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California GAMA Special Study:
A Well Vulnerability Assessment Tool

Ate Visser, A. Jake Harm, Jory Lerback, Jean E. Moran*

Lawrence Livermore National Laboratory

**California State University, East Bay*

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Final Report for the California State Water Resources Control Board

GAMA Special Studies:
A Well Vulnerability Assessment Tool

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GAMA: AMBIENT GROUNDWATER MONITORING & ASSESSMENT PROGRAM SPECIAL STUDY

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Key Points

- The report describes a well vulnerability assessment tool that will complement the GAMA Online Tools that were created to help users understand groundwater quality in California
- The tool assesses contamination vulnerability at 3,095 individual wells in the Central Valley groundwater basins, using contaminant concentrations and environmental tracers that are applied to determine groundwater age, recharge temperature, and recharge water source
- Stoplights give users quick indications of well vulnerability in categories that include vulnerability to land surface contaminants, vulnerability to geologic contaminants, and factors affecting groundwater sustainability

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1. Introduction

The purpose of the Well Vulnerability Assessment Tool (VAT) (described herein) is to provide possible reasons why water supply wells in California's Central Valley are adversely affected by contaminants. The VAT compliments the Groundwater Ambient Monitoring Assessment (GAMA) Program's online tools, which were developed to help users understand groundwater quality in California (California State Water Resources Control Board, n.d.-a). Groundwater is a major component of California's water supply; 16,000 public water supply wells and more than 600,000 private wells are used as drinking water sources. Public water systems, including public supply wells, are tightly regulated for contaminants with state and federal maximum contaminant limits (MCLs). Domestic and small system wells (serving 1-14 connections) are often outside of regulatory reach though, and nearly one million Californians, mostly in rural, disadvantaged communities, may access groundwater that does not meet regulatory guidelines. Access to a reliable drinking water source may also be compromised by drought and over-pumping by nearby wells. Assessing the vulnerability of wells to contaminant and water supply reliability challenges is an important step to ensuring every California resident's human right to clean, safe, and affordable drinking water.

Contaminant concentrations are measured precisely and frequently in public supply wells and requirements for remedial actions are straightforward in relation to MCLs. These wells are monitored for regulated contaminants, while private domestic wells may be monitored infrequently, or not at all. In all cases, however, a lack of understanding of *why* a contaminant is present in a well hinders management and remedial planning. While large amounts of concentration data have been collected for some 90 chemical constituents with primary MCLs at public supply wells, concentration data alone cannot typically be interpreted to determine the reasons for the presence or absence of contaminants. The VAT aims to assess the hydrogeologic and geochemical drivers of contaminant occurrence, and to indirectly assess the source and fate of contaminants.

For more than 20 years, the California State Water Resources Control Board's (State Water Board) GAMA program has included the analysis of environmental tracers in wells tested under the program. When combined with contaminant concentrations, these tracers can be used to understand hydrogeologic and geochemical drivers of contaminant occurrence and transport. The tracers include stable isotopes of the water molecule which allow identification of the source(s) of recharge to wells, whether local precipitation or river water generated from snow melt. Groundwater age, or residence time, as determined using tritium or the tritium-helium system, can indicate a well's susceptibility to contaminants from the land surface when it produces recent recharge, or, on the other end of the time scale, to geological contaminants that often are sourced from long term water-rock interaction (Belitz *et al.*, 2022). When contaminants are not present because sources are not present, these tracers still provide useful information about groundwater sustainability, including susceptibility of wells to going dry during droughts, vulnerability to unsustainable extraction, and the likelihood that recharge sources to the well will be affected.

The VAT is based on statistical analyses of tracer-contaminant pairs and on hydrogeological conceptual models that delineate groundwater flowpaths from recharge to discharge. For example, Visser *et al.*, (2018) show that river water from Sierra Nevada runoff can be identified in wells in the Central Valley, while Castaldo *et al.*, (2021) show that river water brings lower nitrate. Thus, to follow the example, the VAT would indicate that the reasons for (surface-sourced) nitrate occurrence at problematic concentrations in a well may be because nitrate correlates positively with young groundwater and negatively with (low-nitrate) river water contribution.

The VAT is not intended to provide a spatial or temporal predictive capability for contaminant occurrence or concentration trends. Groundwater ages and groundwater age distributions, calculated using the same data set, are interpolated and predicted in other recent studies (Jurgens, 2016; Visser *et al.*, 2016; Faulkner *et al.*, 2023; Azhar *et al.*, 2024). Furthermore, only a handful of contaminants, particularly those from AB1249 (Assembly Bill No. 1249, 2014) (arsenic, nitrate, perchlorate, hexavalent chromium), and uranium (some of the most frequently occurring in the Central Valley), are included in the VAT. Emerging contaminants, contaminants with advisory levels, and volatile organic compounds are not included in the VAT.

The VAT focuses on contaminant occurrence at approximately 3,000 individual wells where all or most of the tracers and contaminant concentrations have been measured. The goal is to provide well owners and water managers with a hydrogeologic context, based on evidence from tracers, for contaminant occurrence.

Functionally, the VAT is envisioned as a Geographic Infromation System (GIS) enabled, web-based tool that uses 'stoplights' (red, yellow, green) to depict contaminant concentrations relative to benchmarks, and to represent vulnerability to contamination using explanatory factors based on tracer results, at individual wells. Based on stoplight outcomes, when vulnerabilities are identified, the tool offers general recommendations for possible remedial actions by well owners and water managers. In particular, the tool can be used by Groundwater Sustainability Agencies (GSAs) engaged in activities that boost water supply while guarding against water quality degradation under California's Sustainable Groundwater Management Act (SGMA).

This report describes the data set upon which the VAT is based, how the tracers are applied as explanatory indicators for contaminants and sustainability, the statistics used to test the relationships between tracers and contaminants, criteria for stoplight cutoffs, and example results for wells. Limitations posed by the data set and by the methods are also outlined.

2. Methods

2.1. Data Sources

Wells included in the VAT study were sampled for isotopic tracers under the following programs: 1) the California State Water Board GAMA Priority Basin Project (PBP) (U.S. Geological Survey), 2) the Groundwater Contamination Susceptibility and GAMA Special Studies projects (Lawrence Livermore National Laboratory (LLNL)), or 3) the Private Domestic Wells project (UC Davis). These projects generally, but not always, included the AB1249 contaminants. The dataset is augmented with analyses of contaminants and tracers from the U.S. Geological Survey's National Water Information System (NWIS) database. When isotopic tracers and contaminants were not sampled on the same date, the result nearest in time to the isotopic tracer sampling date was paired with tracer results and the combined data were used to carry out the assessment. Well IDs were cross-referenced to exclude repeat analyses since data sets use different identifiers. For the combined data set, 'Non-detect' and results with a '<' modifier were set to 0 when detection limits were less than values identified as maximum acceptable detection limits (Table 2). In addition to the analytes shown on Table 2, the maximum acceptable detection limit for tritium was set to 1 pCi/L.

Table 1. Number of wells with information used in study and data source.

Dataset	**Total**	**Recharge Source**	**Groundwater Age**	**Noble Gas Recharge Temperature**	**Fossil Water**
U.S. Geological Survey NWIS	1261	1124	70	35	36
U.S. Geological Survey (State Water Board GAMA PBP)	971	968	731	835	852
LLNL (GAMA and others)	643	638	486	583	596
UC Davis Private Domestic Wells Project	200	200	152	192	198
Newly Sampled (GAMA)	20	20	20	20	20
Total	**3095**	**2950**	**1459**	**1665**	**1702**

(USGS: U.S. Geological Survey; NWIS: National Water Information System; GAMA: Groundwater Ambient Monitoring and Assessment; PBP: Priority Basin Project; LLNL: Lawrence Livermore National Laboratory)

The total number of samples for each tracer from each data source is presented in Table 1, while the total number of results for each water quality analyte is shown in Table 2. The limited data for dissolved oxygen were combined with other factors, such as nitrate, manganese, and iron concentrations to determine the redox characteristics of the groundwater, as outlined in more detail in section 2.4.2.

To augment this dataset, twenty domestic wells were identified and sampled for this project to fill data gaps in areas of the San Joaquin Valley where high numbers of domestic wells have been reported to the Department of Water Resources' (DWR) Dry Well Reporting System (California State Water Resources Control Board, n.d.-

c). More information on selection criteria for these wells and a map showing these wells (Figure 2) are in Section 4.2.

TABLE 2. NUMBER OF WELLS WITH ANALYTE MEASUREMENTS USED IN STUDY

Analyte/Measurement	***n***
Nitrate as N[1]	2641
Arsenic[2]	2496
Perchlorate[3]	980
Hexavalent Chromium*	1215
Uranium[4]	1794
Manganese[5]	2197
Iron*	2308
Dissolved Oxygen*	946

[1] $NO_3(N)$ maximum acceptable detection limit set to 5 mg/L
[2] As maximum acceptable detection limit set to 1 μg/L
[3] ClO_4^- maximum acceptable detection limit set to 0.5 μg/L
[4] U maximum acceptable detection limit set to 1 pCi/L
[5] Mn maximum acceptable detection limit set to 0.5 μg/L
* all 'ND' and '<' results for Cr(VI), Fe, and DO set to 0

Well selection, sample collection, laboratory analyses, and calculations of derived parameters such as noble gas recharge temperatures, tritium-helium age and terrigenic helium-4, are described in several GAMA reports by the U.S. Geological Survey and LLNL, and in published papers (Cey *et al.*, 2009; Visser *et al.*, 2014; California State Water Resources Control Board, n.d.-b). U.S. Geological Survey Data Series reports under GAMA (and references therein) describe well selection, sampling, and analytical methods (e.g., Mathany *et al.*, 2009). Concentration data for the five included contaminants are found on the U.S. Geological Survey NWIS and SWRCB GAMA GIS sites. Visser *et al.* (2016) outline the data reduction methods for the derived parameters and a geostatistical analysis of these tracers that aligns with the conceptual models used in the well vulnerability assessment.

2.2. Conceptual Models

The VAT is based on concepts and analyses that were developed over the last twenty years, since the inception of the GAMA program. GAMA provides the structure and support for collection of both water quality data for individual constituents, often at levels below regulatory limits, along with isotopic and geochemical tracers that can be interpreted to understand groundwater flow and well vulnerability. Conceptual models of groundwater flow and contaminant transport evolve as new data, analytical techniques, and models emerge, and SGMA Groundwater Sustainability Plans (GSPs) have incorporated updated conceptual models.

In the San Joaquin Valley, GSPs present conceptual models that show the predominance of recharge via irrigation return flow (with water supplied by Sierra Nevada Rivers and cyclical groundwater) and nearly-closed basins where pumping exceeds recharge over decadal time periods. The major rivers are mostly separated from direct connection to groundwater and much of the discharge from the major rivers is diverted for irrigation. All of the SGMA criteria, except seawater intrusion (lowering water levels, loss of storage, land subsidence, depletion of interconnected surface water, and degradation of water quality) are under scrutiny in the San Joaquin basins. Compared to the San Joaquin Valley, where nearly all basins are categorized as critically over drafted, the Sacramento Valley has no critically over drafted basins and SGMA criteria under scrutiny generally include only lowering water levels, loss of storage, and depletion of interconnected surface water (California Department of Water Resources, n.d.-a). Recharge in the Sacramento Valley comes from surface water diversions that sustain irrigation return flow, precipitation, and losing streams, with significant recharge in the foothills and along the valley margins.

While the VAT can be applied to address sustainability of groundwater extraction using groundwater age and recharge water source tracers, direct connections can also be made with water quality, where general notions of contaminant sources align with the indicators. As noted above, each of the AB1249 contaminants (nitrate, perchlorate, arsenic, hexavalent chromium) and uranium is presented in the VAT with a stoplight (Section 3.2; Figure 5).

Nitrate, the most frequently occurring chemical contaminant at concentrations above the MCL in groundwater in California, is sourced from agricultural activity (fertilizers and animal operations) and to a lesser extent from onsite wastewater treatment discharge (California State Water Resources Control Board, n.d.-c). Nitrate is transported conservatively in groundwater, except when geochemical conditions (very low dissolved oxygen and sufficient electron donors) lead to denitrification. Since nitrate is released at or near the ground surface, it is associated with young groundwater, and because mountain river water has very low nitrate concentrations, wells recharged by river water are likely to be lower in nitrate (Castaldo *et al.*, 2021). Compared to nitrate, sources of perchlorate (solid propellant for rockets, fireworks, flares, explosives, etc.) are much more spatially limited in the Central Valley and its occurrence at problematic concentrations is much less frequent. Transport of perchlorate is, however, similarly conservative and perchlorate is similarly released at the ground surface.

Arsenic is naturally occurring in aquifer materials and is a widespread contaminant in the San Joaquin Valley and some areas in the center of the Sacramento Valley. Hazardous levels of arsenic are typically associated with anaerobic conditions and over-pumping of clay layers where arsenic has been sorbed to sediments, but where reducing conditions are prevalent, which has led to increased arsenic concentrations in San Joaquin Valley groundwater (Smith *et al.*, 2018). Under these conditions, high arsenic concentrations are therefore typically geogenic and associated with older groundwater and also associated with reducing (low dissolved oxygen) conditions. However, the bulk of pumped groundwater may have a young age but also contain a component of water with high arsenic pumped from clay layers. In the Sacramento Valley, hazardous levels of arsenic occur where granitic- or volcanic-derived sediments and reducing conditions are prevalent, as found in areas around the Sutter Buttes (Bennett V et al., 2011). Anthropogenic arsenic sources include surface sources such as pesticides and wood preservatives.

Hexavalent chromium (Cr(VI)) has both natural and anthropogenic sources. Natural, geogenic chromium is concentrated in ultramafic or metamorphic rocks and water-rock interaction under oxygenated conditions over long periods of time leads to mobilization of chromium as Cr(VI). This process is the likely mechanism for concentrating Cr(VI) in groundwaters of the western Sacramento Valley, and possibly elsewhere in the Central Valley. However, Cr(VI) concentrations are also increased through release of industrial pollution and through anthropogenic processes that enhance oxidation of Cr(III) (Hausladen *et al.*, 2018). Cr(VI) has multiple sources and pathways, both from surface processes and from water-rock interaction with subsurface sediments in the Central Valley. Groundwater age and recharge water source tracers may offer information on why Cr(VI) is high in an area, but patterns cannot be extrapolated for the valley-wide VAT because of the disparate sources and pathways. Groundwater redox state is relevant regardless of the source of Cr(VI), as mobility is enhanced under oxidizing conditions. In October 2024, the SWRCB Division of Drinking Water adopted a new, lower MCL of 10 μg/L for hexavalent chromium, which is the benchmark used by the VAT.

