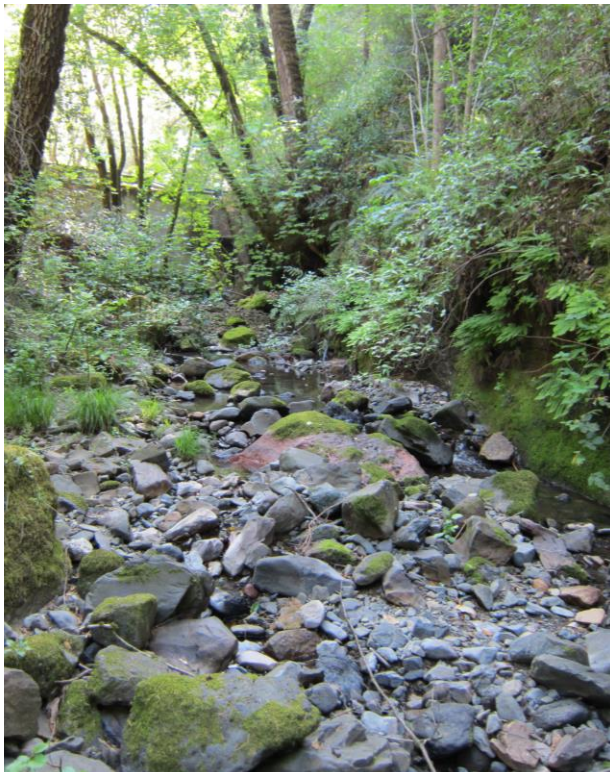

Report on the Hydrologic Characteristics of Mark West Creek

November 14, 2014 (updated January 28, 2015)

ABSTRACT

Mark West Creek is an important stream for the recovery of salmon in the Russian River watershed. One of the principal challenges to recovering these fishes is maintaining sufficient flowing water through the summer dry season, when human water demands can result in reduced flow during a time when it is naturally very low. Analyses of rainfall dynamics, streamflow dynamics, and human development indicate that there is sufficient water on an annual scale to meet existing human and environmental water needs; but diverting water from aquifers, springs, and streams has likely contributed to less water in upper portions of Mark West Creek than would be present naturally. Agricultural needs and residential needs are similar in magnitude, and if water is stored in winter to meet these needs rather than obtained during the dry season, these management changes could have a meaningful benefit on streamflow during the dry season.

Center for Ecosystem Management and Restoration

Cover photo: Mark West Creek downstream of Neal Creek, Summer 2013.

Contents

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Center for Ecosystem Management and Restoration

November 14, 2014

1. Introduction

Mark West Creek is one of the largest tributaries to the Russian River, draining a catchment of 51 square miles before its confluence with the Laguna de Santa Rosa southwest of Windsor. NOAA Fisheries regards the Mark West Creek watershed as having high potential for supporting anadromous salmonids, ranking it as critical habitat for steelhead and coho salmon, and assigning it as a Phase 1 stream for coho recovery in its CCC ESU Coho Salmon Recovery Plan (Figure 1). Anecdotal reports from stakeholders in the Mark West Creek watershed and fish-monitoring groups also indicate that Mark West Creek and its tributaries currently support salmonids (mostly steelhead trout), though in lower numbers than were present in the recent past.

Like many parts of rural Sonoma County, the Mark West Creek watershed has undergone land use changes that are believed to alter the dynamics of the hydrologic regime (NMFS 2012). In recent decades, vineyards have expanded to join the many rural residences in the Mark West Creek watershed; concerns have arisen about proposed industrial facilities (namely, wineries) as well. Depending on how water is obtained, each of these human developments may alter the flow regime: data from across the county indicate that a number of water uses, ranging from agricultural to recreational to domestic, all have potential to influence streamflow during the summer dry season, in part because streamflow is naturally very low. Concerns have also arisen that water storage in winter could reduce winter flows during salmon migration periods, though studies have indicated that these impacts are variable through the Russian River watershed (Deitch et al. 2013).

This report describes the hydrologic characteristics and factors that influence the water balance of the upper Mark West Creek watershed (Figure 2). Much of this report focuses specifically on the area upstream of the confluence of Humbug Creek with Mark West Creek (near the west end

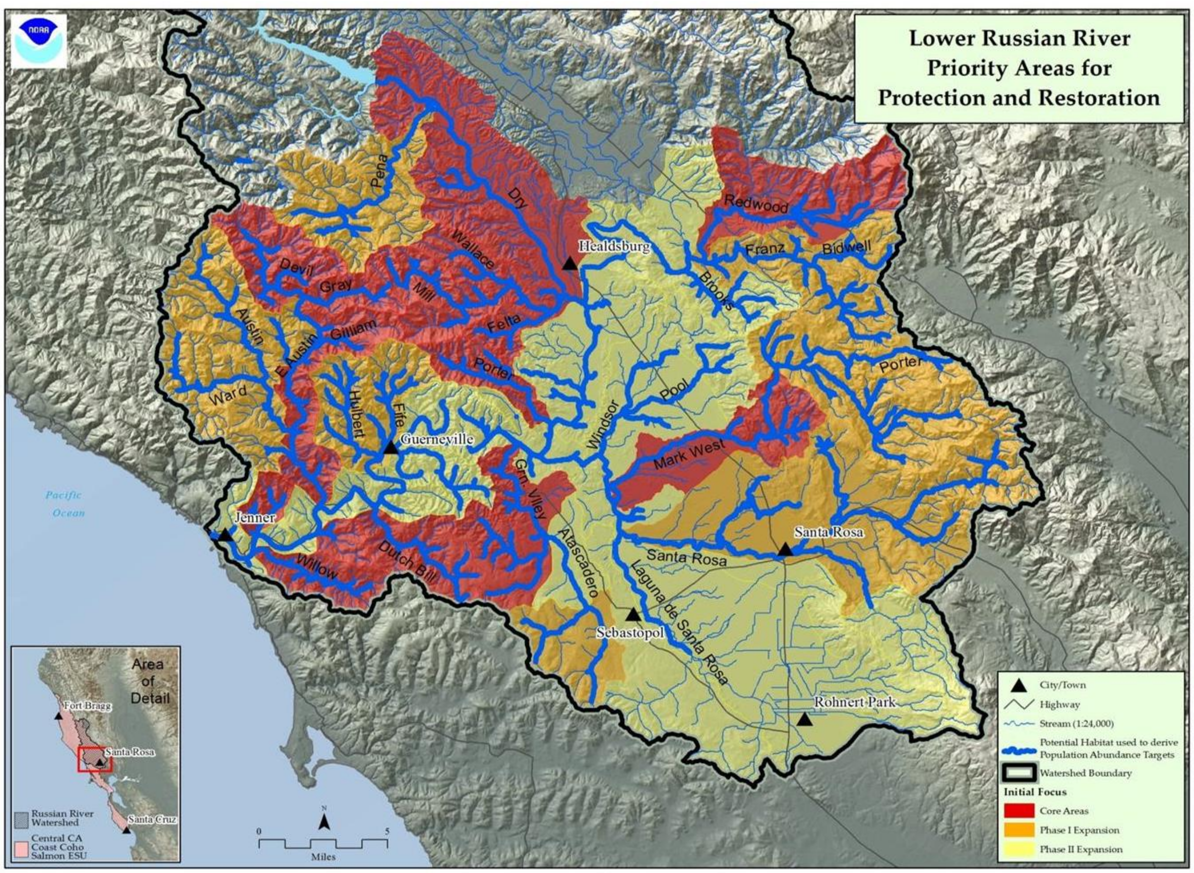


Figure 1. Areas in the lower Russian River watershed in the NMFS CCC Coho Recovery Plan, by priority (NMFS 2012).

of St. Helena Road), referred to henceforth as *Upper Mark West Creek*. In particular, this report focuses on characteristics of land cover and human development, rainfall and runoff, geology, and channel geomorphology as they pertain to the hydrology of the upper Mark West Creek watershed. Based on the information presented, we conclude the report by summarizing management tools that could be utilized to increase summer base flow in Mark West Creek.

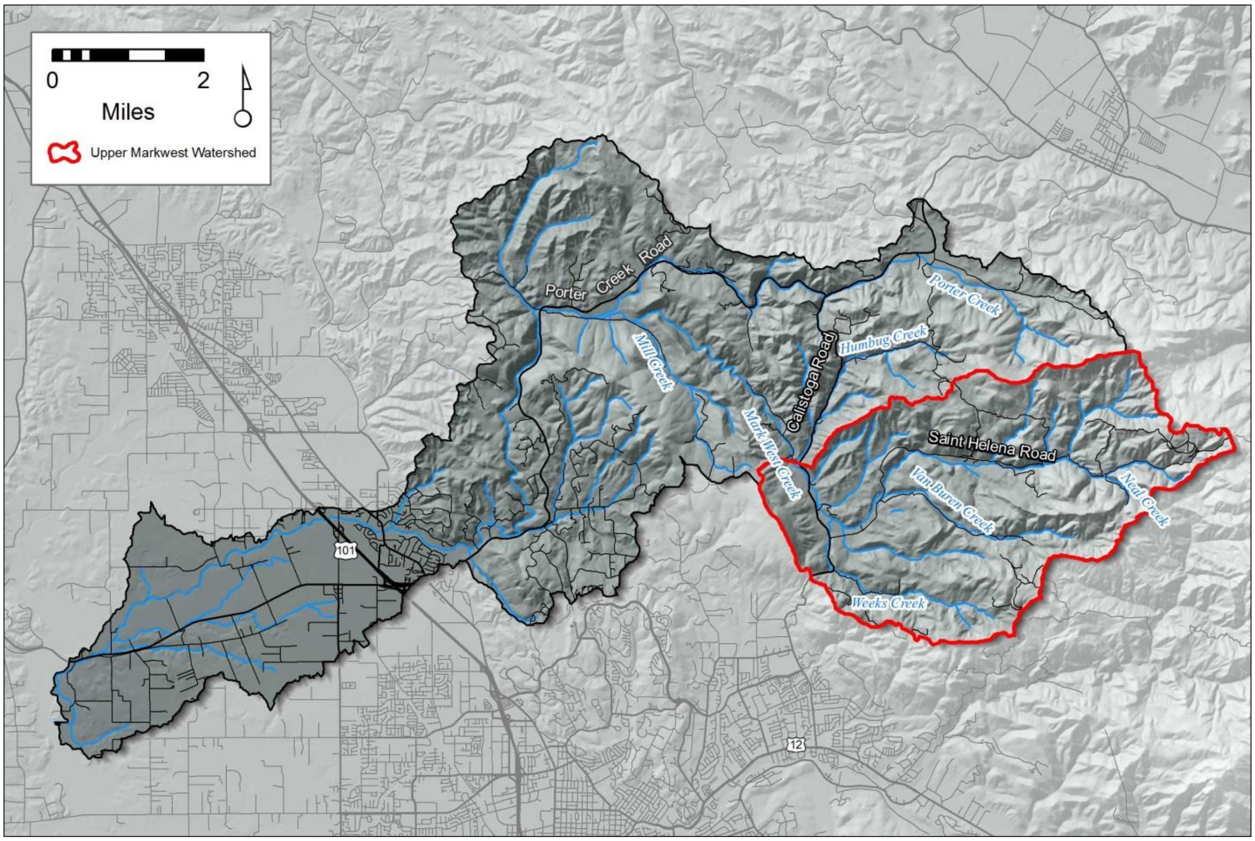


Figure 2. Mark West Creek watershed, with the upper Mark West watershed used in this study identified.

2. Rainfall

Rainfall is the principal driver of hydrologic processes in coastal California. Virtually all precipitation occurs as rainfall, and streams generally respond quickly to rainfall with elevated streamflow. When rainfall ends, streamflow gradually recedes until the following rainfall event (which, depending on the time of year, may occur several months later). In addition, streamflow in years with higher-than-average rainfall have appreciably different streamflow dynamics than in years with less-than-average rainfall (Deitch and Kondolf, 2012). These streamflow dynamics define instream conditions for anadromous salmonids through the year: fishes such as steelhead trout and coho salmon migrate upstream to spawn during and following high-flow pulses, and juvenile fishes rear in freshwater streams for at least one year before migrating to the ocean as smolts (coho spend one year as juveniles in freshwater streams, while steelhead may spend up to three). The purpose of this section is to quantify the amount of rain that falls on the Mark West Creek watershed, based on standard data sources; describe differences between these standard sources and measured data within the watershed; and estimate the differences between rainfall in a "normal-type" versus "dry-type" year.

Annual-scale rainfall

On an annual scale, the Mark West Creek watershed receives a considerable amount of rainfall. Reports on the Mark West Creek watershed frequently cite an average annual precipitation of 50 inches of rain in the upper portion of the watershed (e.g., ESA 2012, Todd Engineers 2006). Our analysis of spatial rainfall data based on the PRISM data set (Parameter-elevation Regressions on Independent Slopes Model, developed by researchers at Oregon State University, which is frequently cited as the standard for rainfall estimation in California) provides a slightly lower estimate of 42.5 inches in an average year for the entire watershed, including the lower portion in the Santa Rosa Plain (Figure 3). Orography influences the spatial variability of rainfall: whereas PRISM estimates the low-relief downstream portion of the watershed receives 35 inches in an average year, the upper high-relief portion receives more than 50 inches on average. This underestimates local rainfall measurements taken at the Mark West headwaters: local measurements indicate an average of approximately 65 inches through the year, recorded from 1965-2011 (Doerksen, unpublished data).

Based on the PRISM average annual rainfall data set (which, as described above, provides a low estimate of rainfall in the headwaters), 42.5 inches of rainfall over the 51 square mile watershed. This corresponds to 117,000 acre-ft, or 38.2 billion gallons, of water as rainfall to the Mark West watershed in an average year (Table 1). As discussed above, upper Mark West Creek is the wettest portion of the Mark West watershed: PRISM estimates that it receives approximately

46.4 inches of rain over its 14 square mile catchment (34,500 acre-ft, or 11.2 billion gallons) in an average year. Though this is likely an underestimate based on locally collected data described above, the PRISM rainfall data provide a conservative estimate from a water resource perspective.

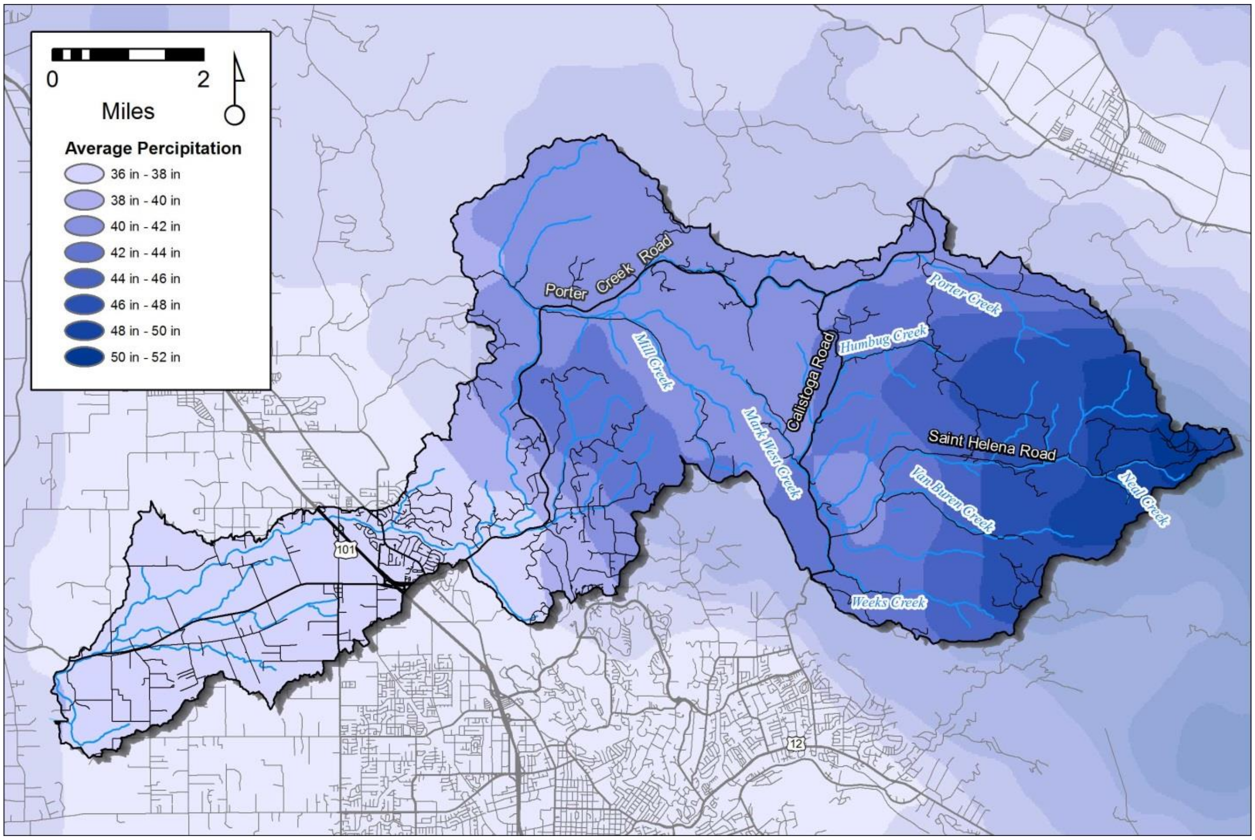


Figure 3. Average annual rainfall over the Mark West Creek watershed (PRISM data).

Table 1. Average and dry-year rainfall in the Mark West Creek watershed and upper Mark West watershed, in inches, acre-feet, and gallons.

		Average annual rainfall			Estimated dry-year rainfall		
Watershed	**Catchment area, mi^2**	**Rainfall, inches**	**Total precip, acre-ft**	**Total, gallons**	**Rainfall, inches**	**Total precip, acre-ft**	**Total, gallons**
Mark West Watershed	51.70	42.5	117,000	38,200,000,000	21.2	58,600	19,100,000,000
Upper Wark West watershed	14.0	46.3	34,500	11,300,000,000	23.1	17,300	5,600,000,000

Rainfall in coastal California can be highly variable from one year to the next; thus, multi-annual variability must be considered in any water resources analysis intended to evaluate water availability for human or ecological needs. Long-term data measured at nearby Healdsburg indicate that the rainfall in a very dry year is approximately half of the rainfall in an average year: rainfall in water year 1972, exceeded by 95% of 61 years from 1951 to 2011, was 21.4 inches (half of the average annual rainfall [42.9 inches] recorded at Healdsburg over the 61 year period of record; Figure 4). In a very wet year (e.g., 1995, exceeded by 5% of 61 years), rainfall is approximately two-thirds more than average (71 inches). These comparisons provide useful rules-of-thumb for what might be expected at the opposite ends of extreme rainfall years.

