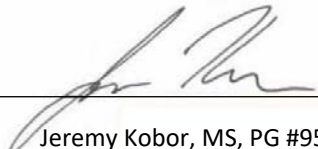1700 9th Street, 4th Floor, Sacramento, CA 95811

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Acknowledgements

Limitations

The descriptions of watershed and streamflow conditions described in this report are based on numerical model simulations which were developed using best available data and professional practices. Available model input data varied widely in its resolution and accuracy, and although the model was calibrated successfully to available streamflow and groundwater monitoring data, the extent of available calibration data is relatively limited. All model scenarios represent hypothetical actions on the landscape and do not imply any interest or commitment on the part of landowners to implement them. Both the existing condition and scenario results represent approximations of real-world conditions that contain uncertainty and should be interpreted as a guide for understanding watershed hydrology and the effects of potential management actions rather than as precise quantitative predictions of actual or future conditions.

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Executive Summary

Introduction

The Mill Creek watershed provides some of the best remaining habitat for coho salmon (*Oncorhynchus kisutch*) in the Russian River watershed, however several factors have been identified as limiting for coho survival including insufficient high quality pool habitat, winter refugia, and spring/summer baseflows. Numerous habitat restoration projects have been implemented in the watershed in recent years aimed primarily at improving pool habitat and removing passage barriers. Additional efforts have begun to address the problem of insufficient stream flow primarily through water storage and flow release projects. Successful efforts to improve streamflow requires greater understanding of the spatial and temporal distribution of flow and the various natural and man-made controls on these flows.

This project facilitates this improved understanding by developing and calibrating a distributed hydrologic model to describe existing conditions in the watershed relative to salmonid habitat requirements and to develop habitat restoration priorities for the watershed. The model also serves as a decision support tool for watershed restoration efforts by evaluating the effectiveness of various potential streamflow improvement strategies and quantifying the expected changes in hydrologic conditions due to ongoing global climate change. The project was completed by O'Connor Environmental, Inc. under the direction of the Coast Range Watershed Institute in cooperation with the Sonoma Resource Conservation District and Trout Unlimited. Funding for the project was provided by a Proposition 1 Streamflow Enhancement Program grant from the California Wildlife Conservation Board.

Methodology

The project synthesized a large volume of data from various sources describing the climate, topography, land cover, soils, geology, hydrology, and water use characteristics of the Mill Creek watershed to develop a physically-based distributed hydrologic model. The model simulates all the land-based phases of the hydrologic cycle including overland flow, channel flow, evapotranspiration, unsaturated flow, saturated flow, stream/aquifer interactions, stream diversions, groundwater pumping, and irrigation using sub-daily timesteps over a 10-yr simulation period from water year 2010 to 2019. This model was calibrated to streamflow gauging data, wet/dry channel mapping data, and groundwater elevation monitoring data to ensure it adequately represents real-world hydrologic conditions.

The spatial and temporal variations in simulated streamflow conditions were related to salmonid habitat requirements to identify the reaches providing the best overall flow-related habitat conditions and prioritize reaches for habitat enhancement. This identification was also informed by previous classifications of winter rearing habitat conditions and fisheries monitoring data describing which portions of the watershed are utilized by salmonids for spawning and summer rearing. A series of "what if" scenarios were tested to identify the most effective strategies for enhancing streamflows including changes in water use, large-scale land management actions (including forest, runoff, and grassland management), and direct flow augmentation efforts

including pond and recycled water releases. Regional projections of future climate were also used to drive simulations of future conditions and place flow and habitat enhancement efforts within the context of ongoing climate change.

Existing Habitat Conditions & Restoration Prioritization

Habitat classification for smolt outmigration and summer rearing life stages of juvenile coho salmon based on model simulations of stream flow indicate that all stream reaches are impaired to varying degrees. The timing of flow conditions allowing downstream passage for outmigrating smolts is of particular importance in the lower alluvial reach of Mill Creek which is the critical portion of the route for smolts leading to Dry Creek, the Russian River, and the Pacific Ocean. Model simulations indicate that impassable flow conditions develop earliest at and above the confluence of Mill Creek and Dry Creek and that during dry years such as 2014 and 2015, impassable conditions developed in this reach as early as late April, just prior to the typical primary pulse of outmigrating salmonids (Figure E1). Summer flows were also found to be limiting for juvenile coho survival with some reaches experiencing complete disconnection of surface flow (particularly during drought conditions) and other reaches retaining small but consistent streamflow throughout the dry season (Figure E2).
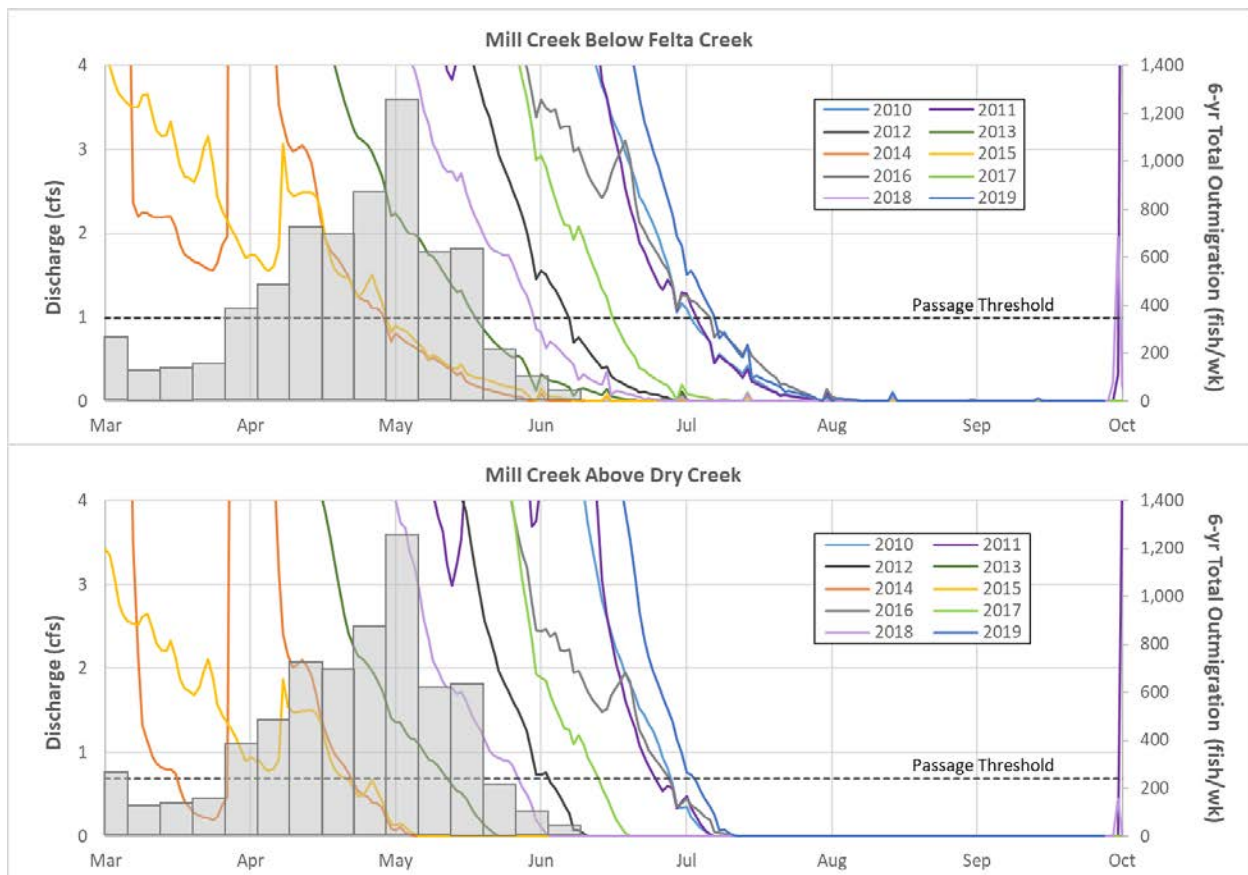
Figure E1: Streamflow hydrographs for the upper and lower portions of the alluvial reach of Mill Creek relative to the timing of outmigrating smolts as documented by California Sea Grant for 2014-2019.
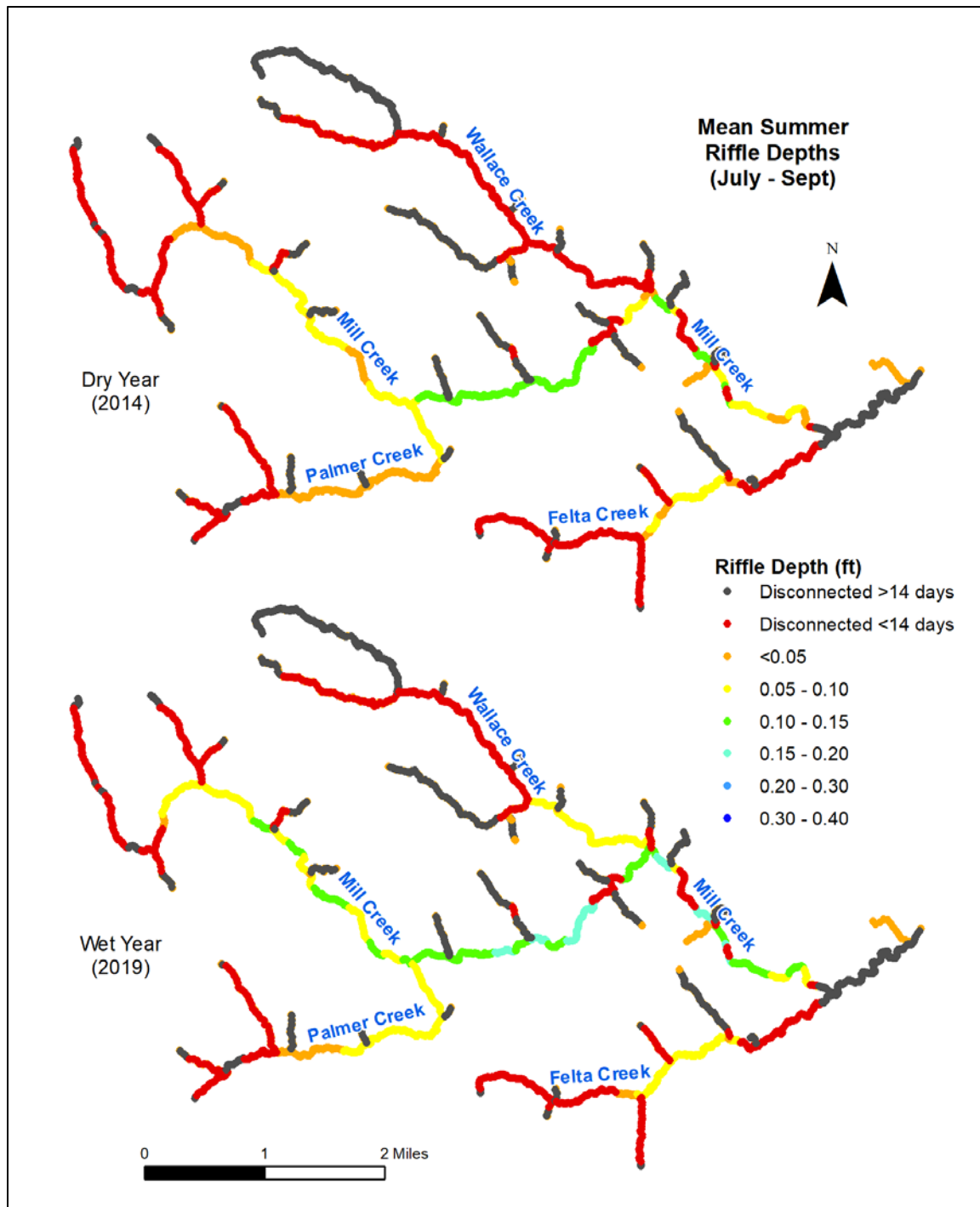
Figure E2: Mean summer (July - Sept) riffle depths and extent of flow disconnection for dry and wet water year conditions simulated with the Mill Creek hydrologic model.

The 2.1-mile reach of Mill Creek extending from the Palmer Creek confluence downstream to one mile above the Wallace Creek confluence (Mill 3) provides the best overall habitat conditions for salmonids in the watershed across a wide range of flow conditions and has relatively frequent

utilization by coho for both summer rearing and spawning (Figure E3). The 2.3-mile reach upstream (Mill 2) and 3.2-mile reach downstream (Mill 4) are the next most suitable reaches for coho, however outmigration flows fall to impassable levels several weeks earlier in Mill 2 and periodic disconnection of streamflow occurs in Mill 4. Other portions of the watershed including the lower alluvial reach of Mill Creek, Wallace Creek, and Felta Creek experience frequent and prolonged disconnection of surface flow and are therefore not considered to be suitable for supporting over-summer survival of juvenile coho. We recommend that habitat enhancement efforts, including large wood placement and off-channel habitat enhancement, be prioritized in reaches Mill 2 through Mill 4 where they have the greatest likelihood of providing meaningful benefits for salmonids.
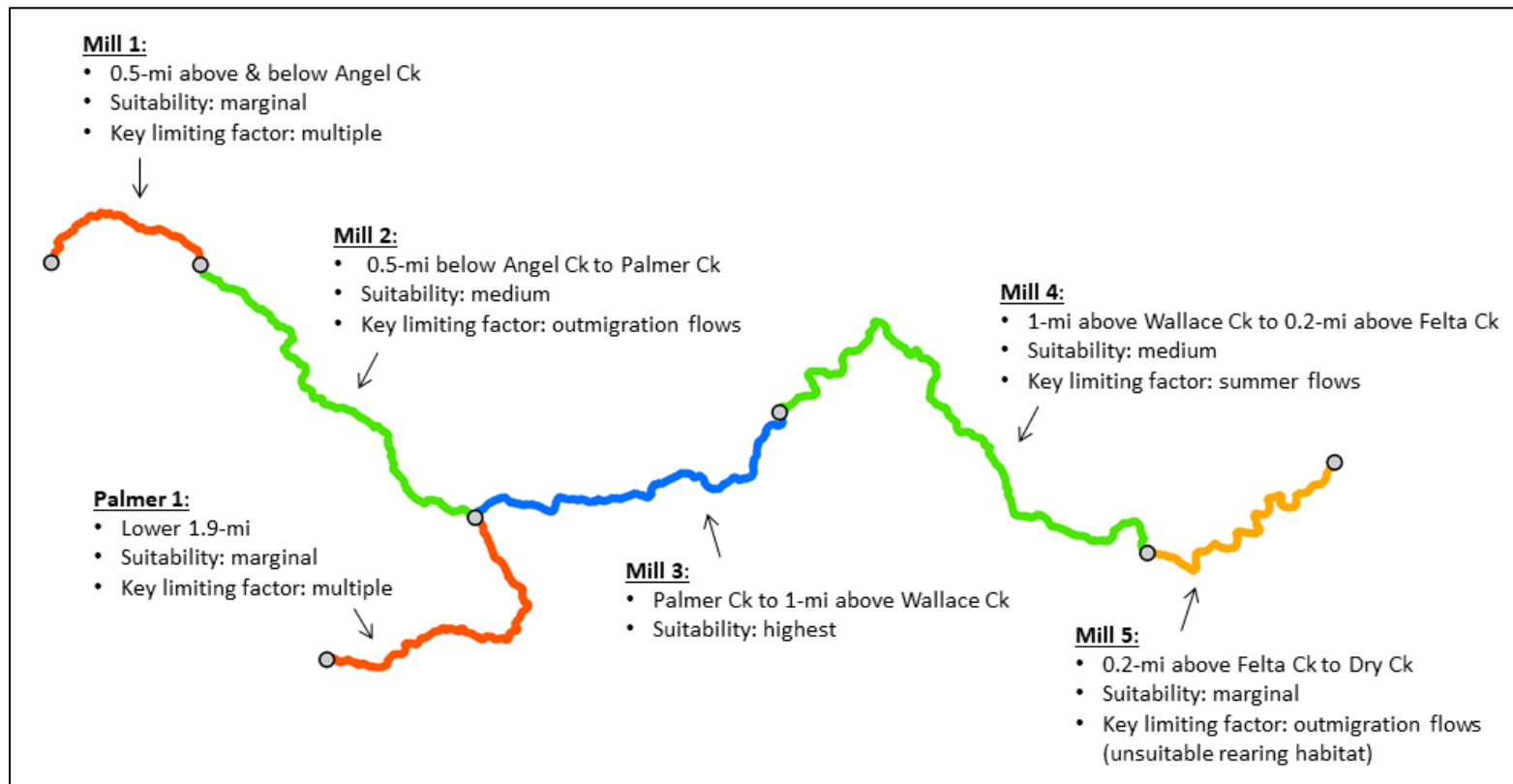
Figure E3: Final reach classification for the Mill Creek watershed (reaches not shown are considered unsuitable/very low priority for habitat enhancement).

Coho attempt to spawn and rear in Felta Creek in most years, however this activity is confined to the lower alluvial reach where summer survival is expected to be minimal. The pattern of coho utilization suggests that the dam site located near the upstream limit of utilization is blocking access to perennially flowing reaches farther upstream. If passage to upstream reaches is restored, the perennially flowing reaches of Felta Creek would become candidates for habitat enhancement work, however the reaches would be considered lower priority than the identified reaches of main-stem Mill Creek due to the degree of flow impairment. Given that a single localized project at the dam site could dramatically improve access for salmonids attempting to spawn and rear in Felta Creek in most years, we believe remediation is warranted despite the marginal quality of the upstream habitat.

Flow Enhancement Recommendations

Of the seven primary streamflow enhancement strategies investigated, release of water from existing ponds is by far the most effective strategy for enhancing summer streamflow. This strategy could potentially increase mean summer streamflows by about 43% and eliminate periodic flow disconnection within the highest priority reaches (Figure E4). Large-scale implementation of forest management focused on reducing evapotranspiration demands (thought to be consistent with fuel management to reduce wildfire hazards) and runoff management focused on maximizing infiltration from impervious areas was also found to result in substantial summer flow improvements on the order of 17% and 14% respectively (Figure E4).
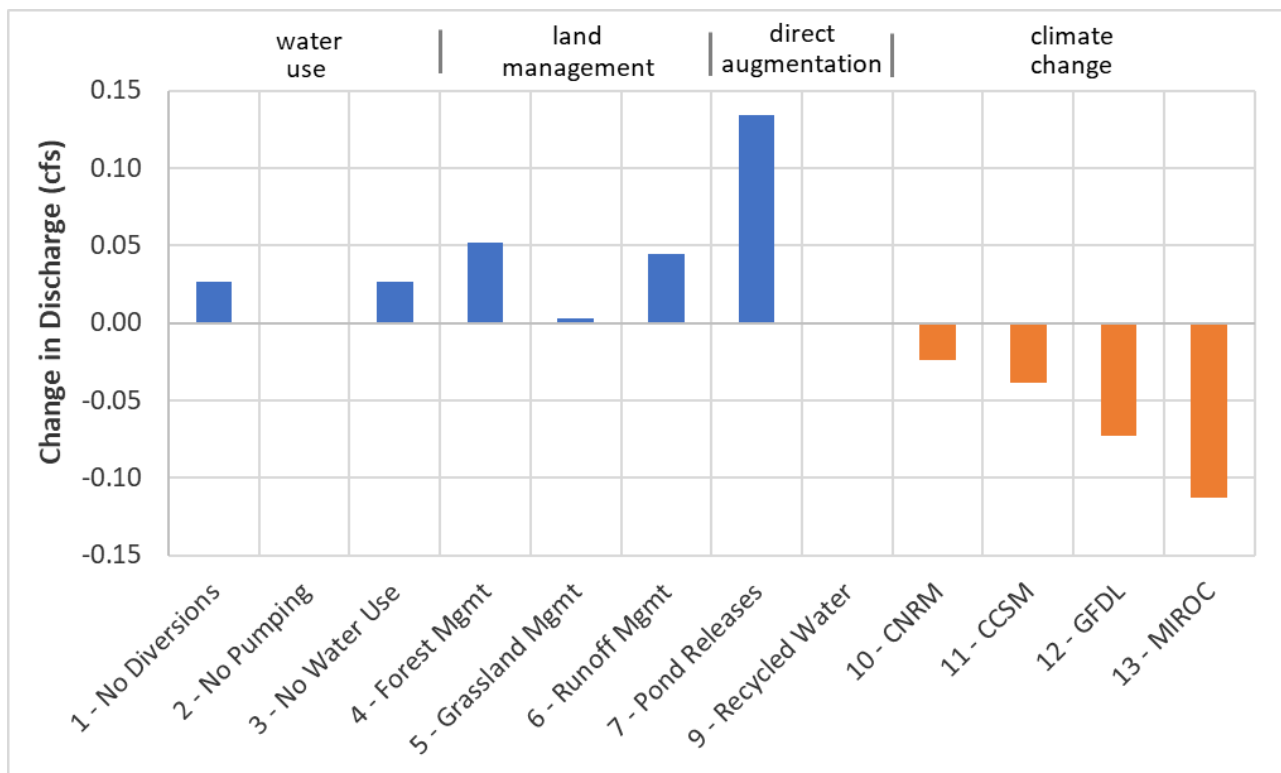
Figure E4: Summary of the simulated changes in mean summer streamflow for the flow enhancement (Scenarios 1-7 & 9) and climate change (Scenarios 10-13) scenarios simulated with the Mill Creek hydrologic model.

Replacement of summer stream diversions with alternative water sources such as bedrock groundwater wells or winter diversion and storage infrastructure also has potential to enhance summer flows. Potential for sustained summer flow enhancement from diversion cessation may only be on the order of 8%, however model simulations indicate that instantaneous diversion demands represent as much as 100% of the available flow in portions of the highest priority reaches and that diversion replacement may reduce or eliminate periodic flow disconnection in this reach. Increasing moisture holding capacity of soils through grassland compost treatment also provided minor benefits. Summer streamflow benefits of reducing groundwater pumping or releasing recycled water in the lower alluvial reach were found to be minimal (Figure E4).

Only three strategies were found to provide meaningful flow enhancement during the smolt outmigration season in late spring. Pond releases were the most effective strategy with potential to extend the duration of passable flow conditions in the most-limiting reach upstream of the Dry Creek confluence by up to 32 days during drought conditions similar to 2014 (Figure E5). The effectiveness of springtime pond releases increased substantially when initiated prior to development of impassable conditions and when release rates were ramped up over time to extend the natural flow recession as opposed to using constant release rates. An alternative release strategy using discrete pulsed flow releases to extend the overall timeframe of passable conditions compared to continuous releases was also found to be effective; however,
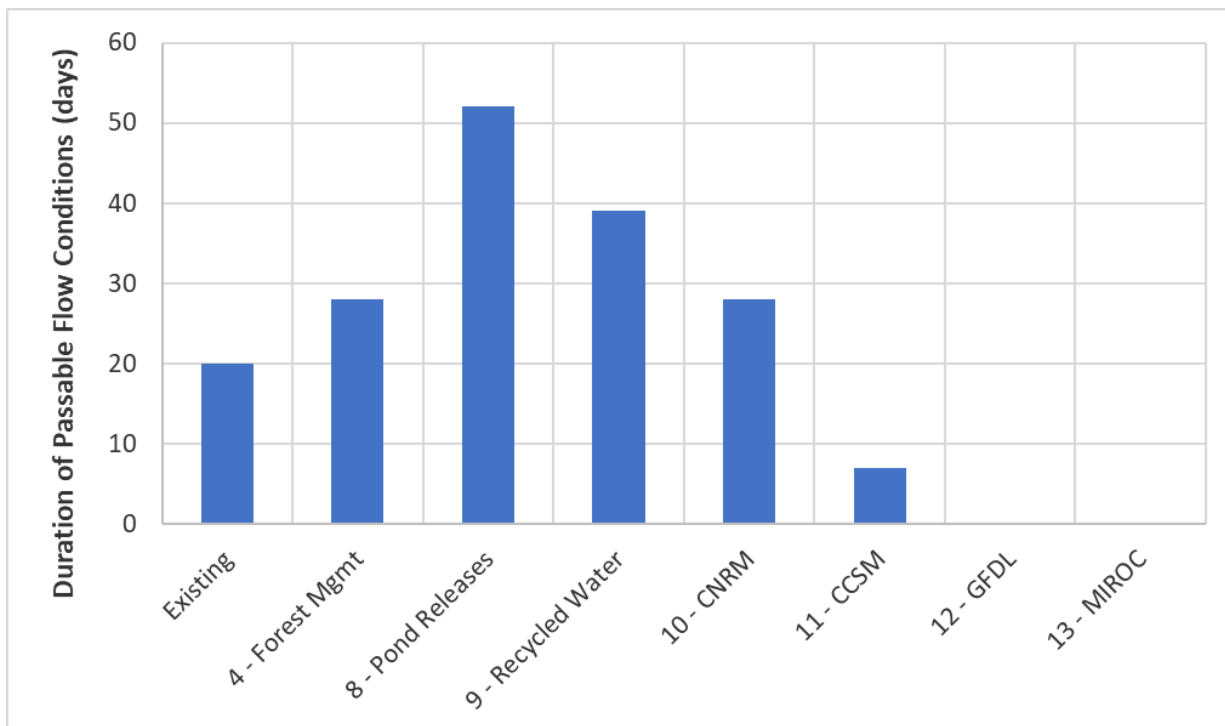
Figure E5: Duration of passable flow conditions in the lower alluvial reach of Mill Creek over the primary smolt outmigration period during dry water years for existing conditions, the three enhancement strategies that affected this metric (Scenarios 4, 8, & 9) and the four climate futures (Scenarios 10-13).

successively larger volumes of water and higher release rates are required to achieve passable conditions in the lower alluvial reach as the spring progresses (Figure E6). The sensitivity of release effectiveness to the timing and rates of release indicate that an adaptive management approach coupled with real-time monitoring data and hydrologic analysis is warranted to ensure optimal benefits for salmonids are provided with the finite volumes available for release.
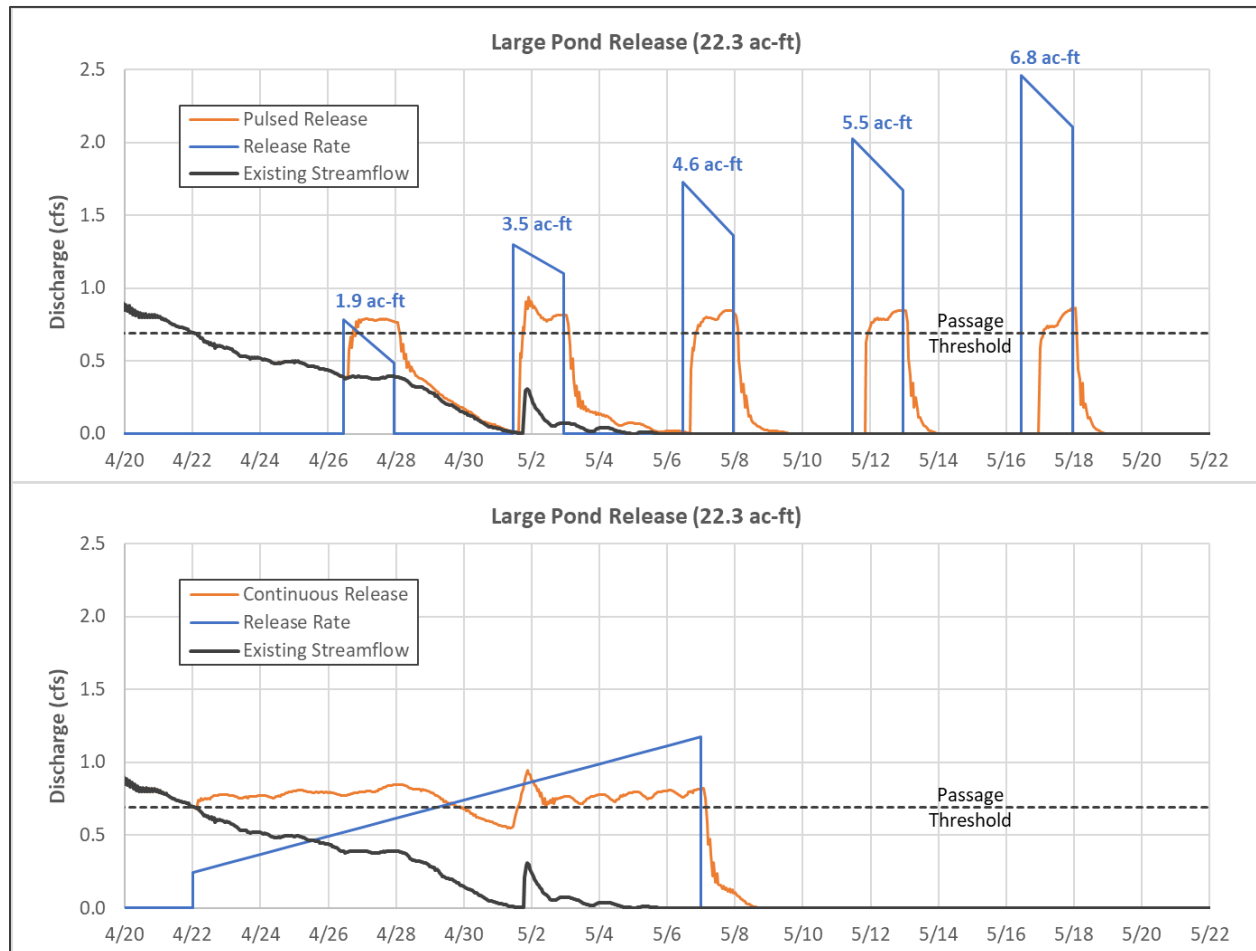
Figure E6: Simulated flow in Mill Creek above Dry Creek resulting from a large single pond release scenario with early-season continuous releases (bottom) and five pulsed releases (top); also shown are the release rates and the total volume of storage represented by each of the five pulsed releases.

Injection or infiltration of recycled water from the City of Healdsburg's treatment plant into the upstream portions of the alluvial aquifer (Figure E7) was also found to be effective at enhancing outmigration conditions with potential to extend the timeframe of passable conditions in the lower alluvial reach by up to 19 days (Figure E5). This strategy was not effective if the water was released into the thicker downstream portions of the alluvial aquifer or if releases began after impassable conditions had already developed. Although this strategy may face substantial cost and permitting hurdles, it likely has other benefits over pond releases in terms of temperature

control and supply reliability and we recommend a feasibility study be conducted to advance this strategy towards design and implementation.

Forest management was the only strategy capable of meaningfully enhancing springtime flow conditions throughout the watershed, not just in the lower alluvial reach. Extension of the duration of passable conditions in the lower alluvial reach was modest compared to other strategies, providing only eight additional days of passable flow (Figure E5). The various land management strategies also have important secondary hydrologic benefits. In addition to enhancing streamflows, these strategies reduce seasonal vegetation moisture stress which may reduce fire hazard. Specifically, climatic water deficits are reduced by forest management through reduced evapotranspiration demands and by runoff management through increased soil moisture availability. These benefits are in addition to the primary non-hydrologic benefits of these types of projects for reducing fuel loads (forest management) and sequestering carbon (grassland management). As forest management for wildfire hazard reduction and post-fire salvage efforts are contemplated and implemented, it is imperative that flow enhancement benefits be considered to maximize this effect where it is most beneficial for salmonids and to ensure that management efforts do not inadvertently result in long-term changes towards forest conditions with higher evapotranspiration demands.
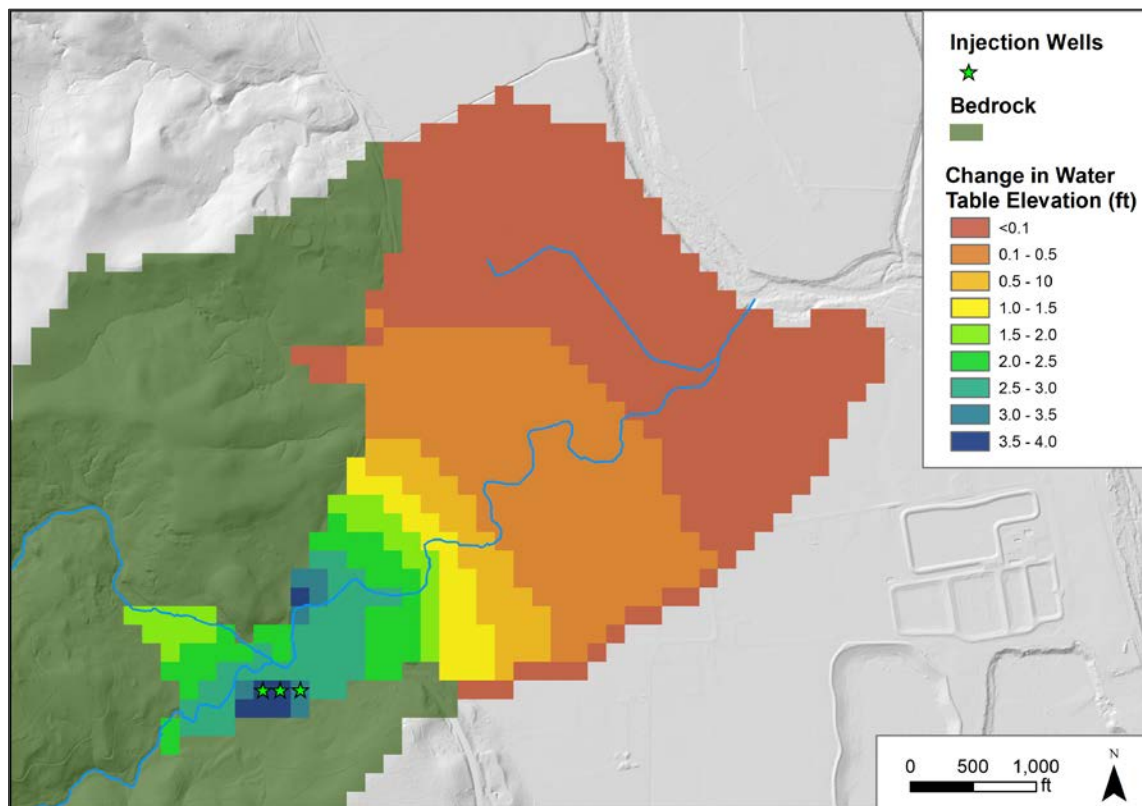
Figure E7: Change in June 1st water table elevations in the lower Mill Creek alluvial aquifer resulting from injection of recycled water (Scenario 9c).

Climate Change Impacts & Adaptation Strategies

Simulations of end-of-century (2070-2099) climate change generated a wide range of predictions with some scenarios indicating wetter overall conditions and others predicting a shift towards drier climate. All the scenarios, however, indicate an increase in the seasonality of precipitation with more rainfall occurring during the core winter months and less occurring during the spring and fall, and three of the four scenarios investigated indicate an increase in drought intensity. The changes in precipitation patterns, and to a lesser extent, the increases in evapotranspiration demands associated with warmer temperatures, result in declines in both spring and summer flows. Mean summer flows are predicted to decline by 8-36% and mean spring flows are predicted to decline by 16-57%.

The magnitude of predicted declines in summer streamflow compared to those of the more effective flow enhancement alternatives indicate that significant mitigation of climate change impacts is likely possible (Figure E4). Specifically, flow enhancement through pond releases appears large enough to completely offset future summer flow declines even in the most pessimistic climate futures, and forest and runoff management appear to be capable of offsetting most or all of the declines depending on which climate future is considered. The decrease in springtime flows likely poses the biggest threat to salmonids with two of the four scenarios indicating that during periods of drought, conditions in the lowest reach upstream of Dry Creek would be impassable for outmigrating smolts throughout the entire primary outmigration season (Figure E5). While it is not possible to completely offset the predicted declines in springtime flow, pond and/or recycled water releases can mitigate the effects of the declines on smolt outmigration by extending or generating periods of passable flow conditions timed to coincide with expected peak smolt outmigration.

Forest management is also an important adaptation strategy because it was the only strategy that resulted in meaningful changes in the overall water balance and increases in springtime flows throughout the watershed rather than just below flow release points (Figure E8). Climatic water deficits (CWD), which are an indicator of vegetation moisture stress and associated fire hazard, are predicted to increase under future climate. Forest management can significantly reduce CWD through reductions in evapotranspiration and runoff management can reduce CWD through increased soil moisture availability. Water temperatures are likely to increase over time and pond storage may pose temperature impairment problems if they are not carefully monitored and mitigated. Forest and runoff management strategies, on the other hand, influence the quantity of groundwater discharge through springs and baseflow which would generally be expected to help mitigate future temperature increases. Flow enhancement efforts should focus on the watershed areas contributing perennial baseflow to the high priority reaches including the watershed area of Mill Creek upstream of Felta Creek excluding the Wallace Creek drainage.
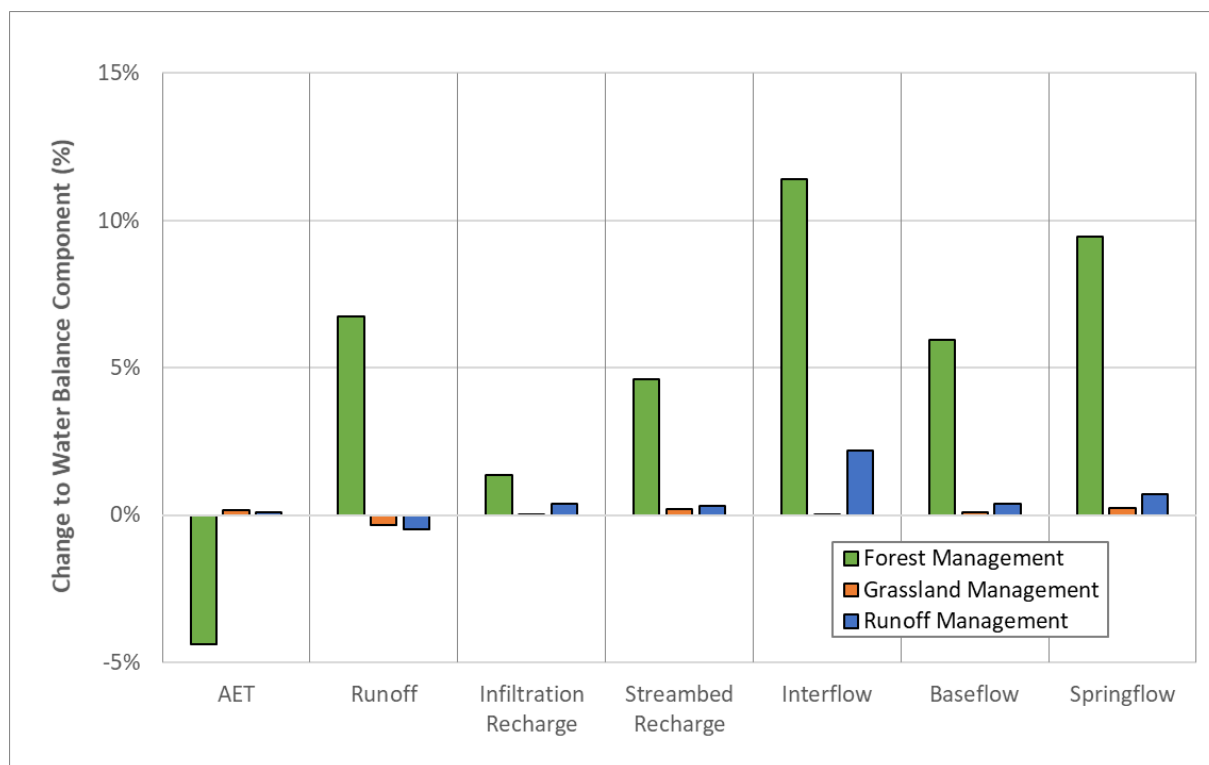
Figure E8: Percent change in select water balance components for the various land management scenarios, AET stands for Actual Evapotranspiration.

Summary of Key Findings & Recommendations

- Focus habitat enhancement work in the 7.6-mile reach of Mill Creek from 0.5 miles below the Angel Creek confluence to 0.2 miles above the Felta Creek confluence where flow conditions are most suitable for salmonids, with the highest priority being the 2.1 mile reach below the Palmer Creek confluence (see Figure E3).

- Enhancement work should focus on improving summer rearing pool habitat through addition of large wood and enhancing/creating off-channel winter rearing habitats where prior prioritization work has identified opportunities within the high priority reach.

- Low but consistent perennial flows persist in the upper portions of the high priority reach, however the lower 3.2 miles experiences periodic flow disconnection and is therefore more limiting with respect to juvenile rearing suitability; flow enhancement targeting this reach may provide outsized benefits for salmonids.

- Flows fall below passable levels for outmigrating smolts just prior to the typical peak of the spring outmigration during drought conditions which is an important limiting factor of equal or perhaps greater significance as low summer flows; efforts to improve smolt outmigration flows should target the lower alluvial reach of Mill Creek and in particular

the lowest reach above the Dry Creek confluence where earliest impassable flows develop.

- Pursue a fish passage improvement project at the dam site in lower Felta Creek which blocks passage to upstream reaches with more suitable flow conditions.

- Pursue opportunities for releasing water from existing and/or new ponds; this strategy has the greatest potential for enhancing both spring outmigration conditions for salmonid smolts and summer rearing conditions for juveniles.

- Develop an adaptive management strategy paired with real-time monitoring and hydrologic analyses to make the most effective use of finite pond storage available for release; ramping release rates and/or discrete pulsed releases have the potential to greatly increase benefits compared to constant releases if carefully timed and optimized.

- Pursue opportunities to replace direct summer stream and spring diversions with alternate water sources or winter diversion and storage; instantaneous diversion demands potentially equal or exceed available flows in portions of the highest priority reaches and coordinated diversion timing or demand reduction may reduce or elimination periodic disconnection of surface flows in some reaches.

- Perform a feasibility study for injecting or infiltrating recycled water from the City of Healdsburg's water treatment plant into the upstream portion of the lower alluvial aquifer which has the potential to extend the smolt outmigration season. Injection beginning too late in the spring or too far downstream is unlikely to be effective.

- Pursue opportunities for integrating forest management efforts focused on reducing wildfire hazard or post-fire salvage with flow enhancement goals; if forest management leads to future forest conditions with lower evapotranspiration characteristics, meaningful enhancement of both smolt outmigration and summer rearing flows is likely possible. It is likely that both reduced fire hazard and streamflow enhancement would persist only if vegetation management occurred on an on-going basis.

- Pursue opportunities to maximize runoff infiltration from developed and impervious areas in the watershed, including roads, focused on areas where runoff is currently being concentrated and discharged to streams. Many project types and scales are possible from downspout disconnects to routing pipes/ditches to swale galleries or infiltration basins.

- Focus forest and runoff management in watershed areas that contribute perennial flow to the highest priority reaches where it is most likely to provide benefits to salmonids which includes Mill Creek upstream of Felta Creek excluding the Wallace Creek drainage.

- Climate change is expected to reduce flows in both the spring and summer months with the greatest threat to salmonids posed by the potential for a complete loss of passable flow conditions during the primary smolt outmigration season in the lower alluvial reaches in dry water years.

- Implementing the more effective flow enhancement strategies can provide resiliency to climate change impacts by offsetting summer flow declines, providing periods of passable flow conditions for outmigrating smolts, and reducing climatic water deficits; the most successful climate change adaptation strategy would likely include a combination of flow releases, large-scale forest and runoff management, and diversion modification.

Chapter 1 – Introduction

The project described in this report was completed by O'Connor Environmental, Inc. (OEI) under the direction of the Coast Range Watershed Institute (CRWI) in cooperation with the Sonoma Resource Conservation District (SRCD) and Trout Unlimited (TU). The project was funded by a Proposition 1 Streamflow Enhancement Program grant (Grant Agreement No. WC-1659EH) from the California Wildlife Conservation Board (WCB).

The Mill Creek watershed has been identified by California Department of Fish & Wildlife (CDFW) and National Oceanic & Atmospheric Administration National Marine Fisheries Service (NMFS) as providing some of the best remaining habitat for coho salmon (*Oncorhynchus kisutch*) in the Russian River watershed. Several factors have been identified as limiting for coho survival in the watershed including lack of quality pool habitat, lack of winter refugia, and insufficient spring and summer baseflows (CDFG, 2004; NMFS, 2012). Numerous restoration projects have been implemented in the watershed in recent years aimed primarily at improving pool conditions and removing passage barriers. Additional efforts have begun to address the problem of insufficient stream flow primarily through water storage and flow release projects. Successful efforts to improve streamflow conditions will require greater understanding regarding the distribution of flow conditions and the various natural and man-made controls on these flows.

The combination of frequent drought conditions, ongoing and future climate change, and increasing human demand for water make development of strategies for sustaining or improving summer streamflow conditions of paramount importance for coho recovery in the Mill Creek watershed. The goal of this project was to conduct a comprehensive analysis of the spatial and temporal distribution of streamflow conditions throughout the watershed relative to coho habitat requirements to assist in prioritizing restoration efforts and developing strategies for protecting/enhancing spring outmigration flows and summer baseflows.

Specifically, this project involved the development, calibration, and application of a distributed hydrologic model (MIKE SHE) with inputs comprised of climate, topographic, land cover, soils, water use, and hydrogeologic data for the watershed. Model outputs include estimates of the annual and seasonal water balance, simulated stream flow hydrographs, and predicted groundwater elevations and flow gradients among many other hydrologic parameters. In conjunction with prior prioritization work and available fisheries monitoring data, the modeling results provided the basis for performing an analysis of streamflow, characterizing the distribution and quality of available habitat for juvenile coho, and making recommendations about restoration priorities for various sub-reaches within the study area.

Additionally, the model has been applied to evaluate potential improvements to streamflow and aquatic habitat conditions resulting from various streamflow restoration strategies including reusing recycled water for groundwater recharge and streamflow enhancement, adjustments to surface diversions and groundwater pumping regimes, and flow releases from existing ponds. The model was also used to investigate the effects of ongoing climate change on streamflow and habitat conditions. In addition to the findings and recommendations discussed in this report, the

model also provides a working Decision Support System for ongoing restoration efforts and land and water management decision making and should be considered a "living" model that can be updated as new data and information become available and utilized to help answer new management questions as they arise.

Chapter 2 – Study Area Description

Overview

The Mill Creek watershed is part of the Coast Range Geomorphic Province draining approximately 23 mi^2 of the lower Russian River watershed discharging to Dry Creek about 0.7 miles upstream of its confluence with the Russian River. Mill Creek watershed is commonly divided into an upper watershed draining upland terrain of the Coast Range and a lower watershed which flows over an alluvial fan as it enters the Dry Creek Valley. Neighboring watersheds include Pena Creek to the northwest, small tributaries of Dry Creek to the north and east, Porter Creek and adjacent small drainages to the south, and East Austin Creek to the west.

The study area covers the entirety of the Mill Creek watershed above its confluence with Dry Creek. An additional ~0.2 mi^2 area of the Dry Creek Valley was also included south of Mill Creek in the lower watershed where the watershed divide is in very close proximity to the stream (Figure 1). The upper Mill Creek watershed is characterized by relatively steep topography, confined channels, and bedrock geology. Elevations range from 78 feet above sea level near the Dry Creek confluence to over 1,900 feet along the ridge separating upper Mill and Felta Creeks from East Austin Creek. The study area includes 12 river miles of Mill Creek, several major tributaries such as Wallace, Palmer, and Felta Creeks as well as numerous smaller tributary streams.

Upper Mill Creek was severely affected by the August 2020 Wallbridge Fire which burned through approximately 58% of the study watershed (13.4 mi^2). Following the fire, forest management and fuel reduction have become a greater concern to many residents in the watershed. In addition to being identified in state and federal recovery plans as a high priority watershed for restoration of endangered coho, Mill Creek watershed is one of a handful of focus watersheds prioritized in two ongoing planning studies by CDFW (the North Coast Salmon Project) and the Sonoma Land Trust (the Russian River Subwatershed Conservation Assessment) and it has also been identified as a priority watershed in the Russian River Coho Water Resources Partnership's planning efforts.

Climate

The Mill Creek watershed has a Mediterranean climate characterized by cool wet winters and warm dry summers. Precipitation varies substantially across the study area from an average of approximately 42 inches per year in the Dry Creek Valley to approximately 64 inches per year along the western ridges (Flint & Flint, 2014). Daily temperature fluctuations increase with decreasing elevation with higher highs and lower lows amounting to about 6.3°F of additional daily variation in the winter and 8.5°F of additional variation in the summer in the Dry Creek

Valley relative to the ridges in the upper watershed (Flint & Flint, 2014). The temperature gradients also have a weaker south to north component with the Felta Creek watershed experiencing smaller temperature extremes than the Wallace Creek watershed.
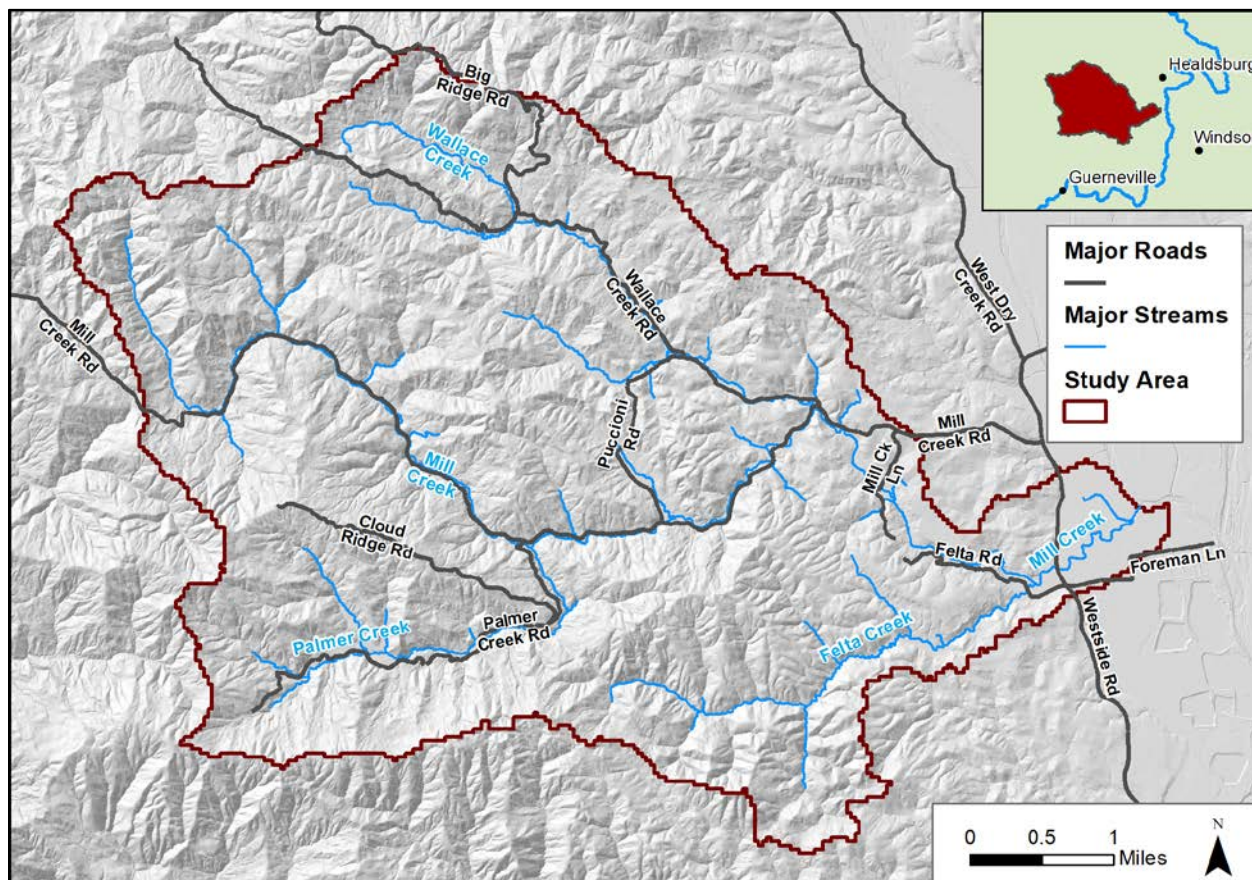
Figure 1: Map of the study area showing major roads and streams.

Land Use

The watershed was part of the Rancho Sotoyome Mexican land grant where livestock grazing and farming were introduced in the 1840s including the first orchards and vineyards. The watershed's namesake comes from the mill that was constructed in 1850, later moved downstream and then operated until 1881. A crushed stone quarry was developed in the early 1900s, and by the 1920s the settlement in Mill Creek was large enough to warrant a post office and a name, Venado. The surrounding area has emerged as a world class wine region, and today the lower watershed on the floor of Dry Creek Valley is comprised predominately of vineyards. The upper watershed has much more limited development due to the steep forested terrain and is comprised of private holdings with a mixture of land uses including rural residential, vineyards, timber production, vegetable and fruit production, livestock, and a few wineries.

Existing land cover is primarily forest (84%), with the remainder divided between grassland (10%), agriculture (4%), shrubland (1%), and developed (1%). The forested areas are comprised primarily of Coast Redwood (32%), various species of oak (24%) and Douglas Fir (20%) with significant stands of Madrone (12%), Tanoak (6%), and Bay Laurel (4%) comprising most of the remainder. Vegetation recovery and potential changes to vegetation patterns following the August 2020 Walbridge Fire which burned about 58% of the study watershed have not been well-quantified.

Geology

The majority of the upper watershed is comprised of Cretaceous and Jurassic-aged units of the Franciscan Complex. A northwest by southeast-trending fault separates units of the Coastal Belt Franciscan (which underlies most of the Mill Creek drainage upstream of Wallace Creek as well as the Palmer and Felta Creek drainages) from those of the Central Belt Franciscan (which underlies most of the Wallace Creek drainage and the Mill Creek drainage below Wallace). The early-Pleistocene and Pliocene-aged Glen Ellen Formation and basaltic units of the Pliocene and late-Miocene-aged Sonoma Volcanics outcrop in portions of the Mill Creek drainage below Wallace Creek and the lower Felta Creek drainage. The erosion-resistant character of the volcanics creates high-gradient reaches in Mill and Felta Creeks where the stream crosses these materials, including a series of cascades in lower Mill known as 'the falls'. The lower watershed is underlain by Quaternary alluvial fan and fluvial deposits which overlie Franciscan bedrock to depths ranging from less than 25 ft upstream of the Felta confluence to more than 300 ft near the Dry Creek confluence. The upstream portions of the deposits comprise an alluvial fan consisting of alternating layers of fine and coarse sediments. Farther downstream the watershed becomes part of the larger Dry Creek Valley and the deposits become more fluvial and uniformly coarse-grained in nature.

Aquatic Habitat

Coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) are present in Mill Creek and its tributaries. Other listed species are also present including the California freshwater shrimp (*Syncaris pacifica*) and the California red-legged frog (*Rana draytonii).* Coho from the Russian River Coho Salmon Captive Broodstock Program have been released in Mill Creek every year since 2004 and in Palmer Creek every year since 2005 (except 2015). Coho were also released in Angel Creek in 2011. CDFG habitat surveys in 1957, 1973, 1982, and 1995 found generally good spawning habitat, elevated water temperatures, inadequate pool frequency and shelter, insufficient summer baseflow, and a lack of large wood. The Mill Creek Watershed Management Plan was completed by the Sonoma RCD in 2015 (SRCD, 2015) and the Mill Creek Streamflow Improvement Plan was also completed in 2015 by the Russian River Coho Water Resources Partnership (RRCWRP, 2015). These studies recommended the removal of several passage barriers (the most significant of which was removed in 2016), installation of instream habitat structures designed to enhance pool habitat, and efforts to enhance stream flow by reducing direct diversions. Numerous large wood (and wood and rock) structures have been installed in Mill, Felta, and Palmer creeks. A 2012/2013 Large Wood Assessment found that some of the older structures are decaying, however many are still functional.

Chapter 3 – Numerical Modeling Methodology

The hydrologic model of the Mill Creek watershed was constructed using the MIKE SHE model (Graham & Butts, 2005; DHI, 2017). Model code development activities have been ongoing since its inception in 1977 and the model has been applied successfully to hundreds of research and consultancy projects covering a wide range of climatic and hydrologic regimes around the world (Graham & Butts, 2005).

The MIKE SHE model is a fully-distributed, physically-based model capable of simulating all the land-based phases of the hydrologic cycle including overland flow, channel flow, evapotranspiration, unsaturated flow, saturated flow, and stream/aquifer interactions. The distributed nature of the model makes it well-suited for examining the hydrologic impacts of changes in climate and water management. Complex physics-based watershed models, while powerful tools, require extensive input data and should ideally be well-calibrated to observed stream flow and groundwater data spanning a number of years. It is important to bear in mind that a model is a simplification of a complex and in some ways unknowable hydrologic system and although it can provide useful estimates of various flows and storages within the system, the estimates contain uncertainty and should not be viewed as a replacement for real data or as a static condition. Such models are best updated on a periodic basis as new data become available.

Overland Flow

The overland flow component of MIKE SHE solves the two-dimensional St. Venant equations for shallow free surface flows using the diffusive wave approximation. A finite-difference scheme is used to compute the fluxes of water between grid cells on a two-dimensional topographic surface. Net precipitation, evaporation, and infiltration are introduced as sources or sinks and the model assumes that a sheet flow approximation is valid for non-channelized surface flows and that roughness is uniform over various flow depths. The primary inputs of the overland flow module include topographic information in the form of a digital elevation model (DEM) and a corresponding spatial distribution of overland roughness coefficients (Manning's n) which is generally referenced to the model's land cover categories. Sub-grid-scale depressions in the topography and barriers to overland flow are represented conceptually through use of a detention storage parameter.

Channel Flow

The channel flow component of the model calculates unsteady water levels and discharges using an implicit finite-difference formulation to solve the one-dimensional St. Venant equations for open channel flow. The model is capable of simulating ephemeral stream conditions and backwater effects and includes formulations for a variety of hydraulic structure types including bridges, weirs, and culverts. Either a no-flow or a discharge boundary can be used as the upstream boundary condition, and the downstream boundary can be represented using a stage or stage discharge relation. Other than boundary conditions, the primary inputs for the channel flow model include channel geometry information and roughness coefficients for channelized flow (Manning's n).

Channel Flow Interactions

Interaction between the channel flow and overland flow components for the model is driven by the gradient between the overland water depths in a given grid cell and the head in a corresponding computational node in the channels and is computed using a broad crested weir equation. Depending on the direction of the gradient, the channel flow component of the model can either receive overland flow during runoff events or release water back into the floodplain as overland flow. The model is also capable of simulating backwater effects onto the overland flow plane due to restricted channel flow.

Evapotranspiration and Interception

Evapotranspiration (ET) is handled in the model using a two-layer water balance approach which divides the unsaturated zone into a root zone from which water can be transpired and a lower zone where it cannot. The model computes actual evapotranspiration (AET) as a function of potential evapotranspiration (PET) and the available water content in the vegetation canopy, overland flow plane, and the unsaturated zone. The model first extracts water from interception storage which is based on vegetation properties including leaf area index (LAI) and an interception storage coefficient. Next, water is extracted from ponded water on the land surface and, finally, from within the unsaturated zone or, if the rooting depth exceeds the depth to water for a given timestep, the saturated zone. PET can be adjusted for each land cover category in the model through use of a crop coefficient (Kc). The simulated position of the water table along with the specified rooting depth determines the thickness of the zone of transpiration.

Unsaturated Flow

The unsaturated flow component of MIKE SHE functions with the two-layer water balance method described above. The method considers average conditions in the unsaturated zone and tracks available soil moisture to regulate ET and groundwater recharge using a one-dimensional (vertical) formulation. A soil map Is used to distribute the primary soil properties used to drive the model, including saturated hydraulic conductivity (K_{sat}) and moisture contents (Θ) at saturation, field capacity, and wilting point. The unsaturated flow component of the model interacts with the overland flow component by serving as a sink term (infiltration) and with the groundwater flow component by serving as a source term (recharge).

The unsaturated zone component of the model does not explicitly represent lateral movement through and discharge from the unsaturated zone commonly referred to as interflow. In the Mill Creek watershed, interflow occurring at or near the contact between soils and underlying bedrock is expected to be an important process. Because interflow is often associated with a temporary increase in groundwater elevations during and following precipitation events, interflow processes can be approximated in MIKE SHE with a saturated zone drainage function.

Saturated Flow

The groundwater component of the model solves the three-dimensional Darcy equation for flow through saturated porous media using an implicit finite difference numerical scheme solved using the preconditioned conjugate gradient (PCG) technique which is nearly identical to that used in MODFLOW, a widely used U.S. Geological Survey groundwater model. The primary inputs to the

model are horizontal and vertical hydraulic conductivity, specific yield, storage coefficients, and the upper and lower elevation of each layer(s) considered in the model. External boundary conditions can be no-flow, head, or gradient boundaries and pumping wells can be added as internal sinks. The lower boundary of the model is zero-flux or a specified flux-boundary, and the upper boundary condition is a flux term calculated by the unsaturated flow component of the model (recharge). If the water table reaches land surface, the unsaturated flow calculations are disabled and the groundwater component of the model interacts directly with the overland flow plane.

Chapter 4 – Model Construction

Model Overview

The Mill Creek hydrologic model domain is defined as the entire Mill Creek watershed upstream of the Dry Creek confluence plus an additional 0.2 mi^2 area south of the creek in the lower watershed. This additional area was included because the watershed divide is located near the top of the south stream bank in this reach and it was desirable to place model boundaries farther away from the area of interest in and around Mill Creek. The model is discretized into over 29,000 45-meter by 45-meter (0.5-acre) grid cells covering a 22.7 mi^2 area. The grid resolution was selected to represent the watershed in as much detail as possible consistent with the overall resolution of input data while enabling reasonable computation times (about 60 hours).

The model simulates a continuous 10-yr period from 10/1/2009 through 9/30/2019 (water years 2010 - 2019). This period was selected because it corresponds to the period with the most data available for model calibration, is representative of long-term average precipitation conditions, and includes a wide variety of precipitation conditions ranging from the very dry water year (WY) 2014 when annual precipitation at the Healdsburg and Venado climate stations was 22.3 and 29.7 inches respectively to the very wet WY 2017 when annual precipitation at the two stations was 79.5 and 152.4 inches respectively (Figures 2 & 3). Based on the long-term precipitation record for Healdsburg from 1894 - 2019, WY 2014 was the 7th driest year on record and WY 2017 was the 2nd wettest (Figure 2). Mean annual precipitation at the Healdsburg climate station for the simulation period was 44.9 inches, which is similar but slightly wetter than both the 1894-2019 and 1981-2010 averages of 40.9 and 43.7 inches respectively (Figure 2).

The Wallbridge Fire burned through much of the watershed relatively late in the study period once calibration of the model was already complete; therefore, the current model does not represent post-fire hydrologic impacts and subsequent recovery. While significant hydrologic effects may be expected in the first few years following disturbance, vegetation recovery is expected to proceed quickly, and the long-term recovered landscape is likely to more closely resemble the pre-fire landscape than the short-term post-fire landscape. While it is advisable to update the model to incorporate the fire during subsequent work, we believe the pre-fire conditions represented by the current analysis remain an appropriate basis for evaluating long-term planning-level management decisions.
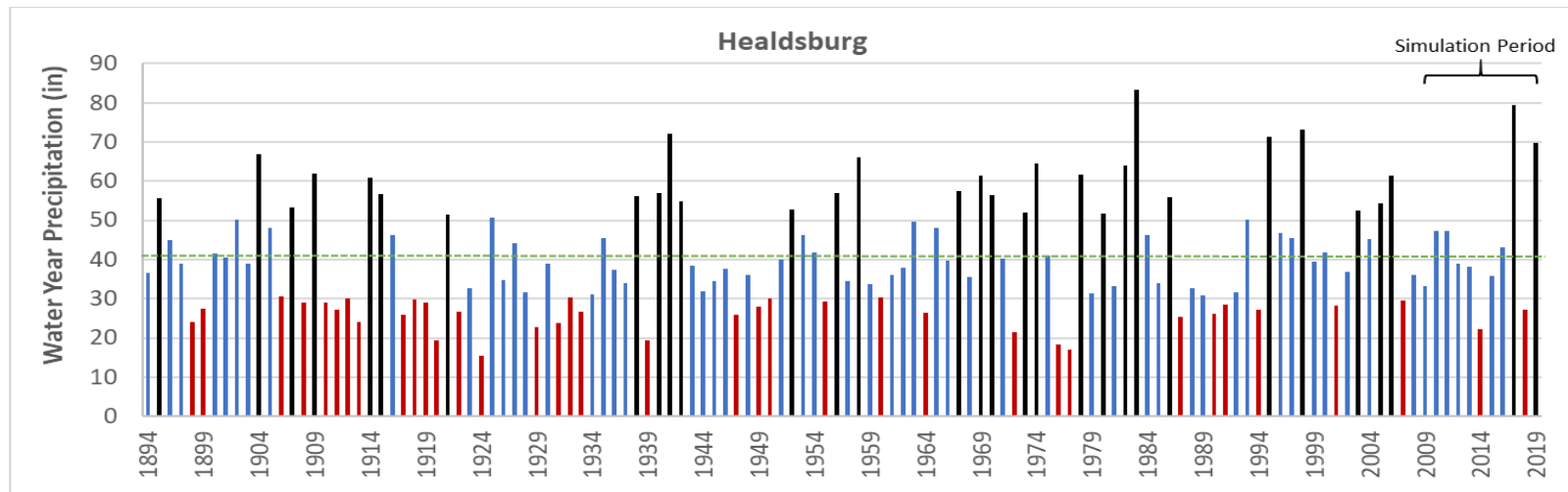
Figure 2: Long-term annual precipitation record for the Healdsburg COOP climate station (black and red values indicate wet and dry years, respectively, defined as +/- 25% of the long-term average as shown with the dashed line).
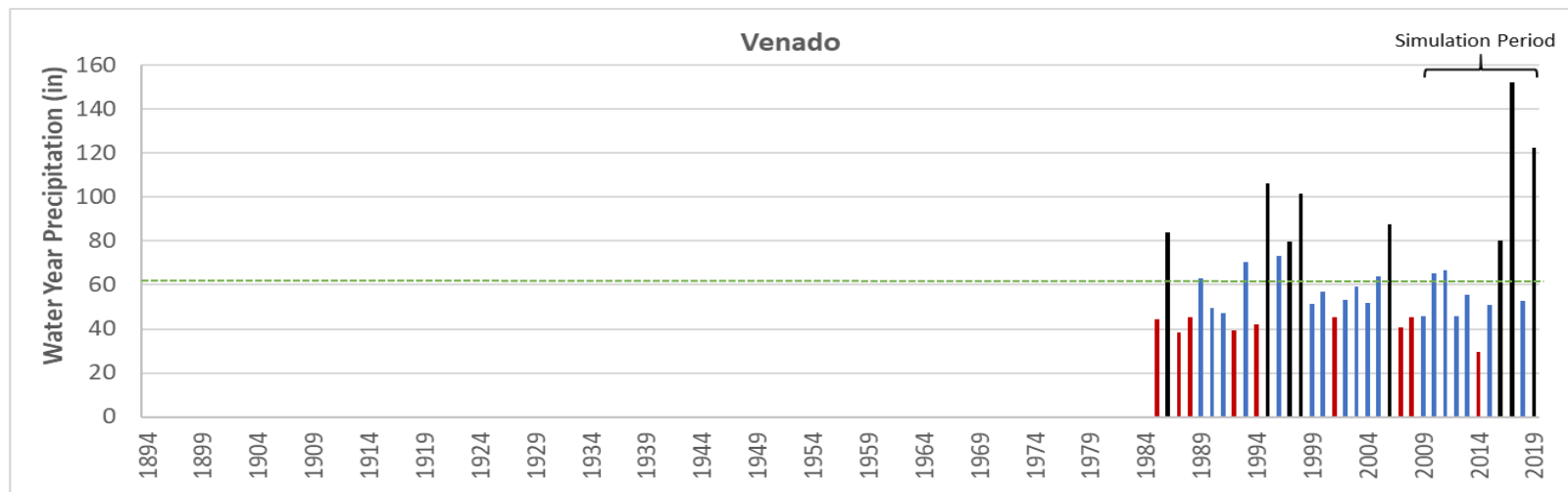
Figure 3: Long-term annual precipitation record for the Venado climate station (black and red values indicate wet and dry years defined as +/- 25% of the long-term average as shown with the dashed line).
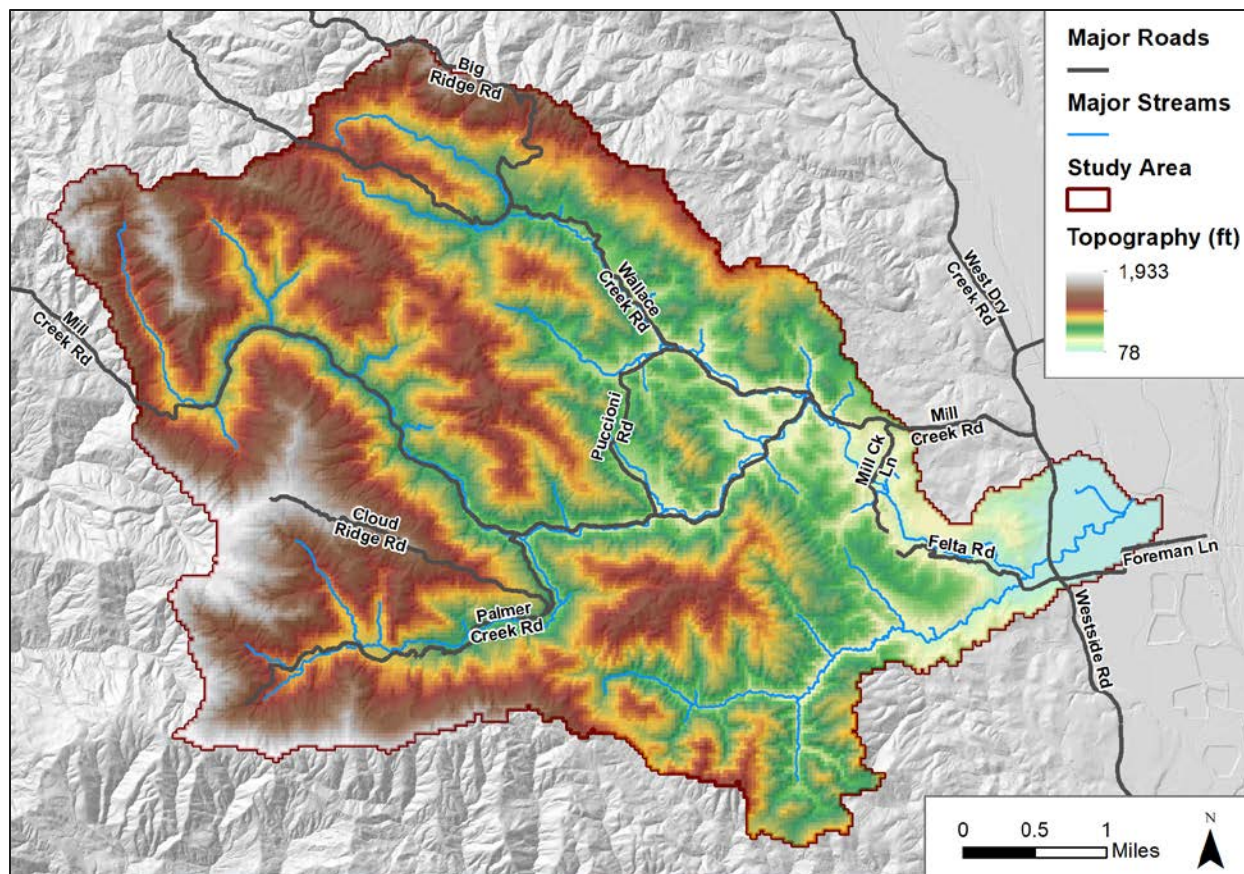
Figure 4: Topography used in the Mill Creek hydrologic model.

Topography

Model topography is based on the 3-foot resolution Sonoma County LiDAR dataset (WSI, 2016) which was resampled to conform to the 45-meter grid cells used in the model. Elevations in the model domain range from 78 feet at the Dry Creek confluence to 1,933 feet on the ridge separating the watershed from the East Austin Creek drainage to the west (Figure 4).

Climate

Precipitation and potential evapotranspiration (PET) are the primary climatic inputs to the model; both are represented on a daily timestep. Based on the Basin Characterization Model (BCM) (Flint et al., 2013; Flint & Flint, 2014) which provides gridded estimates of average annual precipitation for the 1980-2010 period throughout California, a significant east-west gradient in precipitation exists across the watershed. Mean annual precipitation is estimated to increase from 42 in/yr in the Dry Creek Valley to 64 in/yr near the western watershed divide. Based on analysis performed for this study (as described below) PET varies primarily with aspect and is estimated to range from 29 to 51 in/yr. To account for the spatial variability in climate, the model domain was divided into 1-inch interval precipitation and PET zones (Figures 5 & 6).

Precipitation

There are several representative weather stations near the watershed (Figure 5). A long-term daily precipitation record dating back to water year (WY) 1894 is available from the Healdsburg station operated by the National Oceanic & Atmospheric Administration (NOAA) and located 2.3 miles northeast of the Mill Creek outlet. Data for this station was not available after water year 2012, therefore the record was extended through water year 2019 by scaling the Healdsburg 3.7 WNW station (located 2.4 miles north of the watershed in the Dry Creek Valley) based on the ratio of mean annual precipitation between the two stations as indicated by the BCM (Flint & Flint, 2014). A higher elevation station (1,260 ft) with a mostly complete record dating back to water year 1985 is also available at the Venado station operated by the California Department of Water Resources (CDWR) and located about 0.4 miles west of the watershed (Figure 5). Another significant record dating to WY 1991 is available from the Windsor station operated by the California Irrigation Management Information System (CIMIS) and located near the Town of Windsor.

The model domain is divided into 23 precipitation zones to account for the east to west gradient in precipitation (Figure 5). These zones are based on 1-inch annual isohyets derived from the BCM 1981-2010 mean annual precipitation data which is available at a 270-meter spatial resolution (Flint & Flint, 2014). Each zone was assigned to a rainfall station and precipitation was scaled up or down based on the ratio of the mean annual precipitation in the zone to the mean annual precipitation at the corresponding weather station. Zones 42 to 53 are represented using the collated daily record from the Healdsburg station, zones 54 to 58 use a blended timeseries based on the average of the Healdsburg and Venado records, and zones 59 to 64 use the daily Venado record (Figure 7).

Potential Evapotranspiration (PET)

Daily PET data from the Windsor CIMIS station was used to derive the PET timeseries used in the model (Figures 6 & 8). A gridded distribution of mean annual PET was created using the Hargreaves-Samani equation (Hargreaves & Samani, 1982). The calculations were performed using gridded solar radiation data from the National Solar Radiation Database (NSRDB, 2010) and average monthly minimum and maximum temperatures for the 1980 -2010 period from the BCM dataset (Flint & Flint, 2014). The empirically derived KT coefficient was calibrated based on reported PET from the Santa Rosa and Windsor CIMIS Stations. A KT value of 0.152 was selected, consistent with KT values of 0.15 to 0.16 previously proposed for the Bay Area.