Uranium is a common contaminant in Central Valley groundwater. Uranium is mobile as the uranyl ion (UO_2^{2+}), in which uranium is in the oxidized +6 state. Although uranium is geogenic and ultimately sourced from granitic and rhyolitic parent material, it is mobilized as a result of agricultural practices that favor formation of non-sorbing uranyl-Ca-carbonato species (Lopez *et al.*, 2021). Important sediment-water reactions that mobilize uranium by formation of uranyl-Ca-carbonato species take place in the vadose zone. When uranium is mobilized by such agricultural processes, its occurrence aligns with surface-sourced contaminants rather than geogenic contaminants.

2.3. Vulnerability Indicators and Thresholds

Concentrations of contaminants were classified into three categories, following health-based benchmark thresholds employed by the U.S. Geological Survey for the GAMA program (e.g., Bennett *et al.*, 2023): High, Moderate, and Low. Wells with contaminant concentrations exceeding the MCL are classified as High. For nitrate, arsenic, and uranium, the threshold between Low and Moderate classifications is 50% of the MCL; for perchlorate and hexavalent chromium, this threshold is 10% of the MCL (Figure 1).

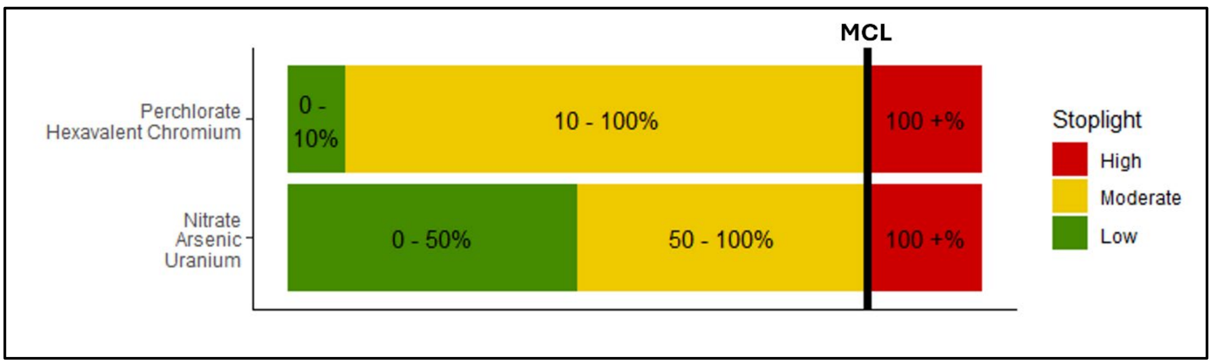


FIGURE 1. ***BENCHMARK THRESHOLDS AND CORRESPONDING STOPLIGHTS FOR THE 5 CONTAMINANTS INCLUDED IN THE VAT.***

Three types of vulnerability indicators are presented: vulnerability to land surface contaminants, vulnerability to geological contaminants, and factors affecting sustainability. The indicators are presented below, with their motivation and technical basis. Four tracers (groundwater age, recharge source, recharge temperature, and terrigenic helium-4) are used for multiple indicators (Table 3). Depending on the perspective, the interpretation of the vulnerability can be different. For example, river water indicates a lower vulnerability to land surface contaminants, but a higher vulnerability for a well going dry due to low recharge rates in dry years. Each indicator is described in detail in this section.

TABLE 3. DESCRIPTION OF VULNERABILITY TYPE WITH INDICATORS AND METRICS.

Type	Indicator	Tracer or metric
Land surface contaminant vulnerability	Young groundwater	Tritium-helium age
	Recharge source	Oxygen-18 of water
	Warm recharge	Noble gas recharge temperature
	Redox condition	Oxygen, nitrate, iron, and manganese concentrations
Geological contaminant vulnerability	Fossil water	Terrigenic helium-4
	Warm discharge	Noble gas recharge temperature
	Redox condition	Oxygen, nitrate, iron, and manganese concentrations
Factors affecting sustainability	Very young water	Tritium-helium age
	River water	Oxygen-18 of water
	Fossil water	Terrigenic helium-4
	Distance to dry well	Distance to nearest dry well

The thresholds for the vulnerability indicators derived from environmental tracer concentrations were based on a combination of physical or chemical properties and the conceptual model (Table 4). For indicators with no physical or conceptual threshold, the data were divided into three groups of approximately equal size using rounded thresholds. Indicators with higher than average vulnerability are indicated by a red stoplight, average with yellow, and lower than average with green. The light is left white when no data is available for the indicator.

The redox condition of the water is presented using a separate light color scheme because the oxidation state of water can change contaminant concentrations for the better or for the worse. Presenting the redox condition itself provides information about the vulnerability of the well to the different contaminants. In the VAT, the redox condition is indicated using the following color scheme: oxic water is shown as blue, anoxic water as black, and mixed water as purple. As before, when the redox condition of the water is not known due to lack of data, the light is left white.

TABLE 4. THRESHOLDS USED FOR EACH ANALYTE USED TO IDENTIFY VULNERABILITY.

Type	name	unit	Primary threshold		Secondary threshold	
			qualifier	value*	qualifier	value
cont	Nitrate	mg/L	>	10	>	5
cont	Arsenic	ug/L	>	10	>	5
cont	Perchlorate	ug/L	>	6	>	0.6
cont	Hexavalent Chromium	ug/L	>	10	>	1
cont	Uranium	pCi/L	>	20	>	10
lscv	Young water	years	<	30	<	70
lscv	Recharge source[SJV]	‰	>	-9	>	-12
lscv	Recharge source[SAC]	‰	>	-8.7	>	-10.3
lscv	Warm recharge	° C	>	0	>	-2
gcv	Fossil water	cm^3STP/g	>	4.65×10^{-8}	>	4.65×10^{-9}
gcv	Warm discharge	° C	>	5	>	3
gcv	Redox condition**	mg/L				
sv	Very young water	years	<	12	<	12
sv	River water[SJV]	‰	<	-12	<	-9
sv	River water[SAC]	‰	<	-10.3	<	-8.7
sv	Fossil water	cm^3STP/g	>	4.65×10^{-7}	>	4.65×10^{-8}
sv	Distance to dry well	meter	<	1000	<	1500

TYPES OF INDICATORS: CONT: CONTAMINANT; LSCV: LAND SURFACE CONTAMINANT VULNERABILITY; GCV: GEOLOGICAL CONTAMINANT VULNERABILITY; SV: SUSTAINABILITY VULNERABILITY.

* THE PRIMARY THRESHOLD VALUE FOR THE CONTAMINANTS EQUALS THE MCL.

** THE REDOX INDICATOR IS BASED ON DISSOLVED OXYGEN, NITRATE, IRON, AND MANGANESE CONCENTRATIONS, AS DESCRIBED BELOW.

SJV: THRESHOLDS FOR WELLS IN THE SAN JOAQUIN VALLEY

SAC: THRESHOLDS FOR WELLS IN THE SACRAMENTO VALLEY

2.3.1. Explanation of Indicators

2.3.1.1. Indicators of Vulnerability to Land Surface Contaminants

Age: Apparent groundwater ages, referred to hereafter as "ages", indicate the amount of time that has elapsed since water entered the saturated zone (Burow *et al.*, 2010; Castaldo *et al.,* 2021; Levy *et al.,* 2021; Faulkner *et al.,* 2023). The age can be derived from several different environmental tracers. For this study, the age was derived from tritium and its decay product helium-3. Tritium (^3H) occurs naturally in the environment through cosmic ray spallation in the atmosphere and through anthropogenic means, as the product of nuclear weapons testing and nuclear fuel reprocessing (Michel, 2005).

The onset of atmospheric nuclear testing in the 1950s provides a clear distinction between pre-modern (recharged prior to 1953) and modern groundwater (Clarke *et al*., 1976; Surano *et al.*, 1992). Pre-modern water has lower than average vulnerability to land surface contaminants. Thirty-four percent of samples in the VAT are pre-modern. The primary threshold was placed at 30 years, separating young from intermediate age groundwater. Young water indicates a relatively rapid rate of recharge along shorter groundwater flowpaths and is typically found at shallower depths, giving it more opportunities to interact with and mobilize contaminants, like nitrogen fertilizers, percolating down from the land surface. Young water therefore has higher than average vulnerability to land surface contaminants. Thirty-five percent of samples have an age of less than 30 years. Thirty-one percent of samples have an intermediate age. Since most of the samples were collected between 2000 and 2020, the 30-year threshold also separates equal ranges of groundwater recharge years: from 1950 to 1980, and from 1980 to 2010.

Recharge Source: The recharge source was based on the measured $\delta^{18}O$ value in groundwater samples. River water originating in high elevation watersheds has lower $\delta^{18}O$ than local rain; however, because the watersheds of the rivers in the San Joaquin Valley are at higher elevations than the watersheds of the Sacramento Valley rivers, different thresholds are necessary to differentiate the recharge sources in the two basins (Dansgaard, 1964; Ingraham & Taylor, 1991). The thresholds for the San Joaquin Valley were based on a prior study of river water recharge that showed groundwater with a $\delta^{18}O$ value of less than -12 ‰ originated as river water and groundwater with a $\delta^{18}O$ value of greater than -9 ‰ originated as local rain (Visser *et al.*, 2018). The thresholds for the Sacramento Valley were set as $\delta^{18}O$ less than -10.3 ‰ river water and $\delta^{18}O$ greater than -8.7 ‰ local rain, based on previous studies of streams in the valley (Davisson, 2001; Grimm, 2020; Sowers *et al.*, 2017). Combined, 13% of wells are recharged by river water, 42% of wells are recharged by local rain, and 45% of wells have a mixed recharge source. River water indicates a lower vulnerability to land surface contaminants, while rain water recharge indicates a higher vulnerability.

Recharge Temperature: Noble gases have temperature dependent solubility rates in water, which can be used to estimate the temperature of the water at the time of recharge. Groundwater typically recharges at the mean annual air temperature (MAAT) in the unsaturated zone, with the noble gas concentrations that dissolve at that temperature (Cey *et al.*, 2009). The difference between the recharge temperatures and the MAAT at the well can indicate whether the groundwater recharged locally or at higher altitudes in a watershed in the Sierra Nevada or Cascade Range mountains (Cey *et al.*, 2009; Visser *et al.*, 2014; Peters *et al.*, 2018). A recharge temperature below the MAAT is indicative of fast wintertime recharge due to direct river infiltration or Managed Aquifer Recharge (MAR). Recharge that occurs at or above the MAAT is attributed to slow infiltration in deep unsaturated zones or summertime irrigation return flow. The threshold for warm recharge was set at a temperature difference of 2 °C (5 °F) above the MAAT and is associated with higher than average vulnerability to land surface contaminants. Thirty-four percent of wells have a recharge temperature below the MAAT, 39% of wells have a recharge temperature of more than 2 °C above the MAAT, and 26% have a recharge temperature 0 - 2 °C higher than the MAAT.

2.3.1.2. Indicators of Vulnerability to Geological Contaminants

Fossil Water: Fossil water, or water that recharged thousands of years prior to sampling, is determined using the isotopic tracer terrigenic helium-4. Terrigenic helium-4 accumulates in groundwater from fluxes in the crust and mantle and as the product of the decay of uranium and thorium in aquifer materials (Kulongoski *et al.,* 2008). In ideal circumstances, the accumulation rate of terrigenic helium-4 from this decay can be accurately estimated from the porosity and the concentrations of U and Th in the sediment. Because of the variability of uranium and thorium across Central Valley sediments and the addition of crustal and mantle helium via slow upward diffusion, the accumulation rate varies substantially.

Fossil water can be used as an indicator of vulnerability to geogenic contaminants, since prolonged contact with aquifer materials allows for greater dissolution. The threshold for terrigenic helium-4 for vulnerability to geological contaminants was set relative to the concentration of atmospheric helium in groundwater (4.65×10^{-8} cm^3STP/g). Samples with a terrigenic helium-4 concentration of less than 10% of the dissolved helium concentration from the atmosphere were assigned a lower than average vulnerability. Samples with a terrigenic helium-4 concentration greater than the dissolved helium concentration from the atmosphere were assigned a higher than average vulnerability. Samples with a concentration in between these thresholds were assigned an average vulnerability to geological contaminants. Forty-nine percent of wells have low terrigenic helium-4 concentrations, 13% have a terrigenic helium-4 between 10% and 100% of atmospheric, and 37% have a high terrigenic helium-4 concentration.

Geothermal Warming: Geothermal warming of groundwater can be used as an indicator of vulnerability to geological contaminants due to deep groundwater flowpaths and increased dissolution of material from aquifer sediments. To calculate the amount of geothermal warming of the groundwater, the temperature of the water at the time of sampling was compared to the noble gas recharge temperature. Thresholds for warm groundwater discharge were set at +3 °C (+5 °F) and +5 °C (+9 °F), resulting in three equal groups containing 39% of wells (< 3 °C warming), 31% of wells (3-5 °C warming), and 30% of wells (>5 °C warming). Higher temperatures indicate higher than average vulnerability to geological contaminants. Assuming a geothermal gradient of 25 °C per kilometer depth, these thresholds correspond to groundwater flow path depths of 120 m (~400 ft) and 200 m (~650 ft). However, geothermal gradients vary across the Central Valley and the relationship between flow path depth and temperature is complicated by mixing of multiple flow paths at the well screen.

2.3.1.3. Redox Processes

Redox Processes: As previously noted, geochemical processes involving the oxidation state of dissolved species can change contaminant concentrations in multiple ways and therefore affect vulnerabilities to both land surface and geological contaminants. For example, while nitrate is typically removed in anoxic groundwater, various geological contaminants can be mobilized under anoxic conditions. Recharging groundwater typically contains oxygen and is considered oxic. A complete analysis of the redox state of groundwater requires precise measurements of dissolved oxygen, nitrate, manganese, iron, sulfur species, methane, and hydrogen. Because these analyses are not available for many wells, a simplified classification was used, based on dissolved oxygen and/or nitrate as indicators of oxic groundwater, and dissolved oxygen, manganese and/or iron as indicators of anoxic groundwater.

In the VAT, “Oxic” water has either a dissolved oxygen concentration of more than 1 mg/L or a nitrate concentration of more than 0.5 mg/L. “Anoxic” groundwater has either a manganese concentration of more than 50 µg/L, an iron concentration of more than 100 µg/L, or a dissolved oxygen concentration of less than 0.5 mg/L. If both oxic and anoxic groundwater is detected using these criteria, the sample is classified as “Mixed”. If none of these criteria are met, the redox state of the sample was “Not available”. Fifty-five percent of samples in the VAT are oxic, 12% are anoxic, 12% have a mixed redox state, and 21% have an unknown redox state. Vulnerabilities based on the redox condition of the water are presented in the description of the redox condition (section 3.3).