Evaluations that consider dry-year conditions are especially important because they depict water availability during times of scarcity. If rainfall in a very dry year is approximately half of the average, then water managers need to consider the implications of having half the rainfall that typically occurs for facilities such as water storage and water delivery systems. If a very dry year were to have half the rainfall of an average year, the Mark West watershed would receive approximately 58,600 acre-ft (19.1 billion gallons) of water as rainfall over the entire watershed in a very dry year (Table 1, above, with 17,300 acre-ft of rainfall in the upper Mark West watershed in a dry year).

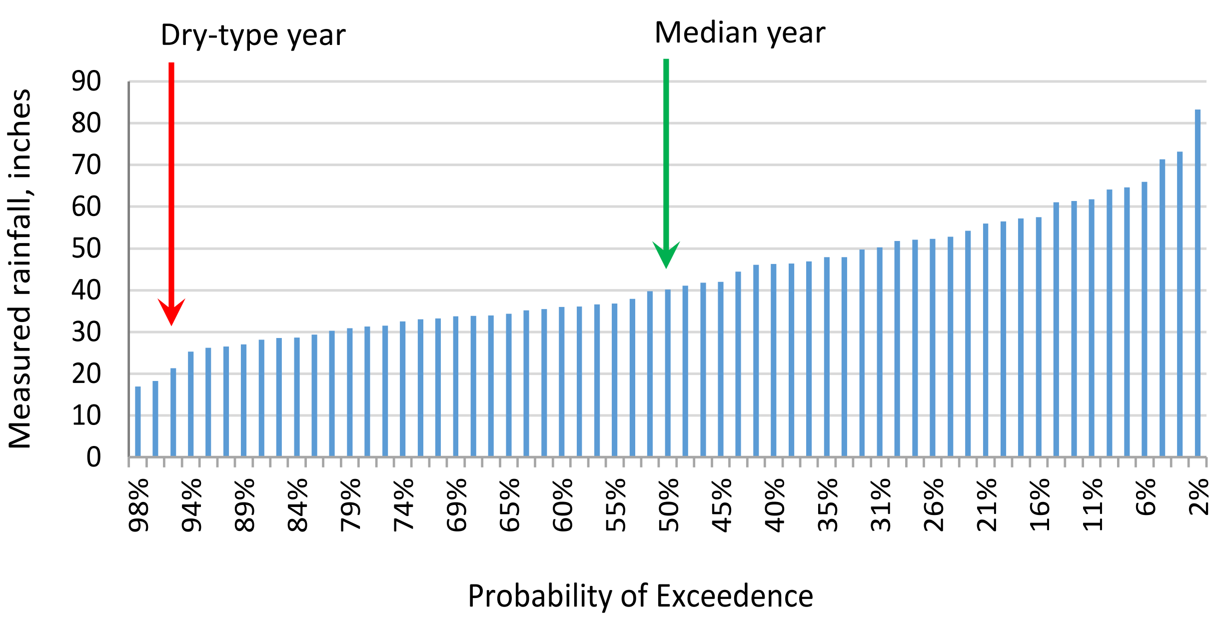


Figure 4. Probability of exceedence for annual rainfall recorded at Healdsburg, CA, 1951-2011 (by water year).

Seasonal variations in rainfall

Though dry-year and wet-year rainfall analyses in the Mark West watershed provide important insights into water resources that reach the watershed over the entire year, annual-scale analyses neglect important characteristics about the timing of water that influence the capacity for water to meet human and ecosystem needs within the year. Like most of coastal California, climate patterns in eastern Sonoma County are characteristically Mediterranean, resulting in a very wet season and a very dry season. The 61-year data set of rainfall at nearby Healdsburg, CA used in the above analysis also show that 90 percent of the average annual rainfall occurs during the wet half of the year November through April; less than 2 percent of the average annual rainfall occurs from June through August (Figure 5). While the total amount of rainfall may be variable from one year to the next, the seasonality of precipitation is consistent among all years (Deitch and Kondolf, 2015).

This seasonal variation has profound implications for people living and working in the Mark West watershed and across coastal California. Rainfall will not provide water to meet agricultural, industrial, or domestic needs during the summer dry season, so water is instead typically obtained through sources such as wells and springs. If wells and springs provide an uncertain or unsteady supply of water, it may be advantageous to store water in reservoirs or water tanks in winter for use during summer. This seasonality also has implications for stream hydrology (further described below): streamflow begins to recede at the end of the rainy season toward intermittence through the dry season until rainfall occurs again the following water year.

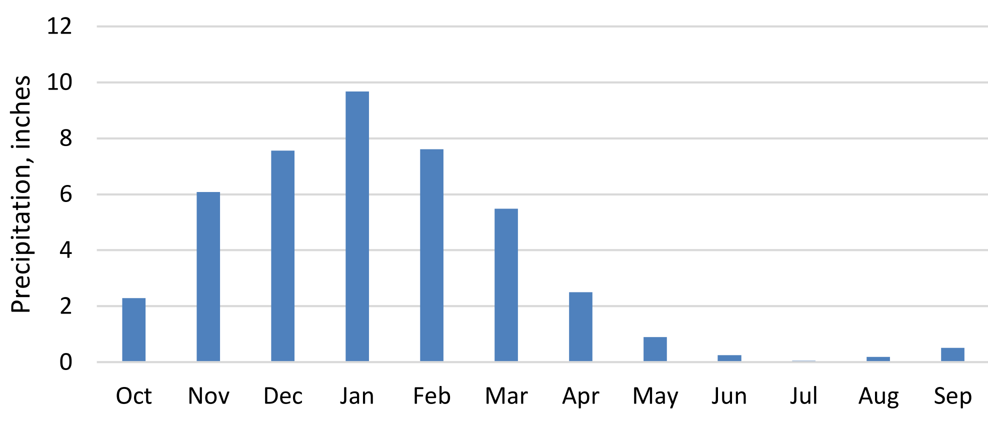


Figure 5. Average monthly rainfall recorded at Healdsburg, CA.

3. Land cover and land use

The term "land cover" classifies the features found on the surface of the earth. It usually focuses on vegetation cover, including types of forest (deciduous, riparian, evergreen, mixed), or other vegetation (*e.g.*, shrub/scrub, grassland), but also may include features such as barren land (*e.g.*, exposed rock), and various types of human development (classified as either developed or cultivated crops). Variations in land cover help to understand the extent of human footprint in a watershed, as well as how features such as geology, soil type, and climate influence the types of plants that grow in an area. In addition, land cover can influence watershed hydrology (described further in subsequent sections). In this section, we use existing land cover data sets to explore the spatial distribution of the human footprint in the Mark West watershed, and develop an estimate of human water need in the upper portion of the study area.

Land Cover by Percentage

Like the rest of the Russian River watershed, the land cover of the Mark West watershed is diverse. We used the 2011 National Land Cover Database (Jin et al. 2011, a US Geological Survey product available through the Multi-Resolution Land Characteristics Consortium, mrlc.gov) to identify the variations in land cover in the Mark West Creek watershed; we further refined the cultivated crop data to reflect an agricultural crop data set prepared by researchers at UC Berkeley and the University of California Cooperative Extension in 2004 and updated by CEMAR in 2014, to more accurately reflect the actual agricultural coverage in the watershed (this was necessary because much of the agricultural coverage, especially in the upper portions of the watershed, were not included in the Land Cover Database).

As summarized below (Table 2), the majority of the Mark West Creek watershed is covered in either forest (43.8 percent) or shrub/scrub (22.2%). The additional 33% of land cover includes grassland/pasture (11.3%), cultivated crops (12.6%), and developed (9.8%, including urban and open space such as parks). Most of the Upper Mark West watershed is evergreen forest, with some portions as grassland, mixed forest, shrub/scrub, developed, and cultivated crop (Figure 6B).

Table 2. Percentage of the Mark West Creek watershed by land cover type (based on 2011 National Land Cover Database and CEMAR agricultural crop GIS data).

	Evergreen	Deciduous/ Mixed forest	Grass-land	Shrub/ scrub	Developed	Cultivated crop	Reservoirs	Barren land
Lower (Santa Rosa Plain, 5,700 ac)	0.03	1.2	11.5	1.1	22.6	63.5	0.13	0.06
Middle (18,460 acres)	32.8	16.7	12.4	27.2	8.9	1.9	0.06	0.13
Upper (8.960 acres)	51.6	7.9	9.6	25.5	3.5	1.8	0.02	0.04
Total (33,120 ac)	**32.3**	**11.6**	**11.3**	**22.2**	**9.8**	**12.6**	**0.06**	**0.10**

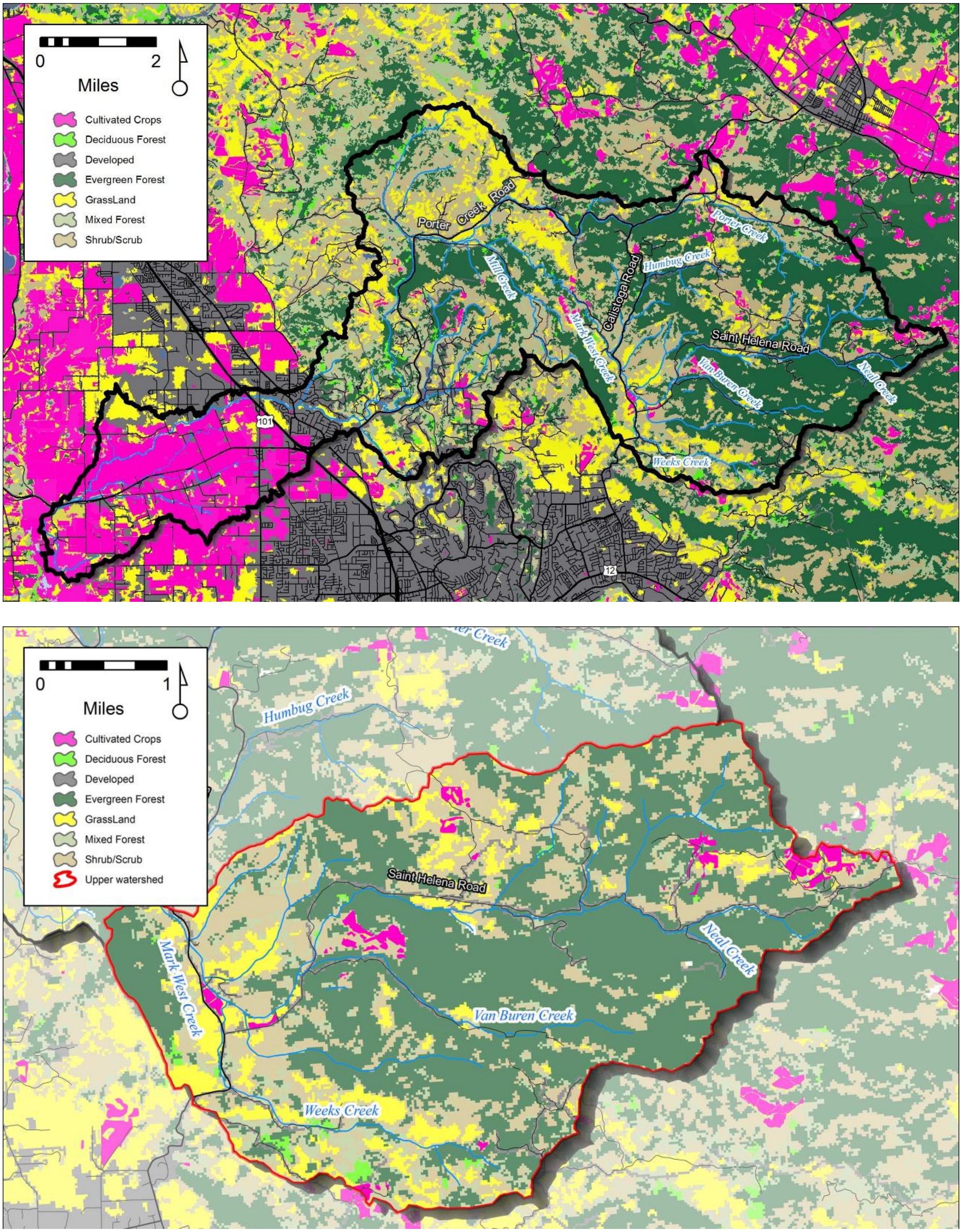


Figure 6A-B. Land cover in the Mark West Creek watershed and surrounding area (top), and land cover in Upper Mark West watershed (bottom).

Ninety-seven percent of cultivated crop (i.e., vineyard) coverage is in the lower region of the Mark West watershed (the Santa Rosa Plain), but cultivated crops are found elsewhere as well: based on compiled aerial imagery by CEMAR (updated in 2014), 3,620 acres of vineyard are located in the Santa Rosa Plain (lower Mark West Creek), 338 acres of vineyard are located between the Santa Rosa Plain and the confluence with Humbug Creek, and 158 acres of vineyard are located upstream of the Humbug Creek confluence (where vineyards straddle drainage divides, this only includes portions of vineyards that are within the Mark West watershed).

In some parts of the Mark West watershed, agricultural and domestic water needs are met through storing water in small reservoirs. Overall, reservoirs cover approximately 113 acres of the Mark West Creek watershed (0.34%). In the lower Mark West watershed, reservoirs cover approximately 38 acres; in middle Mark West, approximately 61 acres; and in upper Mark West, approximately 14 acres. Based on a relationship correlating surface area storage volume described by Deitch *et al.* (2013), this corresponds to approximately 180 acre-ft stored in the upper Mark West watershed in reservoirs (though this is likely an overestimate of stored water because the relationship used is more accurate for larger reservoirs than smaller ones).

Other development in upper Mark West Creek

In addition to reservoirs and agricultural development, many buildings have been constructed in the Mark West watershed. These include residences, residential storage structures, agricultural structures (*e.g.*, barns), water tanks, and commercial/industrial facilities (*e.g.*, supermarkets, wineries). Sonoma County has made available a GIS shapefile of building structures throughout the county, identifying the footprint of each structure as a polygon, but did not distinguish among types of structure. After reviewing the data set, we determined that the shapefile did not capture all of the structures in the watershed. For this project, we created a new shapefile of building structures in the upper Mark West Creek watershed (identified as points, rather than polygons), based on aerial imagery in an ArcMap GIS project. We then closely reviewed each structure to identify each as a residence, garage/storage building, industrial/commercial building, agricultural structure, water tank, or unknown/other structure (*e.g.*, Figure 8).

In the upper Mark West watershed (the portion of the watershed above the Humbug Creek confluence), we identified 222 houses among 457 structures (Figure 9).

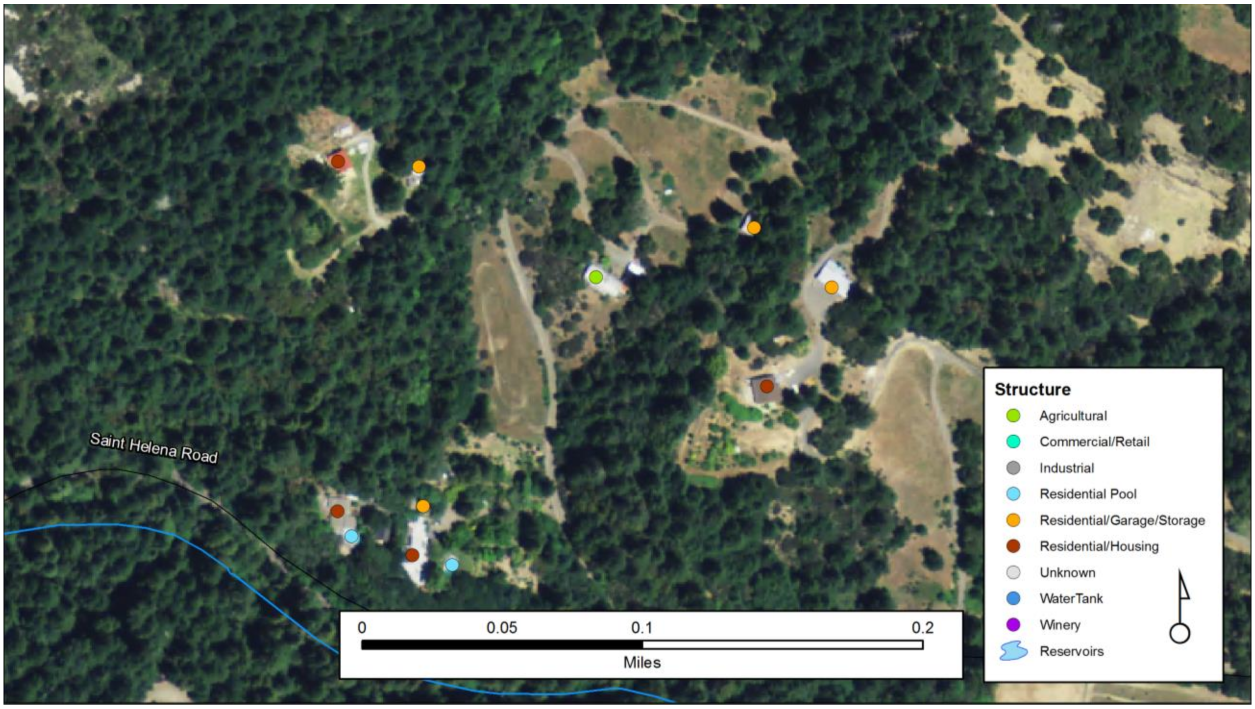


Figure 8. Example of structures identified on aerial photographs near Mark West Creek.

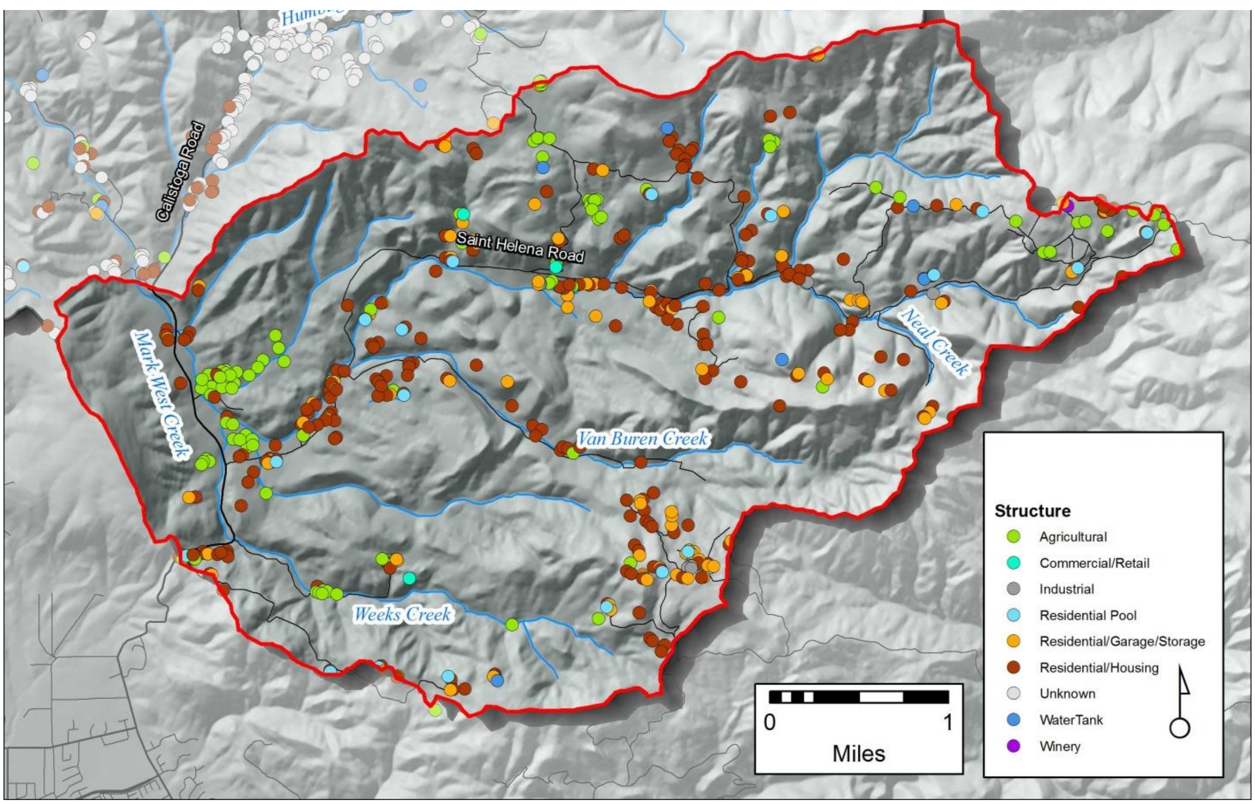


Figure 9. Building structures by type in the upper Mark West Creek watershed.