From this annual distribution, the model domain was divided into zones, each corresponding to a one-inch range in average annual PET. Scaling factors were calculated for each zone as the ratio of PET at the Windsor CIMIS gage and the PET for a given zone. These scaling factors were then applied to the daily CIMIS data and applied to each zone in the model. From February 2013 to March 2017 PET was not reported at the Windsor CIMIS gage. This gap was filled using scaled data from the Santa Rosa CIMIS gage located west of Sebastopol. Smaller gaps and missing days of data were also filled using Santa Rosa data.
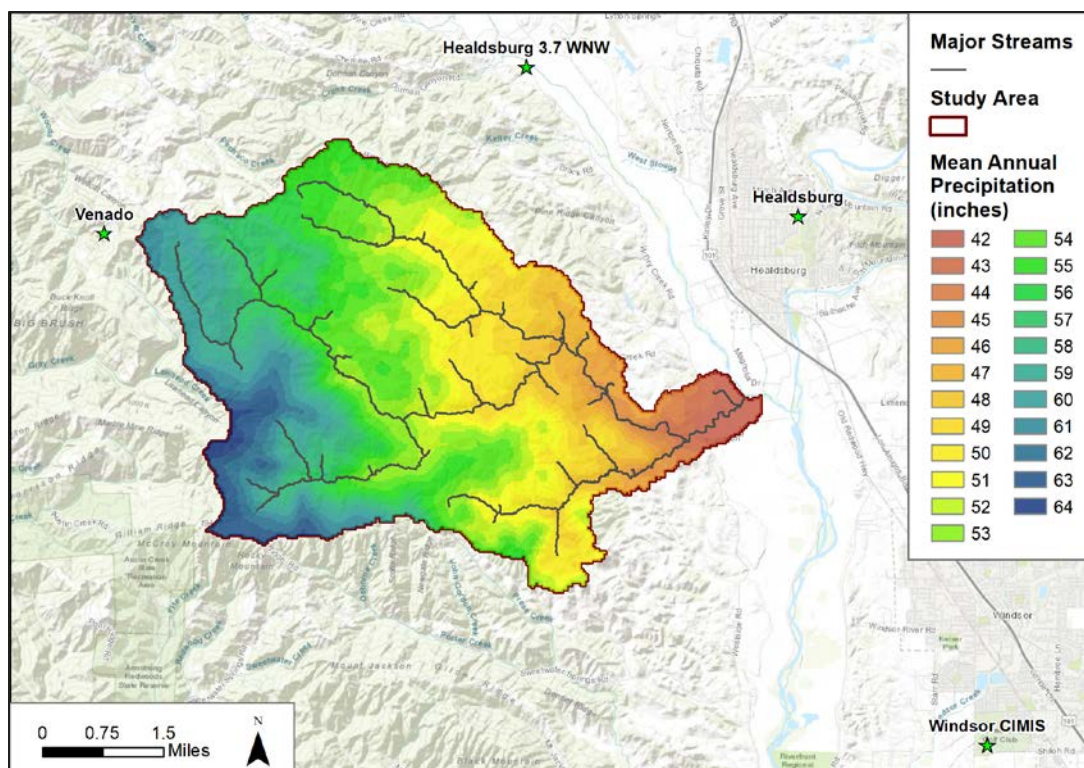
Figure 5: Precipitation zones and climate stations used in the Mill Creek hydrologic model.
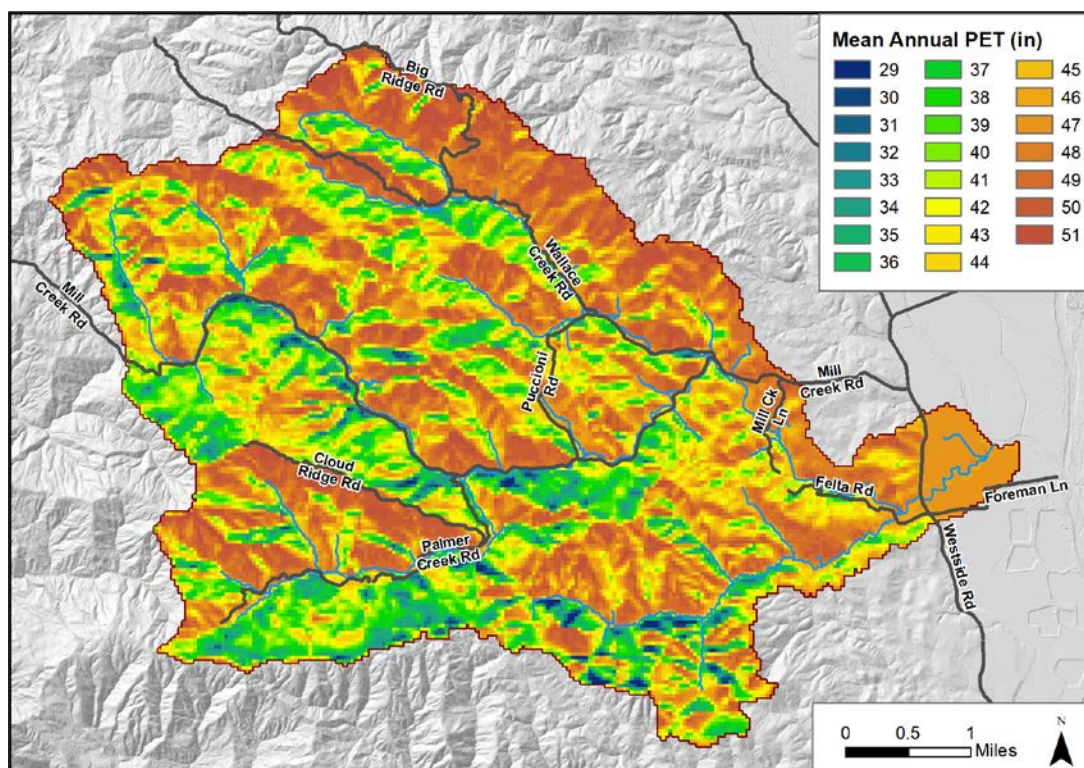
Figure 6: PET zones used in the Mill Creek hydrologic model.
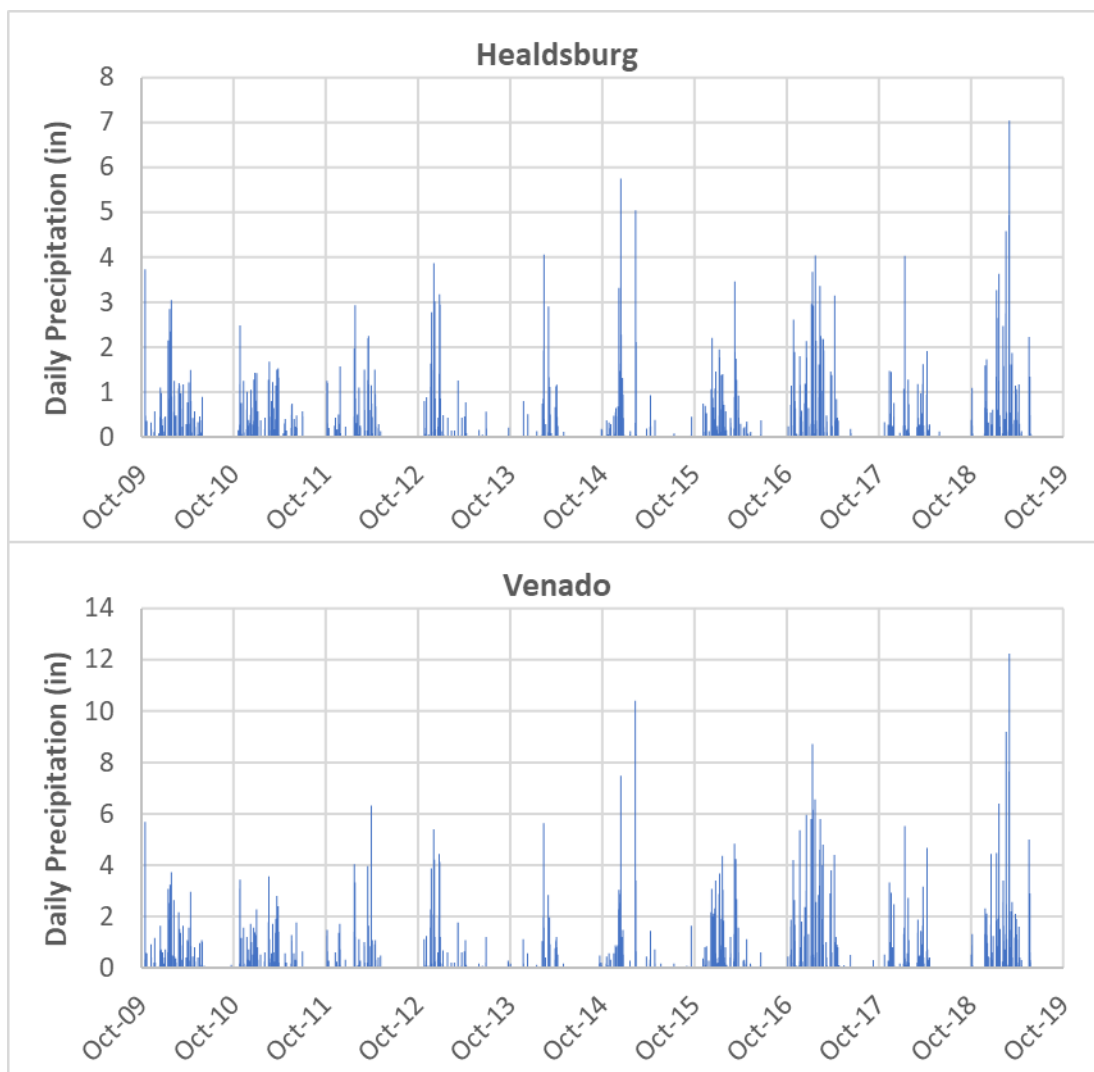
Figure 7: Daily precipitation at the two climate stations used in the Mill Creek hydrologic model for the WY 2010 - 2019 simulation period.
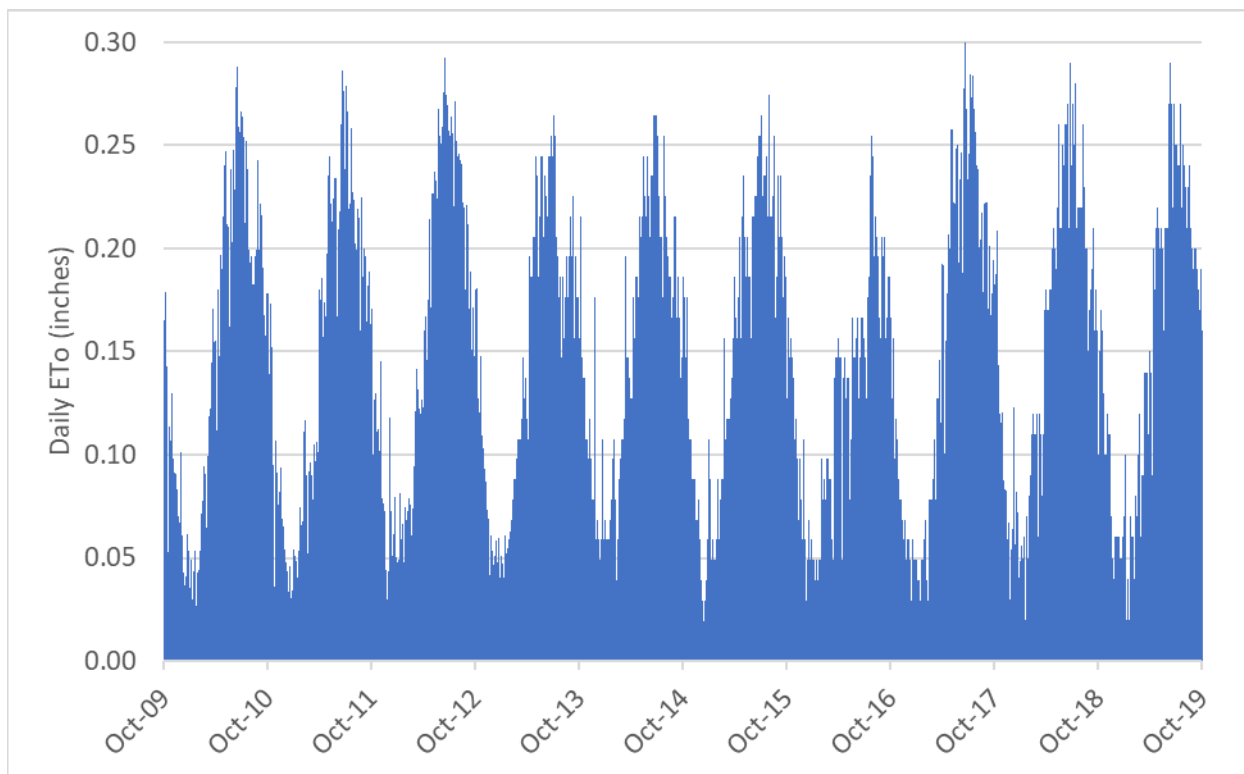
Figure 8: Daily PET at the Winsor CIMIS station used in the Mill Creek hydrologic model for the WY 2010 – 2019 simulation period.

Land Cover

Within the Mill Creek watershed, coniferous and deciduous forest are the dominant landcover types with grasslands making up much of the remaining area (Table 2). Land cover varies significantly throughout the watershed with three distinct zones. The largest zone which comprises most of the upper Mill, Palmer, and Felta Creek drainages is predominately forested with Coastal Redwood and Douglas Fir being the predominant species. The next largest zone comprises the Wallace Creek drainage and portions of the Mill Creek drainage between the Wallace confluence and the Westside Road crossing. This zone is dominated by oak woodlands of various varieties with scattered grasslands. The third zone comprises lower Mill Creek downstream of Westside Road where the majority of the landscape is planted in vineyards. These zones roughly correspond to the major geologic types in the watershed and the associated variations in soils as discussed in greater detail below, with the coniferous forest zone corresponding to the Coastal Belt Franciscan, the oak woodland and grassland zone corresponding to the Central Belt Franciscan, and the lower vineyard area corresponding to Quaternary alluvial deposits.

The model domain was discretized into 22 land cover zones based on vegetation classes from the Sonoma County Vegetation Mapping & LiDAR Program's Fine Scale Vegetation and Habitat Map (Figure 9) (SCVMLP, 2017). This map was generated for the Vegetation Mapping & LiDAR

Program using automated processing of returns from the 2013 countywide LiDAR flight and interpretation of aerial imagery by the modelers (SCVMLP, 2017). It includes a detailed accounting of dominant species including several species of oak and conifer and is intended for use at a scale of 1:5000 or smaller. With the exception of water and orchard, land cover zones that represent less than 0.2% of the model domain (approximately 0.05 mi^2) are grouped with similar or adjacent cover types. Because these land cover zones are based on 2013 data, they do not reflect changes caused by the 2020 Wallbridge Fire.

A unique combination of model parameters was assigned to each of the 22 land cover zones. These parameters include leaf area index (LAI), rooting depth, Manning's roughness coefficient for overland flow, and detention storage. For land cover types with a deciduous vegetation component, the leaf area index and rooting depth vary seasonally based on an assumed growing season of April 15th to October 15th with gradual parameter transitions occurring from March 15th to April 15th and from October 15th to November 15th. Dormant season values for deciduous land cover types were assumed to be equivalent to grassland values. For grasslands, the growing season was assumed to occur from December 15th to May 15th and the dormant season was assumed to occur from July 1st to October 15th with gradual parameter transitions in between.
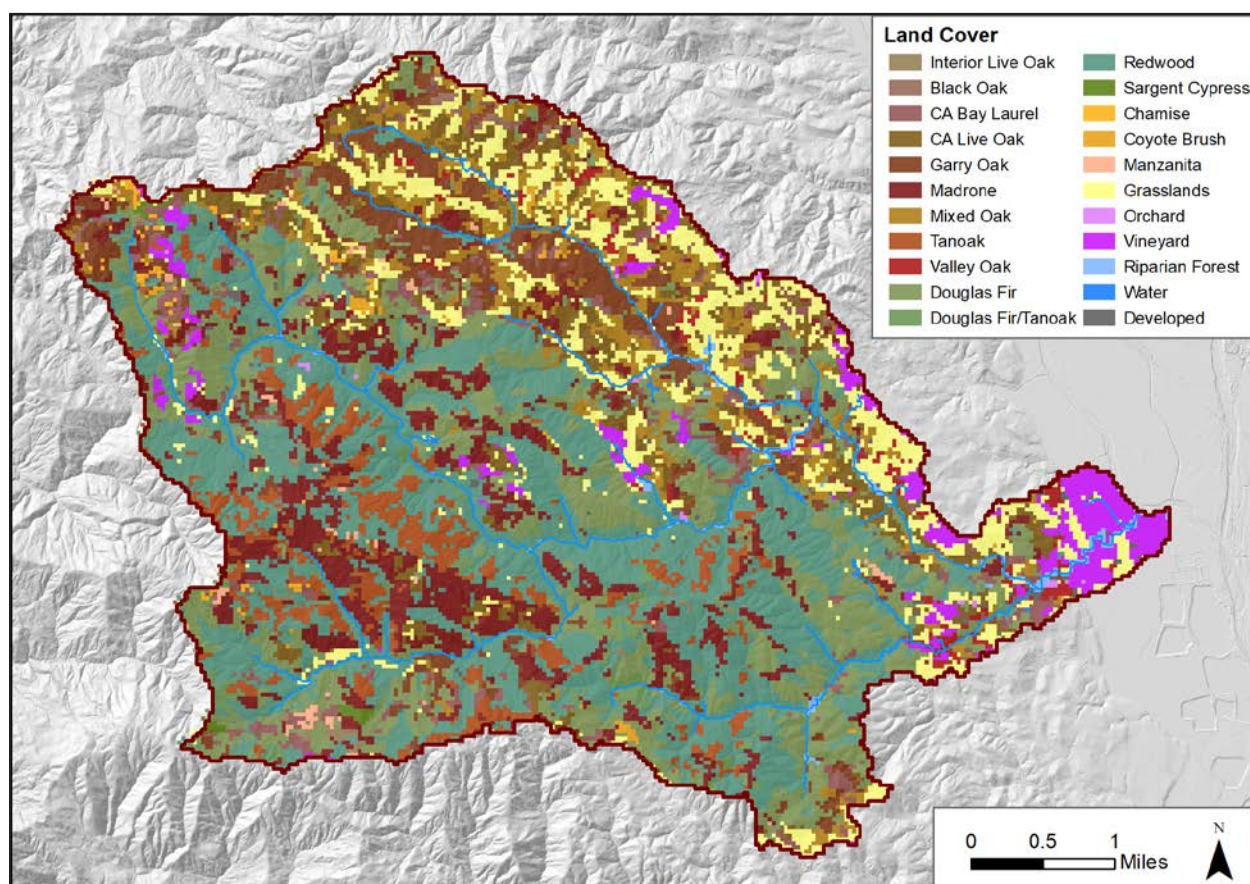
Figure 9: Land cover categories used in the Mill Creek hydrologic model.

Many of these parameters are difficult to measure in the field and site-specific values are generally unavailable. With the exception of LAI, land cover parameters were initially estimated from literature values (e.g. Allen et al., 1988; TNC, 2018) and then adjusted within the range of reasonable limits as part of the calibration process (Table 1).

LAI was estimated for each vegetation zone using a spatially distributed LAI dataset created by the University of Maryland (Tang, personal communication; Tang, 2015) (Figure 10). This dataset was created using vegetation returns from the countywide LiDAR dataset and has a 3-foot spatial resolution. The remotely sensed LAI values in this dataset represent a combination of the canopy properties of individual plants and the density and spacing of those plants. This differs from LAI values representing individual plant specimens which is the standard convention for empirical evapotranspiration equations used in our model. We compared the remotely sensed LAI values for various vegetation classes with individual specimen values from the literature (Iio & Ito, 2014; Johnson, 2003; Karlik & McKay, 2002; Scurlock et al., 2001) and translated the LiDAR-derived values to specimen values consistent with the literature by applying a uniform scaling factor to the LiDAR-derived LAI (Figure 11). LAI values were calculated for each of the vegetation zones in the model by calculating the mean LAI for each zone from the scaled LAI dataset (Table 1).
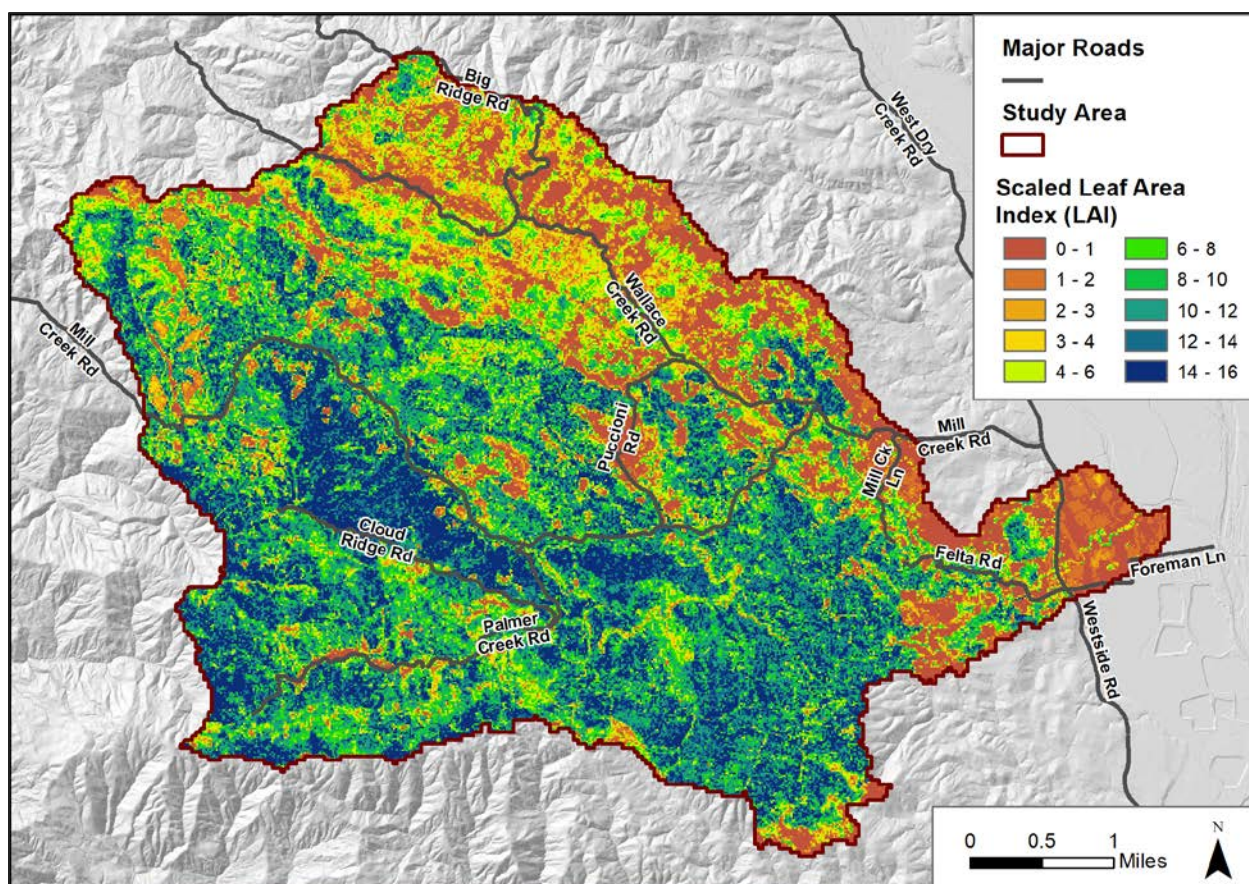
Figure 10: Distribution of LiDAR-derived Leaf Area Index (LAI).

Table 1: Land cover types and associated hydraulic and vegetation properties used in the Mill Creek hydrologic model.

Land Cover Category	Proportion of Model Domain	Overland Flow Mannings n	LAI	Rooting Depth (ft)	Detention Storage (in)
Chamise	0.3%	0.40	4.2	6.4	0.3
Madrone	9.9%	0.60	9.8	8.6	0.9
Manzanita	0.4%	0.40	6.2	6.6	0.3
Coyote Brush	0.3%	0.40	2.1	6.5	0.3
Grasslands	10.2%	0.24	0.8	2.1	0.3
Sargent Cypress	0.2%	0.60	6.3	5.6	0.9
Tanoak	5.4%	0.60	11.8	15.0	0.9
Orchard	0.1%	0.24	2.1	6.7	0.9
Douglas Fir/Tanoak	1.3%	0.60	12.7	9.4	0.9
Douglas Fir	17.0%	0.60	11.0	3.7	0.9
Mixed Oak	5.3%	0.60	4.8	19.5	0.9
CA Live Oak	5.9%	0.60	5.4	24.0	0.9
Black Oak	0.3%	0.60	3.8	8.5	0.9
Interior Live Oak	0.4%	0.60	8.4	24.0	0.9
Garry Oak	7.1%	0.60	5.3	15.0	0.9
Valley Oak	1.2%	0.60	3.5	24.0	0.9
Redwood	26.5%	0.60	11.1	11.1	0.9
CA Bay Laurel	3.5%	0.60	8.0	3.0	0.9
Riparian Forest	0.7%	0.60	6.4	7.3	0.9
Vineyard	3.4%	0.24	1.2	4.9	0.3
Water	0.1%	0.04	1.0	0.5	0.0
Developed	0.6%	0.04	2.4	5.9	0.0
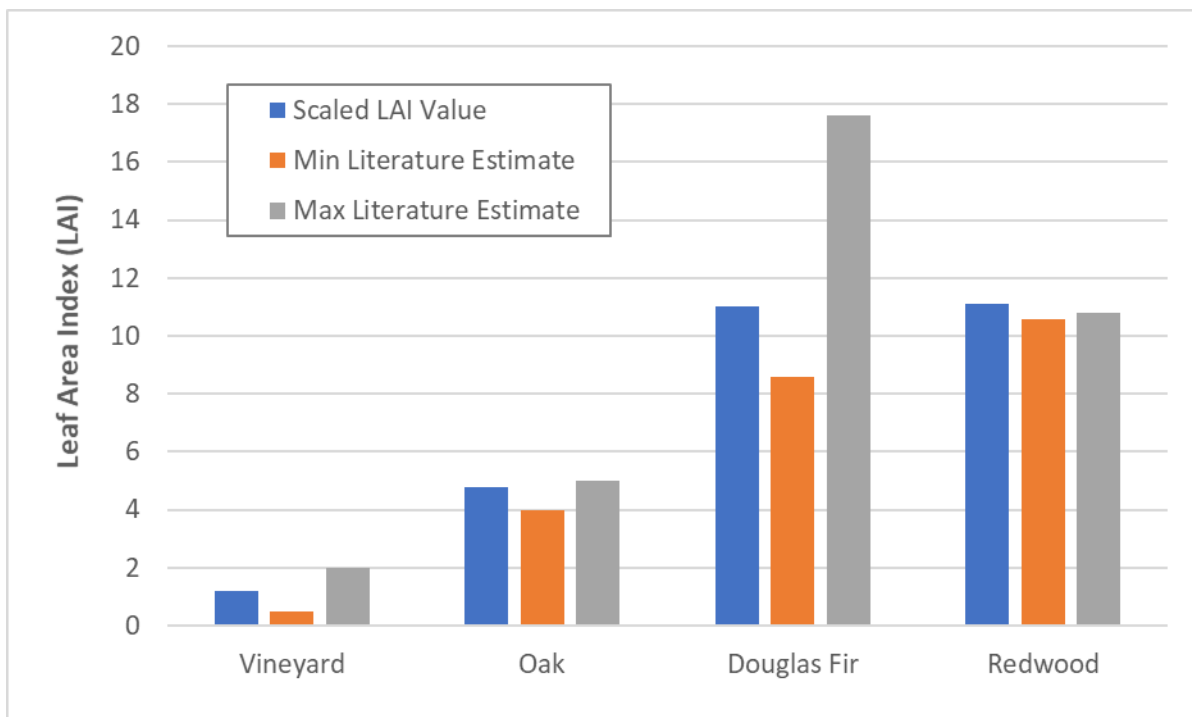
Figure 11: Comparison between scaled LAI values used in the Mill Creek hydrologic model and estimates from the literature for various vegetation types.

Surface Water

Channelized flows are represented using a detailed stream network derived from the 3-foot resolution Sonoma County LiDAR dataset (WSI, 2016). This network includes all major perennial streams and many smaller tributaries as well as all major on-stream ponds. Off-channel ponds, some intermittent streams, and ephemeral tributaries are not explicitly represented in the stream network. In total, 40 river miles of stream and 13 on-stream ponds are included and represented by approximately 2,250 cross-sections in the surface water hydraulics component of the model.

Streams

The stream network includes all channels with a drainage area of more than 0.2 mi^2 and a stream length of at least 500 feet (Figure 12). These limits were designed to maximize the extent of the channel network within the limits of the ability of the LiDAR data to accurately represent channel geometry and to avoid excess computational burden. These thresholds allow for inclusion of all perennial streams and all reaches with slope characteristics (<7%) indicative of potential salmonid habitat suitability.

The stream network was derived from the 3-foot Sonoma County LiDAR dataset by computing flow directions and flow accumulations using standard ArcGIS techniques. Channel-cross sections were extracted from the LiDAR DEM at 100 ft intervals for major channels and those

known to contain salmonids, including Mill, Palmer, Felta, Wallace, Angel, and Salt Creeks. For the remaining channels, cross-sections were extracted at 200 ft intervals.

Prior to defining the stream network and extracting cross sections, a series of cross sections were surveyed in the field and compared to LiDAR-derived cross sections at various drainage areas and locations throughout the watershed. These comparisons revealed that the LiDAR dataset represents the channel geometry with acceptable accuracy at drainage areas above about 0.2 mi^2. In some cases, accuracy was reasonably high in smaller drainage areas; however, when smaller streams were incised relatively deeply the LiDAR did not capture the details of the channel geometry in sufficient detail for hydraulic modeling. Examples comparing survey- and LiDAR-derived cross sections with accuracy judged to be acceptable for purposes of hydraulic simulation in the model are shown in Figure 13.

A uniform Manning's Roughness coefficient (n) of 0.055, representative of rocky channels with brush along the banks (Chow, 1959), was applied to all cross-sections. A downstream boundary condition was defined as a rating curve established using normal depth calculations for the downstream-most cross section in the model. Because all inflows are generated by other spatially distributed components of the MIKE SHE model, upstream boundary conditions are zero-discharge inflows.
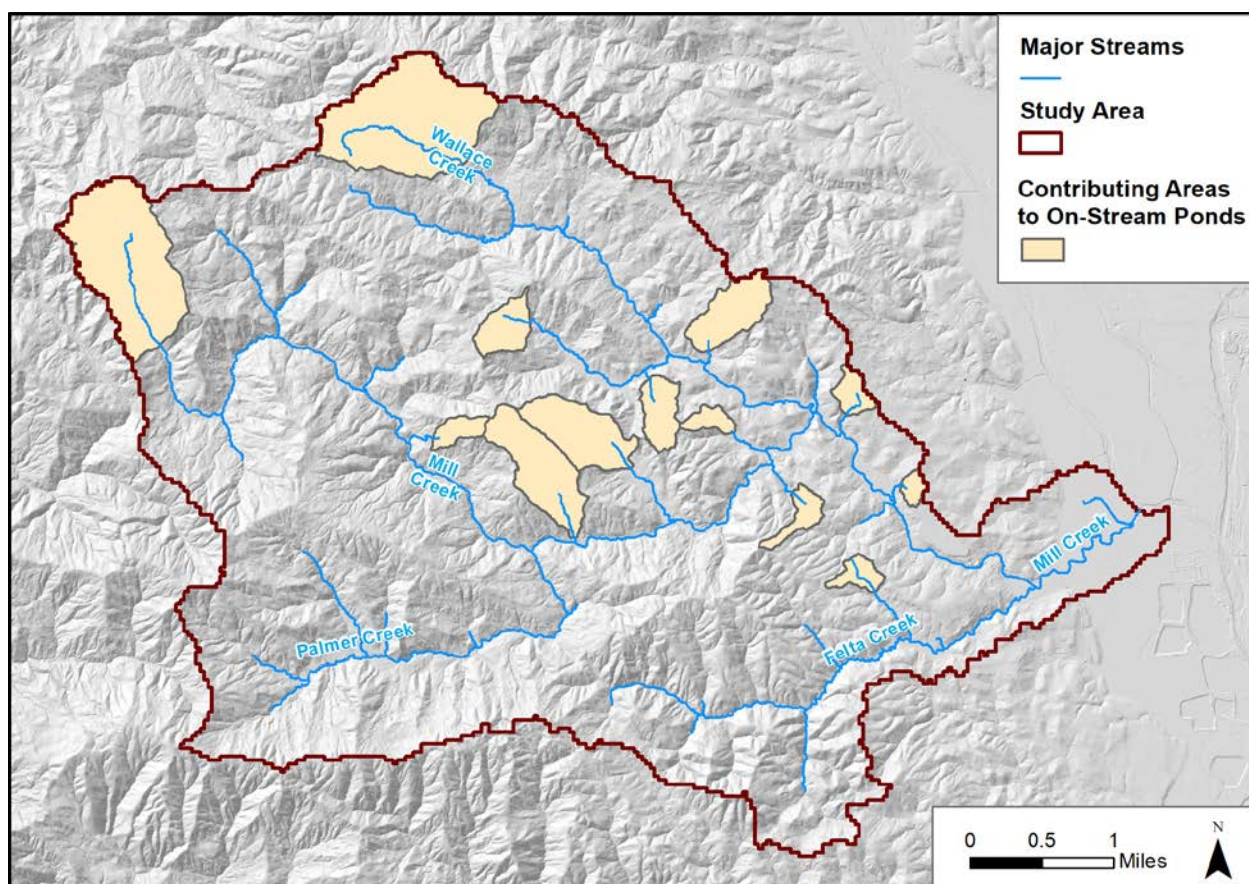
Figure 12: Stream network and on-stream ponds included in the Mill Creek hydrologic model.
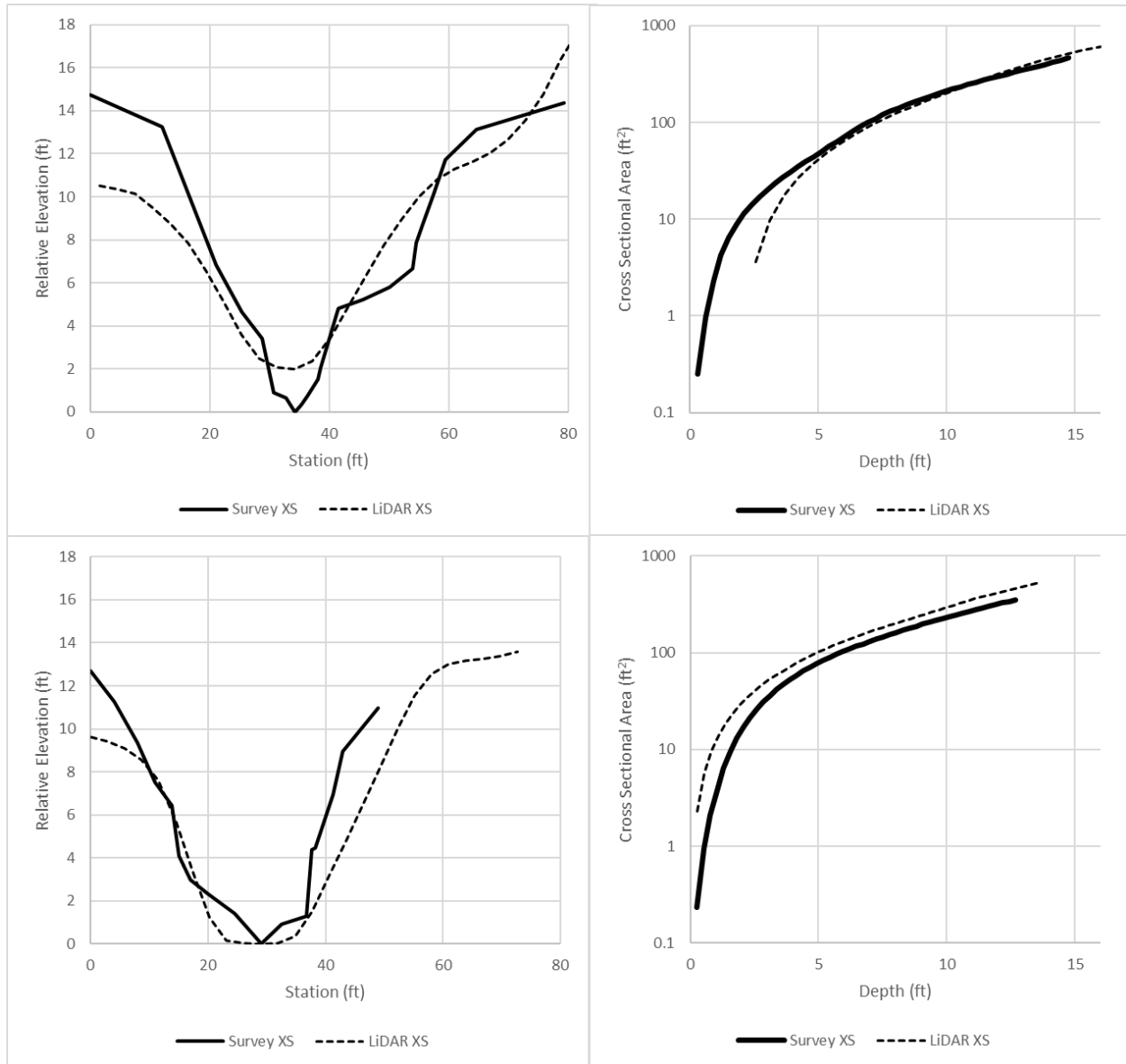
Figure 13: Comparisons between survey- and LiDAR-derived channel cross sections and corresponding depth/area relationships for two locations in Mill Creek with a 5.1 mi² drainage area (top) and a 12.7 mi² drainage area (bottom).

Ponds

Within the model domain, approximately 50 ponds have been identified using the 3-foot Sonoma County LiDAR DEM and aerial photography. The majority of these are small off-stream ponds which were not explicitly included in the surface water component of the model. Thirteen on-stream ponds with significant (>0.2 mi²) contributing areas were included in the model (Figure 12).

A stage-storage relationship for each of the 13 ponds included in the model was derived from the 3-foot Sonoma County LiDAR DEM. These data were collected in autumn 2013 and observed water surface elevations are assumed to reflect typical end-of-season storage levels in each pond. The stage-storage relationship for a given pond was associated with cross sections at the upstream and downstream edges of the pond, and cross sections were added at the pond's spillway. Water in the ponds is not explicitly represented in the model grid therefore evaporation from each pond was included as a surface water boundary condition based on the surface area of the pond and the daily PET data described above.

Soils

The model domain is discretized into 22 different soil zones based on the National Resource Conservation Service's (NRCS) Soil survey Geographic Database (SSURGO) accessed through the Web Soil Survey (Figure 14). Where reported soil types are similar or where they represent a small portion of the model domain, they are grouped with other similar soil types. Most of the upper watershed is dominated by gravelly loams of the Hugo-Josephine Complex and Josephine Loam.   These are NRCS Hydrologic Soil Group B soils which are relatively well-drained and can absorb and transmit water at relatively high rates. In contrast, the Wallace Creek drainage is dominated by loams and clay loams of the Yorkville-Suther Complex and Laughlin Loam. These are Group C and D soils which absorb and transmit water more slowly and thus generate higher rates of runoff. The distribution of soil textures reflects the underlying geology with the gravelly loams corresponding to the Coastal Belt Franciscan Complex and the finer soils corresponding to the Central Belt Franciscan.

In the lower watershed, soil textures change in the downstream direction as the creek flows over its alluvial fan and into Dry Creek Valley. The upper fan is characterized by gravelly loams, with silt loams occurring down fan, transitioning to loams farther downstream. These textural variations are generally consistent with our subsurface hydrogeologic characterization of the alluvium as discussed in greater detail below.

Initial estimates of the saturated hydraulic conductivity and the moisture contents at saturation, field capacity, and the wilting point for each of these soil types were derived from the physical properties report in the SSURGO database and final values have been determined through model calibration. For each zone, saturated hydraulic conductivity was initially estimated using the rate reported for the most limiting layer of each soil. Initial values for water content at field capacity and wilting point were estimated using the weighted average for all horizons within each zone. Saturated water content is not reported by SSURGO and initial values were estimated using the reported average bulk density for each zone and an assumed soil particle density of 2.65 g/cm^3.

The initial values for soil moisture contents were not adjusted significantly. Excluding the alluvial soils which have significantly different properties, soil moisture content at saturation, field capacity, and the wilting point ranged from 0.43 to 0.49, 0.16 to 0.36, and 0.05 to 0.19 respectively.   Successful calibration required significantly lower Ksat values relative to the SSURGO estimates. This can be attributed to the model's simplified 2-layer water balance approach which does not account for variations in Ksat as a function of soil moisture, and thus

typically requires lower Ksat values to represent overall infiltration dynamics. Additionally, the unsaturated zone in much of the watershed is relatively thick and comprised of soil strata plus underlying weathered and unweathered bedrock, therefore this parameter reflects an average Ksat value for the full unsaturated zone derived from calibration rather than a true soil property. The calibrated saturated hydraulic conductivity values ranged from 0.01 ft/day for clay soils to 2.34 ft/day for alluvial soils (Table 2).
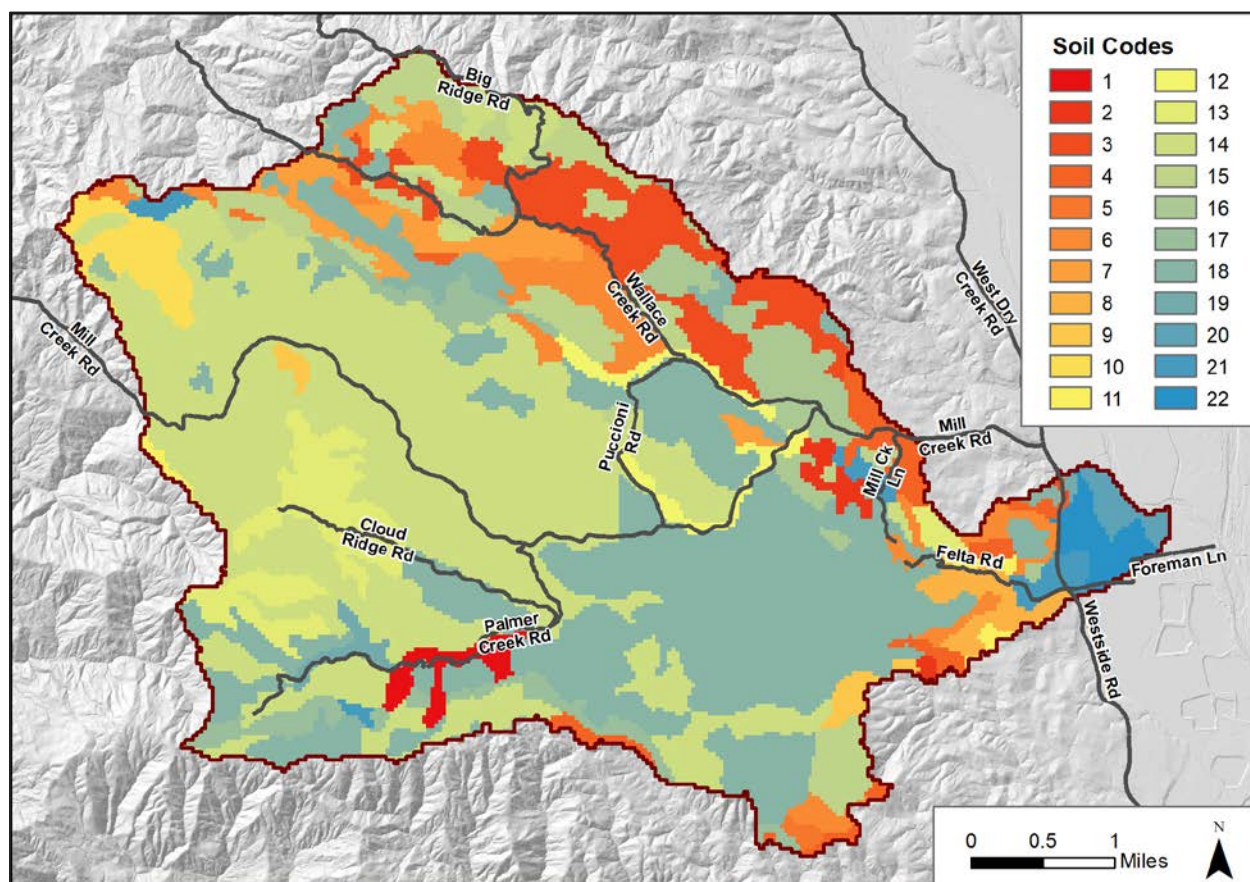
Figure 14: Soil codes used in the Mill Creek hydrologic model, soils are coded in order of increasing saturated hydraulic conductivity (see Table 2 for associated property values).

Table 2: Final calibrated values of soil moisture contents at saturation, field capacity, and wilting point, and saturated hydraulic conductivities used in the Mill Creek hydrologic model.

Soil Code	θsat	θfc	θwp	Ksat (ft/day)
1	0.453	0.161	0.058	0.011
2	0.449	0.228	0.149	0.011
3	0.479	0.274	0.181	0.011
4	0.487	0.363	0.188	0.011
5	0.472	0.216	0.114	0.021
6	0.464	0.274	0.150	0.034
7	0.453	0.228	0.160	0.034
8	0.471	0.235	0.050	0.046
9	0.463	0.240	0.155	0.052
10	0.464	0.194	0.121	0.056
11	0.460	0.231	0.125	0.068
12	0.445	0.249	0.092	0.085
13	0.463	0.251	0.113	0.105
14	0.479	0.199	0.115	0.111
15	0.434	0.228	0.130	0.122
16	0.479	0.254	0.120	0.128
17	0.464	0.194	0.104	0.128
18	0.494	0.263	0.116	0.128
19	0.472	0.306	0.159	0.539
20	0.472	0.283	0.111	1.865
21	0.444	0.222	0.098	2.074
22	0.457	0.304	0.135	2.336

Interflow

As described in Chapter 3, interflow is represented in the model with a saturated zone drainage function. Drain levels and time constants were derived through calibration and primarily influence the springtime flow recession. A constant drain level of 4.6 ft below land surface was used to activate the drainage process and drainage was only activated in areas of the watershed with slopes greater than 25% consistent with the conceptualization of interflow as primarily a hillslope process (Figure 15).
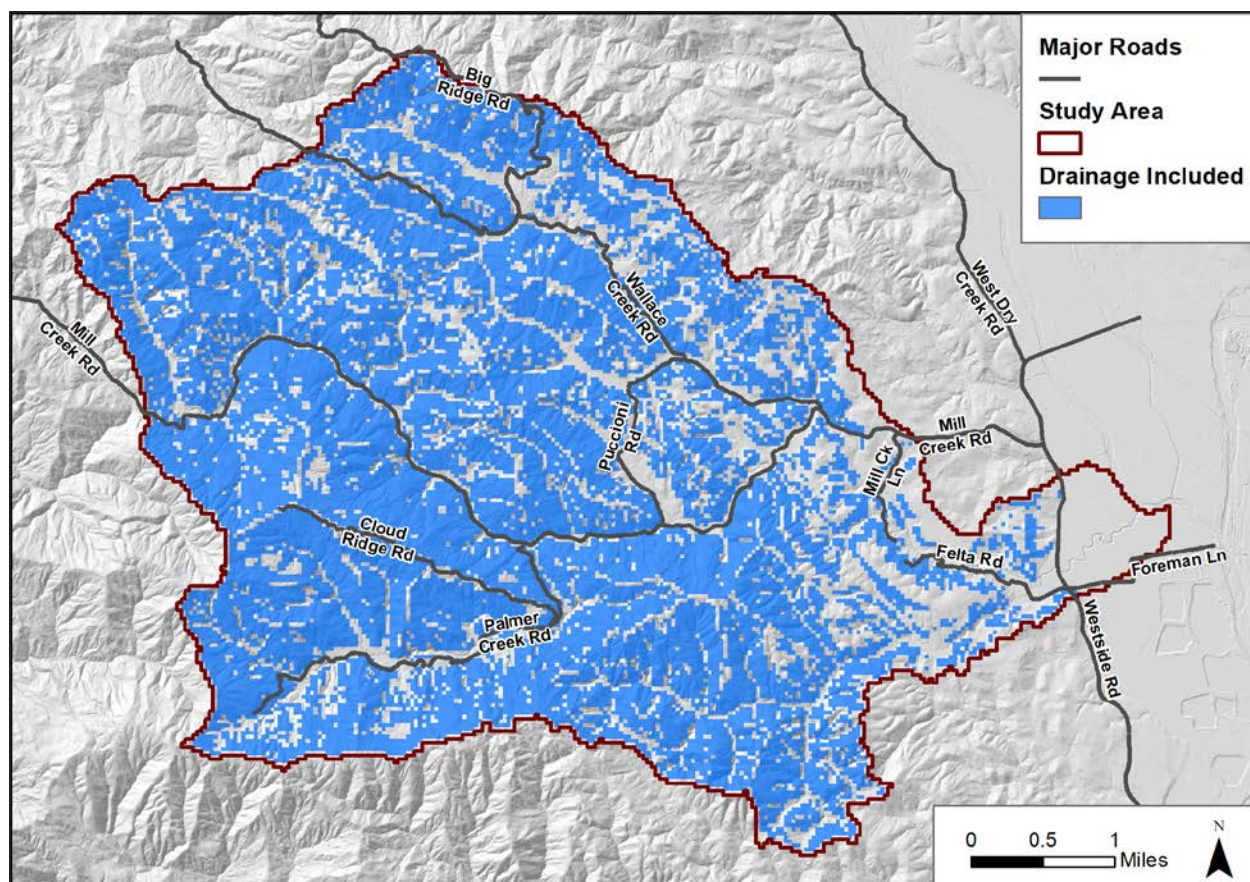
Figure 15: Locations where drainage was activated in the Mill Creek hydrologic model to represent interflow.

Hydrogeology

Model Discretization and Distribution of Hydrogeologic Units

The geology of the upper Mill Creek watershed is primarily comprised of various units of the Franciscan Complex (Figure 16). Groundwater storage and movement in the Franciscan is generally believed to be fairly limited with groundwater generally occurring under confined conditions with flows occurring primarily as fracture-flow. Hydrogeologic properties in the Franciscan may vary widely spatially and with depth depending on the degree of fracturing. There is essentially no available data describing fracture distributions other than what can be inferred from the available geologic mapping and limited aquifer test data. We reviewed numerous geologic logs included in Well Completion Reports (WCRs) for wells completed in the Franciscan, however it is not possible to delineate individual layers or lenses of geologic materials to use in developing the vertical discretization of model layers. Given the lack of interpretable stratigraphy or information describing fractures in the Franciscan, we represented these materials in a very simplistic fashion as a uniform 800 ft thick sequence of low permeability material.

There are very few wells completed in the limited exposures of Glen Ellen Formation and Sonoma Volcanics in the watershed. We similarly assumed a uniform 800 ft sequence for these materials although it is likely that they transition to underlying Franciscan at some unknown depth. Although the Franciscan likely extends to significantly greater depths, none of the identified wells are completed beyond 800 ft and most are less than 400 ft deep. Additionally, groundwater occurring at greater depths is unlikely to be well connected to surficial aquifers or streams. Although hydrogeologic properties are uniform within the bedrock portions of the watershed, the units are discretized into a shallow upper layer (100 ft thick) and a deeper lower layer (700 ft thick) which allows for some vertical flows to occur due to variations in the recharge, interflow, and pumping boundary conditions experienced by the shallow and deep layers.

In contrast to the upper bedrock reach, the lower alluvial reach of Mill Creek is characterized by significant surface water/groundwater interaction and frequent summer drying. Given the importance of the alluvial aquifer to streamflow and salmonid habitat conditions in the watershed, considerable effort was given to representing the character and thickness of the alluvium in the model. We identified 27 WCRs with geologic logs for wells completed in the
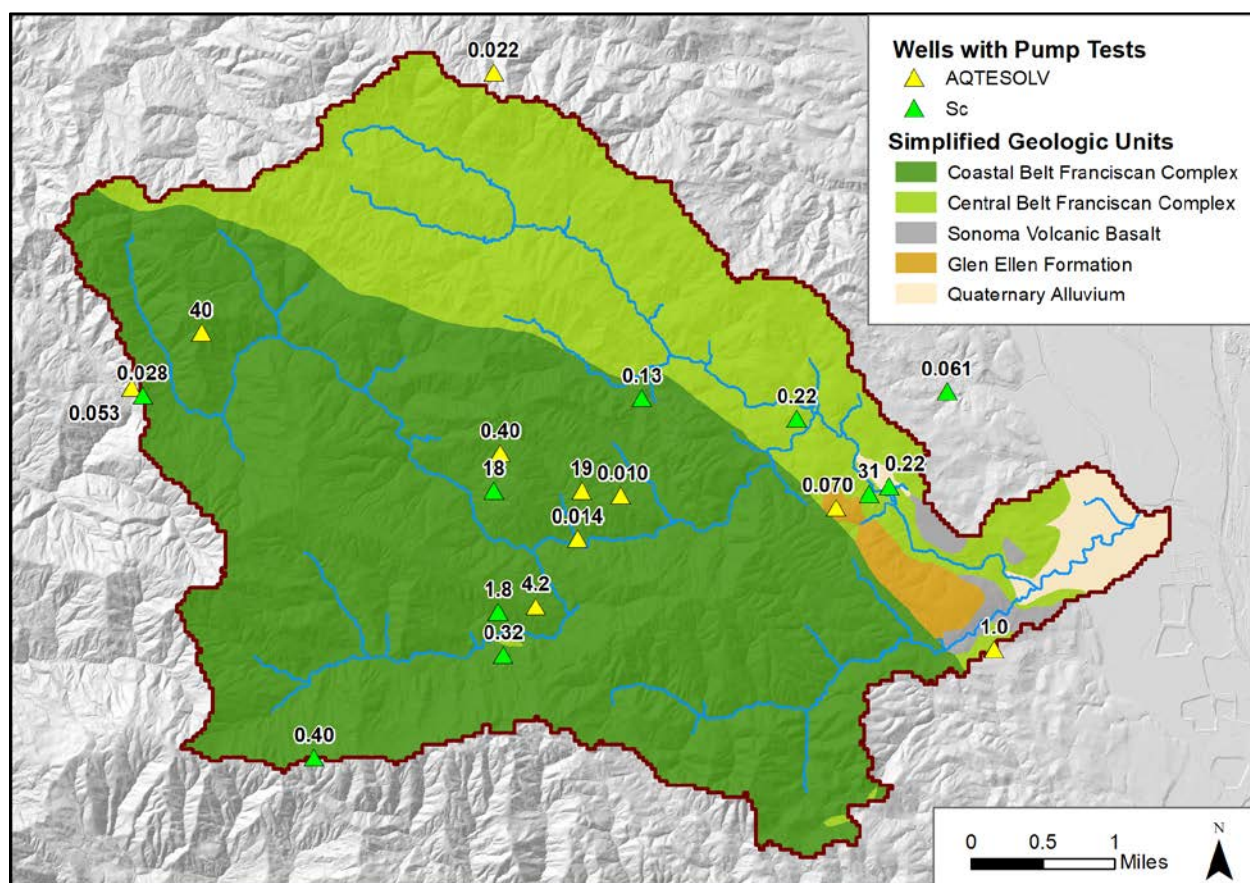
Figure 16: Simplified geologic map (derived from Blake et al., 2002) and locations of wells with available pump test data (numbers indicate pump-test derived hydraulic conductivity (K) estimates in units of ft/day, see Table 3).
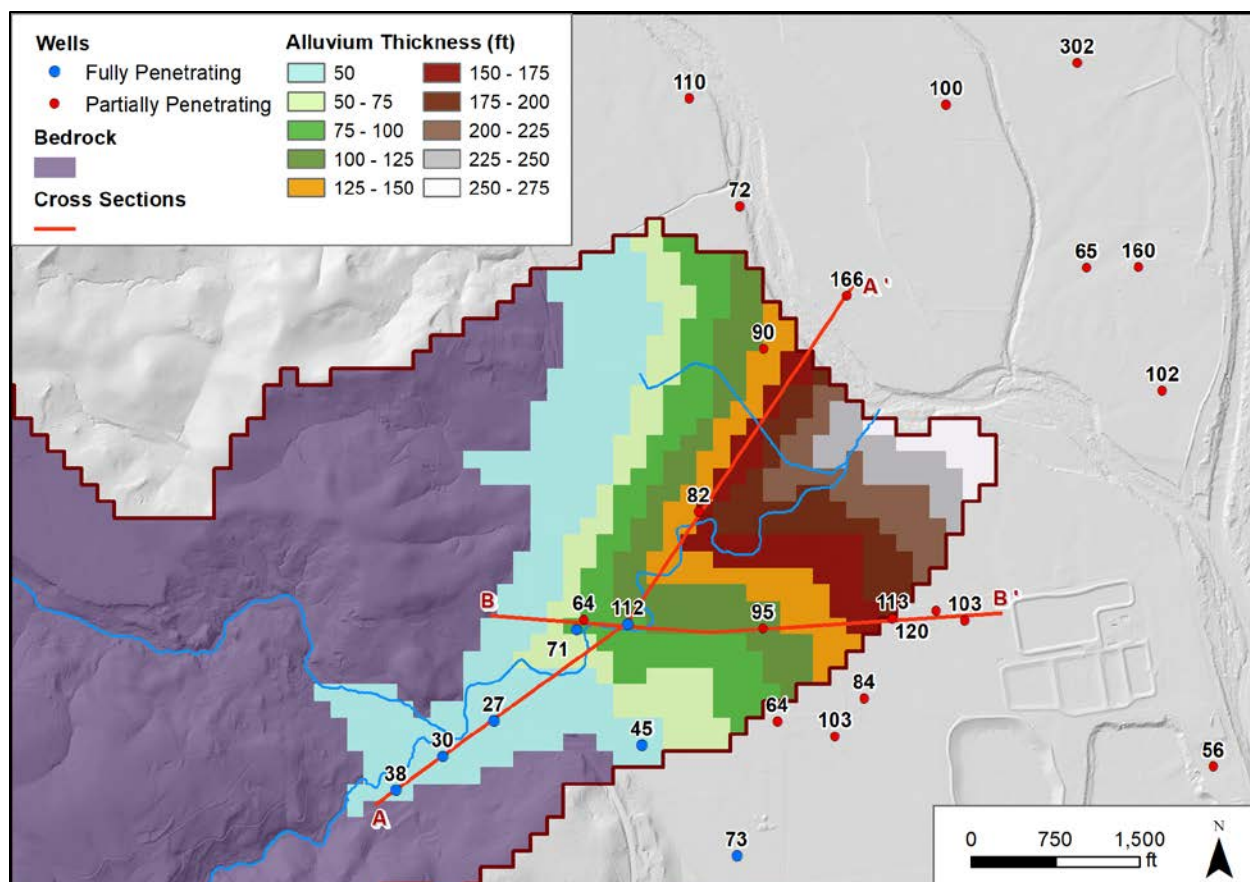
Figure 17: Locations of wells providing depth and textural information for the alluvium; numbers indicate thickness of the alluvial deposits (blue) or minimum thickness (red). Also shown is the interpolated thickness of the alluvium (Layer 1) used in the hydrologic model and the locations of the hydrogeologic cross sections presented in Figures 18 & 19.

alluvium in lower Mill Creek and the surrounding portions of the Dry Creek Valley (Figure 17). Only seven of these wells completely penetrated the alluvium to the underlying bedrock.

These wells indicate that the upper portions of the alluvial aquifer are relatively thin (27-45 ft thick) and that the deposits increase in thickness to over 100 ft by the mid-point between the Felta and Dry Creek confluences (Figure 17 & 18). No wells fully penetrate the aquifer farther downstream and the deepest well in the vicinity (0.7-miles northeast of the Dry Creek confluence near the Russian River) indicates thicknesses of more than 300 ft. Extrapolating the slope of the alluvial/bedrock interface identified in the upper portions of the aquifer downstream suggests that the alluvium is on the order of 250-300 ft thick in the vicinity of the Dry Creek confluence (Figures 18 & 19).

The available subsurface textural information and monitoring data (described in detail below) indicates that the alluvial aquifer is primarily unconfined. We developed a simplified surface representing the base of the alluvium based on the available geologic logs. We assumed a
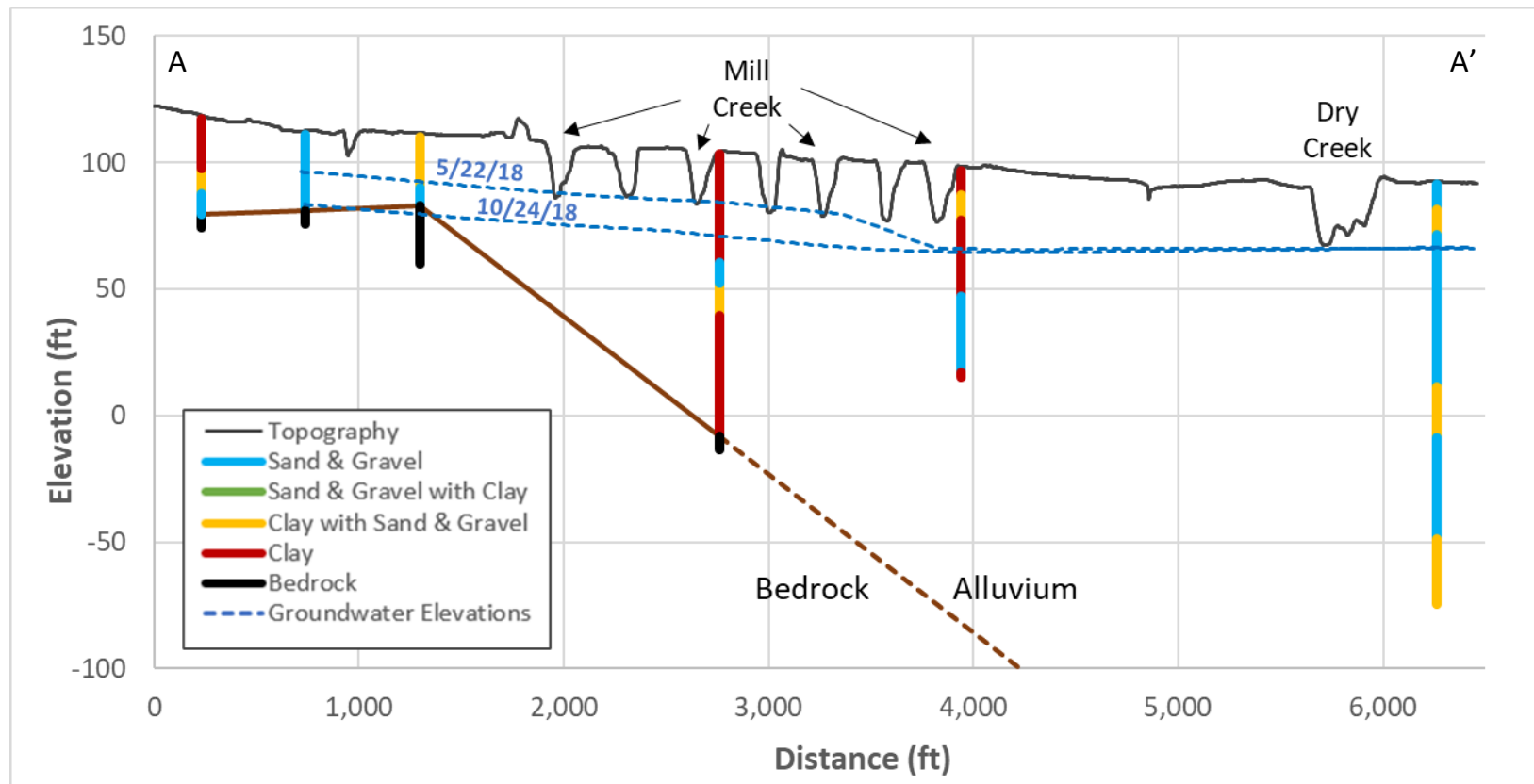
Figure 18: Hydrogeologic cross section A-A' showing the thickness, texture, and groundwater elevations in the alluvium (see Figure 17 for cross section and well locations).
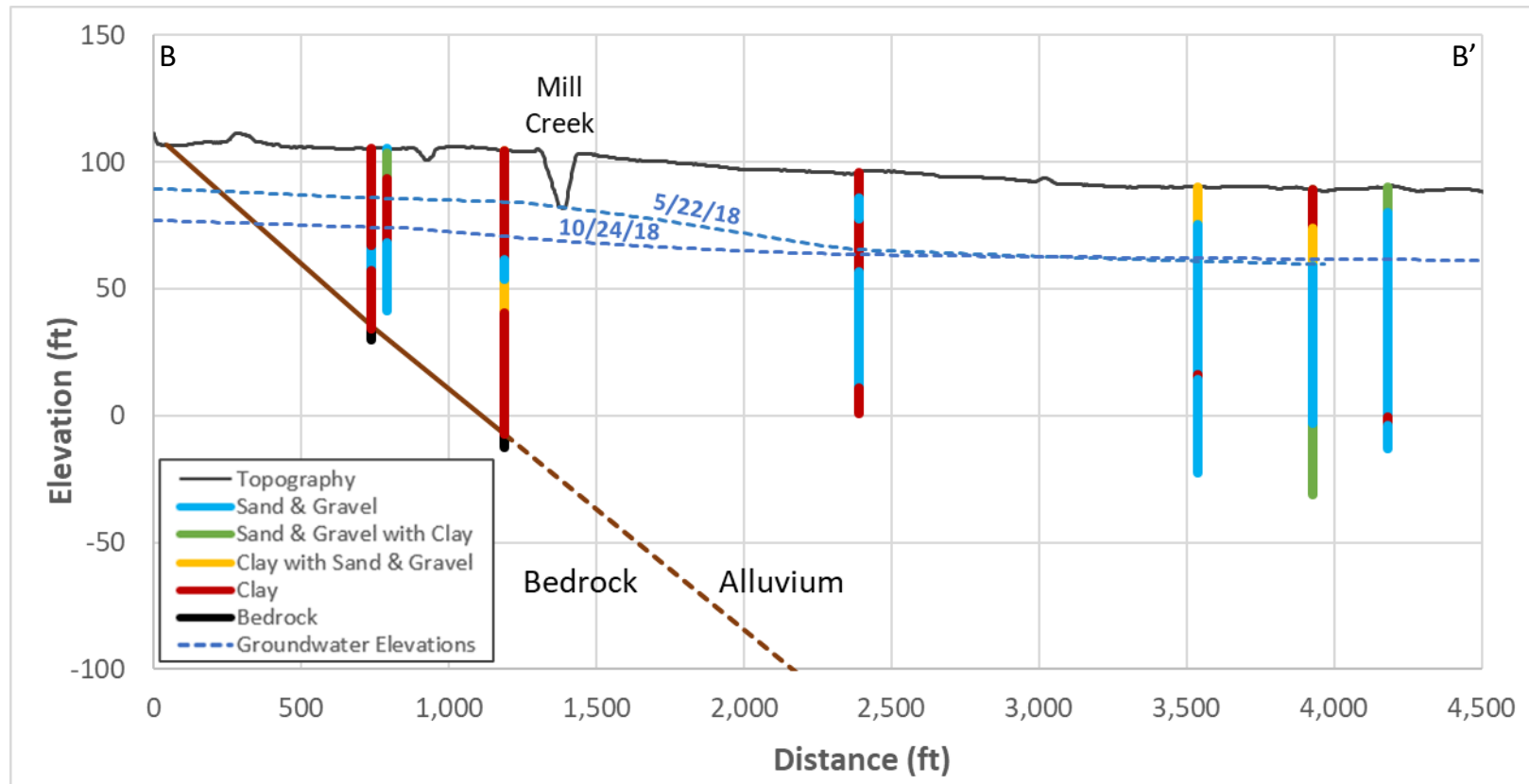
Figure 19: Hydrogeologic cross section B-B' showing the thickness, texture, and groundwater elevations in the alluvium (see Figure 17 for cross section and well locations).

uniform thickness of 50 ft for the upper portions of the alluvial aquifer and thickness that increase in the downstream direction, reaching a maximum of 275 ft near Dry Creek (Figure 17). A 2-layer groundwater model was developed with Layer 1 representing the alluvium with thickness of 50-275 ft. Outside of the alluvial body Layer 1 represents the various bedrock units and has a uniform thickness of 100 ft which decreases gradually to 50 ft around the margins of the alluvial body. Layer 2 only represent bedrock materials and is generally 700 ft thick, except where it underlies the alluvium and has a variable thickness of 525-750 ft such that the sequence of materials represented by both layers is 800 ft thick globally.

Groundwater Elevations and Boundary Conditions

The base of Layer 2 is defined as a no flow boundary as are the lateral boundaries around the model domain within the bedrock portions of the domain. Water level data is virtually non-existent within the bedrock portions of the watershed therefore it is not possible to characterize any groundwater inflows/outflows that may occur across the watershed boundaries. In most areas the no flow boundary assumption (equivalent to assuming a groundwater divide occurs coincident with surface topography) is likely reasonably accurate, however some locally-significant groundwater inflows/outflows may occur which we are not attempting to represent in our analysis.

Within the alluvium groundwater monitoring data was used to place the model boundaries perpendicular to groundwater flow directions (for representation as no flow boundaries) where possible and to define time-varying fixed head boundaries where the data indicated significant inflow or outflow from outside the study area. Sonoma Resource Conservation District monitored water levels in two wells in the alluvial aquifer area periodically during water years 2016 and 2017. This monitoring work was expanded as part of this project to include 9 wells by May of 2018 and 13 wells by October of 2018 (see Figures 20 & 21). The 13 wells were monitored on a monthly basis using a sounding probe and the data was vertically georeferenced using LiDAR-derived ground surface elevations adjusted for casing heights. As of the time of this reporting, the monitoring effort is still active, however data is only discussed through water year 2019 consistent with the hydrologic model simulation period. In addition to the 13 monitored wells, one California Statewide Groundwater Elevation Monitoring Program (CASGEM) well located across Dry Creek from the Mill Creek confluence provides an additional source of water level data. This well provides longer-term perspective on groundwater elevations in the area going back to 1957.

A series of 17 monthly groundwater elevation contours were interpolated from the monitoring data for May 2018 through September 2019. These data indicate that groundwater elevations in the upper portions of the alluvial aquifer are dominated by inflows from Mill Creek and the surrounding uplands with a dominant flow direction parallel to the creek and towards the northeast. Farther downstream, the influence of Mill Creek dissipates and groundwater elevations are controlled by the regional groundwater flow patterns of the Dry Creek Valley with a dominant flow direction parallel to Dry creek and towards the southeast (Figures 20 & 21). Groundwater elevations in the upper portions of the aquifer exhibit seasonal fluctuations in

water levels on the order of 20 to 25 ft whereas the lower portions of the aquifer experience much more stable elevations with seasonal fluctuations of about 5 ft (Figure 22).

Examination of the groundwater contours and elevations relative to the channel bed indicates that during the spring and summer months Mill Creek is primarily a losing reach throughout its alluvial section. During the May 2018 monitoring period, divergent contours (indicative of losing conditions) predominate throughout the middle and upper portions of the alluvial aquifer and the water table remained connected with the streambed.   Farther downstream as the alluvial aquifer becomes deeper and more gravel-rich, groundwater elevations drop relative to the streambed and are more than 10 ft below the bed by about the mid-point between the Felta and Dry Creek confluences (Figures 18 & 20). As illustrated by the October 2018 monitoring data, groundwater elevations fall below the streambed throughout the alluvial reach by the end of the dry season with approximately 10 ft of vertical separation on average (Figures 18 & 21). Divergent contour patterns are however still evident, in this case indicative of a groundwater mound beneath the streambed formed as a response to the streambed recharge that occurs throughout the spring and summer months.
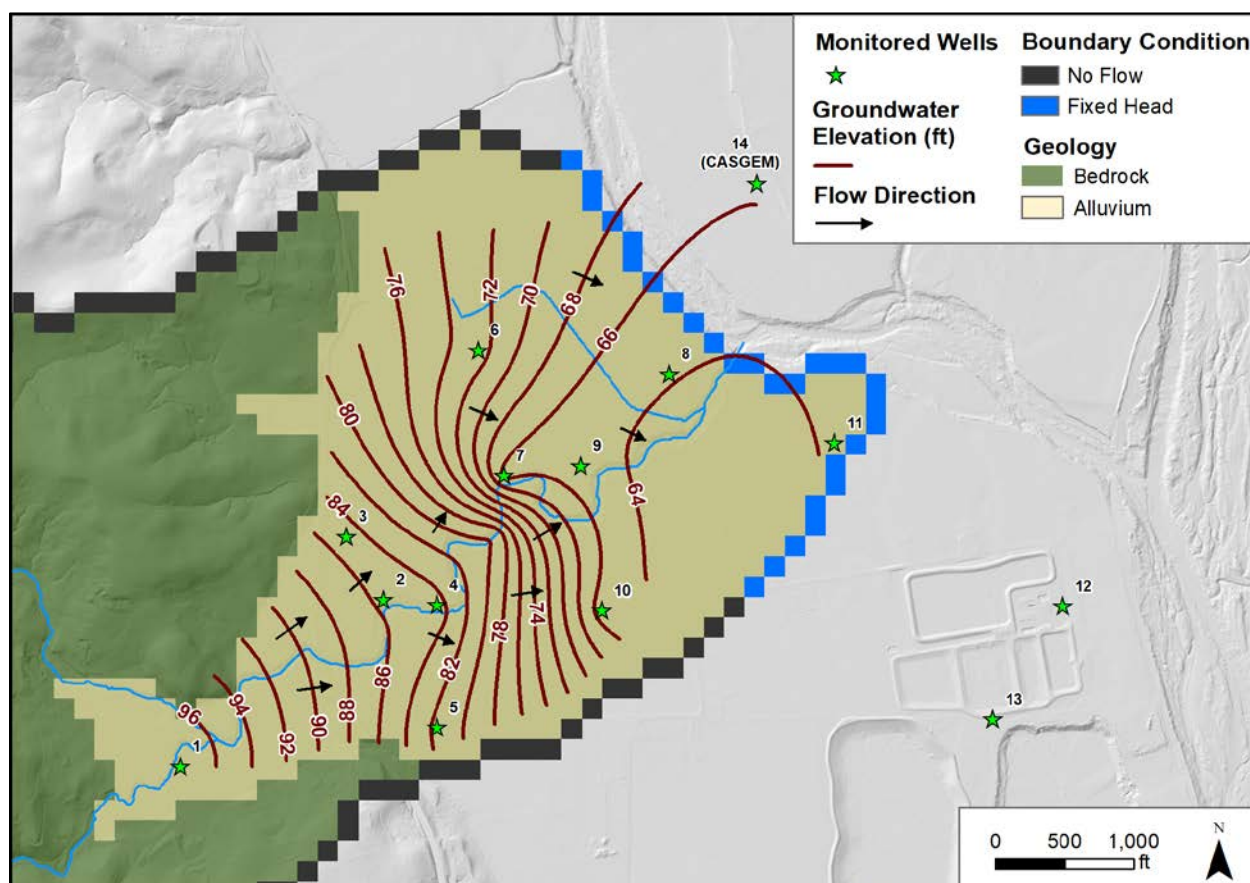
Figure 20: Groundwater elevation contours and approximate flow directions in the alluvial aquifer for May 2018 as well as locations of fixed head and no flow boundary conditions used in the hydrologic model.
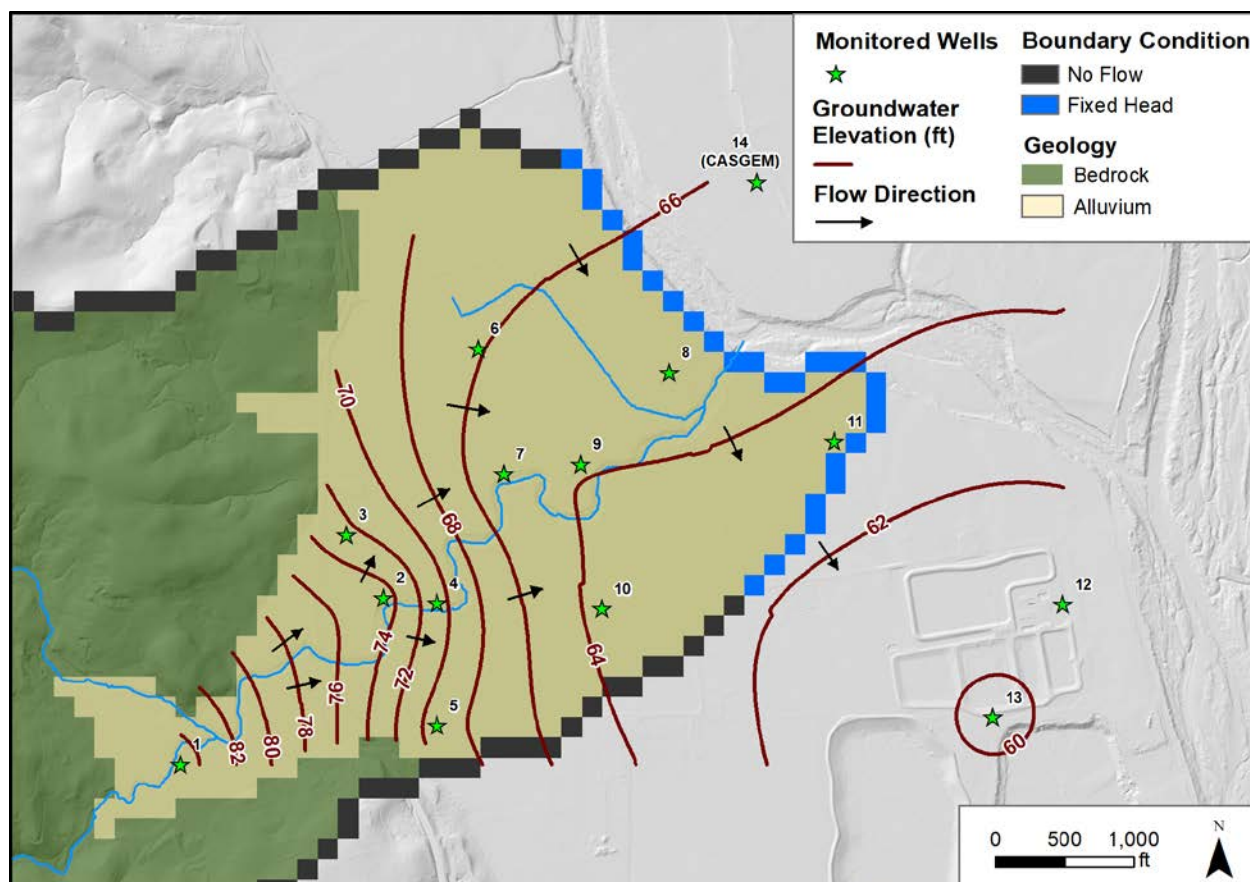
Figure 21: Groundwater elevation contours and approximate flow directions in the alluvial aquifer for October 2018 as well as locations of fixed head and no flow boundary conditions used in the hydrologic model.