2.3.1.4. Factors Affecting Sustainability

Very Young Groundwater. As previously noted, groundwater age was calculated from tritium and its decay product helium-3. Samples with ages of less than 12 years are considered very young, or recharged very recently, indicating a rapid flowpath. Wells containing very young groundwater are more susceptible than average to being adversely affected during a prolonged drought, including the possibility of “going dry.” During prolonged droughts, there is less recharge from both river water and precipitation, and there is increased pumping, which lowers groundwater levels, sometimes on a regional scale. Lessening of recharge over several years would affect these wells more quickly than wells that capture mostly older groundwater. Twelve percent of samples in the VAT have groundwater ages of less than 12 years.

River Recharge: Using the same thresholds discussed for Recharge Source above, the source of recharging groundwater can be an indicator of sustainability. A large proportion of river water found in a well indicates a higher vulnerability to recharge variability due to multi-year droughts, leading to severe groundwater level fluctuations that could cause a well to go dry. Rainwater recharge’s impact on water level is assumed to be dampened by deeper unsaturated zones, resulting in smaller groundwater level fluctuations. Since climate change models predict increased variability (and less precipitation overall) in high-elevation precipitation feeding the rivers, areas that are heavily reliant on river recharge could become increasingly vulnerable to lowering groundwater levels that affect sustainability (Siirila-Woodburn *et al.*, 2021).

Fossil Water: The presence of fossil water indicates a very slow rate of recharge to the aquifer and increased vulnerability to long-term sustainability issues, if the rate of groundwater abstraction exceeds the slow rate of recharge (De Jong *et al.*, 2020). Fossil water may be mined unsustainably if it represents a large fraction of the water produced by the well. As above, the thresholds for terrigenic helium-4 were set relative to the concentration of atmospheric helium in groundwater (4.65×10^{-8} cm^3STP/g). For the sustainability vulnerability indicator, the thresholds are 1x and 10x the atmospheric helium concentration. With these thresholds, 63% of wells have a low terrigenic helium-4 concentration, 22% have a moderate concentration, and 16% have a high concentration. Wells with high terrigenic helium-4 concentrations have a higher proportion of fossil water and are therefore more vulnerable to long-term sustainability issues.

Distance to Dry Well: A well reported dry to DWR’s Dry Well Reporting System is a sign groundwater levels in the local area are declining, indicating nearby wells of similar depth are more vulnerable to going dry. Since aquifer properties can vary over relatively short distances, thresholds of 1 km and 1.5 km from a reported dry well were used to gauge vulnerability to conditions similar to those experienced by the nearby reported dry well. Wells within 1 km of a reported dry well have higher than average vulnerability to going dry. Eighteen percent of wells are within 1 km of a dry well, 8% are between 1 km and 1.5 km of a dry well, and 75% of wells are more than 1.5 km away from a dry well.

3. Results

A majority of the wells included in the VAT were sampled under the GAMA program, which was initiated in 2002 and continues to the present. The GAMA priority basin project uses a grid approach, delineating spatial cells in study units that are based on the size of the area being sampled and the number of public supply wells available for sampling (Belitz *et al.*, 2018). The wells are therefore distributed widely throughout the Central Valley (Figure 2). Basins with large numbers of reported dry wells also typically include a large number of wells covered by the VAT (Table 5).

3.1. Wells Included

TABLE 5. WELL LOCATIONS AND NUMBERS OF WELLS IN THE STUDY

Groundwater Subbasin Name	Basin Number	Basin Name	Included Wells	Reported Dry Wells
Antelope	5-021	Sacramento Valley	6	41
Bend	5-021	Sacramento Valley	2	2
Butte	5-021	Sacramento Valley	64	0
Chowchilla	5-022	San Joaquin Valley	20	68
Colusa	5-021	Sacramento Valley	88	105
Corning	5-021	Sacramento Valley	22	205
Cosumnes	5-022	San Joaquin Valley	43	13
Delta-Mendota	5-022	San Joaquin Valley	228	21
East Contra Costa	5-022	San Joaquin Valley	0	0
Eastern San Joaquin	5-022	San Joaquin Valley	299	133
Kaweah	5-022	San Joaquin Valley	126	798
Kern County	5-022	San Joaquin Valley	311	41
Kettleman Plain	5-022	San Joaquin Valley	3	0
Kings	5-022	San Joaquin Valley	372	1013
Los Molinos	5-021	Sacramento Valley	12	3
Madera	5-022	San Joaquin Valley	69	749
Merced	5-022	San Joaquin Valley	127	166
Modesto	5-022	San Joaquin Valley	145	57
North American	5-021	Sacramento Valley	175	1
North Yuba	5-021	Sacramento Valley	5	0
Pleasant Valley	5-022	San Joaquin Valley	1	1
Red Bluff	5-021	Sacramento Valley	43	129
Solano	5-021	Sacramento Valley	10	3

South American	5-021	Sacramento Valley	75	1
South Yuba	5-021	Sacramento Valley	8	0
Sutter	5-021	Sacramento Valley	29	2
Tracy	5-022	San Joaquin Valley	24	4
Tulare Lake	5-022	San Joaquin Valley	140	119
Tule	5-022	San Joaquin Valley	112	744
Turlock	5-022	San Joaquin Valley	146	93
Vina	5-021	Sacramento Valley	128	34
Westside	5-022	San Joaquin Valley	224	1
White Wolf	5-022	San Joaquin Valley	2	0
Wyandotte Creek	5-021	Sacramento Valley	11	12
Yolo	5-021	Sacramento Valley	25	19

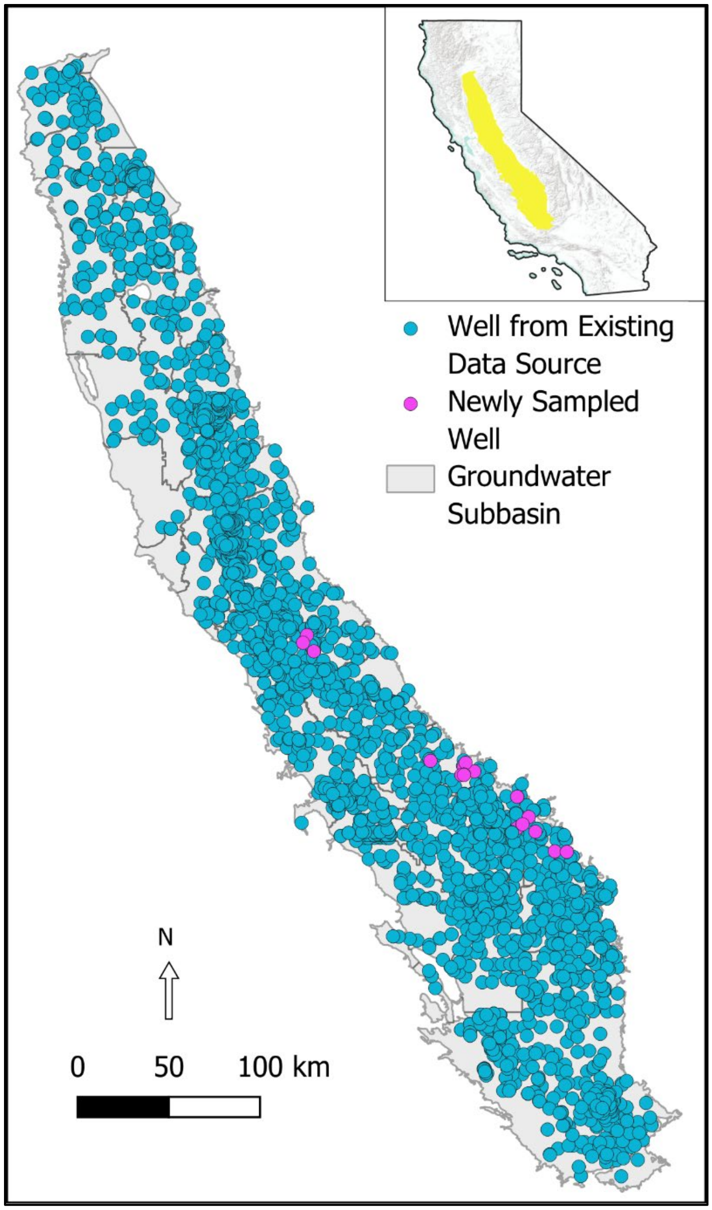


Figure 2. ***Map of all wells included in the tool. Newly sampled wells highlighted.***

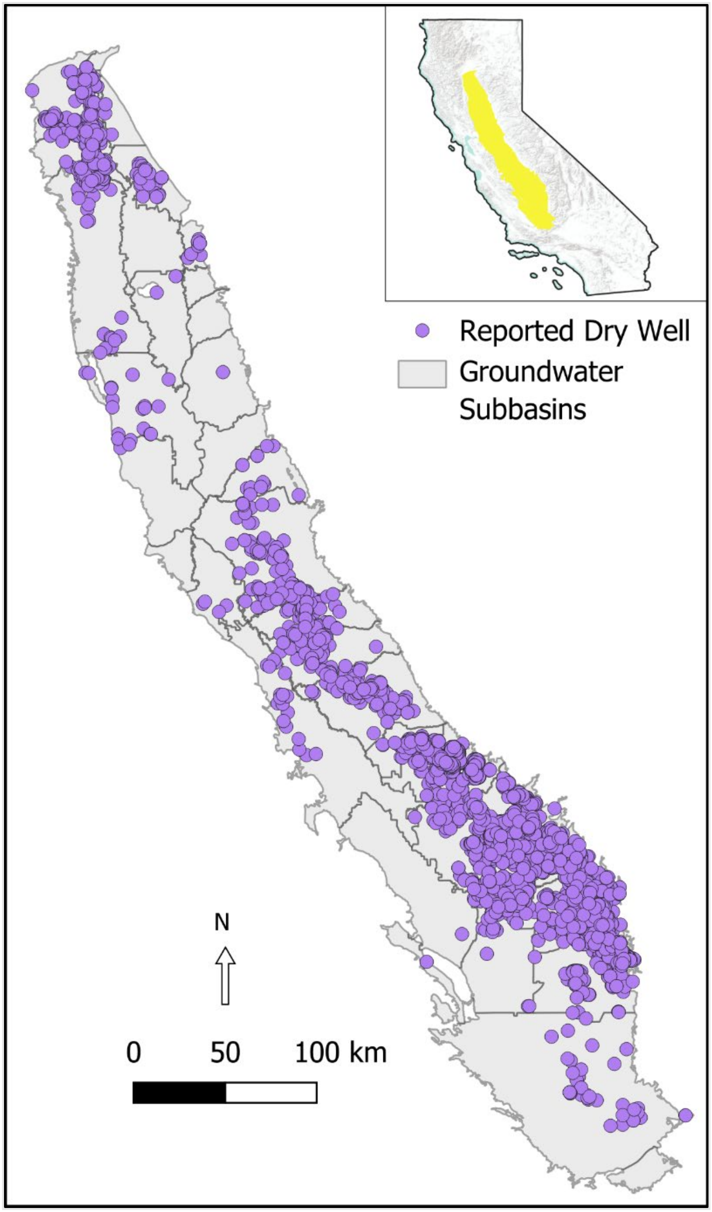


FIGURE 3. ***MAP OF REPORTED DRY WELLS IN THE CENTRAL VALLEY AS OF THE END OF WATER YEAR 23-24***

3.2. Overall Vulnerability Statistics

A summary of the count of wells that fall into each of the stoplight vulnerability categories is shown in Table 6. The justifications for the cutoffs and proportions of samples in each group are described in Section 2.3. Approximately equal numbers of wells in the Discharge Temperature category are the result of binning the data into three, roughly equal groups.

For land surface contaminants, 63% of wells have high top-level vulnerability, 32% have moderate, and 6% have low, of the total number of wells characterized (n = 2961). For geological contaminants, 47% of wells are classified as high top-level vulnerability, 20% as moderate, and 34% as low, of the total number of wells characterized (n = 1704). For factors affecting sustainability, 26% of wells were classified as high top-level vulnerability, 43% as moderate, and 31% as low, of the total number of wells characterized (n = 2961). The highest proportion of wells with a high top-level vulnerability are in the land surface contamination category. Of wells with at least one high vulnerability (n = 2346), 62% have only one, 30% have two, and 7% have all three.

Table 6. Number of wells in each vulnerability class.

Type	Vulnerability	Low	Moderate	High	Total
Land Surface	Age	see pivot tab in table- word online wont let me paste			
Land Surface	Recharge Source				
Land Surface	Recharge Temperature				
Land Surface Top-level					
Geological	Fossil Groundwater				
Geological	Discharge Temperature				
Geological Top-Level					
Sustainability	Very Young Groundwater				
Sustainability	Fossil Groundwater				
Sustainability	Recharge Source				
Sustainability	Distance to Dry Well				
Sustainability Top-level					

For categories based on tritium-helium groundwater age or accumulation of terrigenic helium-4, it should be noted that most wells produce water with a mixed modern and pre-modern age. Likewise, the high number of wells in the Moderate category for Recharge Source are the result of combined precipitation and river water recharge sources to the well. Mixing, caused by dispersion in the heterogeneous Central Valley basin sediments and by mixing in the wellbore, can provide a measure of buffering to both surface-sourced and geological contaminants. Similarly, wells with mixed ages are buffered against the two end members with respect to unsustainable pumping, i.e., mining fossil groundwater and rapid extraction of recently recharged groundwater that is vulnerable to droughts.

While the VAT relies primarily on conceptual models of groundwater flow and contaminant behavior, statistical correlations between the various parameters used in the tool support the application of the tracers to explain water quality patterns. For example, nitrate concentrations vary with oxygen-18 ratios (Pearson's r of 0.28), groundwater age (-0.31), dissolved oxygen (0.27), and recharge temperature (0.15), while arsenic concentrations show correlations with groundwater age (0.20) and dissolved oxygen (-0.31). Relationships between contaminant concentrations and terrigenic helium-4 are more complex, and non-linear. It should be noted that several of the parameters in the VAT vary with well depth (total depth, depth to top perforation, and depth to bottom perforation), including, e.g., groundwater age (Pearson's r of 0.43 with depth to top perforation), geothermal warming (0.43 with total well depth), nitrate (-0.16 with depth to top perforation), and arsenic (0.20 with depth to top perforation). Several of the parameters vary in similar ways with total dissolved solids (TDS), which, like groundwater age, typically increases with depth. Correlations are generally stronger between the tracers and contaminant concentrations than between depth parameters and contaminant concentrations. Some of the patterns and correlations between the parameters applied in the VAT have been documented, quantitatively and qualitatively, in previous publications that rely on GAMA data (Visser *et al.*, 2018; Castaldo *et al.*, 2021; Belitz *et al.*, 2022; Jurgens *et al.* 2022).