Details about building structures can provide insights into impacts of hydromodification due to accelerated runoff (off of impervious rooftops), as well as opportunities for rainwater catchment and impacts that rainwater catchment could cause on winter streamflow. We estimated the total area footprint of building structures by first calculating the average area of buildings in the Mark West watershed based on the Sonoma County buildings polygon shapefile described above (representing approximately half the buildings in the watershed), which was 1,660 square feet (Figure 10). We then multiplied the average footprint area by the total number of structures in the study area. Based on this method, the total footprint of buildings in the upper Mark West watershed is approximately 2.94 acres (128,100 square feet, or 0.033% of the land area).

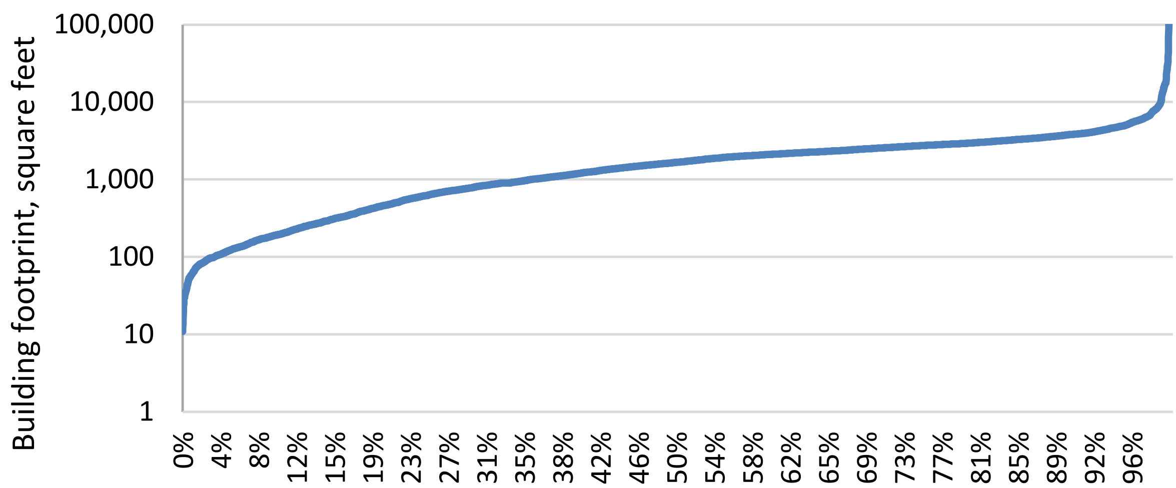


Figure 10. Probability distribution of building footprint in the Mark West Creek watershed (based on a total of 5,821 buildings with known surface area).

For this analysis, we did not digitize additional agricultural (namely, marijuana) development. A few of the buildings identified in the upper Mark West watershed were clearly greenhouses; they were classified as agricultural structures.

Characterizing Human Water Needs

As described above, a goal of this project is to develop quantitative comparisons of human development and associated water uses to characteristics of watershed hydrology. In the Mark West Creek watershed irrigated agriculture and rural residences are the two most evident forms of water use. In addition, wineries and other commercial industries within the region contribute to the human water need. Irrigated agriculture can have varying water needs depending on the type of crop grown. Vineyards are the most prevalent agricultural cover type in watershed, and depending on location and local conditions, may require water for both irrigation and frost protection. Domestic water needs typically include requirements for landscaping and household use. Wineries require water for barrel and equipment cleaning, and for dish washing in tasting rooms.

Within the Upper Mark West region, we compiled agricultural and building structure datasets derived using aerial imagery to construct a model of the human development footprint in the watershed (Figure 11). We used these data to estimate dry-season water need by each water use type through the course of the year.

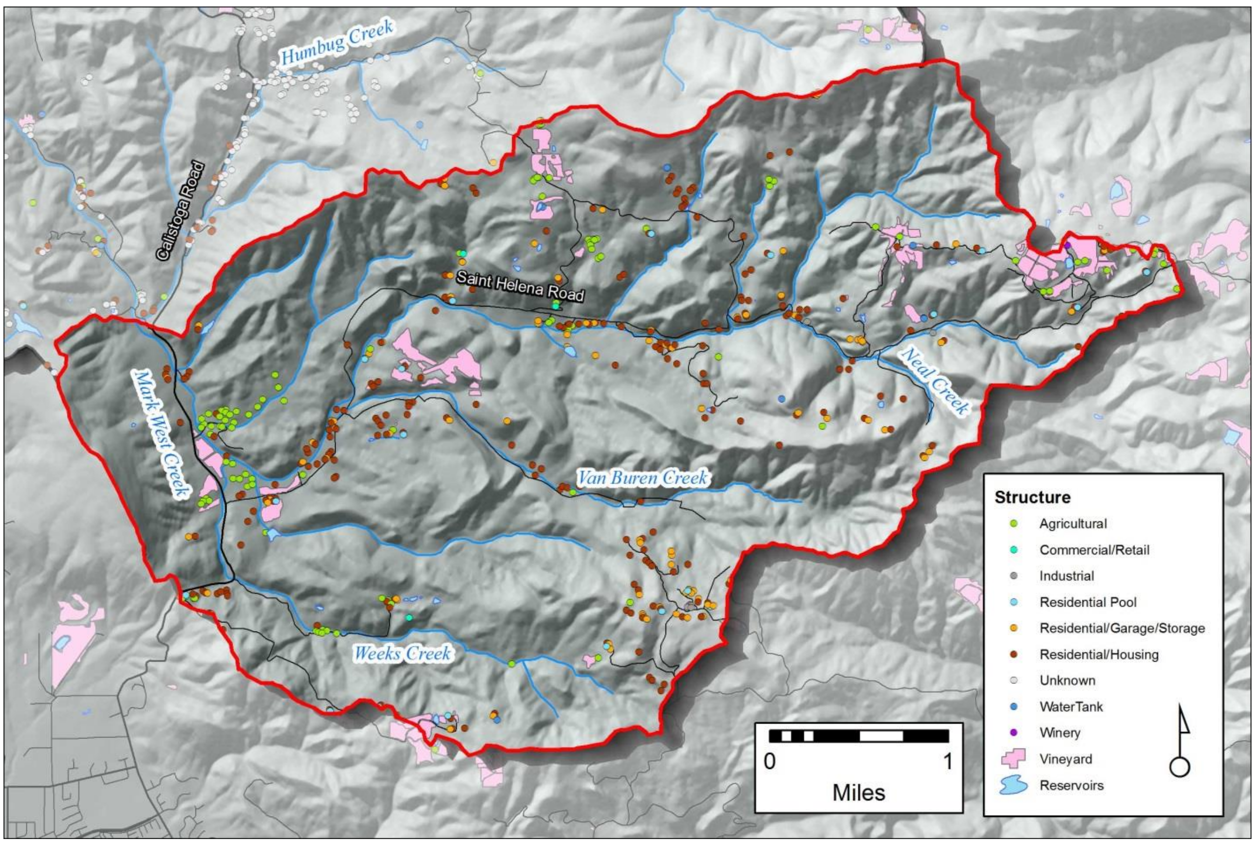


Figure 11. Structures, agricultural fields, and reservoirs in the Upper Mark West Creek watershed.

Agricultural. We used digitized agricultural coverage to estimate the total acreage of land as vineyards in each project watershed, and then calculated total agricultural water need based on regional per-area estimates of water use. However, vineyard water use is not uniform; we describe some of the variation in irrigation water needs here.

Vineyard specialists estimate that new vineyards in coastal Northern California may need up to 0.6 acre-feet of water annually (Smith et al. 2004). Water needs for more established vineyards vary over a range of factors, including climate, antecedent soil moisture, and vine characteristics. For example, UC Cooperative Extension describes survey data from grape growers in the Navarro River watershed that estimate average water use is 0.2 acre-ft per acre (UCCE 2013). Growers on Grape Creek, tributary to Dry Creek in Sonoma County, estimate needing 0.25 acre-ft of water per acre of grapes (Trout Unlimited and CEMAR 2012). Grape growers on valley floors of Napa and the Russian River may continue to need 0.6 acre-ft per acre of vines after the vineyards are established. Growers in hillside vineyards producing premium wines in Santa Clara County (on the eastern side of the Santa Cruz Mountains) do not irrigate during summer after the vines are five years old (Trout Unlimited and CEMAR 2014).

Within the Mark West watershed, the Cornell Winery Draft Environmental Impact Report (ESA 2012) provides an estimate of irrigation water use at the Cornell Farms vineyard to be up to 600,000 gallons per year in a hot dry year (and 300,000 gallons per year in a cool year) for the 19 acres of grapes on the property. This corresponds to 0.1 acre-ft per acre of grapevines under high-need conditions. This low water use is attributed to a system of sensors that measure moisture in the plants and soil, which are used to tell vineyard managers when water should be applied to maximize berry quality (ESA, 2012). Other growers in the region have begun to experiment with similar methods to reduce water use; the other reported benefit of reduced water use under these types of systems is improved wine quality.

There are many uncertainties in estimating average vineyard irrigation water use in the Mark West watershed. The 158 acres of vineyards in the region cover ten different parcel owners, four broad geological types (alluvium, volcanic ash tuff, volcanic flow rock, and Franciscan geologies) and 35 different soil types. Based on the above description of different water use volumes, the average water use in the area is likely somewhere between 0.1 and 0.6 acre-ft per acre of vines. For the purpose of this study, we estimate average water use is 0.3 acre-ft per acre of vines: most grapes in the area are produced on wet hillsides and are used to make expensive wines, so they likely use less water than other vineyards in Sonoma County. (Because of this uncertainty, subsequent analyses also show an upper estimate of water use of 0.6 acre-ft per acre, though this likely overestimates total irrigation need. These calculations can be refined with improved information.)

In addition to irrigation needs, wine grape growers also may need water for frost protection. Frosts that occur in the spring after buds have emerged can cause an entire loss of a year’s crop. To protect against frost, water is commonly sprayed over the vines by overhead sprinklers; much larger volumes are required at a given time than is needed for irrigation (as much as 1 cubic foot per second for ten acres of grapes), though water is typically needed for only a fraction of the day (e.g., from 1:00 AM to 9:00 AM). Two additional factors influence the amount of water needed for frost protection. First, only those vineyards in valleys tend to be frost-prone because cold air that causes freezes tends to result from the settling of cold air (hillside and hilltop vineyards frequently don't have infrastructure for frost protection). Second, some years have more frosty spring mornings than others. The past few years have had relatively few frost events: for example, in spring 2014, many growers in Sonoma County required no water for frost protection (RRPOA, 2014), while growers in other regions required water for between 2 and 6 events. In 2008, many growers needed water more than 20 days for frost protection.

Residential. Residential water use estimates in coastal northern California vary considerably. Estimates of residential water use in the upper Mattole River are, on average, 708 gallons of water per day (TU and CEMAR [2012], based on unpublished data from Sanctuary Forest). Other areas, such as the towns of Willits and Ukiah, estimate that the average person uses approximately 160 gallons per day, so a household of 4 people would require 480 gallons per day. The Valley of the Moon Water District cites that the average Sonoma County household of four uses 200,000 gallons for indoor and outdoor uses annually; the Sonoma County Water Agency estimates that the average family in Santa Rosa uses 99,000 gallons annually for household uses (though it does not state whether this includes indoor and outdoor uses; if it omits outdoor uses, and outdoor landscaping commonly accounts for 50% of household use [DWR, 2011], then the SCWA and Valley of the Moon water use estimates are similar).

Only one of these estimates, from the Upper Mattole River in Humboldt and Mendocino Counties, is from a rural residential area; and many factors distinguish water use patterns in that region from the patterns in the upper Mark West Creek watershed (namely, less amounts of alternative cash crops). To develop a more realistic estimate of household water use in the upper Mark West watershed, we started with the four-person household water use estimate for Santa Rosa of 99,000 gallons per year; this equates to 270 gallons per day, or 68 gallons per person per day. We then estimated the average household to be 2 people per house, based on conversations and meetings with landowners in the area. This results in a household (indoors only) water use estimate of approximately 136 gallons per day.

Based on the above data for Santa Rosa, if the average outdoor household landscaping water use is 100,000 gallons annually (half of the total annual residential water use and equal to the total indoor water use), and that water is used during the dry half of the year (183 days), the average daily landscaping water use is approximately 546 gallons per day per residence through the dry half of the year. This accounts for lawn watering, tree and garden irrigation, and other landscaping needs. A careful review of residences in the Mark West watershed, however, indicates that approximately 4 in 5 residences do not have a lawn, visible garden, or other irrigated landscaping. This may be a reflection of generally low water availability: as described further below, the majority of the watershed is composed of Franciscan assemblages, which provides poor aquifer characteristics. A fraction of residences have green lawns observed in recent NAIP aerial imagery; some have landscaping distributed over a dry cleared space; and a few have small gardens of plants spaced closely in a rectangle and surrounded by a fence.

If 80 percent of the 136 houses use 136 gallons per day, and 20% of the houses use 682 gallons per day (136 indoor and 546 outdoor), then the *average* domestic water use is 245 gallons per day per residence from May through October. This rate was applied to the number of residences within each watershed to estimate the annual residential water need, though this number is more reflective of water needs in summer for landscaping purposes.

As in the case for agricultural water needs, the value used here for household water use rests on several assumptions. These assumptions can be validated or modified with additional information from the area. Analyses that follow will use this household value for most of the discussion, but also will present results of a higher and lower water use estimate.

Industrial. As of 2013, we identified only one winery in the upper Mark West Creek watershed; another is tentatively planned for construction in the near future. To estimate total water need for wine production, we can use water use estimates from reports and studies to develop a total volume of water needed to produce wine from an acre of grapes. Winery water use is a function of production: UCD researchers estimate that, on average, 6 gallons of water are used to make one gallon of wine (Oberholster 2011). To estimate water use for the winery in the Mark West headwaters, we used an average per-acre wine production estimate based on the nearby Napa appellation: an economic impact report of Napa County's wine and vineyards indicated that a total of 19,961,500 gallons of wine were produced from Napa appellation grapes in 2011, from a total of 43,580 acres of land as vineyards (Stonebridge Research Group 2011). The Napa appellation thus produces, on average, 460 gallons of wine per acre of vineyards. If six gallons of water are used to make a gallon of wine, then wineries require approximately 2,750 gallons of water to make wine from an acre of grapes.

Results. Using the moderate water need estimates described above, approximately 140 acre-feet of water is need on an annual basis for all human water uses in the upper Mark West Creek watershed (Table 3). Approximately 48 acre-feet of water is needed vineyard irrigation. A total of 73 acre-feet of water is needed for annual residential water use, divided among 20 acre-feet needed for the 25 residential houses with landscaping, and 53 acre-feet is need for the 197 residential houses without landscaping. Lastly, we estimate that if all grapes grown in the upper Mark West watershed are turned into wine within the watershed, then 1.83 acre-feet (594,000 gallons) of water is needed for winery water use.

Table 3. Annual water needs for human uses in the Upper Mark West watershed, in acre-feet per year (AF/yr).

Water User	Number of Units	Annual Water Need (AF/yr)	Annual Water Need (AF/y, high estimate)
Vineyards	158 acres	47.4	94.8
Orchards	0.7 acres	1.4	1.4
Other Crop	7.7 acres	0.0	0.0
Fallow Fields	0.0 acres	0.0	0.0
Residential houses with landscaping	25 houses	19.8	19.8
Residential houses, no landscaping	197 houses	53	53
Winery	1 winery	1.83	1.83
Total Water Needed		**123.4**	**170.8**

Comparing the human water needs in the upper Mark West Creek watershed to the rainfall volume available in both average and dry years allows us to estimate whether human water needs can be met through the water resources available on site on an annual scale. Our analysis indicates that human water need represents 0.6 percent of the total rainfall that reaches the Upper Mark West watershed in an average year and 1.2 percent of the rainfall in a dry year (Figure 12).

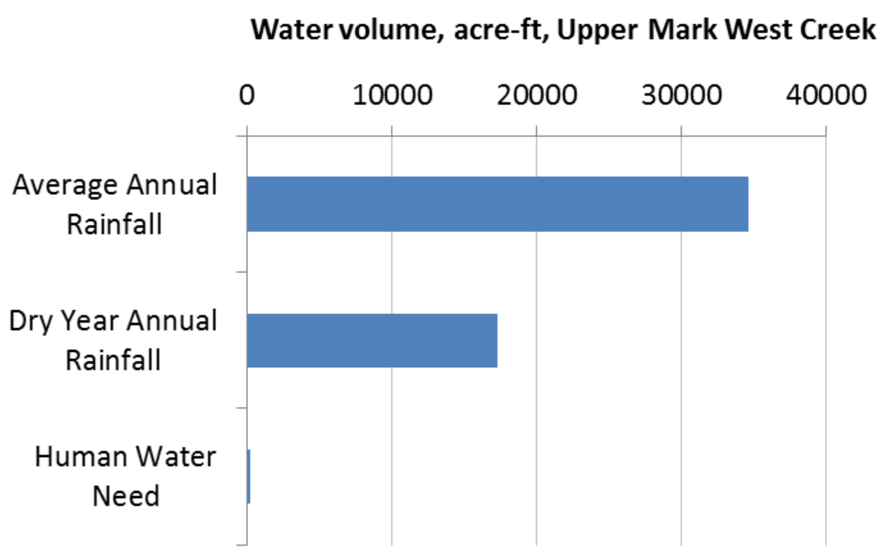


Figure 12. Comparison of rainfall in average and dry years to human water need in the upper Mark West Creek watershed.