Elevations along the boundaries were remarkably similar for the months with data in both 2018 and 2019. At the closest well to the model boundary (Well 11) May groundwater elevations were only 0.7 ft lower after the very dry winter of 2018 versus the very wet winter of 2019 (Figure 22). The measurements from late February 2019 were taken the day after a significant flood event when the vineyards in the lower watershed were flooded, and they indicate atypically high groundwater elevations in the lower portions of the aquifer that returned to near pre-storm levels by the following month's readings.

Examination of the groundwater elevation record at the nearby CASGEM well provides some longer-term perspective on annual and inter-annual fluctuations and indicates a period of declining groundwater elevations from 1957 to 1975 and relatively stable levels from 1986 to present with an intervening data gap (Figure 23). In the earlier period, Spring elevations were consistently 5-10 ft higher than Fall elevations whereas in the recent period, Spring and Fall elevations generally varied by less than 2 ft. The few anomalous years exhibiting higher or lower elevations may be affected by groundwater pumping influences or the timing of the bi-annual readings relative to recharge events.

We hypothesize that the change in groundwater elevations and seasonal fluctuations is related to incision of Dry Creek. In the earlier period, the streambed was likely much less incised than it is today and annual recharge would create large seasonal storage increases in the alluvial aquifer. In contrast, the existing deeply incised channel results in rapid drainage of aquifer recharge and spring elevations that are very similar to fall elevations and within a few feet of the channel bed. Warm Springs Dam was constructed in the period between the two sets of data which may also have played an important role in modifying the aquifer behavior, and changes in groundwater pumping regimes may be an important factor as well.

We sampled the monthly groundwater elevation contours to develop time-varying head boundaries for each of the fixed head boundary cells on a monthly time-step. Given the limited sensitivity of groundwater elevations in the Dry Creek Valley to annual variations in groundwater recharge in recent years, we used the same representative monthly time-series derived from the 2018/2019 monitoring data for each of the 10 years of the simulation.

With the exception of pumping wells which are described in the Water Use section below, all other saturated zone boundary conditions such as infiltration recharge, ET from groundwater, and stream/aquifer interactions are calculated internally by the model through the coupling to other components of the model rather than specified as model inputs.
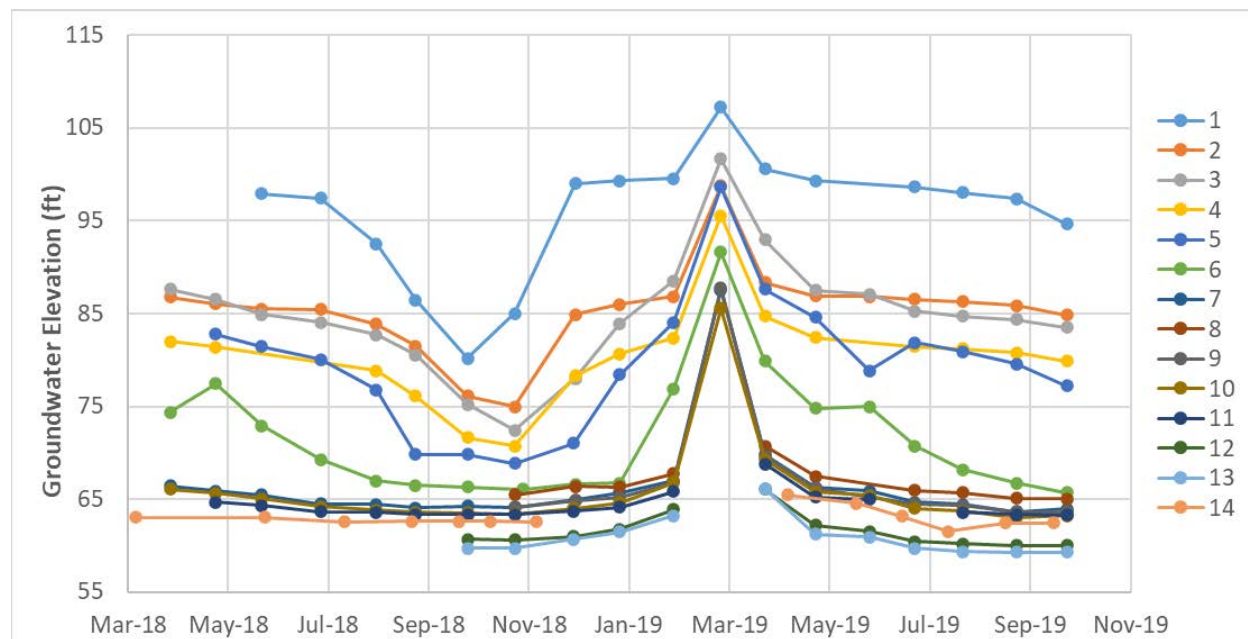
Figure 22: Groundwater elevations at wells monitored in the lower Mill Creek watershed and surrounding areas (see Figures 20 & 21 for locations).
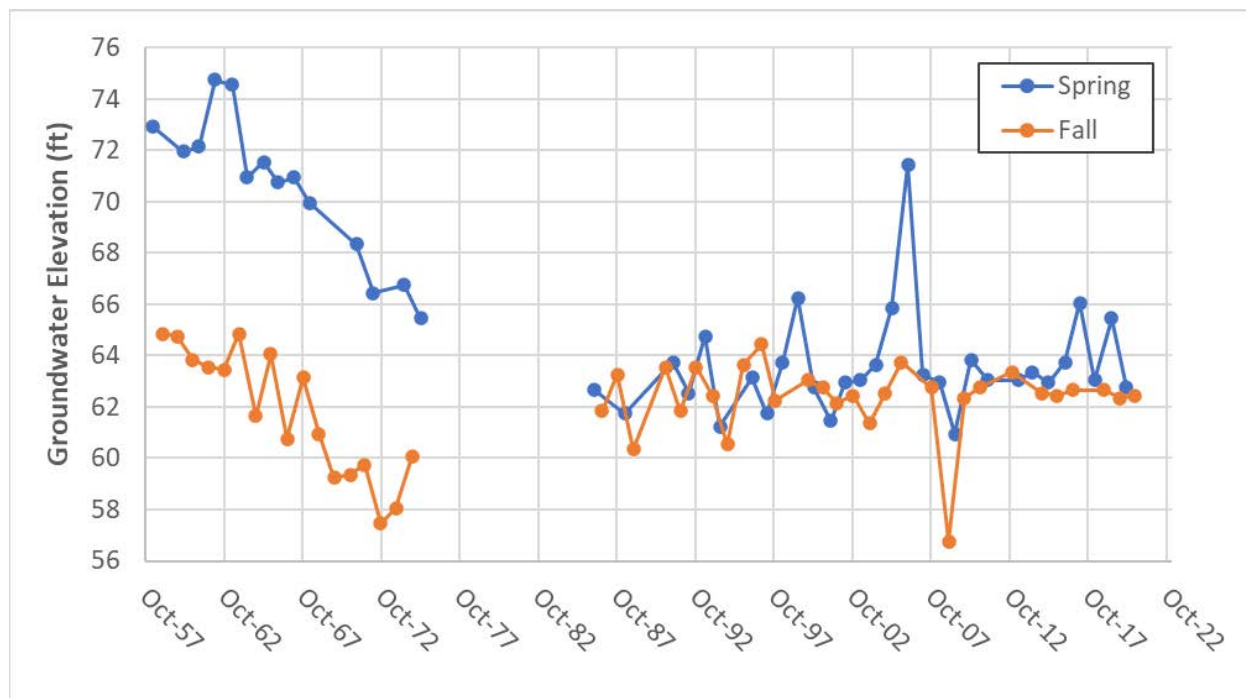
Figure 23: Long-term groundwater elevation record for the lower Dry Creek Valley derived from CASGEM wells #29504 & #52625 (see Figures 20 & 21 for location).

Aquifer Properties

Hydraulic Conductivity Values

We compiled available pump test data collected as part of Sonoma County's regulatory requirements for development in water-scarce areas that culminate in Well Yield Certification (WYC). A subset of ten tests was selected for aquifer analysis based on those tests where 1) the well completion details were known, 2) the test was performed for at least eight hours with a relatively constant pumping rate, 3) drawdowns and pumping rates were reported frequently enough to generate a detailed time-drawdown curve, and 4) the drawdown had stabilized by the end of the test (Figure 16). For the ten tests meeting all criteria, the time drawdown data was analyzed using AQTESOLV software and a type-curve matching approach was used to derive estimates of the aquifer Transmissivity (T). The Storage Coefficient (S) cannot be estimated from single-well test data, therefore we solved for T using a range of reasonable estimates of S from the literature and from our previous experience evaluating aquifer test data in similar geologic materials in the region. Depending on the aquifer conditions and drawdown responses, a variety of solutions were used including radial solutions such as the Theis and Cooper-Jacob solutions (Theis, 1935; Cooper & Jacob, 1946), as well dual-porosity solutions such as the Moench slab blocks solution (Moench, 1984). Where more than one solution provided an equally valid description of the data, final T values were derived by averaging the estimates from the individual solutions.

An additional ten tests also met the afore-mentioned criteria with the exception of the time-drawdown data which was not detailed enough for type-curve matching to drawdown data (Figure 16). For these tests, the specific capacity (Sc) was calculated and used to estimate T and K using an empirical relationship (Driscoll, 1986). We found good agreement between the K values estimated in AQTESOLV and the K values derived empirically using Sc suggesting that the simplified Sc-based approach is capable of providing reasonable estimates of K (Figure 24). The dual-porosity solutions yield an estimate of the hydraulic conductivity (K) directly, and T values from the radial solutions were converted to K estimates using the aquifer thickness as derived from the test data and well completion details (Table 3).

All of the wells with test data are completed in various units of the Franciscan Complex. We found only minor differences between average well completion details and responses to pumping for wells completed in the Coastal Belt versus the Central Belt Franciscan. With the exception of a couple of outliers, well depths fell within a relatively narrow range of 100 to 240 ft, however there was substantial variability in yields (0.8-58 gpm) and specific capacities (0.014-12 gpm/ft).
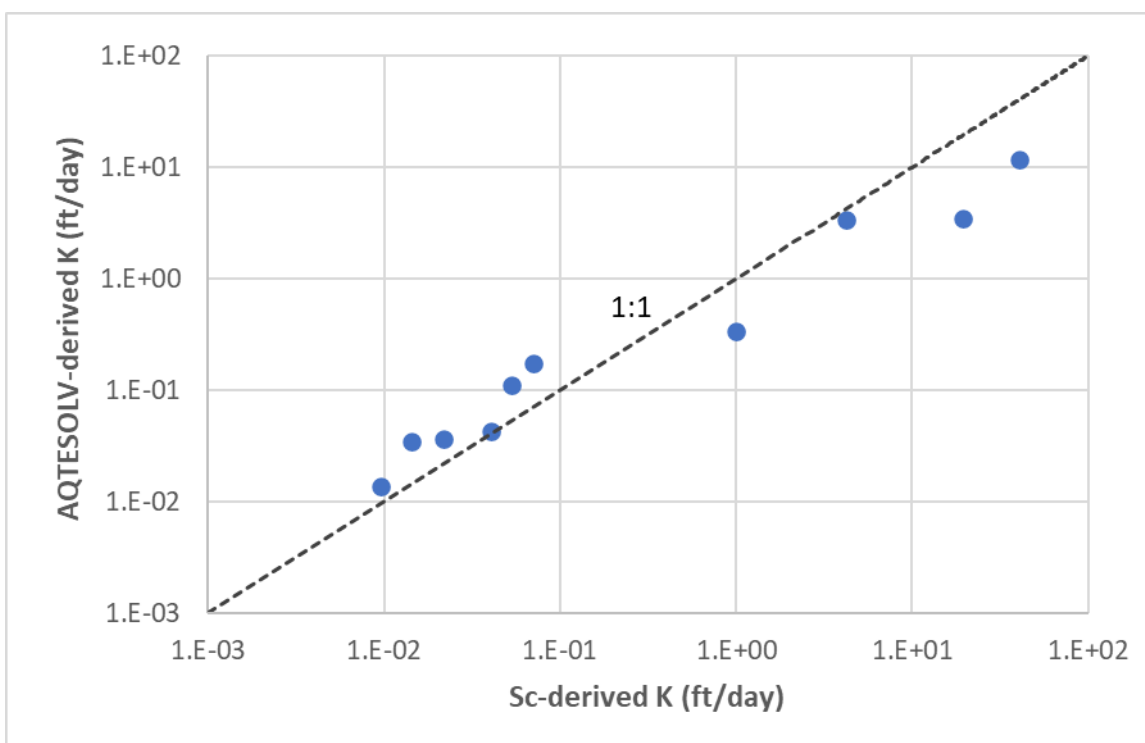
Figure 24: Comparison of estimates of hydraulic conductivity (K) derived from pump test data analyzed in AQTESOLV and calculated based on the specific capacity (Sc).

Table 3: Pump test, well completion details, and estimates of aquifer hydraulic conductivity (ft/day).

	Well Depth (ft)	Drawdown (ft)	Test Length (min)	Average Pumping Rate (gpm)	Aquifer Thickness (ft)	Sc (gpm/ft)	K (ft/day)	Source
Coastal Belt Franciscan	100	31.9	540	16.9	68	0.60	1.8	Sc
	110	53.1	540	5.7	73	0.11	0.32	Sc
	115	31.0	540	2.0	106	0.065	0.13	Sc
	124	9.9	490	0.8	16	0.11	0.053	AQTESOLV
	127	6.5	480	14.0	25	2.2	18	Sc
	140	6.5	510	20.4	81	3.4	4.2	AQTESOLV
	160	130.0	510	4.9	140	0.043	0.040	Sc
	180	8.0	485	28.0	112	3.5	19	AQTESOLV
	186	128.5	715	3.4	153	0.034	0.014	AQTESOLV
	217	84.0	450	21.4	131	0.25	0.40	AQTESOLV
	237	186.5	760	2.4	198	0.014	0.0096	AQTESOLV
	240	141.1	720	3.4	179	0.024	0.028	Sc
	240	5.0	485	58.0	41	12	40	AQTESOLV
Mean	**167**	**63.2**	**556**	**13.9**	**102**	**0.25***	**0.42***	
Central Belt Franciscan	71	31.0	540	1.6	56	0.060	0.22	Sc
	110	2.0	480	22.5	74	11	31	Sc
	160	126.9	720	5.1	146	0.043	0.061	Sc
	173	38.5	485	13.1	62	0.34	1.0	AQTESOLV
	182	136.0	729	4.6	177	0.036	0.022	AQTESOLV
	230	95.1	540	13.5	134	0.14	0.22	Sc
	324	84.7	695	14.5	167	0.18	0.070	AQTESOLV
Mean	**179**	**73.5**	**598**	**10.7**	**116**	**0.19***	**0.28***	
Combined	**171**	**67**	**571**	**13**	**107**	**0.23***	**0.37***	
*geometric mean								

K estimates for the wells varied substantially from 0.0096 to 40 ft/day with a geometric mean of 0.37 ft/day (Table 3). The K values do not appear to correlate with the depths of screened intervals nor do they exhibit any discernable spatial pattern. In some areas, pump tests completed in wells of similar depth and as little as 1,500 ft apart indicate K values that vary by more than three orders of magnitude (Figure 16). The large variability in hydrogeologic conditions is indicative of the fracture flow-dominated system that occurs in the Franciscan

bedrock. Given the lack of discernable spatial pattern to property variations, lack of correlation with depth or subcrop type, and lack of available information describing the distribution and connectivity of fractures, we treated the Franciscan bedrock in a very simplistic manner with uniform hydrogeologic properties. The pump test data provided valuable perspective on the range of plausible hydrogeologic properties to use during model calibration.

No pump test data was available for wells screened within the Sonoma Volcanics, the Glen Ellen Formation, or the Quaternary Alluvium. Pump test data was, however, analyzed for various units of the Sonoma Volcanics as part of a recent study in nearby Mark West Creek. This study found through modeling and pump test analyses that K values in the basaltic units (similar to those found in Mill Creek) are on the order of to 0.053-1.5 ft/day (Kobor et al., 2020). We relied on descriptions of the geologic materials as described in geologic logs on available WCRs to estimate K values for the Glen Ellen Formation and the Quaternary Alluvium from literature values (Domenico & Schwartz, 1990). Our initial estimate of K for the Glen Ellen Formation was 30 ft/day and our estimates of K for the alluvium ranged from 84 to 4,300 ft/day depending on the proportions of coarse and fine materials encountered by the various geologic logs.

A total of 27 wells provided information about the texture of the alluvium, and collectively they indicate high proportions of sand and gravel in both the upstream-most portions of the deposits (above Westside Road) and the lower portions of the deposits in the Dry Creek Valley. In contrast, the deposits in the middle reach downstream of Westside Road (which flow across an alluvial fan) are characterized by significant portions of clay and other fine materials alternating with layers of sand and gravel of varying thicknesses (see Figures 18, 19, & 25).

As described in Chapter 5, the initial K estimates were adjusted within reasonable limits to obtain a good fit between measured and simulated potentiometric surface elevations measured at monitored wells and baseflows as described from stream gauge data. Within the bedrock units, values were adjusted using a uniform scaling factor in order to maintain the degree of contrast between materials as described from the available data. The final calibrated values are ~5% of the original estimates within the various bedrock units which falls within the range of estimates from individual pump tests evaluated in the Franciscan (Table 4). It is plausible that values derived from pump tests over-estimate bulk K values for the large sequences of geologic materials represented by the model layers since most drillers of production wells seek to preferentially screen wells within highly fractured bedrock intervals to maximize well production and efficiency.

Both the spatial distribution and values of K were adjusted within the alluvium as part of the calibration process. The final calibrated values range from 100 to 700 ft/day which is within the range of the initial estimates based on the textural descriptions (Table 4 & Figure 25). Anisotropy in the form of the ratio between horizontal and vertical K was derived through calibration, and the final value was 100 in the various bedrock units and 25 in the alluvium.
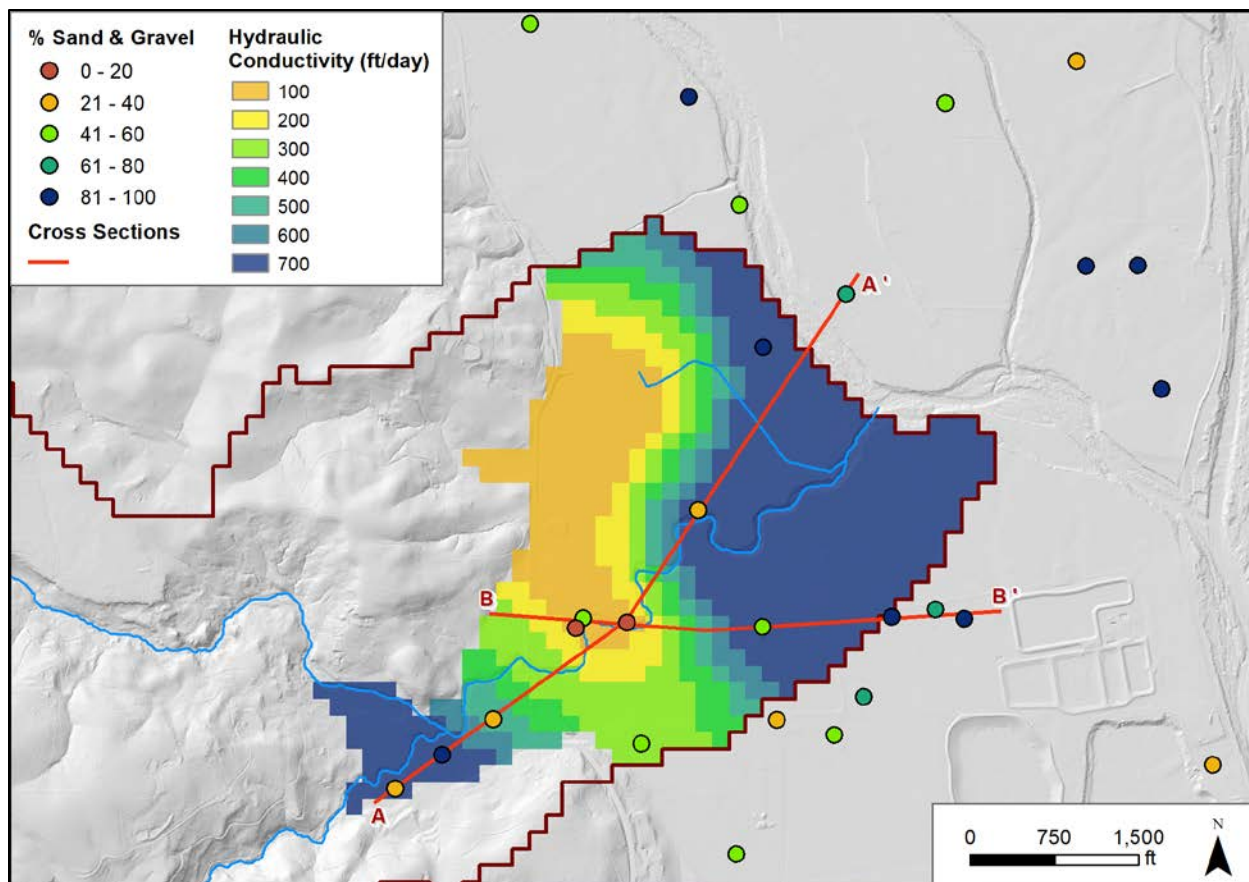
Figure 25: Proportions of sand and gravel at available wells with geologic logs, final hydraulic conductivity (K) values used in the hydrologic model for the alluvium, and locations of hydrogeologic cross sections shown in Figures 18 & 19.

Specific Yield and Storage Coefficient Values

No estimates of Sy were available for the Franciscan Complex or the Alluvium in the study area, thus estimates were based on literature values from similar materials (Freeze & Cherry, 1979; Domenico & Schwartz, 1990). We used values of 0.10 for the Franciscan and values ranging from 0.14-0.25 for the alluvium depending on the texture of the alluvium. Previous estimates of the specific yield (Sy) for the Sonoma Volcanics range from less than 0.01 to 0.05 and estimates for the Glen Ellen Formation range from 0.03 to 0.20 (Cardwell, 1958; Herbst et al., 1982). Our final calibrated value for Sy in the Sonoma Volcanics was 0.05, and we used a value 0.20 for the Glen Ellen (Table 4). Johnson (1977) estimated a Storage Coefficient (S) value of 1.6E-04 (ft^{-1}) for the Sonoma Volcanics, however no estimates of S are available for the other geologic materials in the watershed; therefore, estimates were based on literature values from similar materials (Domenico & Mifflin, 1965; Table 4).

Table 4: Final hydrogeologic properties used in the calibrated Mill Creek hydrologic model.

Material	Present in Layers	Kh (ft/day)	Kh/Kv	Sy	S (ft^{-1})
Franciscan	1 & 2	0.019	100	0.10	1.1E-05
Glen Ellen	1 & 2	1.5	100	0.20	5.1E-05
Sonoma Volcanics	1 & 2	0.070	100	0.05	1.6E-04
Alluvium	1	100 - 700	25	0.14 - 0.25	2.3E-05

Water Use

Water Use Categories and Spatial Distribution

Water uses were calculated on a per parcel basis. We identified the following use categories: Residential, Vineyard Irrigation, Pasture Irrigation, Cannabis Irrigation, Irrigation of Other Miscellaneous Crops, Vineyard Frost Protection, and Winery Production and Visitation Use. The water uses on each parcel were identified using a variety of remotely sensed data and other datasets provided by various governmental entities. Acreages of vineyard, pasture, and other croplands were obtained from the Sonoma County Vegetation Mapping & LiDAR Program's Fine Scale Vegetation and Habitat Map (SCVMLP, 2017). Satellite imagery was reviewed to verify the accuracy of the identified agricultural lands and to identify vineyards planted after 2013 when the underlying LiDAR dataset on which this map is based was collected. In total we found 500.5 acres of vineyard and 12.5 acres of irrigated pasture and other crops (primarily olives).

All vineyards with frost protection systems that use water are required to register with the Sonoma County Agricultural Commissioner's office. Most vineyards in the watershed generally don't require frost protection and some vineyards may also have permanent or portable fans or heaters for frost protection. A review of the Sonoma County Frost Protection Registration database and the SWRCB's 2015 Russian River Information Order (SWRCB Information Order; SWRCB, 2015) revealed that only six parcels within the model domain use water for frost protection. One of these parcels sources water from a well located outside of the study area and another sources water from off-stream ponds outside the watershed leaving four remaining parcels that use water from within the watershed for frost protection of 58 acres of vineyard.

Existing cannabis cultivation operations were identified from registration and permit records from the NCRWQCB and the County of Sonoma. It is common knowledge that many existing operations are not identified in the permit system. To account for water use by unregistered cannabis cultivators, we reviewed publicly-available satellite imagery and identified the size and location of all visible cultivation sites in the watershed. In total we identified 16 parcels with outdoor and hoop-house cannabis operations totaling approximately 1.4 acres of cultivation area. Indoor operations could not be identified by aerial imagery and thus this component of cannabis irrigation use may be under-estimated.

The number of residences on each parcel was obtained from the County of Sonoma's parcel GIS coverage. Census block data from the 2010 U.S. Census provided an estimate of the total population served by water from the watershed. When combined with the corresponding number of residences, this yields an estimate of the average number of people per residence (1.71) which could then be used along with per capita use rates to calculate the total residential use for each parcel. In total there are approximately 415 people served by water obtained from within the watershed.

Winery production volumes and annual guest visitation totals were obtained from a GIS dataset provided by the County of Sonoma. Total winery production for the five wineries in the watershed is approximately 109,000 cases per year. No other industrial water uses were identified in the watershed.

Standard Water Use Rates

Standard use rates were established for the various use categories in the study area using data from the SWRCB Information Order, local municipalities, and literature sources. We examined rates and use categories from the SWRCB Information Order and identified those entries in and around the study area where rates were reported to be based on physical measurements such as totalizer readings or pump fuel usage. In most cases, the method of use estimation was unknown or not based on physical measurements. Given the uncertainty in the accuracy of these estimates, we only relied on those estimates based on physical measurements. In many cases, the reported uses contained a mix of use types (e.g., vineyard irrigation and residential) which prohibited calculation of per acre irrigation or per capita residential use. After careful examination of the data, we were only able to identify three parcels where residential use could be reliably estimated. We were not able to identify any parcels where vineyard irrigation use could be estimated reliably, however data obtained from the City of Healdsburg's recycled water deliveries provided a means of estimating local irrigation rates.

Total annual per capita use calculated for the three residential parcels in the Mill Creek watershed for 2014/2015 ranged from approximately 28,100 to 54,800 gallons (0.086 – 0.168 acre ft/yr). We compared the annual use estimates to data from the nearby Town of Windsor. Based on the available data from the SWRCB's Water Conservation and Production Reports from 2014 to 2018, the average annual per capita use was approximately 26,700 gallons (0.082 acre ft/yr) which is close to the low-end estimate derived from the Mill Creek data and also similar to the mean value estimated for nearby Mark West Creek of 23,100 gallons per capita (Kobor et al., 2020). Due to the small sample size of the local data, the calculated monthly averages are heavily influenced by individual users, whereas the Windsor data is based on thousands of connections and is therefore expected to provide a better estimate of typical use in the area. We relied on the average per capita monthly data from the Town of Windsor to generate use estimates for the model (Table 5 & Figure 26); it is acknowledged that this method may over- or under-estimate actual residential use in the study area.

We obtained recycled water delivery data for 2017/2018 from the City of Healdsburg for four parcels in the Dry Creek Valley totaling 142 acres which provided a very accurate means of

estimating vineyard irrigation rates for the region. The Dry Creek data indicates annual rates ranging from 0.17 to 0.55 ac ft/ac/yr with an average annual total of (0.31 ac ft/ac/yr). Kobor et al. (2020) estimated a very similar rate (0.32 ac ft/yr) for three parcels in nearby Mark West Creek watershed from the SWRCB Information Order (SWRCB, 2015). To provide a more robust estimate of the temporal distribution of vineyard irrigation we calculated monthly mean rates from the three parcels in Mark West plus the four parcels in Dry Creek for use in the model (Table 5 & Figure 27). In the model, vineyards are irrigated from May through October with irrigation peaking at 0.09 acre ft/acre/month in June (Figure 27).

Based on guidance provided by the University of California Davis and Sonoma RCD, the timing of water use for frost protection is based on the wet-bulb temperature (Snyder, 2000; Minton et al., 2017). Wet bulb temperature was calculated on an hourly timestep using air temperature and relative humidity data from the Windsor CIMIS station (Stull, 2011). Frost protection is assumed to occur any time the hourly wet bulb temperature is 0.5°C or lower during the typical March 15th – May 15th frost protection season. The rate at which each parcel uses water for frost protection was calculated as the product of vineyard acreage and reported sprinkler and micro-sprinkler application rates as described in the Sonoma County Frost Protection Registration database (Table 5). Based on these assumptions, the annual number of hours of frost protection ranged from zero in 2017 to 30 in 2012, the average annual application rate was 0.12 ac ft/ac/yr, and the maximum rate was 0.25 ac ft/ac/yr.

Table 5: Standard water use rates and summary of total water use for the various use categories represented in the Mill Creek hydrologic model; the table and model do not include the additional 12.7 ac-ft/yr of recycled water used to irrigate vineyards in the study area but sourced from outside the study area (City of Healdsburg's wastewater treatment plant).

Use Category	Unit Definition	Use per Unit (ac-ft/yr)	# of Units	Total Use (ac-ft/yr)
Residential	Person	0.082	415	34.0
Vineyard Irrigation	Acre	0.32	500.5	160.2
Vineyard Frost Protection	Acre	0.12	58.0	7.0
Pasture/Other Irrigation	Acre	2.00	12.5	25.0
Outdoor Cannabis	Acre	1.34	1.40	1.9
Hoop-house Cannabis	Acre	1.53	0.40	0.6
Winery	1,000 Cases of Wine	0.067	109	7.3
Sum				**235.9**
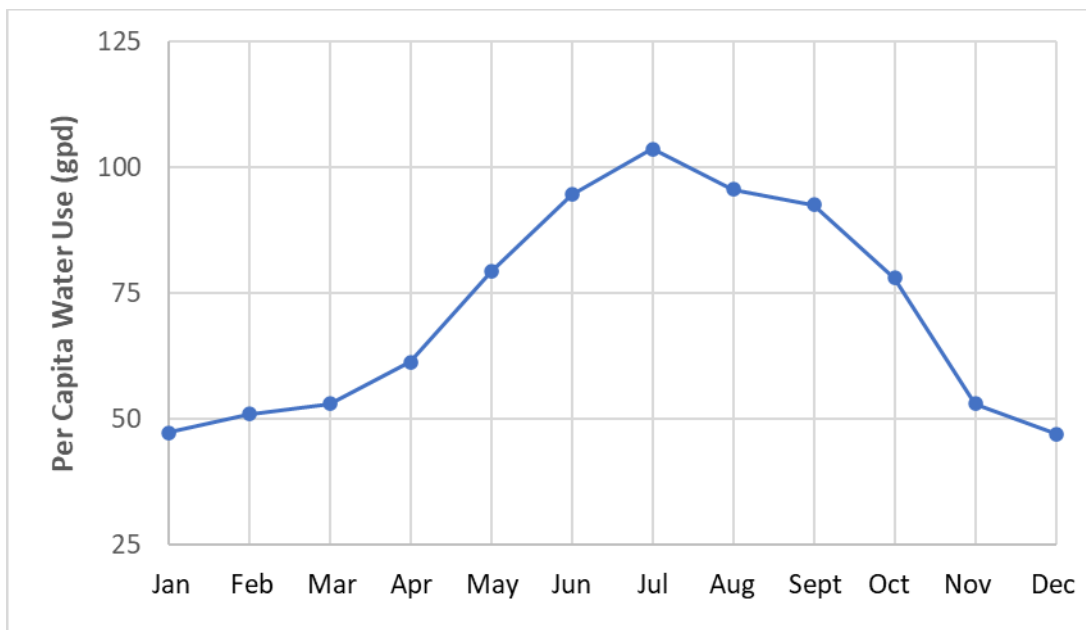
Figure 26: Mean (2014-2018) monthly per capita residential use from the Town of Windsor used to calculate residential use in the Mill Creek hydrologic model.
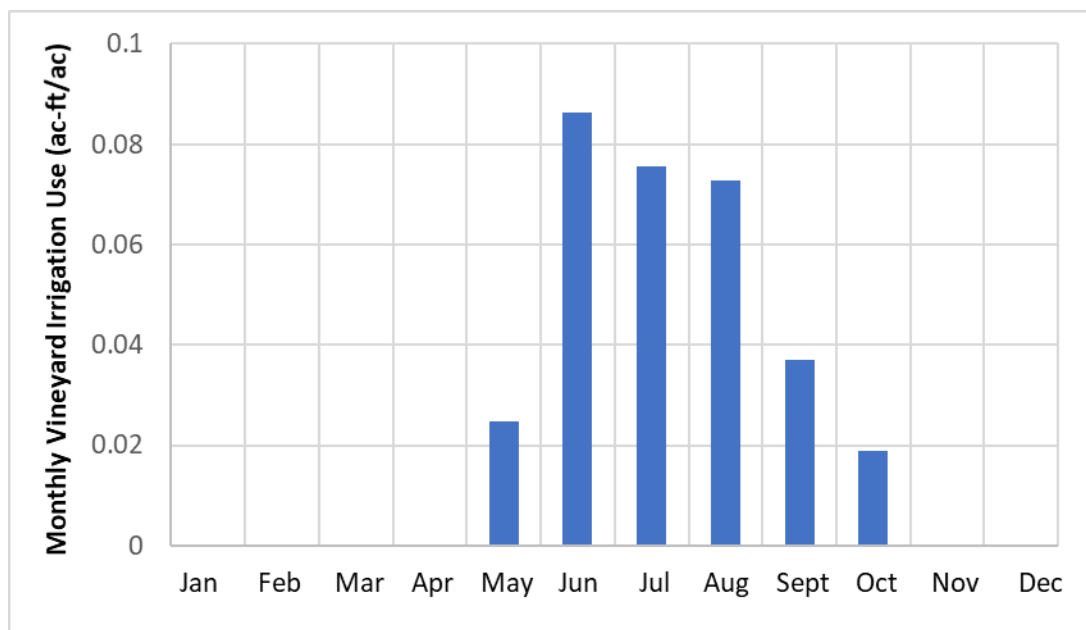
Figure 27: Mean (2014-2015 and 2017-2018) monthly per acre vineyard irrigation use compiled from recycled water delivery data in the Dry Creek Valley and Information Order data in the Mark West Creek watershed and used to calculate vineyard irrigation use in the Mill Creek hydrologic model.

No reliable pasture irrigation rates could be determined from the available data, therefore we relied on a regionally-appropriate value of 2.0 ac ft/ac/yr (County of Napa, 2015). Based on field reconnaissance and review of available aerial imagery and GoogleEarth Street View products, most orchards within the study area are olive orchards which typically do require irrigation and were assumed to be irrigated at rates similar to pasture along with very small acreages of vegetable crops. The total acreage of irrigated pasture, olive orchard, and other crops (besides vineyards) in the study area is only 12.5 acres.

Cannabis use rates are based on cannabis irrigation data collected by the NCRWQCB for Humboldt, Mendocino, and Sonoma Counties. Typical irrigation rates of 1.34 ac ft/acre/yr for outdoor cultivation and 1.53 ac ft/acre/yr for hoop-house cultivation were selected based on a presentation summarizing this data which also provided a monthly distribution of use (Dillis, 2018; Table 5).

Winery production, employee, and guest water use rates were based on the County of Napa's Water Availability Analysis Guidance Document (County of Napa, 2015) (Table 5). The monthly distribution of winery production was taken from the Winery Wastewater Handbook (Chapman et al., 2001). Winery guest use, which is relatively minor within the study area, was assumed to be constant throughout the year (Table 5). SWRCB Information Order rather than on standard rates.

Water Sources
Parcels with surface water diversions were identified from the SWRCB Electronic Water Rights Information Management System (eWRIMS) and the SWRCB Information Order. For unpermitted cannabis cultivation operations where the water source was unknown, we assumed surface water use if there was a perennial stream, spring, or pond located on the parcel. For all other parcels we assumed groundwater use. The only exception to this is for the three parcels in the lower watershed that receive recycled water for vineyard irrigation from the City of Healdsburg's wastewater treatment plant to irrigate a total of 41 acres. Where multiple wells are located on a given parcel, we divided the total use for the parcel between the various individual wells. When eWRIMS or the SWRCB Information Order indicated that a parcel has both surface water and groundwater supplies, surface water diversions were subtracted from groundwater pumping.

After consolidating duplicate records from the various sources, we excluded diversions reported as inactive or with zero use, as well as those where the SWRCB Information Order states use; however, the reported uses are for evaporation losses and recreation or aesthetics rather than for consumptive uses. We extended the model stream network to include all ponds with consumptive uses except for one that had negligible reported use. For spring diversions, we attribute the location of the diversions to the nearest stream in our model, thus treating it as equivalent to a direct diversion. There are a total of 65 surface water diversions in the model, 28 of these are direct stream diversions, 24 are spring diversions, and 13 are diversions from on-stream ponds represented in the model (Figure 28).

Where possible, wells were located at specific locations on a given parcel from location information available on WCRs, the SWRCB Information Order, and in some select cases site visits. The SWRCB Information Order was especially helpful in this regard by providing a means of tying many more wells to specific locations than would have otherwise been possible. Nevertheless, many of the locations reported in SWRCB Information Order data proved to be parcel centroids and it is not possible to locate all wells at a level of detail beyond the parcel scale. More specific location data was used for 125 of the 204 wells in the model, and the remaining wells are located at parcel centroids.

Well completion details could be determined from WCRs for 64 wells and we associated the wells without WCRs with the nearest well with a WCR within the same geologic terrain to estimate well depth and screened interval information for all wells in the model. About 16% of the wells are screened entirely within the upper 50 ft and 27% are screened entirely within the upper 100 ft. About 58% of the wells are screened within the upper 200 ft and 98% are screened within the upper 400 ft. (Figure 28).
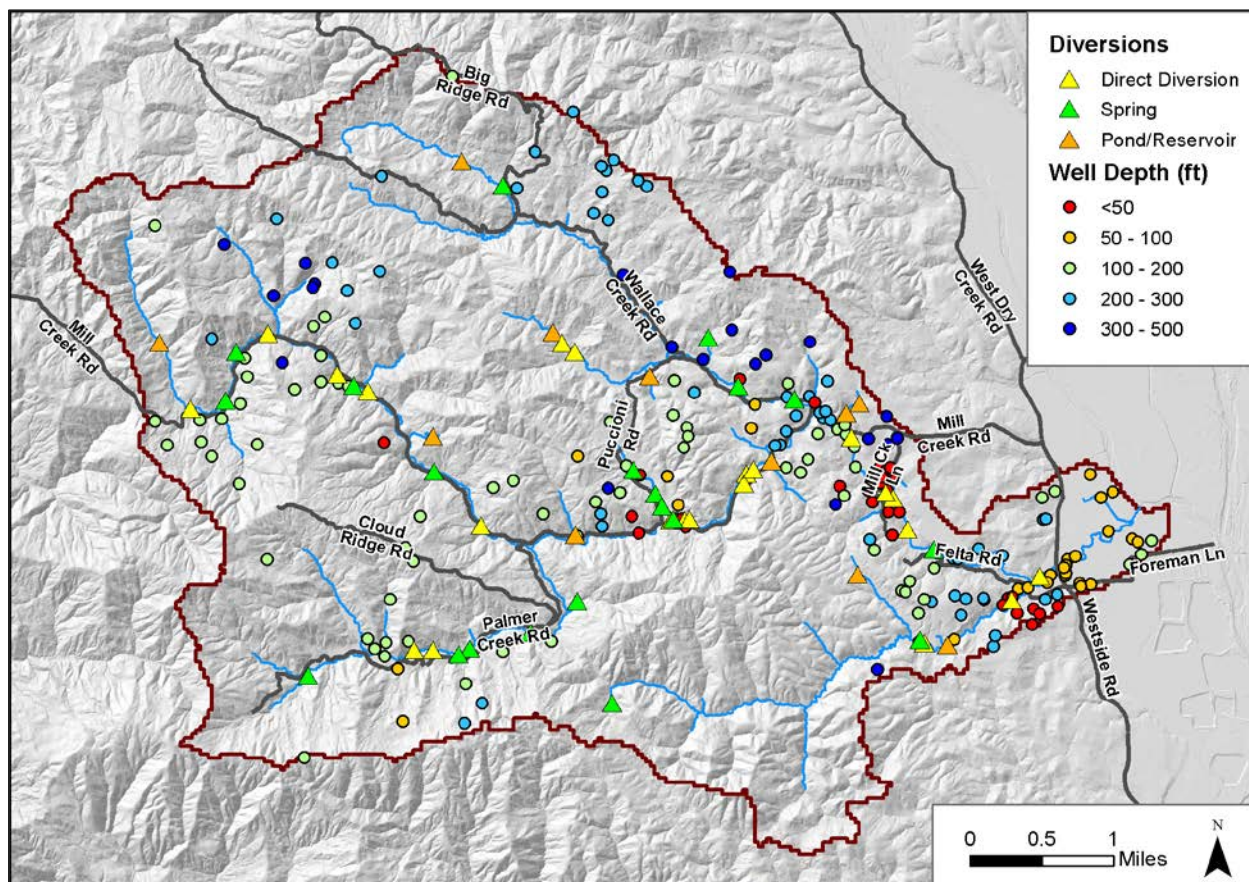
Figure 28: Locations of surface water diversions and groundwater wells in the Mill Creek hydrologic model.

Water Use Timeseries

Surface Water Diversions

Diversion timeseries are based on average monthly diversion volumes. Where possible, reported diversion volumes from eWRIMS and the SWRCB Information Order were used. If reported diversion volumes from the SWRCB Information Order were not based on physical measurements or if no diversion volumes were reported, volumes were calculated using the standard use rates for the uses on a given parcel. The monthly volumes calculated for each diversion are used to calculate a diversion timeseries. These timeseries were calculated on a 6-hour timestep and account for pumps shutting on and off and the estimated capacities of these pumps. A 6-hour timestep was selected to provide a reasonable representation of sub-daily variability while maintaining reasonable computational efficiency. Separate pumping regime assumptions are made for direct diversions and for spring and pond diversions.

Direct diversions were assumed to fill storage tanks completely and then resume once these tanks had been partially emptied. Based on storage tank sizes reported in the SWRCB Information Order, the typical tank size for a residence with a direct diversion is approximately 3,000 gallons. Such a tank would need to be filled completely twice a month to supply a typical residence, or approximately four times per month if the tank were only partially emptied. Less data is available for agricultural tank sizes but the limited data supports use of a similar pumping frequency. Consequently, direct diversions were assumed to divert a fraction of the monthly volume on the 1st, 8th, 15th, and 22nd of each month. Some diversion volumes were met using the assumed pumping rates with less than four pumping events per month, in which case they are only active 1-3 times per month depending how quickly the demand is met for each month. For larger demands, the four per month diversion periods were assumed to continue for as long as necessary based on the diversion rate. Typical spring and pond diversions deliver water in near real-time and thus do not require large storage tanks. This results in more frequent, shorter-duration pumping intervals relative to direct diversions. Therefore, daily use was calculated from the monthly volumes and all daily use was considered to be supplied during a single 6-hour timestep.

In addition to developing estimates of the frequency and duration of diversions, it is necessary for modeling to assume a start time. There is likely little to no coordination between diverters regarding the timing of pump activation, and probably some general tendency for coincident pumping due to coincident timing of irrigation demands and work schedules. We made the conservative assumption that all diversions start simultaneously at the beginning of the day, and the diversions on weekly schedules all occur on the same days. These various assumptions result in a maximum instantaneous diversion rate on the 1st of each month, and spikes in rates at regular intervals which is considered to represent a 'worst case' diversion timing scenario (Figure 31).

Where possible the diversion rates used to calculate the diversion timeseries were obtained from eWRIMS or the SWRCB Information Order. However, most diversions rates were either not reported or the reported rates were not realistic given the reported units. Where specific rates were not available, standard rates were used as derived from reported rates in the SWRCB
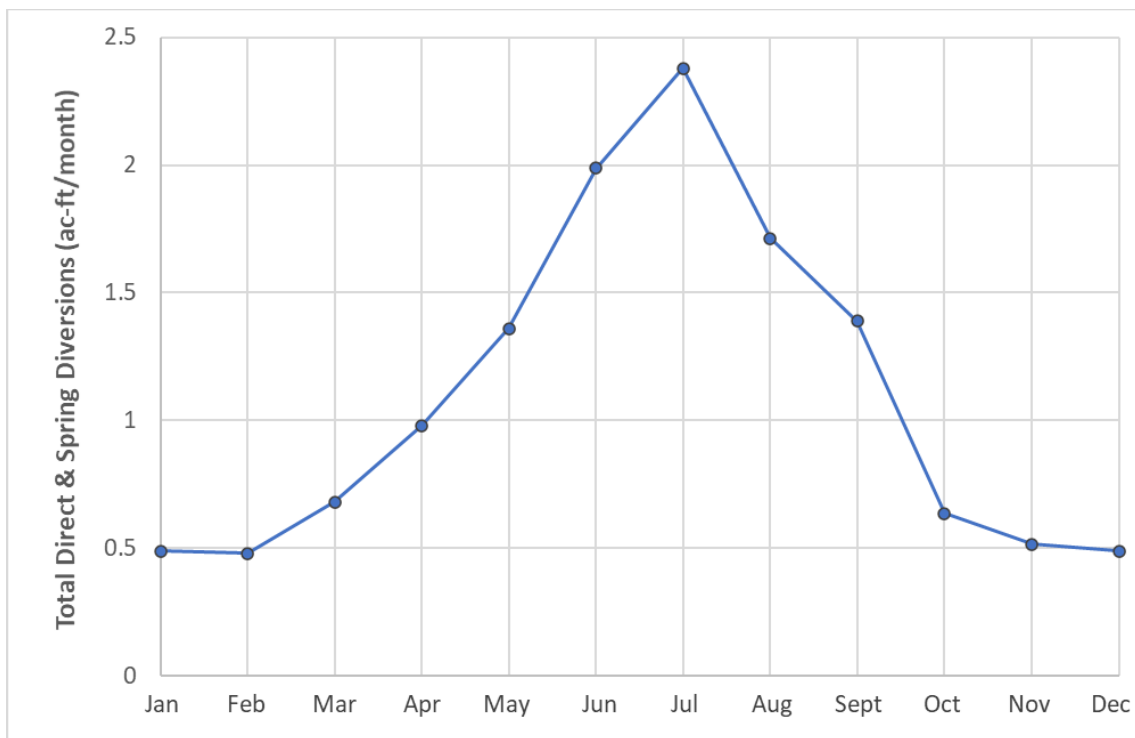
Figure 29: Total monthly direct and spring diversion volumes used in the Mill Creek hydrologic model.
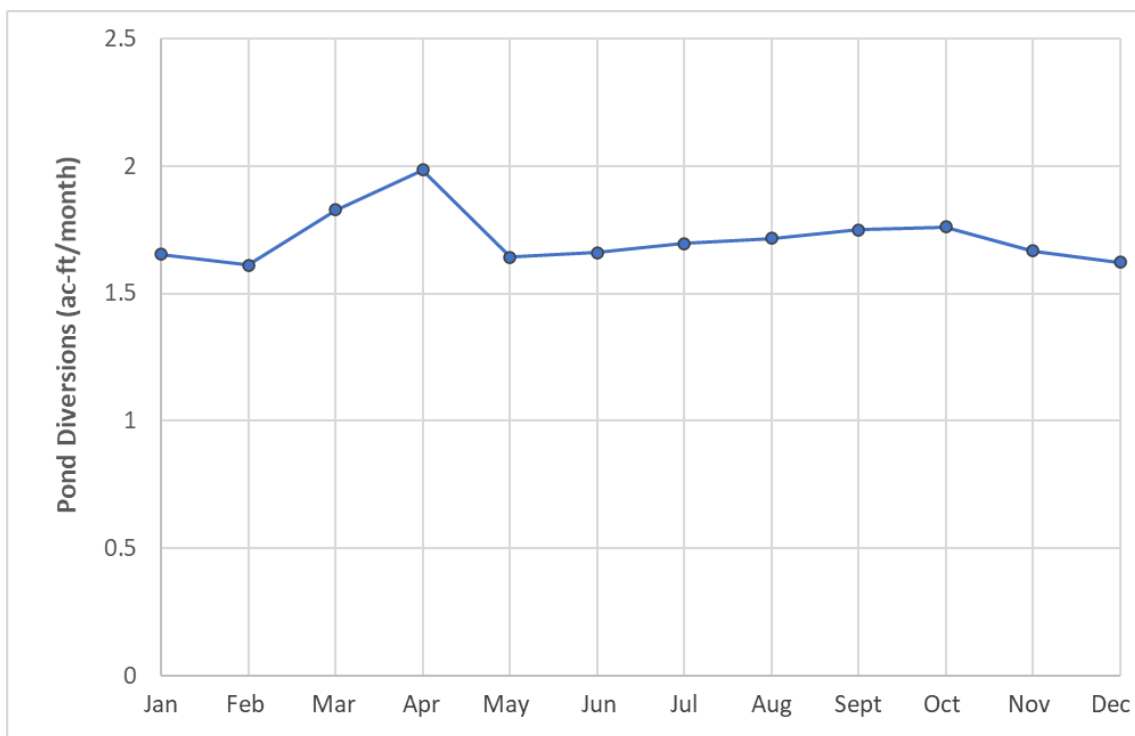
Figure 30: Total monthly pond diversion volumes used in the Mill Creek hydrologic model.
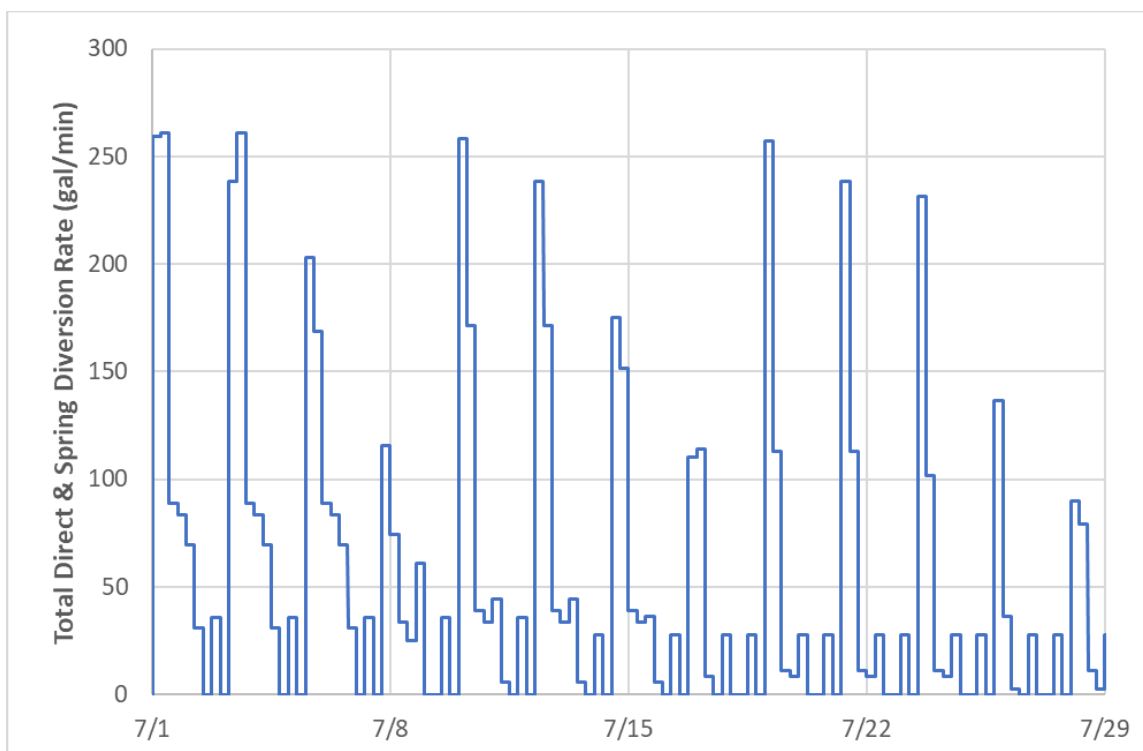
Figure 31: Example of the 6-hr interval timeseries of total direct and spring diversions used in the Mill Creek hydrologic model for July of 2010.

Information Order that were based on actual physical measurements. Standard rates were derived for two diversion types: domestic/small agricultural operations and larger agricultural operations. We combined our analysis of the SWRCB Information Order data for Mill Creek with analysis of the data for Mark West Creek where we completed a similar modeling study (Kobor et al., 2020), and we also restricted the selected entries to include only those based on physical measurements. Based on twelve diversions from the Mill and Mark West Creek Watersheds, the typical residential and small agricultural diversion rate is estimated to be 2.69 gpm (0.006 cfs). Diversion rates for larger agricultural operations varied greatly but typically ranged between 0.01 and 0.03 cfs and a typical diversion rate of 9.0 gpm (0.02 cfs) was used. A monthly timeseries of the total direct and spring diversion volumes and the total pond diversion volumes in the model are shown in Figures 29 and 30, and an example of the 6-hr interval total direct and spring diversion timeseries for July 2010 is shown in Figure 31.

Groundwater Wells

Wells are assumed to be pumped on a daily basis to either supply water in real-time or top off a tank. The groundwater pumping timeseries was calculated by converting estimated monthly volumes to a daily demand and pumping each well at its estimated yield until this daily demand was met. This timeseries was calculated on an hourly timestep consistent with the hourly timestep used to drive the groundwater component of the model. Estimated yields for wells completed in bedrock materials are based on pump test data associated with Well Yield
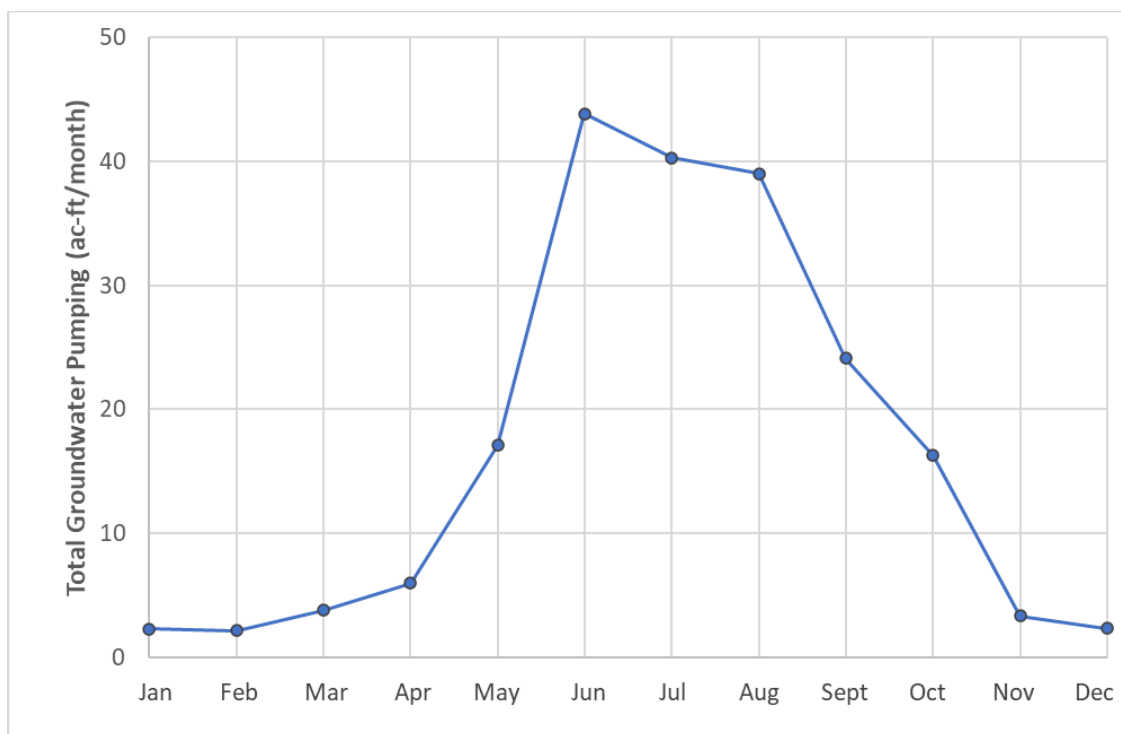
Figure 32: Total monthly groundwater pumping volumes used in the Mill Creek hydrologic model.
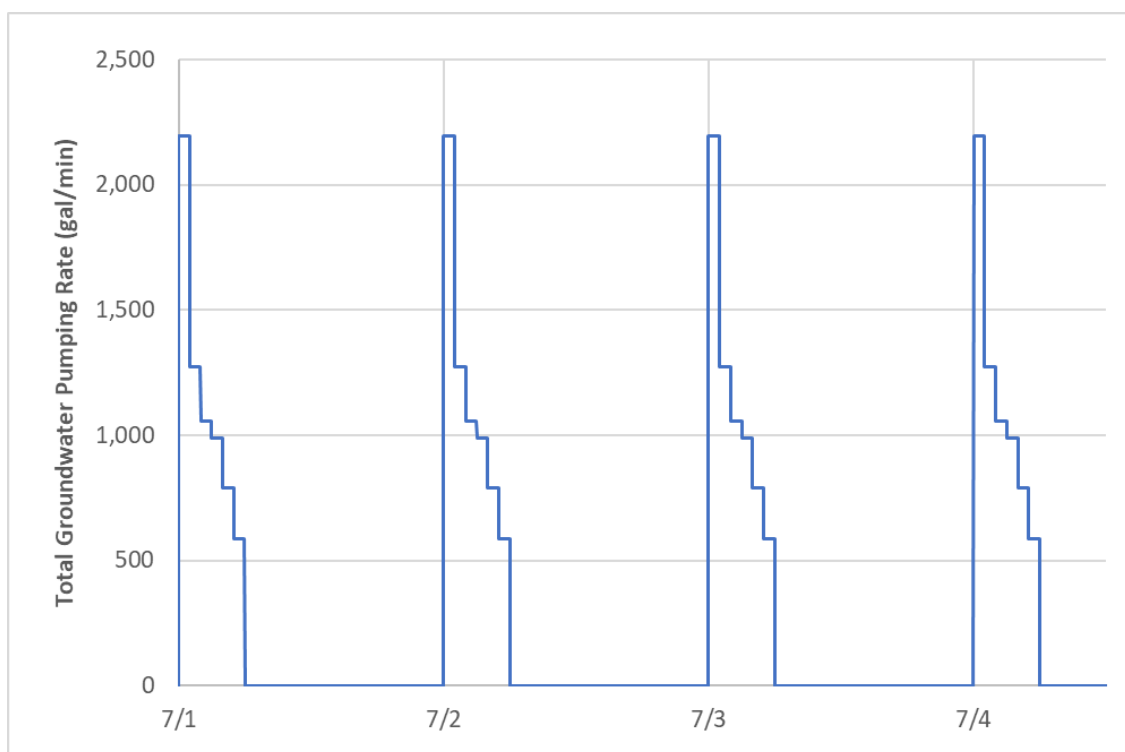
Figure 33: Example of the 1-hr interval timeseries of total groundwater pumping in the Mill Creek hydrologic model for a 4-day period in early July.

Certifications obtained from the County of Sonoma as analyzed and discussed in the Aquifer Properties section. Estimated yields for wells completed in the alluvium were based on reported pumping rates from available Well Completion Reports. Typical yields of 10.4 gpm and 30.0 gpm were calculated for the Franciscan and other bedrock units and for the alluvium respectively.

The only component of pumping that varies in the model from year to year is the frost protection pumping which accounts for a relatively small component of the total pumping. A monthly timeseries of the total groundwater pumping volumes applied in the model is shown in Figure 32 and an example of the hourly total pumping timeseries for a 4-day period in early July is shown in Figure 33.

Water Use Summary
Total water use from all sources in the watershed is estimated to be approximately 248.6 ac ft/yr. The largest use is vineyard irrigation which accounts for about 68% of the total water use (Table 5 & Figure 34). Residential use (14%) and irrigation of pasture and olive orchards (11%) accounts for most of the remaining use. The remaining 7% consists of vineyard frost protection (3%), winery use (3%), and irrigation of cannabis (1%) (Table 5). About 81% (200.7 ac ft/yr) of the total use in the watershed is from groundwater, 14% (35.2 ac ft/yr) is from surface water sources, and 7% (12.7 ac ft/yr) is derived from recycled water delivered to irrigate vineyards on four parcels in the lower watershed (Figure 34). About 61% (21.6 ac ft/yr) of the total surface water use comes from pond storage, 31% (10.9 ac ft/yr) comes from direct stream diversions, and 8% (2.6 ac ft/yr) comes from springs.

Direct stream and spring diversions occur throughout the bedrock reaches of main-stem Mill Creek and Palmer Creek as well as in lower Wallace and Felta Creeks (Figure 28). The distribution of wells reflects the pattern of development in the watershed which has occurred along the major roads in the watershed which generally follow the paths of the major stream channels. Well development is also concentrated in the middle and lower portions of the watershed (Figure 28).

Irrigation
The water extracted from wells and surface water diversions for irrigation of vineyards, pasture, and other crops is applied to the land surface as irrigation in the model (see Figure 9 for locations of irrigated crops in the model). The monthly application volumes match the standard use rates as discussed above. Based on previous work with vineyard operators in Sonoma County, vineyards are typically irrigated at intervals of about one week to one month. We assumed a twice-monthly irrigation schedule and developed our irrigation timeseries by distributing the monthly volumes between the two irrigation events each month. We assumed a similar irrigation frequency for pasture and other irrigated crops in the model. Although many vineyard operators use a block rotation schedule for irrigation, the twice-monthly schedule accounts for the temporal effects of irrigation on soil moisture and is decoupled in time from the extraction of that water which is based on assumed pumping rates and tank storage volumes as discussed above. We did not apply water used for cannabis as irrigation in the model since cultivation areas are generally smaller than the 0.5-acre grid scale and many cultivators use pots or fabric bags

which limit the potential for interaction with surrounding soils. Water for frost protection of vineyards was also applied back to the land surface as irrigation in the model in real-time based on the calculated demand as discussed above.
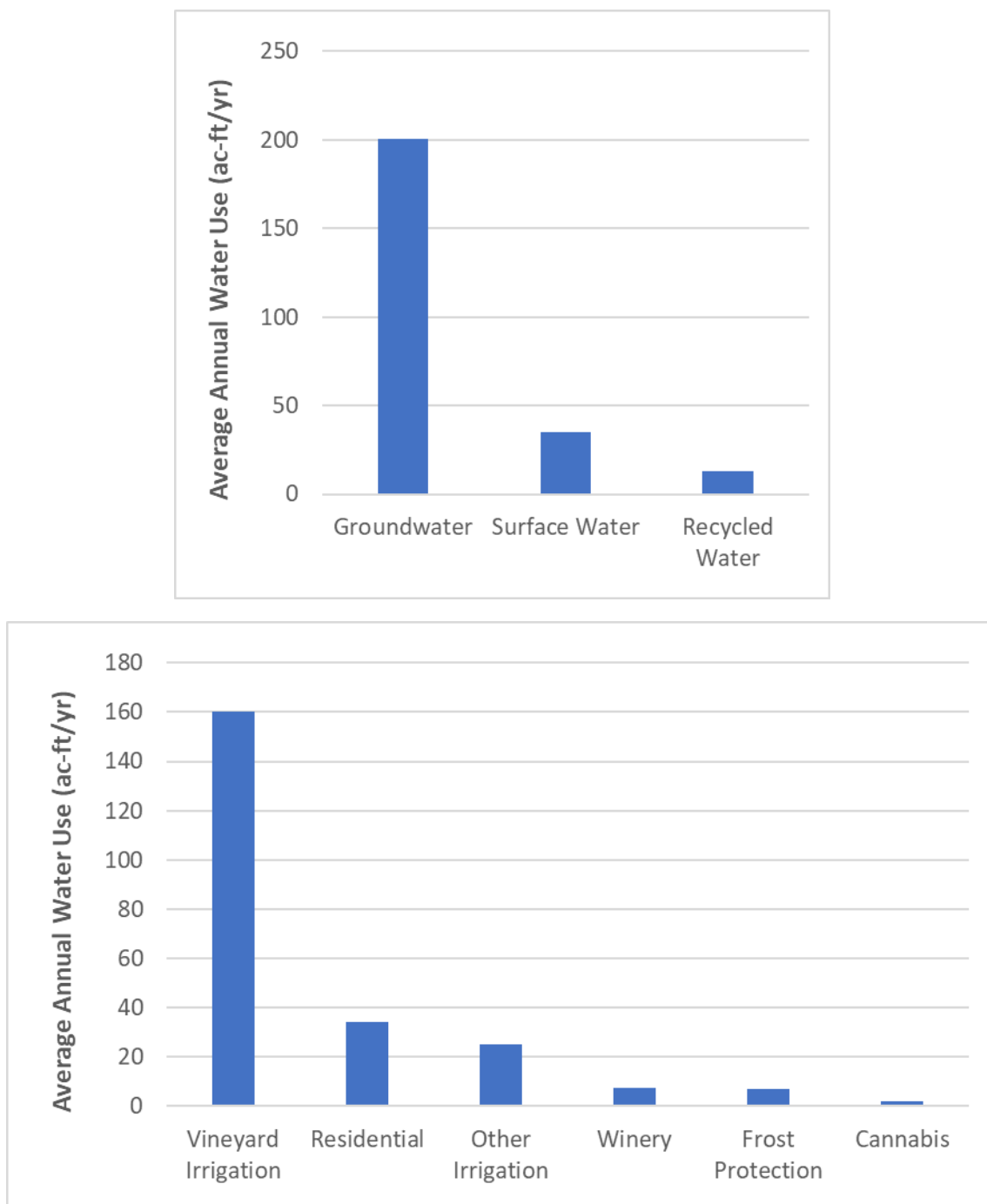
Figure 34: Breakdown of total water use in the Mill Creek hydrologic model by water source (top) and water use category (bottom).

Chapter 5 – Model Calibration

Calibration of a distributed hydrologic model like MIKE SHE is complicated by the large number of inter-related process and parameters involved. Previous modeling experience indicates that results are most sensitive to a relatively small subset of the model parameters including the overland flow detention storage and roughness, unsaturated zone saturated hydraulic conductivity and available water capacity, interflow drain level, groundwater hydraulic conductivity, and the streambed leakage coefficient. The calibration focused on adjusting these seven parameters within a range of plausible values to obtain the best fit to measured discharge, groundwater elevation, and wet/dry mapping data.

Available Data

Several stream gauges have been operated in the watershed at various times over the past ten years including a series of gauges installed in 2010 and 2011 by the Center for Ecosystem Management and Research (CEMAR–no longer in existence). Some of the CEMAR gauge sites were re-occupied by Trout Unlimited (TU) in 2018 along with development of new gauging sites.

Despite the relatively large number of stream stage (i.e. water elevation) sensor records available, most of the available data is only from the past few years and development of stage-discharge rating curves and discharge measurements had been collected only during the low flow season. Thus, prior to this study, no continuous rating curves or streamflow (i.e. discharge) records at gauge sites extending through the winter rainy season had been developed in the watershed. To fill this critical data gap we selected three sites on main-stem Mill Creek for additional streamflow gauging and rating curve development. One site is in the upper watershed at a location known as Bear Flat, one site is located above the Wallace Creek confluence in the central portion of the watershed, and a third site is located between the Wallace and Felta confluences above the high-gradient reach known as 'the falls' (Figure 35).

We measured discharges at moderate to high flows at the three sites during rainy seasons of water years 2018 and 2019 which were complemented by measurements taken by TU during periods of lower flow, approximately May–October. For lower flows when it was safe to wade the stream, we used standard USGS wading techniques and a topset rod and flow meter (USGS 2010). For higher flows we standard USGS techniques with a bridge crane and a flow meter. We obtained the discharge measurements collected by CEMAR from earlier gauge locations which operated for various lengths of time between spring of 2010 and fall of 2016. No information was available with which to vertically georeference the original CEMAR pressure transducer data, therefore it was not possible to integrate the earlier CEMAR data with the newer TU/OEI data for the sites for the purposes of rating curve development. Sufficient streamflow measurements were, however, available to allow for rating curve and streamflow record development for flows up to about 5 to 20 cfs for most years between 2010 and 2016, providing for good representation of the May through September low flow season.
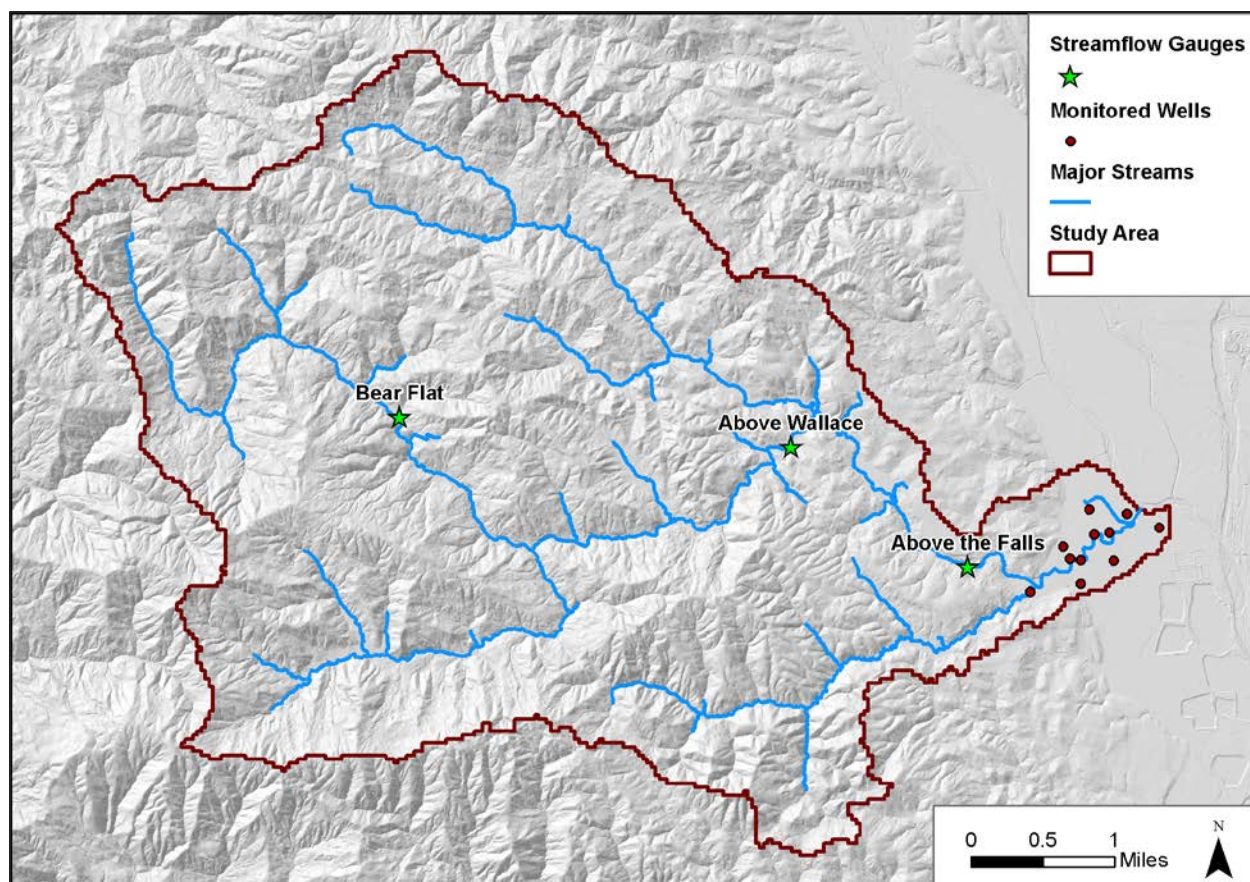
Figure 35: Locations of streamflow gauges and groundwater wells used for calibration of the Mill Creek hydrologic model.

We were unable to obtain sufficient high flow measurements to allow for comprehensive rating curve development at the Bear Flat and Above The Falls sites. Timing measurements relative to short-duration peak flows was a challenge at the Bear Flat site, and excessive turbulence resulted in suspect velocity readings during high flow gauging at the Above The Falls site. At the middle site (Above Wallace) we were able to obtain enough accurate flow measurements covering a sufficient flow range to allow for continuous rating curve and flow record development. The resulting flow record covers all of water year 2018 and 2019. Flow measurements collected by OEI and TU at the other two sites were sufficient to allow for low flow rating curve development and generation of streamflow records for May–September of 2018 and 2019.

In addition to streamflow data, periodically repeated observations of the spatial extent of continuous flow, intermittent flow, and dry channel conditions (referred to as 'wet/dry mapping') collected by California Sea Grant (CSG) provided a supplemental source of calibration data. Wet/dry mapping data was collected at least once per year each year since 2013. In 2017-2020, mapping was performed at approximately 2-week intervals between May and October. We selected six wet/dry maps with more complete spatial coverage that were representative of the

range of observed flow conditions for performing model calibration. Data from September 2014, July 2015, and September 2015 describe conditions during dry years, data from October 2016 describes conditions during a near average year, and data from June and October 2017 describe conditions during a wet year. For purposes of this comparison, we considered flows less than 0.01 cfs as equivalent to a field condition of dry and flows less than 0.10 cfs as equivalent to a field condition of intermittent.

As discussed earlier, SRCD has been monitoring groundwater elevations in 13 wells in and near the lower Mill Creek watershed on a monthly basis since March 2018 (Figure 22). Eleven of these wells are located within the model domain and provided a means of calibrating the groundwater component of the model within the lower Mill Creek alluvial aquifer (Figure 35). A complete lack of available groundwater monitoring data in the upper bedrock portions of the watershed prohibited direct calibration of the groundwater component of the model in these areas.

Streamflow Calibration

Five goodness-of-fit statistics were used to evaluate the agreement between model simulated stream discharges and measured stream discharges. These statistics included the Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), the total Percent Volume Error (PVE), and the Nash-Sutcliffe model efficiency coefficient (NSME) (Nash & Sutcliffe, 1970). MAE and RMSE provide information on the overall accuracy of the model, and ME and PVE provide information about model bias. The NSME provides an overall measure of the predictive capability of the model. A NSME value of zero indicates that model predictions are as accurate as the mean of the measured data and a value of one indicates a perfect calibration. ME, MAE, and RMSE have been calculated at all three gauges for the May through September low flow period (2010 – 2019) and for the full period of record at the Above Wallace location (water years 2018 and 2019). The PVE and NSME have only been calculated for the continuous data at the Above Wallace station since it they are not well-suited for describing data with limited temporal variability such as spring/summer baseflow recessions. To avoid the May through September statistics for calibration being skewed by a handful of days with storm runoff, we defined an upper threshold below which to calculate statistics more representative of the model's ability to predict flow recession and baseflow. The thresholds were 4 cfs, 6 cfs, and 10 cfs at the Bear Flat, Above Wallace, and Above the Falls gauges, respectively.

Due to the limited period of record, it was deemed appropriate to calibrate the model to all of the available data rather than divide the simulation into calibration and validation periods as is more typically done when long-term gauging data is available. Figure 36 shows the comparison between model-simulated and measured discharges at the Above Wallace sites for the full period of record, and Figures 37 through 39 show the comparison between model simulated and measured discharges at all three sites for just the May through September low flow season that is particularly critical from the perspective of salmonid habitat.

The agreement between simulated and measured stream flows was generally good at the Above Wallace station where continuous data was available (Figure 36). The model reproduces the

quick flow responses in stream flow during runoff events that is characteristic of the watershed and the overall shape of rising and receding flows. Peak flows are captured reasonably well; however, there is a tendency to over-predict peak flows during smaller runoff events. Simulated storm recession limbs fall more steeply in the model compared to the measured data, however the magnitudes of baseflows and the low-flow recession in the spring and summer are generally well-captured in the model. The ME and RMSE values for the calibration to the 2-yr continuous record were -1.7 and 67.4 cfs respectively. The NSME was 0.70 and the PVE was -6.4%. We established targets for successful calibration as a NSME value of 0.60 or greater and a PVE of +/- 10%, both of which were met (Table 6).

During low flow periods most critical for characterizing coho habitat as a function of streamflow, the model performance is also generally very good at all three stations with available May through September flow data. The shape and timing of the spring flow recession is well captured in most cases as are the magnitudes of summer baseflow. There is a tendency to under-predict spring recession flows during the wetter water years such as 2011 and 2019, as well as a tendency to over-predict late summer baseflows during the drier years such as 2014 and 2015 (Figures 37-39). MAE values for the May through September low flow period ranged from 0.06 cfs at the Bear Flat gauge to 0.13 cfs at the Above the Falls gauge and RMSE values ranged from 0.45 cfs at the Bear Flat gauge to 0.72 cfs at the Above the Falls gauge (Table 6). We established a target for successful calibration of the low flow data as a MAE of 0.20 cfs or less and achieved significantly lower errors indicating a successful model calibration to the available May through September low flow data (Table 6).

Table 6: Streamflow calibration statistics for the Mill Creek hydrologic model.