3.3. Tool Visualization

Conceptually, six distinct windows will be available for each well included in the VAT. The top-level stoplight window will indicate the highest level of vulnerability for any of the contaminants or indicators in each sub-category, symbolized by a red, yellow, or green "light" (Figure 4). For example, if any one of the specific contaminants is above thresholds leading to a red light (i.e., above an MCL), then the top level 'Vulnerability to Specific Contaminants' indicator (under the flask symbol) would be red. The other sub-categories are (from left to right): 'Vulnerability to Land Surface Contaminants', 'Vulnerability to Geological Contaminants', 'Factors Affecting Sustainability', and 'Possible Mitigation Actions'. Clicking on their respective symbols brings up expanded windows with stoplights for each of the vulnerability indicators in the group, along with text that explains the meaning of the stoplight color.

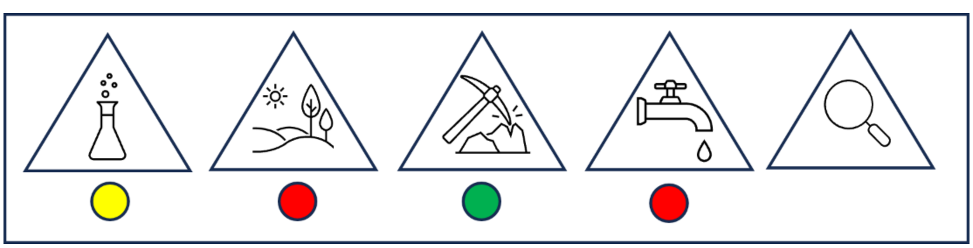


FIGURE 4. OVERVIEW WINDOW, DISPLAYING THE TOP-LEVEL VULNERABILITY CATEGORIES AND THEIR RESPECTIVE STOPLIGHTS

Clicking on the flask symbol expands the window to display the vulnerability indicator stoplights for each of the contaminants (Figure 5). Each contaminant is assigned a stoplight color based on the contaminant concentration, as described in section 2.3. The MCL for each contaminant and a link to the SWRCB's website about the contaminant in drinking water, where users can get more information, are provided.

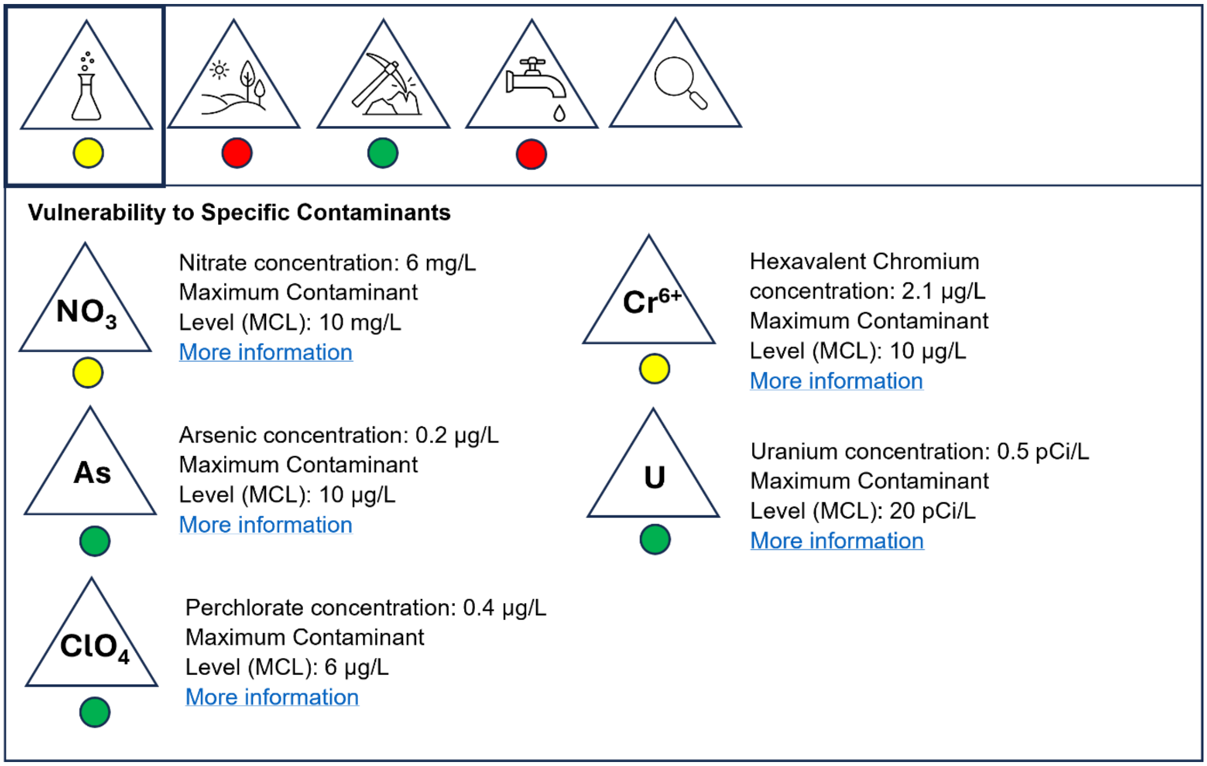


FIGURE 5. SPECIFIC CONTAMINANTS WINDOW, DISPLAYING INDIVIDUAL CONTAMINANT STOPLIGHTS AND CONCENTRATIONS

Selecting subsequent categories opens expanded windows with individual vulnerability indicators and their associated stoplights. The vulnerability level for each is described, followed by a brief explanation of the vulnerability and how it is derived (Figures 6, 7, and 8).

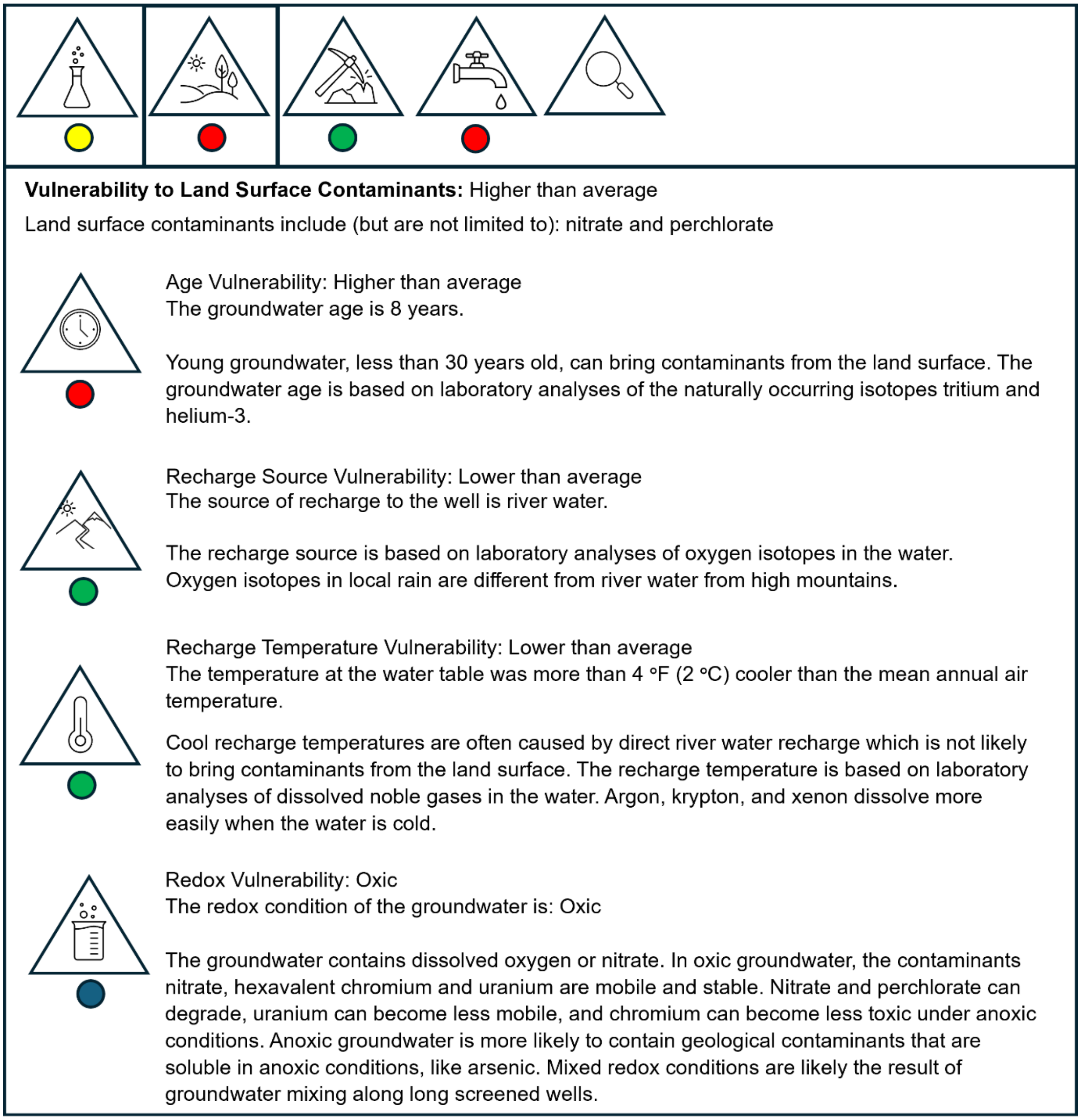


FIGURE 6. VULNERABILITY TO LAND SURFACE CONTAMINANTS WINDOW, DISPLAYING INDIVIDUAL VULNERABILITY STOPLIGHTS AND DESCRIPTIONS

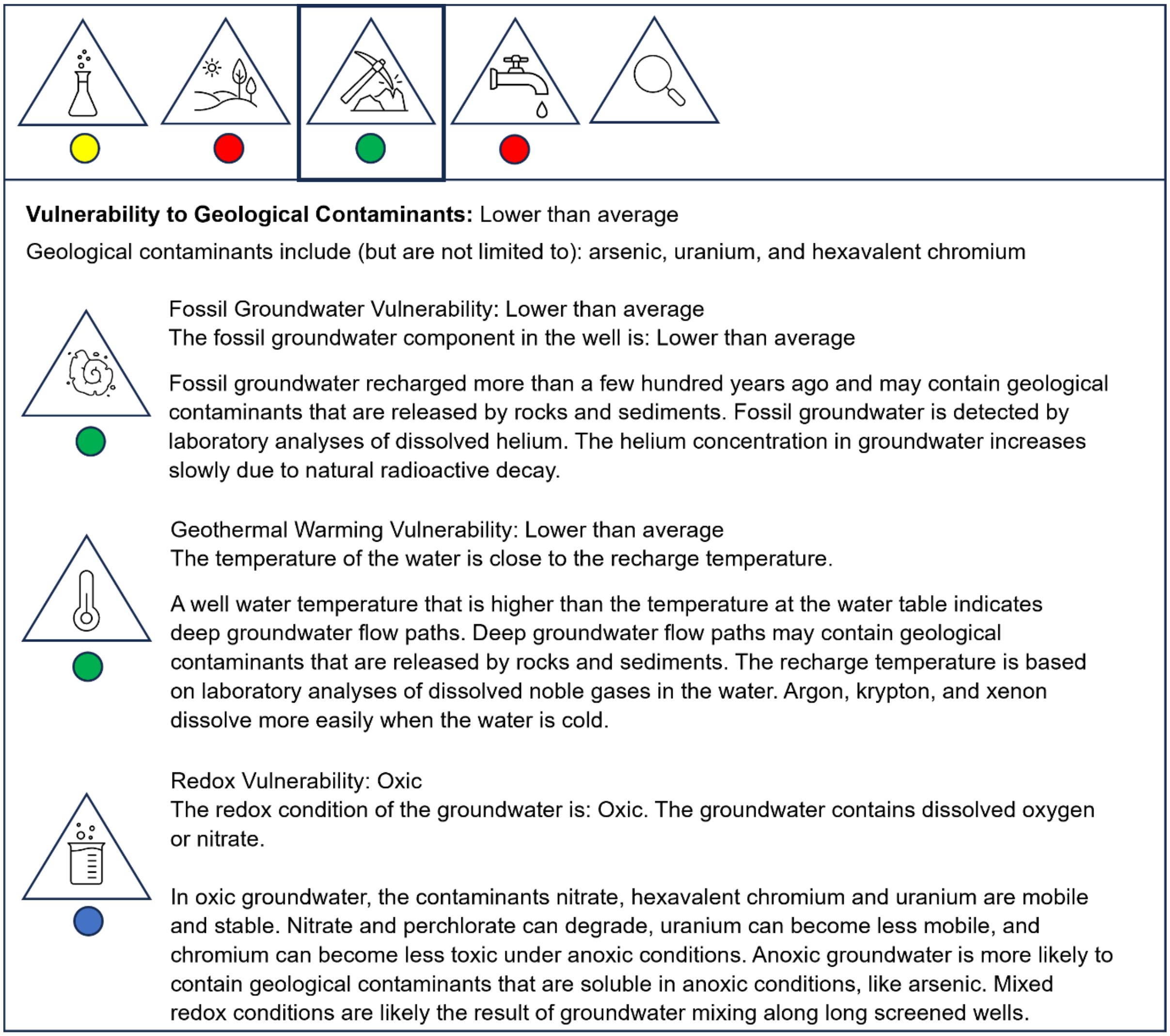


FIGURE 7. VULNERABILITY TO GEOLOGICAL CONTAMINANTS WINDOW, DISPLAYING INDIVIDUAL VULNERABILITY STOPLIGHTS AND DESCRIPTIONS