4. Streamflow

Streamflow is an essential subject of reference for understanding the interaction between humans and the surrounding ecosystem in a watershed. These data provide the foundation for many applications, such as helping to identify reaches that are impaired by human water uses, and quantifying the magnitude of the existing impairments that water use may cause on streamflow. Streamflow data have also been used in other watersheds to identify reaches that may benefit most from projects to restore streamflow and the types of projects that could achieve tangible outcomes. Streamflow data also are important for determining the means by which water can be obtained and stored in winter to minimize the impacts to environmental resources such as salmonid habitat (as stipulated in the SWRCB North Coast Instream Flow Policy; SWRCB 2010).

Streamflow Data, Summer 2013

Six pressure transducers were installed in the Mark West Creek watershed to serve as streamflow gauges between April and November 2013. Three were installed as part of the Russian River Coho Partnership, and three others were installed by NOAA Fisheries. Each pressure transducer was set to record water level at 15-minute intervals. Streamflow was measured by CEMAR and/or NOAA staff at approximately monthly intervals following protocols outlined in CEMAR's Protocols for Measuring Streamflow in Wadeable Streams (CEMAR 2014) and the CDFW Standard Operating Procedures for Discharge Measurements in Wadeable Streams (CDFW 2013), using a Price Mini current meter. Using the measured streamflow values we created rating curves to correlate streamflow with discharge and developed 15-minute streamflow records for each site.

Our streamflow gauge network design can be described as measuring flow from three headwater tributaries, and then measuring flow at three mainstem sites below. The three tributaries are the mainstem Mark West Creek, Neal Creek, and the North Fork of Mark West Creek (an unnamed tributary on USGS topographic maps, but with similar catchment area as the mainstem Mark West Creek at its confluence). Our two farthest-upstream gauges on Mark West Creek were within 300 ft of each other: one was upstream of Neal Creek and the other was immediately below.

Streamflow data from summer 2013 show important variations among tributaries (Figure 13). The mainstem Mark West Creek above Neal Creek was intermittent by mid-May and the North Fork was intermittent shortly after in early June; but Neal Creek (and thus, Mark West Creek below Neal Creek) continued to flow throughout summer 2013. The dry conditions in the North Fork and mainstem above Neal Creek may be due to a number of factors described in more detail below, but the data presented here indicate a critical point for the hydrology of Mark West Creek: Neal Creek maintains flow even in a dry year such as 2013, and is critical for the persistence of flow in Mark West Creek below.

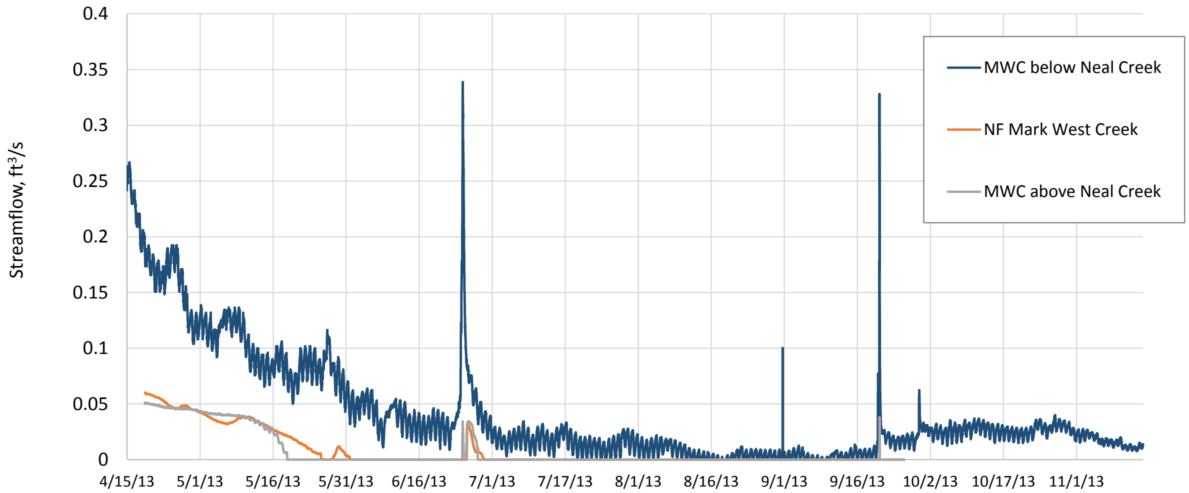


Figure 13. Streamflow recorded at the three "headwater streams"—North Fork Mark West Creek, Mark West Creek above and Mark West Creek below Neal Creek—spring to fall 2013.

Streamflow on the mainstem Mark West Creek from Neal Creek to the Tarwater Road gauge show a few other important trends in catchment hydrology farther downstream (Figure 14). Mark West Creek accrues streamflow from Neal Creek to the Puff Lane gauge throughout summer, though flow at both sites is less than 1 gallon per second (or 0.13 ft^3/s) from mid-May through mid-November. Streamflow downstream at the Tarwater Road gauge is approximately double the flow at Puff Lane in April, 3 to 4 times the flow in May, and as much as 10 times the flow at Puff Lane by September. Similar to the variations in the headwater tributaries, these mainstem variations may be attributed to a number of factors described below; but the differences in flow indicate that the reach of Mark West Creek between Puff Lane and Tarwater Road provides a substantial amount of base flow even in a year as dry as 2013.

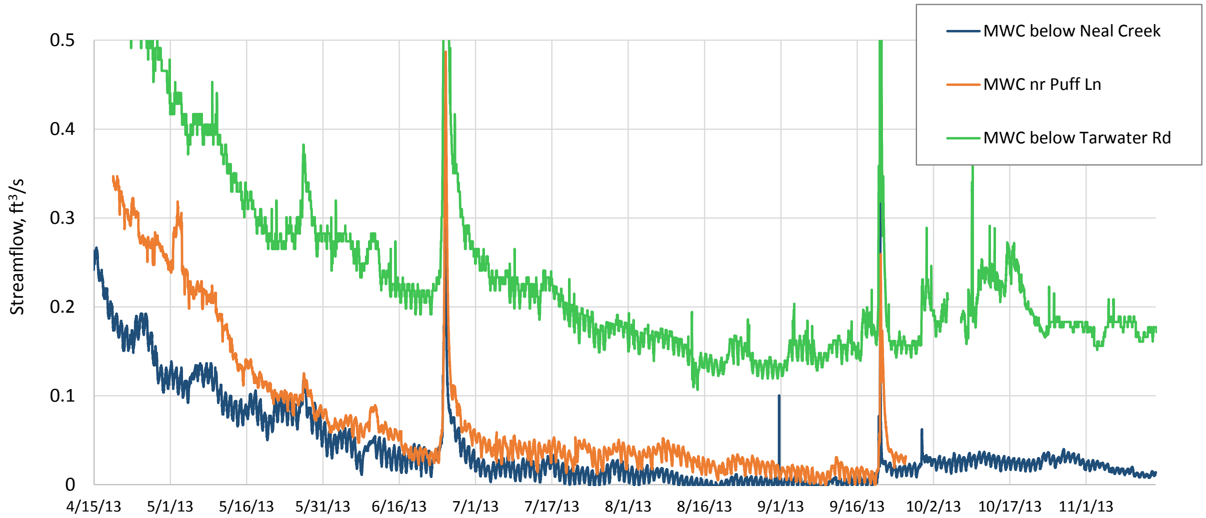


Figure 14. Streamflow data at three locations on the mainstem Mark West Creek, from Neal Creek to below Tarwater Road, dry season 2013.

Comparisons with Summer Streamflow Data, 2010 – 2012

The streamflow data from the mainstem Mark West Creek gauges show relatively stable and consistent flow throughout summer 2013. Daily fluctuations (commonly attributed to watershed evapotranspiration) are on the order of 0.03 ft^3/s, comprising as much as 100 percent of flow at upper gauges but approximately 10 to 20% of flow at the downstream Tarwater Road gauge. Similar patterns of stable base flow occurred at the Tarwater Road and Neal Creek gauges in 2010, 2011, and 2012 (Figure 15).

There appear to be no sudden large changes in flow that could be attributed to instream diversions in our Mark West Creek streamflow data sets. Streamflow at the Upper Mark West Creek gauges exhibit more consistent stable flow through summer months, compared to gauges on other Russian River tributaries in Sonoma County such as Austin Creek and Maacama Creek (both available through USGS), Mill Creek, Dutch Bill Creek, and Green Valley Creek (Deitch et al., in review).

While the data here show relatively stable flow through the dry summer, they also indicate persistent low flow, especially in the headwaters. Combined with the water needs assessment above, which indicates that residential and agricultural water needs exceed discharge throughout the dry season May-October, these results suggest that changes in water management practices among grape growers and residents in the upper Mark West watershed toward reducing dependence on water from wells and springs in summer could have meaningful benefits to summer streamflow in Mark West Creek.

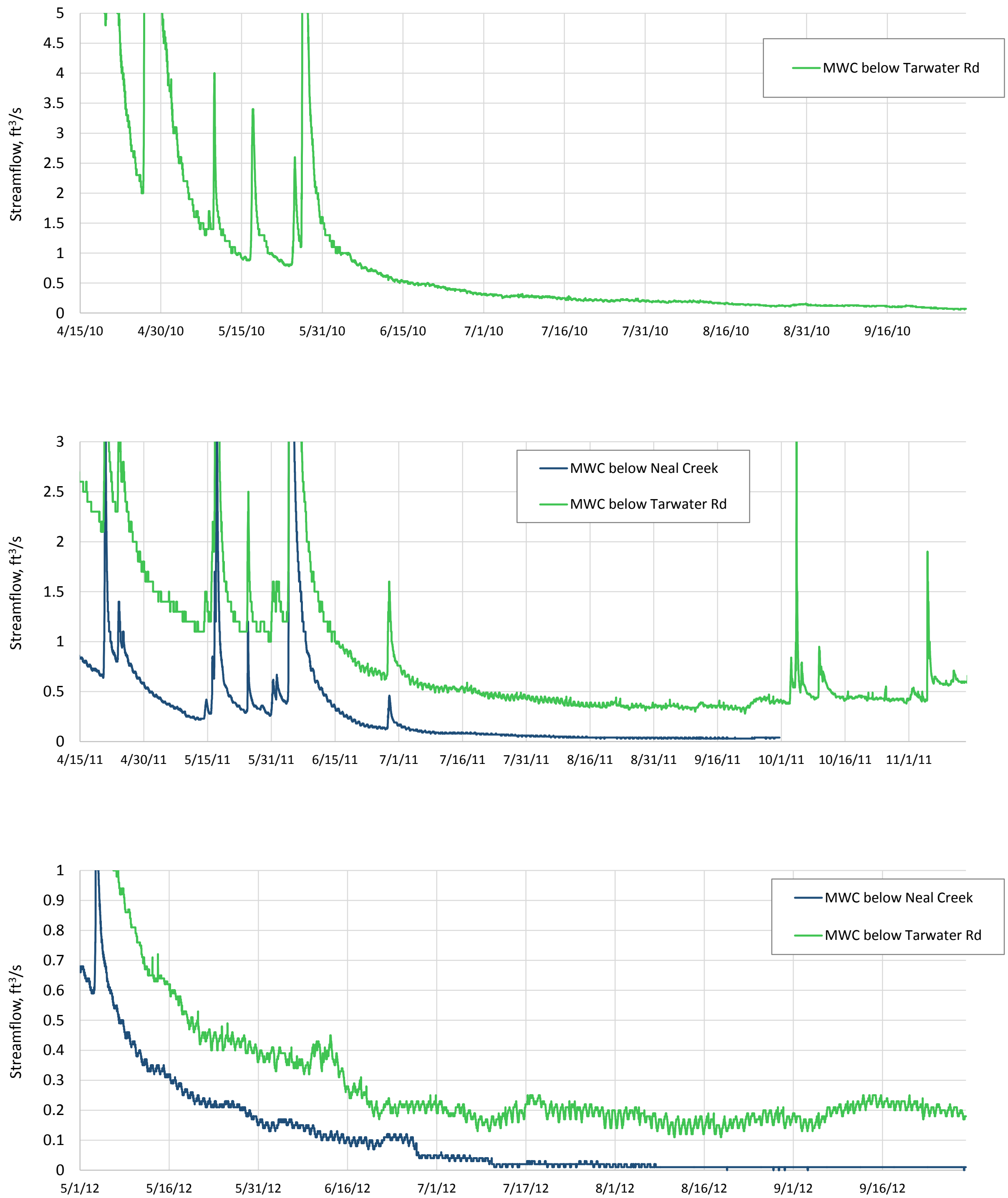


Figure 15. Mark West Creek streamflow below Tarwater Road and below Neal Creek, summer 2010 (top), 2011 (middle), and 2013 (bottom; the "below Neal Creek" gauge was not installed until 2011).

Figure 16. Mark West Creek below Tarwater Road, where the creek flows through an ash-tuff channel with volcanic-derived boulders and cobble.

Synthesis

While the comparison of human water needs and rainfall in Figure 12 above paints an optimistic picture about annual water availability for human and ecological needs, examining measured streamflow against demand on a monthly scale highlights potential conflicts between human water uses and instream resources. In particular, water need during the dry season when agricultural and residential needs are greatest may constitute a large proportion (or even exceed) streamflow quantities.

We used data from a gauge operated on Mark West below Tarwater Road to calculate the average monthly discharge from May through October, historically the driest months of the year with the lowest streamflow levels. We then estimated water need during the same timespan to compare water need to discharge, assuming that dry-season water need is consistent among months. We calculated two water need estimates, one using the low water need numbers, and the other using the high water need numbers (described above). We used the following approach to calculate human water need: agricultural water needs were divided evenly over five months, and residential water needs were divided over twelve months. The results indicate that water need in summer months exceeds the discharge in Mark West Creek (Figure 13). The higher water need estimates are at least two times the dry-year discharge in late summer, and the lower water need estimates are on the order of dry season discharge even in a wet year.

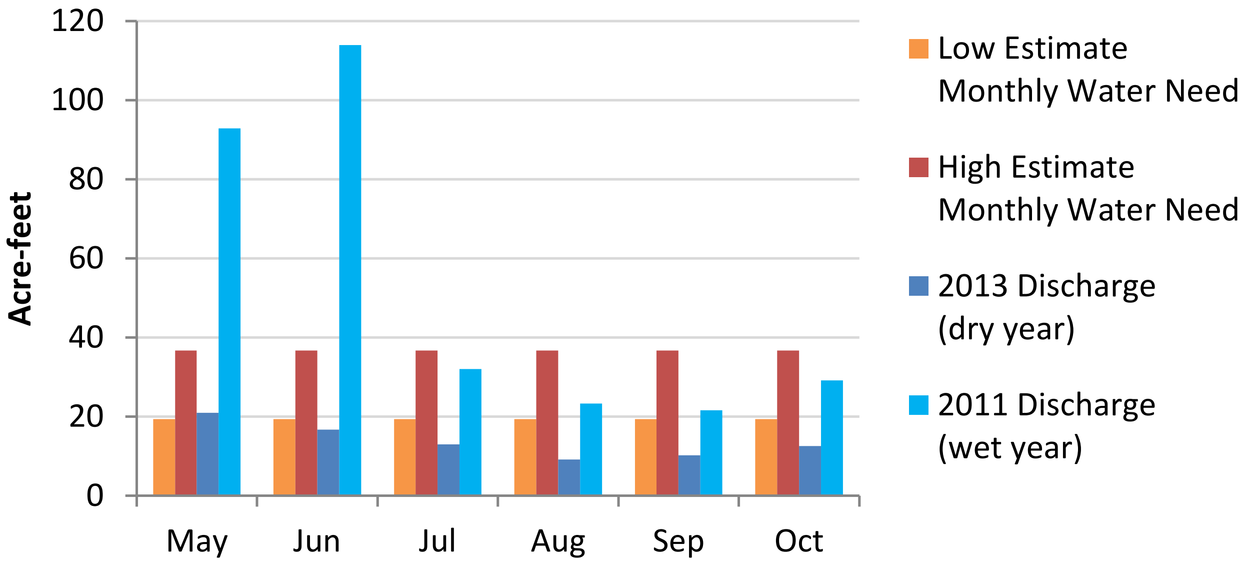


Figure 13. Monthly discharge in a wet and dry year, compared to monthly water need, in the Upper Mark West Creek watershed.

The results of this water needs analysis indicate that dry-season discharge in Mark West Creek cannot meet all the agricultural and residential needs in the watershed. Though there may be very few existing "straws" in Mark West Creek itself, water needs satisfied through pumping groundwater or from spring boxes likely remove water that would otherwise become base flow. The amount of rainfall that falls on Mark West Creek suggests that there is ample water available overall in the watershed to meet all current human water needs (for example, rainfall in a dry year is approximately 80 times greater than human water need) while maintaining ecological processes, so long as water is stored in winter at appropriate times and through appropriate methods. The results also suggest that base flow in late summer could increase substantially if human water needs met through pumping groundwater or diverting from streams during the dry season were reduced.

5. Geology

The Mark West Creek watershed is among the most geologically and topographically diverse in Sonoma County. Geological surveys indicate that, overall, the majority of the watershed has a surface geology derived from volcanic activity dating back to the Tertiary (now referred to as the Neogene) Period, to an age of approximately 2.9 million years (Figure 17). Frequently referred to as Sonoma Volcanic geology, this is most commonly represented in the watershed by settled and hardened ash, called tuff; and also includes harder flow rock (in particular, andesite and basalt). In addition to the Sonoma Volcanic geology, a large portion of the watershed has surface geology characterized as Franciscan Complex; the Franciscan assemblage in the Mark West watershed is referred to as Central Belt (Graymer et al. 2007), referring to a combination of mélange and greywacke (pressurized sedimentary rock, often resulting in minerals like quartz, feldspar, and other minerals formed within the pressurized sedimentary matrix), formed originally as ocean floor during the Jurassic and Cretaceous Period (to an age of 60 to 200 MY) and pressurized through tectonic uplift. Portions of the watershed also have surface geology of the Glen Ellen formation, which is considered soft sedimentary rock (including clay and silt; DWR 1982) of late Pliocene and Pleistocene age (which covers a range of approximately 12,000 to 5M years).