Period	Gauge	Drainge Area (mi^2)	# of Daily Observations	ME (cfs)	MAE (cfs)	RMSE (cfs)	PVE (%)	NSME
Full Record	Above Wallace	11.5	723	-1.7	3.7	67	-6.4%	0.70
	Bear's Flat	4.2	871	-0.19	0.06	0.44	-	-
May - Sept	Above Wallace	11.5	974	-0.14	0.13	0.70	-	-
	Above the Falls	18.3	552	-0.23	0.08	0.72	-	-
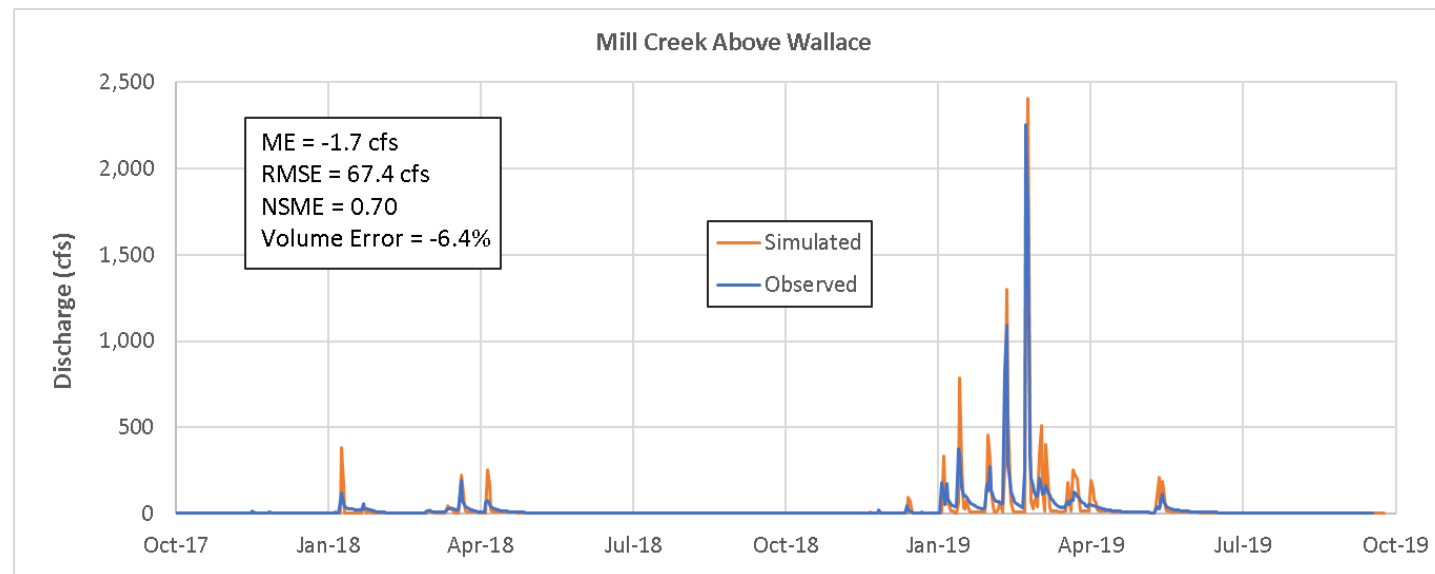
Figure 36: Comparison between model simulated and observed streamflow for the water year 2018 – 2019 period of record with continuous data at the Mill Creek Above Wallace Creek gauge.

Mill Creek At Bear Flat
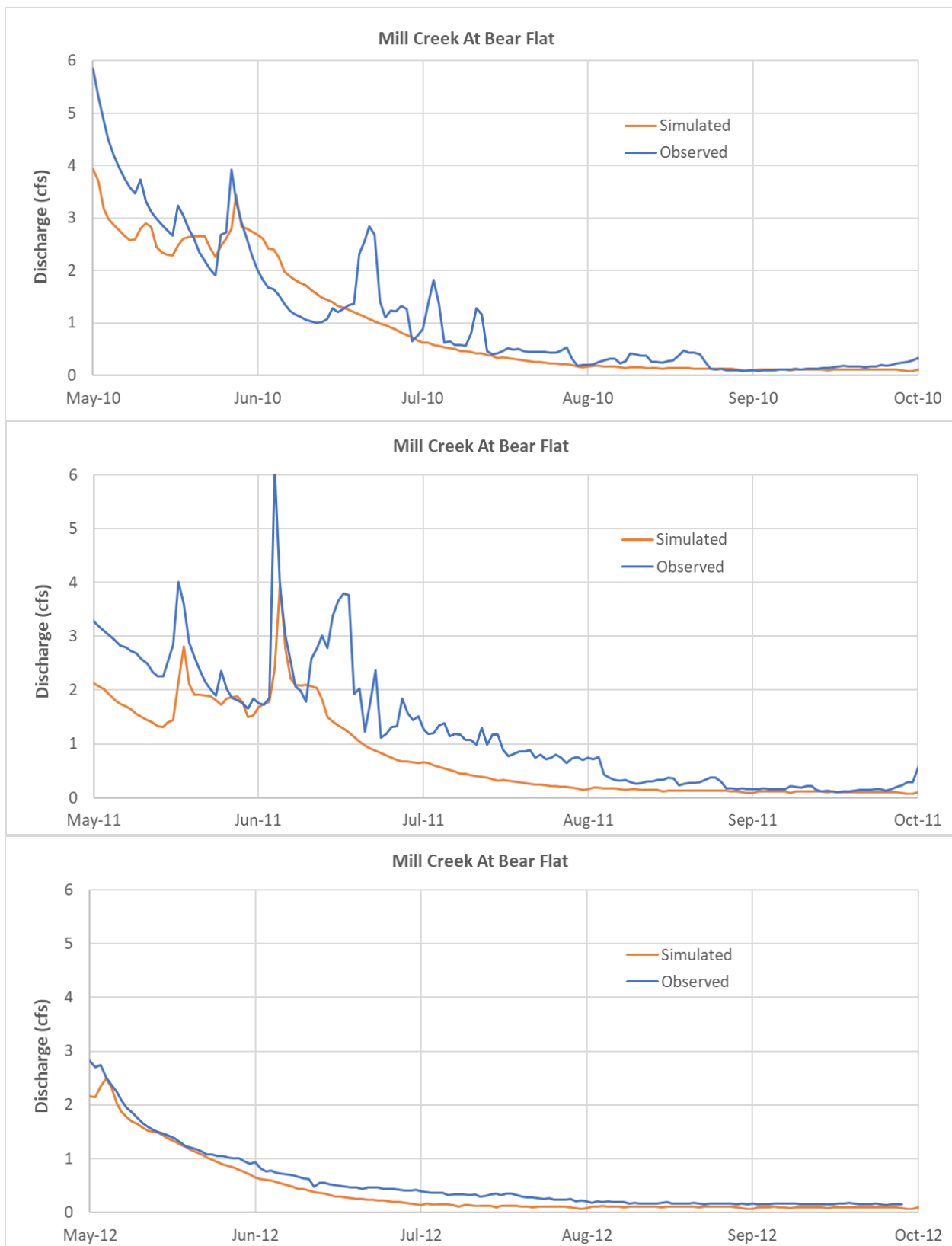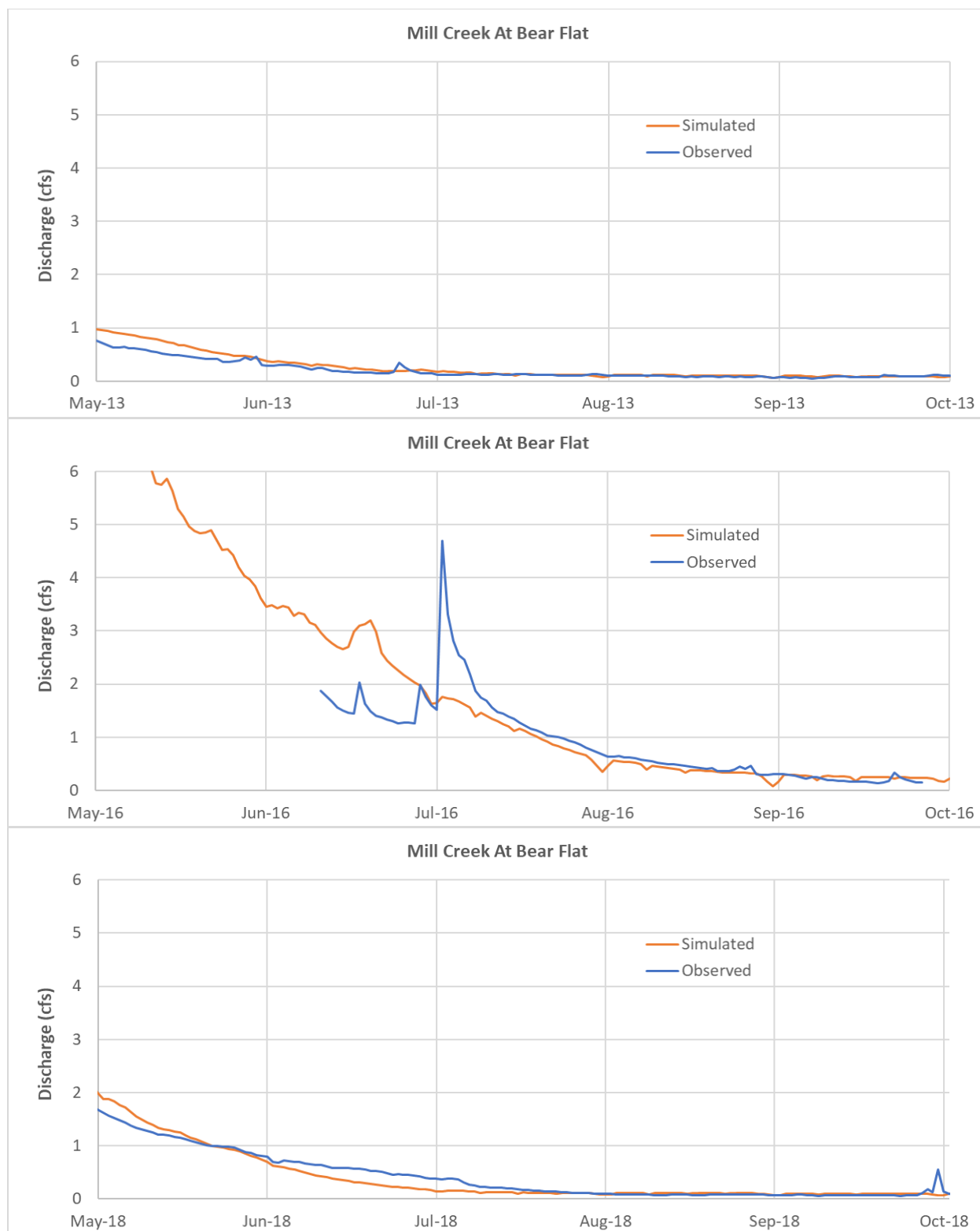
Figure 37: Comparison between model simulated and observed streamflow for the 2010 – 2013, 2016, and 2018 May through September low flow period at the Mill Creek at Bear Flat gauge.

Mill Creek Above Wallace
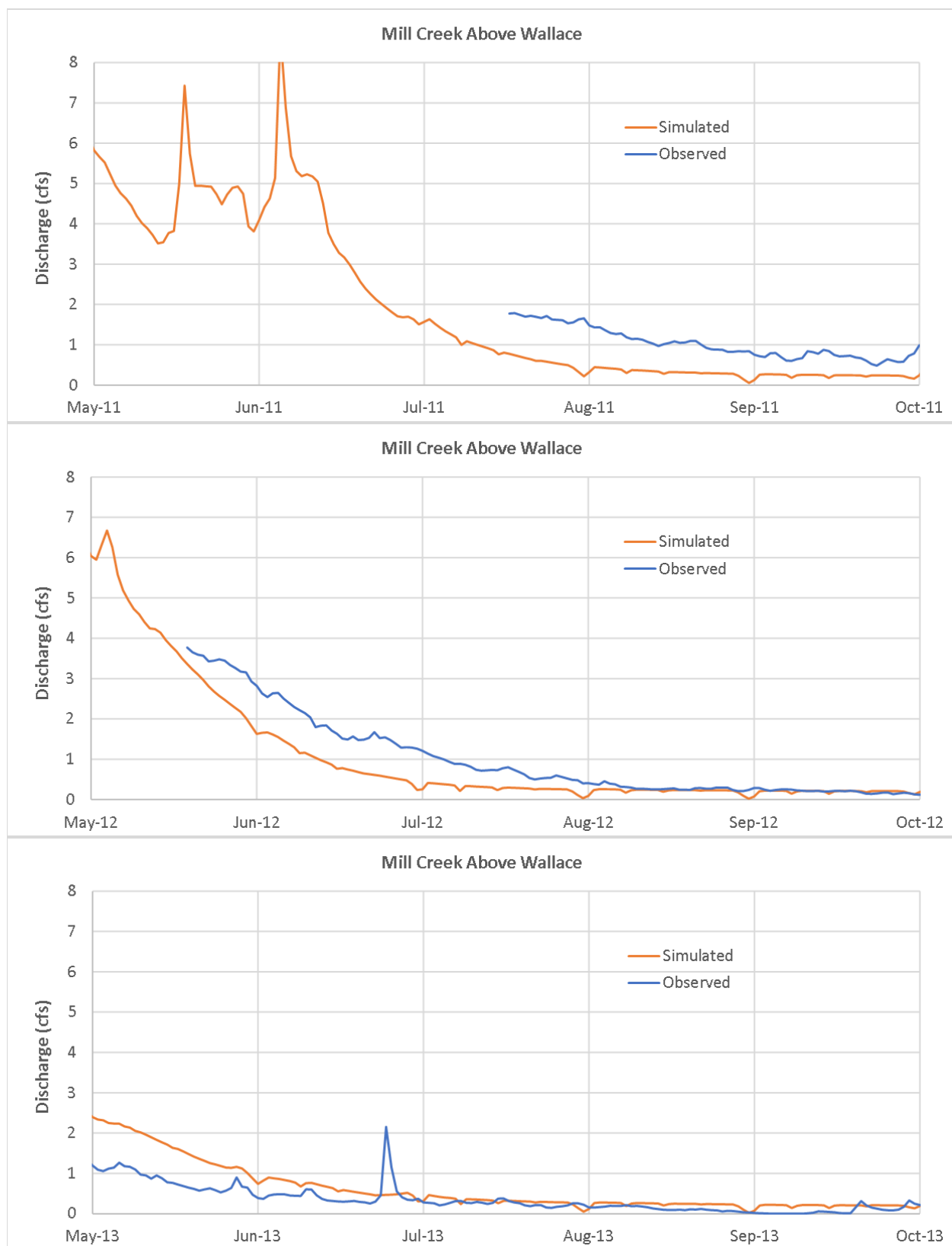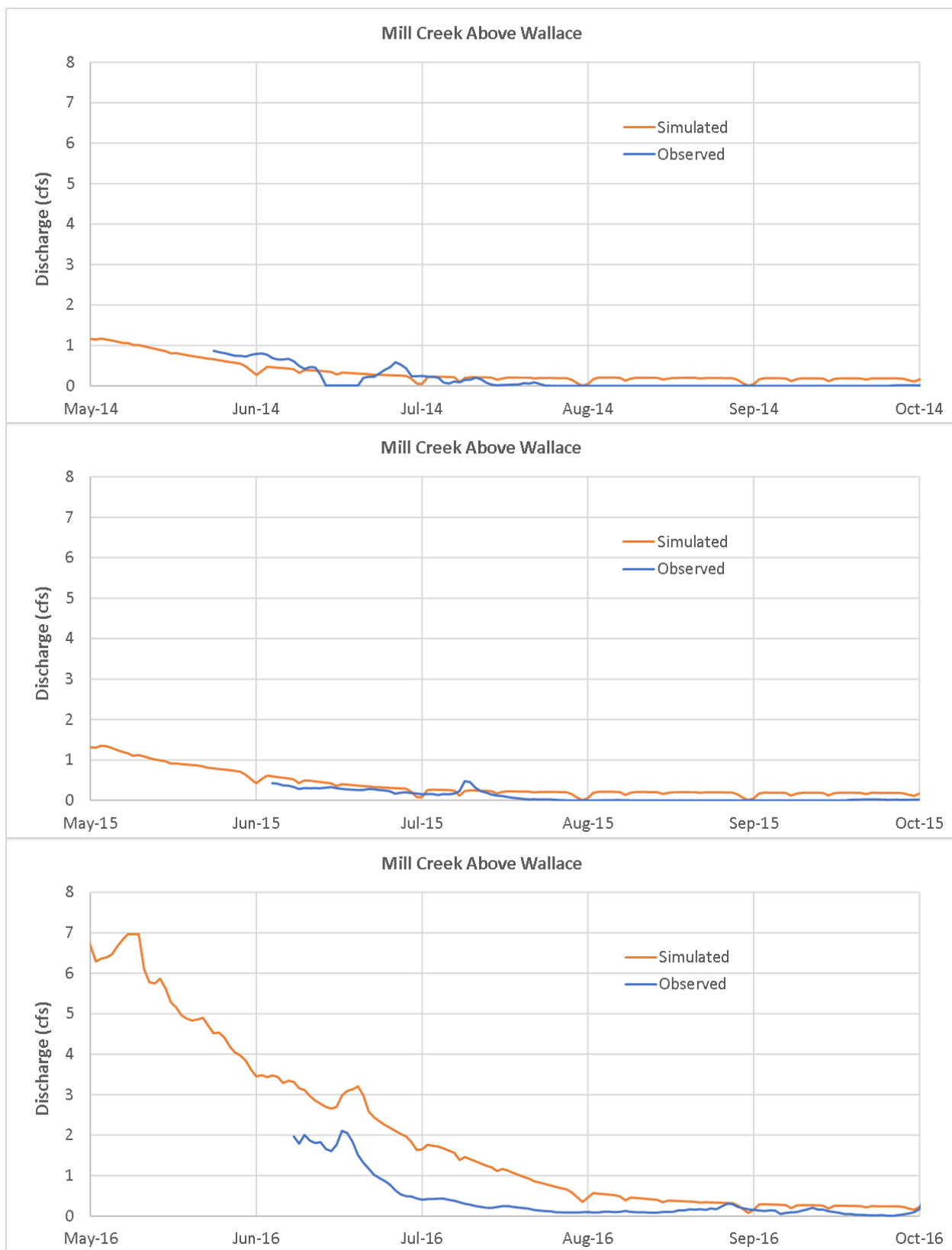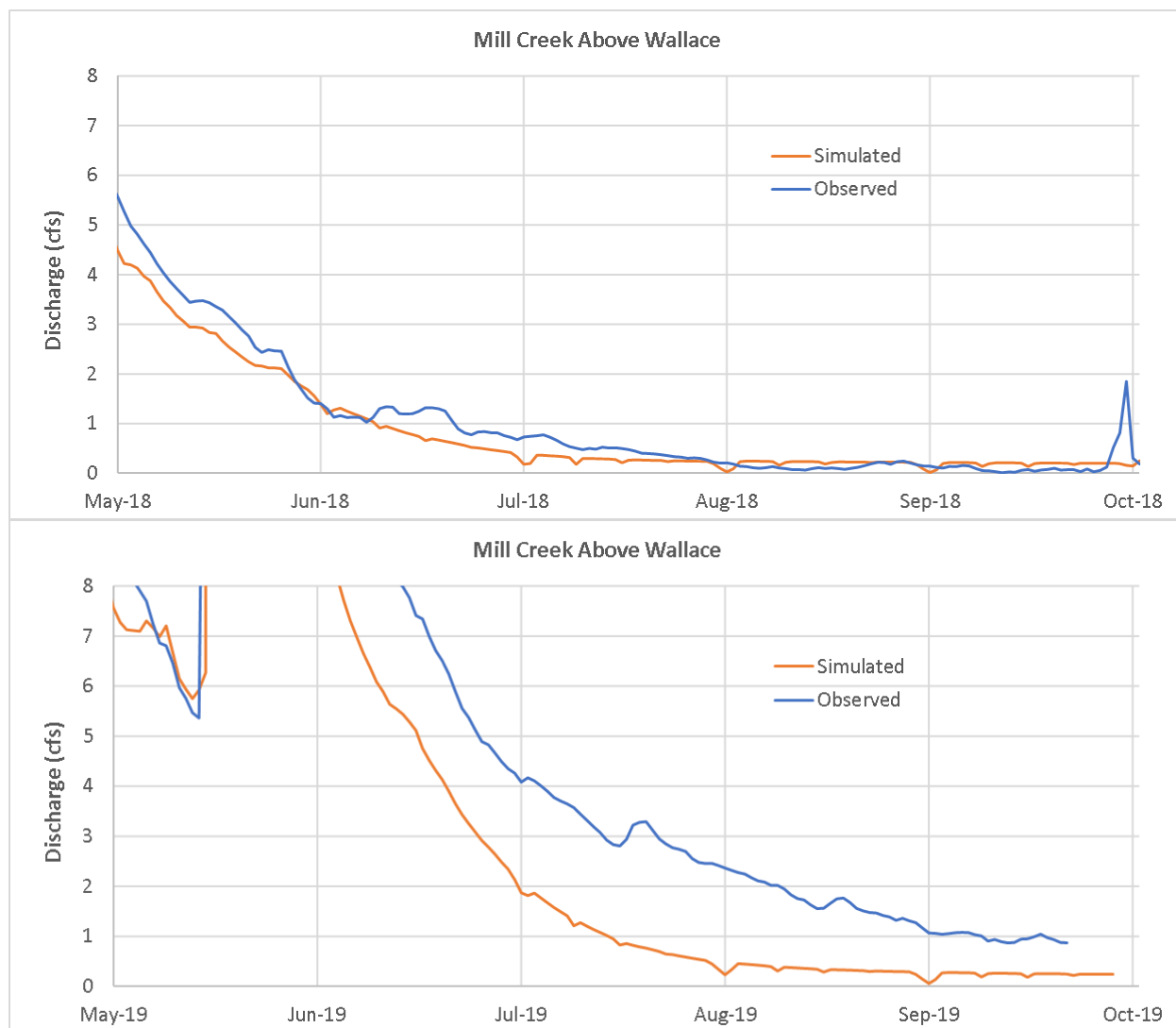
Figure 38: Comparison between model simulated and observed streamflow for the 2011 – 2016, and 2018 - 2019 May through September low flow period at the Mill Creek above Wallace Creek gauge.

Mill Creek above the Falls

Mill Creek Above the Falls

Mill Creek Above the Falls
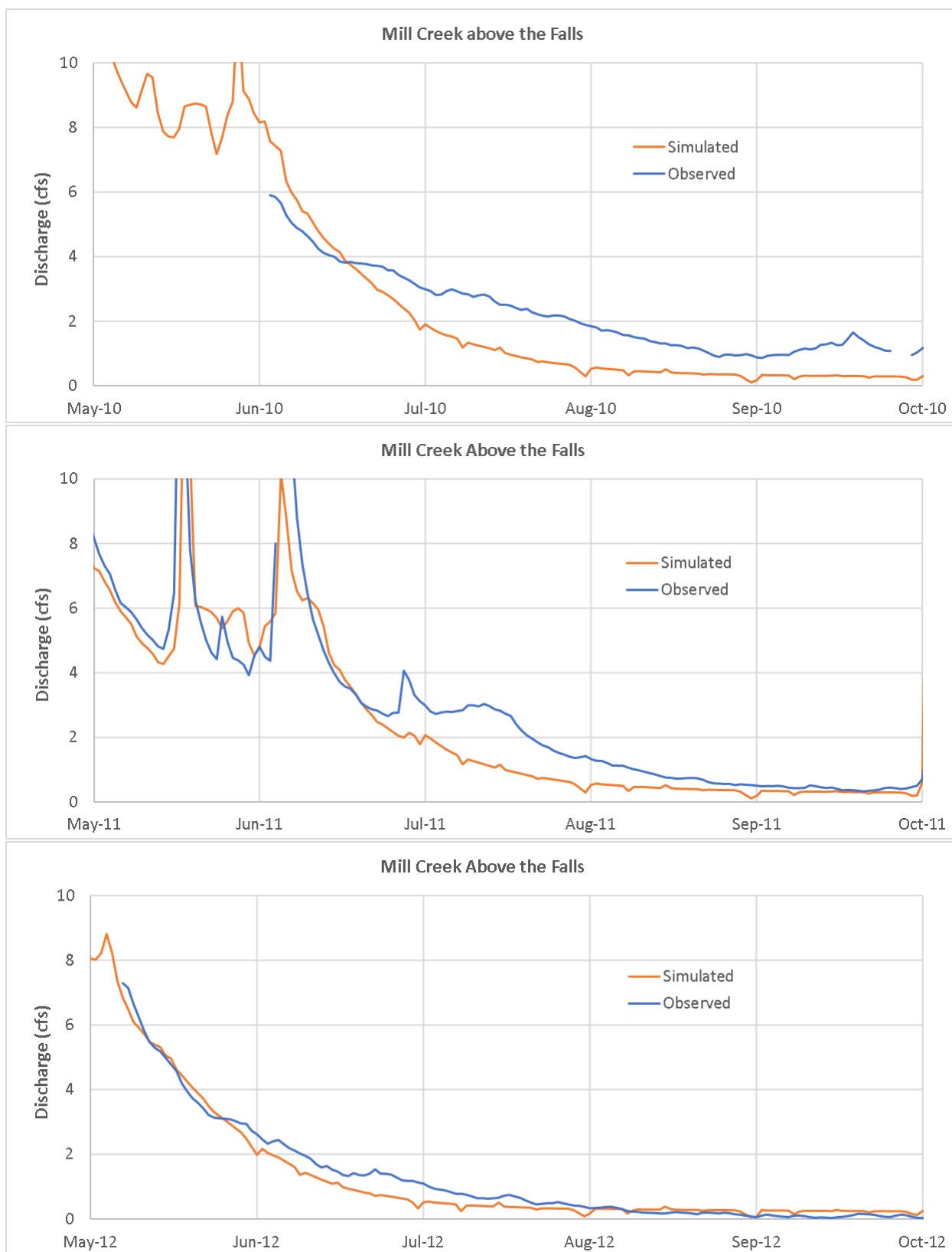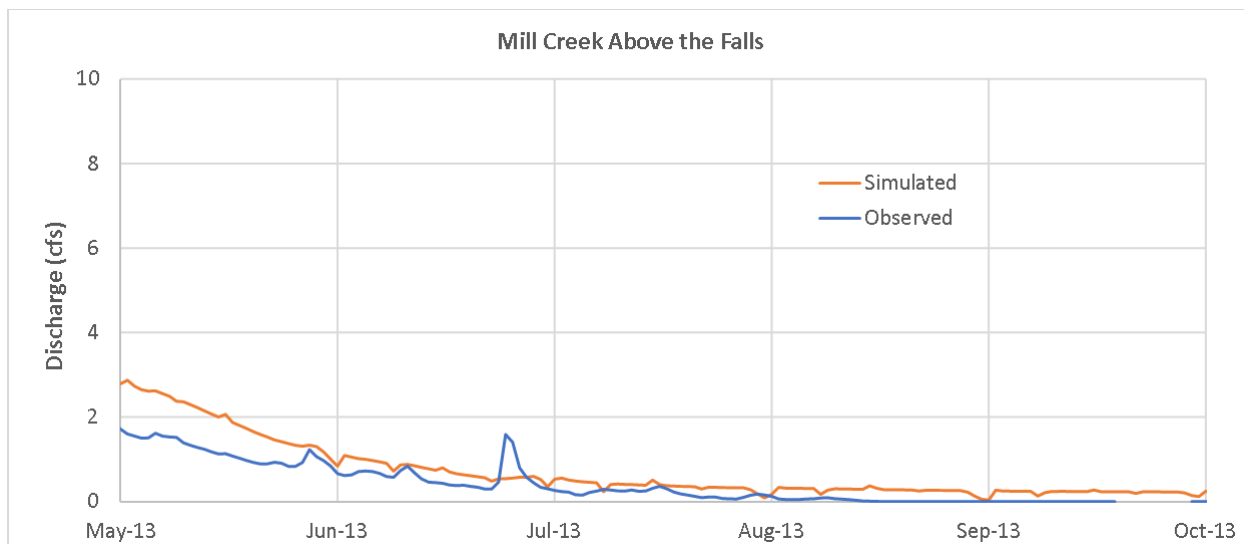
Figure 39: Comparison between model simulated and observed streamflow for the 2010 – 2013 May through September low flow period at the Mill Creek above The Falls gauge.

Comparison between wet/dry mapping data collected by CSG and a model simulated wet/dry classification for equivalent dates indicates that the model was able to re-produce the overall spatial and temporal patterns of streamflow disconnection (Figures 40-45). During dry conditions, as represented by the September 2014 and 2015 maps, the model correctly identified dry conditions in Wallace Creek, Felta Creek, and the alluvial reaches of lower Mill Creek with more persistent flow conditions in Palmer Creek and the middle and upper reaches of Mill Creek. The model shows wetter conditions in the reaches of Mill Creek above and below Wallace Creek compared to the field data (modeled short dry reaches compared to observed more continuous flow disconnection).

The model reproduced the September 2016 conditions (which followed an average precipitation season) with very good accuracy as well as the wet conditions represented by the June 2017 map (Figures 43 & 44). Late season flow disconnection in lower Mill Creek is generally well-predicted by the model, however the model shows disconnection occurring earlier and more completely than is indicated by the field data (see July 2015 and October 2017 maps, Figures 41 & 45).
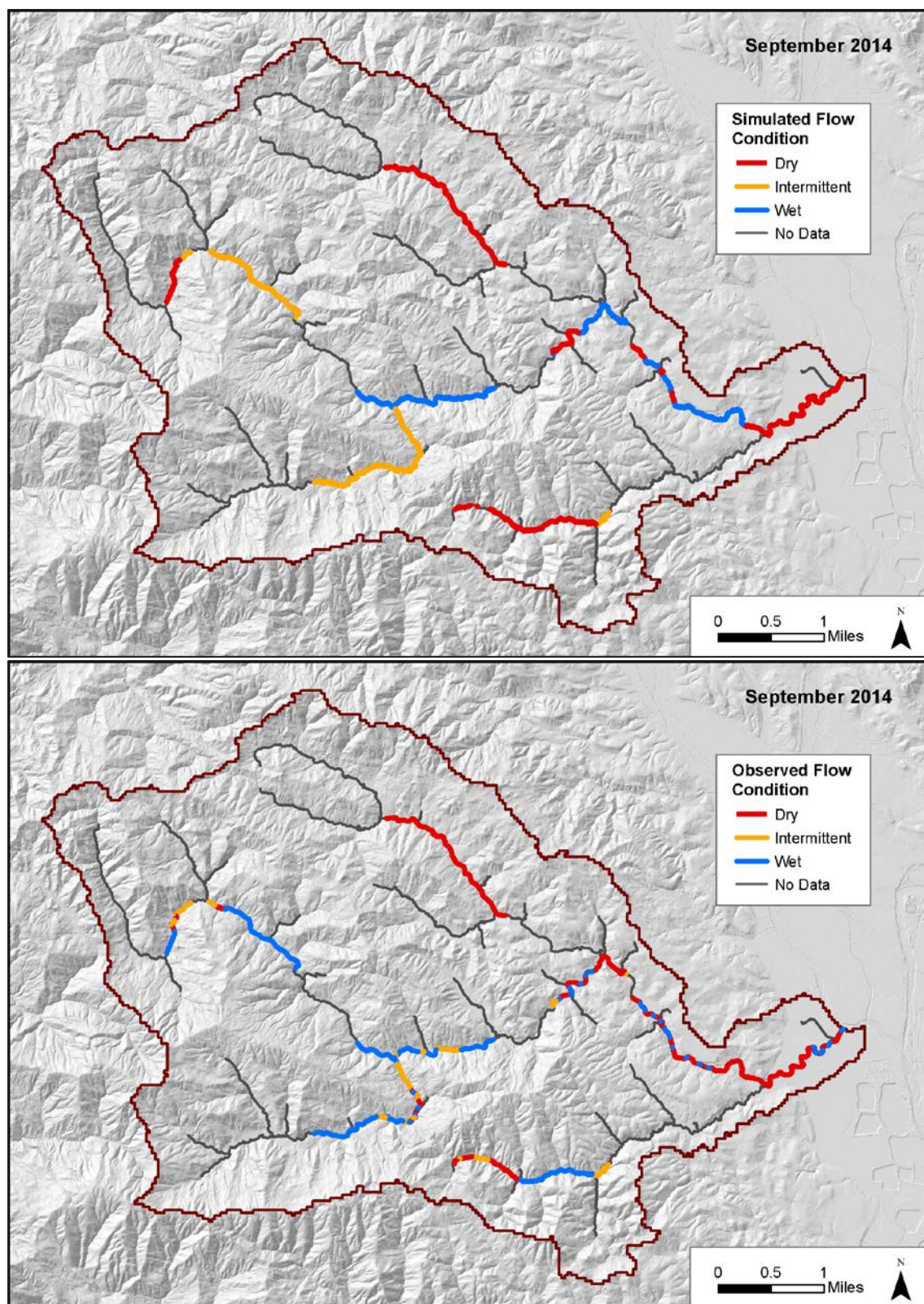
Figure 40: Comparison between model simulated flow conditions and flow conditions observed by CSG during September 2014.
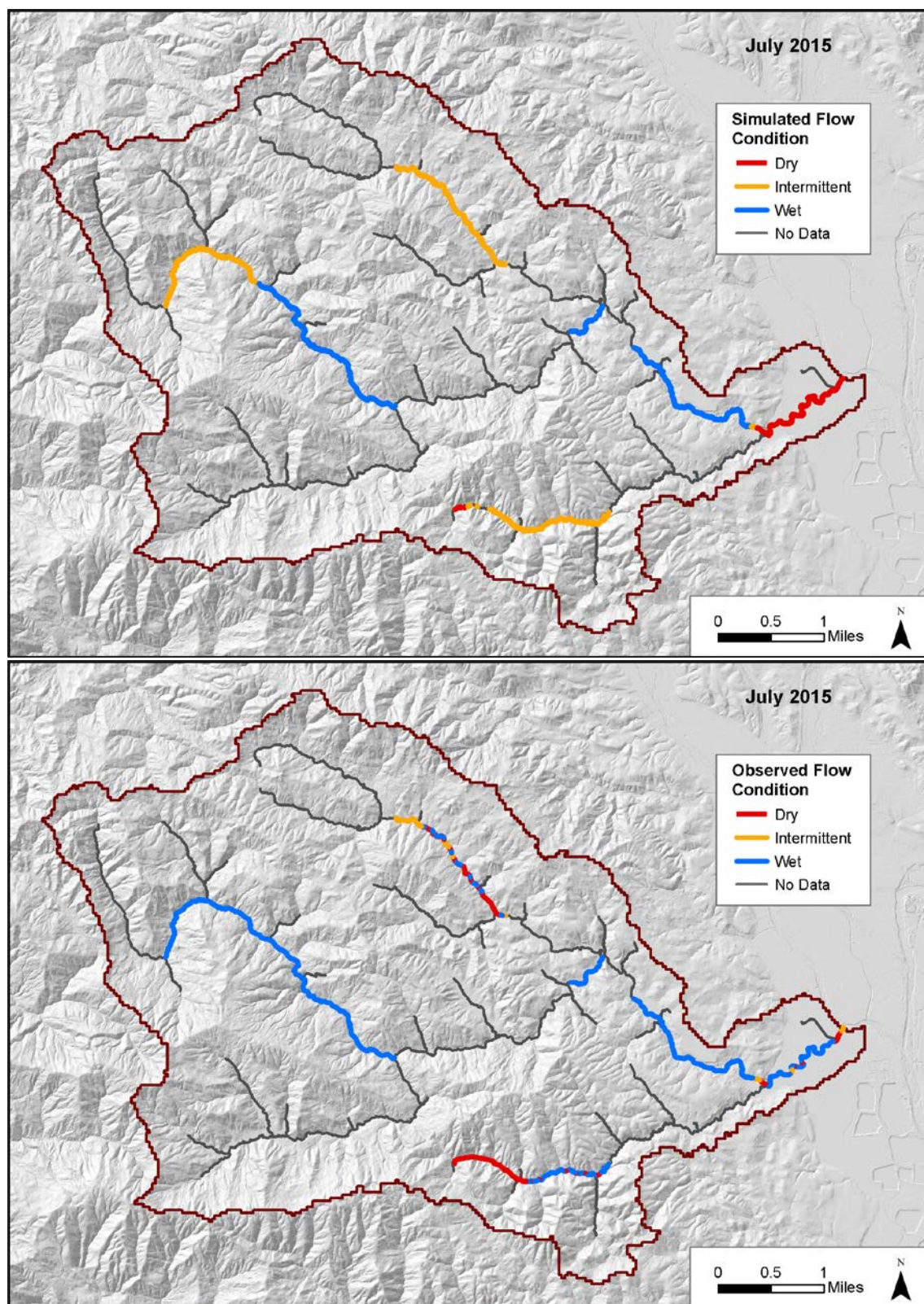
Figure 41: Comparison between model simulated flow conditions and flow conditions observed by CSG during July 2015.
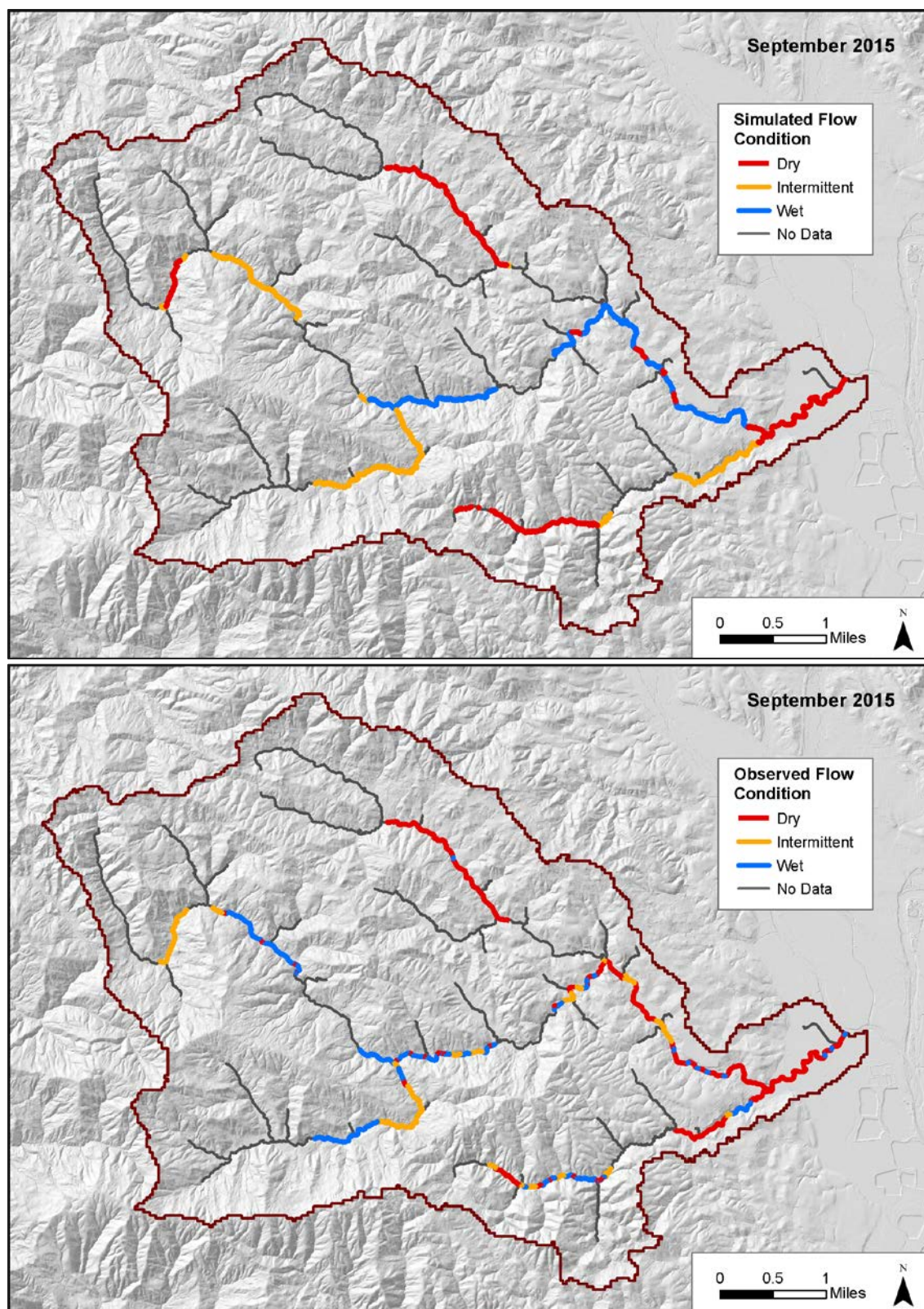
Figure 42: Comparison between model simulated flow conditions and flow conditions observed by CSG during September 2015.
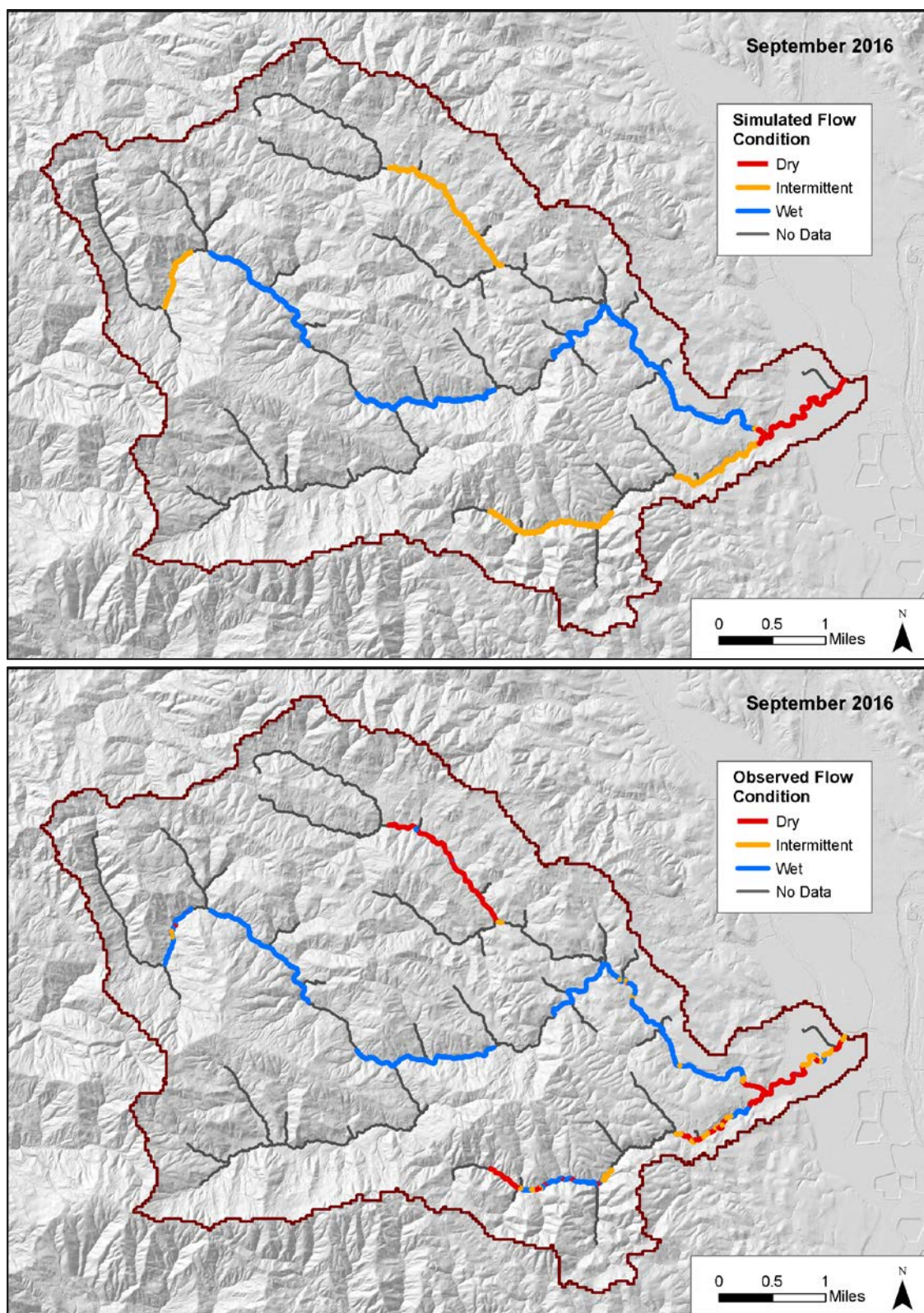
Figure 43: Comparison between model simulated flow conditions and flow conditions observed by CSG during September 2016.
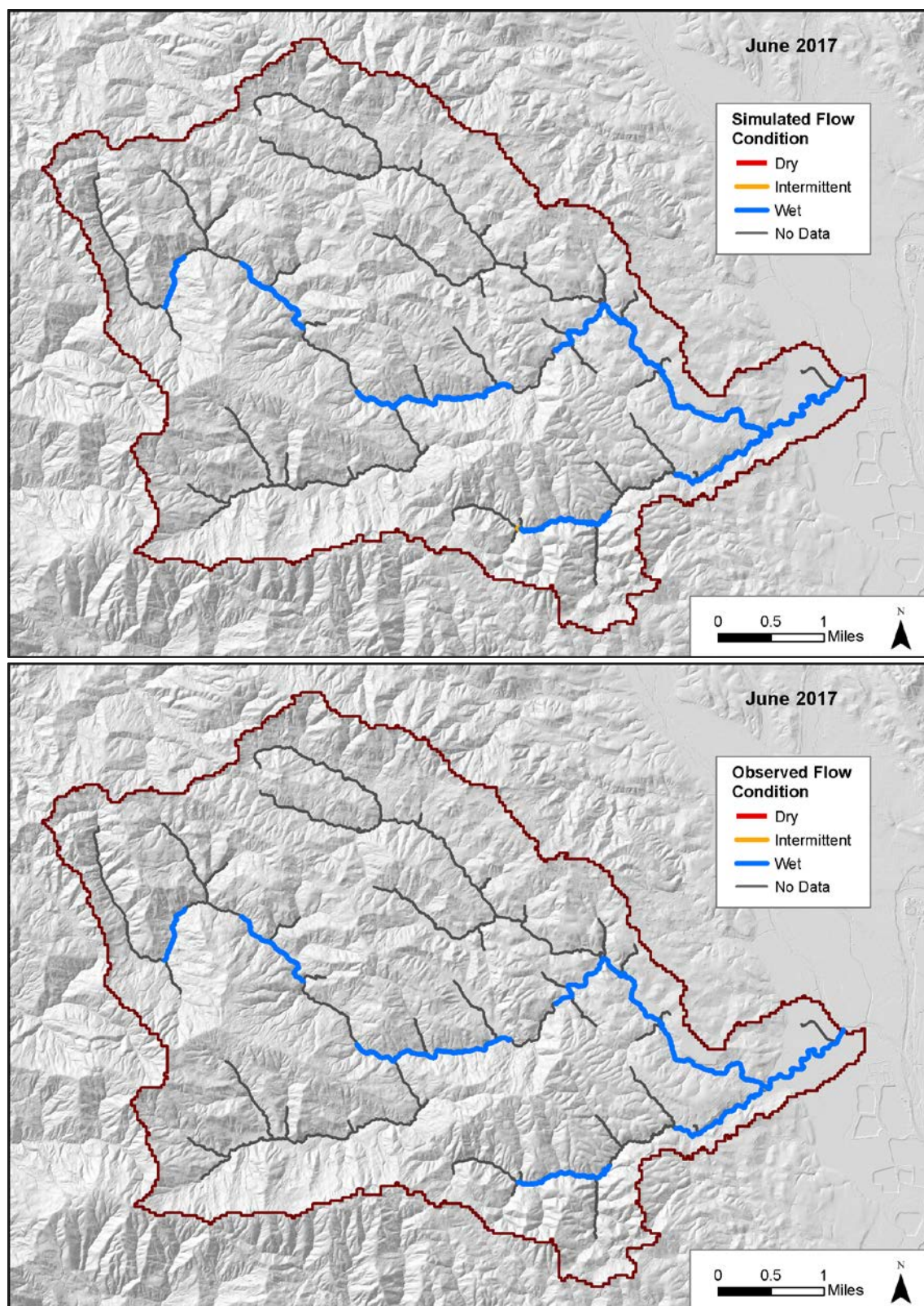
Figure 44: Comparison between model simulated flow conditions and flow conditions observed by CSG during June 2017.
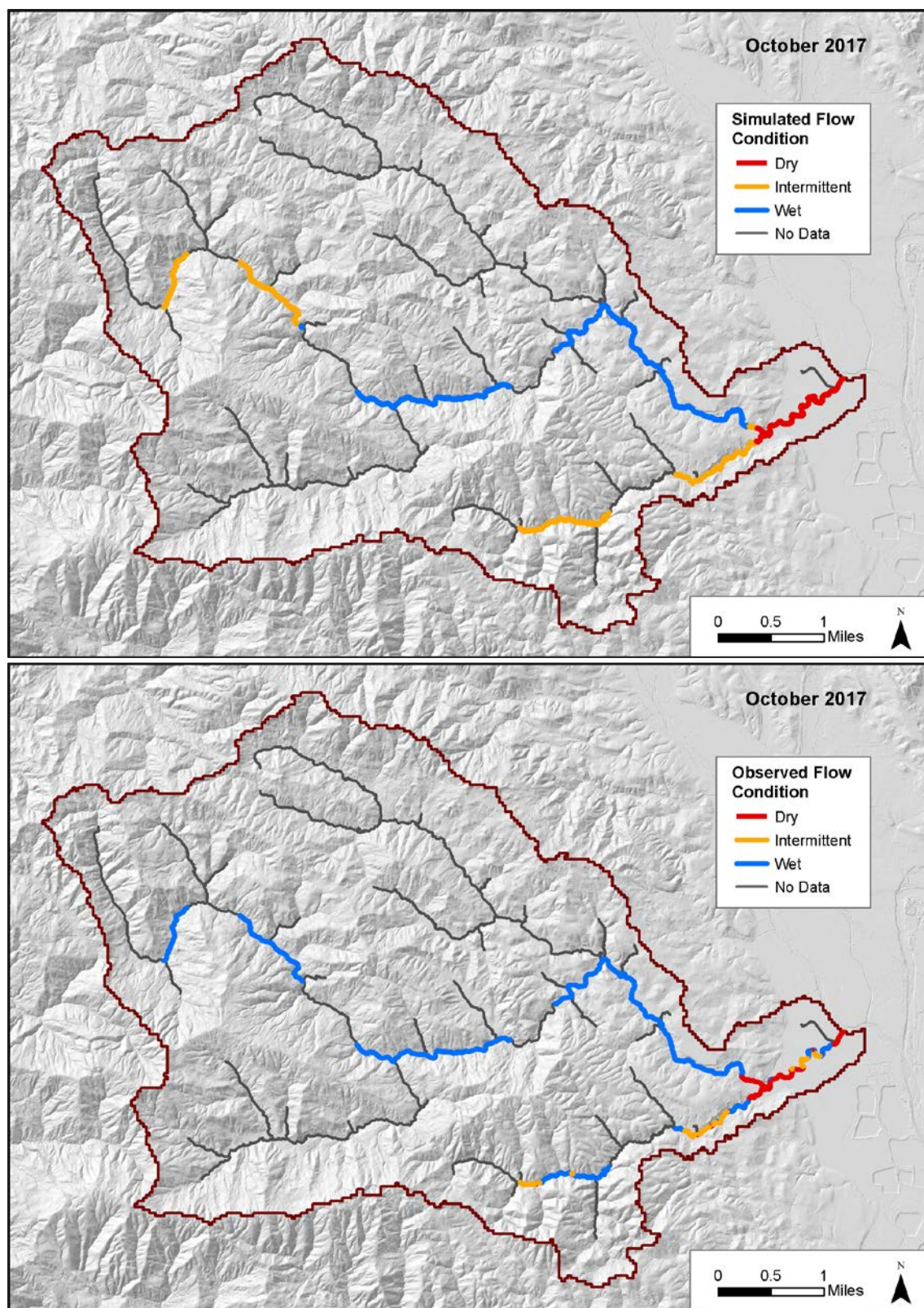
Figure 45: Comparison between model simulated flow conditions and flow conditions observed by CSG during October 2017.

Groundwater Calibration

To evaluate the agreement between model simulated groundwater elevations and measured groundwater elevations, Mean Error (ME), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) were calculated for the residuals (difference between simulated and observed groundwater elevations) at each of the thirteen monitoring wells. Due to the limited periods of record at the available monitoring locations it was deemed appropriate to calibrate the model to all of the available data rather than divide the simulation into calibration and validation periods as is more typically done when long-term monitoring data is available. Figure 46 shows the comparison between model-simulated and measured groundwater elevations for each of the thirteen monitoring wells with available data and calibration statistics are presented in Table 7.

The model was able to reproduce the observed timing and magnitudes of seasonal variations in groundwater elevations as well as the spatial variations in aquifer behavior between wells. The model tends to under-predict groundwater elevations particularly at Wells 2 through 6. Both the model and the observations indicate greater seasonal fluctuation in groundwater elevations in the upstream portions of the aquifer and a transition in groundwater flow direction in the down-gradient direction from largely parallel to Mill Creek to largely parallel to Dry Creek. MEs range from –9.9 to 3.6 ft with an average error of -2.7 ft, and MAEs range from 1.2 to 12.6 ft (Table 7). It is useful to interpret the errors relative to the average range in observed groundwater elevations at individual wells (~24 ft) and between all of the wells (~52 ft). We considered the calibration successful if the MAE was less than 12 ft, which was achieved at ten of the eleven wells, with an average MAE of 4.9 ft (~20% of the average range at individual wells).

Table 7: Groundwater calibration results for the Mill Creek hydrologic model (see Figure 35 for locations).

Well ID	# of Observations	ME (ft)	MAE (ft)	RMSE (ft)
1	16	-2.4	3.8	4.4
2	22	-9.9	9.9	10.6
3	19	-9.2	9.2	9.5
4	16	-4.0	12.6	20.0
5	18	-4.8	4.8	5.6
6	19	-4.1	4.1	5.1
7	19	0.9	1.3	1.7
8	11	0.0	1.4	2.5
9	10	-1.2	1.2	1.4
10	22	1.0	1.8	2.3
11	16	3.6	4.1	15.5
Mean	**17**	**-2.7**	**4.9**	**7.1**

Well #4

Well #5

Well #6

Well #7

Well #8

Well #9
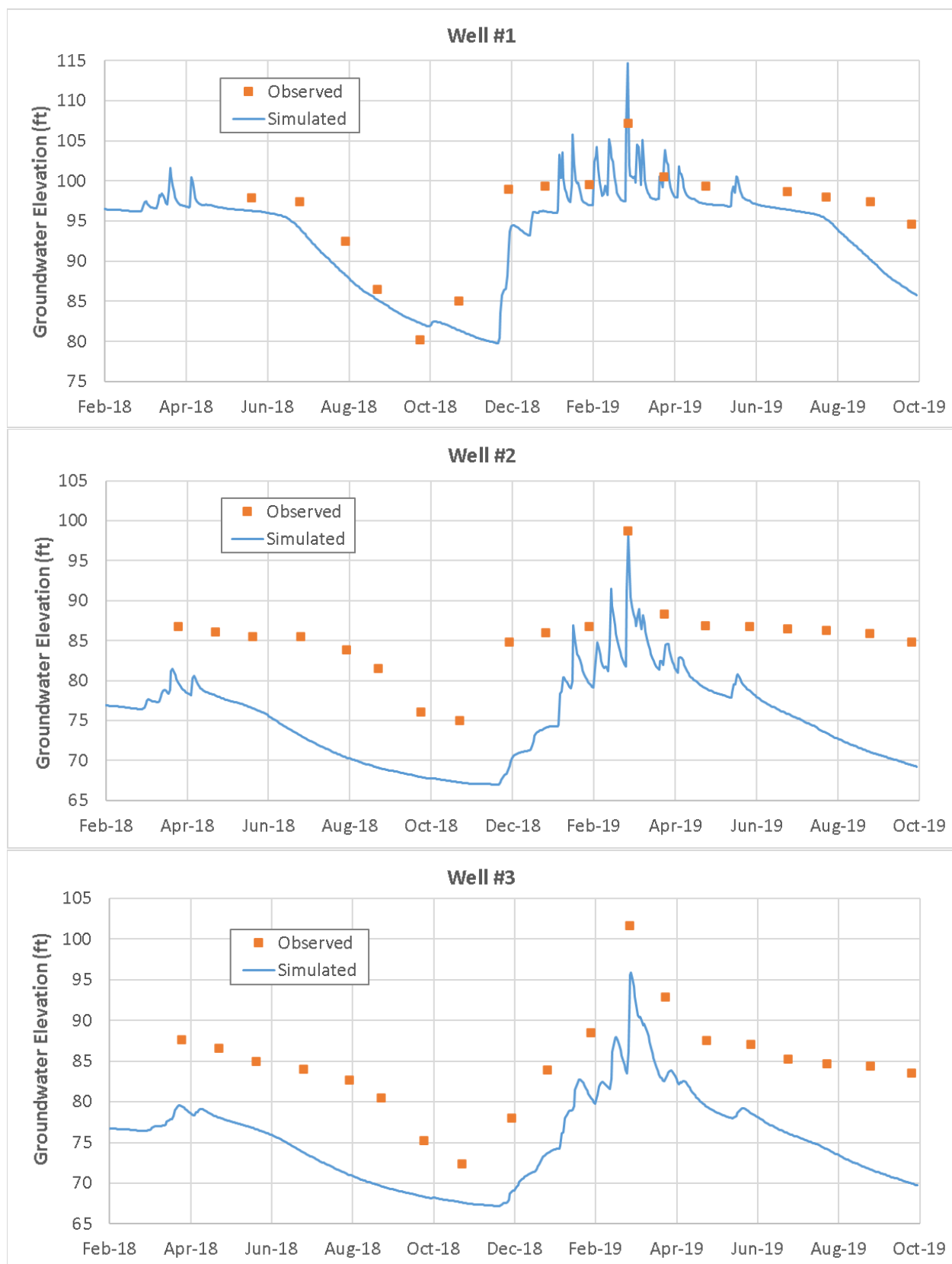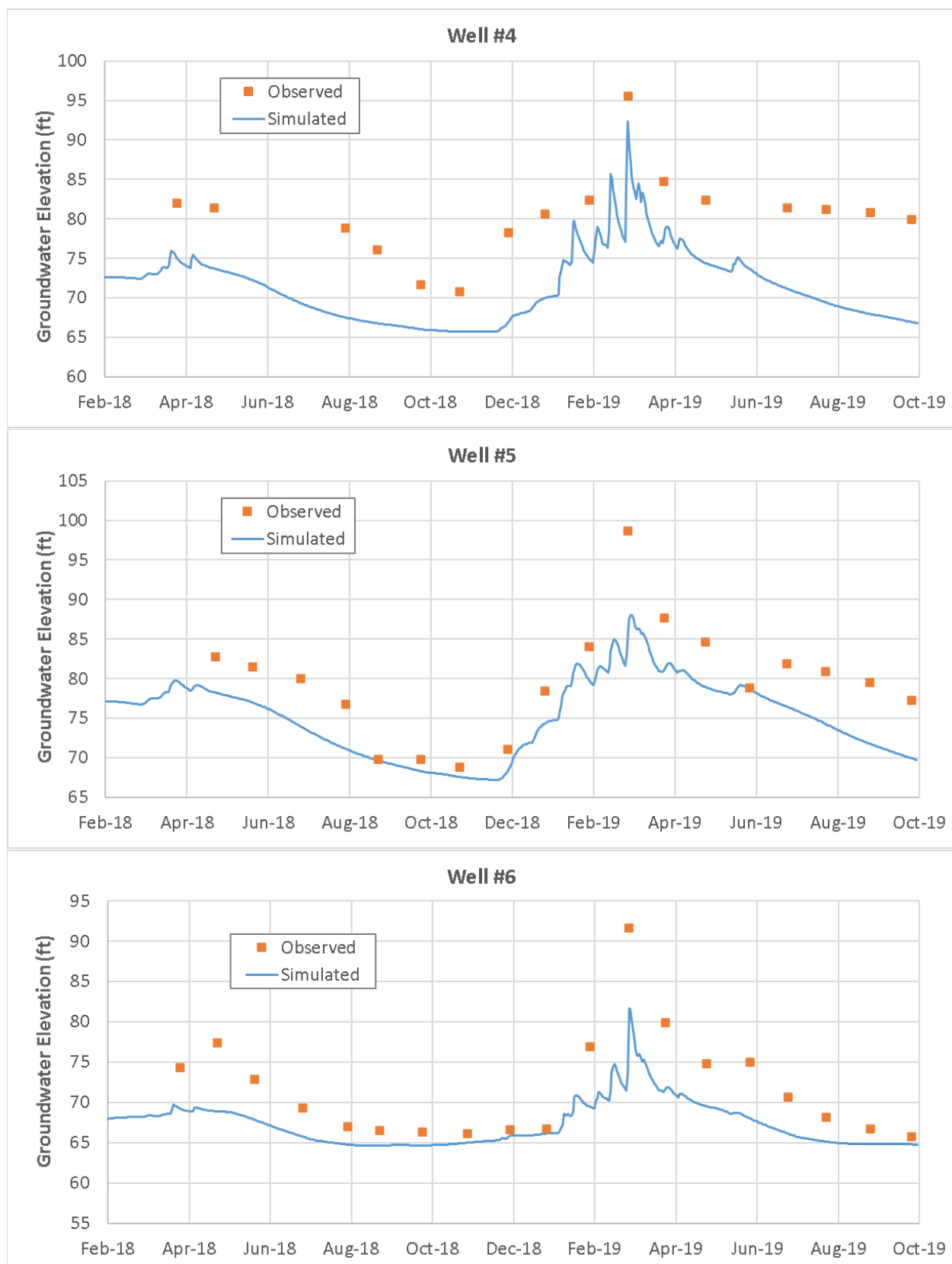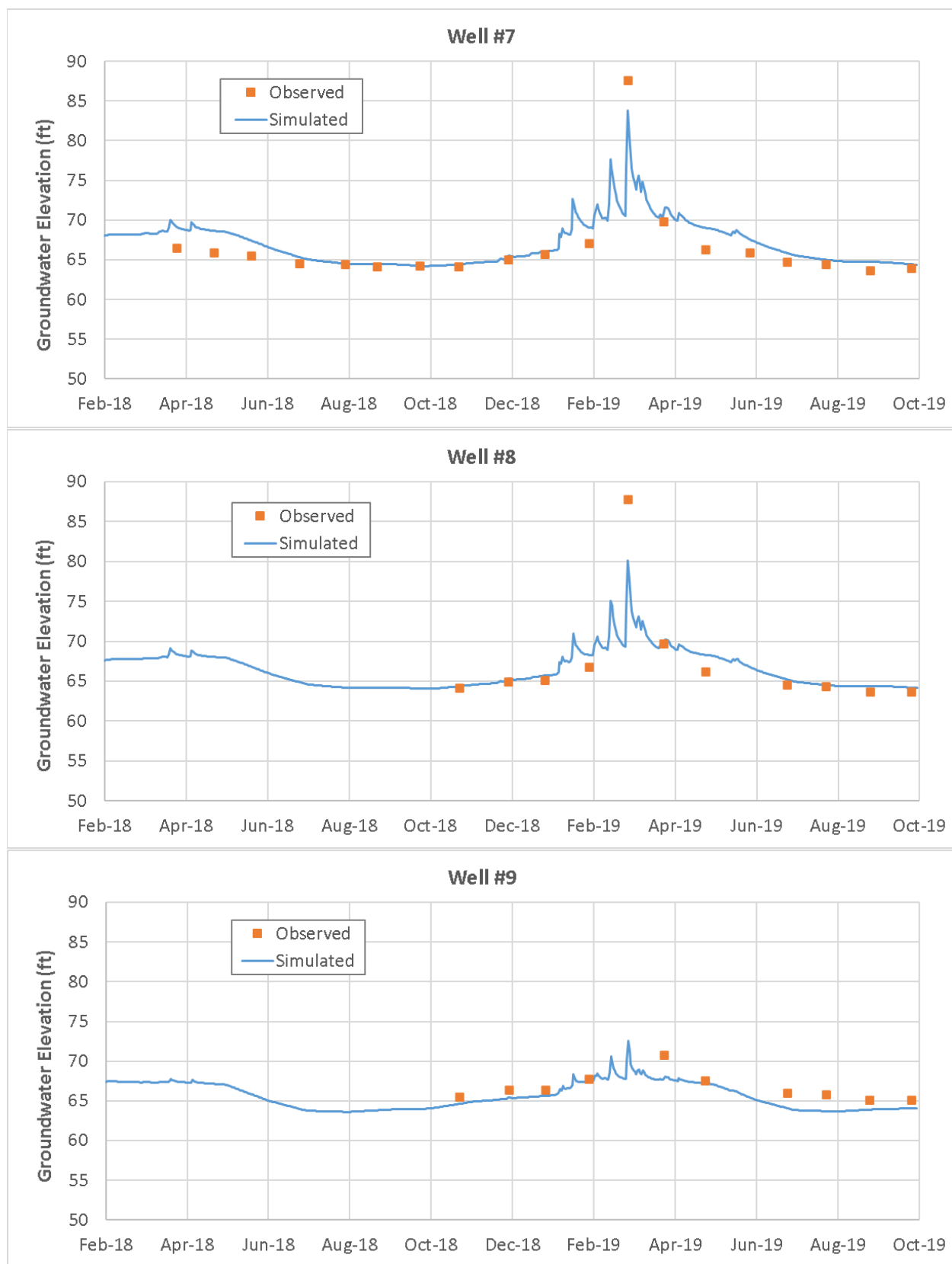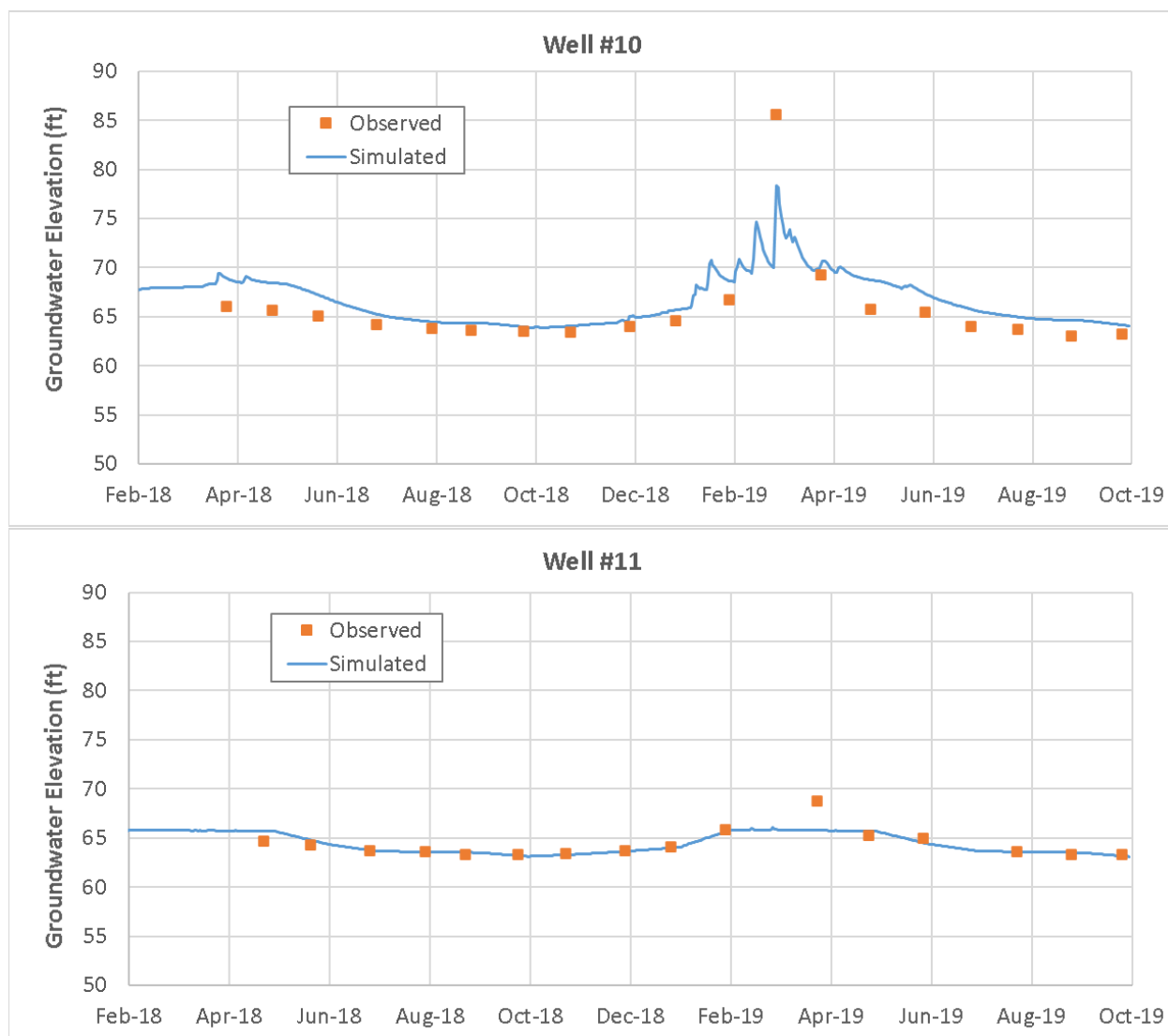
Figure 46: Comparison between model simulated and observed groundwater elevations in the alluvial aquifer (see Figure 35 for locations).

Chapter 6 – Model Results

Water Balance

A quantitative description of the watershed water balance is a fundamental output from the model providing much perspective on hydrologic processes of interest for management purposes. Water balance information can be extracted for the full study area or for any subarea. A water balance may be highly detailed (e.g., decompose ET into interception, evaporation, transpiration from the unsaturated zone, and transpiration from groundwater) or more general, and can be developed for the watershed as a whole or for a specific component of the hydrologic system such as the saturated zone. A general annual water balance for the whole watershed and a more detailed groundwater water balance have been developed for each of the simulated water years of 2010 - 2019. A monthly water budget is also presented for selected water budget terms as are maps depicting the spatial variations of key water budget components.

Watershed Water Balance

The primary inflow to the Mill Creek watershed is precipitation, which ranged from 26.4 inches in the dry water year 2014 to 107.5 inches in the wet water year 2017 (Table 8). This degree of variability is thought to be larger than most lower Russian River watersheds due to the very high rainfall generated in the vicinity of the ridgelines separating the watershed from the East Austin Creek watershed. Irrigation is a minor additional source of inflow (0.15 in/yr) and it was uniform between water years owing to the way irrigation demands were estimated. Except for the two wettest years of the simulation (2017 & 2019) when streamflow exceeded Actual evapotranspiration (AET), AET was the largest outflow from the watershed. Variations in AET were significantly less than variations in precipitation and ranged from 27.2 inches in 2014 to 34.5 inches in 2012. Stream flow was the next largest outflow from the watershed, and it varied substantially and in a similar fashion to precipitation ranging from 6.3 inches in 2014 to 68.8 inches in 2017. Groundwater pumping was approximately two orders of magnitude less than AET or stream flow (0.13 in/yr) and was relatively uniform owing to the methods used to estimate water demand (Table 8).

The watershed boundaries were represented as no-flow boundaries in all components of the model except for the groundwater component which was represented with time-varying head boundaries along the lower margins of the alluvial aquifer (see Chapter 4). Subsurface inflows representing groundwater entering the model domain from the surrounding Dry Creek Valley ranged from 2.1 to 2.9 inches and subsurface outflows representing groundwater exiting the model domain towards Dry Creek and the Russian River ranged from 3.7 to 5.6 inches. Increases in storage of up to 10.1 inches occurred in water year 2016 following storage depletion from the 2012-2015 dry period and decreases in storage of up to 7.9 inches occurred during the dry water year 2014 (Table 8).

Groundwater Water Balance

Infiltration recharge (derived from precipitation across the watershed) represented the largest source of inflow to the groundwater system in the Mill Creek watershed and varied widely, primarily as a function of precipitation, from 1.9 inches in 2014 to 20.1 inches in 2019 (Table 9).

Streambed recharge (derived from water flowing in stream channels) also exhibited substantial temporal variability ranging from 0.8 inches in 2014 to 3.8 inches in 2017. Subsurface inflows to the lower alluvial aquifer of Dry Creek Valley were relatively constant averaging 2.6 inches per year. Infiltration recharge was the dominant recharge component in all years with streambed recharge typically representing about 11 to 19% of total recharge. Under drought conditions such as occurred in 2014, streambed recharge becomes a more significant fraction of the total recharge accounting for about 30% of total recharge. Subsurface outflows towards Dry Creek and the Russian River represented the largest source of outflow, averaging 4.4 inches per year. ET from groundwater was the next largest outflow term and was relatively uniform ranging from 2.4 to 3.7 inches (Table 9).

A significant proportion of the total recharge (~21%) leaves the groundwater system quickly as interflow which ranged from 1.1 to 4.7 inches. Springflow and baseflow are also significant outflow terms. Both represent groundwater discharge in the model with the former representing discharge to the land surface or along unsaturated stream banks and the later representing discharge through the bed and wetted banks of the stream. Both these discharge components varied in response to variations in recharge. Springflow ranges from 0.8 to 3.7 inches and baseflow ranges from 0.3 to 1.9 inches (Table 9). Streambed recharge is approximately 2.3 times greater than baseflow indicating a net loss of streamflow through the bed and wetted banks of streams when averaged across the watershed. As discussed in greater detail below, there is substantial spatial variability in surface water/groundwater interaction with gaining conditions predominant in the upper bedrock portions of the watershed and losing conditions predominant in the lower alluvial reaches in or near Dry Creek Valley where most of the streambed recharge occurs. Groundwater pumping was a relatively small component (~1%) of the total outflow at 0.13 inches. Storage decreases of up to 2.9 inches occurred in dry years such as 2014 and storage increases of up to 8.2 inches occurred in 2016 following a four-year period with below average recharge from 2012-2015 during which available storage space in the aquifer increased (Table 9).

Table 8: Annual watershed water budget simulated with the Mill Creek hydrologic model; all units are inches.

Water Year	Inflows			Outflows				Change in Storage
	Precipitation	Irrigation	Subsurface Inflow	AET	Streamflow	Groundwater Pumping	Subsurface Outflow	
2010	56.80	0.15	2.50	34.46	21.28	0.13	4.37	-0.80
2011	57.17	0.15	2.48	34.11	20.68	0.13	4.40	0.47
2012	44.24	0.15	2.64	34.52	14.44	0.13	4.10	-6.17
2013	46.56	0.15	2.56	30.52	15.98	0.13	4.18	-1.54
2014	26.40	0.15	2.87	27.18	6.30	0.13	3.67	-7.86
2015	42.56	0.15	2.61	28.42	13.32	0.13	4.05	-0.60
2016	58.13	0.15	2.57	27.58	18.79	0.13	4.30	10.05
2017	107.54	0.14	2.14	34.12	68.78	0.13	5.62	1.19
2018	37.46	0.15	2.76	32.50	8.99	0.13	3.85	-5.11
2019	90.18	0.14	2.37	33.63	46.95	0.13	5.06	6.92
Average	**56.70**	**0.15**	**2.55**	**31.71**	**23.55**	**0.13**	**4.36**	**-0.35**

Table 9: Annual groundwater water budget simulated with the Mill Creek hydrologic model; all units are inches.

Water Year	Inflows			Outflows						Change in Storage
	Infiltration Recharge	Streambed Recharge	Subsurface Inflow	Interflow	Baseflow	Springflow	ET from Groundwater	Groundwater Pumping	Subsurface Outflow	
2010	12.37	2.09	2.50	3.64	1.01	2.71	2.98	0.13	4.37	2.12
2011	12.82	2.13	2.48	3.53	0.98	2.61	2.92	0.13	4.40	2.86
2012	7.41	1.56	2.64	2.50	0.72	1.94	3.13	0.13	4.10	-0.91
2013	9.73	1.67	2.56	2.59	0.75	1.96	2.83	0.13	4.18	1.52
2014	1.91	0.83	2.87	1.10	0.31	0.81	2.45	0.13	3.67	-2.86
2015	7.98	1.50	2.61	1.66	0.58	1.41	2.47	0.13	4.05	1.79
2016	16.02	1.95	2.57	2.63	0.88	2.02	2.35	0.13	4.30	8.23
2017	18.60	3.82	2.14	4.72	1.92	3.73	3.53	0.13	5.62	4.92
2018	5.58	1.29	2.76	1.88	0.49	1.43	2.83	0.13	3.85	-0.98
2019	20.07	3.54	2.37	4.02	1.41	3.69	3.70	0.13	5.06	7.95
Average	**11.25**	**2.04**	**2.55**	**2.83**	**0.91**	**2.23**	**2.92**	**0.13**	**4.36**	**2.46**

Spatial and Temporal Variations of Water Budget Components

Monthly water balance results illustrate the strong seasonality of precipitation and streamflow typical of Mediterranean climates (Figure 47). As a result of the seasonal fluctuations in potential evapotranspiration and soil moisture availability, AET was generally lowest during the late fall and early winter and highest during the spring, progressively decreasing throughout the summer months as available soil moisture diminished (Figure 47). During average and wet water years, infiltration recharge occurred in most months between November and April, whereas during the 2013-2015 drought recharge only occurred during two months of a given year (Figure 47). The number of days with significant (>0.1-in) recharge varied widely between 15 days in 2013 and 68 days in 2016.