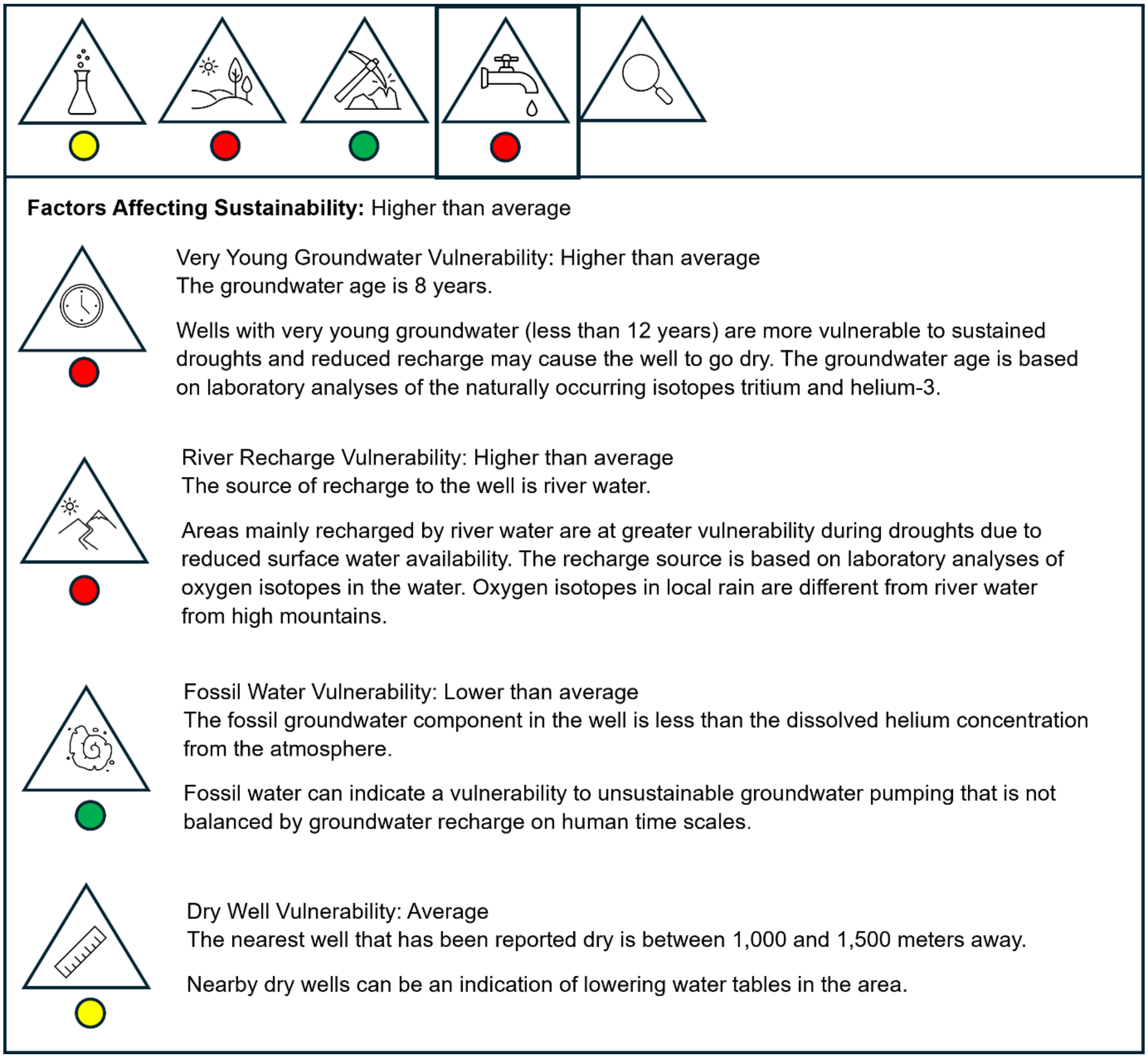


FIGURE 8. FACTORS AFFECTING SUSTAINABILITY WINDOW, DISPLAYING INDIVIDUAL VULNERABILITY STOPLIGHTS AND DESCRIPTIONS

The 'Possible Mitigation Actions' category (magnifying glass) doesn't have an associated stoplight but provides suggested actions well owners or water managers could take for a well with similar vulnerabilities (Figure 9). Based on the vulnerabilities identified for the specified well, possible actions are presented with a brief explanation for why the action was suggested. The possible actions include more frequent water quality testing, water treatment, blending with another source, use of an alternative source, local groundwater level monitoring, and well deepening.

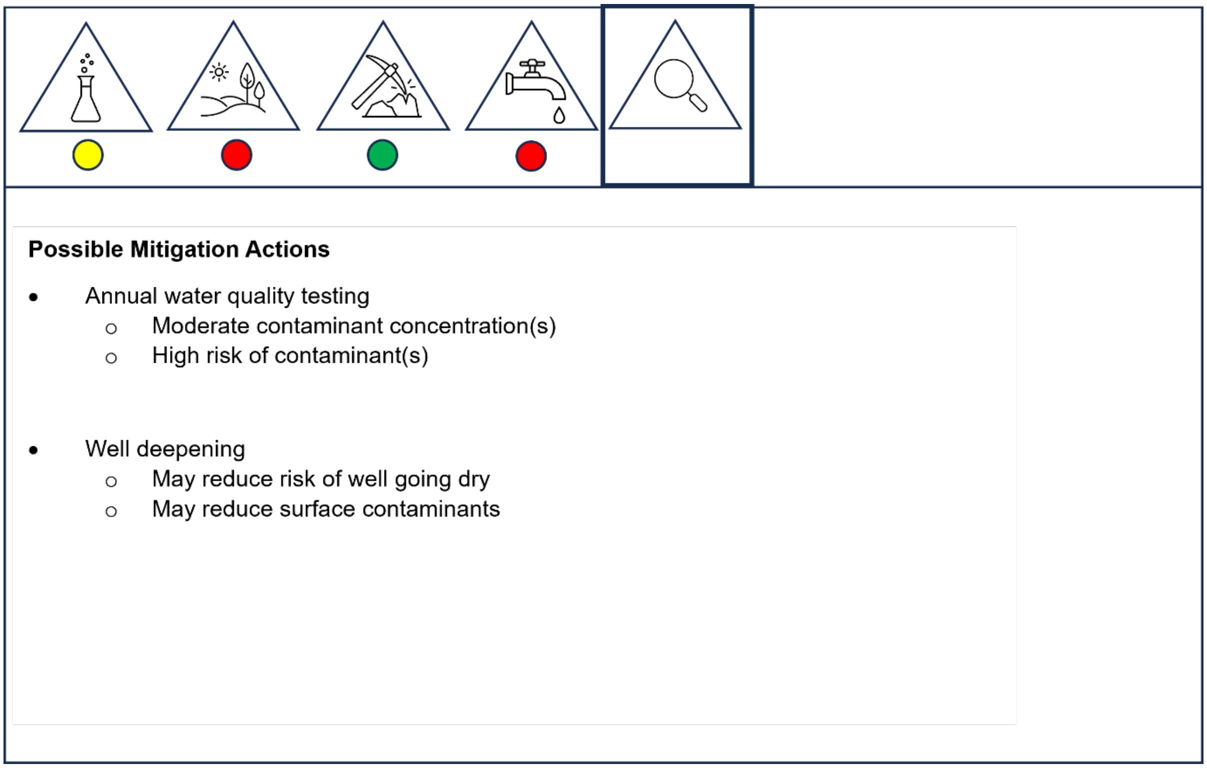


FIGURE 9. POSSIBLE MITIGATION ACTIONS WINDOW, DISPLAYING RECOMMENDATIONS FOR ACTIONS BASED ON THE VULNERABILITIES OUTLINED IN PREVIOUS WINDOWS

4. Testing the tool

4.1. Accuracy Tests

To evaluate the meaning of higher and lower vulnerabilities based on environmental tracer indicators, we analyzed the proportion of wells with high contaminant concentrations (above the MCL) in each of the vulnerability categories (Table 7). In this section, the proportion of wells with a high contaminant concentration are used as the probability that a high nitrate concentration is present in a well. Based on the probabilities for higher than average and lower than average vulnerability scores, we calculate how much more likely it is to find a high contaminant concentration, based on each indicator independently. These metrics are intended to qualify the predictive power of each of the vulnerability indicators, rather than to precisely predict vulnerability for each well. Accuracy statistics for all three categories of contaminant concentration (not just high) are shown in the table in the Appendix. Many factors contribute to contaminant vulnerability, and we did not combine indicator results into a single probability.

TABLE 7. PROPORTION OF WELLS WITH A HIGH CONTAMINANT CONCENTRATION (ABOVE THE MCL) WITHIN GROUPS OF WELLS WITH A VULNERABILITY INDICATOR AVAILABLE (OVERALL), OR AN INDICATOR VALUE OF "HIGHER THAN AVERAGE", "AVERAGE", OR "LOWER THAN AVERAGE".

Contaminant:	NO3N	AS	PCATE	CR6	U
Young water					
Overall	15%	13%	1%	4%	8%
Higher than Average	26%	6%	2%	3%	13%
Average	16%	10%	3%	4%	8%
Lower than Average	2%	22%	0%	6%	2%
Recharge source					
Overall	20%	14%	2%	5%	10%
Higher than Average	24%	14%	3%	7%	7%
Average	20%	14%	1%	4%	12%
Lower than Average	9%	17%	0%	0%	11%
Warm recharge					
Overall	15%	11%	2%	4%	8%
Higher than Average	21%	9%	1%	6%	10%
Average	16%	13%	2%	4%	9%
Lower than Average	8%	12%	2%	3%	4%
Fossil water					
Overall	15%	11%	2%	4%	8%
Higher than Average	7%	18%	2%	4%	5%
Average	17%	10%	2%	5%	7%
Lower than Average	21%	7%	2%	5%	10%
Warm discharge					
Overall	14%	12%	1%	5%	7%
Higher than Average	9%	20%	1%	6%	5%
Average	15%	9%	0%	5%	7%
Lower than Average	16%	9%	1%	5%	9%

Contaminants associated with land surface processes (nitrate, perchlorate, uranium) are analyzed with respect to the Land Surface Contaminant indicators Groundwater Age, Recharge Source, and Recharge Temperature, as well as Redox. Geological contaminants (arsenic) are discussed with respect to the Geological Contaminant indicators Fossil Water and Discharge Temperature, as well as Redox.

4.1.1. Land Surface Contaminants

4.1.1.1. Nitrate

In the subset of wells with a Groundwater Age vulnerability score, 15% of wells in the VAT have a nitrate concentration above the MCL.

Groundwater Age: High nitrate is 2x more likely in young well water with a higher than average vulnerability based on the groundwater age. In contrast, high nitrate is 8x less likely in old (pre-modern) well water with a lower than average vulnerability. Combined, wells with young water are 12x more likely to have a nitrate concentration above the MCL.

Recharge Source: High nitrate is 20% more likely in wells with local rain as the primary recharge source, compared to 2x less likely in wells with river water as the primary recharge source. Combined, nitrate is 3x more likely in wells with local rain as the primary recharge source than wells with river water as the primary recharge source.

Recharge Temperature: A high nitrate concentration is 40% more likely in wells with warmer recharge temperature and 2x less likely in wells with a cooler recharge temperature. Combined, wells with warm recharge temperature are 3x more likely to have a high nitrate concentration than wells with a cool recharge temperature.

Redox: Because samples with more than 0.5 mg/L nitrate were classified as oxic or mixed, high nitrate concentrations are not detected in anoxic groundwater, by definition. High nitrate concentrations are equally likely in groundwater with an Oxic or Mixed redox state (26%).

4.1.1.2. Uranium

Overall, 10% of wells in the VAT have a uranium concentration above the MCL. 8% of wells in the VAT with groundwater age data have a uranium concentration above the MCL.

Groundwater Age: High uranium is 60% more likely in young groundwater and 4x less likely in pre-modern groundwater. Combined, high uranium is 7x more likely in young water than in pre-modern water.

Recharge Source: High uranium is equally likely in wells with local rain or river water recharge sources.

Recharge Temperature: High uranium is 30% more likely in wells with warm recharge temperatures and 2x less likely in wells with cooler recharge temperature. Combined, high uranium is 3x more likely in warm vs cool recharge.

Fossil Water: High uranium is 60% less likely in wells with a fossil water component and 30% more likely in wells without a fossil water component. Combined, uranium is 2x more likely in wells *without* fossil water than wells with fossil water.

Warm Discharge: High uranium is 40% less likely in wells with a warmer discharge temperature and 30% more likely in wells with a normal discharge temperature. Combined, high uranium is associated with normal discharge temperatures.

The higher likelihood of high uranium in wells with land surface contaminant vulnerabilities and the lower likelihood in wells with geological contaminant vulnerabilities indicates that uranium is associated with land surface activities, although the source is release from aquifer materials. This pattern follows from intensive agriculture and is likely specific to agricultural basins like the San Joaquin Valley.

Redox: High uranium is equally likely in oxic or anoxic groundwater (~9%) but 2x more likely in groundwater samples with a Mixed redox state.

4.1.1.3. Perchlorate

Overall, 2% of wells in the VAT have a perchlorate concentration above the MCL. In the subset with groundwater age data, only 1% of wells have a high perchlorate concentration. Perchlorate concentrations are correlated with nitrate concentrations in the data set, and the aquifer conditions that dictate occurrence and fate are similar for the two contaminants.

Groundwater Age: Young groundwater is 2x more likely to have a high perchlorate concentration. High perchlorate is 3x more likely in intermediate age groundwater (30-75 years). Perchlorate was not detected in pre-modern groundwater samples.

Recharge Source: High perchlorate is 50% more likely in locally recharged groundwater and perchlorate was not detected in wells with a primarily river water recharge source.

Recharge Temperature: No differences were found in the proportion of wells with high perchlorate concentrations with respect to warmer or cooler recharge temperatures.

Redox: High perchlorate concentrations are equally likely in Oxic or Anoxic groundwater (1%) but 5x more likely in groundwater with a Mixed redox state. Natural, microbial degradation of perchlorate occurs under anaerobic conditions in the presence of electron donors (Shrout and Parkin, 2006; Robertson *et al.,* 2013), similar to conditions favorable to denitrification.

4.1.2. Geological Contaminants

4.1.2.1. Arsenic

High arsenic concentrations are found in 14% of all wells in the VAT and in 13% of wells in the VAT with groundwater age data.

Fossil Water: High arsenic concentrations are 60% more likely in wells with a large fossil water component but 60% less likely in wells with a small component or no fossil water. Combined, high arsenic is 3x more likely in wells with fossil water.

Warm Discharge: High arsenic is 70% more likely in wells with a discharge temperature more than 5 °C (9 °F) above the MAAT, and 30% less likely in groundwater with no sign of geothermal heating. Combined, arsenic is 2x more likely if well water is more than 5 °C (9 °F) warmer.

Redox: High arsenic is 3x less likely in Oxic groundwater and 3x more likely in Anoxic groundwater. High arsenic is 50% more likely in Mixed redox groundwater. Combined, a high arsenic concentration is 8x more likely in Anoxic groundwater than in Oxic groundwater.