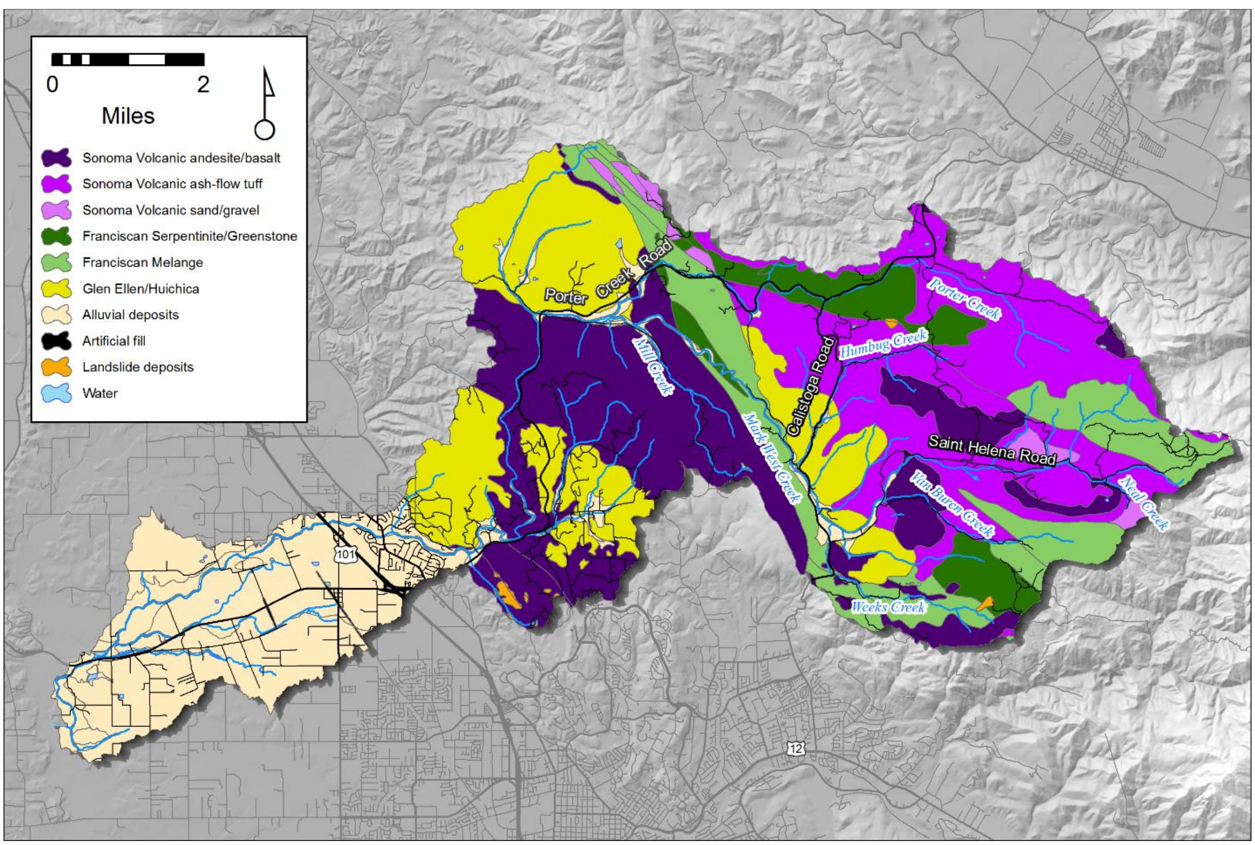


Figure 17. Surface geology of the Mark West Creek watershed.

Each of these geological formations has markedly different geohydrological properties. The purpose of this section is to characterize the geology, topology, and geomorphology of the Mark West Creek watershed, especially as it pertains to surface water-groundwater interactions in the upper portion of the watershed. In particular, we present two analyses: (1) groundwater, wells, and summer base flow; and (2) runoff, infiltration, and influence of land cover modifications.

Groundwater, summer base flow, and influence of wells

During summer, streamflow in Mark West Creek is comprised of base flow: rainfall that gets stored in soil and bedrock during winter slowly moves downward through its solid matrix to become streamflow months, sometimes years, later (Rodgers et al., 2005, Soulsby and Tetzlaff 2008). In addition to supplying base flow, water stored below the surface also provides a resource for meeting human water needs in the form of springs and wells: conversations with landowners in the area indicate that many people rely on springs and wells to meet agricultural and residential water needs through the dry season. Water removed for various uses likely depletes base flow, but it is difficult to discern the precise effects of pumping groundwater or diverting from springs on hydrologic conditions without detailed information describing how the systems operate and what happens in nearby streams when systems operate. However, several factors influence the capacity for wells and springs to affect base flow, and those factors are described here.

The most fundamental property that influences the potential for a type of rock to supply base flow is the capacity for water to move through it. Barlow and Leake (2012) describe a number of terms geologists use to describe the capacity for water to move through a solid matrix, including hydraulic conductivity ("K", which characterizes the rate of groundwater flow, in distance per time) and transmissivity ("T", which characterizes the rate of groundwater flow per area, in distance squared per time, calculated as K times vertical aquifer thickness "b"). They also describe Specific Yield, "S_y", which describes the potential for a type of rock to serve as an aquifer (defined as a ratio of the volume of water that can be drained by gravity from an aquifer material to the total volume of the material). Each of these is individually useful to characterize potential interactions between surface water and groundwater; together, Barlow and Leake (2012) also use these terms to characterize the influence of wells in different types of geology to affect the timing of streamflow depletion (described further below).

Geohydrologic differences: Hydraulic conductivity, transmissivity, and specific yield

The difference in geohydrological properties between the most common types of surface geology in the Upper Mark West watershed are substantial. In a Memorandum on aquifer storage and recovery feasibility, Pueblo Water Resources (2012) reported hydraulic conductivity data from four of the City of Santa Rosa's test wells in Sonoma Volcanic geology as 3.0, 22.3, 24.9 and

79.9 ft per day. These are similar to estimates of hydraulic conductivity for volcanic ash tuff (similar to some of the Sonoma Volcanic geology; see Figure 17, above) reported by Belcher et al. (2001) from a different location, on average, 5 meters per day. The Pueblo Water Resources (2012) Memorandum also reports hydraulic conductivity for Glen Ellen formations approximately 4 ft per day. In contrast, the North Coast Regional Water Quality Control Board (SWRCB 2011) and Palmer (2001) both report hydraulic conductivity through Franciscan bedrock as approximately 0.001 ft per day, approximately *one-ten thousandth* of the values reported for Sonoma Volcanic geology.

Additionally, a report on groundwater in Sonoma County by the Department of Water Resources (DWR 1982) describes Specific Yield, directly related to the ability for a rock to serve as an aquifer, for geologic types in Sonoma County:

- Sonoma Volcanic types have variable S_y ranging from 0 to 15%, with flow rock (andesite and basalt) at the lower of the range and ash tuff/ sand-gravel (described as a "good water producer") at the upper end. Corroborating this range, Kleinfelder (2003), summarizing data from Ford (1975), states that wells in the ash tuff of Sonoma Volcanics are highly productive; whereas the hard flow rock tends to yield very little water.
- Franciscan complex (including mélange, greenstone, metamorphosed sandstone, and serpentinite) is described as having "very low" S_y (less than 3%), and likely not being suitable as an aquifer. (The DWR report uses the word impermeable.) DWR (1982) reports that Franciscan mélange has very low porosity (resulting from shearing). However, the Franciscan mélange tends to be highly fractured (a result of uplift) and many residents who live in areas of the Mark West watershed in Franciscan geology describe springs and sufficiently productive wells in the landscape. (This point is revisited below.)
- Glen Ellen formation has a low S_y, ranging from 3 to 7 percent, likely due to high clay and silt content (which results in moderate porosity but poor hydraulic conductivity) and cementation of alluvial deposits.

Each of these factors has important implications for interactions between surface water and groundwater under different geological formations. For example, hydraulic conductivity can be used to estimate the linear velocity of water through a bedrock. Average linear velocity (ALV) can be estimated via Darcy's Law by first calculating Darcy velocity, *v*

$$v = -K\left(\frac{dh}{dl}\right)$$

where K is hydraulic conductivity and dh/dl is the hydraulic gradient (*i.e.*, the difference in elevation of the aquifer from one point to another divided by distance between the two points). ALV[1] can be calculated as Darcy velocity divided by the porosity of the bedrock material:

$$ALV = \frac{v}{porosity}$$

These equations show that linear velocity is directly related to hydraulic conductivity, which means that, under conditions of similar hydraulic gradient (e.g., 0.1) and porosity (e.g., 0.1), average linear velocity through Franciscan bedrock is approximately *four orders of magnitude* less than average linear velocity through Sonoma Volcanic ash tuff. (Porosity is inversely related to average linear velocity, so that if porosity of Franciscan bedrock is ten times less than porosity of Sonoma Volcanic ash tuff, average linear velocity through an aquifer of Franciscan bedrock with similar hydraulic gradient would still be *three orders of magnitude* less than ash tuff.)

Transmissivity, which describes the rate of groundwater flow through an aquifer under a unit hydraulic gradient, is also *directly related* to hydraulic conductivity as

$$T = K \times b$$

where b is vertical aquifer thickness. Thus the flow through an aquifer composed of Sonoma Volcanic ash tuff with similar aquifer thickness and hydraulic gradient will be four orders of magnitude greater than if it were composed of Franciscan bedrock. Overall, the substantial difference in hydraulic conductivity suggests that Sonoma Volcanic ash tuff can provide much more base flow than unfractured Franciscan bedrock, even if the Franciscan aquifer is a hundred times thicker than that of the ash tuff. (A discussion of fractured Franciscan bedrock is below.)

Hydraulic diffusivity and streamflow depletion

The two factors that most influence the timing and rate of streamflow depletion are the distance from a well to the stream and the aquifer's hydraulic diffusivity (Barlow and Leake 2012). For an unconfined aquifer (i.e., an aquifer without a confining layer above), hydraulic diffusivity (D) can be calculated as

[1] Porosity is a component of calculating the average linear velocity of water through a subsurface matrix because it takes into account the circuitous movement of water through the interstices of the matrix, rather than the direct movement of the water along the hydraulic gradient.

$$D = \frac{Transmissivity}{Specific\ Yield}$$

Barlow and Leake (2012) use the hydraulic diffusivity and distance to a well to define a term they call the Stream Depletion Factor (SDF), which is a relative measure of how rapidly streamflow depletion occurs from groundwater pumping:

$$SDF = \frac{d^2}{D}$$

The SDF (which Barlow and Leake [2012] speculate could more specifically be called "streamflow depletion response-time factor") is in units of time. A low SDF indicates that streamflow depletion will occur relatively quickly, while a high SDF indicates that streamflow depletion will occur relatively slowly (based on the work of Jenkins [1968]).Table 4 shows how differences in hydraulic parameters influence the potential for groundwater pumping to affect the stream. The parameters used for these calculations, such as aquifer thickness and distance from the well to the stream, are hypothetical and are intended to show how changes influence the SDF.

Table 4. Streamflow depletion Factors for Sonoma Volcanic ash tuff and Franciscan bedrock under varying aquifer thickness and distance from a well to the stream.

Condition	Sonoma Volcanic ash tuff, 100 ft thick	Franciscan bedrock, 100 ft thick	Franciscan bedrock, 1000 ft thick	Sonoma Volcanic ash tuff, 100 ft thick	Franciscan bedrock, 100 ft thick	Franciscan bedrock, 1000 ft thick
Hydraulic conductivity, ft/day	10	0.001	0.001	10	0.001	0.001
Aquifer thickness, ft	100	100	1000	100	100	1000
Calculated transmissivity, ft^2/day	1,000	0.1	1.0	1,000	0.1	1.0
Specific yield	0.15	0.03	0.03	0.15	0.03	0.03
Calculated D	6,700	3.3	33	6,700	3.3	33
Dist. from well to stream (ft)	1000	1000	1000	200	200	200
Calculated SDF	150	300,000	30,000	6.0	12,000	1,200

The calculations presented in Table 4 are hypothetical but inputs such as proximity to the stream and aquifer depth are on the order of the conditions encountered in upper Mark West Creek watershed. The goal of the above analysis is to show how the differences among the hydrologic properties of the two most prevalent types of surface geology affect the potential for wells within them to deplete streamflow. These calculations indicate that the potential for groundwater pumping to deplete streamflow is much greater for Sonoma Volcanic geology than Franciscan bedrock, even if the Franciscan bedrock is thicker and closer in proximity to the stream. Additionally, the calculations in Table 4 indicate the importance of Sonoma Volcanic ash tuff in providing base flow to Mark West Creek in summer and the potential for near-stream groundwater pumping in ash tuff to deplete base flow.

Realities of the Upper Mark West Creek region: Franciscan geology, and well locations

The above characterization of upper Mark West Creek geohydrology is an oversimplification of the Franciscan geology, neglecting an important feature: the uplift that created the Mayacamas Mountains and other mountain ranges in coastal California resulted in many fractures in the bedrock. These fractures allow water to move much more easily through Franciscan formations than it can through the bedrock itself; local geohydrologists attribute these fractures, which have greater porosity, permeability, and hydraulic conductivity, as the reason why springs are common and wells can provide adequate yield for domestic and some agricultural uses in Franciscan geology (*e.g.*, Phillips 2012).

While these features are common in the landscape, characterizing their overall influence on streamflow in nearby streams is difficult. This type of evaluation would require (1) a delineation of the abundance and extent of subsurface fractured bedrock, and their hydrologic properties, over a large portion of the region; and (2) a more detailed stream gauging operation to determine where streams are gaining and losing from groundwater as streams flow through Franciscan geology. Conversely, however, an evaluation of the impacts of groundwater pumping on streamflow could be accomplished through a simpler evaluation: detailed streamflow gauging at a few strategically chosen locations near the well during its period of operation could determine how streamflow varies near a groundwater well and how those variations change over time. Because these fractured bedrock aquifers are so variable, conclusions of groundwater pumping effects on streamflow are likely not possible without this type of specific cause-effect evaluation.

Because fractured bedrock can more efficiently convey groundwater, pumping groundwater from fractured bedrock aquifers could potentially reduce the amount of base flow in a stream: fractures in Franciscan bedrock will likely provide base flow at a much faster rate than non-fractured bedrock. However, the extent of base flow depletion is likely not uniform among all fractures and instead will be related to the size and hydrologic properties of the fracture. A large fracture containing a large volume of water could be an important source of base flow through spring and summer; a small fracture containing less water may not be sufficient to provide base flow past early summer. Additionally, as Darcy velocity is directly proportional to hydraulic gradient and hydraulic conductivity, a steep fracture filled with material that can easily convey water could discharge most of its water volume early in the dry season and convey little water later in the dry season. Given the range of possible scenarios for describing surface water-groundwater relationships in fractured bedrock, it is not possible to know how pumping groundwater from fractured bedrock may affect streamflow without conducting a test of well operation and streamflow response to see whether and how streamflow patterns deviate from baseline conditions when water is pumped.

Characteristics of wells in the upper Mark West Creek watershed can help to further understand the potential for groundwater pumping to affect streamflow. For this project, NOAA obtained well completion reports from the Department of Water Resources (DWR) for the region of the Mark West watershed outlined in blue rectangle in Figure 18, below.[2] Data from well completion reports were used in accordance with DWR requirements of confidentiality. The presence of a well completion report on file with DWR does not necessarily mean the well is in use today.

Analysis of the data within these well completion reports indicates two important findings about wells and their potential influence on streamflow in the region:

- There were 102 wells with completion reports on file with DWR within the blue rectangle in Figure 18, and of these, 72 had adequate information to determine approximate locations of the wells (based on features such as parcel number, location addresses, hand-drawn maps, or coordinates). Of the 72 wells with adequate geographic information to give approximate location, 46 (nearly two-thirds) were located in the area near Mark West Creek outlined in yellow. This corresponds to a region with a high number of relatively small parcels (indicating rural residential development) along Mark West Creek. As described above, these wells may not all be in use; but the proximity of several wells near the stream in a geological formation with a high potential streamflow depletion factor (ash-flow tuff and sand/gravel) suggests that wells operating in this region could individually or cumulatively have adverse effects on streamflow in Mark West Creek during the dry season.

[2] DWR requires that well drillers submit a well completion report for the drilled well describing (among other features) the location of the well, its depth, the composition of the material with depth, depth to water, and initial pump rate and drawdown. Newer wells, such as those drilled since the 1980s, tend to have more detailed and complete information about all of these characteristics, while older wells frequently have incomplete information and poor descriptions of well locations.

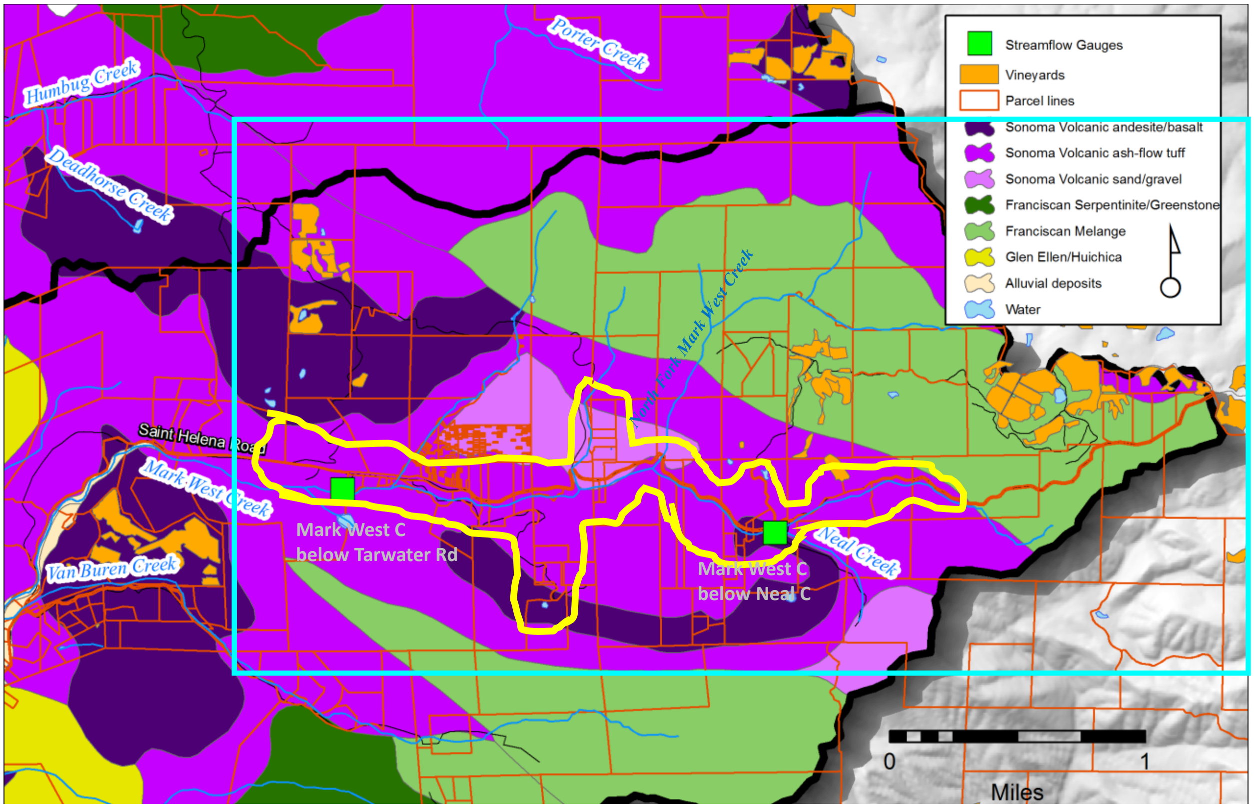


Figure 18. Portion of the Mark West Creek region for which DWR well records were obtained by NOAA.