In most of the watershed, relatively thin soils overlie Franciscan bedrock typical of the Coast Range and recharge rates are relatively high with spatial variability controlled primarily by topographic position and variations in soil conditions (Figure 48). Recharge rates are lower in the Wallace Creek watershed (underlain by older Central Belt Franciscan bedrock) relative to the other subwatersheds underlain by younger Coastal Belt Franciscan bedrock. This results from the contrast in soil properties associated with the variations in bedrock geology. Typical 10-yr mean annual rates outside of valley bottoms in the Coastal Belt Franciscan watersheds range from 10 to 16 in/yr and from 4-10 in/yr in the Wallace Creek watershed and other areas underlain by Central Belt Franciscan (Figure 48). The lower alluvial areas in or near Dry Creek Valley and the small area between the Wallace and Felta confluences underlain by the Glen Ellen Formation have the highest rates of recharge with typical 10-yr mean annual rates of 20 to 30 in/yr. Within the upper bedrock watershed, recharge rates are highest on ridgetops and hillslopes where rates are not limited by shallow groundwater conditions, whereas the narrow valley bottoms and stream channels exhibit low or negative recharge due to the predominance of shallow groundwater and groundwater discharge characteristic of these portions of the watershed. During the very dry year of 2014, rates were substantially lower throughout the watershed with a similar spatial distribution and values on the order of 10 to 20% of the long-term average rate (Figure 49).

There are four components to streamflow represented in the model including runoff, interflow, and two forms of groundwater discharge: springflow (subaerial discharge) and baseflow (subaqueous discharge). During the rainy season, runoff is the dominant component of streamflow representing up to 65% of the total streamflow with most of the remainder (~25%) coming from interflow (Figure 50). During the spring timeframe, which is most critical for smolt outmigration, interflow becomes the dominant discharge component for the months of April and May. As spring progresses into summer, interflow declines and springflow becomes the dominant flow component (up to 85% of total flow) responsible for maintaining summer flow from July through October. Baseflow is an important secondary component representing 10 to 15% of the total flow over the summer period (Figure 50).

Locations of perennial springflow predicted by the model are distributed throughout the bedrock portions of the study area with the highest concentrations in the Felta Creek watershed (Figure 51). Most of the springs occur at channel heads and along channel margins in headwater reaches,

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consistent with general observations in the region. Some springs, particularly in the Felta drainage, are coincident with stream channels too small to be included in the open-channel hydraulics component of the model. Here the distinction between groundwater discharge accounted for as springflow and groundwater discharge accounted for as baseflow becomes somewhat arbitrary and dependent on the level of detail incorporated into the open-channel flow model. The distribution of springs and water balance results suggests that groundwater discharge at channel heads and along headwater tributary streams is the primary source of summer streamflow. Field reconnaissance to confirm the general distribution of springs would provide a relatively simple means of validating this component of the hydrologic model.

The spatial patterns of surface water/groundwater interaction indicate that gaining conditions predominate throughout the spring and summer months in the upper Mill Creek, Palmer Creek, and upper Felta Creek watersheds with small (<0.01 cfs/mile) rates of groundwater discharge in most areas and modest rates in other areas (<0.1 cfs/mile) (Figures 52 & 53). Within the Wallace Creek, middle Mill Creek, and middle Felta Creek watersheds, the model indicates very limited surface water/groundwater exchange. In the alluvial reaches of lower Mill and Felta creeks, losing conditions predominate in the spring months with rates of streamflow losses ranging from <0.1 cfs/mile to nearly 10 cfs/mile (Figure 52). Localized areas of groundwater discharge occur near the Mill/Felta confluence, however the overall pattern is one of losing conditions. In the summer months, streamflows entering the alluvial reach from Mill and Felta Creeks are very low, and below the confluence dry bed conditions prohibit surface water/groundwater interaction (Figure 53).

AET varies substantially throughout the watershed and rates typically range from about 16 to 40 in/yr (Figure 54). The overall spatial variability of AET is primarily a function of variability in available soil moisture and vegetation water requirements, with the two factors being inextricably linked. Lower values in portions of the Wallace and middle Mill watersheds coincide with grassland areas and soils with limited water holding capacity, whereas higher values in portions of the upper Palmer and Felta watersheds reflect forested areas with southern exposure where vegetation water requirements are highest. Climatic water deficit (CWD) is defined as the difference between PET and AET and is a useful metric for describing the seasonal moisture stress. In the 10-yr average condition the annual CWD ranged from 5 to 35 in/yr across most of the watershed, except locally where rates were near zero due to accessibility of shallow groundwater and associated insensitivity to soil moisture availability (Figure 55). Topographic aspect appears to be a primary control on the spatial variability of CWD with north-facing slopes characterized by lower PET having significantly lower CWD values relative to south-facing slopes. During the drought of 2014, CWD values increased substantially to between 10 and 40 in/yr across most of the watershed (Figure 56). The 10-yr mean CWD across the watershed was 13.0 in/yr compared to 18.9 in/yr in 2014.
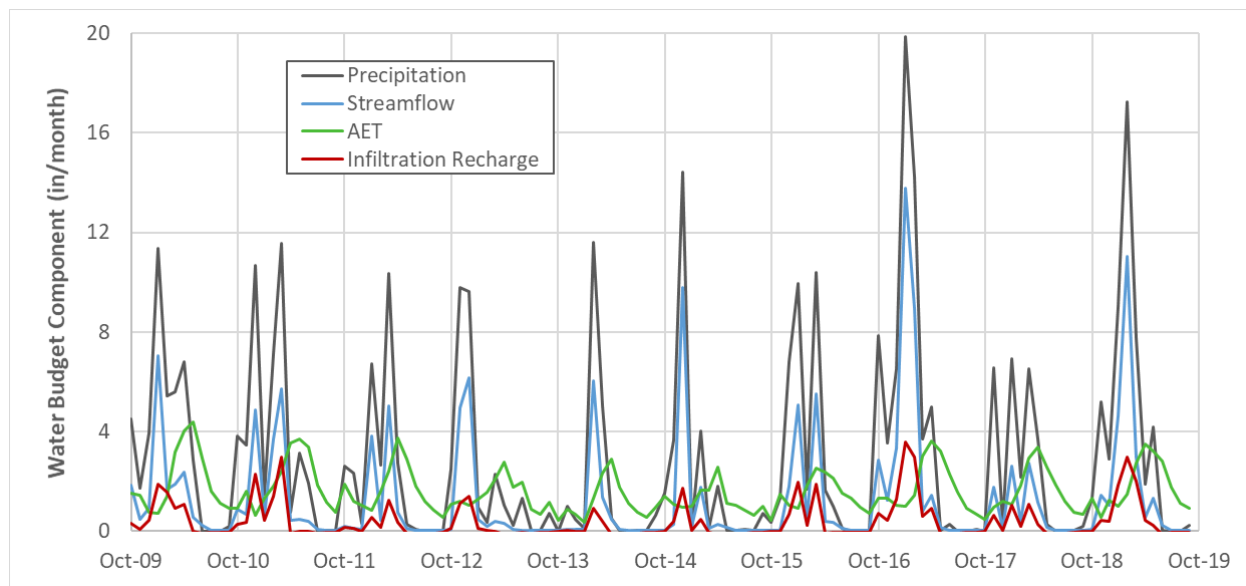
Figure 47: Monthly variation in select water budget components simulated with the Mill Creek hydrologic model.
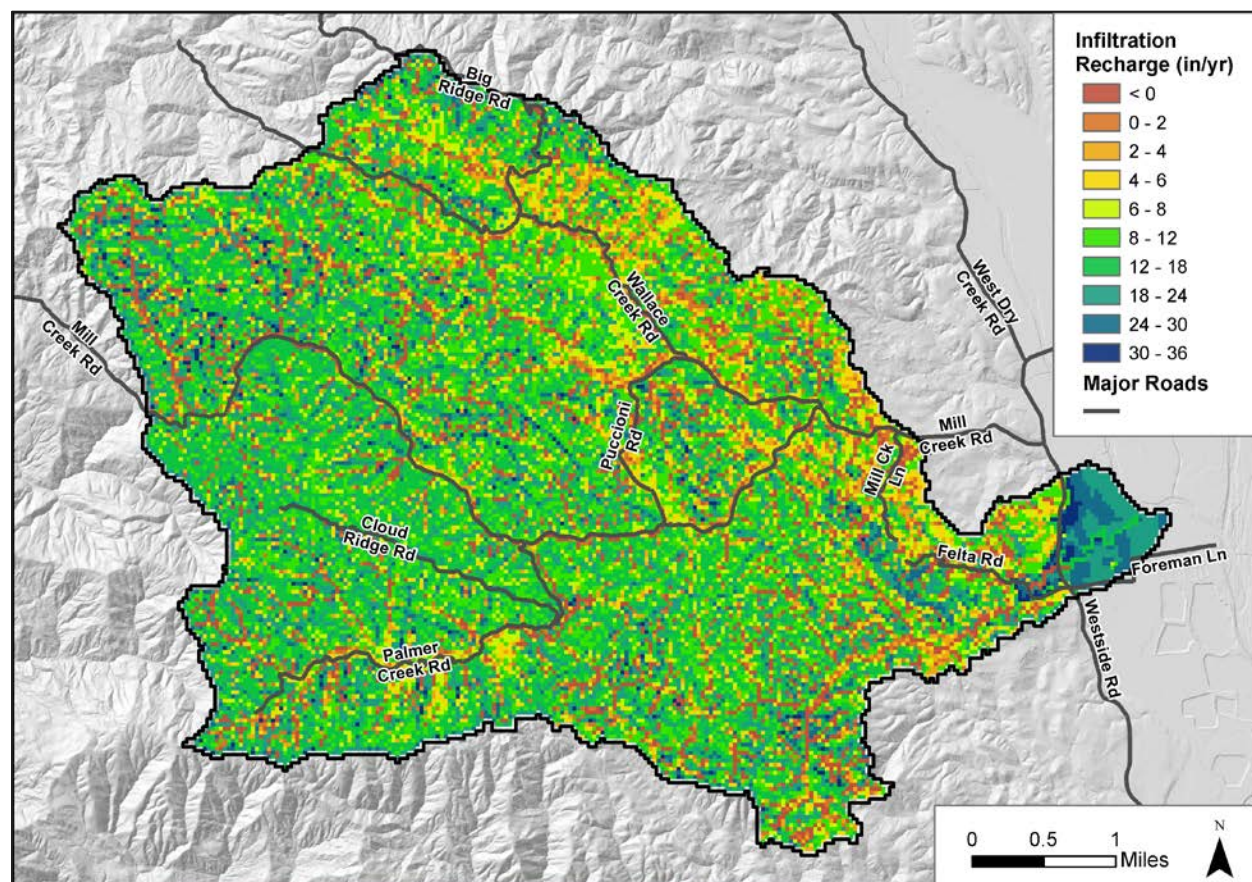
Figure 48: Mean annual infiltration recharge for water years 2010-2019 simulated with the Mill Creek hydrologic model.
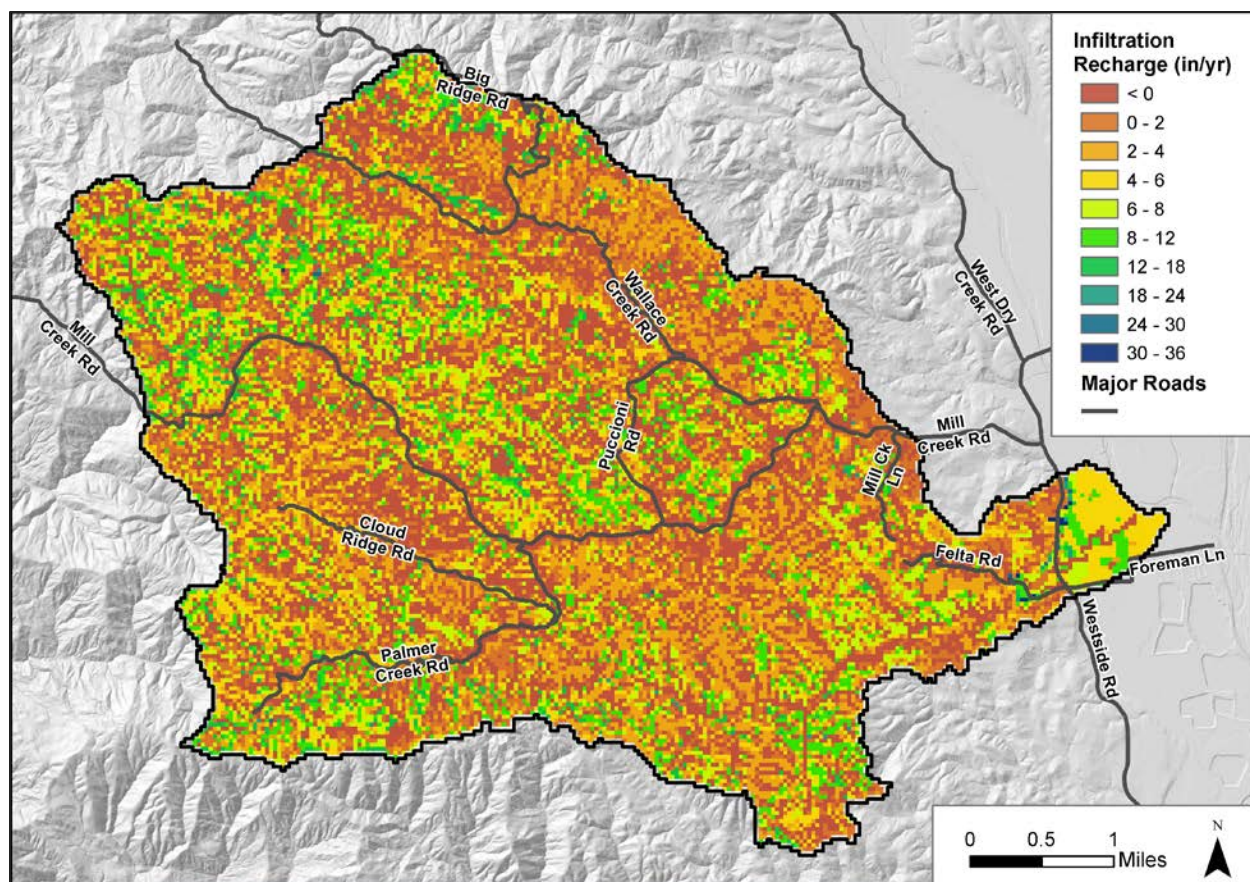
Figure 49: Infiltration recharge for water year 2014 simulated with the Mill Creek hydrologic model.
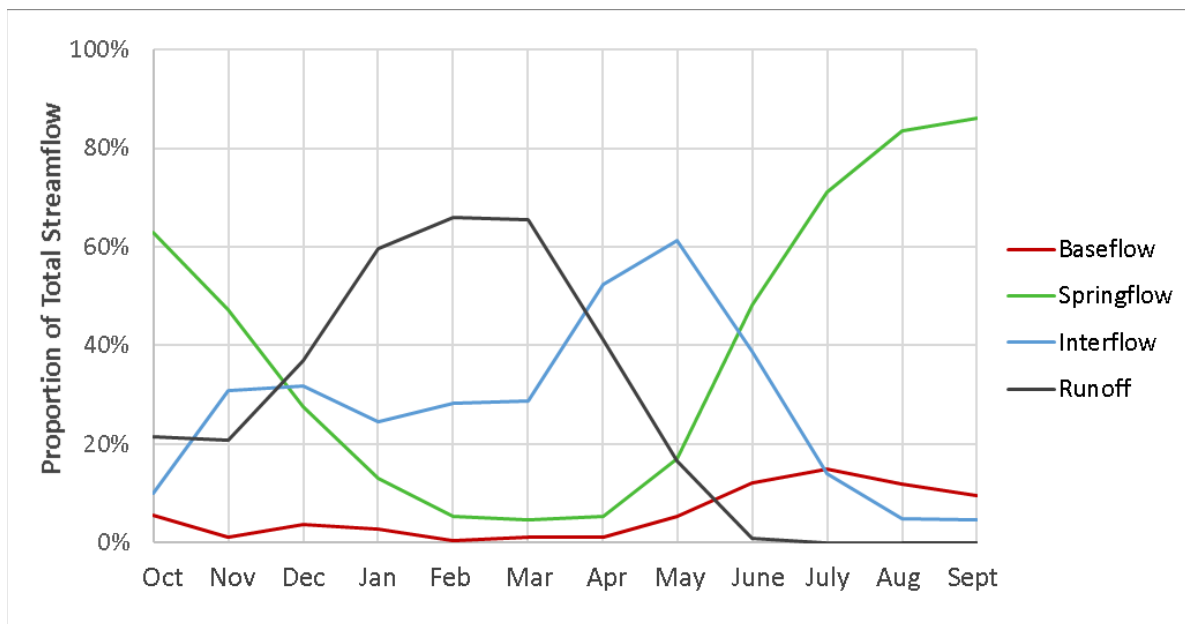
Figure 50: Proportion of total 2010-2019 mean monthly streamflow generated from the various sources represented in the Mill Creek hydrologic model.
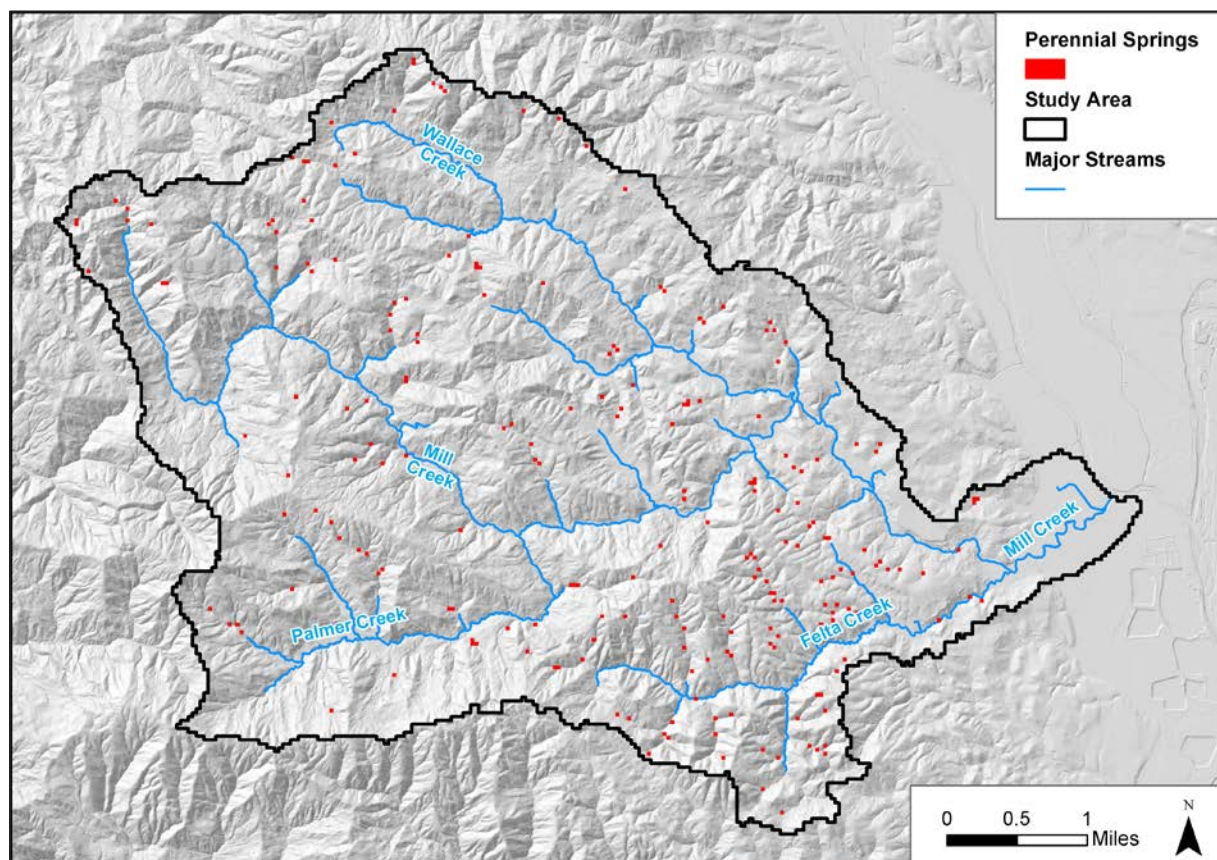
Figure 51: Locations of perennial springflow as simulated in the Mill Creek hydrologic model.
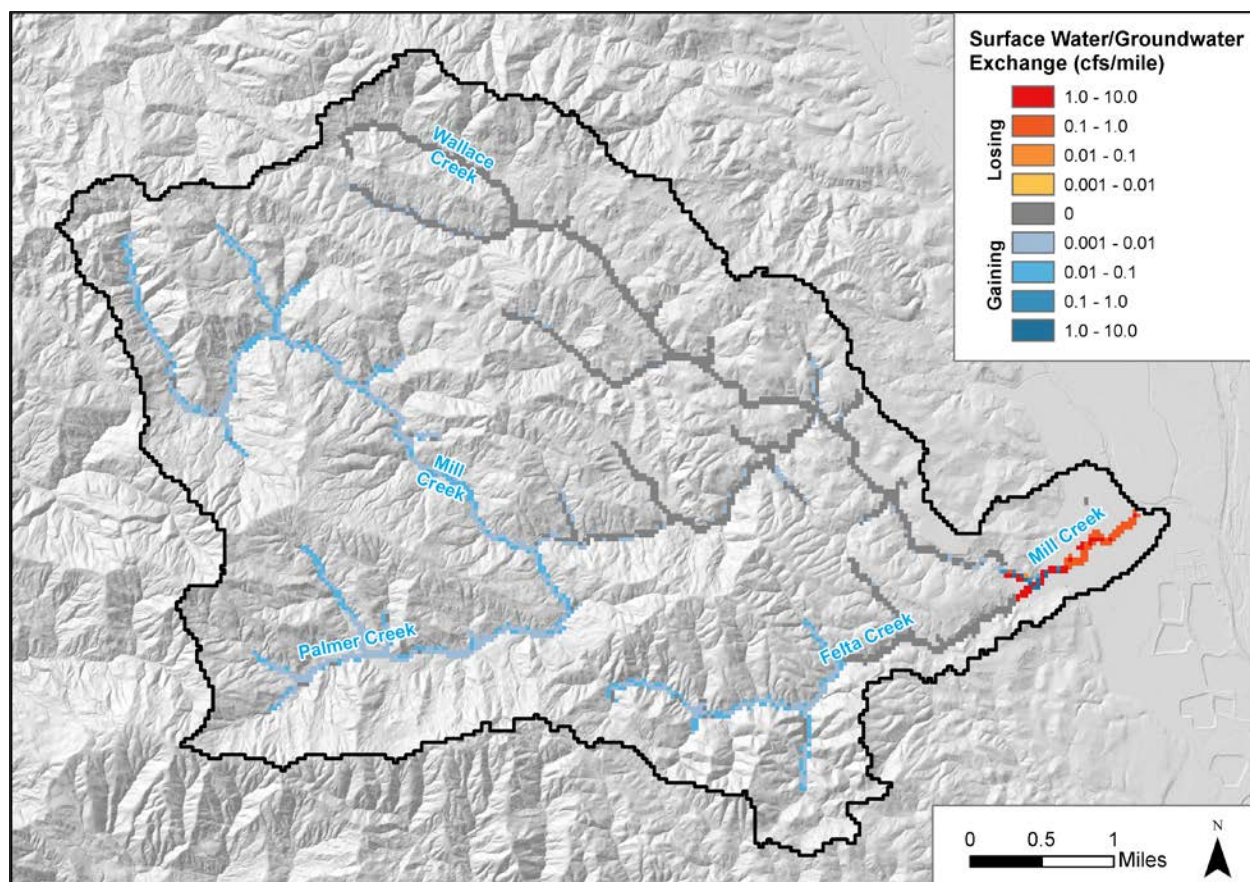
Figure 52: Rate of exchange between streams and groundwater for the month of April (2010-2019 mean) as simulated with the Mill Creek hydrologic model.
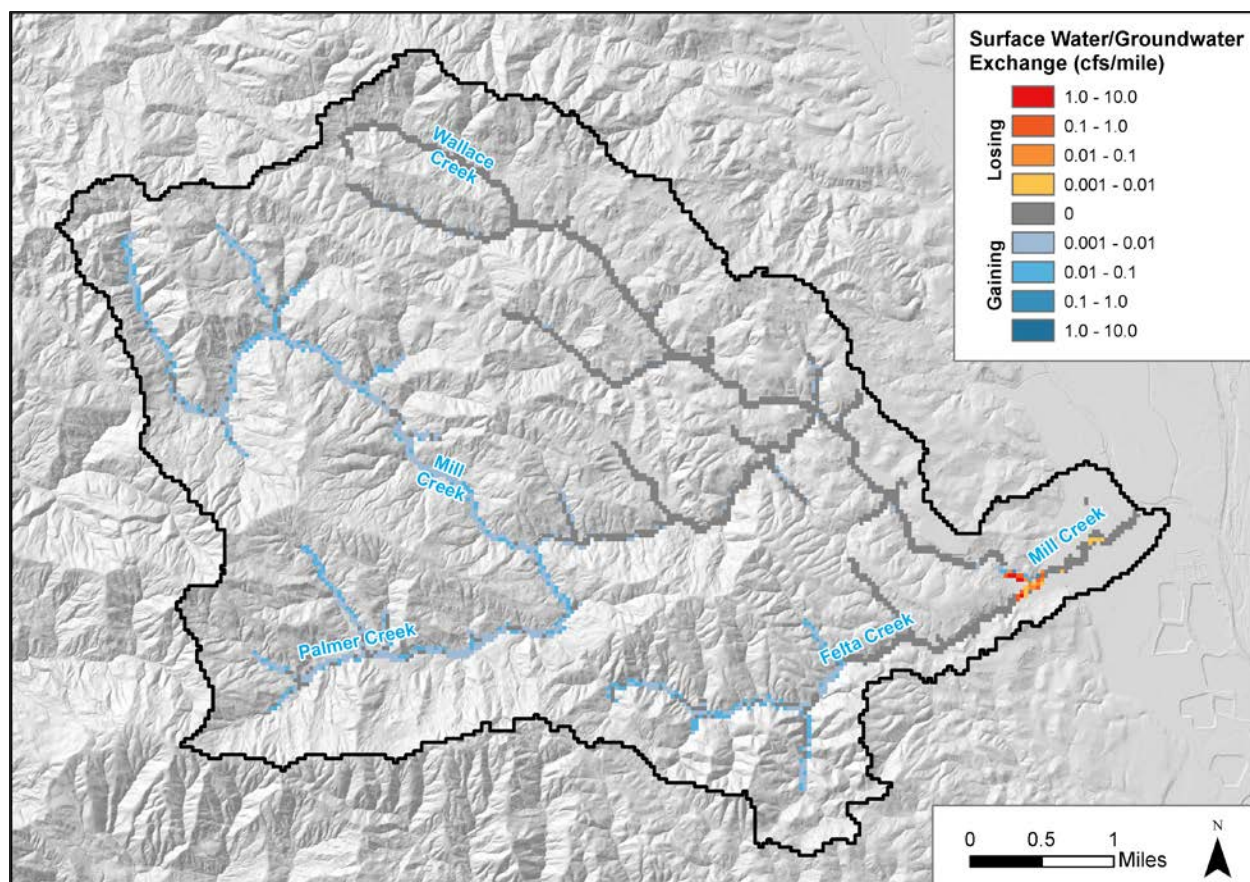
Figure 53: Rate of exchange between streams and groundwater for the month of August (2010-2019 mean) as simulated with the Mill Creek hydrologic model.
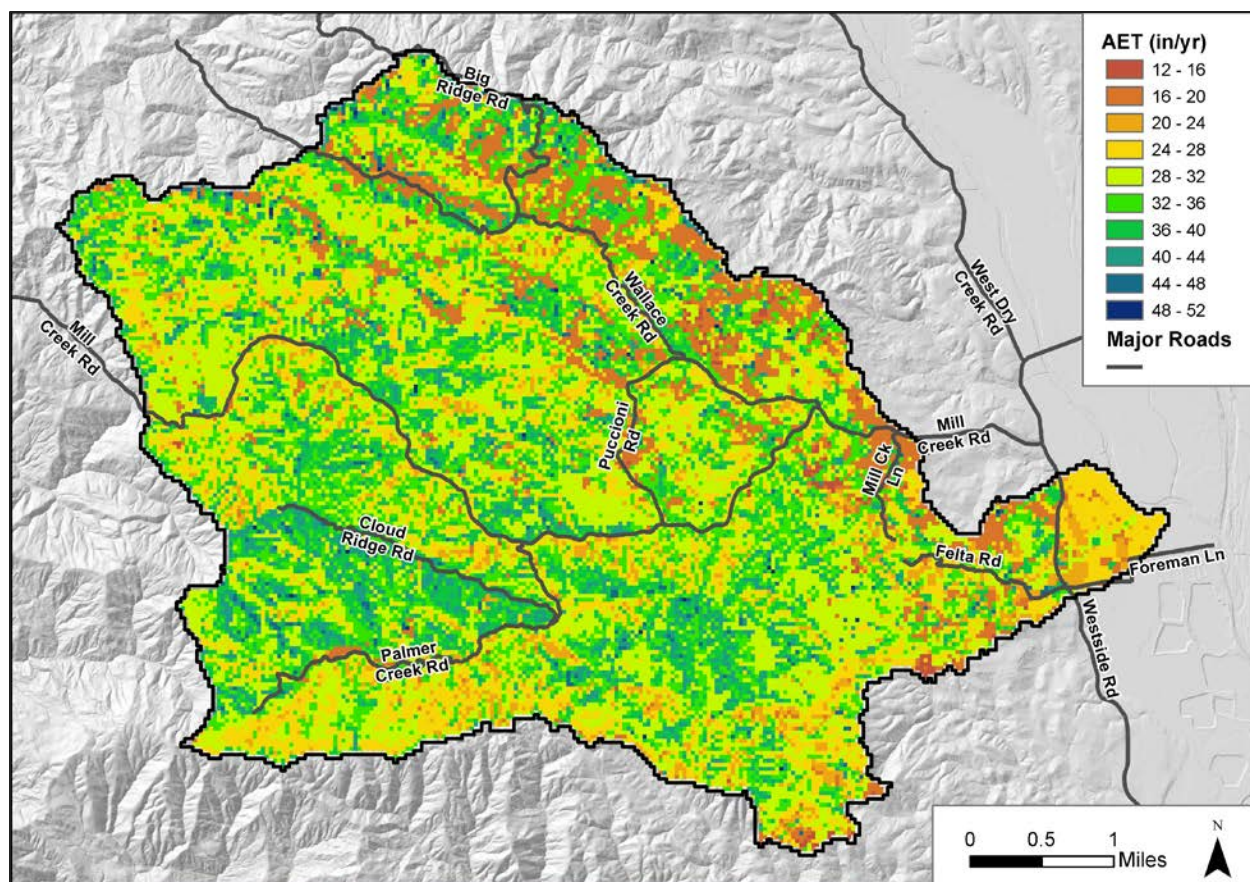
Figure 54: Mean annual actual evapotranspiration (AET) for water years 2010-2019 simulated with the Mill Creek hydrologic model.
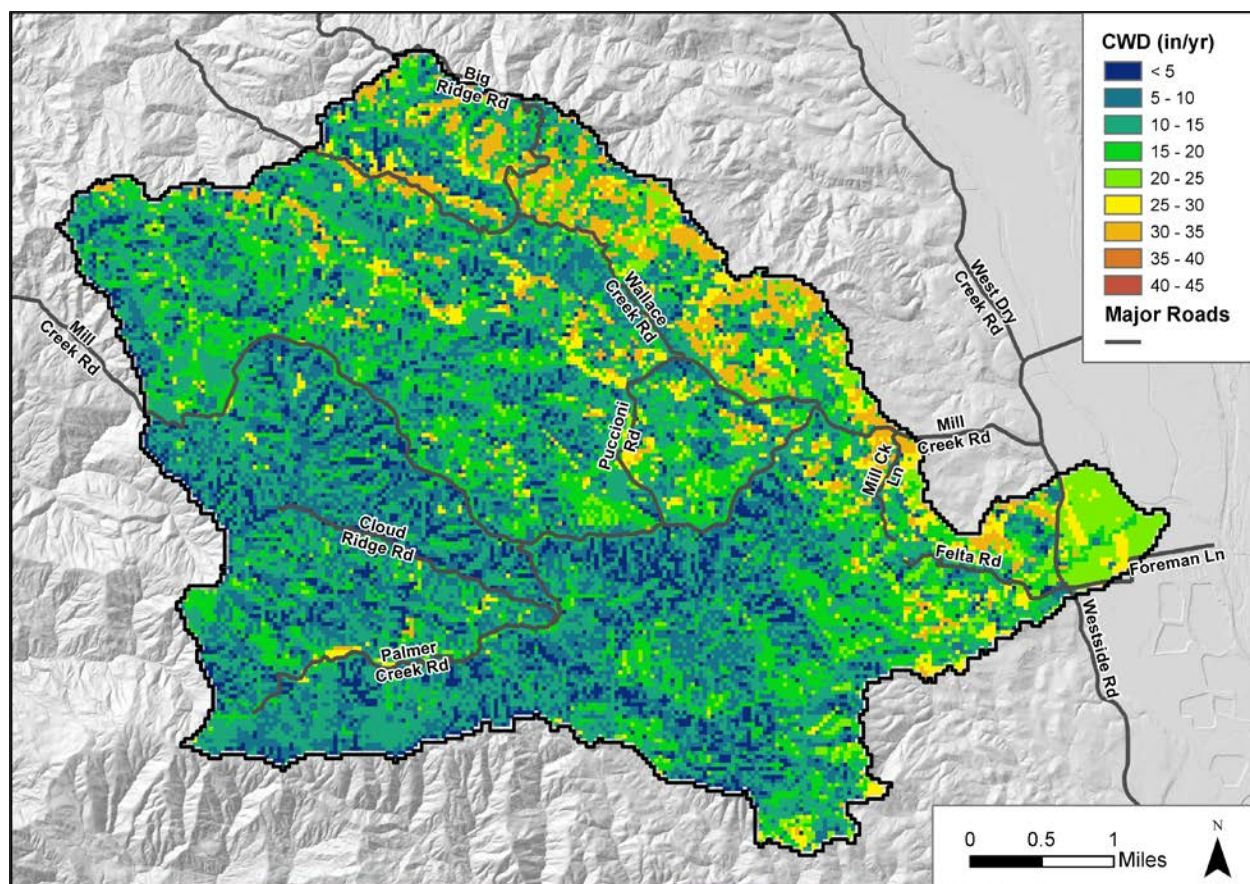
Figure 55: Mean annual climatic water deficit (CWD) for water years 2010-2019 simulated with the Mill Creek hydrologic model.
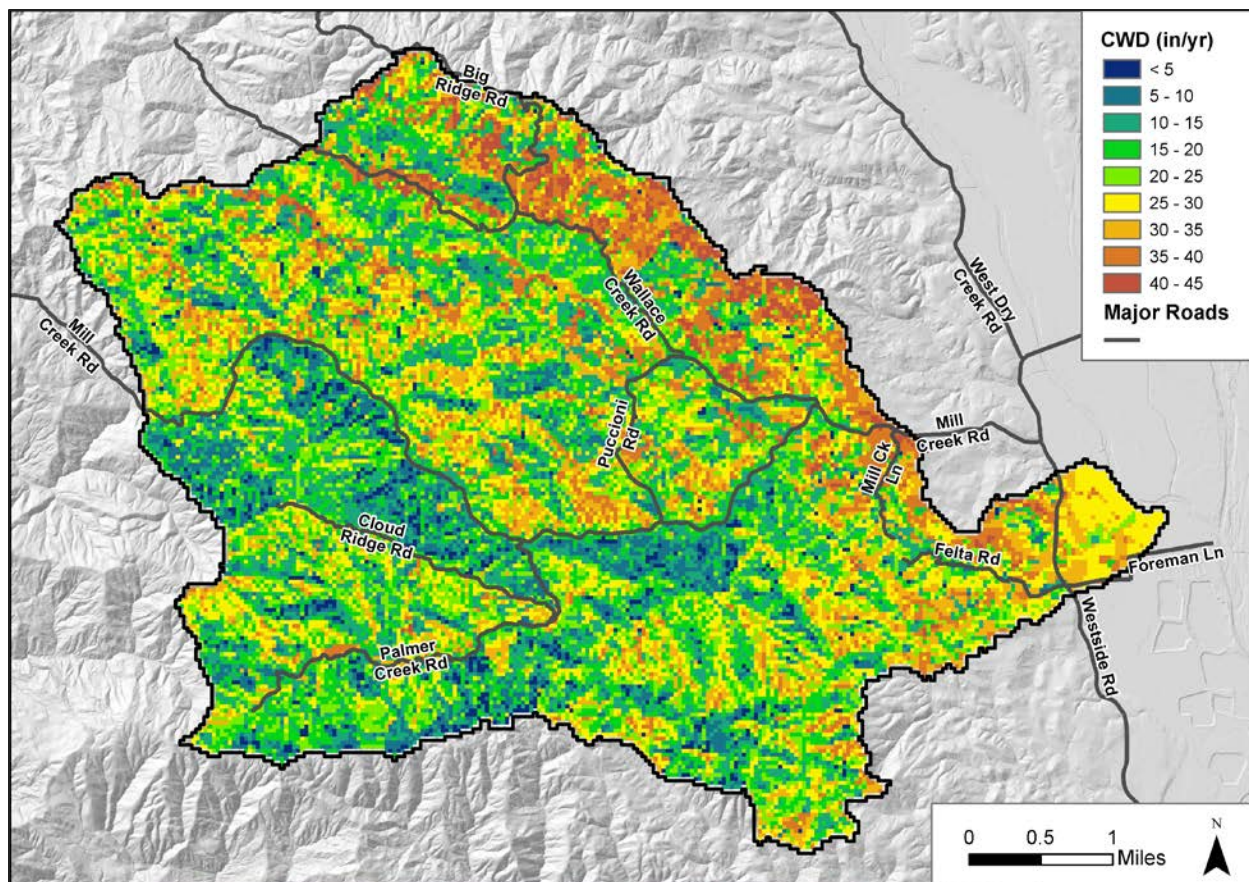
Figure 56: CWD for water year 2014 simulated with the Mill Creek hydrologic model.

Streamflow & Riffle Depths

April through June (hereafter referred to as Spring) mean streamflows varied substantially between water years with the driest conditions occurring in water year 2014 when flows ranged from less than 0.5 cfs in upper Mill Creek and the major tributary watersheds to more than 2 cfs in portions of middle and lower Mill Creek (Figure 57). The wettest conditions occurred in water year 2019 with flows in upper Mill Creek and tributaries on the order of 3-6 cfs and flows in Mill Creek below Wallace Creek greater than 20 cfs. July through September (hereafter referred to as Summer) mean streamflows were significantly lower than during Spring and also varied much less between water years (Figure 58). The driest conditions occurred in 2014 when flows ranged from less than 0.1 cfs in upper Mill Creek and the major Mill Creek tributaries to 0.2-0.3 cfs in the wettest reaches of Mill Creek below the Wallace confluence. In the lower alluvial reaches of Mill and Felta creeks, flows dropped to zero throughout the Summer in 2014 and for large portions of Summer even in wet years like 2019; additional discussion of flow disconnection timing is provided below (Figure 58).

To assist in relating flow conditions to salmonid habitat requirements, we also compiled simulated water depths (hereafter referred to as riffle depths) which were found to be loosely

equivalent to riffle crest thalweg depth conditions as discussed in greater detail in Chapter 7. The results were derived from model output data by extracting the minimum simulated depth per 1,000 ft of channel length (10 cross sections) to better represent riffle crest conditions observed in the field. Average Spring riffle depths during the drought of 2014 were less than 0.1 ft in Wallace Creek and portions of Palmer and Felta Creeks. Depths in Mill Creek were typically between 0.1 and 0.2 ft upstream of the very dry alluvial reach except for the reaches upstream and downstream of the Wallace confluence where mean Spring depths exceeded 0.2 ft (Figure 59). During the wet conditions of 2019, mean Spring depths remained above 0.2 ft throughout most of Mill Creek and the middle/lower portions of the major tributaries, with large sections of Mill Creek having depths greater than 0.3 ft. The very lowest section of Mill Creek above the Dry Creek confluence experienced a much lower mean Spring depth reflective of the timing of flow disconnection which proceeds from the confluence upstream.

Mean Summer riffle depths are significantly lower than Spring depths and are relatively consistent between water years. In both wet water years like 2019 and dry years such as 2014, flows dropped to zero intermittently in Wallace Creek and much of Felta Creek as well as in portions of the reach of Mill Creek extending from about 1.0 miles upstream of Wallace Creek to 1.5 miles downstream (Figure 60). The extent of the reaches experiencing flow disconnection did not change substantially between dry and wet water years except lower Wallace Creek which remained connected in 2019 but not 2014. The reach extending downstream from the Palmer Creek confluence to about 1 mile upstream of the Wallace Creek confluence, maintained continuous flow with riffle depths in the range of 0.10-0.15 ft even during the dry conditions of 2014 (Figure 60). As described above relative to streamflows, the lower alluvial reaches of Mill and Felta Creeks experience zero flow conditions for an extended period even during wet years like 2019.
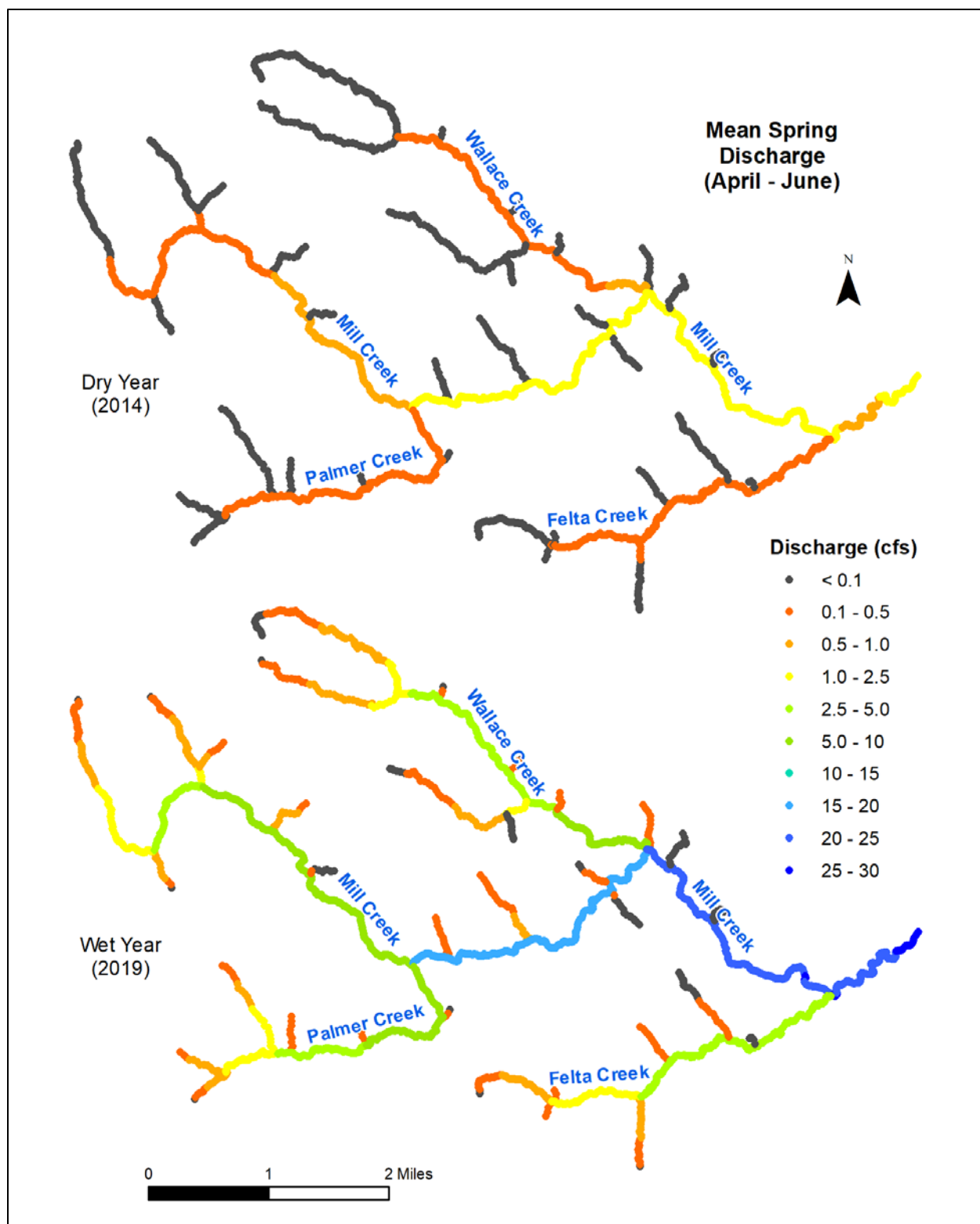
Figure 57: Mean simulated Spring (April – June) streamflows for dry and wet water year conditions.
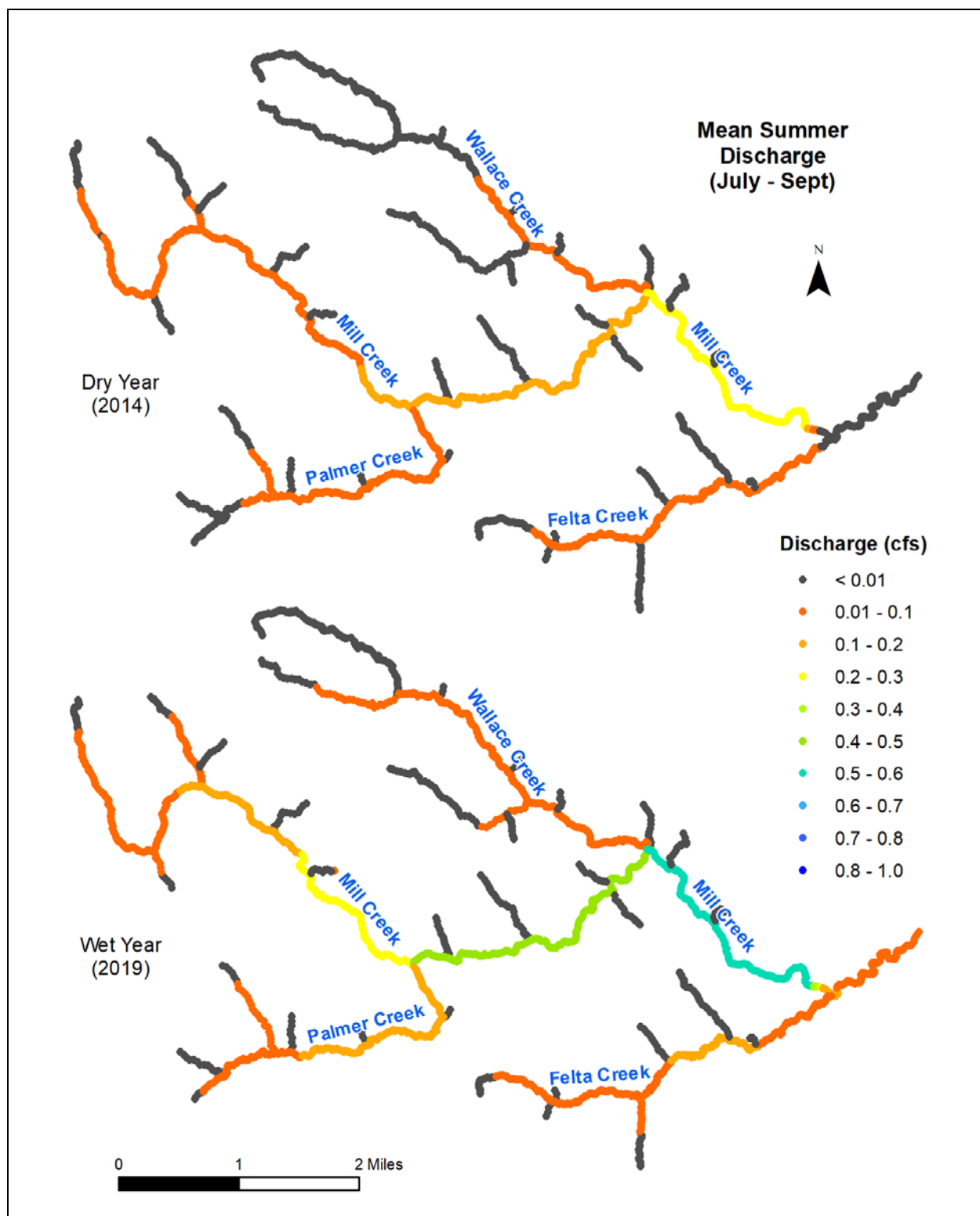
Figure 58: Mean simulated Summer (July - Sept) streamflows for dry and wet water year conditions.
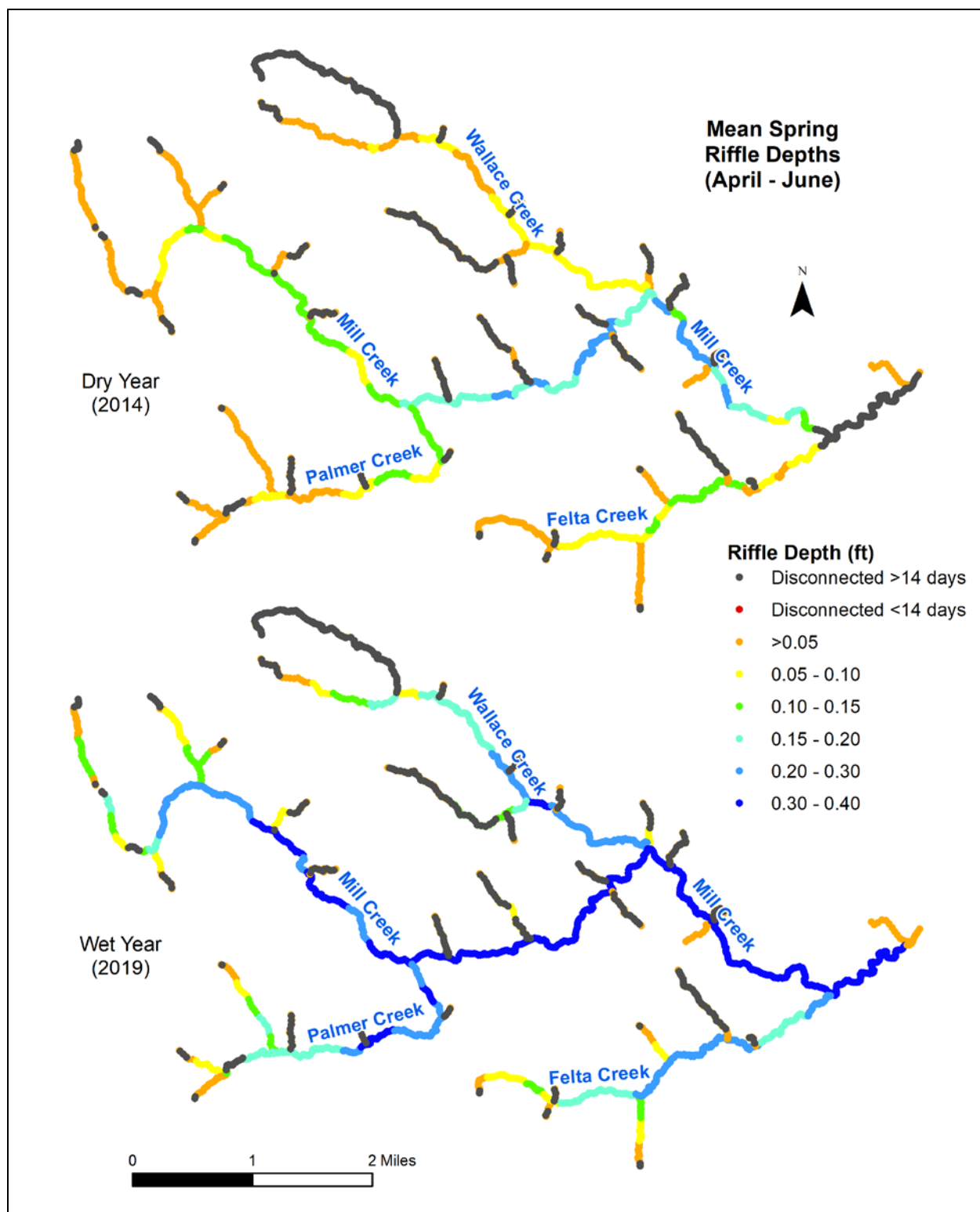
Figure 59: Mean simulated Spring (April – June) riffle depths for dry and wet water year conditions.
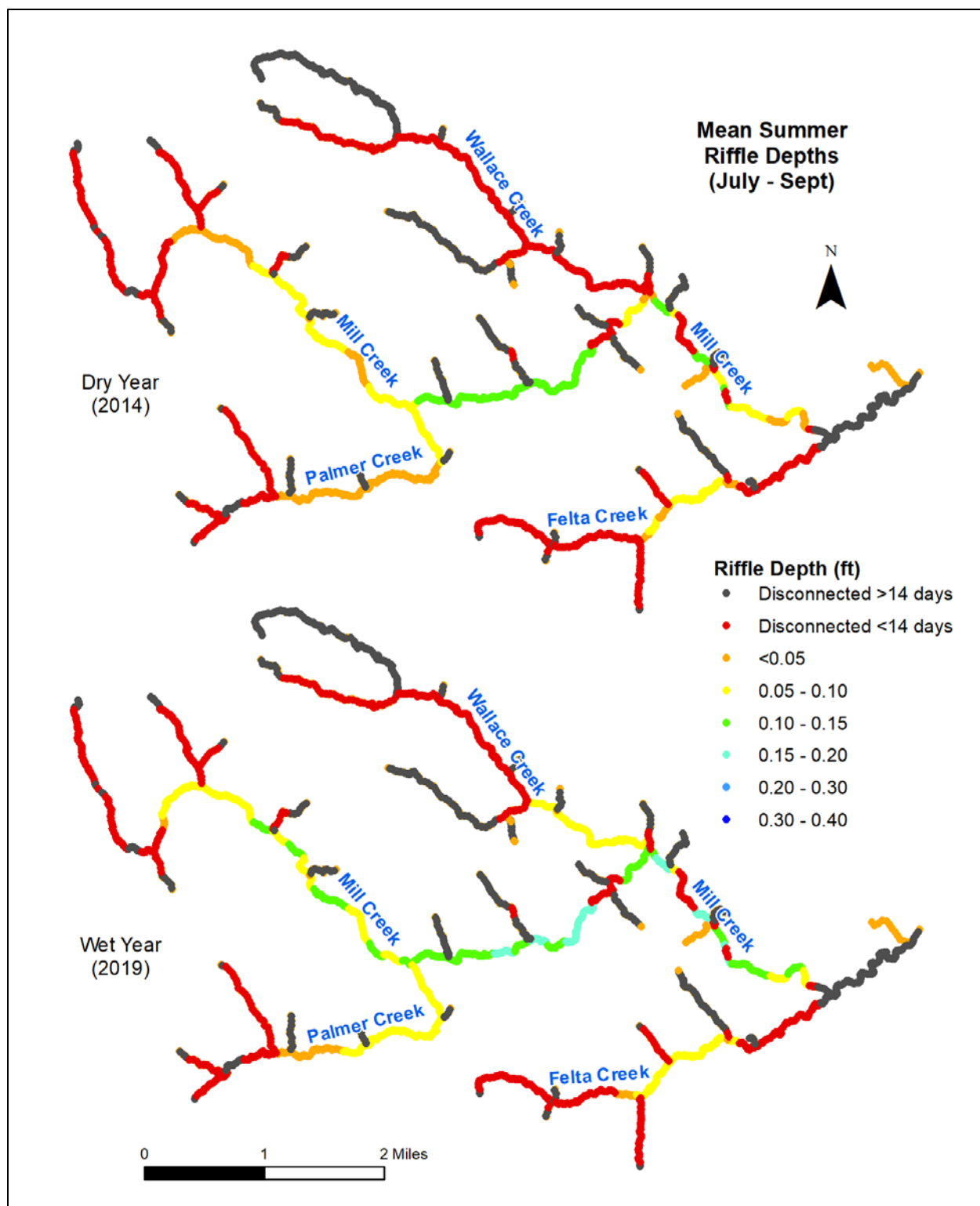
Figure 60: Mean simulated Summer (July - Sept) riffle depths for dry and wet water year conditions.

Chapter 7 – Habitat Characterization and Prioritization

Background

Inadequate stream flow to support juvenile rearing habitat during the summer months has been identified as a primary limiting factor for coho survival in Russian River tributaries (CDFG, 2004; NFMS, 2012). Flows during the spring outmigration period may also be limiting in some cases. Numerous methods have been developed to relate stream flow conditions to habitat quality and define minimum flow requirements for a specific species and life stage of interest. These methods include applying regional regression equations that have been developed from multiple habitat suitability curve studies (e.g., Hatfield & Bruce, 2000), wetted perimeter and critical riffle depth methods (e.g., Swift, 1979; R2 Resource Consultants, 2008), and direct habitat mapping approaches (e.g., McBain & Trush, 2010).

Regional regression equations produce discharge estimates for Mill Creek and other Russian River tributaries that are an order of magnitude higher than typical conditions during the summer months. For example, using the model-simulated values for mean annual discharge and applying the regional regression equation from Hatfield & Bruce (2000) for juvenile coho yield estimates of minimum flow requirements of 2.9 to 3.4 cfs in main-stem Mill Creek whereas mean summer flows simulated in the model for the same reaches range from 0.17 to 0.39 cfs. Given that coho persist in these tributaries despite these very low flow conditions, application of these regional equations may be of limited value for delineating the extent and quality of existing habitat with respect to streamflow. Direct habitat mapping approaches require extensive fieldwork and site-scale characterization, which is beyond the scope of this regional planning study; a concurrent CDFW Instream Flow Study utilizing such methods is being conducted in the nearby upper Mark West Creek watershed.

A simple approach to utilizing hydrologic model results to delineate habitat availability (and the selected approach for this study) is to relate water depths simulated in the model to riffle crest thalweg depths (RCTDs), which have been investigated as important indicators of salmonid habitat suitability. This approach assumes that the simulated water depths are representative of conditions at riffle crests. This assumption is consistent with the limitations of the LiDAR topographic data, which does not penetrate water and therefore would be expected to capture riffles and the water surface of pools but not stream channel geometry of pools.

To validate this assumption, we examined field measurements of riffle crest thalweg depths (RCTDs) collected by UC Berkeley PhD candidate Brian Kastl (Kastl et al., 2019). This data consisted of RCTD and discharge measurements collected in spring 2018 and 2019 at 10 riffles in an ~800 ft reach of Mill Creek upstream of the Felta confluence and at 18 riffles in an ~1,400 ft reach of lower Felta Creek. It should be noted that these measurements represent a mix of locations with bedrock-controlled step-pool morphology and gravel-bedded riffle-pool morphology, the later of which is much more common in the watershed. Additional validation of the utility of the approach and equivalency of model-simulated and field-derived RCTDs is provided through similar work completed in the Mark West Creek watershed (Kobor et al., 2020). There are relatively few field measurements available at the lowest flow conditions that are of

primary interest for quantifying summer salmonid habitat, therefore some error is introduced through the linear interpolations between field measurements that we used to derive the field-based threshold discharges discussed below.

We plotted the discharge versus RCTD data and compared these data to the model RCTD/discharge relationships for representative cross sections in the hydraulic model (Figure 61). There was generally good agreement between the measured and simulated discharge/RCTD relationships, particularly when comparing the most-limiting riffles measured in the field (shallowest RCTD for a given discharge) with the most-limiting cross sections from the model. In the Mill Creek reach, the model indicates 1.5 and 4.7 cfs would be needed to achieve RCTDs of 0.2 and 0.3 ft, respectively. The field values for equivalent depths were 1.1 and 5.4 cfs (Figure 61; Table 10). One of the riffles in the Felta reach was an extreme outlier suggesting flows three times as large as the next most-limiting riffle would be needed to achieve these depth targets. Given the limited spread of the data from next three most-limiting riffles it seems likely that these data may be compromised, or at least not representative of typical conditions in the reach. The model indicates 1.8 and 4.1 cfs would be needed to achieve RCTDs of 0.2- and 0.3 ft respectively in the Felta reach, whereas the field data indicates these values would be 2.1 and 4.4 cfs (neglecting the data from the anomalous riffle) (Figure 61; Table 10). Overall, these comparisons indicate that our approach (sampling depth results from the most-limiting cross section in a given 1,000 ft reach) provides a reasonable approximation of RCTDs at the most-limiting riffles measured in the field.

Previous research has demonstrated relationships between RCTDs and various indicators of salmonid habitat suitability including fish passage, water quality, and abundance of benthic macroinvertebrates. Maintaining suitable riffle depths to allow for fish passage is critically important during smolt outmigration (typically mid-February to mid-June) and is also important for facilitating pool selection prior to summer rearing. A minimum passage depth of 0.3 feet has been estimated for juvenile coho (R2 Resource Consultants, 2008; CDFW, 2017). This depth criterion and methodology is somewhat conservative by design and fish passage is thought to occur in Russian River tributaries at shallower depths, therefore it is useful to define a lower criterion below which passage is presumably not possible. For the purposes of this study, that depth was defined as 0.2 feet expressed as a RCTD. It is important to note that we are applying this depth threshold to RCTDs rather than depth thresholds based on CDFW critical riffle methodology (CDFW, 2017) that produce significantly higher summer flow thresholds (e.g., Kobor et al., 2020).

Another key factor in summer survival is the suitability of water quality conditions in the pools that provide rearing habitat for salmonids. Maintaining sufficient flow between riffles is key to maintaining oxygenation in pool habitats, and monitoring in Mill Creek and other lower Russian River tributaries including Grape, Green Valley, and Dutch Bill creeks, has shown that coho survival begins to decline when pools become disconnected, with mortality increasing as a function of length of disconnection (Obedzinski et al., 2018). Through extensive field monitoring in these four subwatersheds California Sea Grant (CSG) found a statistically significant
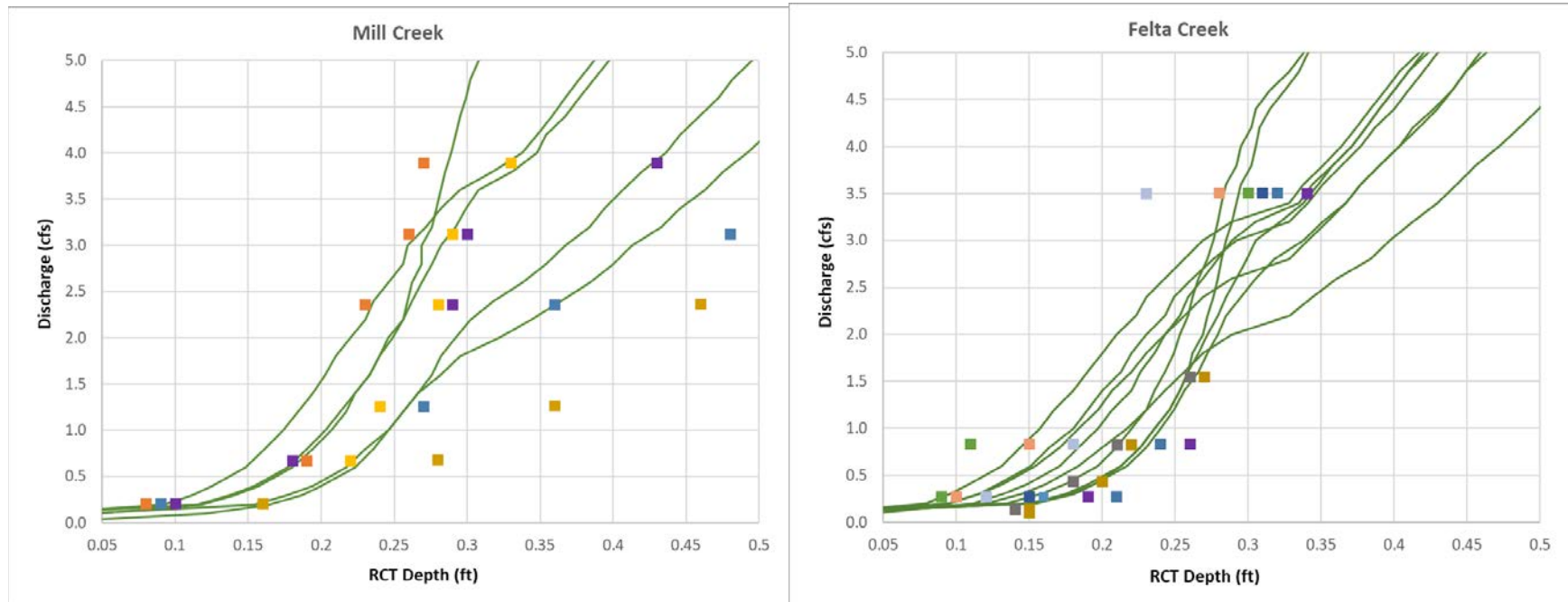
Figure 61: Comparisons between RCTD/discharge relationships measured in the field (points) and simulated with the Mill Creek hydrologic model (lines). The five most limiting locations (out of ten) are shown for the Mill Creek study reach and the nine most-limiting locations (out of 18 and excluding one outlier) are shown for the Felta Creek reach.

Table 10: Discharges required to achieve 0.2 and 0.3 ft RCTDs at the three most-limiting locations in the Mill and Felta creek study reaches as indicated by the hydrologic model and the field data.

	Mill		Felta	
	Flow to Reach RCTD of 0.2-ft	**Flow to Reach RCTD of 0.3-ft**	**Flow to Reach RCTD of 0.2-ft**	**Flow to Reach RCTD of 0.3-ft**
Field Riffle 1	1.09	5.42	1.85	4.42
Field Riffle 2	0.87	3.12	1.90	4.01
Field Riffle 3	0.75	1.63	2.10	3.50
Most-limiting	**1.09**	**5.42**	**2.10**	**4.42**
Model Riffle 1	1.52	4.67	1.8	4.14
Model Riffle 2	0.95	3.65	1.4	3.74
Model Riffle 3	0.89	3.42	1.26	3.26
Most-limiting	**1.52**	**4.67**	**1.80**	**4.14**

relationship between RCTDs and dissolved oxygen (DO) concentrations in intervening pools with ~80% of the pools with RCTDs greater than ~0.2 ft maintaining suitable DO concentrations above 6 mg/L (Nossaman et al., 2019).

In addition to suitable water quality, another factor critical to summer rearing habitat for salmonids is the availability of a reliable food supply in the form of benthic macroinvertebrates (BMI) which are concentrated in riffle habitats with sufficient flow velocity. Velocities at riffles between about 1.0 and 2.5 ft/s have been shown to be optimal for BMI (Giger, 1973; Gore et al., 2001). While we did not have riffle velocity measurements available in Mill Creek, data from three reaches of Mark West Creek covering a range of gradients broadly similar to those in the Mill Creek watershed indicated that sufficient velocities for BMIs were achieved at flows required to produce 0.2 ft RCTDs. Further investigation in this area is warranted but it is assumed that the 0.2 ft RCTD threshold is also sufficient for achieving suitable velocities for optimal BMI productivity in Mill Creek.

Approach

Two streamflow classifications were developed with respect to salmonid habitat conditions, one for smolt outmigration and one for juvenile rearing. Both classifications focus on the 0.2 ft RCTD threshold which is intended to represent the minimum flow conditions required to provide suitable (not optimal) habitat for salmonids. It is important to note that the primary goals in defining a minimum flow threshold for this study were: 1) to assist in distinguishing between reaches with varying levels of habitat suitability under existing and plausible future flow conditions in the watershed to aid in prioritizing reaches for restoration projects, and 2) to distinguish between conditions that are likely suitable versus not suitable rather than attempting to distinguish between optimal and suboptimal conditions. Optimal summer rearing habitat

conditions for salmonids, particularly coho salmon, are rarely found or non-existent in most Russian River tributaries.

Smolt outmigrant data collected by CSG for 2014-2019 were obtained for Mill Creek (Obedzinski et al., 2015; SCWA & CSG, 2015; CSG, 2016, 2017a, 2018b, 2019b, 2020b). These data show that smolts outmigrated between late February and late June, but that the outmigration was concentrated between late March and late May, with 88% of the total 2014-2019 outmigration occurring between March 26th and May 27th. Although there are modest differences in timing between individual years, the percentage of outmigrants during this primary outmigration period (POP) fell into a relatively narrow range of 80-95%. We developed habitat suitability criteria based on RCTD conditions during this 62-day timeframe deemed most important for characterizing the conditions experienced by the large majority of outmigrating smolts. We acknowledge that this approach may not accommodate potential ecological advantages that may in fact accrue to smolts that migrate early or late. Although it may be tempting to expand the time window to cover the 5-20% of smolts moving earlier or later than the POP, doing so would cause the results to be controlled primarily by conditions at the very beginning and very end of the outmigration period (rather than the period when most smolts are moving) due to the nature of the receding flow hydrographs typical of this timeframe. The criteria are based on the frequency with which passable (0.2 ft RCTD) conditions are present during the POP, and are listed in order of increasing habitat quality as follows:

- Passable for at least 7 days during the POP in the 10-yr average condition
- Passable for at least 30 days during the POP in the 10-yr average condition
- Passable throughout the 62-day POP in the 10-yr average condition
- Passable for at least 7 days during the POP in drought conditions
- Passable for at least 30 days during the POP in drought conditions
- Passable throughout the POP in drought conditions

We followed a similar approach for the juvenile rearing habitat classification focused on July-September conditions. Through field monitoring in Mill, Grape, Green Valley, and Dutch Bill creeks, CSG has found that coho can survive in pools that become disconnected for short periods of time, however survival decreases sharply as a function of the duration of pool disconnection (Obedzinski et al., 2018), thought to be influenced primarily by the low dissolved oxygen conditions that develop in disconnected pools. Thus, in addition to delineating reaches where passage between pools is possible it is useful to delineate reaches that become disconnected for short periods of time and reaches that become disconnected for extended periods of time. Duration of disconnection of 14 consecutive days was used for this analysis which corresponds to an ~80% survival rate averaged across the CSG bedrock study reaches of Mill, Grape, Green Valley, and Dutch Bill creeks (Obedzinski et al., 2018); survival in alluvial reaches was much lower at 14 days (~50%).

Few reaches in the watershed remain flowing throughout the summer with RCTDs above the threshold value of 0.2 ft indicative of adequate water quality and BMI conditions. Therefore, it was useful to define a lower threshold of 0.1 ft to distinguish between reaches where flows are

very low (RCTD <0.1 ft) and reaches where flows are modest (RCTD of 0.1 to 0.2 ft) but still below the target 0.2 ft RCTD.   We developed a set of habitat suitability criteria for summer rearing habitat conditions as follows:

- Pools become disconnected (zero flow) for 14 or fewer consecutive days in the 10-yr average condition
- Pools remain connected with shallow RCTDs (<0.1 ft) in the 10-yr average conditions
- Pools remain connected with modest RCTDs (0.1 to 0.2 ft) in the 10-yr average condition
- Pools remain connected with modest RCTDs (0.1 to 0.2 ft) in drought conditions
- Pools remain connected with RCTDs above 0.2 ft in the 10-yr average condition
- Pools remain connected with RCTDs above 0.2 ft in drought conditions

Each 1,000 ft stream reach in the model was assigned a score of zero to six based on the number of these criteria that were met to develop flow-based habitat classification maps for smolt outmigration and juvenile rearing.

In addition to sufficient flow to enable passage, maintain water quality, and support benthic macroinvertebrates, there are many other important habitat parameters that characterize suitable salmonid habitat. These include presence of pools with sufficient depth and cover, suitable spawning gravels, and availability of refugia from high velocity winter flows, among others. To account for some of these habitat factors in our classification, we compiled winter rearing habitat suitability data from previous work in the watershed (Kobor & O'Connor, 2018). These data were developed based on hydraulic model simulated depth and velocity conditions examined relative to juvenile coho requirements. Hydraulic conditions were examined over a wide range of winter flows and were used to identify the reaches with the highest abundance of suitable in- and off-channel winter rearing habitat as well as reaches where winter habitat is particularly limiting (Kobor & O'Connor, 2018).

Evaluation of water temperature and dissolved oxygen conditions were not part of this investigation, however CSG monitoring has found that water quality conditions in much of the watershed are generally suitable for salmonids except during periods of drought when flows become very low or pools disconnect. Finally, available fisheries monitoring data collected by CSG between 2017 and 2021 (CSG, 2017b, 2018a, 2018c, 2019a, 2019c, 2020a, 2020c, 2021) were compiled to gain perspective on where in the watershed salmonids are spawning (redd surveys) and where they are rearing over the summer (snorkel surveys).

We then examined all the data described above to produce a generalized multi-factor habitat classification map. This process involved combining the juvenile rearing, smolt outmigration, and winter rearing classifications and then overlaying the fisheries monitoring data. The resulting maps are intended to delineate the reaches providing the best overall habitat value for salmonids in the watershed as well as the reaches where conditions are likely unsuitable due to one or more critical limiting factors. We also interpreted the data to identify important habitat factors that have been observed to be absent or lacking both within and outside of the identified high value habitat reaches.

Results

The flow-based habitat classification results indicate that all reaches are impaired to varying degrees with respect to flow both in terms of smolt outmigration and summer rearing (Figure 60). The smolt outmigration classification indicates that during average water years passage would likely be possible for smolts throughout Mill Creek and its tributaries for a significant portion of the primary outmigration period (POP). Below the Palmer Creek confluence, conditions are passable throughout the full POP down to the confluence with Dry Creek; upstream of Palmer Creek and within the tributaries, many reaches are only passable for portions of the POP (score of 1 or 2) (Figure 62). During drought, passage conditions are considerably more challenging for salmonids, with impassable conditions in Mill Creek upstream of Palmer Creek and in the tributaries throughout most or all of the POP (score <4). Conditions in the lower alluvial reach of Mill Creek are passable during drought but only for less than half of the POP score <5). The most suitable passage conditions in the watershed are present in Mill Creek between the Palmer Creek confluence and the high-gradient reach known as 'the falls' (Figure 62) where passable conditions persisted during drought for more than half of the POP.

The timing of passable flow conditions relative to smolt outmigration is of particular importance in the lower alluvial reach which provides the route for smolts originating anywhere in the watershed to reach Dry Creek, the Russian River, and the Pacific Ocean. We examined the timing of model-simulated flow recession and development of impassable conditions in the lower reach over each of the ten simulated water years (2010-2019) relative to the observed distribution of smolt outmigrants and the POP (Figure 63). This exercise revealed that impassable flows occurred earliest at and above the Dry Creek confluence with conditions becoming impassable farther upstream near the Felta confluence about 4 to 8 days later. Conditions remained passable throughout the POP during seven of the ten years, however conditions became impassable above the Dry Creek confluence by the third week of April in the 2014 and 2015 drought and by the second week of May 2013 (Figure 63). The timing of the development of impassable conditions in Mill Creek above Dry Creek during 2014 and 2015 corresponds to the point in time when approximately 55% of the outmigrating smolts were observed by CSG in the upper portion of the alluvial reach, suggesting that a significant portion of the outmigrants were unable to reach Dry Creek and the Russian River.

The model results indicate that, although the duration of flow disconnection may vary substantially between water years, the extent of reaches that experience disconnection is relatively constant. Long-term (>14-days) flow disconnection occurred throughout the lower alluvial reach, and short-term disconnection occurred in portions of Mill Creek upstream and downstream of the Wallace confluence and in much of Wallace and Felta Creeks (Figure 62). Most of the remainder of Mill Creek and Palmer Creek retains surface flow even in dry water years (score >1), though flows become very low by late summer and none of the reaches maintain RCTDs above the 0.2 ft threshold even in an average water year. Portions of Mill Creek upstream of the Palmer confluence and downstream of the Wallace confluence maintain RCTDs above 0.1 ft during average years (score >2), however with the exception of a few short reaches downstream of Wallace Creek, only the reach between the Palmer confluence and about 1-mile upstream of the Wallace confluence retains RCTDs above 0.1 ft during drought (score =4) which

represents the most suitable flow conditions for juvenile salmonid rearing habitat found in the watershed (Figure 62).

The winter rearing classification results indicate relatively high potential for winter rearing suitability in many reaches of Wallace Creek, Palmer Creek, and Mill Creek upstream of a point about 1.5-miles below the Wallace Creek confluence (Figure 64). Below this point downstream to the Dry Creek confluence and in Felta Creek, suitable locations for winter rearing habitat become more scattered and conditions are believed to be more limiting. Please refer to Kobor and O'Connor (2018) for a full discussion of the winter rearing classification methodology and results.