In the Central Valley, arsenic is the only contaminant with a stoplight that occurs as a geological contaminant; however, other elements have been identified as being geogenic in various settings, including iron, manganese, vanadium, selenium, fluoride, iodine, and molybdenum (Pichler *et al.*, 2016; Mukherjee *et al.*, 2024; Wang *et al.*, 2020). These elements can become contaminants at high concentrations and are expected to occur with fossil groundwater and high groundwater discharge temperatures (Degnan *et al.*, 2020). Chromium and uranium are geogenic in many areas, but land and water use in the Central Valley complicate their occurrence and fate, as described above.

4.1.2.2. Hexavalent Chromium

Four percent of wells in the VAT have a high hexavalent chromium concentration. Across the Central Valley, there are no differences in the proportion of wells with high hexavalent chromium with respect to fossil water or warm discharge. At individual wells, its association with fossil groundwater (as identified using high terrigenic helium-4 and geothermal warming) would likely indicate a geological source. High hexavalent chromium is only detected in wells with a local recharge source, and not in wells with a river recharge source.

Redox: High hexavalent chromium was not detected in anoxic groundwater. The likelihood of high hexavalent chromium is similar for oxic and mixed redox groundwater (4-6%).

4.2. Well Vulnerability within GSA Areas

We analyzed the proportion of wells with higher than average vulnerability and high nitrate concentrations in the 20 GSAs with more than 20 wells for which groundwater age data were available. The proportion of wells with high nitrate (P_{High_NO3N}) varies from 0% to 63% in the West Turlock Subbasin GSA area. In general, GSAs with a high proportion of wells with higher than average age vulnerabilities (P_{Higher_age}, horizontal axis) also have a higher proportion of wells with a high nitrate concentration (vertical axis; $R^2 = 0.44$; $P_{High\_NO3N} = 0.40 \times P_{Higher\_age}$). For most GSAs, the P_{High_NO3N} is equal to or smaller than P_{Higher_age}, with the exception of the West Turlock Subbasin GSA, where P_{High_NO3N} (63%) is much larger than P_{Higher_age} (35%). Kings River has both a high proportion of vulnerable wells (63%) and a high proportion of wells with high nitrate (59%). More than 50% of wells in Greater Kaweah and Central Kings GSA have a higher than average age vulnerability and a relatively high proportion of wells with high nitrate (>20%). In contrast, more than 50% of wells in Vina, Kern River, and North Kings have a higher than average age vulnerability, but a much lower proportion of wells with high nitrate (0-13%). Other factors (nitrogen loading, denitrification) play a role in these GSAs, effectively limiting the proportion of high nitrate wells.

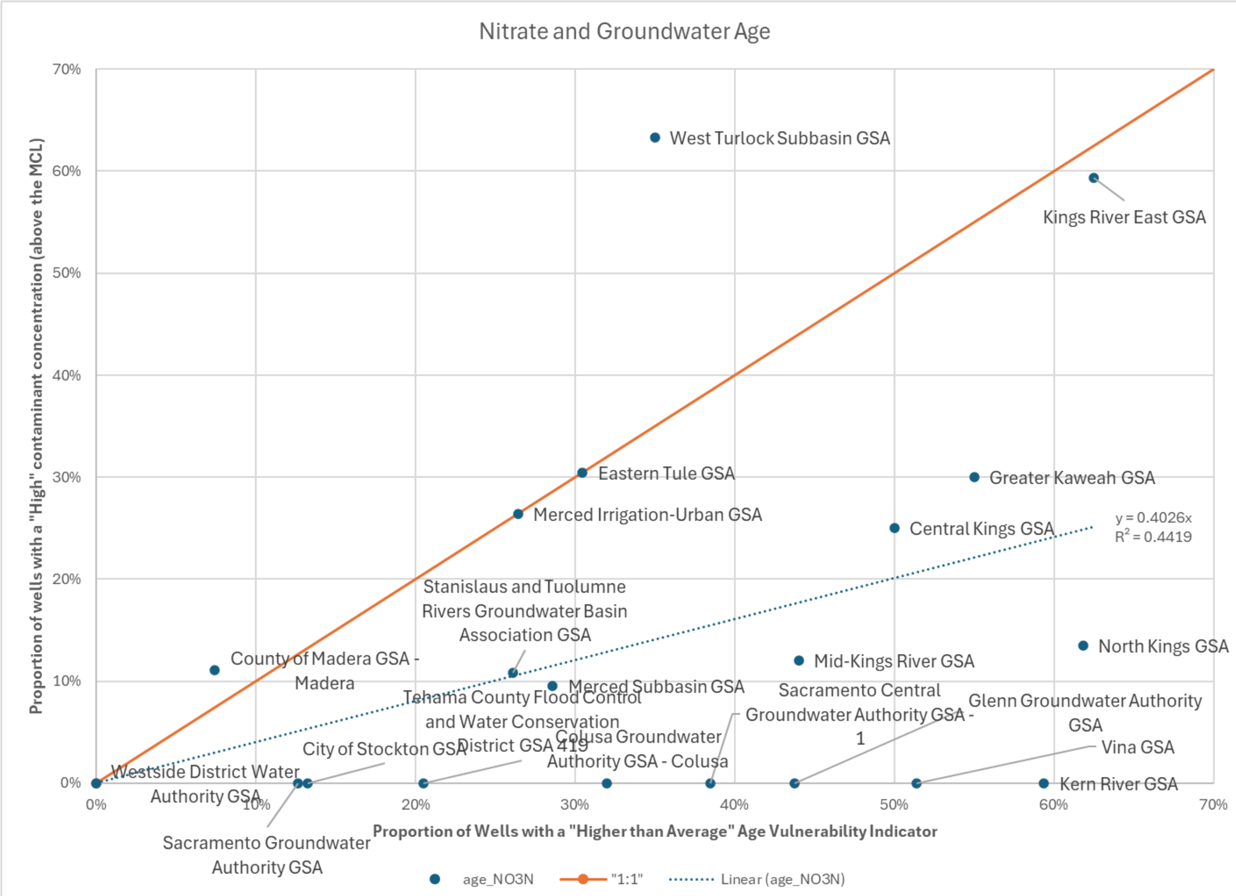


FIGURE 10. PROPORTION OF WELLS WITH HIGH NITRATE CONCENTRATION IN 20 GSAS WITH RESPECT TO THE PROPORTION OF WELLS WITH A HIGHER THAN AVERAGE GROUNDWATER AGE VULNERABILITY.

4.3. Dry Well Accuracy

Shallow domestic wells are the most vulnerable to going dry when groundwater levels drop and in some areas are the sole source of drinking water for local communities (Jasechko & Perrone, 2020; California Department of Water Resources, n.d-d.). Since the start of the DWR's Dry Well Reporting System in 2014 through the end of water year 2024, 4,582 wells were reported dry in the Central Valley, 99.0% of which are primarily or partially for domestic use (California Department of Water Resources, n.d-c.). Of these dry wells, 72.2% are located in four subbasins in the San Joaquin Valley: Kaweah, Kings, Madera, and Tule (Figure 11). All four of these subbasins are designated as critically over drafted (California Department of Water Resources, 2021).

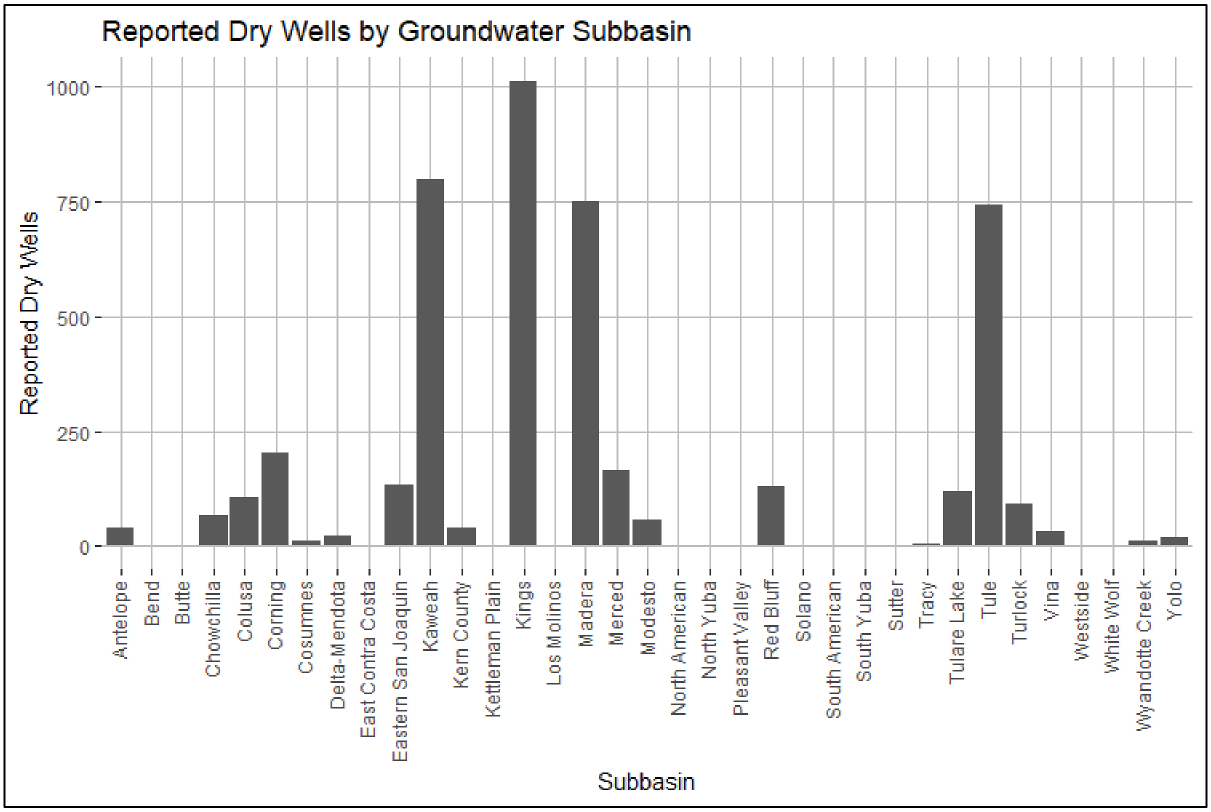


FIGURE 11. FREQUENCY OF REPORTED DRY WELLS IN EACH GROUNDWATER SUBBASIN IN CALIFORNIA'S CENTRAL VALLEY

To augment the existing data in the VAT, twenty wells were selected for sampling in areas with clusters of reported dry wells and with either lower densities of GAMA wells or where GAMA wells had not been sampled in the previous ten years. All the newly sampled wells are private, domestic wells located in the Kings, Madera, or Turlock subbasins (Figure 12). The targeting of wells in areas identified as vulnerable to sustainability issues due to the frequency of reported dry wells makes them useful for accuracy testing the sustainability criteria. All twenty of the newly sampled wells are classified as having higher than average vulnerability to sustainability issues based on one or more of the vulnerabilities in the category. Nineteen of twenty wells (95%) are within 1 km of a reported dry well, as per the selection criteria for newly sampled wells; however, twelve out of the twenty wells (60%) have at least one other higher than average vulnerability among factors affecting sustainability (Table 8).

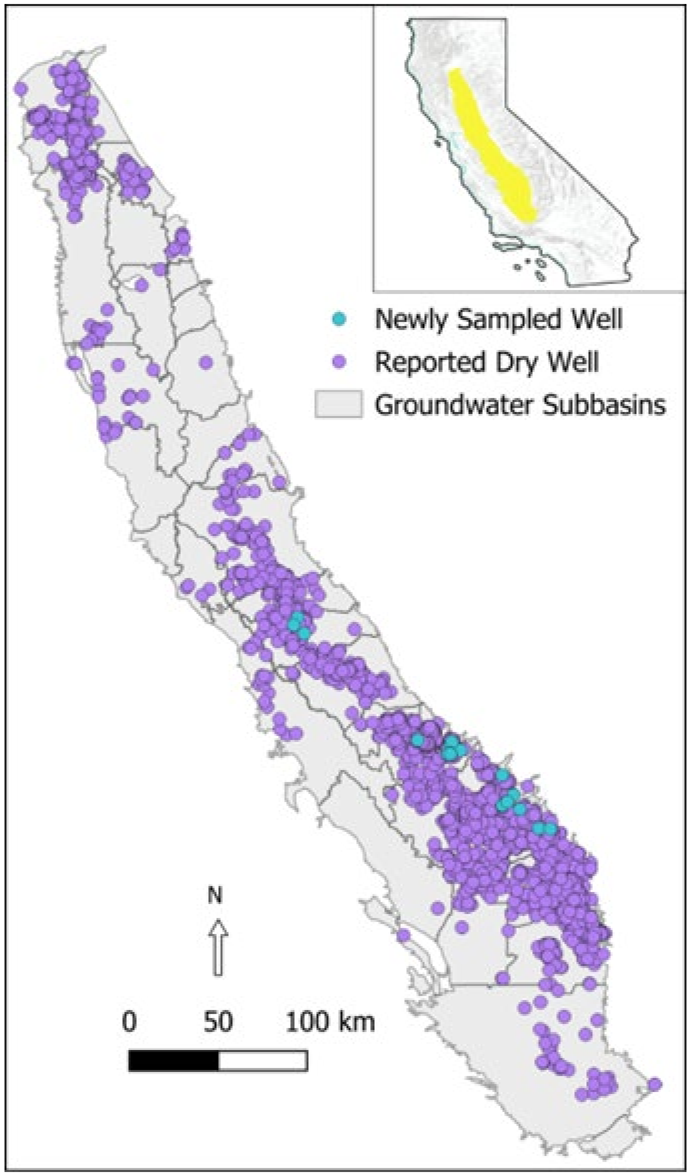


FIGURE 12. MAP OF THE CENTRAL VALLEY SHOWING NEWLY SAMPLED WELLS PROXIMAL TO REPORTED DRY WELLS

Four out of twenty wells (20%; compared to 12% in the larger data set) have very young groundwater, with ages of less than 12 years, making them more vulnerable to adverse effects during prolonged droughts. Young groundwater indicates these wells draw from aquifers that rely on rapid recharge. During droughts, precipitation and river water availability decrease and groundwater abstraction increases, lowering groundwater levels, sometimes on regional scales. These four wells are located in the Kings subbasin, which has the highest number of reported dry wells.