- Of the 72 wells described above with adequate information to give an approximate location, 52 had a value given for an initial onsite well yield test performed by the driller. This preliminary test does not necessarily correspond to the yield of the well over the long term, but it provides a relative value for comparing the initial ability for the well to provide water at the time of drilling. Initial pumping rates were compared based on differences in geology as indicated in surface geology GIS maps (Figure 19). These pumping rates indicated that wells in Franciscan Complex often provide among the lowest yields, but can provide relatively high yields as well. Wells in Sonoma Volcanic geology, which represent 85% of the wells with adequate information to determine approximate location and initial pump rate, also provide varying yield. However, they tend to be the most productive: half provide an initial yield greater than 20 gallons per minute, and three-quarters provide more than 15 gallons per minute.

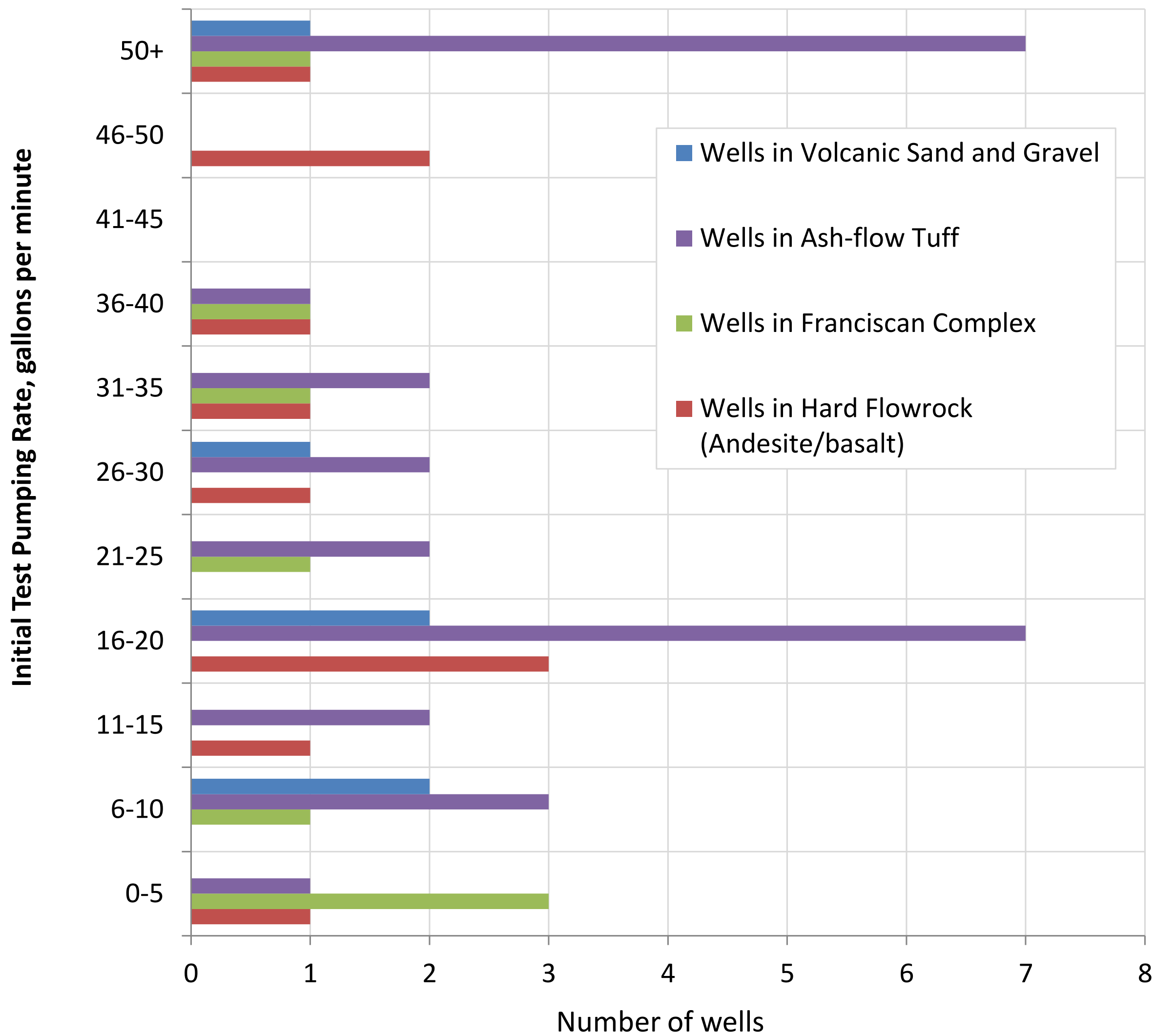
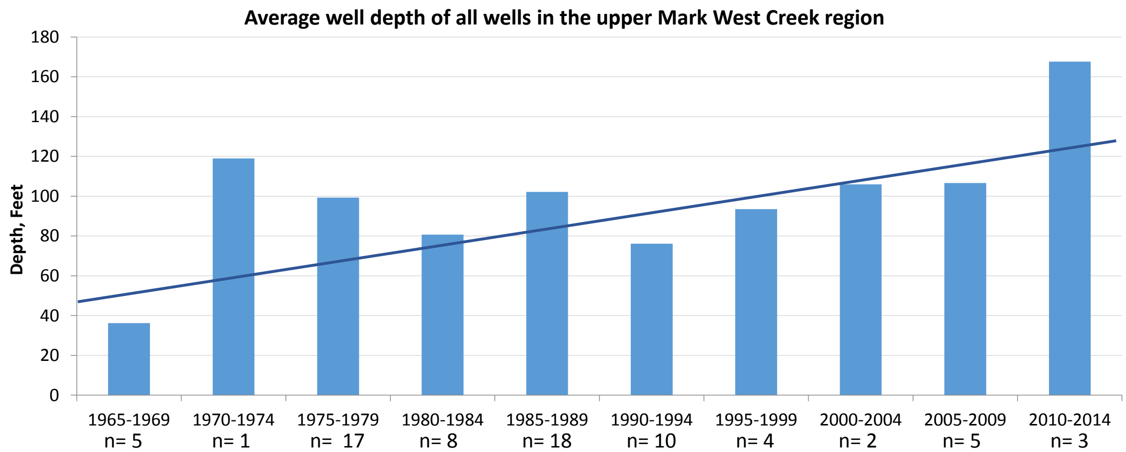


Figure 19. Number of wells plotted against initial well yield (based on pump test performed by driller) for wells with geographic information sufficient to estimate location in the upper Mark West Creek watershed, along with differences in surface geology.

The above comparisons are intended to provide a general description of well locations and yields for the upper Mark West Creek watershed, rather than specific features about particular wells or wells in certain regions. Many of the data sets used above have uncertainties that should be acknowledged. First, well completion reports are often incomplete. The data are skewed to reflect reports for newer wells because newer well reports tend to have more complete information than older reports. Second, the analyses of geological type are based on surface geology GIS data. While the GIS geology data set used in this analysis is the most recent and highest-resolution data set available for the region (created in 2013), it does not likely include all the geological variations that are in the region. Additionally, it only shows the surface geology: well completion reports indicate that surface geology layers such as ash tuff or volcanic sand/gravel may only be tens of feet deep, overlaying Franciscan bedrock hundreds of feet below. Finally, well completion reports only indicate conditions when a well was drilled and do not indicate the long-term well yield or if the well is still used today.

In addition to the pump test rates, well completion reports also describe the depth to water at the time when the well was drilled. We compared depth to water over time for two sets of wells: those wells that are within one-quarter mile of Mark West Creek (corresponding to approximately the area outlined in yellow, Figure 18) and those in the entire region from which data was requested. The data describing depth to water in the well completion reports indicate an overall trend of greater depth to water among those wells over the entire region, as well as those wells within one-quarter mile of Mark West Creek (Figure 20).



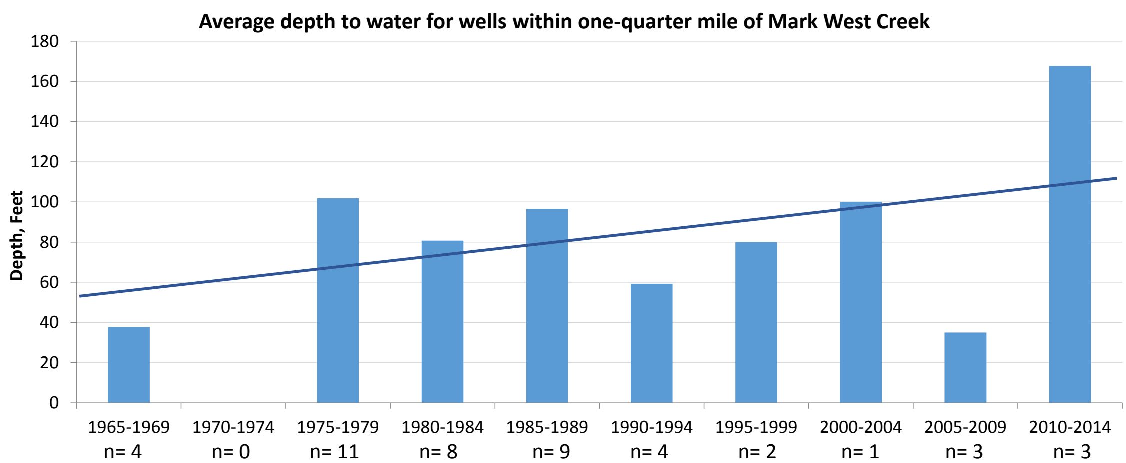


Figure 20. Average depth to water for wells in the Upper MW region, every five years; and average depth to water for wells within a quarter-mile of Mark West Creek; and overall trendlines. Trend lines indicate deeper water over time, but data are skewed by one very deep well drilled in 2010.

We performed an additional analysis of initial depth to water (as reported in driller logs) over time in the upper Mark West Creek region. Wells tended to be clustered in groups along the creek, indicating relatively dense development. We examined initial depth to water over time in five clusters of wells (Figure 21), with number of wells ranging from six to 8 per cluster, covering a period of the 1970s to 2014 (total of 35 wells). The purpose of this analysis was to assess if the initial depth to water in wells has changed over time; if depth to water among wells in the same aquifer is greater today than it was 40 years ago, that would suggest the aquifer is lower than it was in recent decades. This analysis assumes that all wells in each cluster are in the same aquifer; given the heterogeneity of geologic conditions in the region, this assumption may not be valid.

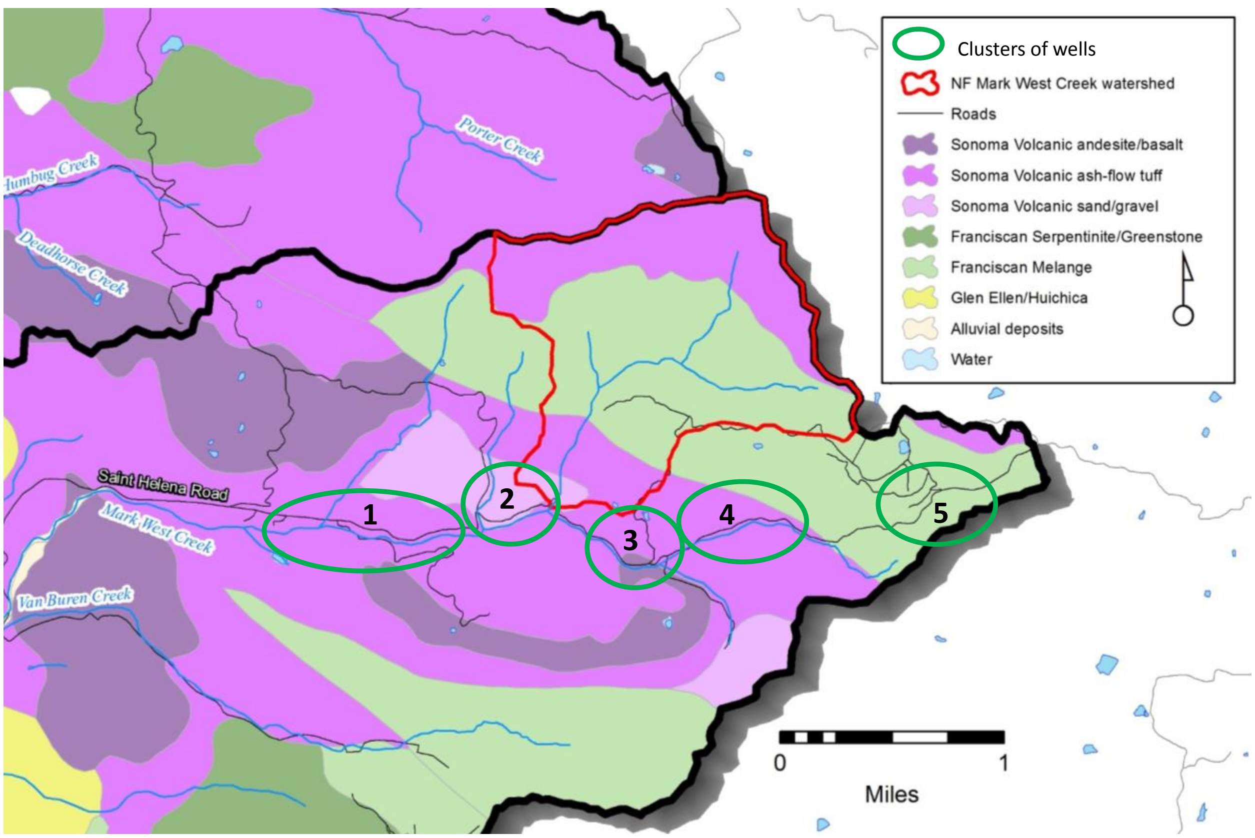


Figure 21. The majority of wells in the upper Mark West Creek region tended to be clustered in five areas, circled and numbered one through 5. Analysis of initial depth to water over time in each of these circles appears in Figure 22.

Overall, the initial depth to water in the well clusters does not appear to have consistently changed over time (Figure 22). Group 1 and Group 4 show greater initial depth to water, through the trendline in Group 1 is skewed by one particular well (and otherwise would show a decreasing trendline); the other three show a weak trend of less depth to water over time.

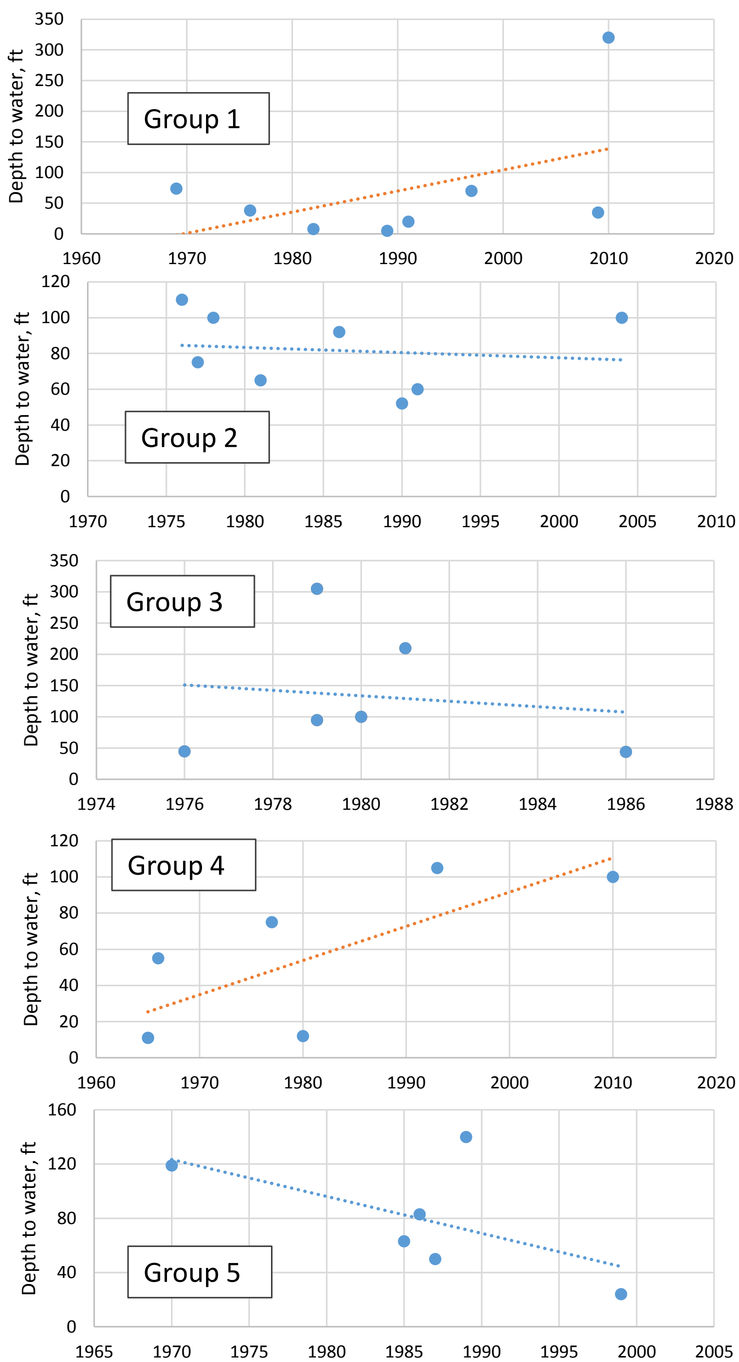


Figure 22. Initial depth to water over time among wells in each of the five clusters of wells in the upper Mark West Creek region (as identified in Figure 21).

Additional field observations and measurements, summer 2013

The importance of Sonoma Volcanic geology in sustaining Mark West Creek base flow was evident in observations made in the field in summer 2013. As described in the previous Hydrology discussion (Section 4), streamflow in the North Fork and mainstem Mark West above Neal Creek ended in late spring 2013, while flow immediately below Neal Creek and subsequent mainstem gauges downstream continued to flow through summer. Figure 17, above, shows that the surface geology of the North Fork watershed and upper mainstem Mark West watershed is mostly Franciscan bedrock, while the Neal Creek watershed and subsequent lower Mark West gauged watersheds had larger portions of Sonoma Volcanic geology.

NOAA and/or CEMAR staff visited Mark West Creek approximately monthly through summer 2013 and regularly observed springs and seeps from the bedrock alongside Mark West Creek. The creek was accessed to make observations at three locations between Neal Creek and Tarwater Road: at the St. Helena Road crossing just below Neal Creek; at a private residence on St. Helena Road near Puff Lane; and at a private residence downstream of Tarwater Road. At each visit, water was observed seeping from the Sonoma Volcanic bedrock (e.g., Figure 23); water was often observed seeping from bedrock on both sides of the channel. Additionally, in early summer 2013, NOAA walked from where the North Fork Mark West Creek flows beneath St. Helena Road, downstream to the confluence with Mark West Creek, then downstream to a private residence on St. Helena Road near Puff Lane (where permission had been granted to exit the creek). During that half-mile walk, many springs and seeps were noted on both sides of Mark West Creek.