Summer snorkel survey data is available from CSG monitoring from 2013-2020, however we focused on the 2017-2020 data because the earlier data reflects fish distributions prior to the removal of a small dam in the middle reach of Mill Creek that substantially blocked fish passage to reaches farther up in the watershed. We mapped the point-based snorkel survey data onto standard 1,000 ft reach lengths used in the earlier winter rearing classification. To identify the reaches consistently utilized by coho for summer rearing, we tabulated the number of years out of four when three or more coho were observed in pools located within the reach, as well as the reaches where zero coho were observed over the 4-yr period (Figure 65). No coho were documented in Wallace or Felta Creeks (excepting the lowest ½ mile of Felta Creek). Fish were concentrated in the lower alluvial reaches of Mill and Felta Creeks, where coho used most reaches in three or four out of four years; ~36% of all observed coho were in this relatively small portion of the watershed. Relatively frequent utilization (three out of four years) also occurred in a few reaches upstream of the Palmer confluence and in portions of the reach between about 1-mile upstream of the Wallace confluence to above the falls. Utilization in one or two of four years also occurred in Palmer Creek and in Mill Creek below the Palmer confluence (Figure 65).

We processed the CSG redd monitoring data for winter 2016/2017 through winter 2020/2021 following a similar procedure to the snorkel data to calculate the number of years out of five when coho spawning occurred in a given 1,000 ft reach (Figure 65). No spawning was documented in Wallace or Felta Creeks (except in the lowest ½ mile of Felta Creek). Spawning was concentrated in the lower alluvial portions of Mill and Felta Creeks, where most reaches saw utilization in one or two out of five years. The reach of Mill Creek between the Palmer confluence and the falls saw sporadic spawning activity, with spawning occurring in some reaches in one or two out of five years and no spawning occurring in other reaches. Spawning activity in Mill Creek upstream of the Palmer confluence and in Palmer Creek was limited to relatively short reaches with a single year of spawning activity (Figure 65).
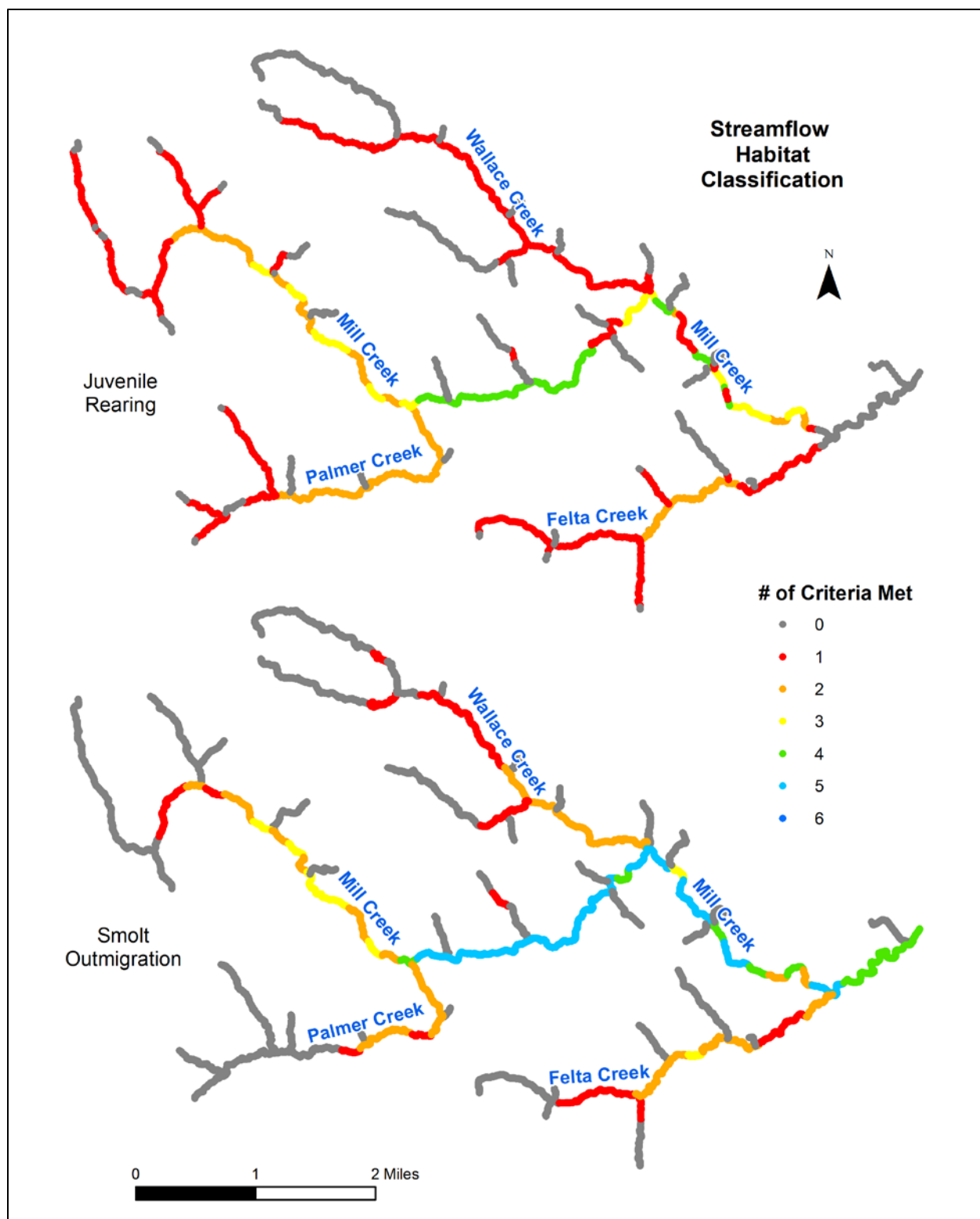
Figure 62: Flow-based habitat suitability classifications for juvenile summer rearing and smolt outmigration.
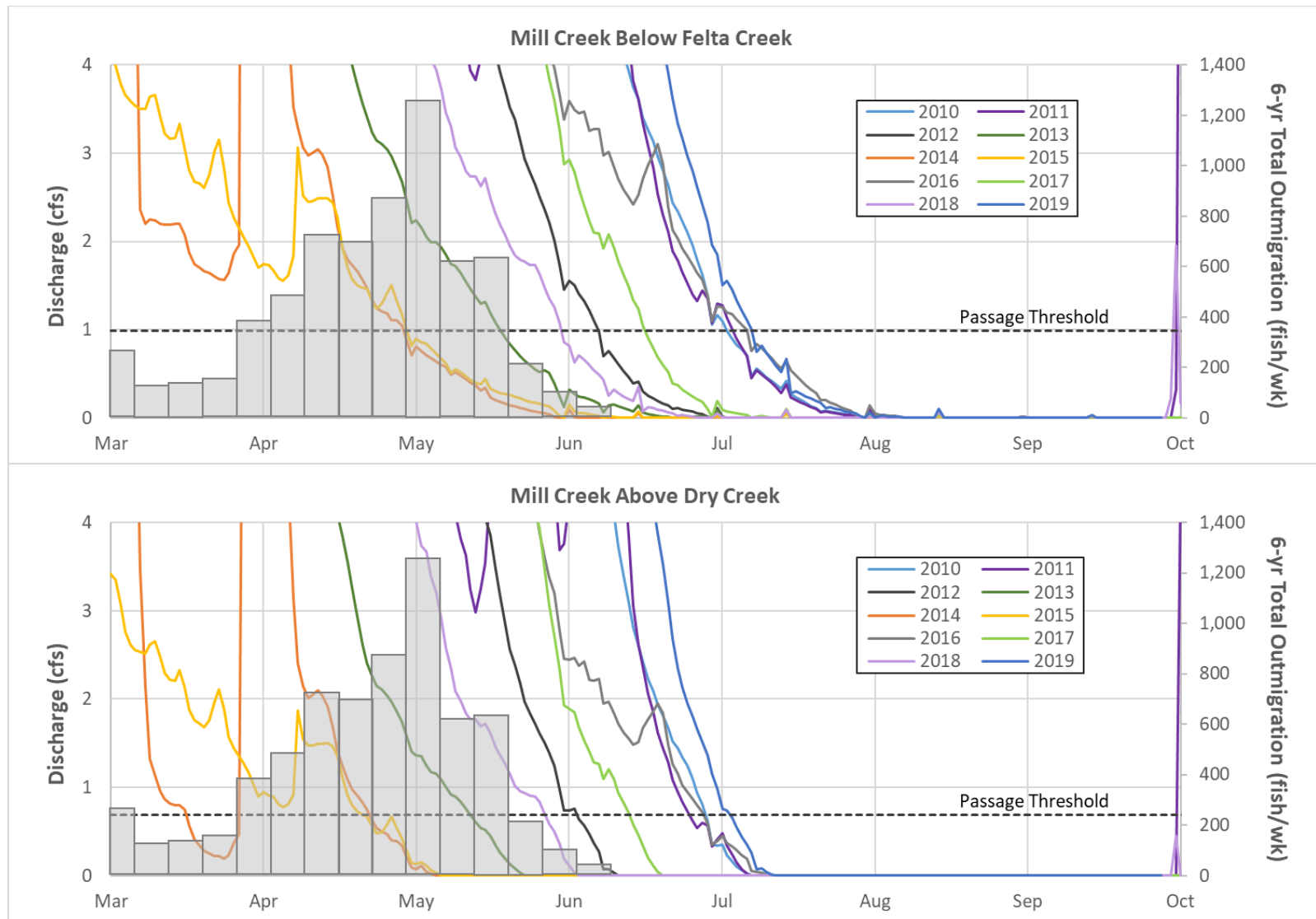
Figure 63: Streamflow hydrographs for the ten simulated water years (2010-2019) in the upper (top) and lower (bottom) portions of the alluvial reach of Mill Creek relative to the timing of outmigrating smolts as documented by CSG for 2014-2019.
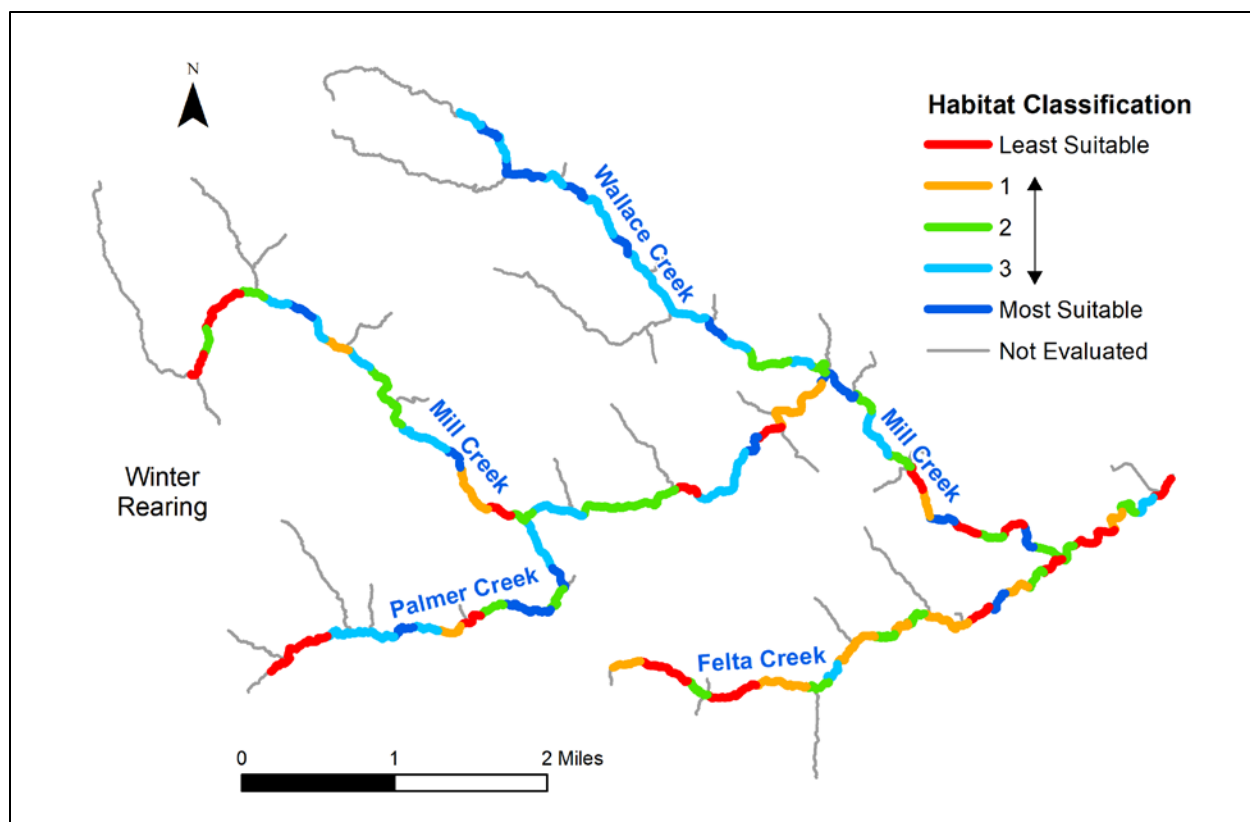
Figure 64: Habitat suitability classification for winter rearing from Kobor and O'Connor (2018).
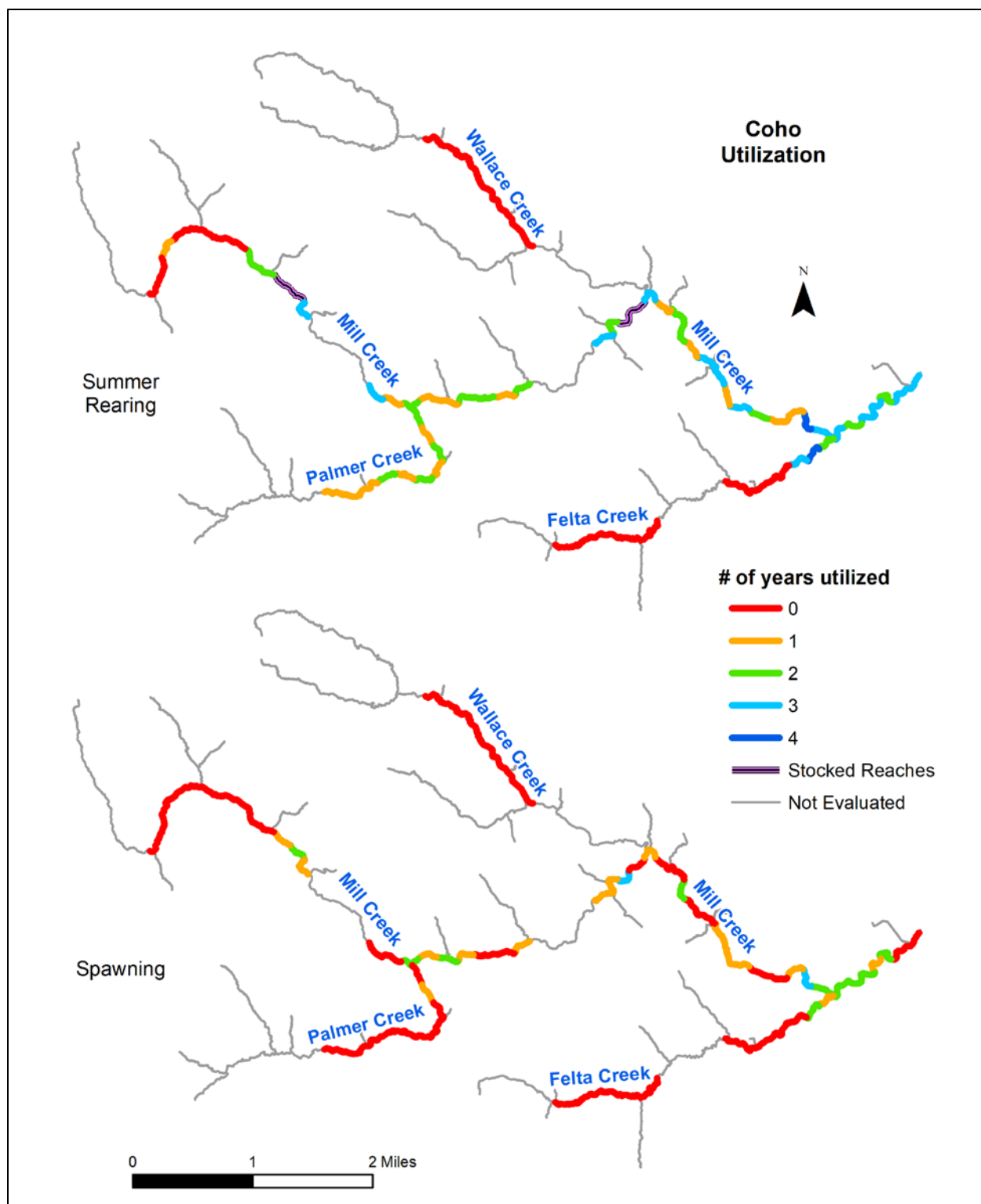
Figure 65: Coho summer rearing (top) and spawning (bottom) utilization classification based on summer snorkel surveys and winter redd surveys conducted by CSG between 2016 and 2021.

Restoration Prioritization & Recommendations

To assist in visualizing and interpreting the spatial relationships between the various habitat suitability and coho utilization classifications, we generated simplified versions of these maps to identify and compare locations of the reaches with high and medium suitability/utilization (Figure 66). This exercise revealed that suitable habitat for coho is restricted to the lowest 10.2-mi of Mill Creek and 1.9-mi of Palmer Creek.

Wallace Creek is not considered suitable habitat because flow-conditions are severely limited with impassable conditions developing early in the spring outmigration season and extensive drying occurring in the summer months. Additionally, no spawning or summer rearing has been documented in the surveyed reaches of the creek. Although perennial flow conditions persist in some middle-upper reaches, the majority of the channel is subject to frequent and prolonged drying and becomes impassable early in the outmigration season.

Winter rearing suitability is also low in Felta Creek relative to the other portions of the watershed and no recent coho spawning or rearing was documented outside of the lower 0.4-mi alluvial reach. In contrast to the lack of utilization in the majority of Felta Creek, a significant proportion of the total coho in the watershed (~14%) attempt to rear over the summer in the lower alluvial reach of Felta Creek. Survival is expected to be close to zero for these salmonids, given that the reach and adjacent reaches of Mill Creek experience prolonged periods of flow disconnection in the later summer months. The pattern of fish utilization suggests that access to the majority of the habitat in Felta Creek is blocked or at least severely limited by the barrier posed by an old dam site located at the upstream end of documented coho spawning/rearing. Given the degree of flow impairment and lack of access to upstream perennially flowing reaches posed by the dam site, Felta Creek is not considered suitable habitat for coho under current conditions. If a successful fish passage improvement project were implemented at the dam site, some suitable habitat would become available in the upper and middle reaches of the creek, however it would generally be expected to be of marginal suitability due to the degree of flow impairment.

The upstream extent of suitable habitat in Palmer Creek is easily identifiable by the presence of a natural barrier which corresponds to the upstream extent of observed summer coho utilization. The upstream extent of suitable habitat in Mill Creek corresponds to a change in stream gradient and flow regime about 0.5-mi upstream of Angel Creek, above which no summer rearing has been documented, and the downstream extent corresponds to the transition from a bedrock to an alluvial stream that occurs upstream of the Felta Creek confluence. The remaining 12.1-mi of suitable coho stream habitat was classified into six reaches based on transitions in suitability and/or utilization (Figure 67).

The 2.1-mile reach extending from the Palmer Creek confluence downstream to 0.9-miles above the Wallace Creek confluence (Mill 3) provides the best overall habitat for salmonids in the watershed (Figure 67). This reach is considered most suitable because hydraulic conditions are most favorable for salmonids across a wide range of flow conditions and it has relatively frequent coho utilization for both summer rearing and spawning. The upstream and downstream reaches (Mill 2 & 4) provide the next most suitable overall conditions, although each of these reaches lack

some habitat characteristics thereby making conditions somewhat less suitable for coho relative to Reach 3, as described below.

Perennial flows do persist in the 2.3-mile reach upstream of the Palmer confluence (Mill 2), however riffle depths become very shallow, and flows recede below passable levels several weeks earlier during the spring outmigration season relative to downstream reaches. The 3.2-mi reach extending from 0.9-mi upstream of the Wallace confluence downstream to the beginning of the alluvial reach above Felta Creek (Mill 4) is prone to periods of flow disconnection. Perennial flow generally persists in wetter water years and some sub-reaches may remain flowing during drier years, however the overall consistency of summer flow is less than in reaches Mill 2 and 3. Outmigration flows are expected to be less problematic for smolts owing to the timing of flow recession and relatively late development of impassable conditions in the spring outmigration season. Winter rearing suitability also appears to be somewhat less in this reach relative to Mill 2 and 3. Coho utilized reach Mill 4 in significantly greater numbers than in reaches 2 and 3, suggesting that work to address the flow limitations would be particularly beneficial in this reach.

Reach Mill 4 is also significant in that the lower ~0.4-mi is a high gradient bedrock and boulder-bedded reach known as 'the falls', which is expected to pose a migration challenge for both in- and out-migrating salmonids. The fact that the highest observed concentration of coho utilization in the watershed occurs immediately below this reach in an area considered unsuitable for summer survival may be indicative of the challenging passage conditions posed by the high gradient reach. The degree to which winter flow conditions affect upstream passage through the falls was not investigated as part of this analysis however the presence of this migration challenge is worth noting in the overall context of this discussion.

Reach Mill 5 experiences seasonal disconnection of surface flow during the summer months which can extend into spring and fall during dry years and is therefore not considered to be suitable rearing habitat. Unfortunately, it contains the highest density of coho utilization with many of these salmonids attempting to over-summer in the reach below the falls, as discussed above. Despite unsuitable summer conditions, Reach 5 is of critical importance as the key migration corridor for outmigrating smolts. During average or wet water years, flows remain passable throughout the outmigration season, however during drier years flows become impassable relatively early in the outmigration season. Flow enhancement efforts intended to sustain or extend the spring flow recession to ensure passable conditions for outmigrating smolts in Mill 5 is one of the most important restoration goals for the watershed.

Reaches Mill 1 and Palmer 1 both suffer from lower summer riffle depths and early development of impassable conditions during the spring outmigration season relative to downstream reaches. Summer rearing also occurred at significantly lower densities relative to the other reaches. Spawning activity was very limited in Palmer 1 and was not documented at all in Mill 1. For these reasons, Mill 1 and Palmer 1 are considered lower priority for enhancement work compared to other reaches. While they may have lower priority for habitat enhancement work, they are of

critical importance to the watershed as source areas of summer baseflows to downstream high priority reaches.

Although the high priority reaches we identified (see Figure 67) have the highest overall habitat quality in the watershed, habitat conditions nevertheless leave much to be desired owing to low summer stream flow, pool habitat with insufficient cover and large wood, and limited winter-rearing habitat. Previous prioritization work (Kobor & O'Connor, 2018) identified multiple opportunities for enhancing off-channel habitat in the high priority reaches (CRWI is currently developing off-channel habitat designs for a portion of reach Mill 3) and there are many opportunities to improve pool habitat with LWD projects within these critical reaches. We recommend that restoration projects aimed at enhancing both pool and off-channel habitat be implemented in the high priority reaches where they are likely to provide the greatest benefits to salmonids. Additional recommendations with respect to flow enhancement strategies and needs is provided in Chapter 9.
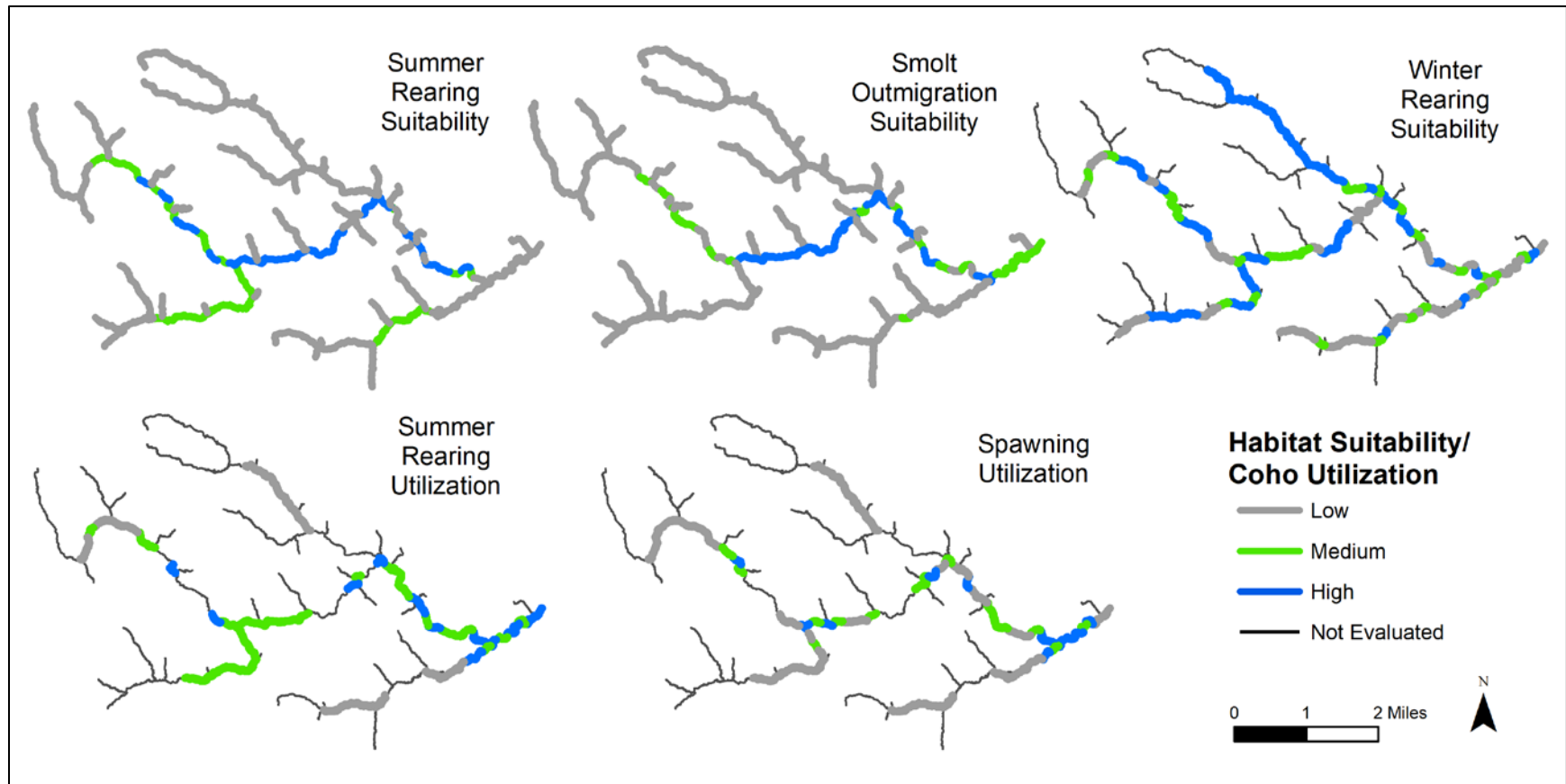
Figure 66: Simplified classifications for summer rearing, smolt outmigration, and winter rearing habitat suitability (top), and coho summer rearing and spawning utilization (bottom).
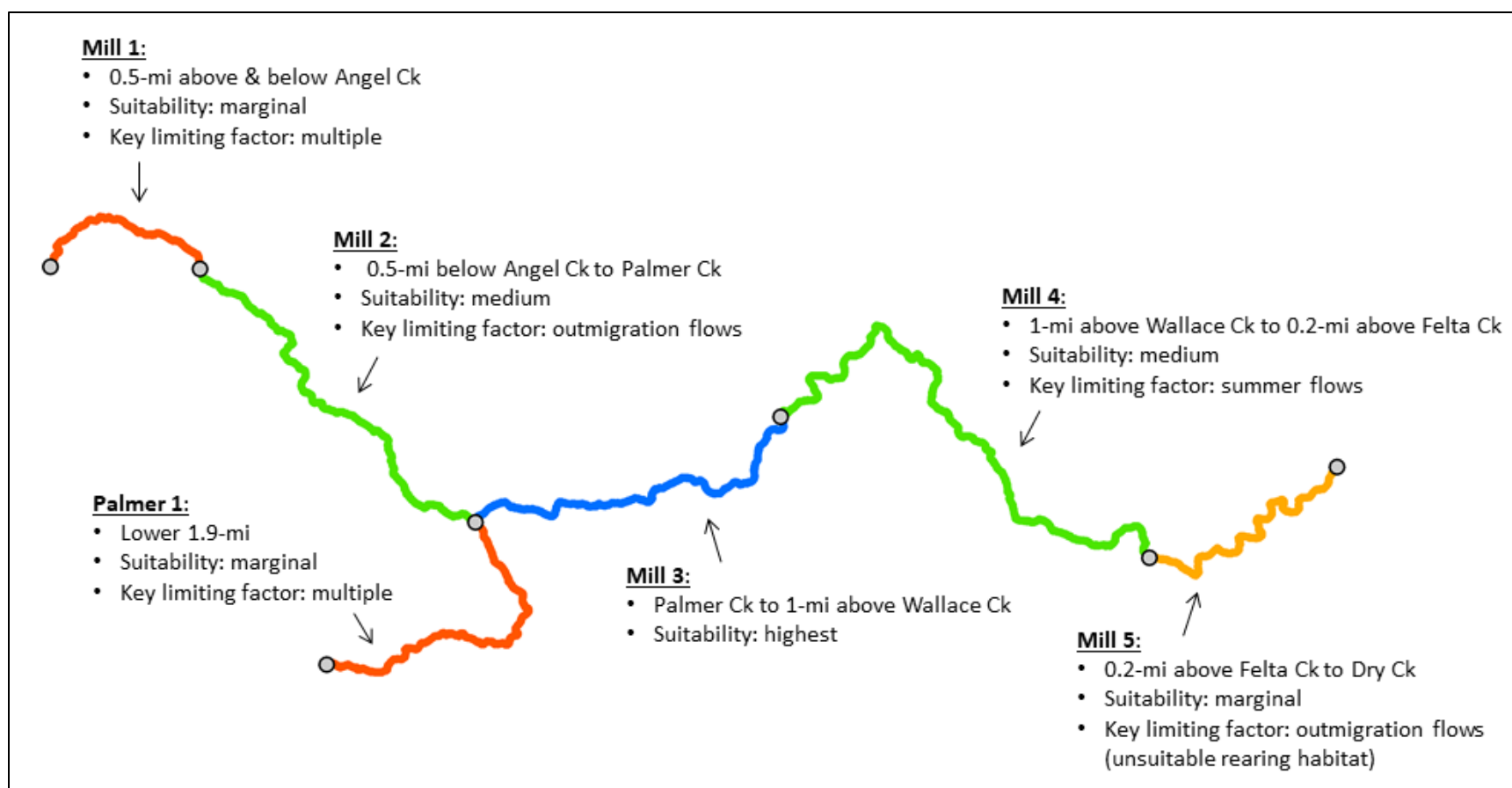
Figure 67: Final reach classification for the Mill Creek watershed (reaches not shown are considered largely unsuitable/very low priority for habitat enhancement, the classification could expand to include portions of Felta Creek were access to upstream habitat improved).

Chapter 8 – Scenario Analysis

Overview

Efforts to sustain and enhance streamflow have become a new focus for restoration practitioners working in tributaries of the lower Russian River. Some actions have already been implemented such as pond and flow release projects in Green Valley, Dutch Bill, and Porter Creeks, and rainwater and diversion storage projects aimed at reducing dry season water use have been implemented in the Mill Creek watershed and other tributaries. On the other hand, the watershed is subject to increasing pressure for new development and associated water use as new vineyard, winery, cannabis, and residential development projects are proposed while local and state regulatory agencies attempt to determine how to appropriately regulate new groundwater use to avoid detrimental effects on streamflow and instream habitat. These challenges are further complicated by ongoing global climate change and the uncertainties associated with future hydrologic conditions.

There is a clear need for methods and approaches capable of quantitative evaluation of the relative benefits of various flow enhancement strategies as well as the cumulative effects of land development and water-use on the landscape, and to do so within the context of future climate predictions so that more informed and effective management outcomes can be achieved. To assist in meeting this need, we developed a series of model scenarios designed to provide an understanding of the hydrologic sensitivity of various hypothetical management and restoration/enhancement actions as well as the effects of global climate change. There are a total of 20 scenarios grouped in four primary categories: Water Use, Land Management, Direct Flow Augmentation, and Climate Change as described below (Table 11). Each scenario was implemented by changing one or more model inputs and comparing model results to existing hydrologic conditions as simulated with the calibrated model described in previous chapters.

Approach

Water Use Scenarios

Three water use scenarios were developed to estimate the cumulative effects of diversions and groundwater pumping in the watershed: 1-No Diversions, 2-No Groundwater Pumping, and 3-No Water Use. Implementation of these scenarios was a simple matter of turning off inputs to the model that represent groundwater use from wells and stream diversions. Irrigation associated with wells and diversions was also turned off.

Table 111: Overview of the scenarios evaluated with the Mill Creek hydrologic model.

Scenario Category	Scenario #	Scenario Name	Brief Description
Water Use	1	No Diversions	All surface water diversions turned off
	2	No Groundwater Pumping	All groundwater pumping turned off
	3	No Water Use	All surface diversions and groundwater pumping turned off
Land Management	4	Forest Management	Forest treatment on 12,198 acres of forest
	5	Grassland Management	Application of organic matter on 1,297 acres of grasslands
	6	Runoff Management	Manage runoff from 82 acres of developed lands to maximize infiltration
Direct Flow Augmentation	7	6 Pond Summer Releases	Release water from six ponds with a total release of 0.38 cfs from July 1st to October 1st
	8a	6 Pond Spring Releases	Release water from six ponds ramping from 0.2 to 2 cfs over 34 days
	8b	Small Pond Spring Releases - continuous	Release water from smallest of the six ponds ramping from 0.2 to 1.2 cfs over 4 days
	8c	Small Pond Spring Releases - pulsed	Release water from smallest of the six ponds in one 36-hr 1.2 cfs pulse
	8d	Large Pond Spring Releases - continuous	Release water from largest of the six ponds ramping from 0.2 to 0.5 cfs over 17 days
	8e	Large Pond Spring Releases - pulsed	Release water from largest of the six ponds in five 36-hr 0.6-2.3 cfs pulses
	9a	Recycled Water Injection - downstream	Inject 500 gpm of treated wastewater into the downstream portion of the alluvial aquifer
	9b	Recycled Water Injection - upstream	Inject 500 gpm of treated wastewater into the upstream portion of the alluvial aquifer
	9c	Recycled Water Injection - upstream/early	Inject 500 gpm of treated wastewater into the upstream portion of the alluvial aquifer beginning prior to disconnection
	9d	Recycled Water Infiltration - upstream/early	Infiltrate 500 gpm of treated wastewater into the upstream portion of the alluvial aquifer beginning prior to disconnection
Climate Change	10	CNRM Climate Change	2070-2099 timeframe future climate as predicted by the CNRM model under the rcp8.5 emmisions pathway
	11	CCSM4 Climate Change	2070-2099 timeframe future climate as predicted by the CCSM4 model under the rcp8.5 emmisions pathway
	12	GFDL Climate Change	2070-2099 timeframe future climate as predicted by the GFDL model under the SRES B1 emmisions pathway
	13	MIROC esm Climate Change	2070-2099 timeframe future climate as predicted by the MIROC esm model under the rcp8.5 emmisions pathway

<u>Land Management Scenarios</u>
Three scenarios were developed to evaluate the potential streamflow enhancement resulting from large-scale application of landscape management actions including: 4-Forest Management, 5-Grassland Management, and 6-Runoff Management.

Forest Management
In the aftermath of the 2020 Walbridge Fire which burned through a large swath of the watershed, there is a very high level of awareness and interest in managing forests to reduce fuel loads. Douglas Fir, redwood, and other forest types are characterized by high tree densities and abundant ladder fuels. This scenario is designed to represent wide application of forest treatment strategies such as thinning and controlled burning and the effects of these forest treatments on hydrologic conditions and streamflows.

Significant additional work is needed to better understand how various forest treatment approaches may affect evapotranspiration (ET). Work in experimental watersheds in northern California and Oregon has shown that stand age plays a significant role in driving forest ET rates as indicated by significant and long-lasting changes in streamflow following clear-cuts (e.g. Cobble et al., 2020). Additional paired watershed studies are currently underway to study effects of thinning and other treatments but conclusive results from these studies requires decades of monitoring. Watershed-scale hydrologic experiments at Caspar Creek in the Jackson Demonstration State Forest in coastal Mendocino County are likely most applicable to the lower Russian River watershed. Through earlier work in Mark West Creek watershed, OEI compared Leaf Area Index (LAI) in stands of Douglas Fir and oak that did and did not require thinning for purposes of fuel reduction; the stands requiring treatment had model-simulated annual actual evapotranspiration (AET) that was about 5% higher than stands with lower density of small stems and ladder fuels (Kobor et al., 2020).

For the purposes of this scenario, we simply assumed a 5% reduction in AET across all 12,198 acres of forested lands in the watershed (Figure 68). Some areas may not require treatment and treatments in other areas are expected to vary in terms of the type and level of required interventions. The scenario is intended to represent potential benefits of forest treatments implemented across the watershed over the short to medium-term. Greater benefits may be achievable in the long term if treatments and subsequent land management leads to changes in the overall stand age composition and ET characteristics of forested lands. We achieved the reduction in AET in the scenario simply by reducing the potential evapotranspiration (PET) across forested areas by about 7.5% to result in the desired 5% decrease in AET.

While this strategy does not directly simulate the changes in canopy interception and evaporation and associated changes in throughfall and soil moisture that occur from forest treatment, it does allow for a simple conceptual representation and sensitivity analysis of the net effect of reduced AET on soil moisture, groundwater recharge, and streamflow dynamics. Current forest conditions in areas burned by the Walbridge Fire are not captured in the LiDAR-derived vegetation mapping and LAI data, and the degree of treatment needs and potential

reductions in ET in burned areas should be incorporated into the model during subsequent updates and as post-fire data becomes available.
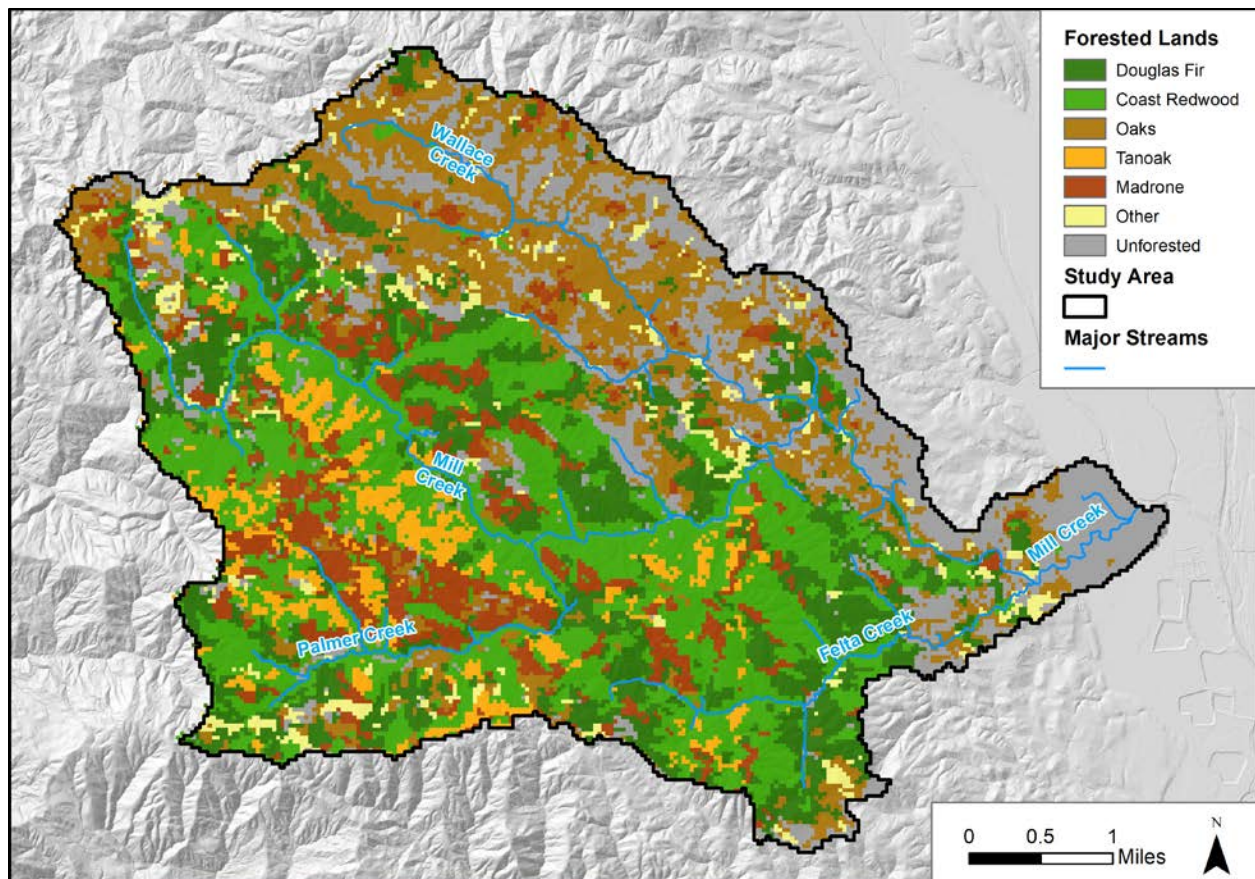
Figure 68: Forested areas included in the forest management scenario (Scenario 4).

Grassland Treatment

Increasing Soil Organic Carbon (SOC) on grasslands through compost application or strategic grazing practices has been identified as an important strategy for sequestering carbon (e.g., Ryals & Silver, 2013; Zomer et al., 2017). In addition to carbon sequestration benefits, increasing SOC may result in hydrologic benefits through increases in soil water availability and associated effects on seasonal soil water deficits and groundwater recharge. This scenario is designed to examine the potential hydrologic effects of large-scale adoption of grassland management practices designed to increase SOC. We assumed a 3% increase in SOC would be achievable (Flint et al., 2018) and related that change in SOC to a change in soil moisture contents at saturation, field capacity, and the wilting point based on data from 12 studies compiled by Minasny and McBratney (2018).

We implemented the grassland treatments in all grasslands in the model with more than a 2-acre contiguous area as identified in the fine-scale vegetation mapping (SCVMLP, 2017) covering a total of 1,297 acres (Figure 69). These grasslands were in 14 different soil types as represented in the model (see Figure 14), and we classified each as fine, medium, or coarse and applied the associated mean estimates of the change in moisture contents from a 1% increase in SOC from Minasny & McBratney (2018). We scaled the estimates up to reflect a 3% increase in SOC which resulted in increases in soil moisture content at saturation, field capacity, and the wilting point of 0.10-0.14, 0.04-0.07, and 0.02-0.03 respectively, and increases in available water capacity (AWC) of 0.044-0.068. These estimates are generally consistent with the changes in AWC estimated for a 3% increase in SOC for soils of similar textures by Flint et al. (2018) which were based on the work of Saxton & Rawls (2006).
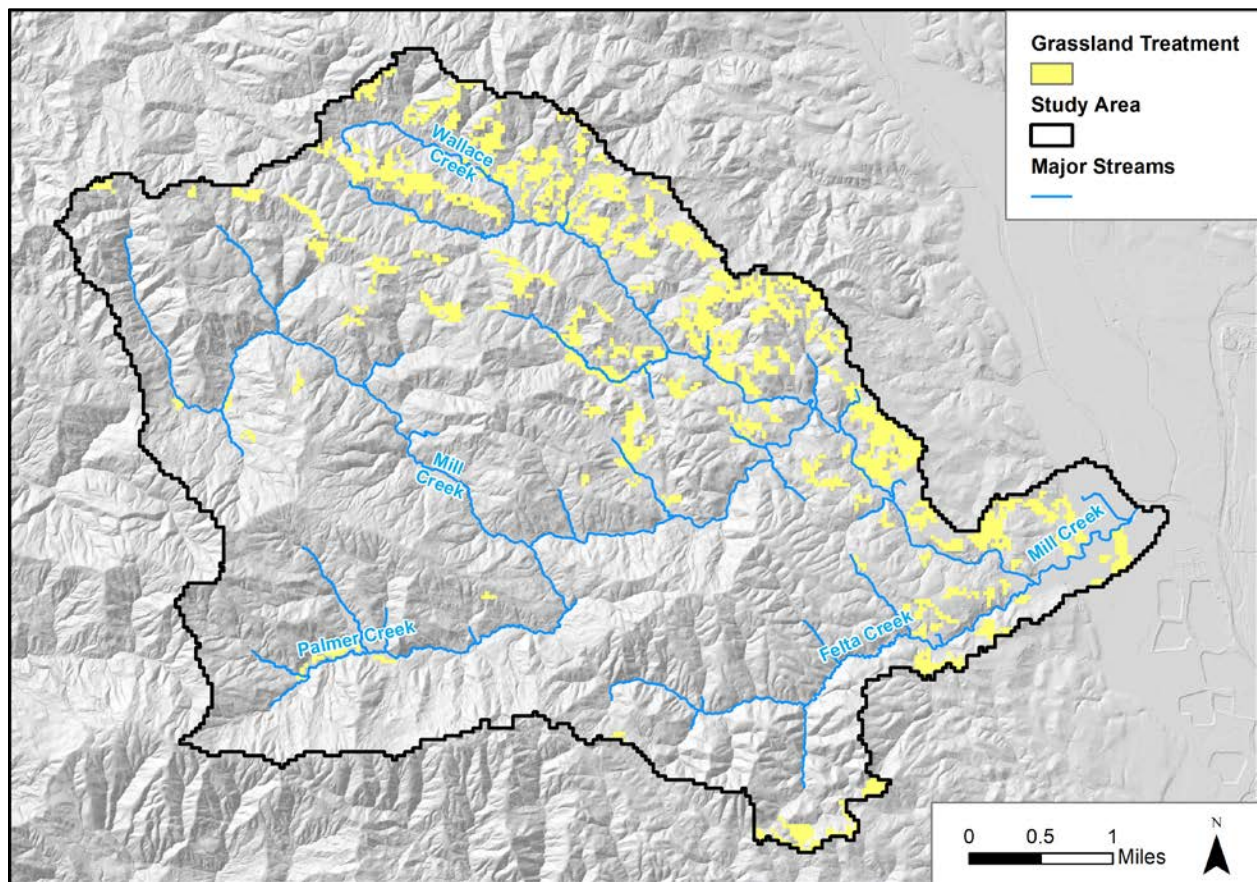
Figure 69: Treated grasslands included in the grassland management scenario (Scenario 5).

Runoff Management

Managing runoff from rooftops and impervious areas around residential and other developed areas to encourage infiltration has been recognized as an important best management practice for new development and is commonly referred to as Low Impact Development (LID). Most developed areas in Mill Creek watershed were constructed prior to adoption of LID techniques. Traditional runoff management, on the other hand, is more likely to encourage runoff to flow quickly away from infrastructure and towards receiving water bodies via downspouts, drains, and ditches. This scenario is designed to examine the potential hydrologic benefits of large-scale adoption of LID practices on existing developed lands in the watershed.

We identified areas of contiguous impervious surface in the watershed from the developed category in our model land cover data. This spatial data is based on non-roadway impervious areas identified in the fine-scale vegetation map (SCVMLP, 2017) and resampled onto the 0.5-acre model grid. The resampling results in the exclusion of smaller impervious areas and the identification of the larger contiguous impervious areas most suitable for runoff management projects with potentially significant benefits. Roads are not represented in the scenario, although large-scale management of road runoff could have significant additional hydrologic benefits beyond what was simulated here. The developed areas represented in the scenario total 82 acres (Figure 70) which is about 62% of the total impervious area (including roads) in the watershed. There are multiple strategies possible for enhancing infiltration of runoff from these lands including use of level spreaders, bioswales, or infiltration basins. The most appropriate strategy and design for a given location is site-specific and implementing the details of these stormwater management features is not practical at the 0.5-acre grid scale used in the model. Thus, for the purposes of this regional planning-level study we simply assume that practices could be implemented to prevent all runoff generated directly from the identified developed lands from leaving the site. The scenario was implemented in the model by preventing runoff from entering or leaving each area through the use of the separated overland flow area option, and allowing water to pond, infiltrate, and evapotranspire according to the precipitation patterns and soil and evapotranspiration properties present at a given site.

The largest storm event in the 10-yr simulation was approximately a 10-yr event based on comparison to NOAA Atlas 14 precipitation frequency estimates. Thus, for projects to be equivalent to the model scenario they would need to be able to handle the peak flows and runoff volumes from a 10-yr storm. The model results indicate that the 48-hr volume from this event over a 0.27 acre average per parcel developed area would be about 0.20 to 0.28 ac-ft. This would require a 4 ft deep open basin on the order of 2,600 ft^2 or a gravel-filled basin of about 7,600 ft^2. These basins are large but likely feasible in most cases given 75% of the developed parcels are five acres or larger. Runoff management projects of a smaller scale are also possible; however, the goal of this scenario is consistent with the other scenarios in its focus on estimating the maximum potential benefits of runoff management projects.
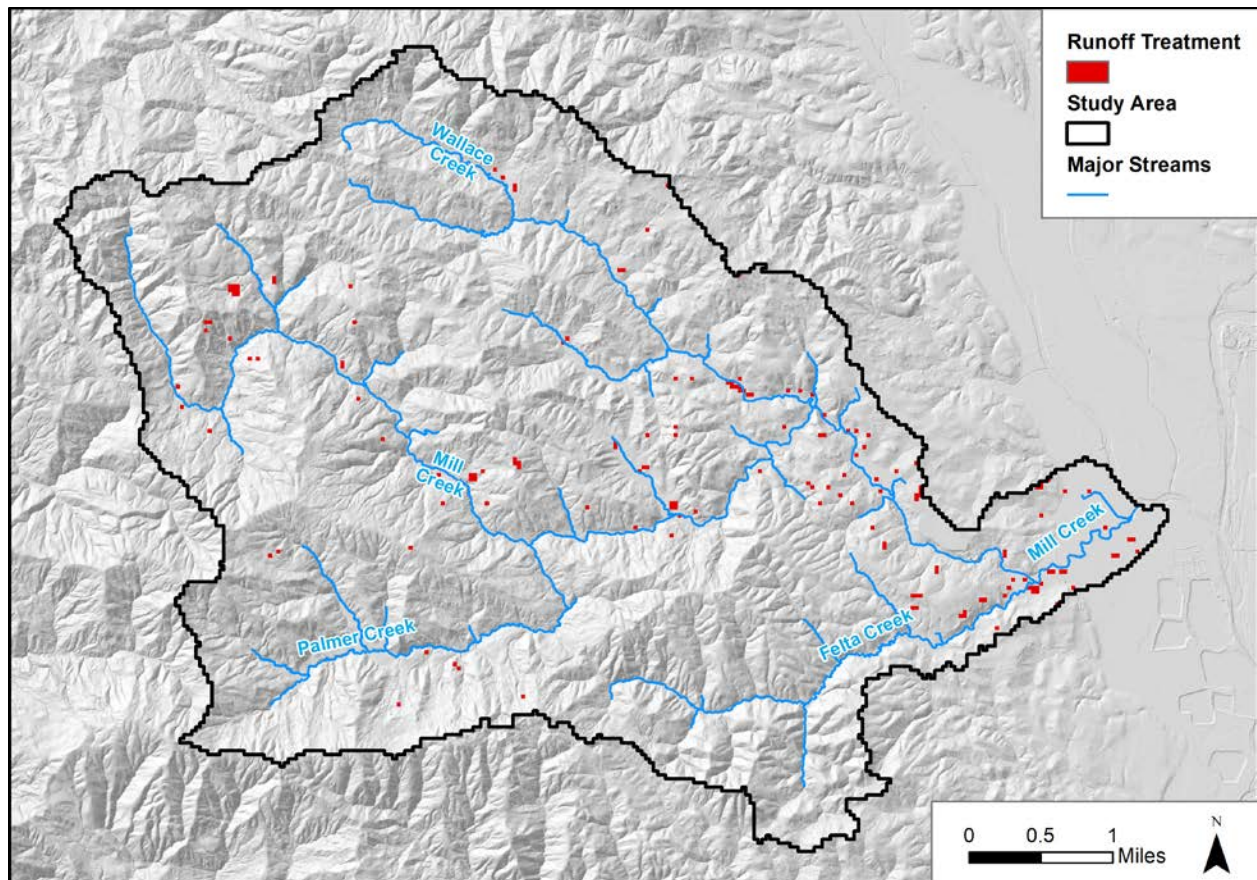
Figure 70: Developed areas included in the runoff management scenario (Scenario 6).

<u>Direct Flow Augmentation Scenarios</u>
Ten scenarios were developed to evaluate the effects of releasing water either directly to the creek from existing ponds or as near-stream aquifer recharge from recycled water injection or infiltration. These scenarios include: 7-Summer Pond Releases, 8-Spring Pond Releases, and 9-Recycled Water Reuse. Scenario 8 is subdivided into five sub-scenarios to investigate how the release of various volumes of water and the timing of those releases influences the efficacy of this flow enhancement strategy. Scenario 9 is subdivided into four sub-scenarios to investigate how the location, mode, and timing or recycled water reuse influences the efficacy of the strategy.

Pond Releases
Releasing water from existing ponds has been recognized as a potentially important strategy for enhancing streamflows in the lower Russian River and pond release projects have been implemented in recent years in Green Valley and Porter Creeks. Most of the ponds in the Mill watershed are too small to allow for a viable release project, but we identified at least six ponds that appear large enough for such projects and focused on these for our analysis. To respect the privacy of landowners, we identify only approximate locations of release points into main-stem

Mill or Wallace Creeks. Available storage volumes for releases were estimated using the LiDAR-captured water surface elevations as the late-summer residual storage levels (after water use and infiltration/evaporation losses) and a simple relationship between dam height approximated from the LiDAR and pond storage (USACE, 2018).

The six ponds include two in the Wallace Creek watershed, one in the upper Mill Creek watershed, and three in the middle watershed. Residual storages for these ponds range from 7.4 to 44.7 ac ft for a combined total storage of about 137 ac ft (Table 12). Consumptive water use associated with the ponds is evidently small, and the residual storage estimates reflect water levels at the end of the irrigation season, therefore releasing water to augment streamflow is believed to be compatible with existing uses. Landowners we spoke with expressed concerns about fully depleting ponds because of the desire to maintain recreational and aesthetic value and maintain an emergency water source in the event of wildfire. To address these concerns, we have assumed that only half of the available residual storage could be released, and the other half would be retained in storage for other uses. We also examined the simulated runoff volumes contributing to each pond and found that there is sufficient winter runoff to replenish the released volumes for all the ponds in average water years and for all but the largest pond during drought conditions. This suggests that the total amount of water available for release would likely decrease by 25-35% following the first year of a multi-year drought period.

We developed six flow release scenarios, one focused on enhancing summer juvenile rearing habitat (Scenario 7) and five focused on enhancing spring smolt outmigration (Scenarios 8a-8e; Table 12). The summer release covers a 92-day period each year between July 1st and October 1st and release rates ranged from 0.02-0.12 cfs for a total release rate of ~0.37 cfs. The spring releases were targeted to initiate 1-day prior to the development of impassable conditions in the lower alluvial reach above the Dry Creek confluence and continue for as long as available storage allowed. Several iterations were performed to determine the optimal release rates required to maintain flows just above the threshold for passage and it was found that releases that ramp up from about 0.2 to 2.0 cfs over 34 days was the optimal strategy for enhancing spring outmigration flows. The ramping release rates are preferred because they coincide with a period of receding streamflow resulting in a sustained period of relatively constant passable flows above Dry Creek, whereas constant releases result in an initial pulse of high streamflow followed by declining flows and a shorter overall period of passable conditions.

Scenario 8a represents spring releases from all six ponds as described above. Scenarios 8b-8e are intended to acknowledge the challenges in developing coordinated releases from six ponds and instead simulate releases from only the smallest of the six ponds (8b-8c) and from only the largest of the six ponds (8d-8e). These scenarios are also intended to better understand the minimum amount of water storage needed to meaningfully enhance outmigration flows for salmonids. We also examined two different strategies for releasing the water, one where flows are continuously released with a ramping release rate (8b & 8d) and one where flows are released in one or more 36-hr pulses (8c & 8e). The later strategy is designed to extend the timeframe over which passable conditions are created later into the outmigration season relative to the

Table 122: Overview of the pond release volumes and rates included in Scenarios 7 and 8a-8b.

Location	50% Residual Storage (ac-ft)	Scenario 7		Scenario 8a		Scenario 8b		Scenario 8c		Scenario 8d		Scenario 8e	
		Release Rate (cfs)	Duration (days)	Release Rate (cfs)	Duration (days)	Release Rate (cfs)	Duration (days)	Release Rate (cfs)	Duration (days)	Release Rate (cfs)	Duration (days)	Release Rate (cfs)	Duration (days)
Mill 1	12.3	0.067	92	0 - 0.36	34	-	-	-	-	-	-	-	-
Mill 2	3.8	0.021	92	0 - 0.11	34	-	-	-	-	-	-	-	-
Mill 3	3.7	0.020	92	0 - 0.11	34	0.25 - 0.49	4*	1.24	1.5	-	-	-	-
Mill 4	22.3	0.122	92	0 - 0.65	34	-	-	-	-	0.25 - 1.17	15**	0.63 - 2.28	7.5
Wallace 1	19.0	0.104	92	0 - 0.56	34	-	-	-	-	-	-	-	-
Wallace 2	7.3	0.040	92	0 - 0.21	34	-	-	-	-	-	-	-	-
Total	**68.4**	**0.375**		**0 - 2.00**		**0.25 - 0.49**		**1.24**		**0.25 - 1.17**		**0.63 - 2.28**	

*Rounding to 24-hr intervals resulted in releases equivalent to 81% of available volume

**Rounding to 24-hr intervals resulted in releases equivalent to 95% of available volume

continuous release strategy which is designed to maximize the number of days of passable conditions. Release rates for the various scenarios are summarized in Table 12. Release volumes were within 2% of available volumes estimated assuming availability of 50% of residual storage calculations except in the continuous single pond scenarios where rounding to 24-hr intervals resulted in 81% storage utilization for Scenario 8b and 95% for Scenario 8d.

Recycled Water Releases

The City of Healdsburg's wastewater treatment plant (WWTP) is near lower Mill Creek and the City delivers tertiary-treated recycled water to several parcels in and around the lower watershed, primarily for vineyard irrigation. An existing recycled water pipeline runs down Foreman Lane to near Westside Road, thus delivering water as represented in this scenario would require pipeline extension on the order of 0.5 miles. At the time of our development of the recycled water scenarios in 2019, the city indicated the WWTP had approximately 100 million gallons of water available between May 15th and September 30th. They also indicated that water could potentially be made available earlier than May 15th but noted that injection or infiltration of recycled water is not a currently approved use.

There are at least four hypothetical means of using recycled water to enhance streamflows including: direct release to the creek, well injection into the near-stream shallow alluvial aquifer, injection via infiltration trenches into the shallow subsurface, and filling of near-stream infiltration basins. We simulated two of these that appear to be the most easily implemented and that the model was best-suited to simulate (well injection & infiltration basins).

We selected two areas for recycled water well injection based on preliminary landowner outreach and location within the lower alluvial reach. The first location is near the confluence of Mill and Felta Creeks in the upper portion of the alluvial aquifer where the alluvium is relatively thin (~50 ft). The second location is about 1,200 ft upstream of the confluence with Dry Creek where the alluvium is much thicker (~200 ft). Based on available volume of recycled water (at the time of our discussions with the City of Healdsburg in 2019), approximately 500 gpm of recycled water could theoretically be delivered from as early as the beginning of April through the end of September. The injection well scenarios utilized a series of three injection wells parallel to the stream and located one model grid cell (148 ft) away from the stream and from each other, with a uniform injection rate of 167 gpm. Scenarios 9a and 9b begins injection on May 15th at the downstream and upstream locations, respectively. Scenario 9c examines the effects of beginning injection 3-days prior to the development of impassable conditions (April 20th in 2014) at the upstream location. Scenario 9d adds water to an infiltration basin located in the same vicinity as the upstream well field at 500 gpm beginning prior to development of impassable flow conditions.

Climate Change Scenarios
Four model scenarios were developed to evaluate the effects of future climate changes on hydrologic and aquatic habitat conditions in the Mill Creek Watershed. Each of these scenarios was based on projections of future climate for the 2070-2099 timeframe derived from a Global Circulation Model (GCM) scenario. The scenarios reflect changes in precipitation and temperature as predicted by each GCM, but do not address other aspects of climate change that may affect hydrologic and habitat conditions such as long-term changes in vegetation or irrigation demands that may occur in response to a modified future climate regime.

Global Circulation Model Selection
The selection of the four GCM scenarios ('futures') was based largely on the recommendations from the Climate Ready North Bay Vulnerability Assessment and the North Coast Resource Partnership's climate planning efforts (Micheli et al., 2016; 2018), which selected a subset of six GCM futures from an ensemble of 18 futures analyzed by the USGS using the Basin Characterization Model (BCM) (Flint et al., 2013; Flint & Flint, 2014). These 18 futures were selected from approximately 100 GCM futures included in the Intergovernmental Panel on Climate Change's (IPCC) Fourth and Fifth Assessment Reports (IPCC, 2007 & 2014) using statistical cluster analysis. The North Coast Resource Partnership study selected six of the 18 futures included in the BCM, and our analysis focuses on four of these six (Figure 71 & Table 13).

The selection of these futures was designed to represent the full range of plausible changes to precipitation and temperatures, and to include a scenario representative of the mean projections (Micheli et al., 2016 & 2018). Three of the futures represent the "business as usual" emissions scenario (rcp 8.5) adopted by the IPCC's Fifth Assessment Report (IPPC, 2014). This pathway assumes high population growth and a slow adoption of clean and resource efficient technologies with atmospheric carbon dioxide concentrations rising to 936 ppm by 2100 (Hayhoe et al., 2017). One of the futures represents the "highly mitigated" emissions scenario (sres B1) reflecting a future with low population growth and the introduction of clean and resource efficient technologies; this pathway is comparable to rcp 4.5 with atmospheric carbon dioxide concentrations rising to 650 ppm by 2100 (Hayhoe et al., 2017).

Scenario 10 is a "Warm & High Rainfall" scenario based on the CNRM rcp 8.5 future, which projects a 34% increase in average annual precipitation and a 7.8°F increase in average maximum temperatures by the 2070 - 2099 timeframe relative to 1981 – 2010 (Table 13). Scenario 11 is a "Warm & Moderate Rainfall" scenario based on the CCSM4 rcp 8.5 future, which approximates the ensemble mean of the 18 futures selected for use in the BCM model and projects a 5% decrease in average annual precipitation and a 7.1°F increase in average maximum temperatures. Scenario 12 is a "Warm & Low Rainfall" scenario based on the GFDL sres B1 future which projects a 14% decrease in average annual precipitation and a 5.0°F increase in average maximum temperatures (Table 13). Finally, Scenario 13 is a "Hot & Low Rainfall" scenario based on the MIROC esm rcp 8.5 future, which projects a 21% decrease in precipitation and an 11.5°F increase in temperature (Table 13).

Table 13: Overview of the four climate change scenarios evaluated with the Mill Creek hydrologic model.

	GCM	Emissions Scenario	Change in Annual Precipitation (%)	Change in Maximum Temperature (°F)
Scenario 10	CNRM	rcp 8.5 (business as ususal)	34%	7.8
Scenario 11	CCSM 4	rcp 8.5 (business as ususal)	5%	7.1
Scenario 12	GFDL	sres B1 (highly mitigated)	-14%	5.0
Scenario 13	MIROC esm	rcp 8.5 (business as ususal)	-21%	11.5

Methodology
For all scenarios, precipitation and minimum and maximum temperature timeseries were derived from daily data from the World Climate Research Program's Coupled Model Intercomparison Project Phases 3 & 5 (CMIP3 & CMIP5) (USBR et al., 2013). The CMIP provides monthly and daily outputs from the GCMs included in the IPCC's Fourth and Fifth Risk Assessments statistically

downscaled to a uniform 1/8th degree grid using a revised version of the bias corrected constructed analog method (BCCA v2).

Several studies have reported that GCMs are biased towards creating "drizzle" days with trace amounts of precipitation (Maurer et al., 2010). Mauer et al. (2010) claims that the BCCA method corrects this issue. However, when compared to observed precipitation records, downscaled precipitation timeseries still contained an un-representatively high number of days with trace precipitation. To address this documented issue, precipitation events with less than 0.02 in/day were removed from the precipitation timeseries. This removed between 20 and 40 trace events per year but changed average annual precipitation totals by < 1% over the 2070 - 2099 period. While this approach may not fully resolve the issue, it removes a significant number of trace precipitation events which if not filtered out could artificially increase simulated canopy interception and evapotranspiration.

Daily potential evapotranspiration (PET) timeseries were calculated from the CMIP minimum and maximum daily temperature timeseries using the Hargreaves-Samani Method (Hargreaves & Samani, 1982). These calculations used extraterrestrial solar radiation rates for a flat plane located at the model centroid and a KT value of 0.162 calibrated using reported temperature and evapotranspiration data from the Windsor CIMIS station. More details about the PET calculations can be found in Chapter 4.
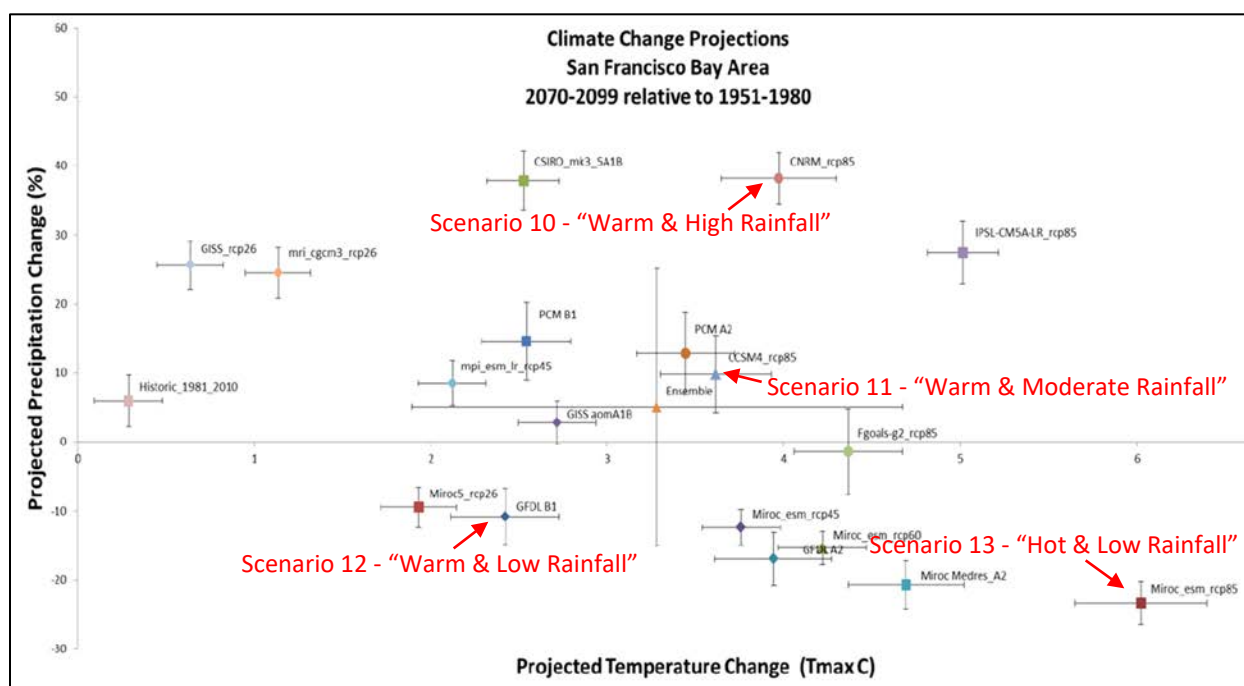
Figure 71: Projected regional changes in average annual precipitation and average maximum summer temperatures for the 18 GCMs analyzed using the Basin Characterization Model (BCM), modified from Micheli et al. (2016) to show the four scenarios included in this study.

As in the existing conditions model, precipitation and PET zone-based distributions were developed to account for the spatial variations in these parameters across the model domain. Precipitation zones are based on 1-inch average annual isohyets derived from the BCM 2070 - 2099 average annual precipitation dataset for each selected GCM future. Future PET distributions were created using the same methodology as the historic distribution discussed in the Chapter 4, in this case using average 2070 - 2099 monthly minimum and maximum temperature distributions from the BCM model. These distributions show similar spatial patterns to the historic distribution, although the range of values across each distribution varies significantly. Precipitation and PET timeseries were applied to these distributions using the same scaling factor approach as for historic conditions.

Scaling factors were calculated as the ratio of the value for each zone and the 2070 - 2099 means for the timeseries. Adjustments were made to the scaling factors applied for precipitation to correct for a high precipitation bias in the BCM dataset relative to historical conditions as observed at local climate stations (see Chapter 4 for further discussion). These adjustments were calculated such that simulated precipitation means preserve the percentage increases in mean annual precipitation between the 1981–2010 and 2070–2099 normals as estimated by the BCM.

To reduce computational requirements, each climate scenario uses timeseries from a continuous representative 10-year subset of the processed CMIP timeseries from the 2070 - 2099 period. These subsets were selected such that average annual precipitation was within 2% of the average annual precipitation estimated for the 2070 - 2099 normal for each future and such that each subset contained at least one extremely dry and one extremely wet year, as well as a multi-year drought (if present in the original 30-yr period). A summary of the annual and daily precipitation and PET inputs for the selected periods is shown in Figures 72-75. While the results of these scenarios will be compared against one another, it is not necessary for these time periods to match. GCMs simulate general climatic conditions, not specific weather events, and one would not expect conditions modeled for a given year to be comparable to conditions modeled for the same year using a different GCM.

Inputs Summary
In addition to the changes in average annual precipitation and average maximum temperatures, the GCMs used as the basis for these scenarios predict several important inter- and intra-annual changes in precipitation and PET. Previous studies of large GCM ensembles have indicated that precipitation will become more volatile, that large precipitation events will become more frequent, and that the seasonal distribution of precipitation will concentrate in the core winter months (e.g., Swain et al., 2018). To assess the degree to which each of the selected GCM futures reflect these projected trends, several statistics were calculated. These include the frequency of historically wet and dry years (defined by the 80th and 20th percentile annual precipitation totals), the magnitude of large precipitation events (maximum 24-hr precipitation), and the seasonal distribution of precipitation (defined by the ratio of precipitation occurring during the core winter months of November - February and the peripheral months of October, March, and April). The baseline for these comparisons is the 2009-2019 simulation period, however as

discussed in Chapter 4, conditions during this period are broadly representative of 1981-2010 conditions which is widely used as the baseline period for interpreting future climate changes.

The Scenario 10 (CNRM rcp8.5) future predicts a general shift towards wetter conditions. Both the frequency and magnitude of wet years increases, as well as the frequency of higher intensity precipitation events (Table 14; Figures 72 & 74). Much of this additional precipitation is projected during the core winter months, leading to a marked shift in the seasonal precipitation distribution. However, despite the large increase in average precipitation, the frequency and magnitude of dry years is projected to remain similar to historic conditions. Despite the low increase in average annual precipitation, the Scenario 11 (CCSM4 rcp8.5) future predicts a large increase in annual and seasonal variability (Table 14; Figures 72 & 74). It projects the single highest annual precipitation total (128.5 in), the greatest inter-annual variability, and the strongest seasonal shift in precipitation towards the winter months. It also predicts individual dry years of similar frequency and magnitude to historical conditions, but more frequent multi-year droughts.

The Scenario 12 (GFDL sresB1) future predicts a general shift towards drier conditions, with increases in both the frequency and intensity of droughts (Table 14; Figures 72 & 74). Although the MIROC esm rcp8.5 future projects slightly drier average conditions, the GFDL sres B1 future projects the single driest year, with an average of 18.1 inches of precipitation. The Scenario 13 (MIROC esm rcp8.5) future also projects a general shift towards drier conditions with both the frequency and intensity of droughts increasing (Table 14; Figures 72 & 74). Historically dry years are projected to become roughly twice as common. Although no years with annual totals exceeding the historic 80th percentile are projected, moderately wet years with up to 73.4 inches of precipitation are still present. During these wetter years, maximum daily precipitation totals are projected to be similar to historic conditions, but much lower during normal and drier years.

Despite the large differences in future projections between the scenarios, all four scenarios share some commonalities. Regardless of the scenario, droughts are predicted to become more extreme and precipitation is predicted to have increased seasonality with more precipitation focused in the core winter months. Additionally, all four scenarios predict increases in PET which vary between scenarios based on the magnitude of the predicted increases in temperatures and represent increases of about 3-8% relative to historic conditions (Table 14; Figures 73 & 75).

Table 144: Summary of key climate statistics for each climate scenario evaluated with the Mill Creek hydrologic model.