TABLE 8. FACTORS AFFECTING SUSTAINABILITY IN NEWLY SAMPLED WELLS

Well ID	Very Young Groundwater Vulnerability	River Recharge Vulnerability	Fossil Water Vulnerability	Dry Well Vulnerability
114056	NA	Average	Lower than avg	Higher than avg
114057	NA	Average	NA	Higher than avg
114058	NA	Average	Lower than avg	Higher than avg
114060	NA	Lower than avg	Higher than avg	Higher than avg
114196	NA	Lower than avg	Higher than avg	Lower than avg
114197	NA	Lower than avg	Higher than avg	Higher than avg
114198	NA	Lower than avg	Higher than avg	Higher than avg
114199	NA	Lower than avg	Average	Higher than avg
114200	NA	Lower than avg	Higher than avg	Higher than avg
114201	NA	Lower than avg	Higher than avg	Higher than avg
114202	NA	Lower than avg	Average	Higher than avg
114203	NA	NA	Lower than avg	Higher than avg
114224	Higher than avg	Higher than avg	Lower than avg	Higher than avg
114225	NA	Average	NA	Higher than avg
114226	NA	Lower than avg	Average	Higher than avg
114227	NA	Average	Lower than avg	Higher than avg
114229	Higher than avg	Lower than avg	Lower than avg	Higher than avg
114230	Higher than avg	Lower than avg	Lower than avg	Higher than avg
114231	Higher than avg	Higher than avg	Lower than avg	Higher than avg
114232	NA	Average	Lower than avg	Higher than avg

Two of twenty wells (10%) are recharged primarily by river water, which indicates a higher than average vulnerability to recharge variability due to multi-year droughts and can lead to severe groundwater level fluctuations. These wells also have higher than average vulnerability due to very young groundwater, indicating this river recharge is relatively rapid, which leaves smaller buffers to groundwater level fluctuations when surface water is decreased due to prolonged droughts (Harm, 2023). These two wells are located in the Kings subbasin. Another six wells (30%) have water that is a mix of local precipitation and river recharge and may experience smaller groundwater level fluctuations and be impacted by prolonged droughts.

Six of twenty wells (30%) contain a high concentration of terrigenic helium-4, indicating a large fraction of fossil groundwater is produced by the well. The slow recharge rate of an aquifer containing fossil groundwater indicates abstraction in excess of this slow recharge rate will deplete the aquifer, placing these wells at higher than average vulnerability to sustainability issues in the longer term. These six wells are located in the Madera subbasin and contain pre-modern groundwater ages consistent with large fossil groundwater fractions (Harm, 2023).

California's DWR recently released the Dry Domestic Well Susceptibility Tool (DDWST), which estimates areas of the state where domestic wells may be in danger of going dry, based on well location, depth, and nearby groundwater levels (California Department of Water Resources, 2024). This tool is part of DWR's Be Well Prepared campaign, which seeks to aid domestic well owners in understanding and safeguarding their water supply (California Department of Water Resources, n.d.-b). A comparison of VAT wells with one or more higher than average vulnerabilities among factors affecting sustainability (excluding proximity to reported dry wells) with areas of increased density of domestic wells susceptible to going dry in the DDWST for 2024 is presented in Figure 13. Overall, the VAT vulnerability indicators spatially align well with the DDWST's predictions, particularly in the central and eastern San Joaquin Valley and northern Sacramento Valley. A cluster of VAT wells appears in the North American subbasin, near Sacramento, that does not appear in an area of high susceptibility on the DDWST; however, the factor affecting sustainability for these wells is fossil water, which is an indicator of longer term vulnerability to going dry than the DDWST is designed to detect.

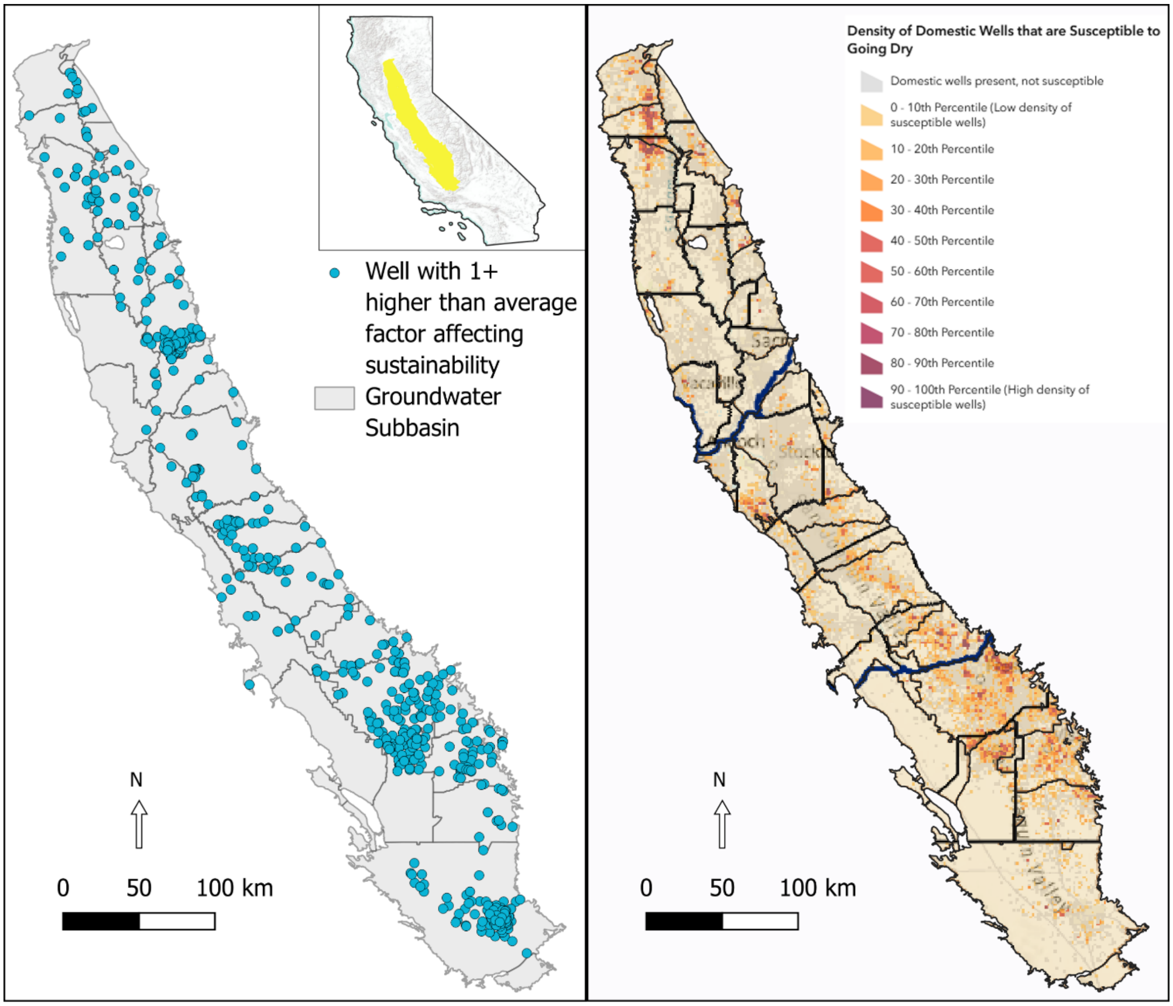


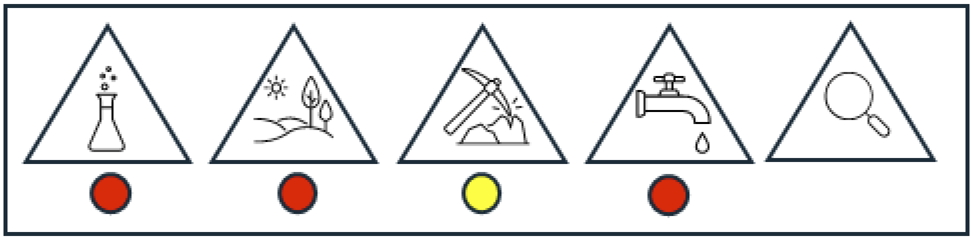
FIGURE 13. SIDE-BY-SIDE COMPARISON OF VAT WELLS WITH AT LEAST ONE HIGHER THAN AVERAGE FACTOR AFFECTING SUSTAINABILITY (LEFT; EXCLUDING REPORTED DRY WELL PROXIMITY) WITH THE DWR'S DRY DOMESTIC WELL SUSCEPTIBILITY TOOL (RIGHT; MODIFIED FROM CALIFORNIA'S GROUNDWATER LIVE: DRY DOMESTIC WELL SUSCEPTIBILITY TOOL)

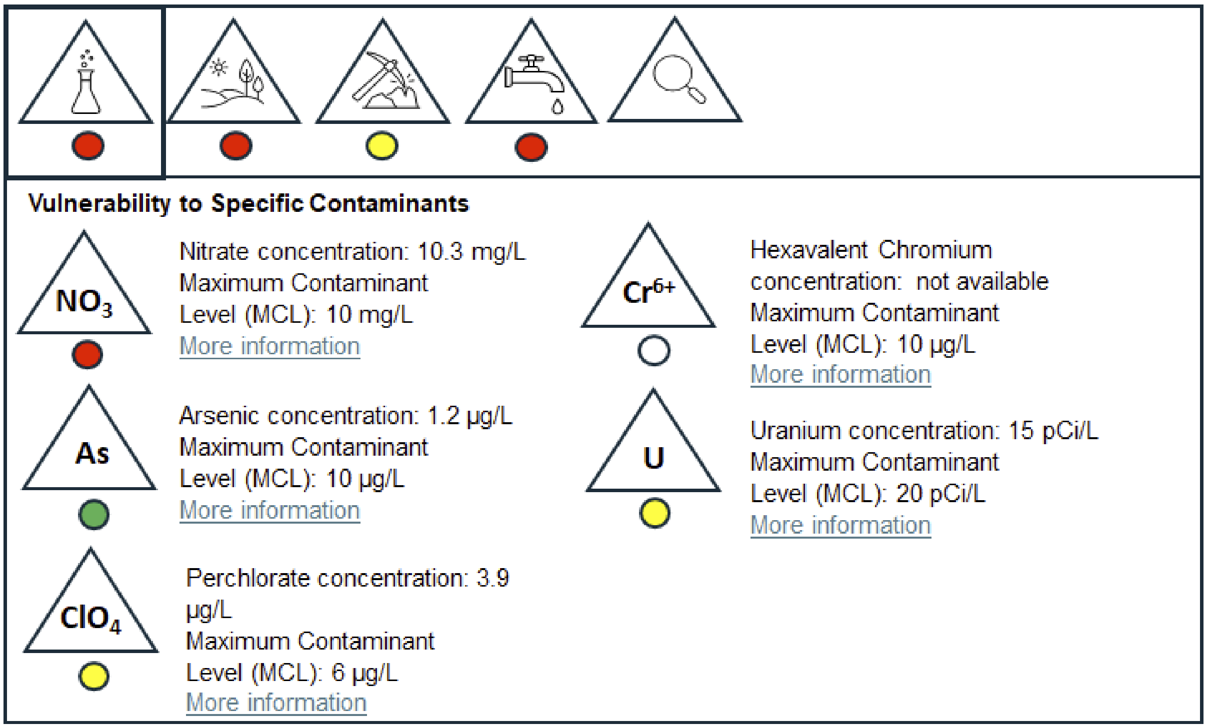
4.4. Examples from Wells

The following examples from individual wells illustrate the utility of the VAT and highlight some limitations. Sample windows showing the vulnerabilities of each well are shown with actual data and VAT analysis language.

4.4.1. Example Well 1: KINGFP-11

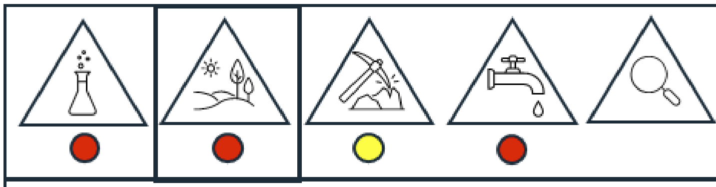
KINGFP-11, is a 158' deep monitoring well, screened from 148 to 153 ft below ground surface (bgs), sampled under the GAMA priority basin project, and located in an agricultural area between Fresno and Sanger.





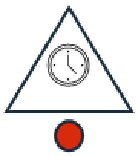
Water quality results and stoplights

The top-level vulnerability to specific contaminants is high, indicated by the red light. The concentration of nitrate as N is 10.3 mg/L, above the MCL of 10 mg/L; Arsenic is 1.2 µg/L compared to the MCL of 10 µg/L; Perchlorate is 3.9 µg/L compared to the MCL of 6 µg/L; Hexavalent Chromium does not have a result, and Uranium is 15 pCi/L compared to the MCL of 20 pCi/L. Nitrate has a red light because its concentration is above the MCL. Hexavalent chromium is white because of missing data, and perchlorate has a yellow light because its concentration is more than 10% of the MCL. Uranium is yellow because its concentration is more than 50% of the MCL.



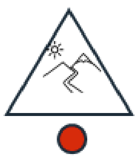
Vulnerability to Land Surface Contaminants: Higher than average

Land surface contaminants include (but are not limited to): nitrate and perchlorate



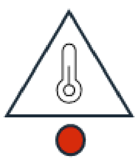
Age Vulnerability: Higher than average
The groundwater age is 9 years.

Young groundwater, less than 30 years old, can bring contaminants from the land surface. The groundwater age is based on laboratory analyses of the naturally occurring isotopes tritium and helium-3.



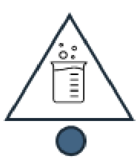
Recharge Source Vulnerability: Higher than average
The source of recharge to the well is local rain.

Recharge by local rain is more likely to bring contaminants from the land surface. The recharge source is based on laboratory analyses of oxygen isotopes in the water. Oxygen isotopes in local rain are different from river water from high mountains.



Recharge Temperature Vulnerability: Higher than average
The temperature at the water table was warmer than the mean annual air temperature.

Warm recharge temperatures are often caused by irrigation in summer that can bring contaminants from the land surface. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



Redox Vulnerability: Oxic
The redox condition of the groundwater is: Oxic

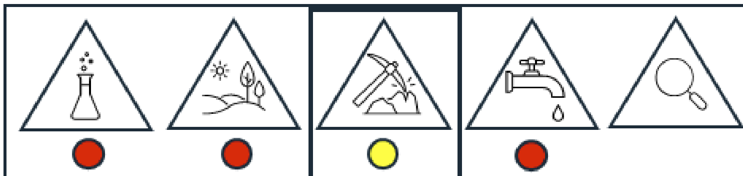
The groundwater contains dissolved oxygen or nitrate. In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

Tracer results and Well Vulnerability Stoplights

This well has a (top-level) *Vulnerability to Land Surface Contaminants* that is higher than average, indicated by the red light. Three subcategories have red lights. With a tritium-helium groundwater age of 9 years, less than the threshold of 30 years, the vulnerability due to age is higher than average. The oxygen-18 isotope ratio of -8.53 per mil indicates local rainwater as the source of recharge, which results in a higher than average Recharge Source Vulnerability since local rain or cyclic groundwater are more likely to bring contaminants from the land surface.