NOAA staff also walked along the North Fork Mark West Creek upstream from the St. Helena Road crossing to a boulder cascade possibly marking the upper limit of anadromy on the North Fork Mark West Creek (assuming salmonids could get past the St. Helena Road culvert). No springs and seeps were observed through this reach. Though this reach was identified in surface geology GIS data sets as volcanic sand and gravel, the bedrock at creek level was Franciscan (Figure 24).

Figure 23. Water seeping out of bedrock, Mark West Creek below Neal Creek (at St. Helena Rd crossing), May 2011 (wet year, upper photo) and July 2013 (very dry year, lower photo). Seeping groundwater is not limited to fractures in bedrock, and it was observed in many places along Mark West Creek between Neal Creek and Tarwater Road in summer 2013, on both sides of the creek.

Figure 24. Stream channel, North Fork Mark West Creek, upstream from St. Helena Road (July 2013).

Additionally, CEMAR and NOAA Staff walked alongside Mark West Creek on St. Helena Road in summer 2013; no springs or seeps were observed through this reach and the stream channel was completely dry over the observable portion of the creek from Neal Creek upstream (a total distance of 0.8 miles). Whereas Mark West Creek below Neal Creek has a narrow active channel with boulders, gravel, and bedrock-bottomed (albeit shallow) pools (Figure 25A), the channel above Neal Creek was broader and covered with finer gravel and cobble to the tops of boulders (Figure 25B).

Many factors may contribute to the dry conditions of the mainstem Mark West Creek above Neal Creek. Wells on the hilltops of the watershed divide, where most of the watershed's vineyard development is located, could be affecting summer base flow; the majority of the watershed is Franciscan formation, which correlates with poor base flow; and much gravel and cobble has accumulated in this reach of Mark West Creek, likely elevating the level of the channel bed while still allowing hyporheic flow through the coarse alluvial matrix. At this point, it is not possible to distinguish between correlation and causation. However, the accumulation of gravel, especially above the undersized culverts along St. Helena Road, is substantial (e.g., Figure 26 A-B). This gravel accumulation fills pools throughout Mark West Creek, and disproportionately affects the creek upstream of road culverts (where deposits are especially large).

Figure 25A (top) – B (bottom). Mark West Creek immediately below Neal Creek at the St. Helena Road Crossing (top), and immediately above Neal Creek (bottom).

Figure 26 A-B. Accumulation of coarse material in Mark West Creek above Neal Creek, along St. Helena Road, upstream of St. Helena Road culvert--facing downstream (top) and upstream (bottom).

North Fork Mark West Creek

The North Fork of Mark West Creek (NF MWC) has been a subject of much attention in recent years, focusing on concern over the effects of vineyard development in a portion of the watershed on summer base flow. Nearby stakeholder groups have noted that NF MWC becomes intermittent earlier than in the past and that it has become dry in most recent years where it had not in the past. The purpose of this section is to describe the features that could be contributing to reduced base flow in NF MWC.

The majority of the NF MWC watershed is covered by surface geology of Franciscan mélange (Figure 27), indicating that much of it is unlikely to directly produce consistent base flow through summer. However, as described above, fractures in Franciscan bedrock of suitable characteristics (e.g., large enough, with adequate hydraulic conductivity) may provide base flow in summer. The upper and lower portions of the watershed are covered in Sonoma Volcanic surface geology, implying a greater capacity for providing base flow during summer, but no seeps or springs were observed along the NF MWC near the St. Helena Road crossing. Additionally, California Geological Survey maps illustrate an unnamed fault running through the NF MWC watershed; ESA (2012) provides additional speculation as to the origin of this fault and its relationship to other nearby faults.

Specific concerns have been raised that a well providing irrigation water for the vineyard on the ridge separating the North Fork watershed from the mainstem watershed may be reducing summer base flow. Consultants for the vineyard report that the well pumps ten gallons per minute for irrigation through summer totaling 0.1 acre-ft per acre of grapes, for a total of 2.0 acre-ft of water annually (ESA 2012). The consultants describe the location of the well as being on the ridgetop dividing the mainstem and North Fork watersheds, between the two large blocks of vineyards shown in Figure 27.

Given the high stream depletion factor described for Franciscan bedrock above, water is probably not directly losing from NF MWC to the adjacent bedrock. The fairly productive well pumping rate of 10 gallons per minute suggests that part of the well is in a bedrock fracture capable of providing adequate yield for irrigation needs, and its location suggests it is in proximity to the unnamed fault that also crosses NF MWC. If the fracture supplying the irrigation well is hydrologically connected to NF MWC, then removing water would likely reduce flow in NF MWC. However, reducing flow from the well-influenced bedrock fracture to NF MWC would not affect inputs from other fractures: other fractures that provide flow to NF MWC elsewhere in the NF MWC watershed would likely not be affected by groundwater pumping at the vineyard site. While conditions could be imagined whereby water could move from NF MWC toward the vineyard well via bedrock fractures, that movement would: (1) require the potentiometric water surface within the fracture to be below the level of the stream; (2) the fracture would need to have sufficient transmissivity to accommodate water from the stream into the fracture; and (3) the size of the fracture would need to be sufficient to remove water from the NF MWC.

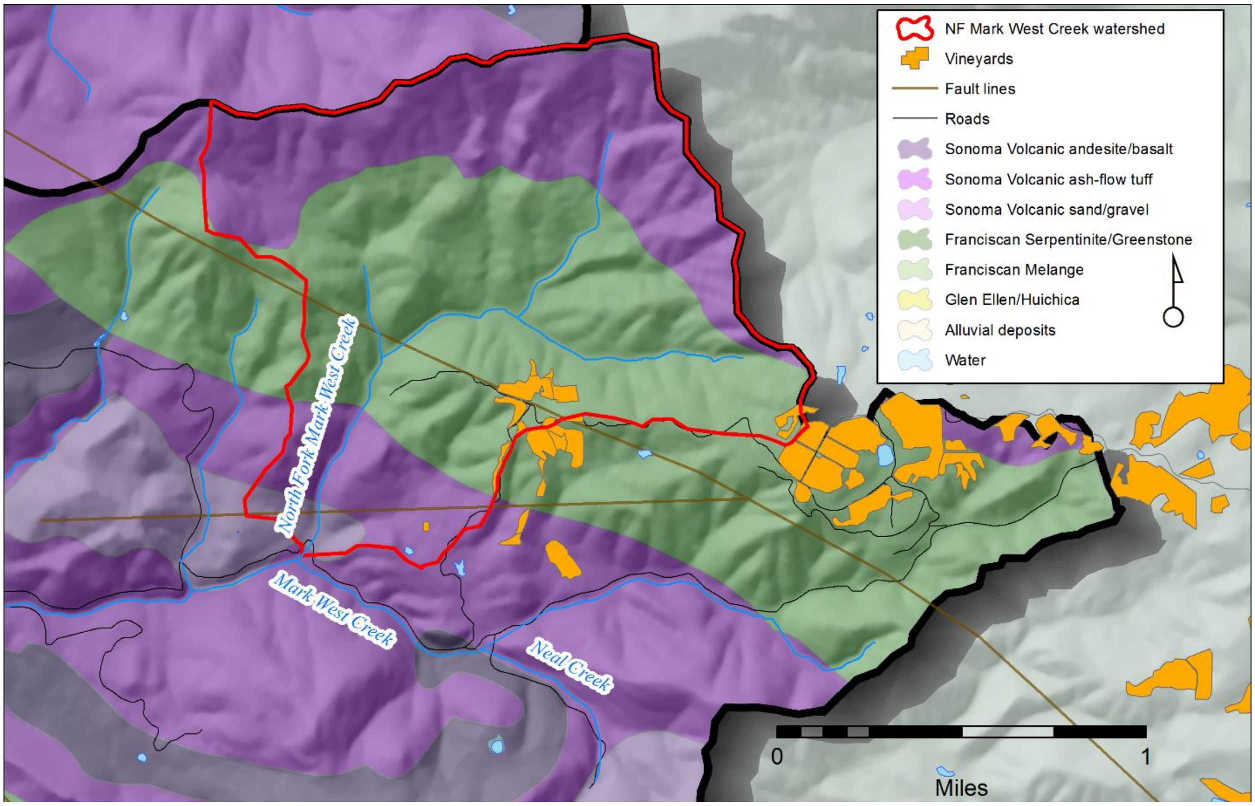


Figure 27. North Fork and mainstem Mark West Creek, with surface geology, roads, and fault lines.

The complexities of groundwater flow in Franciscan bedrock and limited flow data undermine our ability to know for certain how the well providing irrigation water for the vineyard in the NF MWC watershed affects streamflow below without systematic measurements to ascertain baseline conditions and conditions upon pumping. The nature of the geologic material suggests that the effects of groundwater pumping would reduce flow only by proportion of flow the particular fracture provides; other fractures elsewhere in the watershed would continue to provide base flow independent of groundwater pumping at the vineyard well site. The seasonal impact of base flow depletion due to groundwater pumping can also be calculated. If the total amount of water obtained by groundwater pumping is 2 acre-ft annually, and the effects of groundwater pumping are attenuated over the year, it corresponds to an average of 0.003 ft^3/s through the year. Assuming the effects are attenuated evenly over the year, this represents the maximum impact the well can have; it also would assume all the water pumped by the well would otherwise become streamflow in NF MWC. If the effects are attenuated evenly over the two-month period when water is used, and all the water that is pumped from the groundwater well would otherwise become streamflow in NF MWC, the maximum impact would be a reduction of up to 0.016 ft^3/s. Further confounding this evaluation, the North Fork Mark West Creek was dry in June 2013, earlier in the dry season than when water is usually used for irrigation.

Two other factors have likely played a role in the decline of summer base flow in the North Fork of Mark West Creek and the mainstem Mark West Creek above Neal Creek. The first is the nature of hydrologic conditions over the period 2007 to 2014. While two of the past eight years were wetter than average, six of the eight were much drier than average. These multi-annual drought conditions may compound the impacts of drought, resulting in sequentially less base flow from one drought year to the next. From a mechanistic perspective, the cracks and fractures in the bedrock that support base flow through summer do not re-charge sufficiently, resulting in a declining supply of water over multiple years to provide summer flow. The other factor that likely contributes to less summer surface flow is the accumulation of coarse gravel in the channel. Anthropogenic and naturally-caused landslides and channel erosion have caused stream channels to aggrade through much of the upper portion of the watershed. Gravel accumulation is so great in some reaches that the channel has become braided, a common feature of streams with an excessively high sediment load. Studies from elsewhere in the western United States indicate that low rates of discharge, such as those typical in Mark West Creek (ranging from 0.1 to 0.3 ft^3/s) could easily percolate and pass subsurface through coarse gravel that accumulates in channels as a result of erosion upstream in the catchment (May and Lee, 2004).

The streamflow dynamics of the North Fork Mark West Creek is likely affected by such sediment accumulation, especially on the upstream side of the St. Helena Road culvert crossing. Like the mainstem Mark West Creek above Neal Creek, the sediment regime of NF MWC is affected by an undersized culvert. The culvert on the 1.3 square mile North Fork Mark West Creek has a diameter of 6 ft; this has led to an accumulation of coarse gravel and cobble on the upstream side of the culvert (Figure 28; this accumulation is likely exacerbated by upslope landslides to the NF MWC described by Li and Parkinson, 2008).

Figure 28. Sediment accumulation, North Fork Mark West Creek above culvert at the St. Helena Road crossing (May 2013).

On the other end of the culvert, the water level in the stream bed as surveyed on May 20, 2014 was 6.5 ft below the bottom of the culvert (Figure 29). Beyond presenting major challenges to salmonids migrating upstream in NF MWC, this undersized culvert has led to an unnatural channel slope upstream of the culvert as coarse gravel and cobble has accumulated upstream. A survey of the NF MWC from a boulder cascade 400 ft upstream of the St. Helena Road crossing to the confluence with Mark West Creek shows that the overall channel gradient is consistently approximately 1% except immediately above the culvert (Figure 30). Surface flow was observed below the boulder cascade and again below the culvert, but not through the reach where the slope was affected by sediment accumulation.

Figure 29. Downstream end of the culvert on the North Fork Mark West Creek at St. Helena Road.

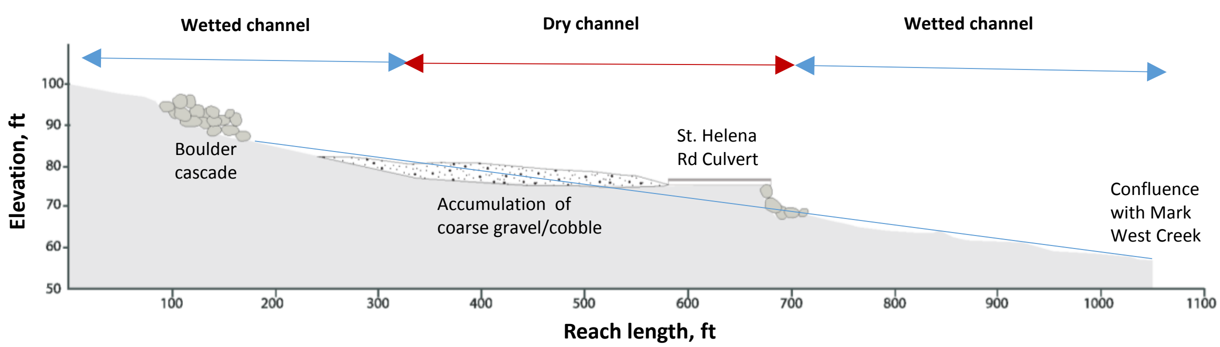


Figure 30. Longitudinal profile of the north Fork Mark West Creek from boulder cascade upstream of St. Helena Road to the confluence with Mark West Creek, indicating the portions of the channel that were wetted and dry during survey (5/20/2013). The continuous line from the boulder cascade down to the confluence with Mark West Creek illustrates a continuous slope through the reach that could correspond with the saturated water level above and below the surface of the channel bed.

The presence of water at the top of the survey and again below the culvert suggests that there could be surface flow throughout NF MWC in the absence of the culvert. The slope of the channel surface has changed upstream of the culvert with the accumulation of gravel and cobble, but the water table gradient through the accumulated gravel and cobble is approximately the same upstream and downstream of the accumulated material. While this points to a benefit of increasing potential salmonid spawning and rearing habitat by replacing the NF MWC culvert with a bridge, the amount of increased habitat is small: the boulder cascade at the upper end of the long profile survey likely limits adult migration, so the amount of increased habitat would only be five hundred feet (the distance from the downstream end of the St. Helena Road culvert to the base of the boulder cascade).

Runoff, infiltration, and influence of land cover modifications

Runoff is water that flows on Earth's surface and in streams during and directly after a rain event (Dunne and Leopold 1978). A number of factors influence how much rainfall is converted to streamflow, including infiltration capacity of the soil, vegetation cover, landscape gradient, and rainfall intensity. The amount of water that gets converted from rainfall to runoff can be altered by human development; for example, addition of impervious surface can reduce infiltration capacity and conversion from forest to grassland can reduce leaf interception. The purpose of this section is to describe some of the characteristics that influence runoff in the Mark West watershed, and how development in the watershed have altered runoff processes.

Estimating runoff

A straightforward and commonly used way to estimate runoff in a watershed is to calculate runoff as a function of rainfall intensity, drainage area, and a term called the runoff coefficient according to the Rational Equation:

$$Q = C \times i \times A$$

In the original Rational Method, Q is defined as peak flow in cubic feet per second, C is the runoff coefficient reflecting the ratio of rainfall to surface runoff, i is the rainfall intensity in inches per hour (in/hr), and A is drainage area in acres. Runoff coefficient values that commonly appear in tables (e.g., Dunne and Leopold 1978) are based on empirical data where rainfall and runoff were measured from small watersheds, where C could be estimated with reasonable accuracy (the Rational Method was designed to apply to watersheds less than 200 acres in size). The runoff coefficient is a function of how quickly water can flow off of a surface, on a scale of 0 to 1, where a low runoff coefficient indicates a low volume of water converted into flow (*e.g.*, a forested understory with soils having high infiltration capacity), and a high coefficient indicates a large volume of water converted to flow (*e.g.*, an impervious surface). Because of the simplicity and clarity of the Rational Method, it is often applied to watersheds much larger than 200 acres and over broader intervals such as seasonal or annual runoff (CalTrans 2001).

Despite these limitations, the runoff coefficient C provides a useful method of comparison for considering how different landscape characteristics influence runoff. The runoff coefficient describes the fraction of total rainfall that appears as a runoff volume, after a portion of it has been infiltrated, and stored in the groundwater table. In addition, runoff coefficients can describe a site's infiltration characteristics, providing useful insights to which areas in a watershed contribute most to recharging groundwater aquifers, and contribute most to base flow later in the year.

To conceptualize runoff variability, we calculated the runoff coefficient across space for the Mark West Creek watershed. Dunne and Leopold (1978) list runoff coefficients according to soil type and land cover; we added runoff coefficient data to include a value for ponds (1.0, implying a full reservoir whereby all water that falls as rain becomes runoff), and for hillside vineyards from 0.45 (as Dunne and Leopold report for cultivated land on shallow soils) to 0.9 (reflecting shallow soils, steep slopes, and often drainage tiles on vineyards). In GIS, we spatially joined the soil and vegetation/ land cover data to correspond with categories for assigned C values based described by Dunne and Leopold (1978). Table 5 describes the runoff coefficient values used in this study, based on soil and land cover.

We conducted this analysis under two conditions. In the first, we used land cover data from a 2002 USGS data set that included no agriculture or reservoirs in the watershed above the Santa Rosa Plain. In the second, we used land cover from a modified 2011 data set that incorporated the vineyards and reservoirs we mapped in the watershed upstream of the Santa Rosa Plain. These two different conditions allowed us to compare how the development of vineyards and ponds in the watershed affects runoff.

Table 5. Runoff coefficients in the Mark West Creek watershed (adapted from Dunne and Leopold [1978]; red text shows modifications based on local conditions).