	Historic	Scenario 10 CNRM	Scenario 11 CCSM4	Scenario 12 GFDL	Scenario 13 MIROC esm
Average Annual Precipitation (in)	56.7	76.1	59.7	48.5	44.9
Maximum Annual Precipitation (in)	107.5	113.1	128.5	72.8	73.4
Minimum Annual Precipitation (in)	26.4	29.6	26.1	18.1	23.3
Interannual Variability (in)	24.7	25.0	32.4	16.8	15.3
Frequency of 80th Percentile Historic Annual Precip (in)	-	3	2	0	0
Frequency of 20th Percentile Historic Annual Precip (in)	-	1	2	2.0	3
Seasonal Precipitation Distribution (Core:Periphery)	2.5	4.5	5.2	3.6	3.6
Maximum 24-hr Precipitation (in)	8.6	8.9	6.5	7.5	6.6
Average Annual ETo (in)	44.7	46.9	46.6	45.8	48.1
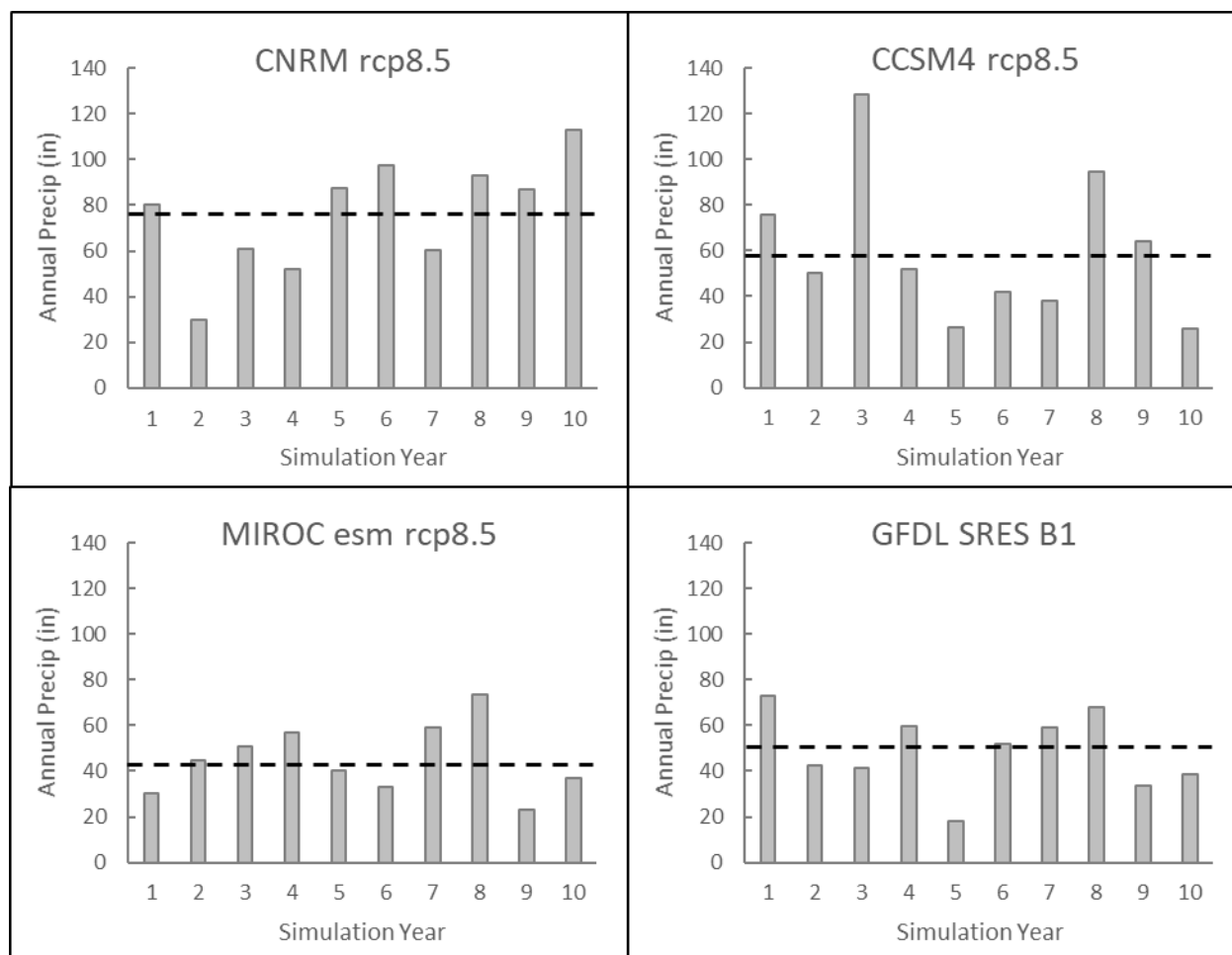
Figure 72: Spatially averaged annual precipitation within the Mill Creek model domain for each of the four selected climate scenarios (dashed black lines indicate the 2070-2099 mean).
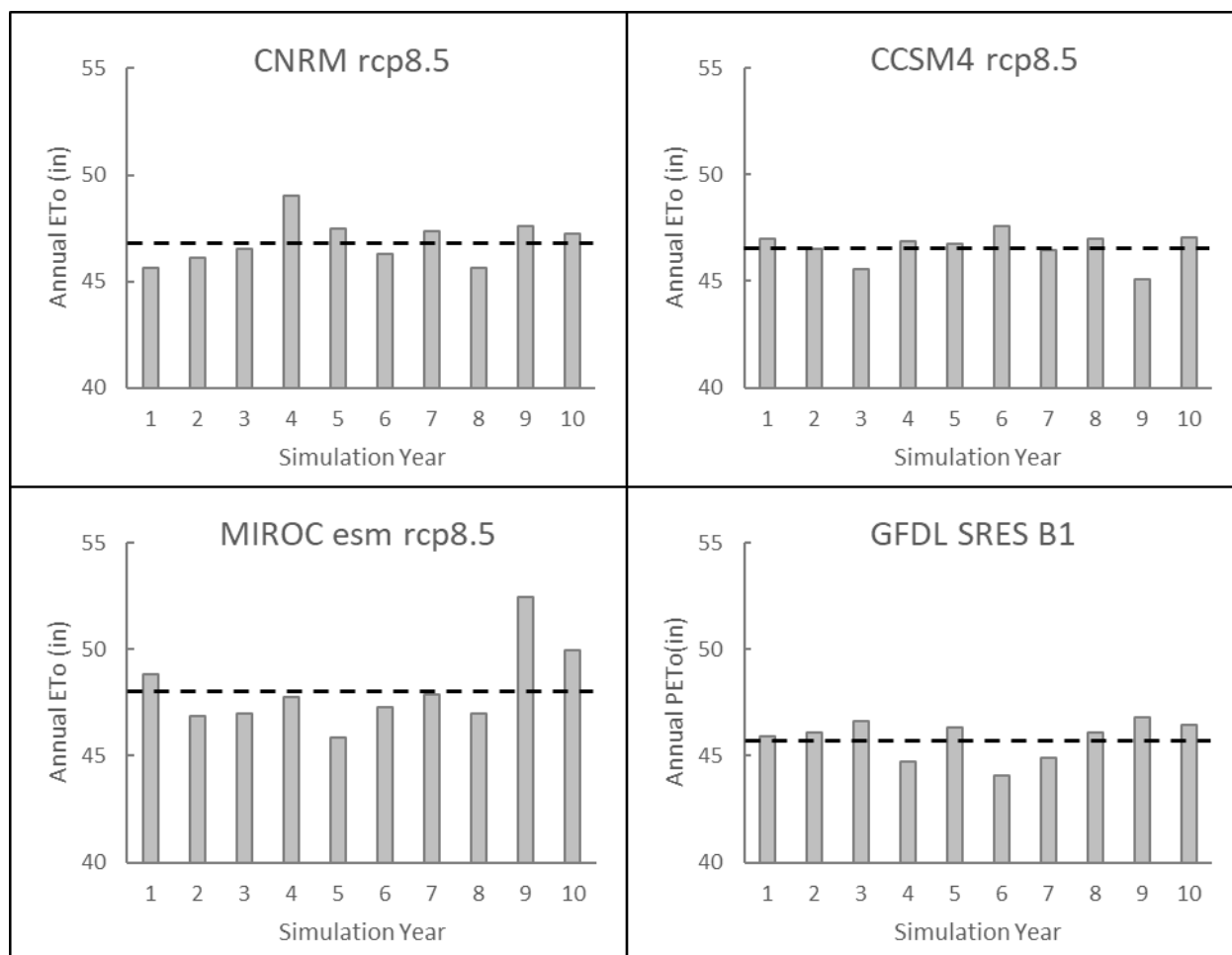
Figure 73: Spatially averaged annual potential evapotranspiration (PET) within the Mill Creek model domain for each of the four selected climate scenarios (dashed black lines indicate the 2070-2099 mean).
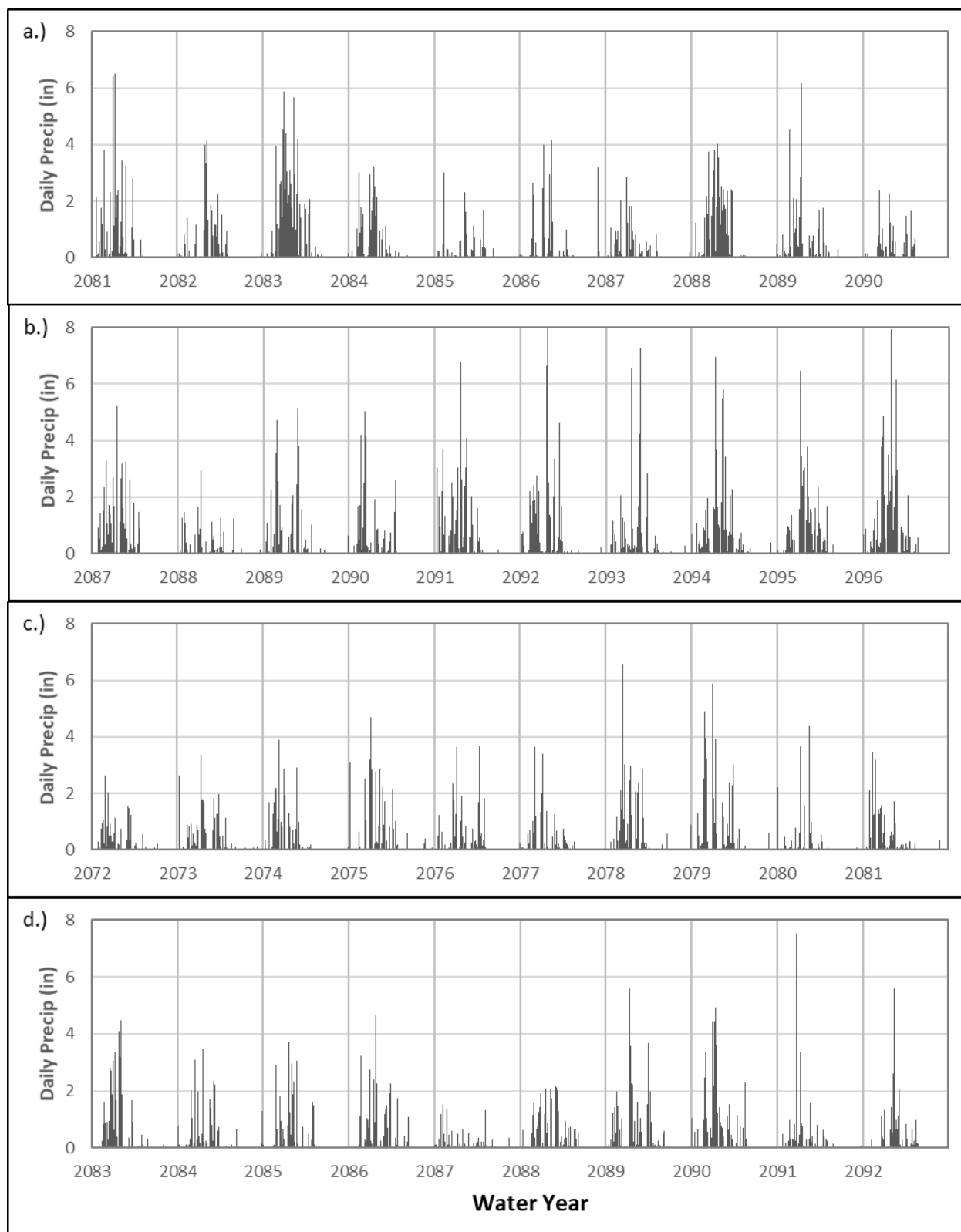
Figure 74: Spatially averaged daily precipitation used in scenarios (a) CNRM rcp8.5, (b) CCSM4 rcp8.5, (c) MIROC esm rcp8.5, and (d) GFDL SRES B1.
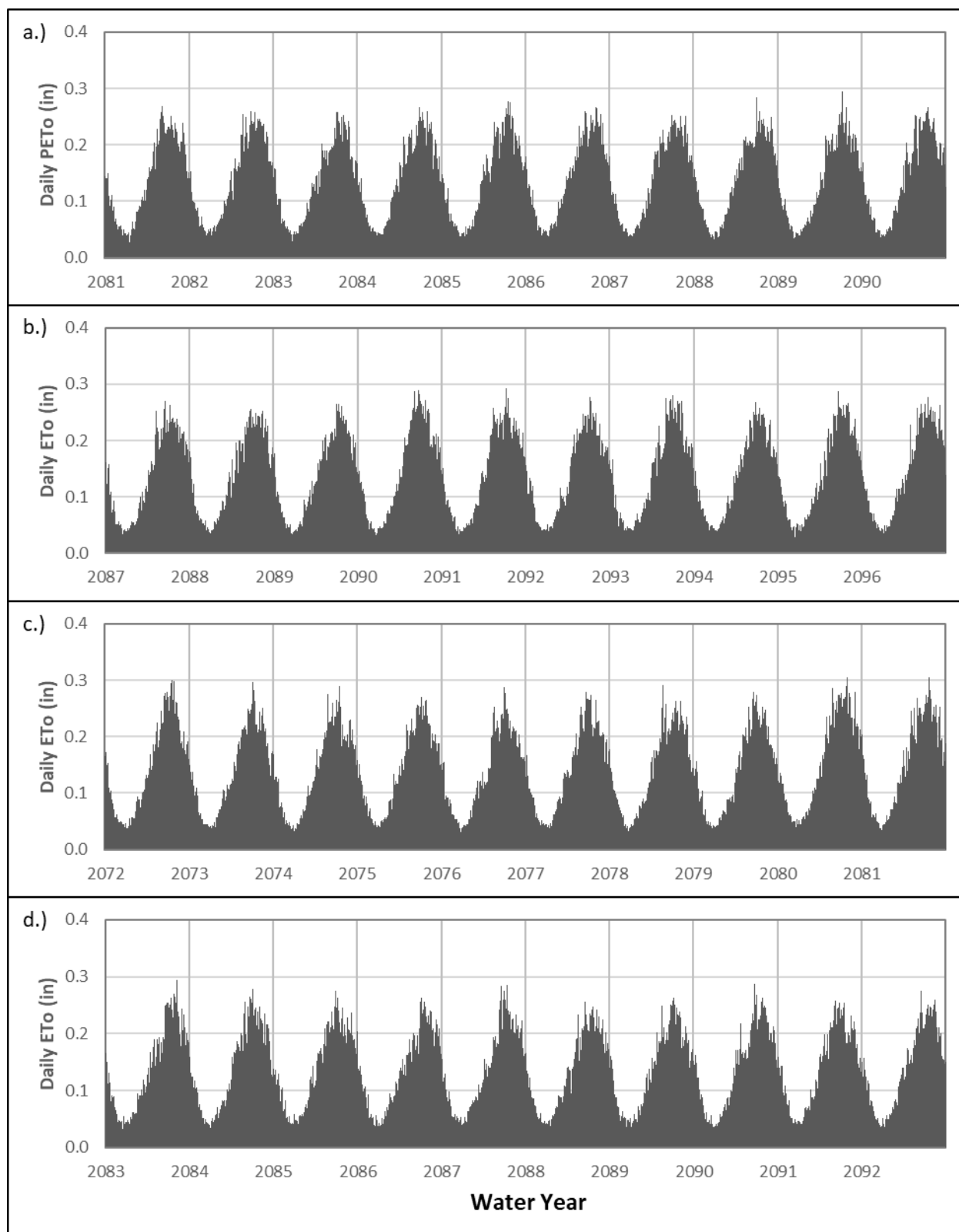
Figure 75: Spatially averaged daily potential evapotranspiration (PET) used in scenarios (a) CNRM rcp8.5, (b) CCSM4 rcp8.5, (c) MIROC esm rcp8.5, and (d) GFDL SRES B1.

Results

Water Use Scenarios

Scenario 1, simulating cessation of surface water diversions, indicates that the sustained cumulative effect of diversions in the watershed is relatively small. In the absence of direct surface water diversions, average summer discharges increased by 0.01-0.05 cfs in most of the upper and middle reaches of Mill Creek and lower Felta Creek (Figure 76). In Wallace, Palmer, and lower Mill Creeks the increase was <0.01 cfs. We compiled hourly discharge results to evaluate potential short-term diversion effects not captured with the mean summer discharge comparison. This revealed that diversions have much more significant short-term impacts on streamflow, with short-term increases in discharge under Scenario 1 of up to 0.1-0.3 cfs upstream of Palmer Creek, and 0.4-0.6 cfs between Palmer Creek and the alluvial reach (Figures 77 & 78). The very dry conditions in the alluvial reach with or without diversions prevents a consistent diversion signal from occurring.

These short-term changes in discharge can represent at least 20% of the total discharge throughout most of Mill and Palmer Creeks. More extreme short-term depletion exceeding 80% of the total flow is predicted for the reach extending from about 1-mile upstream of the confluence with Wallace Creek downstream to the Dry Creek confluence, as well as for lower Felta Creek (Figure 78). Complete disconnection of flow occurs regardless of diversions in the lower alluvial reaches of these creeks, however the reaches of Mill Creek above and below Wallace Creek along with the lower bedrock reach of Felta Creek are predicted to develop short-term flow disconnection (100% streamflow depletion) due to diversions.

The timing of simulated streamflow reductions is closely related to model input assumptions regarding diversion timing and therefore the greatest changes occur on the first of each month when all diversions are active and are near zero during times when few diversions are active. Hence, it is likely that the short-term impacts described above are exaggerated given that the assumptions of coincident timing create a worst-case scenario. Examination of the observed streamflow records at the Above Wallace and Above the Falls gauges does reveal a pattern of fluctuating streamflows, however the fluctuations are more muted than the modeled streamflows, potentially due to the assumptions about diversion synchronicity.

Changes in spring streamflows absent surface water diversion are of similar magnitude to the summer changes, however they represent a much smaller component of the total flow with summer streamflow depletion representing ~8% of mean summer streamflow but ~0.4% of mean spring streamflow. Diversions do not appear to significantly affect the timing of flow disconnection in the lower alluvial reach, and although it is possible that drawdown associated with peak diversion periods could be large enough to influence passage conditions during the smolt outmigration period, this effect is expected to be relatively minor.

Scenario 2, the scenario for cessation of groundwater pumping, indicated that the cumulative effects of groundwater pumping in the watershed are minor. With groundwater pumping
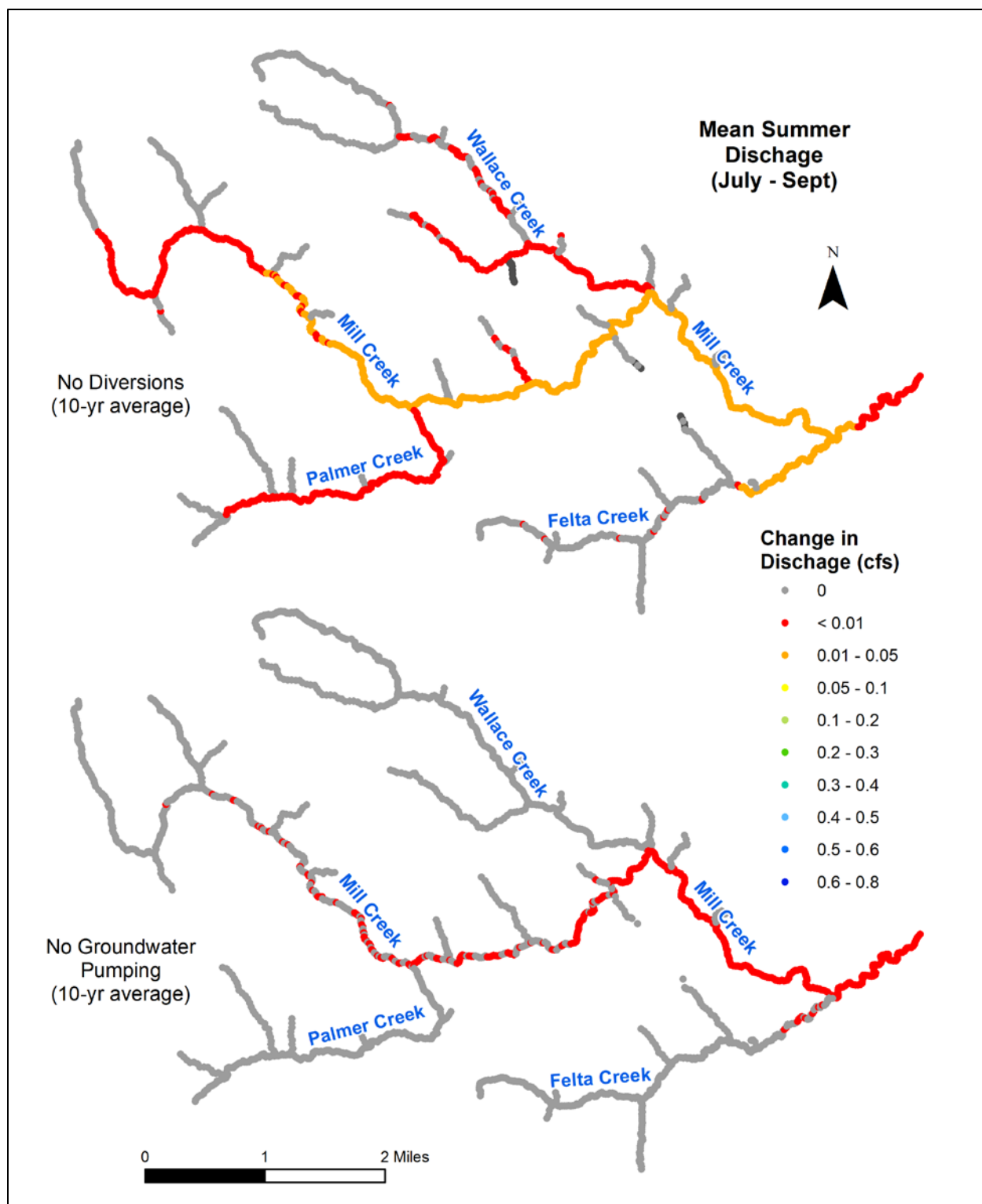
Figure 76: Changes to mean summer streamflow from cessation of all surface water diversions (Scenario 1-top) and cessation of all groundwater pumping (Scenario 2-bottom).
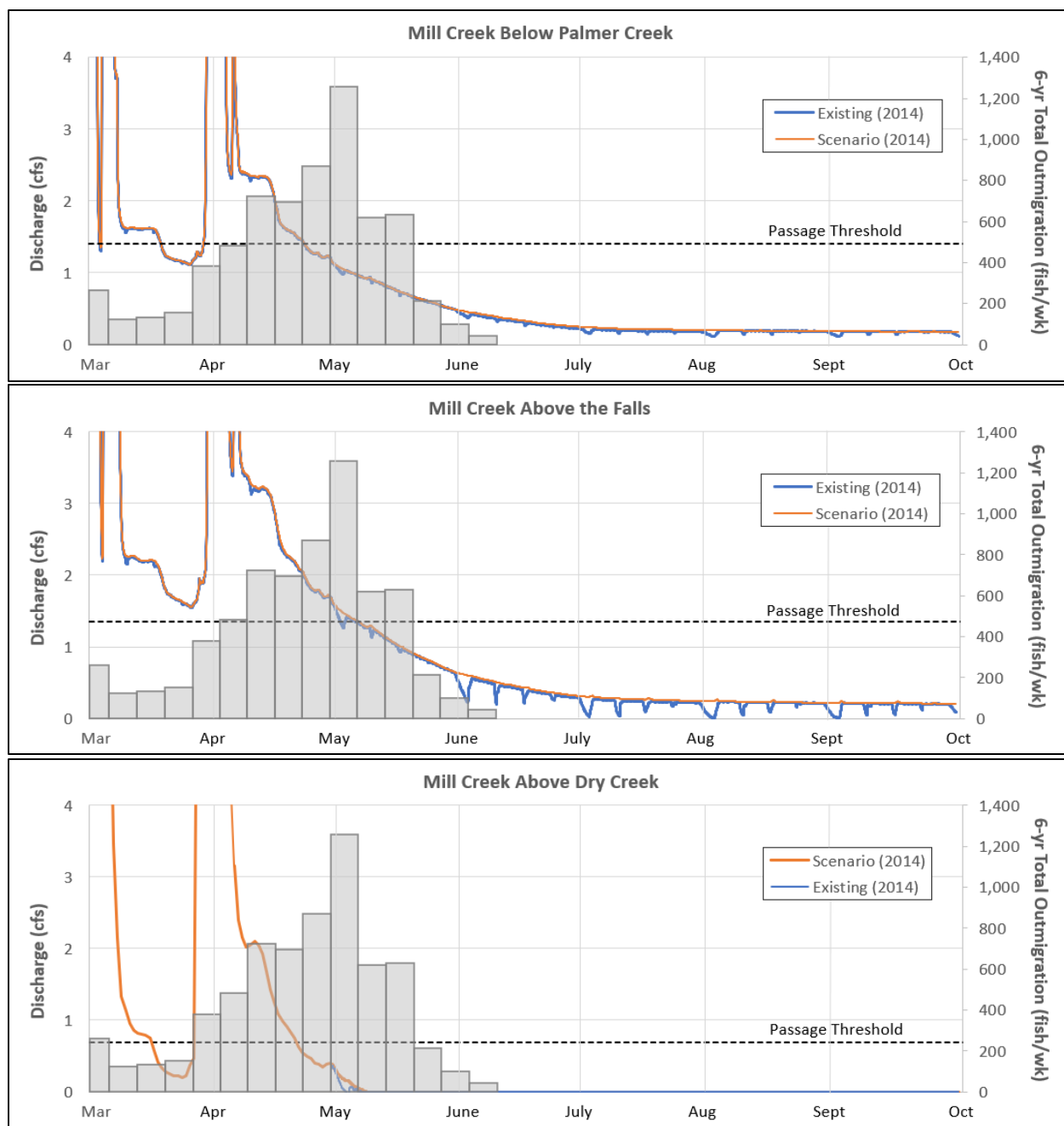
Figure 77: Simulated changes to hourly streamflow in Mill Creek below Palmer Creek, above the falls, and above Dry Creek resulting from cessation of all surface water diversions (Scenario 1).
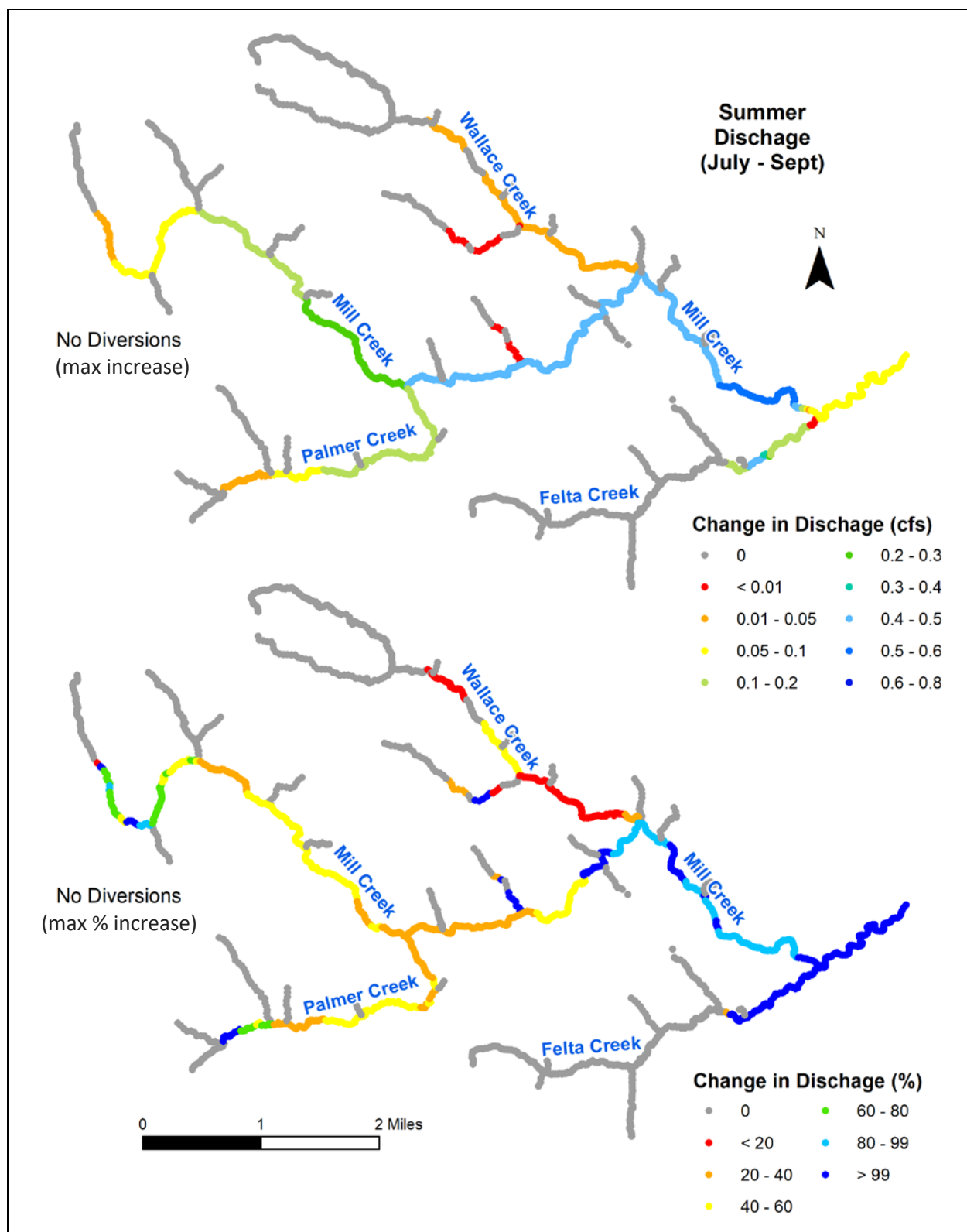
Figure 78: Simulated maximum hourly increases (top) and percent increases (bottom) to summer streamflow from the cessation of all surface water diversions (Scenario 1).

curtailed to zero, the average summer discharge increased by less than 0.01 cfs throughout the watershed (Figure 76). Spring discharge increases were larger but still very small and essentially insignificant relative to the total flow and timing of flow disconnection. We ran the model for an additional four 10-yr simulation cycles to ensure that streamflow depletion had stabilized and found that the results were insensitive to the duration of pumping cessation. The small effects within the bedrock portions of the watershed are not surprising given that groundwater pumping stress is generally very low with total pumping representing only about 0.8% of total mean annual infiltration recharge. The model contains a highly simplified representation of bedrock aquifer conditions and local variations in degree of aquifer fracturing or connectivity with streams may produce larger impacts than those simulated here as broadly representative of typical conditions in the watershed.

The groundwater pumping demand is heavily concentrated (~95%) in the lower alluvial reach and the total pumping stress is higher but still modest with total pumping representing approximately 9% of total mean annual infiltration recharge. Groundwater pumping does result in small reductions in water surface elevations within the alluvial aquifer beginning in the late spring and continuing through summer, however these effects are too small to have an appreciable effect on streamflow. The change in spring and summer water table elevations in the absence of groundwater pumping was generally less than 0.1 ft and reached a maximum of 0.4 ft in the late summer at a time when the potential for streamflow depletion is essentially zero given the dry channel conditions.

Scenario 3, cessation of all diversions and groundwater use, produced changes in streamflow slightly larger than the no diversion scenario (Scenario 1). The results indicate that streamflow depletion from diversions represents approximately 97% of the total water use depletion. Given the similarity of results to Scenario 1, results for Scenario 3 are not discussed further.

Land Management Scenarios
The forest management scenario (Scenario 4) resulted in increases in mean summer discharges of up to 0.05 cfs in Palmer Creek and Mill Creek above Palmer. From the Palmer Creek confluence downstream to the upstream edge of the alluvial reach, the flows increased 0.05-0.10 cfs (Figure 79). These changes are equivalent to a 14-18% increase in mean summer flow depending on the location. The grassland management scenario (Scenario 5) resulted in smaller increases in mean summer flows of <0.01 cfs throughout the watershed (Figure 80). The runoff management scenario (Scenario 6) resulted in increases in mean summer discharge of up to 0.05 cfs in Mill Creek upstream of Wallace Creek and up to 0.10 cfs between Wallace Creek downstream to the beginning of the alluvial reach (Figure 81).

Increases in springtime streamflow for the forest management scenario were much larger than the changes for summer streamflow with increases of 0.2-0.6 cfs above Palmer Creek, 0.6-1.0 cfs between Palmer Creek and Wallace Creek, and 1.0-4.0 below Wallace Creek (Figure 79); these changes represent 8-9% of the total mean springtime flow and are about 20-25 times larger than the changes for the other land management scenarios. Springtime streamflow changes for the

grassland management scenario were minor, and the runoff management scenario produced similar but slightly smaller increases in springtime streamflow relative to summer streamflow (Figures 80 & 81). The changes associated with the forest management scenario are large enough to result in a noticeable shift in the timing of spring flow recessions, with impassable conditions for salmonids occurring about 8-days later in the season relative to existing conditions (Figure 82). The changes associated with the grassland and runoff management scenarios were not large enough to significantly shift the timing of flow recession.

Comparison of the watershed-wide mean annual water balance between existing conditions and flow enhancement Scenarios 4 - 6 indicates that all the forest management strategy results in significant increases in both infiltration recharge (1.4%) and streambed recharge (4.6%). The other strategies also increase recharge slightly, however the effects are much smaller. Forest management results in about a 5% decrease in AET on treated lands which equates to a 4.4% decrease watershed-wide (1,642 ac ft/yr) resulting in more water available for both runoff and infiltration recharge (Figure 83). Increases in infiltration and streambed recharge for the forest management scenario represents a substantial volume of water (~295 ac ft/yr) which manifests in part through increases in groundwater discharge to streams as interflow, baseflow, and springflow (Figure 83). The springflow and baseflow response is of particular interest in that these groundwater discharge components are the primary processes responsible for generating summer streamflow in the watershed. The forest management scenario resulted in the largest increases in springflow (9.4%) and baseflow (5.9%). The grassland and runoff management scenarios also increased baseflow and springflow, however the effects were much smaller (<1%).

It is important to note that the acreages involved in the three scenarios are intended to represent large-scale implementation based on existing potential on the landscape, therefore the locations and acreages involved are very different between the scenarios. To compare the relative hydrologic effects of these various management actions it is useful to normalize the results by acres of managed area. This exercise reveals that runoff management is by far the most effective strategy with per area increases in summer streamflow more than 120 times greater than forest management and 270 times greater than grassland management. The level of effort required to manage stormwater from one acre is, however, expected to be significantly greater than the effort involved in management of one acre of forest or grassland. On a unit area basis, forest management was about twice as effective as grassland management. A significant proportion of the grasslands in the watershed are in the Wallace Creek watershed which does not contribute significant quantities of summer baseflow to the downstream reaches of Mill Creek; this serves to reduce the effectiveness of this strategy relative to the forest and runoff management strategies where treatment areas are primarily located within the subwatersheds containing valuable salmonid habitat. Additional discussion of comparisons between strategies is included below under the heading Summary and Comparison of Scenarios.
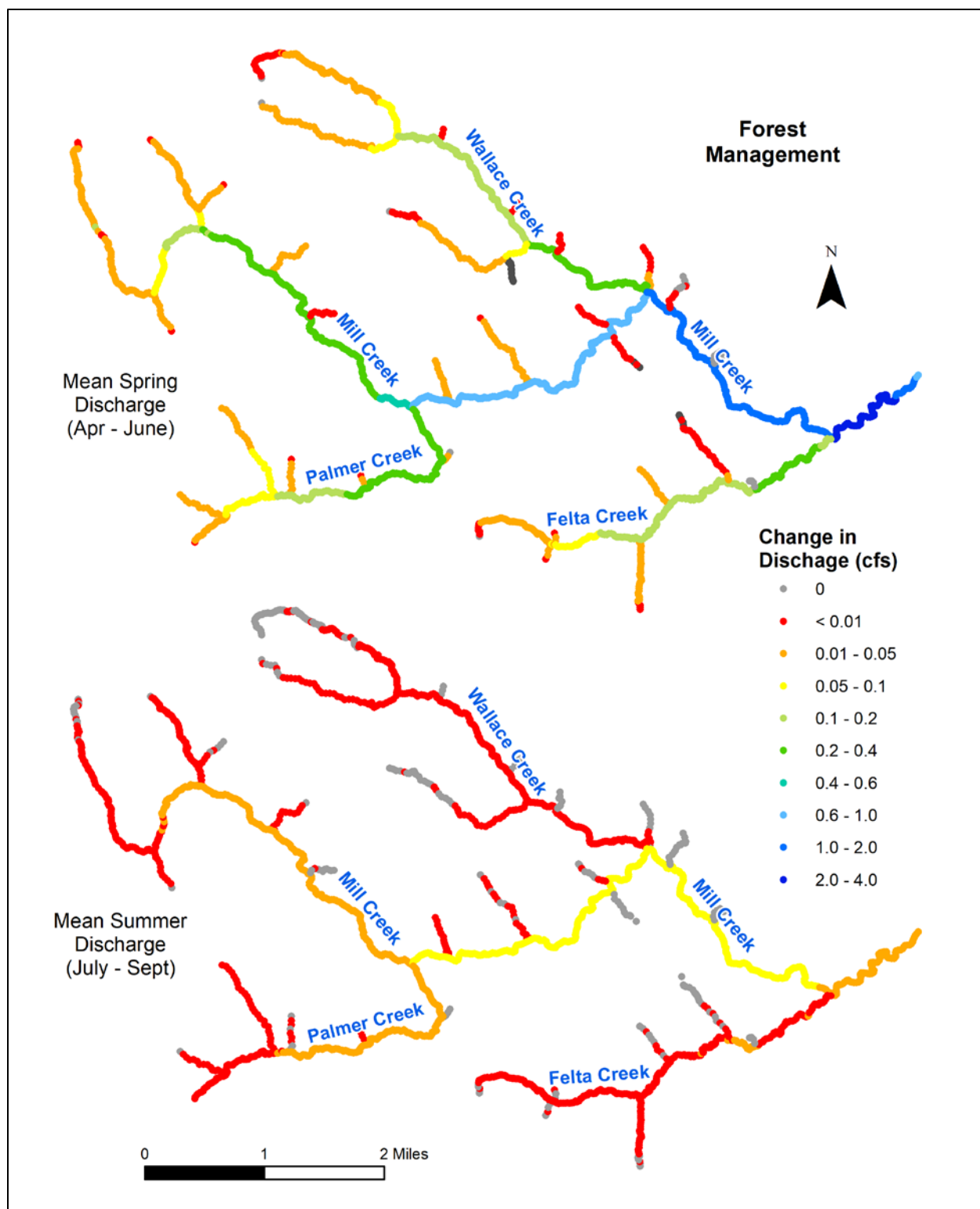
Figure 79: Simulated increases in mean spring (top) and summer (bottom) streamflow for the forest management scenario (Scenarios 4).
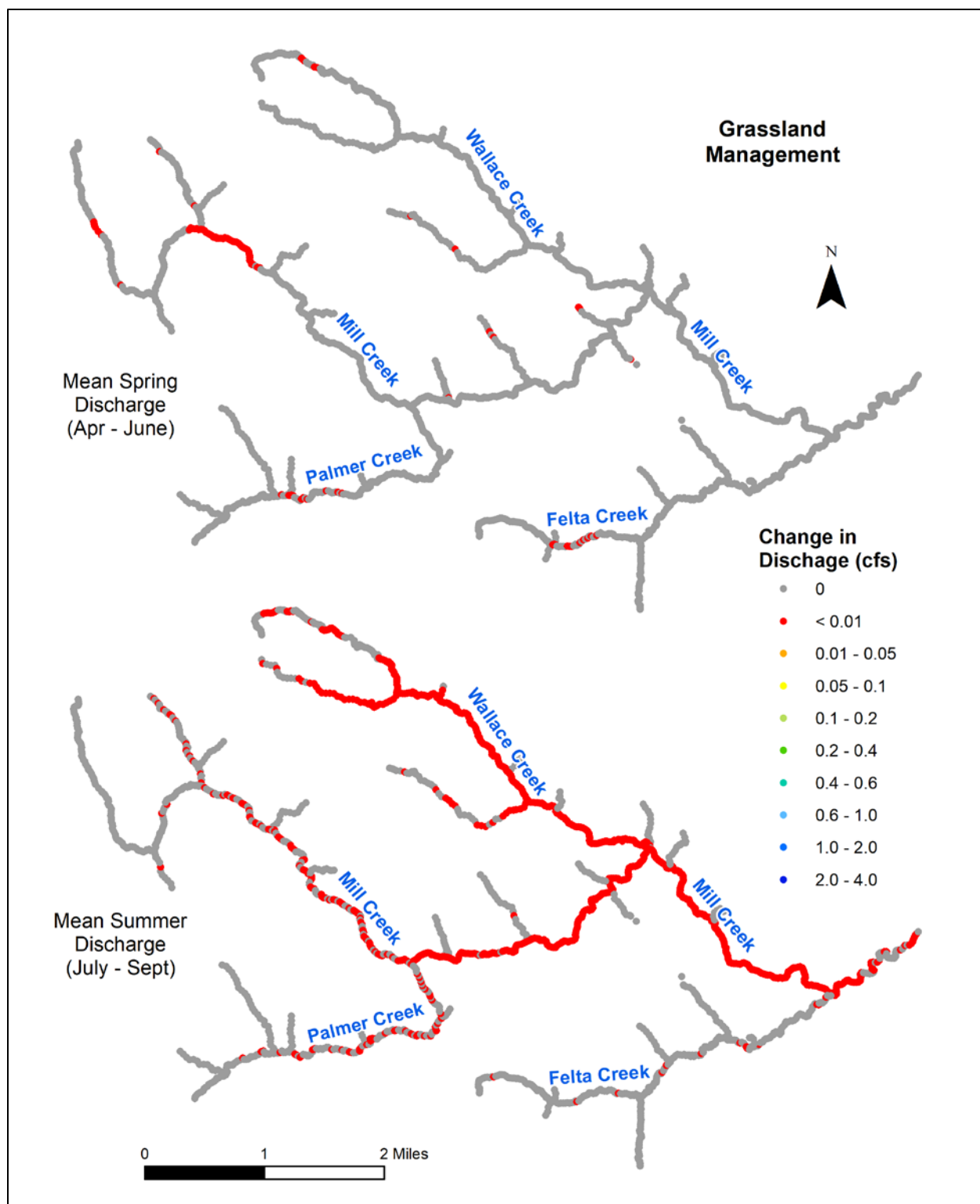
Figure 80: Simulated increases to mean spring (top) and summer (bottom) streamflow for the grassland management scenario (Scenarios 5).
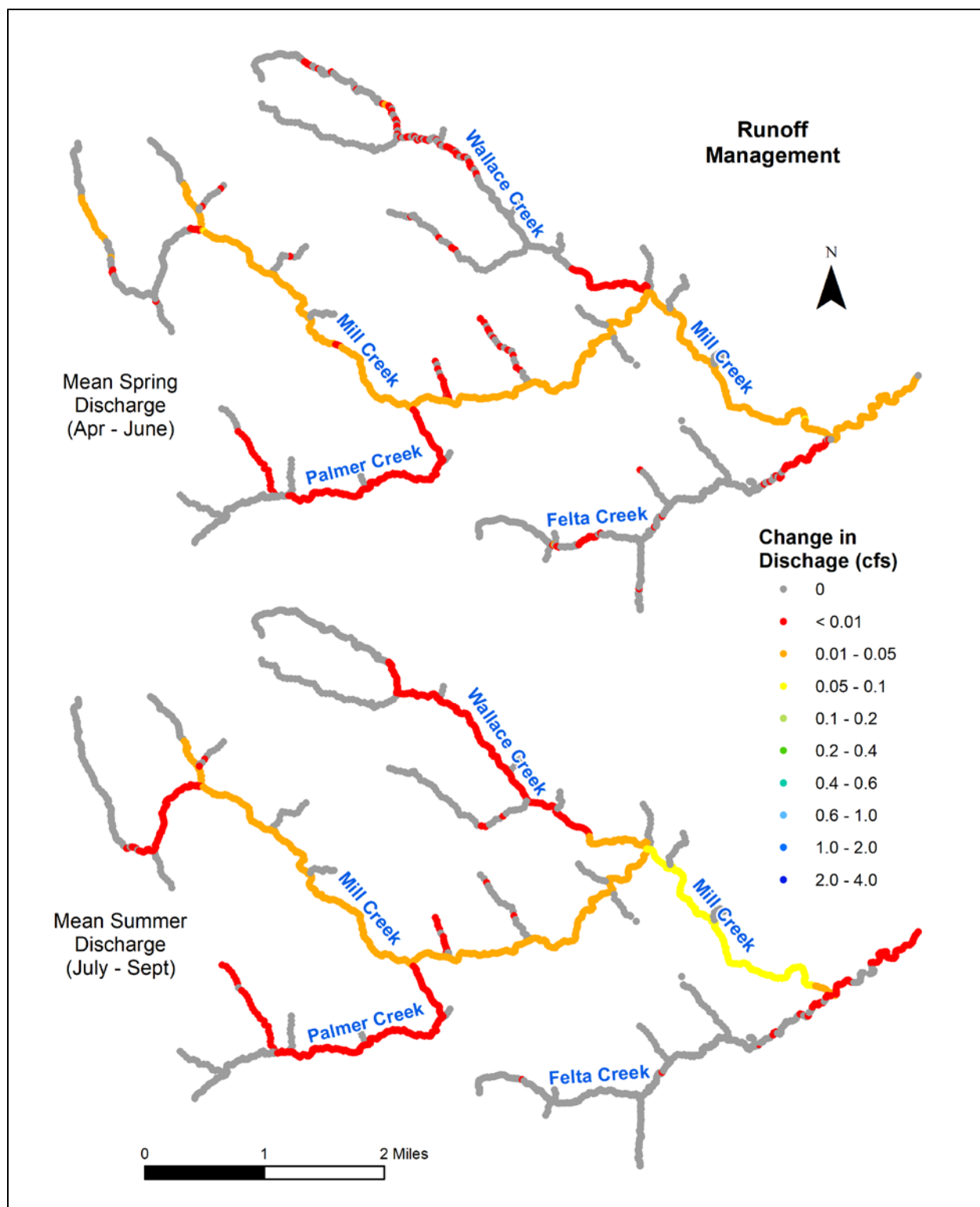
Figure 81: Simulated increases to mean spring (top) and summer (bottom) streamflow for the runoff management scenario (Scenarios 6).
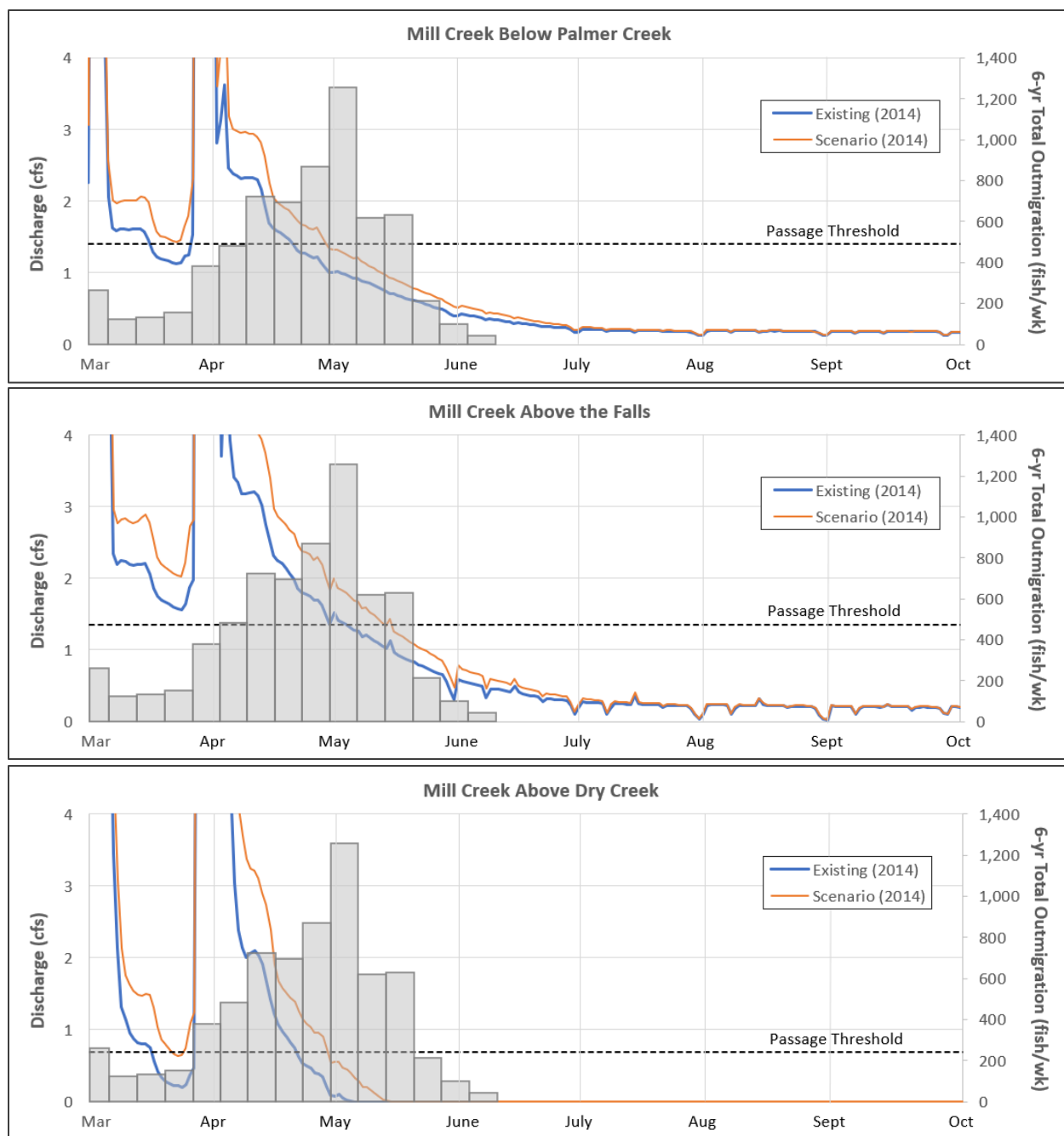
Figure 82: Simulated flow in Mill Creek below Palmer Creek, above the falls, and above Dry Creek resulting from large-scale implementation of forest management (Scenario 4).
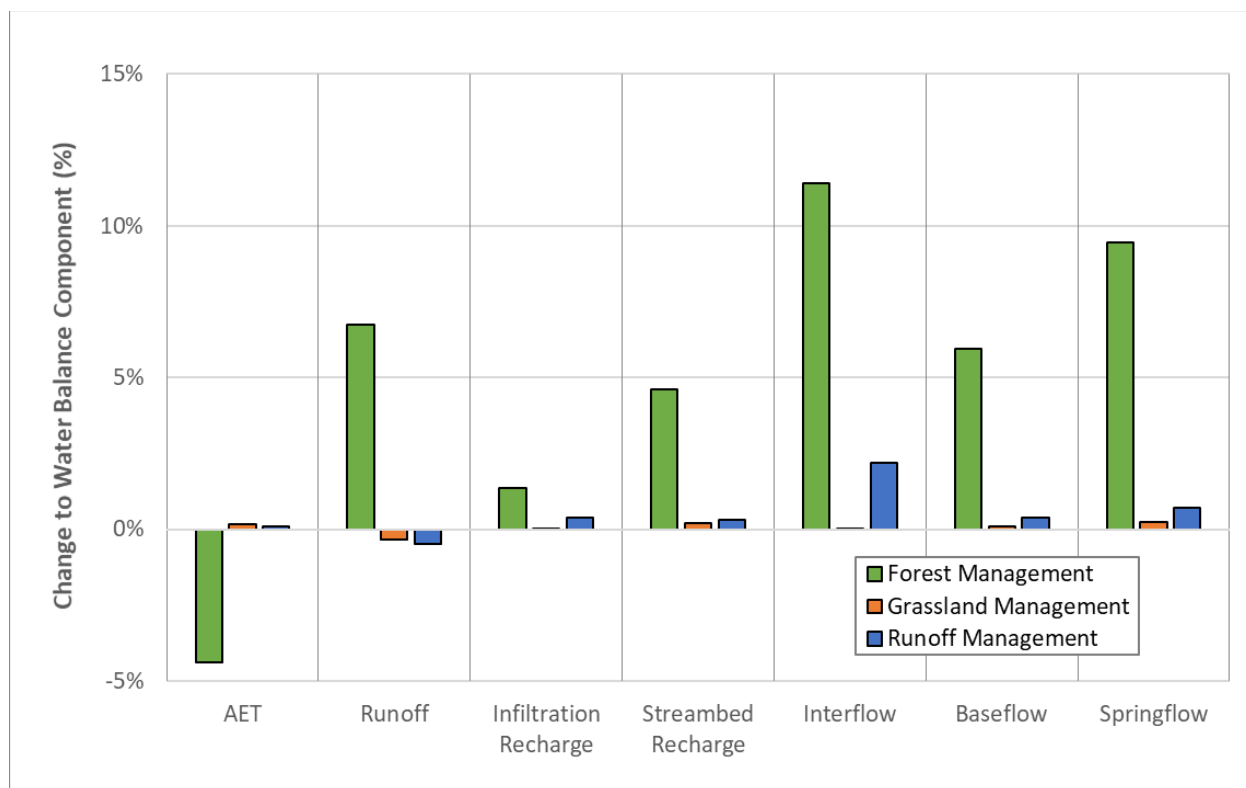
Figure 83: Percent change in select water balance components for Scenarios 4-6.

Direct Flow Augmentation Scenarios

Pond Releases

The summer pond release scenario (Scenario 7) resulted in the largest increases in summer streamflow of any of the scenarios discussed above. Gaining conditions predominate throughout the bedrock reaches of the watershed, therefore very little flow loss occurred upstream of the alluvial reach and the changes in flow are within 97% of the sum of the upstream releases at a given point in the watershed. Upstream of the Wallace confluence, mean summer flow increases ranged from 0.07 to 0.09 cfs, between Wallace Creek and the downstream-most release, flows increased by 0.23 to 0.25 cfs, and below the lowest release flows increased by 0.37 cfs (Figure 84). These increases represent 20-90% of the total flow, and within the highest priority reaches (Mill 2-Mill 4) the average increase is 42%. The flow disconnection in the reach extending from above Wallace Creek downstream to the alluvial reach (Mill 4) is completely eliminated under the flow release scenario. However, in the lower alluvial reach the releases are not large enough to have a significant effect on the timing or duration of flow disconnection (Figure 84).

The spring pond release scenario (Scenario 8a) is designed to extend the duration of passable conditions for outmigrating smolts. Flows within the alluvial reach become impassable earliest at the Dry Creek confluence approximately two weeks earlier than in the reach below Wallace Creek and one week earlier than in the reach between Palmer and Wallace Creeks.
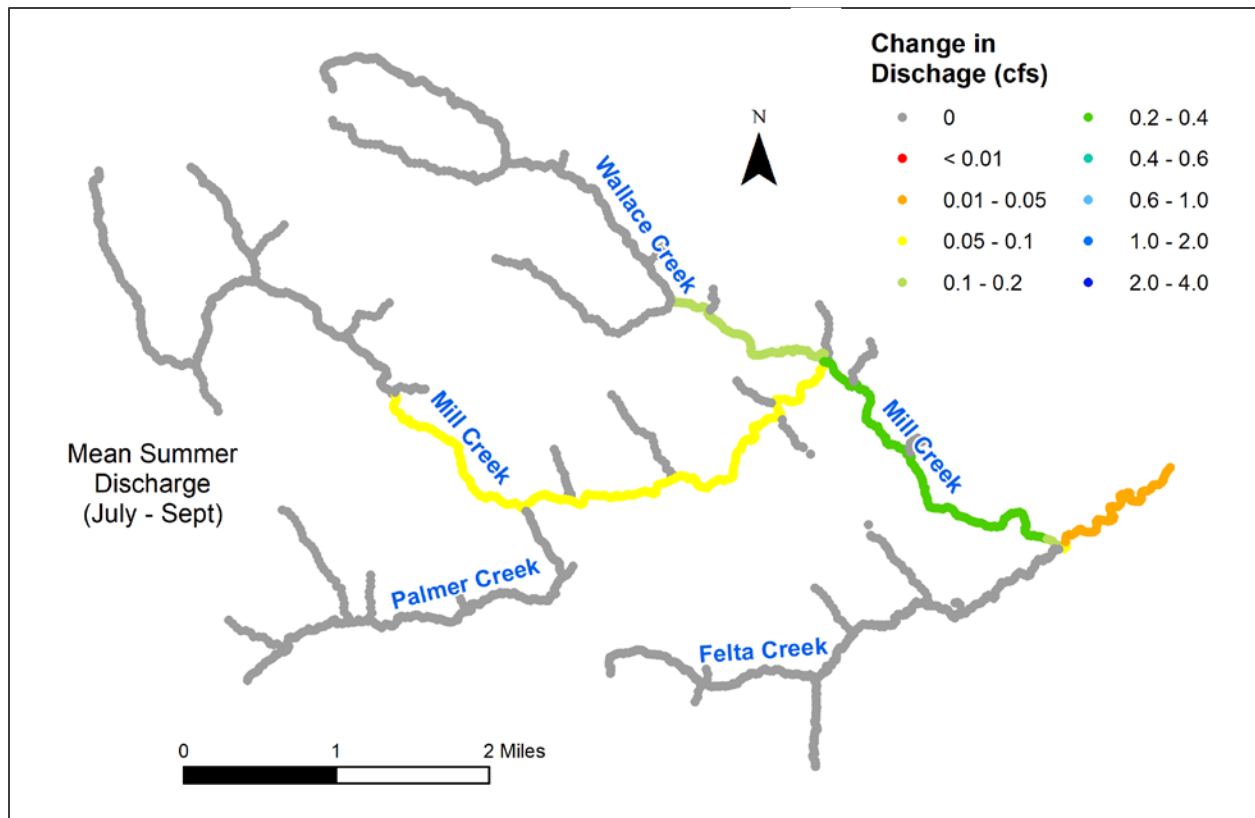
Figure 84: Simulated changes to mean summer streamflow for the summer pond release scenario (Scenario 7).

Therefore, the timing of flow disconnection at Dry Creek is the most critical control on overall smolt outmigration conditions. The available storage from the six ponds included in the scenario is large enough to allow to extend the duration of passable conditions above Dry Creek by approximately 32 days compared to 2014 drought conditions (Figure 85). This would allow passable conditions to persist throughout the primary outmigration period (POP) ending in late May, representing a major improvement over existing conditions where flows were impassable by mid-April.

Initial simulations of Scenario 8a revealed that constant release rates produced a hydrograph above Dry Creek that initially spiked at release initiation and then gradually receded. In order to maximize the duration of passable conditions, it is more desirable to generate a stable hydrograph at the outlet just above the threshold for passage. Given extremely limited availability of stored water, it is critical to optimize releases to avoid excessive release rates that would reduce effectiveness for passage and also avoid insufficient release rates that fail to create passable conditions. The releases are timed to coincide with the natural spring flow recession, so less flow is required initially to maintain passable conditions and as flows recede, progressively greater releases are required. Simulations indicate that a ramping release rate of zero to 2.0 cfs over 34 days is optimal and generates stable hydrograph conditions in the reach of Mill Creek upstream of Dry Creek (Figure 85). With an optimized constant release rate, passable conditions

in this lower reach were only provided for an additional 18 days compared to 32 days in the ramped (and final) version. Adaptive management of releases informed by real-time monitoring data would be required to validate the model predictions and optimize actual releases, however ramping release rates appear to provide significant benefits compared with constant releases when timed with the natural flow recession.
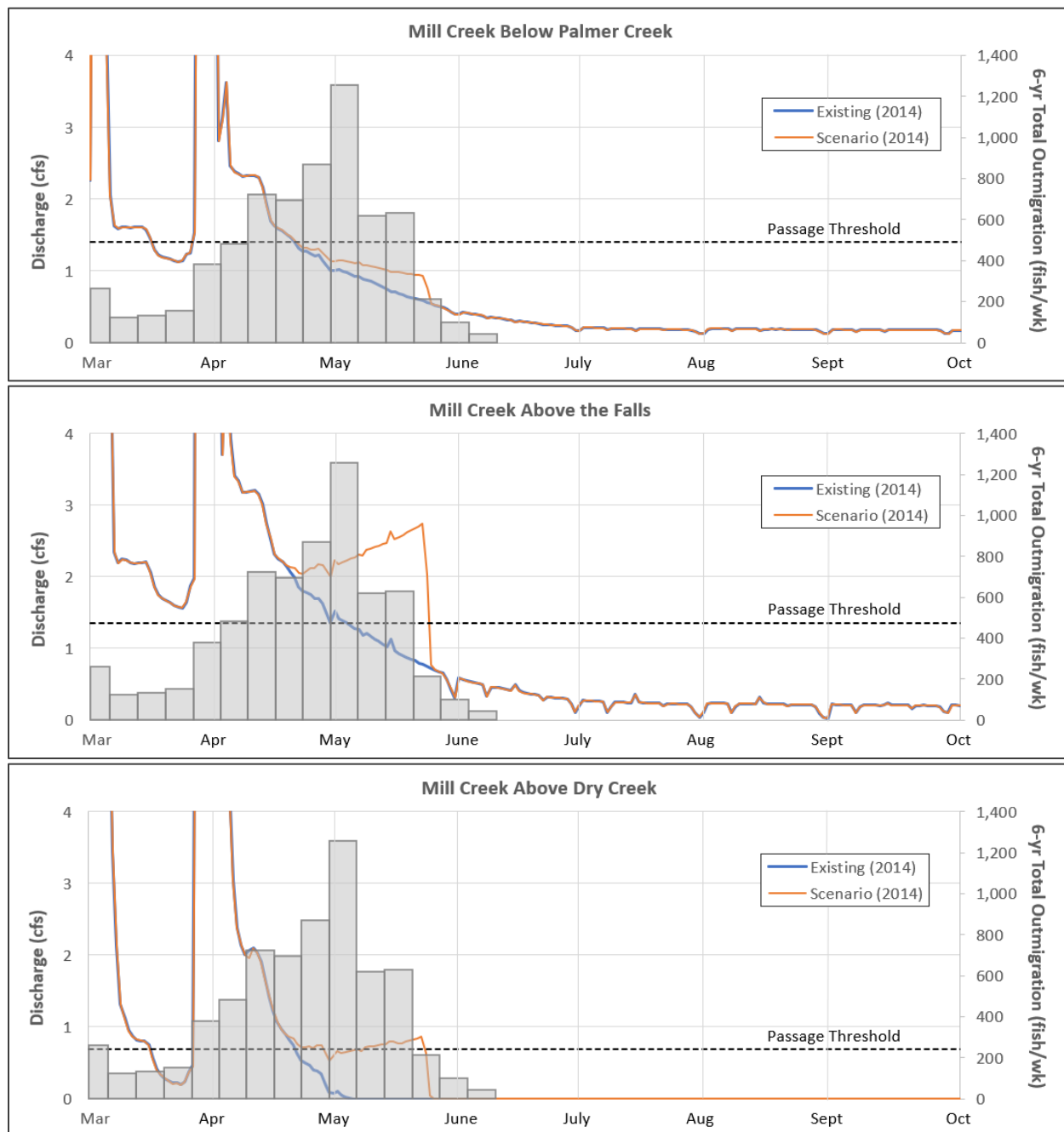
Figure 85: Simulated flow in Mill Creek below Palmer Creek, above the falls, and above Dry Creek resulting from the 6-pond spring release scenario (Scenario 8a).

Scenarios 8b-8e acknowledge the fact that it may be difficult to develop releases for all six ponds included in scenario 8a and is designed to provide some insight on the level of streamflow benefits that could be achieved using only one of the six ponds. Two release strategies were also investigated, continuous releases and pulsed releases. Results for scenarios 8b and 8c indicate that release of 3.7 ac ft from the smallest pond can extend the period of passable conditions above Dry Creek by approximately 4 days or provide one 36-hr period of passable conditions later in the outmigration season (Figure 86). Some flow benefits could be provided with a somewhat smaller pond, however given the uncertainties of benefits and costs of project implementation, 3.7 ac ft may be near the practical minimum storage limited for providing meaningful flow benefits for salmonids.

Results for Scenarios 8d and 8e indicate that release of 22.3 ac ft of water from the largest pond may extend the period of passable conditions above Dry Creek by approximately 15 days or provide five 36-hr periods of passable conditions later in the outmigration season (Figure 87). Based on 2014 drought conditions when flow became impassable an April 22nd, Scenario 8d extends this to May 7th which represents the period of maximum outmigration, with 34% of all outmigrants moving in that 15-day window. The pulsed releases are timed to extend for 36-hours because the vast majority of coho movement occurs at night and this might allow each pulse to provide two nights of passable conditions. Results for Scenario 8e indicate that passable conditions could be provided for five 2-night periods based on 2014 conditions to occur between April 26th and May 17th (Figure 87). While this represents only about 66% of the total increase in duration of passable conditions provided by the constant releases, it extends the end date of disconnection by an additional 10 days. Even with the reduction in total time of passable conditions, extending the total time window of passable conditions with pulsed releases may be more beneficial to the overall success of the outmigrating population. Pulsed releases may also trigger fish movement to some degree, potentially concentrating movement in the release windows.

Scenario 8e also indicates that increasingly larger release rates are required to achieve passable conditions in the lowest reach above Dry Creek, with the first release beginning in late April when streamflow was several tenths of a cfs requiring release of ~0.6 cfs, and progressively higher rates required for subsequent releases up to 2.3 cfs for the mid-May release (Figure 87). Background streamflow reaches zero by the third release; required release rates continue to rise as the water table in the alluvial aquifer falls progressively farther below the streambed and flow losses to the streambed increase. In contrast to long-duration continuous releases, where ramping *up* of release rates provides optimal hydrograph response, ramping *down* release rates appears to provide some benefits for the case of pulsed releases. With constant pulses, the hydrograph above Dry Creek took several more hours to slowly rise to passable levels versus when an initially higher rate was used and then ramped down. This is conceptually sensible in that higher release rates would fill bed and bank storage more rapidly and produce higher average flow velocity. The final pond release scenarios presented here required some optimization to maximize benefits and the results demonstrate that the timing, duration, and rates of release can make a critical difference to most effectively utilizing finite pond storages to enhance outmigration conditions.

They also point to the need for adaptive management and real-time monitoring during implementation.
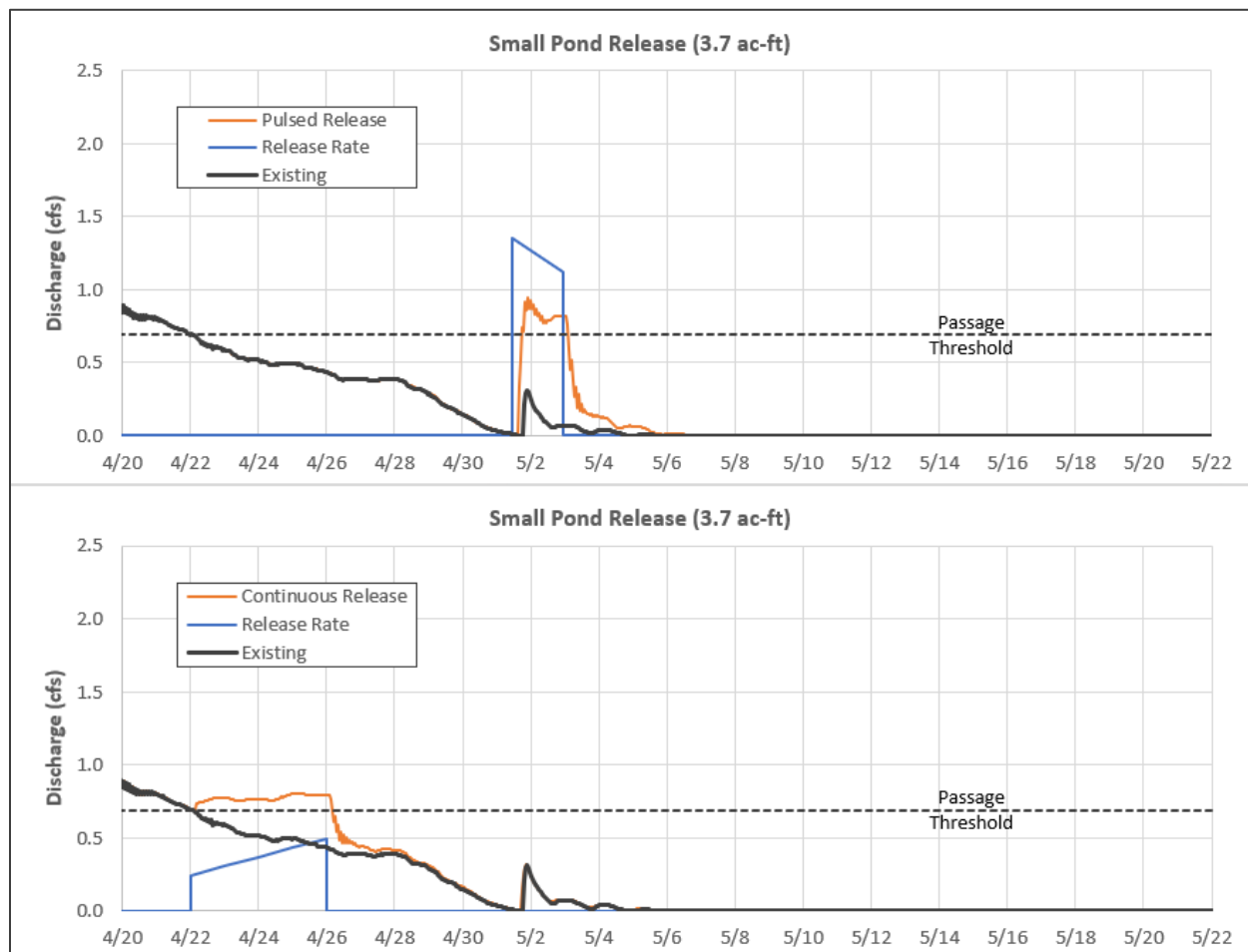
Figure 86: Simulated flow in Mill Creek above Dry Creek resulting from the small single pond release scenario with early-season continuous releases (Scenario 8b-bottom) and a later-season single-pulse release (Scenario 8c-top).
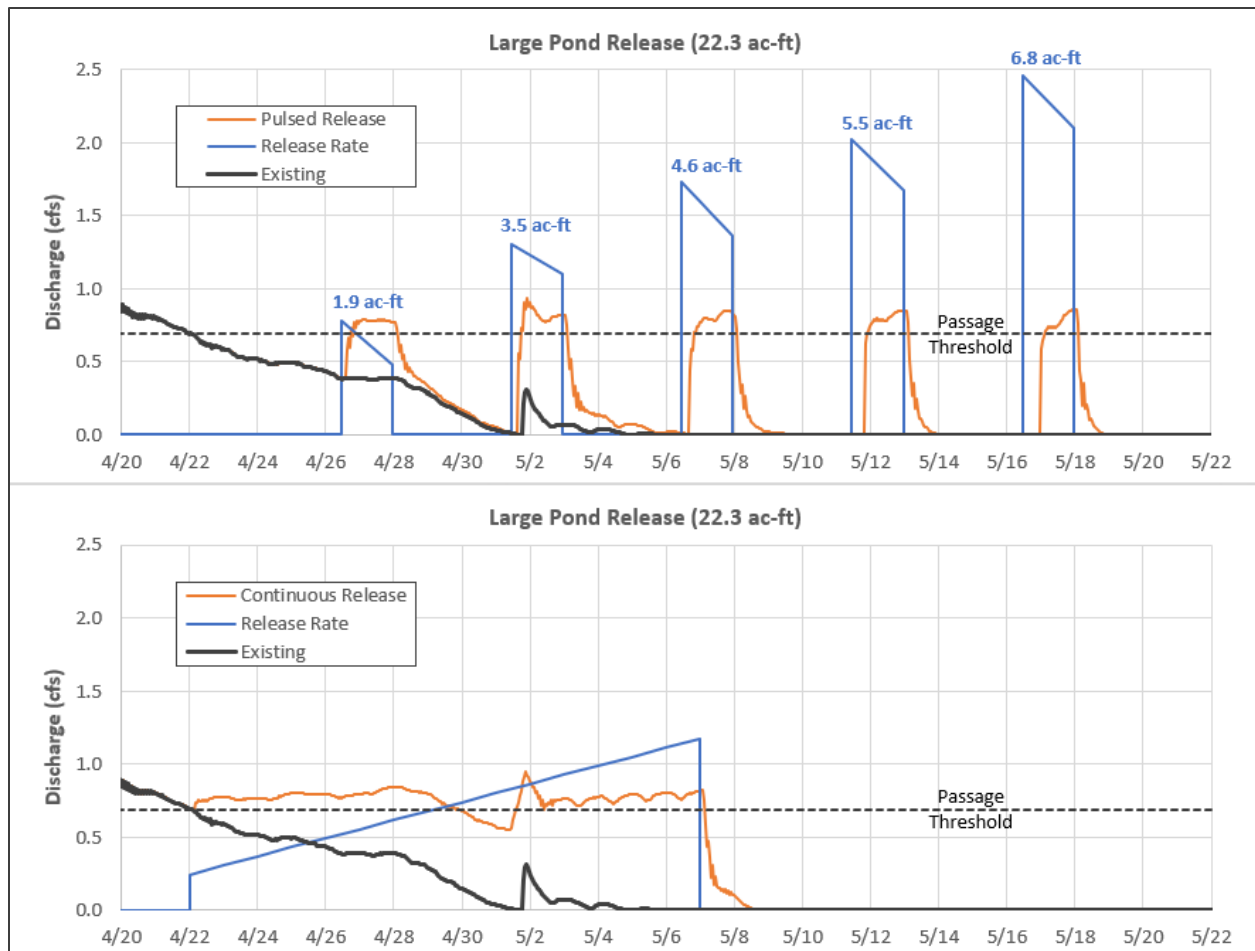
Figure 87: Simulated flow in Mill Creek above Dry Creek resulting from the large single pond release scenario with early-season continuous releases (Scenario 8d-bottom) and five pulsed releases (Scenario 8e-top); also shown are the release rates and the total volume of storage represented by each of the five pulsed releases.

Recycled Water

Scenario 9a-9d involved utilizing available tertiary treated wastewater, "recycled water", to augment streamflows through injection wells or infiltration basins. Results from Scenario 9a where the recycled water was injected in the downstream portion of the alluvial aquifer showed only a limited aquifer response and essentially zero streamflow benefits. At this location, the aquifer is several hundred feet thick, is comprised of very coarse materials, and is hydrogeologically-connected to the regional Dry Creek valley aquifer. Water table elevations in the lower aquifer also fall significantly (>10 ft) below the streambed beginning in early spring. It appears that creation of a groundwater mound of significance to the streamflow conditions in lower Mill Creek is not feasible at least at the injection rates at which recycled water is available.

In contrast to Scenario 9a, Scenarios 9b and 9c where the recycled water was injected in the upstream portion of the alluvial aquifer resulted in formation of a significant groundwater mound and significantly enhanced streamflow. The aquifer in the vicinity of the upstream injection well

field is estimated to be about 50 ft thick, and flows disconnect later in the spring or early summer in the adjacent reach of Mill Creek with a slower water table decline relative to downstream aquifer conditions. These conditions foster a more significant aquifer response; the injection to groundwater offsets the springtime water table declines and extends the duration of gaining conditions. For Scenario 9b with injection beginning May 15th (in the 2014 example), flow increases were not enough to generate passable conditions either adjacent to the injection site or farther downstream, however a small discharge response did persist all the way to the Dry Creek confluence.

Scenario 9c began injection on April 20th, two days prior to development of impassable condition at the outlet. This served to extend the duration of passable conditions in lower Mill Creek above Dry Creek by about 19 days (Figure 88). This benefit is similar to the streamflow enhancement from the large single pond release (Scenario 8d). As described in relation to Scenario 8d, this would be expected to coincide with the period of peak outmigration and provide significant benefits for outmigrating smolts. Although it would be possible to continue the recycled water injection through the summer months, the injection is not enough to do more than delay the onset and reduce the rates of losing conditions, and by July (in the 2014 example), streamflows fall to zero in the upper reach adjacent to the well field and these flows become zero by the end of May in the lowest reaches above Dry Creek (Figure 88).

Examining the effects of the injection on aquifer conditions in more detail reveals that the water table increase associated with Scenario 9c becomes progressively larger over time, however as discussed above, streamflows still decline, and beyond about June 1st the enhancement benefits for salmonids will likely have reached a maximum. In the 2014 example, six weeks after initiation of injection on June 1st, water table elevations are between 3 and 4 ft higher in the vicinity of the well field and increases of 2 to 3 ft occur over a broad area of the aquifer intersecting the stream as far as 1,200 ft downstream (Figure 89). This effect diminishes rapidly beyond this point in the downstream direction, falling to less than 0.5 ft at 2,000 ft downstream of the injection well field. There does not appear to be any year-to-year cumulative storage effects since the injection has essentially no effect on water levels during the following rainy season and heading into the following spring. It appears that ending injection around June 1st would provide essentially the same benefits to salmonids as continuing the releases throughout the summer.

Scenario 9d assumes recycled water would be added to the system via an infiltration basin located in the same area (and with the same rates and timing) as the hypothetical injection wells in Scenario 9c. The benefits of this strategy were very similar to, but somewhat smaller than those of the injection approach with a 17-day increase in the period of passable flow conditions at the outlet and a maximum streamflow increase of 1.3 cfs (compared to 19-days and 1.4 cfs for Scenario 9c; Figure 88). Additional characterization of soil and groundwater conditions would be needed to validate the assumptions and findings of the analysis for recycled water injection or infiltration, however our preliminary findings suggest that this could be a promising strategy if a suitable site is selected in the upstream portion of the alluvial aquifer.
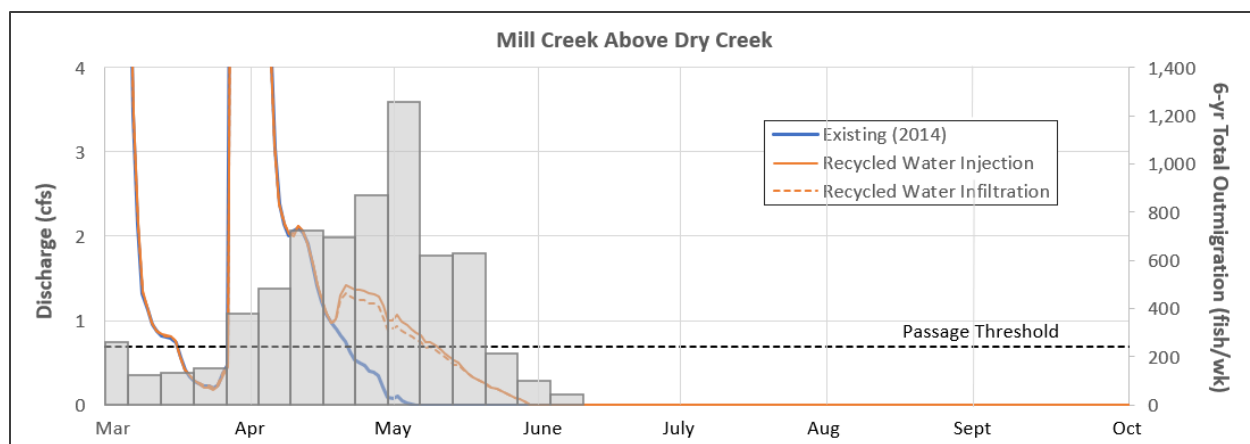
Figure 88: Simulated flow in Mill Creek above Dry Creek resulting from the recycled water injection and infiltration scenarios (Scenarios 9c & 9d).
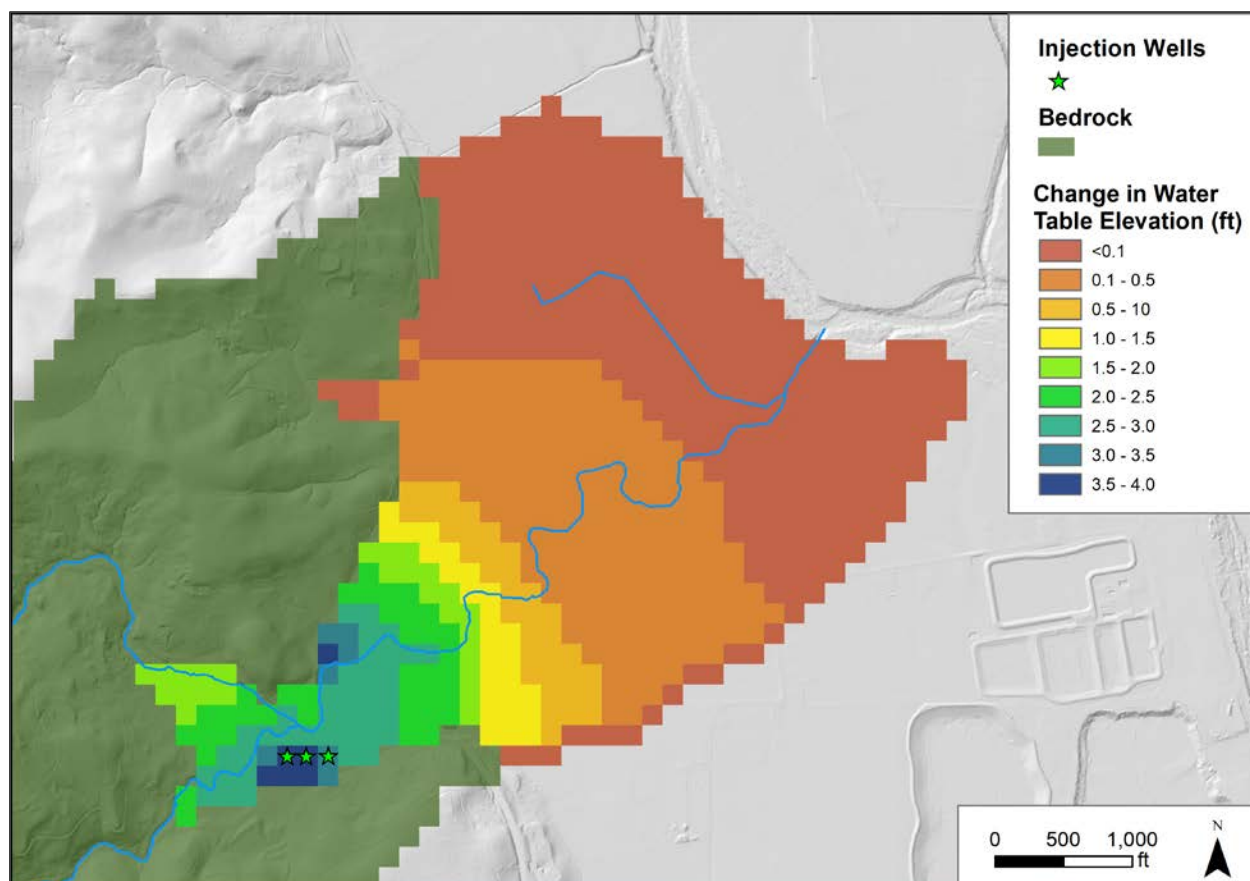
Figure 89: Change in June 1st water table elevations in the lower Mill Creek alluvial aquifer resulting from injection of recycled water (Scenario 9c).