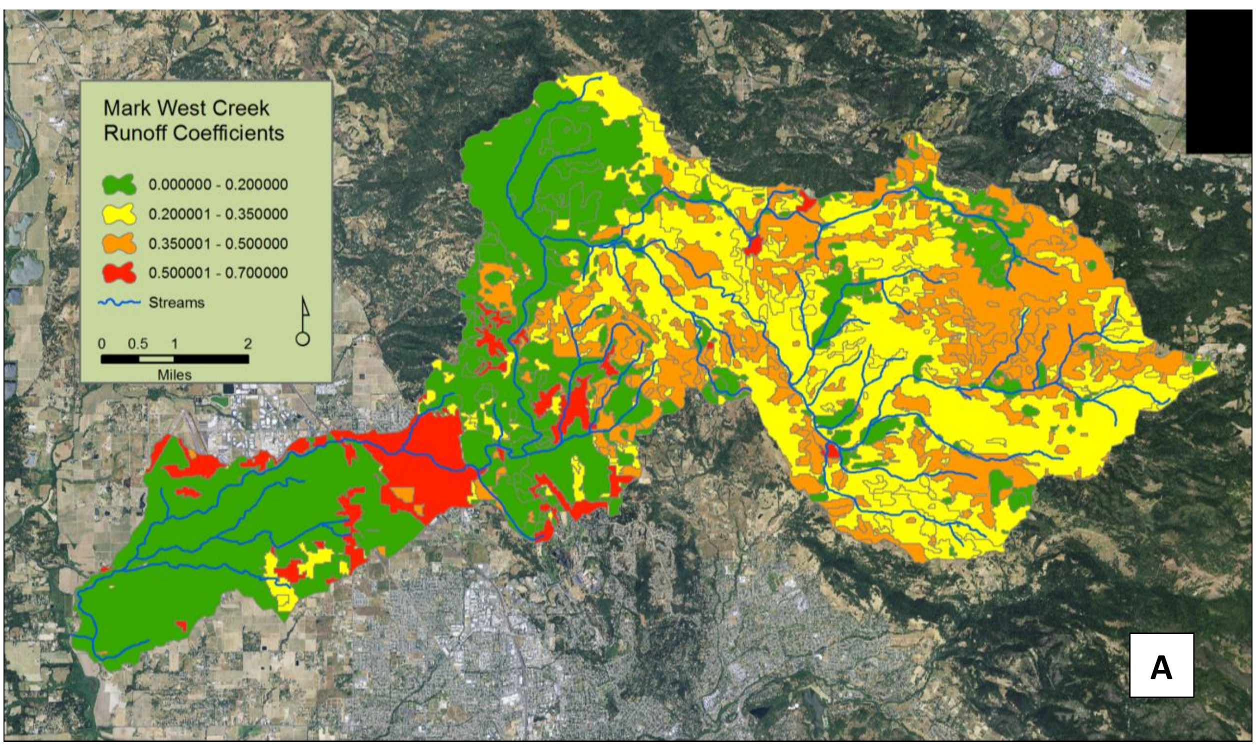
Urban and Rural Single Family Residential	
Urban areas (lower in watershed)	0.7
Residential on sandy and gravelly soils	0.2
Residential on loams	0.3
Residential on clay soils	0.4
Open water	1.0

Sandy and gravelly soils:	
Cultivated (vineyards, etc.)	0.2
Pasture, grasslands	0.15
Woodland, forest	0.1
Open water	1.0

Loams and similar soils with impeding horizons	
Cultivated (vineyards, etc.)	0.4
Pasture, grasslands	0.35
Woodland, forest	0.3
Open water	1.0

Heavy clay soils or those with a shallow impeding horizon (shallow soils over bedrock)	
Cultivated (vineyards, etc.)	0.9
Pasture, grasslands	0.45
Woodland, forest	0.4
Open water	1.0

Overall, the results of this analysis indicate the variation in runoff and infiltration throughout the watershed (Figure 31A). The lower part of the watershed, with soil categorized as "riverwash" and land cover mostly as cultivated crops, has low runoff (and thus high infiltration). Urban areas (e.g., Larkfield/Wikiup) have the highest runoff and lowest infiltration. The areas with low runoff coefficients upstream of Larkfield/Wikiup correspond with sandy soils and forest. Soils upstream in the more mountainous areas have higher clay content (derived from Franciscan and Sonoma Volcanic bedrock) and mixed land cover (as indicated above in Figure 6A). If runoff coefficients are summed to create an average value over the entire watershed, the average runoff coefficient in the Mark West watershed is 0.31.



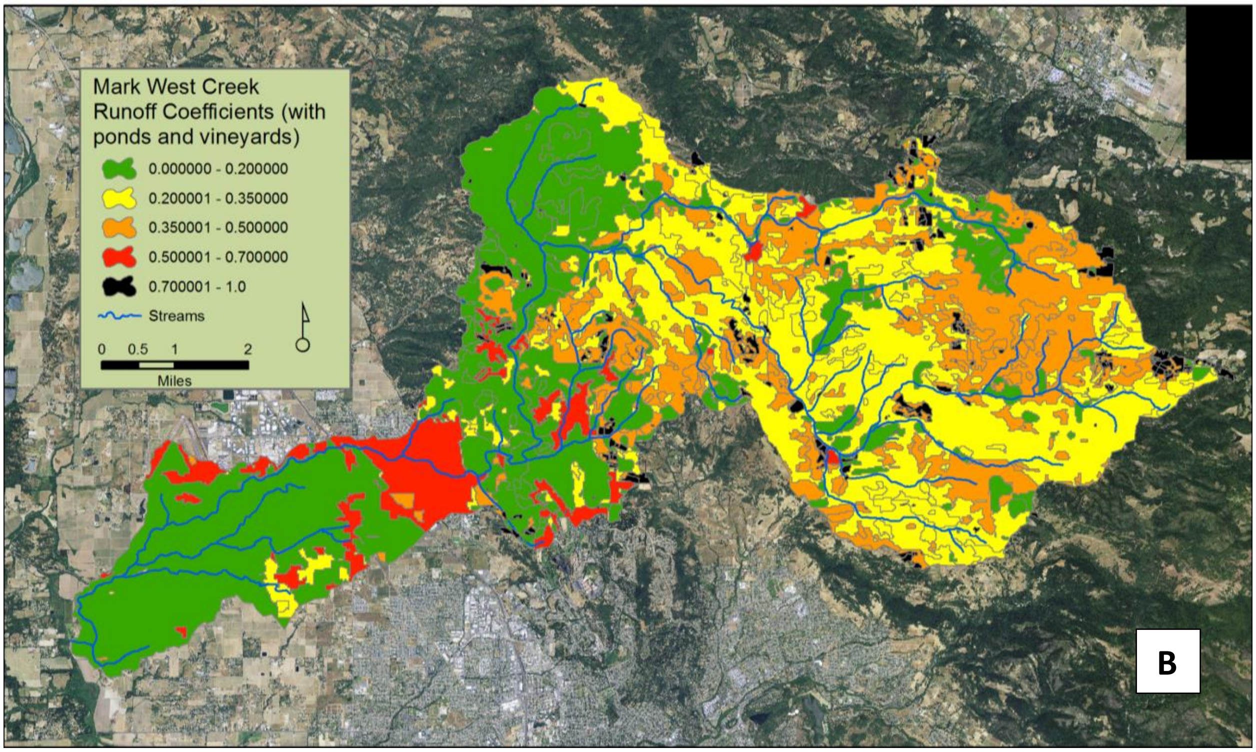


Figure 31A-B. Runoff coefficient values in the Mark West Creek watershed in the absence of ponds and vineyards (A, above) and with ponds and vineyards (B, below).

Because vineyards and small reservoirs represent a small fraction of the overall watershed (Figure 31B), their influence on the overall watershed runoff coefficient is small. The amount of land upstream of the Santa Rosa Plain as either vineyards or reservoirs is approximately 730 acres; when we replaced the runoff coefficients of these areas from initial values to either 0.9 and 1.0 (for vineyards and ponds, respectively), the overall runoff coefficient changes to 0.32 (Table 6).

Table 6. Runoff coefficients for portions of the Mark West Creek watershed based on data sets with and without vineyards in the upper portion of the watershed (i.e., based on data shown in Figures 28A and 28B).

Region	total area, acres	Average runoff coefficient	Middle/upper watershed as vineyard or reservoirs	New average runoff coefficient
Mark West watershed	33160	0.31	730	0.32
Upper Mark West C	8960	0.33	281	0.35
North Fork Mark West C	920	0.36	13	0.37
Mark West C ab Neal C	794	0.32	78	0.38

Given the concerns about development in the upper portion of the watershed, we repeated the comparison of runoff coefficients with and without agricultural development in three other locations: the upper Mark West Creek watershed (above Humbug Creek), the North Fork Mark West Creek watershed, and the Mark West Creek watershed above the MW06 ("below Neal Creek") gauge (Figure 32). Because the amount of agricultural coverage represents a small fraction of the overall watershed area, the new runoff coefficients (including agricultural development) change only slightly. The greatest change occurs in the portion of the watershed above the MW06 gauge, where 10% of the watershed is covered by either ponds or vineyards (Table 6). The change from 0.32 to 0.38 means that a rainfall event may convert 38% of its rainfall into runoff, where previously it would have converted only 32% to runoff.

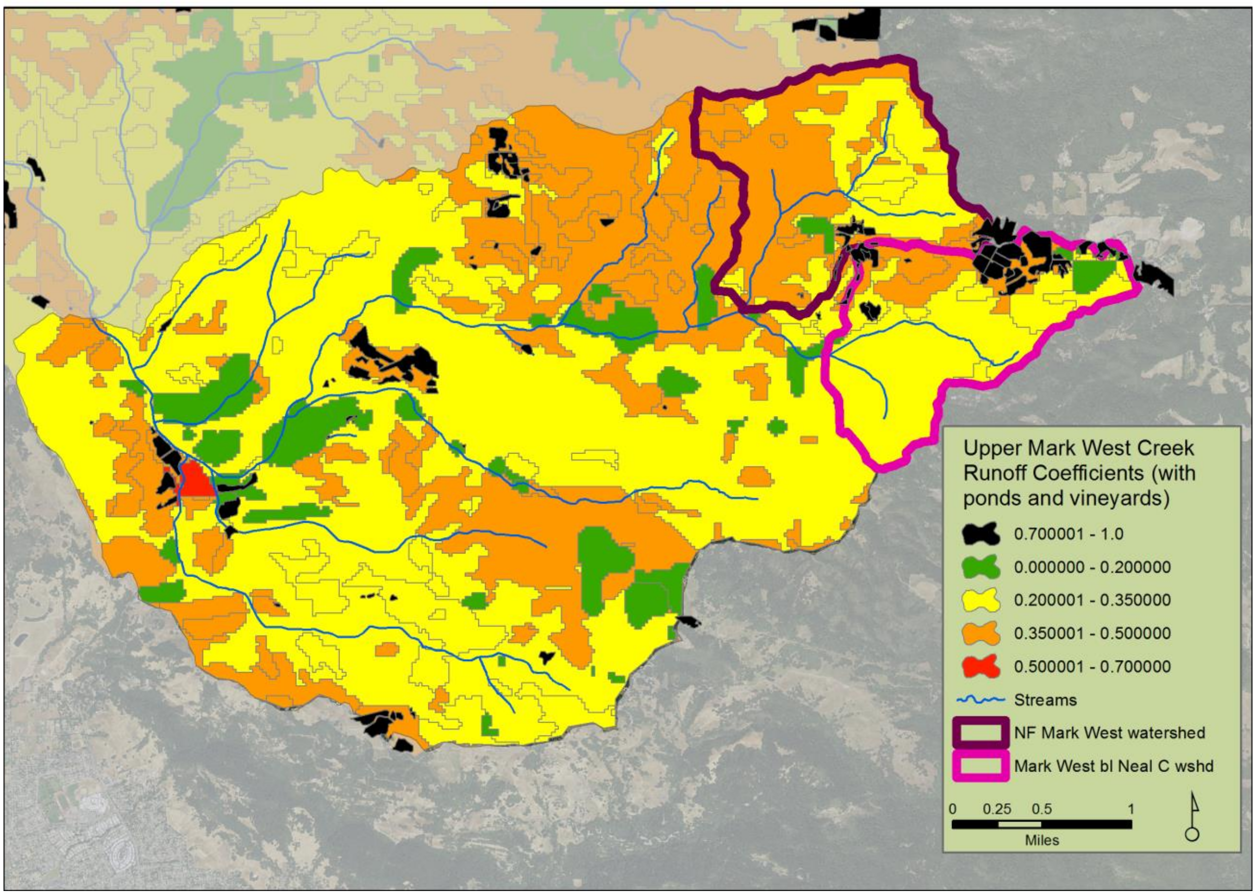


Figure 32. Runoff coefficients in the upper Mark West Creek watershed area, given current agricultural development.

6. Conclusions

Characterizing the interactions between humans, our development, and the natural flow regime is a complex task. Streamflow varies over time (*e.g.,* within the year and among years), and development patterns vary across space (*e.g.,* in the lower watershed compared to the upper watershed). We have attempted to describe some of these complexities in four related discussions (Rainfall, Land Cover/Land use, Hydrology, and Geology) to provide some insights into how streamflow in Mark West Creek has been affected by human development in the watershed.

Overall, our study suggests that streamflow is low in Mark West Creek but does not show many of the characteristic fluctuations associated with streamflow diversions to meet human water needs, even in a dry year. The Sonoma Volcanic surface geology in much of the watershed has capacity to produce base flow through summer, which is likely one of the main reasons why Mark West Creek maintained consistent flow even through the dry year 2013. Also, while there is some development along the upper reaches of Mark West Creek (as shown through locations of houses and wells), groundwater pumping to meet residential needs attenuates the impacts compared to direct instream diversions. Instead, groundwater pumping likely results in reduced base flow. Groundwater pumping to meet agricultural needs may also affect base flow, especially if wells are located in bedrock fractures that would otherwise provide base flow in summer.

Our analyses also show that the amount of water that falls as rain and leaves as streamflow greatly exceeds the amount of water needed for human uses. Normal-year rainfall is more than 150 times our estimate of human water need in the watershed, on an annual scale. Normal-year discharge is likely also much greater than human water need. For example, Rantz (1972) reviewed rainfall and streamflow records from watersheds in northern California and found that approximately 50 percent of the water that falls as rain is converted to streamflow. If this estimate is applied to Mark West Creek, then a discharge value can be added to the water use/rainfall comparisons in Section 2. If typical normal-year rainfall over the upper Mark West watershed is 34,500 acre-ft, discharge can be estimated as approximately 17,300 acre-ft. Our estimate of 260 acre-ft of water needed for human uses comprises approximately 1.5 percent of the discharge from the Upper Mark West Creek watershed under normal-year conditions (Figure 33), and approximately 3 percent of discharge from Upper Mark West Creek in a dry-type year (Based on dry-year rainfall, Figure 12).

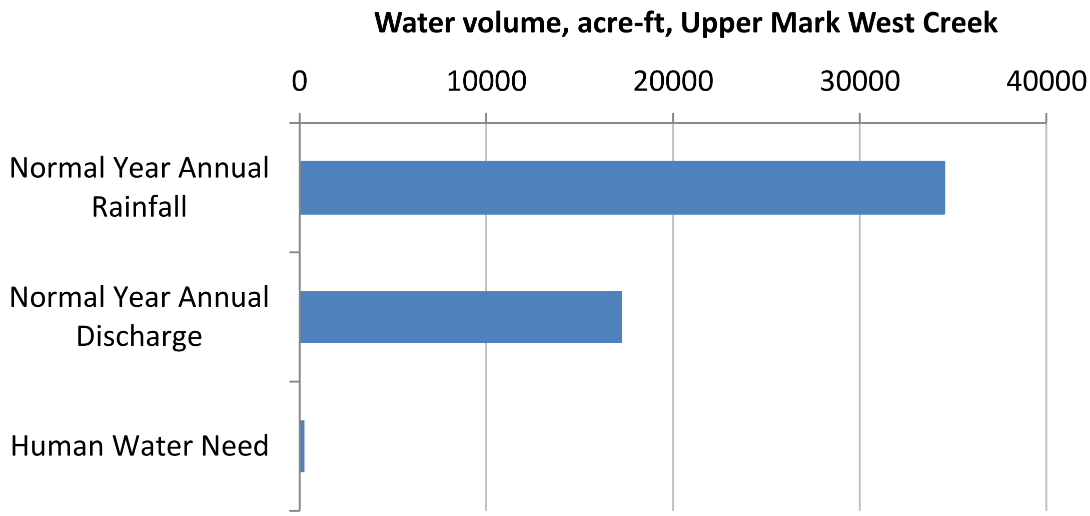


Figure 33. Estimated normal-year rainfall, discharge, and human water need in upper Mark West Creek.

These results suggest that it should be possible to meet all the water needs of the upper Mark West watershed with minimal effects to hydrology if water is obtained through appropriate methods at appropriate times. As indicated above in Figure 13, this cannot occur in summer: the characteristically low discharge through the dry season is not sufficient to support human needs in the basin. The abundance of rainfall and streamflow in normal and in dry years suggests that Methods such as rainwater catchment and reservoir storage could be suitable to meet human needs if operated correctly. Rainwater catchment may be the least hydrologically invasive because it only stores water when it rains in proportion with rainfall intensity, and only affects stream hydrology in proportion to the area of catchment (e.g., house or barn roof, relative to a stream catchment). For example, if one residence stores water off of a 1,000 square foot area, 48 inches of rain would produce approximately 30,000 gallons of water. Based on our estimates, this would be sufficient to meet the needs of the majority of houses in the Mark West watershed through the dry season. If 80 houses in the Mark West Creek watershed above Tarwater Road (total watershed area 2,960 acres) store rainfall off of a 1,000 square foot area, it would result in storage of 0.062% of the total rainfall (storing water that falls on 80,000 square feet over a 129,000,000 square foot watershed). Rainwater catchment has the greatest potential to meet human water needs in the Mark West Creek watershed while minimizing impacts to hydrology, though it may be limited by roof space: it can only store as much water as falls on the roof, and rainwater catchment design should consider total water needs and rainfall in a dry year to ensure needs will be met.

Reservoirs also provide storage from winter to summer. Reservoirs may be located on headwater streams, thus collecting inflow from the upstream channel; or offstream, receiving water pumped from groundwater or from a nearby stream. Onstream reservoirs that collect water from upstream typically fill at some point in winter and begin to spill over and reconnect with the drainage network, but until they do, they are designed to prevent water from flowing downstream. Reservoirs on small streams are now required to have a mechanism that allows some water to bypass the dam and provide water downstream (SWRCB 2010), but whether the bypass flow is sufficient to meet ecological needs or operates correctly is unknown. Equally important, the cumulative effects of many headwater reservoirs could impede flow if they all are storing water in the rainy season. In examining the impacts of headwater "fill-and-spill" reservoirs on streamflow in Sonoma County (including the Mark West watershed), Deitch et al. (2013) found that streamflow in streams that support salmonids can be impaired especially early in the water year, though results are variable: drainage networks with more reservoirs are more impaired than those with few reservoirs. Also, because reservoirs tend to fill through the year, their impacts on salmon streams are often small in a normal-type year (though they can persist longer in a dry-type year). The potential effects of onstream reservoirs should be carefully considered, but they could (with appropriate bypass mechanisms) provide adequate water storage in a way that has low impacts to streamflow below. Given topographic limitations through much of the watershed, offstream reservoirs may not be feasible. However, where they are, they also may provide an opportunity to store water with low impacts to streamflow, so long as water is obtained when there is sufficient flow in the stream and the proportion of water taken for storage is small relative to streamflow.

Overall, the results above indicate that there is enough water on an annual scale to meet all existing human water needs, but diverting water from aquifers, springs, and streams has likely contributed to less water in upper portions of Mark West Creek than would be present naturally. Agricultural needs and residential needs are similar in magnitude, and if water is stored in winter to meet these needs rather than obtained during the dry season, streamflow in Mark West Creek could more than double.

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