Climate Change Scenarios

The four climate change scenarios (Scenarios 10-13) generated a wide range of predictions of future (2070-2099 timeframe) changes in discharge in Mill Creek; nevertheless, there are some commonalities in the predictions of future streamflow trajectories. The average 10-yr mean monthly discharge is predicted to increase during the winter months in two of the four scenarios, with mean February flows nearly twice as large as existing conditions in the CNRM scenario (Figure 90). All four scenarios show large decreases in discharge during spring with mean monthly flows during April decreasing by 20-61%. Flows are zero over much of the summer in the lower alluvial reach both under existing and future climate conditions, therefore it is more useful to examine summer flow changes in the upstream bedrock reaches. All four models indicate declines in mean summer flows on the order of 8-36% within the bedrock reaches.

More detailed review of the range of predicted changes in mean summer flows reveals that the most optimistic scenario (CNRM) predicts small decreases in summer discharges of less than 0.04 cfs, whereas the most pessimistic scenario (MIROC) predicts decreases in discharge in Mill Creek of up to 0.08 cfs upstream of Palmer Creek and up to 0.17 cfs downstream of Palmer Creek (Figures 92 & 93). In terms of mean springtime flows, the scenarios predict decreases of 0.7-2.2 cfs upstream of Palmer Creek and decreases of 1.7-6.4 cfs downstream of Palmer Creek (Figures 94 & 95).

The future changes are more extreme during drought conditions where winter flows are predicted to decrease dramatically in all four scenarios with high streamflow events becoming essentially non-existent in the GFDL scenario (Figure 91). With the exception of the CNRM scenario which indicates more modest decreases in April flows on the order of 13% and increases in May flows of 23%, the other three scenarios indicate large reductions in springtime flows during drought conditions with decreases in April flows of 52-100%. We plotted the daily hydrographs for the driest year within each 10-yr simulation to examine the timing of flow recessions relative to smolt outmigration. This revealed that one future (CNRM) predicts slightly improved smolt outmigration conditions during drought years, one future predicts a modest decline (CCSM) and the other two futures predict dramatic declines (Figure 96). In the GFDL and MIROC futures, flows above the falls were passable for only 2 and 17 days during the primary outmigration period (POP) respectively (compared to 39 days in existing conditions). Farther downstream above Dry Creek, the GFDL and MIROC scenarios predict zero days of passable conditions during drought years compared to 20 days in existing conditions. This suggests that successful smolt outmigration would become nearly non-existent during drought years if future climate resembles that of the GFDL or MIROC futures.

Examination of the 10-yr mean annual water balance (representative of the 2070-2099 timeframe) reveals that the four climate scenarios predict very different changes to the mean annual water balance. Precipitation changes range from a 34% increase in the CNRM scenario to a 21% decrease in the MIROC esm scenario (Figure 97). The significantly higher precipitation in the CNRM scenario leads to increases in AET of about 10%, whereas the other three scenarios result in much smaller changes of +/- 2%. Runoff is predicted to increase in the CNRM and CCSM4

scenarios by 10-79% and decrease in the GFDL and MIROC esm scenarios by 39-55% (Figure 97). The CNRM scenario predicts large increases in both infiltration recharge (27%) and streambed recharge (37%), the CCSM4 model predicts minimal changes in recharge, and the GFDL and MIROC esm scenarios predict significant decreases in infiltration recharge (11-20%) and streambed recharge (13-24%). Increased recharge in the CNRM scenario results in increases in groundwater discharge expressed as interflow (43%), baseflow (40%), and springflow (52%). Similarly, groundwater discharge decreases in the scenarios that predict decreases in recharge. The largest decreases are predicted by the MIROC esm scenario where interflow, baseflow, and springflow are predicted to decrease by 37, 31, and 34% respectively (Figure 97).

Comparison of the water balance for the driest of the 10 years in each simulation reveals that the trajectories of the changes in the water balance between the four scenarios are more similar during drought conditions than for long term average conditions. AET is predicted to increase in all four models while runoff is predicted to decrease (Figure 98). The CNRM scenario remains anomalous in its predictions of increased recharge and groundwater discharge, however the increases are more modest during the driest year relative to the 10-yr average conditions. The GFDL drought predictions are extreme with close to a complete loss of both runoff and infiltration recharge.

At first glance it appears contradictory that infiltration recharge and groundwater discharge increase significantly in the CNRM scenario on an annual basis, however mean spring and summer flows still decrease. Examination of the mean monthly distribution of infiltration recharge and springflow reveals that the change in precipitation seasonality provides the explanation for this. Although both recharge and springflow are higher than existing values in the CNRM scenario during the core of the rainy season, March and April recharge fall off significantly from 2.2 in/yr to 0.8 in/yr (Figure 99). This shift towards more recharge in the core of the rainy season results in a diminishing increase in springflow as spring progresses with near zero increase by June and slight decreases developing by July.

All four scenarios indicate increases in climatic water deficit (CWD). The mean CWD for the watershed over the 10-yr simulation period is predicted to increase from 13.0 in/yr under existing conditions to between 14.0 and 20.2 in/yr under future climate conditions. The increase predicted by the CNRM scenario is a relatively modest change of 8%, however the increases for the other scenarios are quite large and range from 24-55%. Increases in CWD of this magnitude may be expected to lead to significant changes in vegetation communities and increases in fire risk. It is important to note that these simulations represent the hydrologic effects of changes in climate but do not include secondary effects that may be expected under a significantly altered future climate regime such as changes in vegetation cover and irrigation water demands.
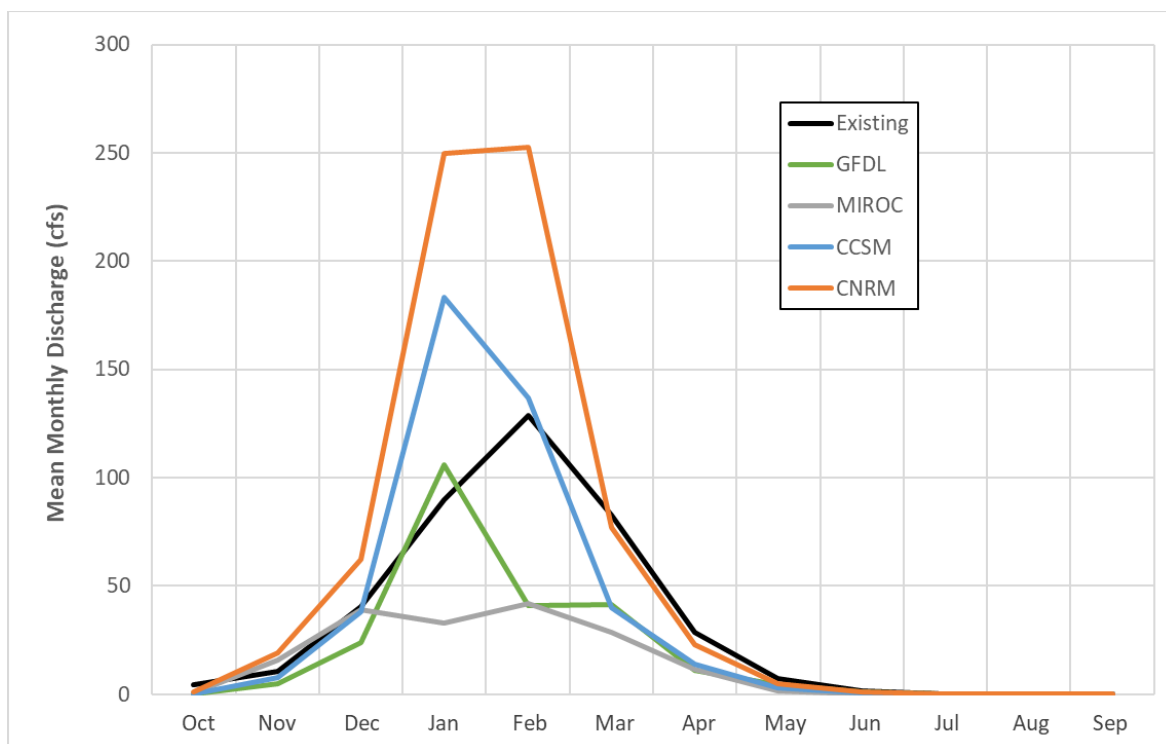
Figure 90: Comparison of mean monthly streamflow averaged over the 10-yr simulation periods for existing conditions and the four climate change scenarios (Scenarios 10-13).
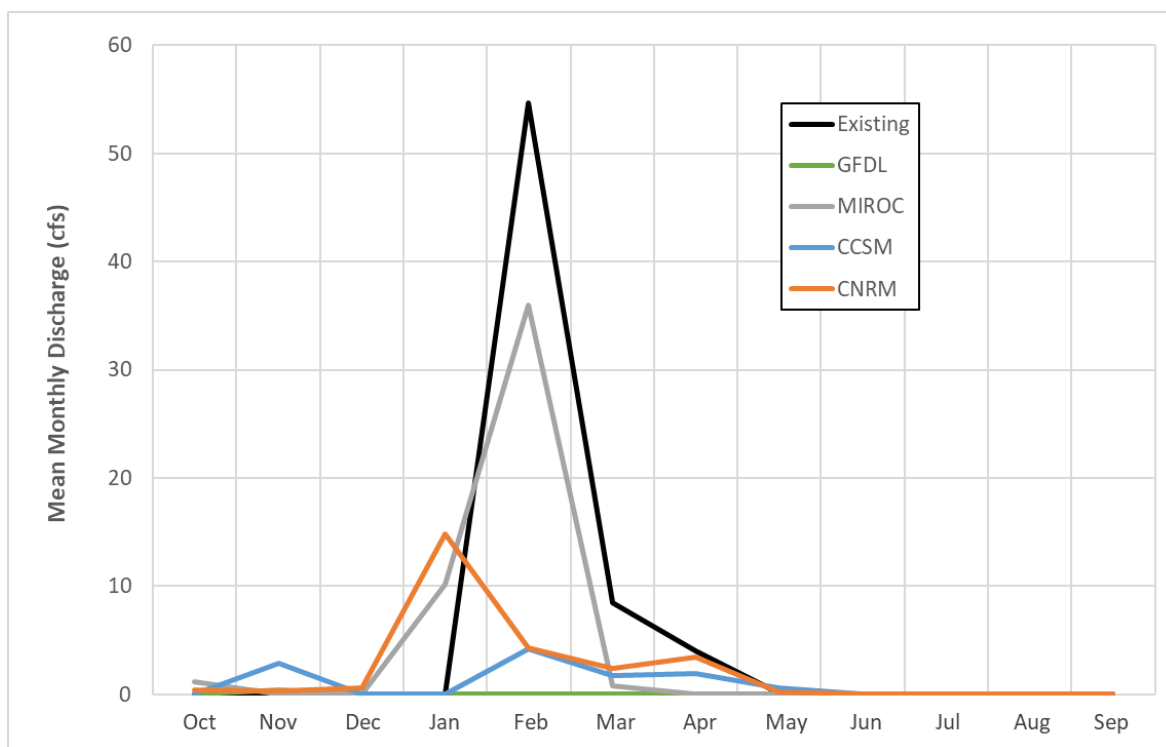
Figure 91: Comparison of mean monthly streamflow for the driest water year in each 10-yr simulation period for existing conditions and the four climate change scenarios (Scenarios 10-13).
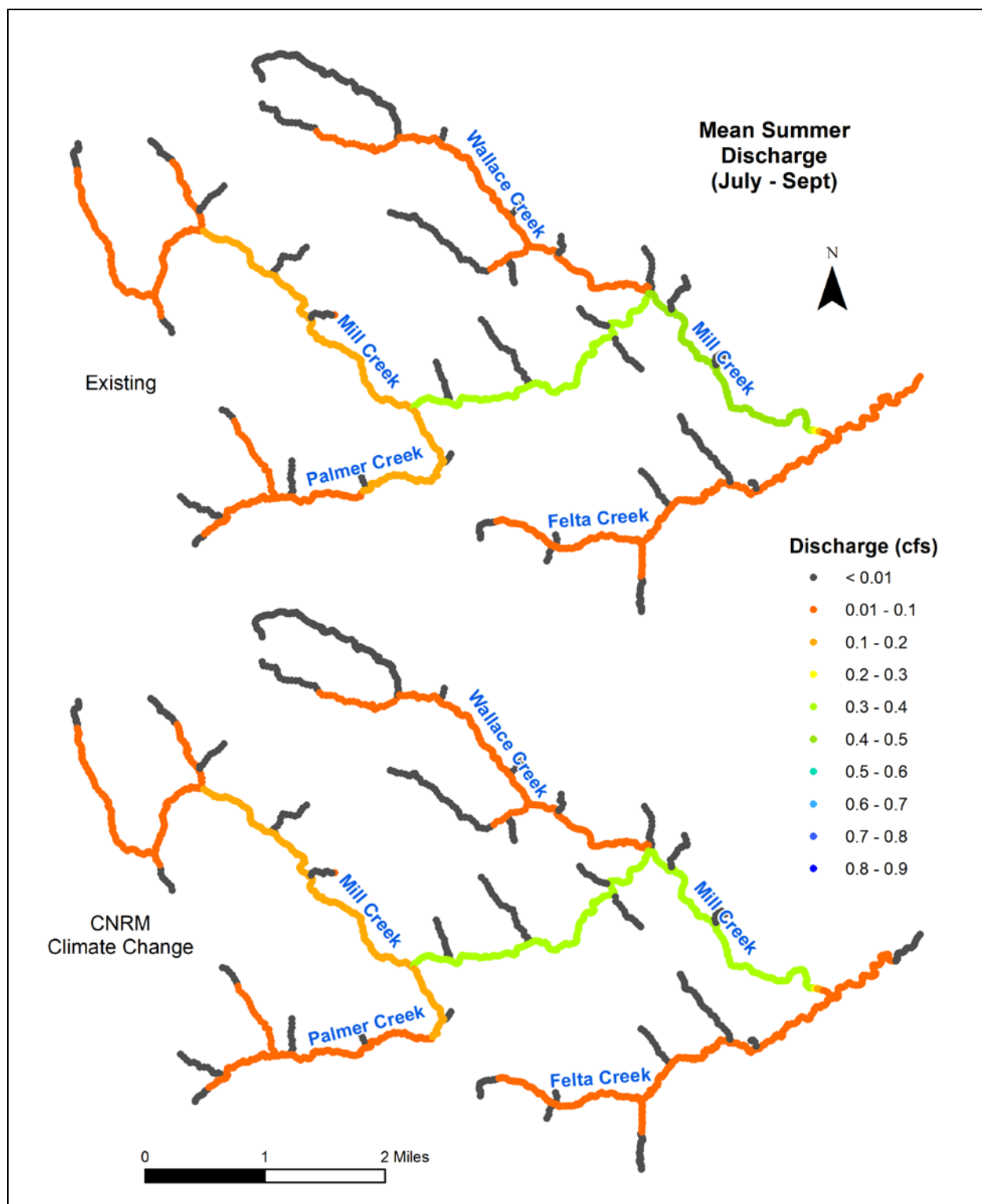
Figure 92: Simulated 10-yr average mean summer streamflow for existing conditions and the CNRM scenario (Scenario 10).
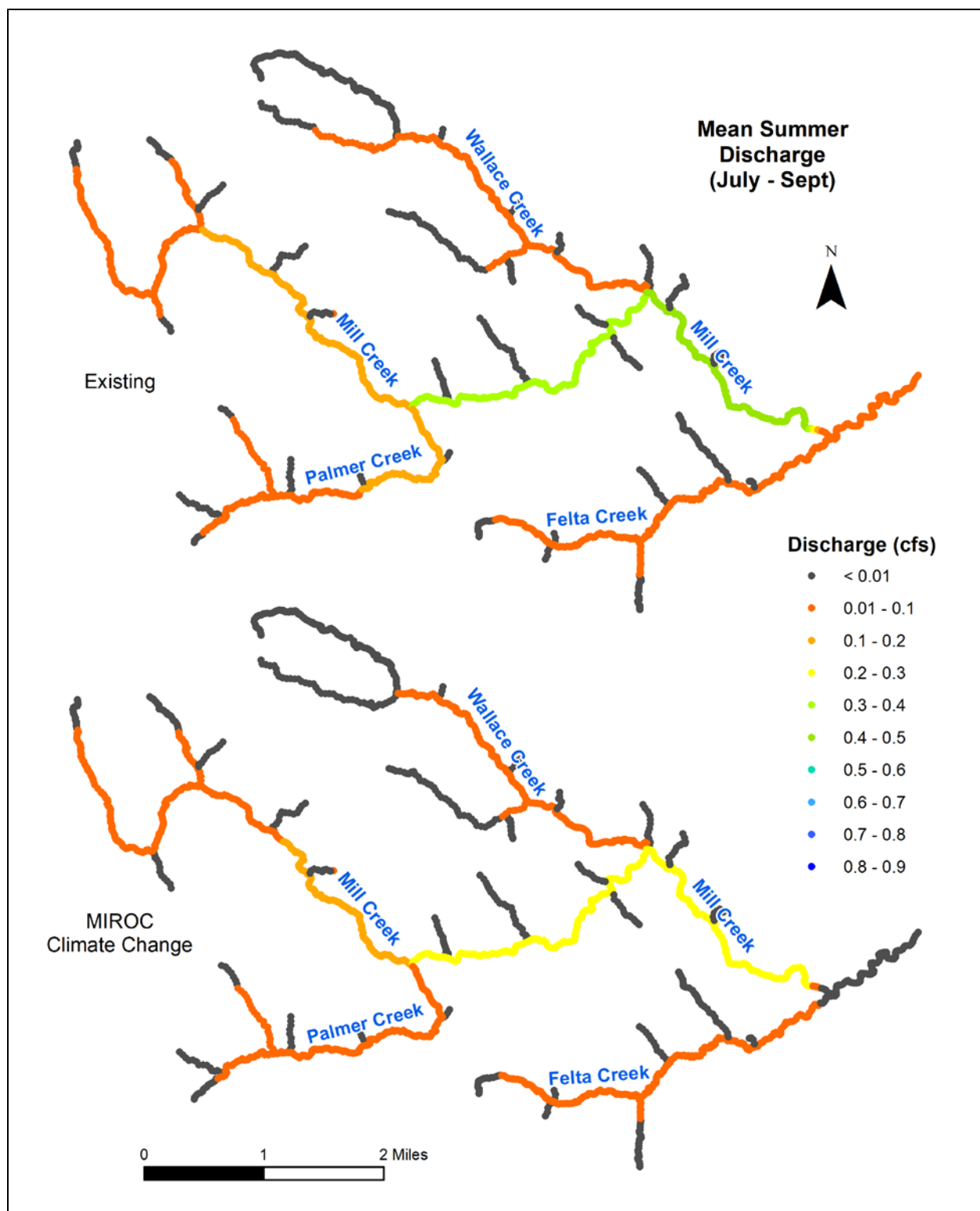
Figure 93: Simulated 10-yr average mean summer streamflow for existing conditions and the MIROC esm scenario (Scenario 13).
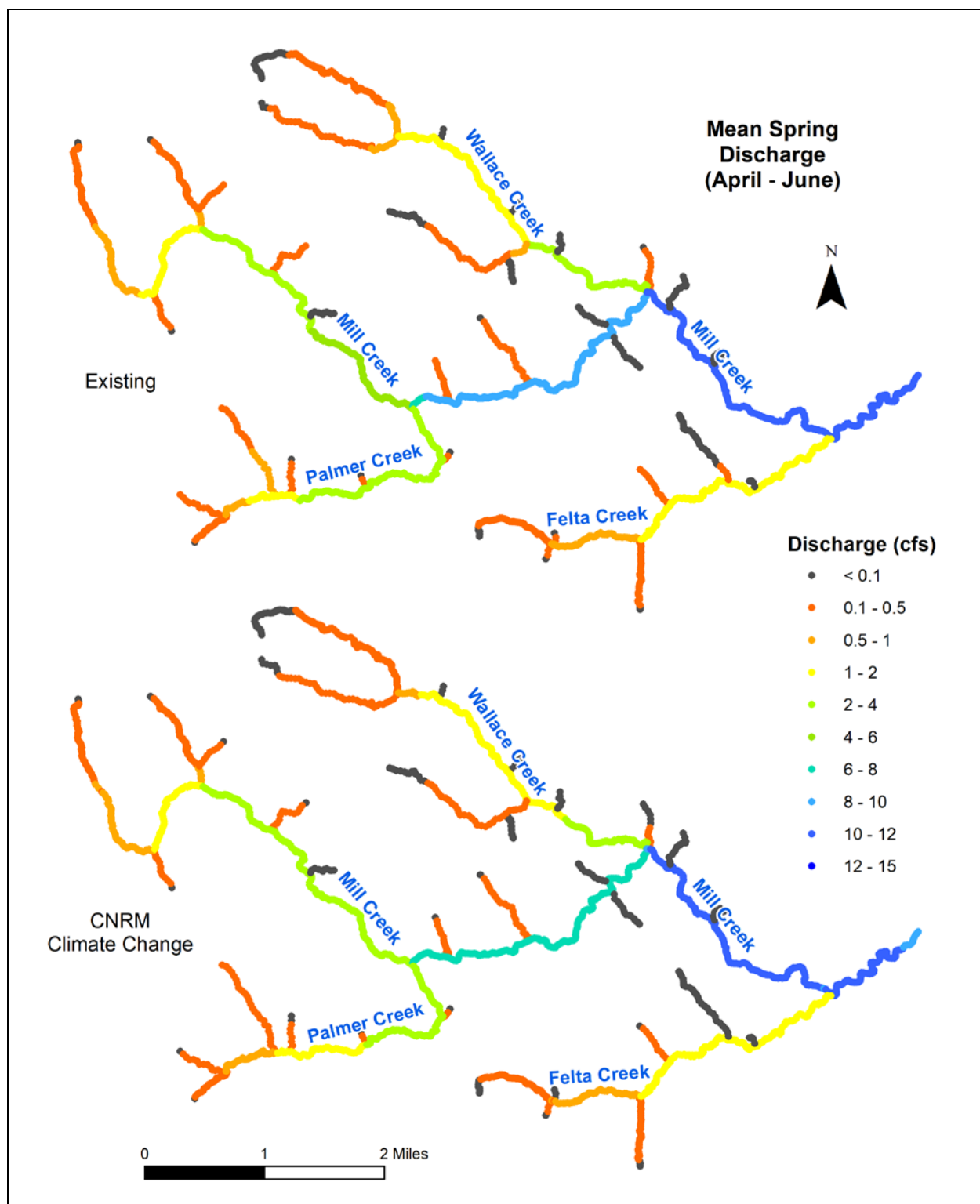
Figure 94: Simulated 10-yr average mean springtime streamflow for existing conditions and the CNRM scenario (Scenario 10).
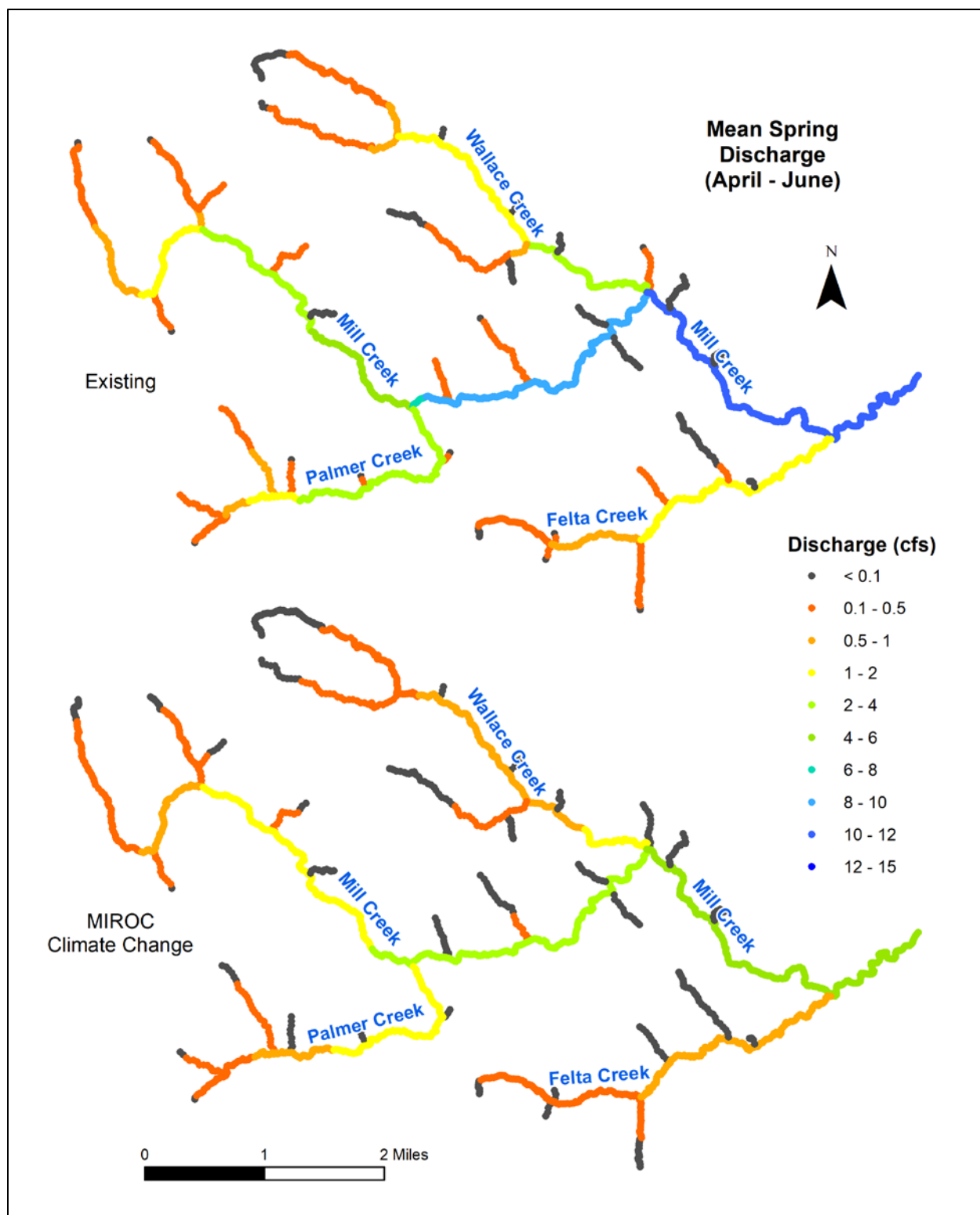
Figure 95: Simulated 10-yr average mean springtime streamflow for existing conditions and the MIROC esm scenario (Scenario 13).
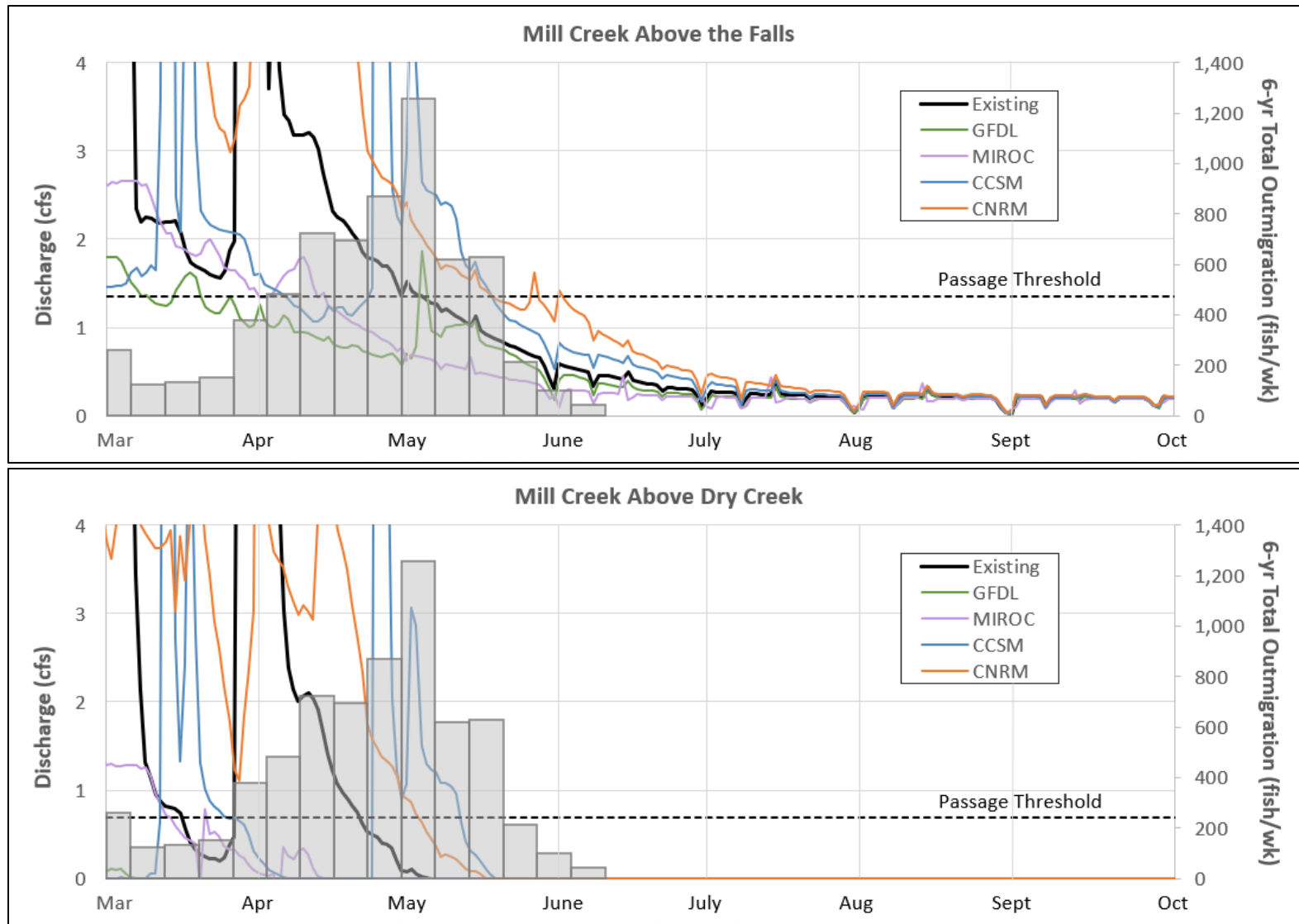
Figure 96: Streamflow hydrographs in the lower portions of the bedrock reach (top) and the alluvial reach (bottom) of Mill Creek for the driest year in the 10-yr simulation period under existing and future climate conditions relative to the timing of outmigrating smolts as documented by CSG for 2014-2019.
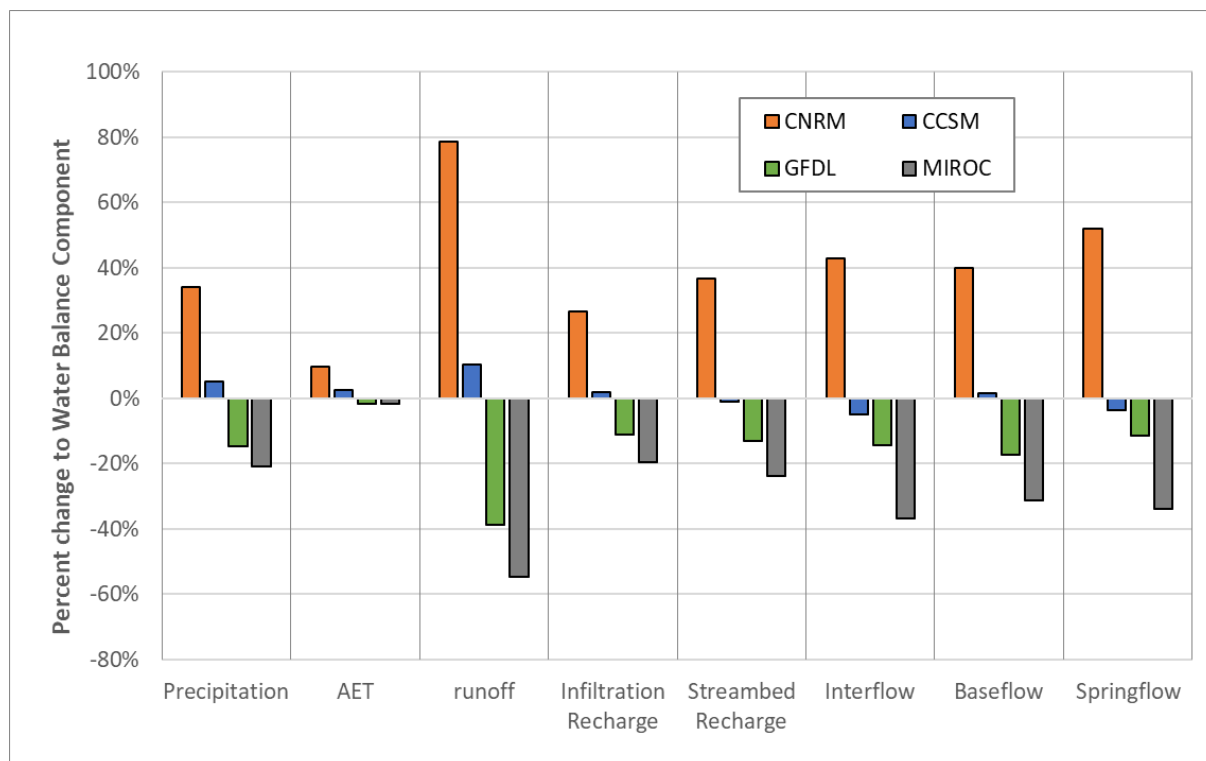
Figure 97: Percent change in various components of the water balance averaged over the 10-yr simulation period for the four climate change scenarios relative to existing conditions.
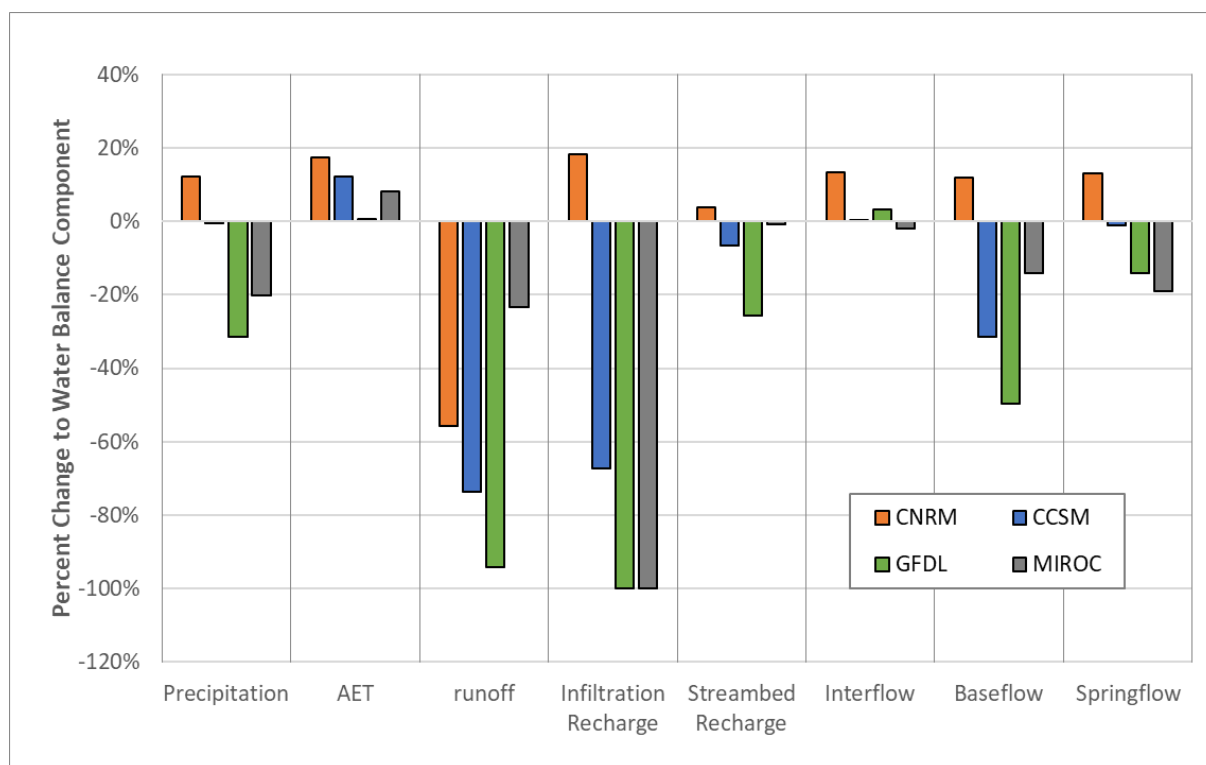
Figure 98: Percent change in various components of the water balance for the driest water year in each 10-yr simulation period for the four climate change scenarios relative to existing conditions.
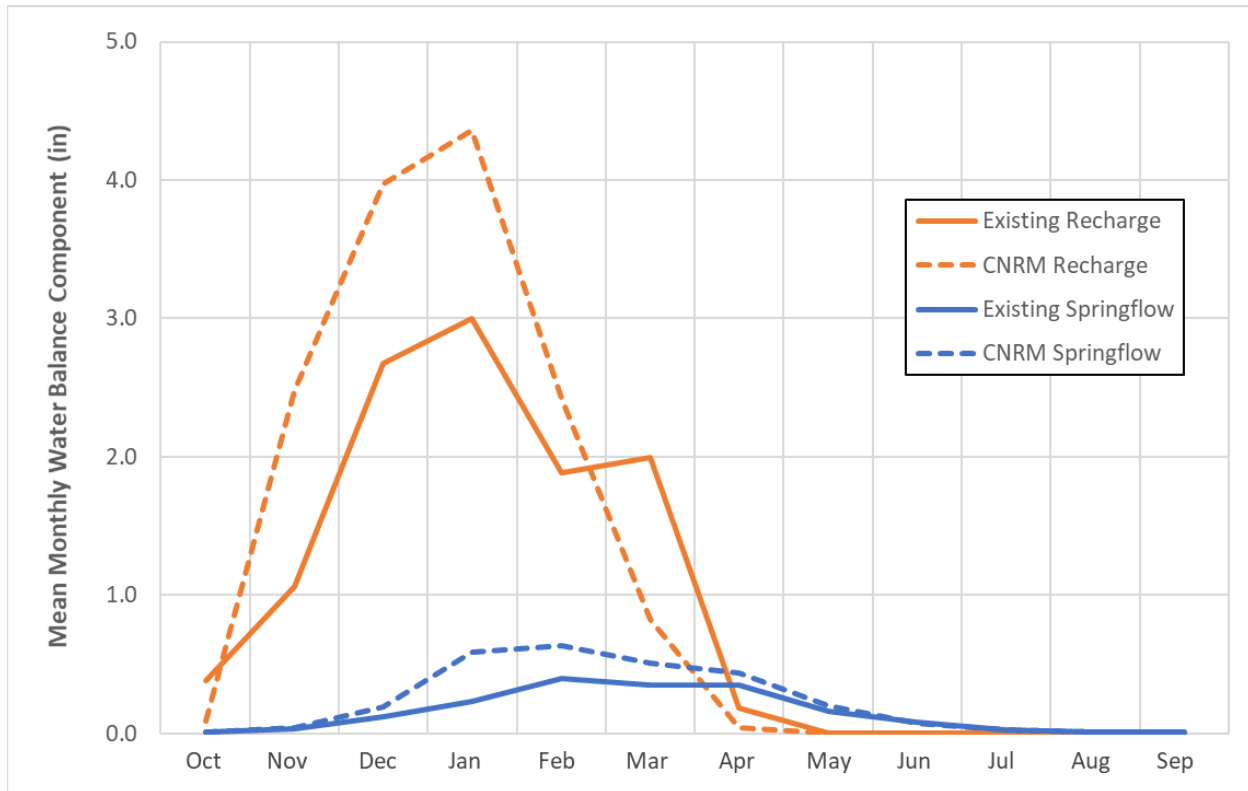
Figure 99: Comparison between mean monthly infiltration recharge and springflow under existing and CNRM future climate conditions (Scenario 10).

Summary and Comparison of Scenarios

Comparison of the changes in summer streamflow between the various scenarios indicates that cessation of all surface water diversions could increase mean summer streamflow by about 8% in the highest priority reach extending from downstream of Angel Creek to the upstream edge of the alluvial reach (Mill 2-Mill 4), hereafter referred to as the highest priority reaches (Figure 100). In contrast, cessation of all groundwater pumping resulted in much smaller summer streamflow changes of <1%. The summer pond release scenario generated the largest increases in summer streamflow of the stand-alone scenarios, with an average increase of 43% in the highest priority reaches (Figure 100). The next largest increases were from the forest management scenario, followed by the runoff management scenario which resulted in a 17% and 14% increase in mean summer flow, respectively (Figure 99). The grassland management scenario also generated small increases in summer flows on the order of 1% (Figure 100).

The climate change scenarios generated a wide range of predictions with mean summer streamflow predicted to decrease between 8 and 36% within the bedrock reaches of Mill Creek (Figure 100). While these reductions in flow are substantial, the flow enhancement associated with the pond release scenario appears to be large enough to completely offset future flow reductions even in the most pessimistic climate futures. The scale of changes associated with

the forest and runoff management scenarios are also large enough to offset most or all of the decreases depending on which climate future is considered. If future climate more closely resembles the predictions of the CNRM or CCSM4 models, pond releases and large-scale implementation of forest and runoff management would be expected to result in flow enhancement above existing conditions.

Several of the scenarios resulted in significant streamflow enhancement during the spring outmigration season including the spring pond release, recycled water release, and forest management scenarios. Cessation of water use, runoff management, and grassland management do not appear to provide streamflow benefits at a meaningful scale for improving salmonid habitat. The largest improvement in spring smolt outmigration flow conditions resulted from the spring pond release scenario which could extend the duration of passable conditions for smolts by approximately 32-days (Figure 101). Recycled water injection was also found to extend the duration of passable conditions in the spring by about 19 days and use of infiltration basins rather than injection wells only reduced this slightly to 17 days. The forest management scenario served to delay the timing of the spring flow recession, maintaining passable conditions for outmigrating smolts for an additional 8 days (Figure 101).

The various large-scale flow enhancement actions represented by the scenarios and the foregoing comparisons are intended to represent implementation of projects of a given type based on the maximum potential on the landscape. The scenarios vary widely in their scale, feasibility, and expected costs. To better understand the relative streamflow benefits of implementing a given project, we calculated approximate costs for seven hypothetical projects centered around each of the flow enhancement strategies represented by the scenarios and then used these costs to normalize the streamflow enhancement benefits to a $25,000 project cost. To normalize the surface water diversion scenario results, we assumed a new well would be drilled to replace the entire diversion volume with groundwater pumping. We divided the cumulative diversion effects by the total number of diversions and then subtracted the cumulative groundwater pumping effects normalized by the volume of diversion offset. In most cases it is not possible or practical to completely offset groundwater pumping with rainwater or runoff capture and storage. Installation of storage tanks is a common and practical means of offsetting groundwater pumping and we assumed 10,000 gallons of tank storage offset to normalize the groundwater pumping scenario results. Forest treatment and grassland treatment was normalized to a per acre cost, and runoff treatment was normalized to cost per a typical 3,000 ft^2 impervious treatment area. The pond release scenario was normalized by simply dividing the cumulative enhancement benefits by the number of release projects (six), and we estimated the cost for implementing the recycled water injection or infiltration strategy as a single lump sum.

The seven projects and estimated costs include:

- Groundwater Pumping Offset – installation of a 10,000 gallon rainwater catchment tank and associated reduction in groundwater pumping - $40,000

- Surface Diversion Replacement – replacement of a direct or spring diversion with a new groundwater well - $33,000
- Runoff Management – construction of an infiltration basin sized to capture the 10-yr 48-hr storm volume from a 3,000 ft^2 rooftop or other impervious area - $27,000
- Grassland Management – compost application on one acre of grassland - $1,522
- Forest Management – thinning and/or controlled burning on one acre of forested lands requiring treatment - $2,680
- Pond Release – summer flow release of 11.4 ac ft from an existing on-stream pond (average release volume of the six ponds in the model scenario) - $20,000
- Recycled Water Injection/Infiltration– 1,800 ft of purple pipe extension, construction of three 45 ft deep injection wells, pumps, mobilization, and erosion control costs - $300,000

These estimates do not include regulatory and permitting costs, which in some cases are likely to be significant.

This comparison revealed that pond releases are by far the most effective strategy for enhancing summer streamflows (Figure 102). On a cost basis, the streamflow benefits of one flow release project were found to be more than 70 times greater than an average surface water diversion replacement project and more than 700 times greater than an average forest management project (the second and third most effective strategies). Replacement of direct stream diversions or spring diversions of surface water with new wells is the second most effective strategy. Forest, grassland, and runoff management showed a similar level of effectiveness on a cost basis and were about an order of magnitude less than the benefits from diversion replacement (Figure 102). Offsetting groundwater pumping with storage was the least effective of the overall strategies considered.

Only three of the strategies resulted in meaningful increases in springtime streamflow and outmigration conditions: forest management, spring pond releases, and recycled water injection/infiltration. On a unit cost basis, spring pond releases are the most effective strategy with benefits on the order of four times the recycled water injection or infiltration strategy (second most effective). The recycled water strategy may have some advantages over pond releases in terms of water temperature control and supply reliability, and costs for its implementation are uncertain, therefore the cost benefit comparison should be interpreted with caution. Forest management benefits were significantly lower on a per cost basis producing about 0.1% of the benefits of pond releases and 0.4% of the recycled water release benefits. Additionally, investment in ongoing follow-up work will be required if forest management is to result in stands with lower evapotranspiration characteristics that persist over time.

It is important to recognize that runoff, forest, and grassland management may provide significant additional benefits besides streamflow enhancement compared to pond release, diversion replacement, or recycled water release projects. These management strategies generate enhanced streamflow primarily via increasing groundwater discharge (see Figure 83), which may be expected to mitigate high water temperature, whereas flow releases from ponds may need to be carefully managed to avoid adverse temperature effects. These strategies also

help reduce seasonal vegetation moisture stress which may decreases fire risk somewhat or at least help offset future increases in risk associated with climate change. In particular, the forest
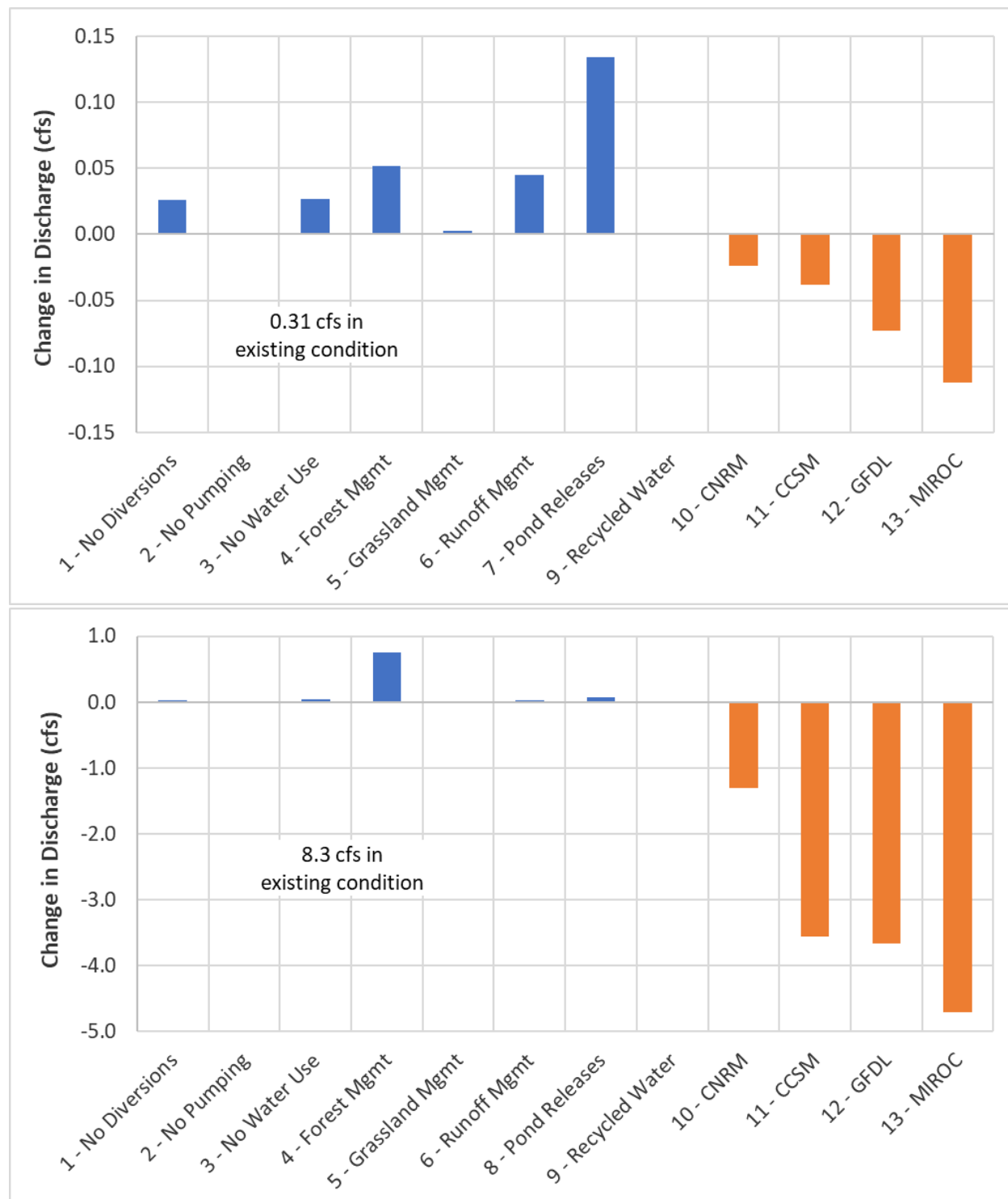
Figure 100: Summary of the simulated changes in mean summer (top) and spring (bottom) streamflow for Scenarios 1-13 averaged over the high-priority habitat reaches (Mill 2-Mill 4).

management scenario reduces actual evapotranspiration by about 5% on treated lands which represents a large volume of water (1,642 ac ft/yr), and the runoff management scenario predicts a substantial decrease in the climatic water deficit on lands where they are implemented. These various benefits are in addition to the primary non-hydrologic benefits of forest and grassland management projects in reducing fuel loads and sequestering carbon, respectively.

All four climate change scenarios representing the 2070-2099 timeframe indicate substantial decreases in springtime flows, with mean April flow decreasing by 20-61%. These changes exceed the potential flow improvements associated with the various enhancement scenarios (Figure 99). Forest management generates the largest increases in mean spring discharges (~9%), and the other individual scenarios only increase spring flows by <1% (Figure 99). As discussed above, while it may not be possible to significantly increase mean discharges during spring relative to the scale of expected decreases resulting from climate change, springtime pond releases and/or recycled water injection or infiltration do provide a means of creating a period of passable flow conditions during critical outmigration periods which may be essential given the scale of the projected decreases in springtime flows.
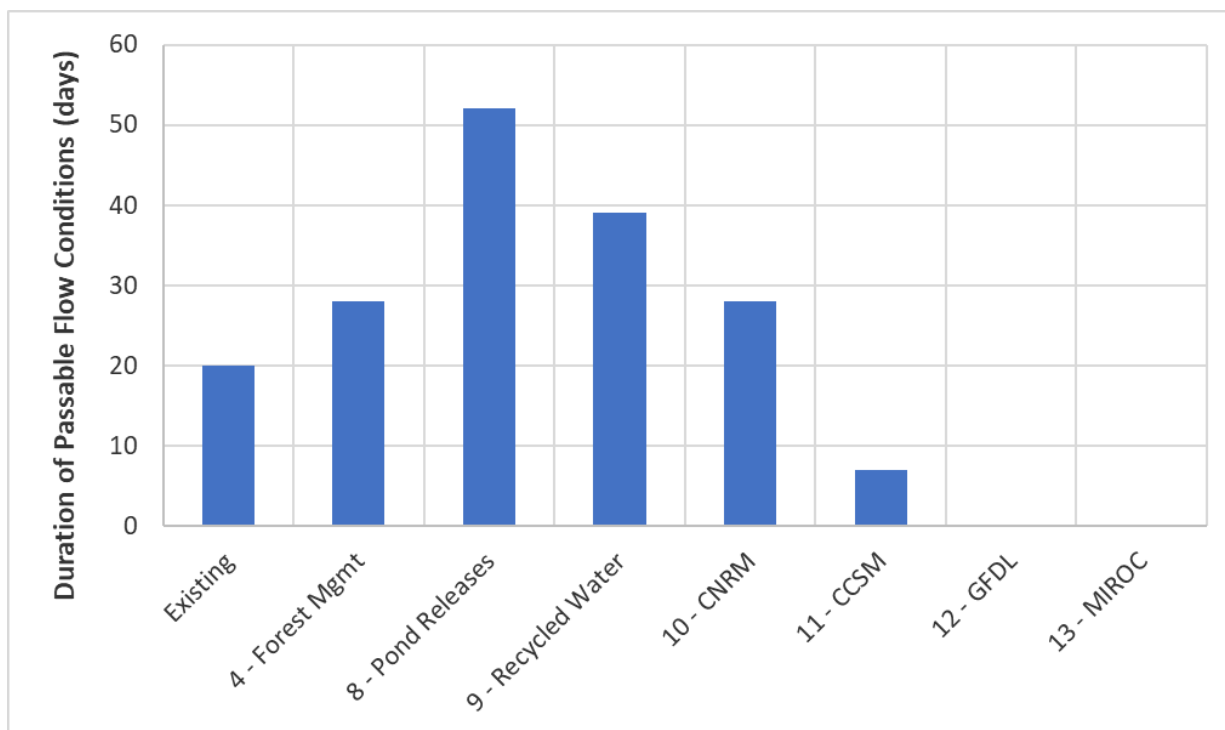
Figure 101: Duration of passable flow conditions in the lower alluvial reach of Mill Creek over the primary smolt outmigration period during dry water years for existing conditions, the three enhancement strategies that affected this metric, and the four climate futures.
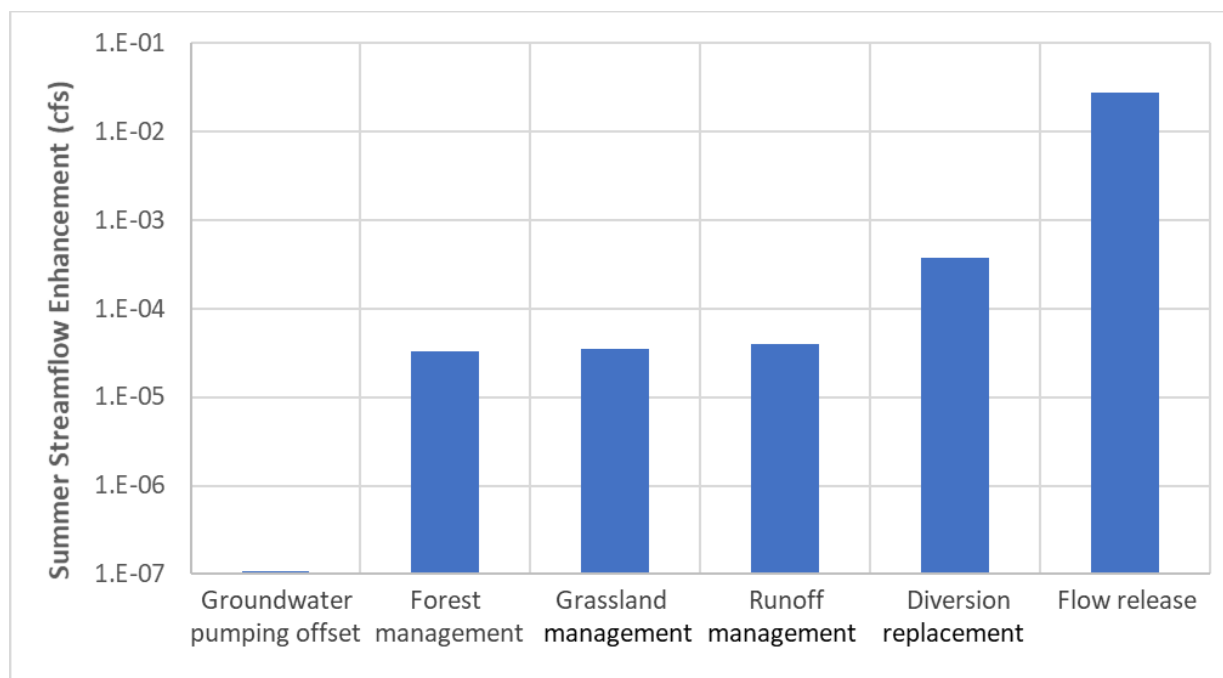
Figure 102: Summary of the simulated increase in mean summer streamflow for the six primary individual flow enhancement actions represented by the model scenarios normalized to a $25,000 project cost (note logarithmic y-axis).

Chapter 9 – Recommendations for Restoration and Management Actions

Habitat Enhancement

Based on streamflow and riffle depth simulations informed by previous habitat characterization and fisheries monitoring data, the 2.1-mile reach extending from the Palmer Creek confluence downstream to 0.9-miles above the Wallace Creek confluence (Mill 3) has the best overall habitat for salmonids (Figure 103). The adjacent 2.3-mile reach upstream (Mill 2) and 3.2-mile reach downstream (Mill 4) also provide significant habitat although conditions are somewhat more impaired relative to Mill 3. Conditions in all three reaches are far from optimal with insufficient summer streamflows and inconsistent spring outmigration flows being principal constraints on overall habitat quality. Mill 2 and 3 retain continuous surface flow throughout the summer even during drought conditions, whereas Mill 4 is prone to flow disconnection. Though flows remain connected in Mill 2, riffle depths fall to critically low levels in the summer and flows become impassable several weeks earlier during the spring outmigration season relative to Mill 3 and 4.

In-stream large wood (trees, logs, and accumulations of woody debris) is very limited in Mill Creek and installation of large wood on a broad scale at sites selected to encourage formation of pools and to provide velocity shelter and cover from predators in pools is recommended. Opportunities for development of off-channel habitat projects to enhance winter rearing habitat are also available in the identified priority reaches, and these types of projects are also recommended. We recommend that such habitat enhancement projects be focused in the 7.6-mile reach from 0.5-miles below Angel Creek downstream to the beginning of the alluvial reach (Mill 2, 3 & 4; Figure 103). The highest priority should be given to enhancing conditions within the 2.1-mile reach below Palmer Creek. An additional 2.4-miles of habitat exists in upper Mill Creek (Mill 1) and lower Palmer Creek, however habitat conditions in these reaches appear to be affected by low streamflow to a greater degree than the downstream reaches and are thus considered of lesser priority for habitat restoration.

Flow conditions in Felta Creek, Wallace Creek, and the alluvial reach of lower Mill Creek are generally unsuitable for coho summer rearing habitat and in the authors' opinion, habitat enhancement work focused on improving coho habitat is unlikely to be cost effective in these portions of the watershed. Given the consistent spawning and rearing activity in the lowest 0.4-miles of Felta Creek and the presence of some marginally suitable habitat farther upstream, a fish passage improvement project at the dam site that currently prevents/restricts upstream access should be implemented. If passage to upstream reaches is restored, the perennially flowing reaches of Felta Creek would become candidates for habitat enhancement work, however the reaches would be considered lower priority than the identified reaches of main-stem Mill Creek. Given that a single localized project at the dam site could dramatically improve access for salmonids attempting to spawn and rear in Felta Creek in most years, we believe remediation is warranted despite the marginal quality of the upstream habitat.

Flow Protection/Enhancement

Summer streamflow throughout Mill Creek is generated primarily by spring discharge and to a lesser extent by groundwater discharge along bedrock stream channels. These groundwater

discharges are distributed throughout the watershed with the lowest rates (1.2 in/yr) occurring in the Wallace Creek drainage and the highest rates occurring in the smaller subwatersheds draining to Mill Creek between the Palmer confluence and the alluvial reach (3.8 in/yr). Rates in the upper Mill, Palmer, and Felta Creek watersheds ranged from 2.1-2.8 in/yr. Given that Felta and Wallace Creeks do not contribute perennial baseflow to the highest priority reaches we recommend that the various flow protection and enhancement actions described below be focused in the watershed area upstream of and including the Palmer Creek drainage as well as in the smaller subwatersheds draining to Mill Creek between Palmer Creek and the alluvial reach where they are more likely to provide flow benefits in the identified high priority reaches (Figure 103).

Managed release of water stored in existing ponds was found to be by far the most effective individual strategy for enhancing both summer streamflows and spring outmigration flows (see Figure 102). The summer streamflow benefits of a cost-normalized flow release project were found to be more than 70 times greater than surface water diversion replacement projects and more than 700 times greater than forest management projects (the second and third most effective strategies). Examination of existing ponds revealed that there are only about six to ten ponds in the watershed with sufficient storage to provide meaningful releases and we recommend that flow release projects be developed for these ponds if possible. There are many challenges that must be overcome to implement these flow release projects including landowner cooperation, uncertainty regarding sustainability, water quality and invasive species, and permitting and water rights requirements.

There are existing ponds that could likely be enhanced for purposes of managed releases, and new ponds could be built specifically to store water for streamflow enhancement. Given the disproportionate effectiveness that pond releases appear to have as a mitigation strategy for effects of climate change on streamflow, this somewhat controversial idea should be given serious consideration. Water temperature and other aspects of water quality should be an important aspect of planning flow release projects since it is critical that flow releases do not increase temperatures above suitable levels. There are various strategies for mitigating elevated pond temperatures (e.g. bottom releases, surface shading, cooling systems) that likely would become considerations during planning and design of managed release projects. Most of the existing ponds with potential for releases are located downstream of the highest priority reach (Reach 3), however virtually all existing ponds locations provide potential enhancement benefits in the most flow-limited of the high priority reaches (Reach 4) where they could potentially eliminate periodic summer flow disconnection.

Smolt outmigration flow conditions appear to be a severe constraint on overall habitat suitability in the watershed during drought conditions that is equal to, or potentially greater than, constraints on habitat imposed by low summer rearing flows. Whether or not managed flow releases in the spring should be pursued in lieu of summer releases should be given careful consideration; for example, spring releases may have much lower potential to cause water temperature issues relative to summer releases. There is also a major benefit from optimizing the timing, duration, and rate of releases compared to much simpler constant rate releases,

particularly with respect to spring releases. Initiating spring releases just prior to development of impassable conditions in the most-limiting reach above Dry Creek coupled with a ramping release rate to extend the natural flow recession nearly doubles the duration of passable conditions compared to constant rates of release. Shorter duration pulsed outmigration flows may provide even greater benefits than continuous ramped releases by extending the overall duration of passable conditions for outmigrating smolts. This strategy in particular requires careful adaptive management because the required release rates increase later in the season as background streamflow rates decline and the groundwater table in the lower alluvial aquifer falls farther below the stream bed. The sensitivity of release effectiveness to release timing and rates indicates that an adaptive management approach aided by real-time monitoring and informed by hydraulic analyses is likely required to ensure that maximal benefits to salmonids are provided through optimized use of the available stored water.

Injection or infiltration of recycled water from the City of Healdsburg's water treatment plant to the shallow aquifer downstream of the confluence of Felta and Mill Creeks appears to be a viable alternative and/or supplement to releasing water from ponds to enhance spring outmigration flows. Injection/infiltration sites lower in the alluvial reach would likely be ineffective owing to the greater depth of the alluvial aquifer and regional controls on water table elevations. Injection in the upstream portions of the alluvial reach beginning before development of impassable flow conditions near the Dry Creek confluence would require an approximately 1,200 ft extension of the existing recycled water pipeline and construction of injection wells or an infiltration basin and associated infrastructure. While permitting and implementing this strategy may be complicated and expensive, it represents the second most effective strategy for enhancing smolt outmigration flows after pond releases and is the only strategy other than forest management with the potential to significantly change outmigration conditions. We recommend that a feasibility study be conducted to assist in moving the recycled water release strategy towards design and implementation.

Our findings suggest that direct stream and spring diversions may have a significant impact on summer streamflow conditions with sustained impacts on the order of an 8% reduction in mean summer streamflow. More significantly, instantaneous diversion demands potentially represent more than 100% of the total flow (if coincident demand timing is assumed), and when all direct and spring diversions were turned off, flow disconnection was almost completely eliminated in Reach 4. Diversions do not appear to have a significant effect on the dry conditions in the alluvial reach nor do they appear to significantly affect the timing of impassable conditions near the outlet during the spring smolt outmigration season. We recommend that efforts to replace dry season direct and spring diversions with winter diversion and storage or groundwater wells be pursued, particularly in the areas of the watershed up-gradient from the high priority reaches. Coordination of dry season diversion timing between diverters also appears to be a viable means of mitigating diversion impacts. In contrast to diversions, groundwater pumping appears to have virtually no effect on streamflows given the very low demands relative to recharge in the bedrock portions of the watershed, and the regional hydrogeologic factors that drive losing and disconnected streamflow conditions in the lower alluvial reach.

These findings suggest that replacing direct stream and spring diversions with storage and/or groundwater pumping is a viable approach for enhancing streamflow conditions but that offsetting groundwater pumping with storage or shifting the timing of pumping from summer to winter is unlikely to lead to appreciable improvements in flow conditions. Of the six general strategies considered, replacement of direct diversions is the second most-effective strategy after pond releases, whereas offsetting groundwater pumping was found to be the least effective strategy (see Figure 102). It is important to note that the total pumping stress in the watershed is relatively small (~3% of mean annual infiltration recharge) and that the limited degree of streamflow depletion under existing conditions should not be understood to suggest that significant streamflow depletion could not occur were the total volume of pumping to increase substantially in the future. Although groundwater simulations are believed to be broadly representative of typical conditions, the model uses a simplified representation of subsurface bedrock conditions and local variations in degree of fracturing and aquifer connectivity with streams may create local situations where groundwater pumping impacts are larger than those simulated here.

On a cost-normalized basis, forest, grassland, and runoff management all produced relatively small summer streamflow benefits of a similar magnitude, though the overall potential for flow enhancement associated with forest management is much larger given that about 84% of the watershed is forested. Forest management is also the only strategy (other than direct pond or recycled water flow augmentation) that significantly shifts the timing of the spring flow recession forward with expected benefits for smolt outmigration conditions in addition to the benefits for juvenile rearing flows. The forest management scenario is, however, highly simplified and specific enhancement benefits associated with various management strategies and intensities remains uncertain but informed to some degree by prior and ongoing research. The various land management strategies also have important secondary hydrologic benefits in addition to enhancing streamflows in that they reduce seasonal vegetation moisture stress which may reduce fire risk. Specifically, forest management reduces actual evapotranspiration on treated lands by about 5% and runoff management decreases climatic water deficits (CWD) in infiltration areas; grassland management only resulted in minor decreases in CWD. These benefits are in addition to the primary non-hydrologic benefits of these types of projects for reducing fuel loads (forest management) and sequestering carbon (grassland management). There are also potential negative consequences of extensive forest management in terms of ongoing costs, potential habitat loss for avian and terrestrial species, or even unintended increases in ET which must be considered.

We recommend that a planning study be conducted for the portions of the watershed contributing baseflow to the high priority reaches. Given that the streamflow benefits of these strategies are about an order of magnitude less than those of diversion replacement and nearly three orders of magnitude less than those of pond releases, the various types of management projects are considered a lower priority than pond release or diversion replacement projects. That said, the long-term maintenance of streamflow under future climate conditions may require all the flow enhancement strategies to be implemented and it is important to gain near-term

experience with these management strategies and to attempt to monitor their effectiveness. Potential hydrologic benefits (or unintended consequences) of forest fuel management intended to reduce fire hazard should be investigated.

The optimal design and effectiveness of runoff management projects is highly site-specific and it is recommended that projects be focused on parcels with significant impervious area that are currently well-connected to surface water features, have relatively high soil infiltration rates, and sufficient space and site conditions to allow for larger-scale infiltration features. Gravel-filled infiltration basins may be required in some cases to prevent ponding of stagnant waters for more than 72-hrs per Sonoma County vector control requirements. Native soil basins will likely work in some situations, and where space is limited basins can be combined or replaced with bioswales and/or features designed to distribute water evenly across the landscape.

In summary, although runoff, forest, and grassland management may not result directly in substantial streamflow improvement, these efforts have multiple benefits and are likely important strategies for managing fire risk and mitigating climate change impacts as discussed in more detail below.

Climate Change Adaptation

Climate change is expected to cause large decreases in springtime flows, with some scenarios indicating much more severe drought conditions with near zero runoff or recharge. Summer baseflows are also predicted to decrease, with some scenarios indicating only minimal changes and other predicting larger declines. The decline in flows during spring is expected to have significant effects on salmonids, particularly outmigrating smolts, with some of the climate scenarios predicting that in some years flows will fall below passage thresholds nearly continuously from mid-February through October. The most feasible means to at least partially mitigate this dire threat to salmonids appears to be the implementation of springtime pond and/or recycled water releases. While it may not be possible to significantly improve conditions throughout the smolt outmigration period, flow releases could extend or generate periods of passable flow conditions timed to coincide with expected peak smolt outmigration (see Figures 85-87).

We recommend that flow release projects be developed and adaptively managed to provide a combination of larger pulses of streamflow during outmigration and enhanced streamflow during summer baseflow depending on conditions in a given year. We also recommended that a feasibility study be performed to consider what permits and studies would be needed to move the recycled water release concept forward towards implementation. The availability of a steady supply of recycled water is an extremely valuable resource that will likely be allocated for consumptive uses in the coming years if it is not dedicated to flow enhancement. It appears that many of the smaller ponds will likely continue to fill even during more extreme future drought conditions that may occur with a changing climate, however the larger ponds will likely not always reliably fill particularly during multi-year drought periods and some ponds may prove unsuitable for releases due to poor water quality. In contrast, the recycled water would be expected to be more reliably available (though not immune from reductions due to drought

conservation) and be of consistent water quality making it a particularly valuable asset for mitigating the impacts of climate change on streamflow conditions.

The runoff, forest, and grassland management strategies influence the quantity of streamflow from springs and baseflow which in general is relatively cold, therefore these approaches may be expected to assist in mitigating elevated water temperatures whereas the more effective strategies (releases and diversion replacement) would not be expected to provide temperature benefits. These strategies also help reduce vegetation moisture stress by increasing the quantity of water available to plants in the case of runoff and grassland management or decreasing water demand from the landscape for the case of forest management. This reduced moisture stress may be an important benefit for wildfire hazard reduction and the increase in wildfire hazard expected as a result of climate change. Among the three land management strategies, large-scale forest management is the only strategy that appears capable of shifting the timing of the spring flow recession with associated improvements to the conditions faced by outmigrating smolts.

In summary, implementation of runoff, forest, and grassland management projects are expected to help build resiliency to climate change by providing multiple benefits beyond potential streamflow improvement and spring and summer pond and/or recycled water releases provide a means of adaptively managing flow conditions for salmonids in the face of a changing climate.
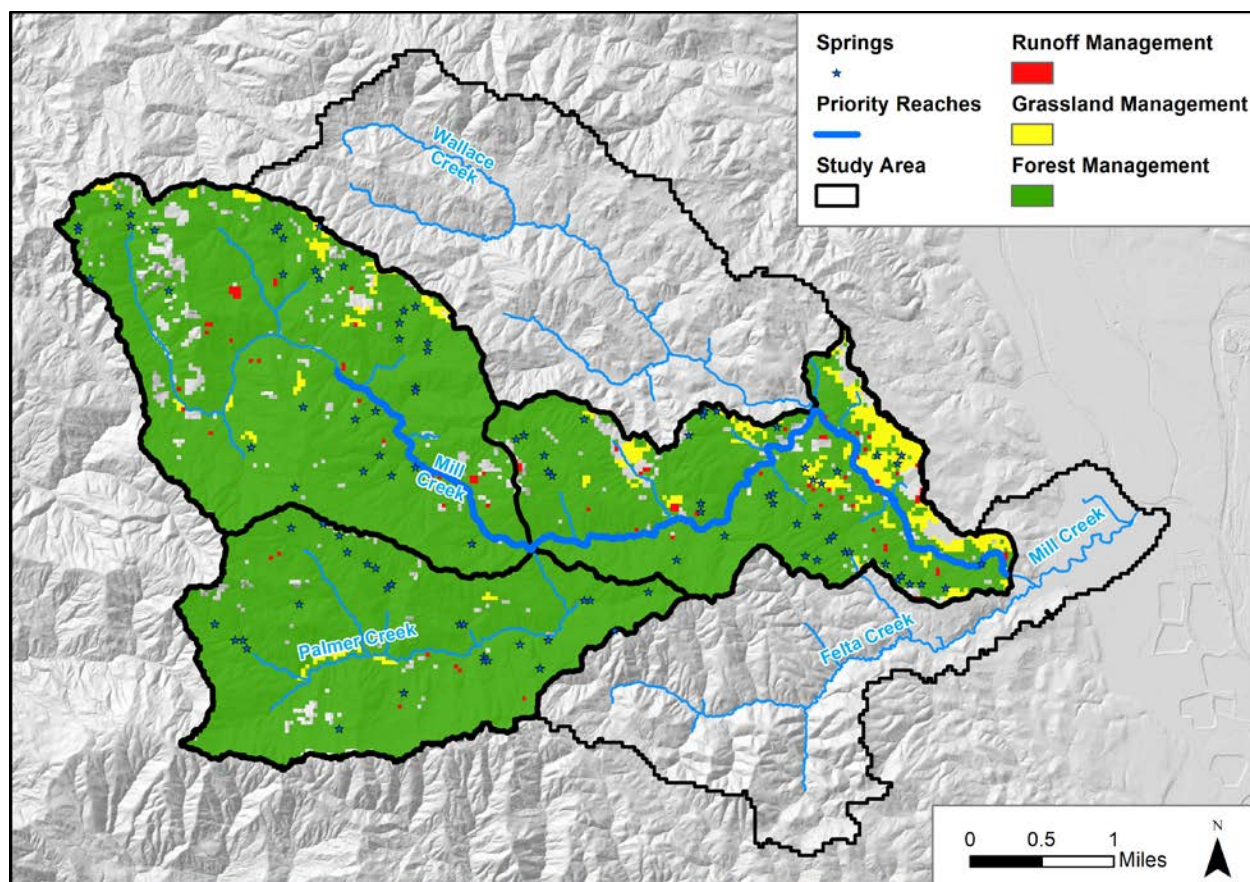
Figure 103: Locations of the identified high priority reaches for habitat enhancement projects and high priority watershed areas for flow enhancement projects.

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