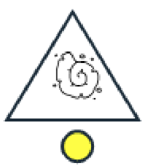
The well has a higher than average Recharge Temperature Vulnerability, indicated by the red light. The calculated noble gas recharge temperature is 18.9 °C which is higher than the MAAT (from PRISM) of 17.6 °C. The well is likely recharged by (warmed) summer irrigation water which may bring contaminants from the land surface.

The redox condition is oxic because the DO concentration is 6.4 mg/L, above the threshold of 1.0 mg/L, and because of the detection of nitrate. Oxidizing conditions are not likely to allow denitrification or degradation of perchlorate, and favor mobilization of uranium.



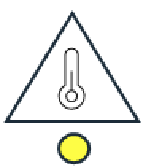
Vulnerability to Geological Contaminants: Average

Geological contaminants include (but are not limited to): arsenic, uranium, and hexavalent chromium



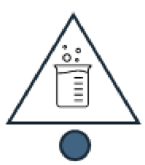
Fossil Groundwater Vulnerability: Average
The fossil groundwater component in the well is: Average

Fossil groundwater recharged more than a few hundred years ago and may contain geological contaminants that are released by rocks and sediments. Fossil groundwater is detected by laboratory analyses of dissolved helium. The helium concentration in groundwater increases slowly due to natural radioactive decay.



Geothermal Warming Vulnerability: Average
The temperature of the water is more than 5 °F (3 °C) warmer than the recharge temperature.

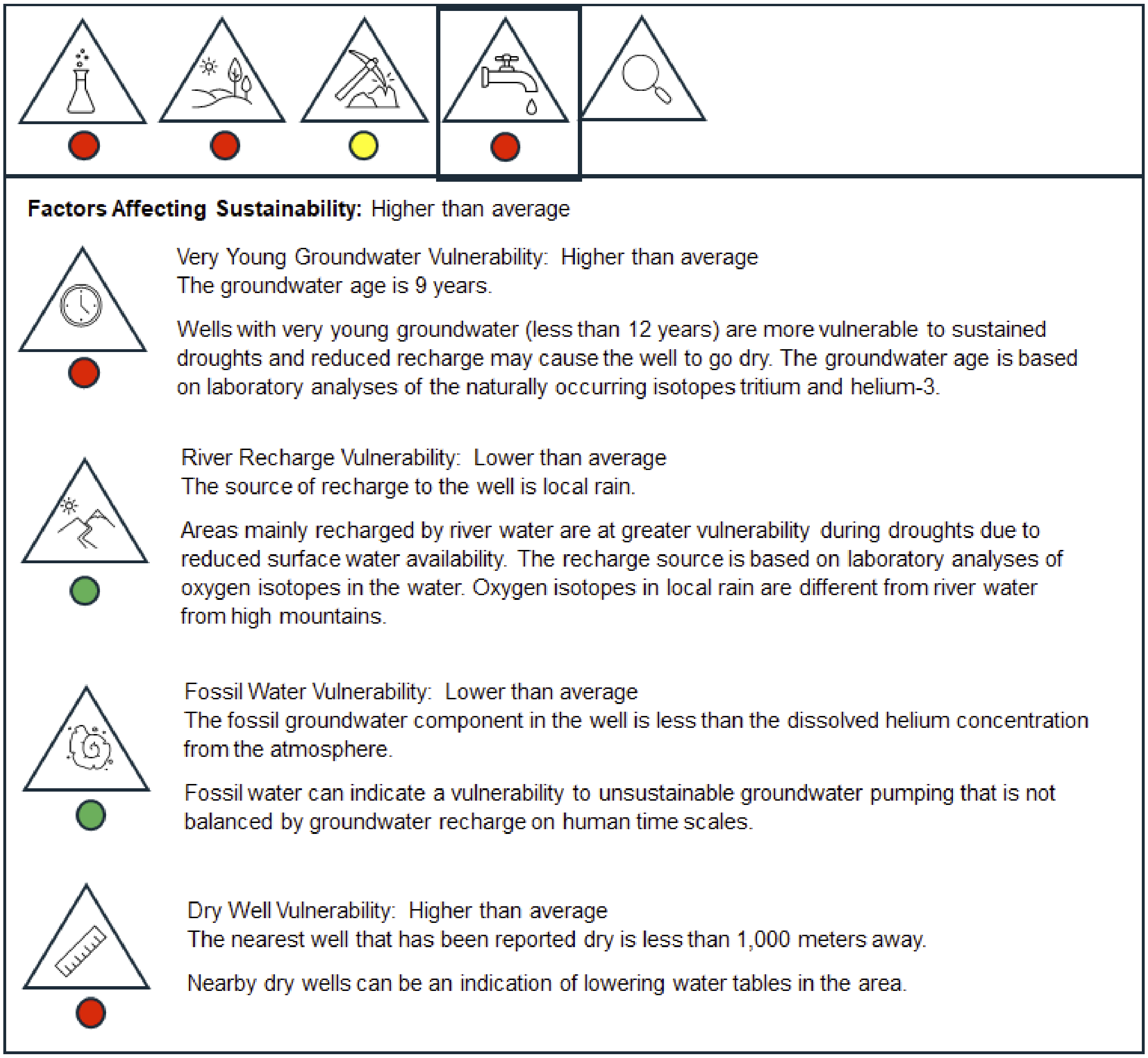
A well water temperature that is higher than the temperature at the water table indicates deep groundwater flow paths. Deep groundwater flow paths may contain geological contaminants that are released by rocks and sediments. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



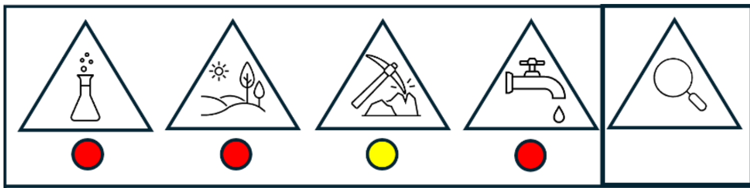
Redox Vulnerability: Oxic
The redox condition of the groundwater is: Oxic. The groundwater contains dissolved oxygen or nitrate.

In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

The well has an average (top-level) *Vulnerability to Geological Contaminants,* indicated by the yellow light. Both subcategories Fossil Groundwater Vulnerability and Geothermal Warming Vulnerability are average. The terrigenic helium-4 concentration is 6.71x10^{-9} cm^3(STP)/g, which is greater than the secondary threshold of 4.65x 10^{-9} cm^3(STP)/g but less than the primary threshold of 4.65x10^{-8} cm^3(STP)/g, leading to a yellow stoplight for the Fossil Water Vulnerability. The discharge temperature at the well is 22.6° C and the difference between the recharge and discharge temperatures is 3.7 °C, which is between the secondary threshold (3 °C) and the primary threshold (5 °C) for the Geothermal Warming Vulnerability. With respect to redox, the oxic groundwater conditions make mobilization of geological arsenic less likely.



The well has a (top-level) higher than average vulnerability for *Factors Affecting Sustainability*, indicated by the red light. The subcategories of Very Young Groundwater and Dry Well Vulnerability are both higher than average. The groundwater age of 9 years, less than the threshold of 12 years, makes the well more vulnerable to the low recharge of sustained droughts. Similarly, the well is within 1000 m of a reported dry well, meaning the well may be affected by lowering water levels during sustained droughts, giving it a higher than average Dry Well Vulnerability. On the other hand, with respect to sustainability, the local rain recharge source results in a lower than average River Recharge Vulnerability, since areas dependent on local rain are assumed to be buffered by deeper unsaturated zones, resulting in smaller groundwater level fluctuations while surface water from rivers is likely to be curtailed during extended droughts. The Fossil Water Vulnerability is lower than average because the terrigenic helium-4 concentration is less than the secondary threshold (atmospheric equilibrium solubility concentration) of 4.65×10^{-8} cm^3(STP)/g.



Possible Mitigation Actions

- Treatment to remove nitrate, blending with or use of an alternative drinking water source recommended; vulnerable populations are pregnant or very young individuals
  - High nitrate concentration
- Quarterly water quality testing
  - Moderate perchlorate concentration
  - Moderate uranium concentration
- Monitor local groundwater levels quarterly
  - Within 1,000m of a reported dry well
  - Very young groundwater (age < 12 years)
- Well deepening
  - May reduce surface contaminants
  - May reduce vulnerability to well going dry

The tool displays possible mitigation actions for this well, based on the various stoplights.

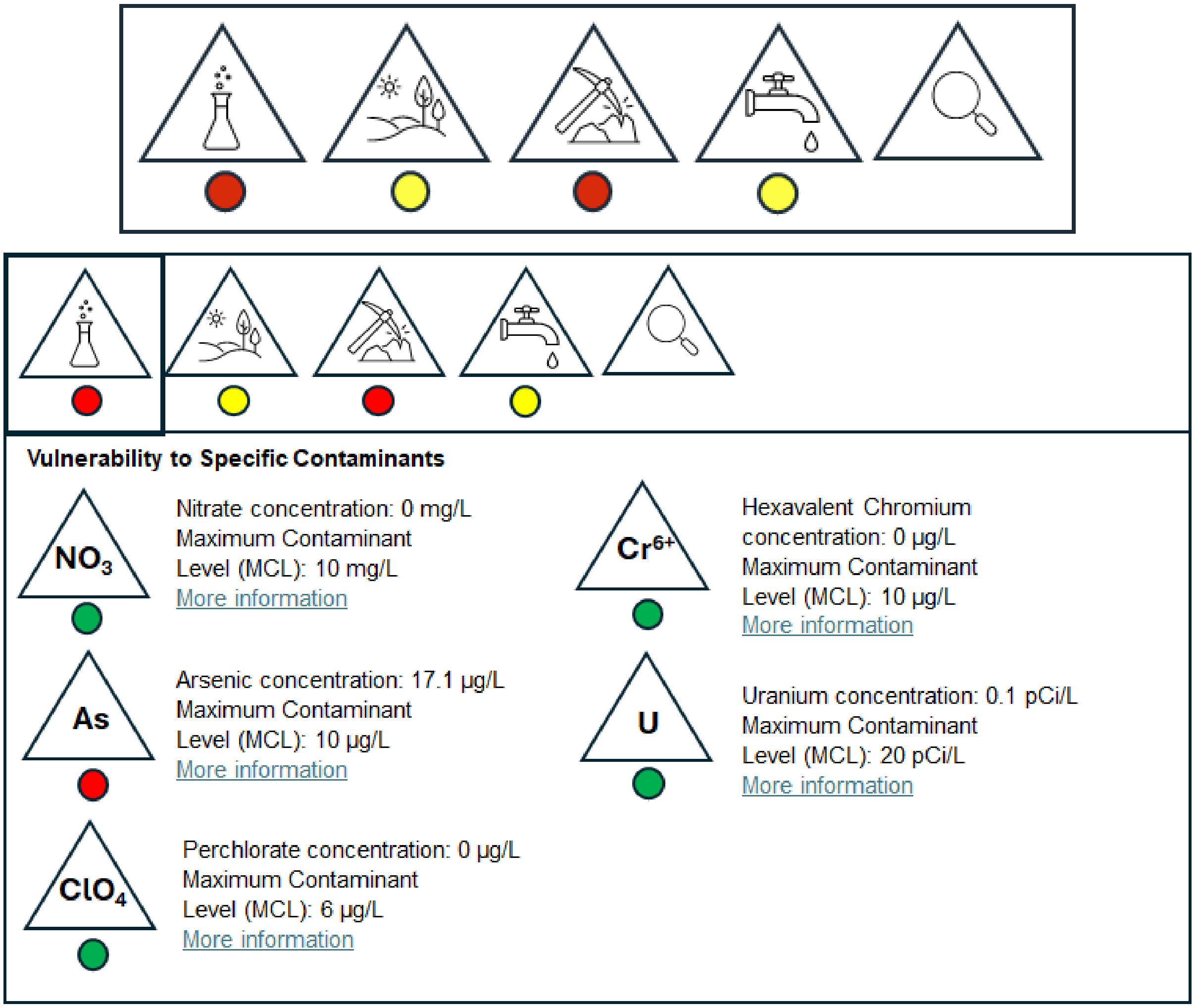
- Red light for nitrate: Treatment to remove nitrate, blending with or use of an alternate water source
- Yellow lights for perchlorate and uranium: Quarterly water quality testing
- Red light for Young Groundwater under Factors Affecting Sustainability: Monitor local groundwater levels annually
- Red light Distance to Dry Well: Monitor local groundwater levels quarterly

Yellow lights under Vulnerability to Geological Contaminants indicate average conditions so there are no related recommended actions. Green lights likewise lead to no recommended actions.

Overall, the VAT highlights the vulnerability of this well to contaminants from the land surface (already manifest in the high nitrate concentration and elevated perchlorate and uranium concentrations) and indicates that the well is susceptible to drought because of its young groundwater age and proximity to a dry well. There is a more subtle indication, based on the average terrigenic helium-4 concentration and average geothermal warming, that a component of older groundwater is also present. This may manifest in the somewhat elevated arsenic concentration. The overall oxic condition of the pumped groundwater makes it likely that nitrate and perchlorate will not degrade.

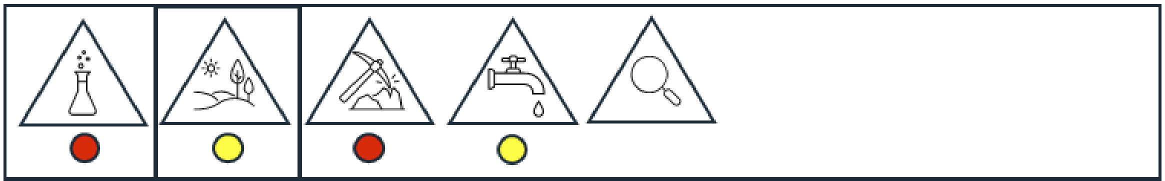
4.4.2. Example Well 2: WS-U-01

WS-U-01, is a 700 ft deep production well in Kettleman City, CA, screened from 400 to 630 ft bgs, and sampled under the GAMA priority basin project.



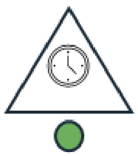
Water quality results and stoplights

The top-level vulnerability to specific contaminants is high, indicated by the red light. Arsenic has a concentration of 17 µg/L, higher than the MCL of 10 µg/L, and is classified as high, indicated by a red light. Except for arsenic, contaminant concentrations in this well are all below water quality benchmarks (MCLs); concentrations of nitrate and uranium are below 50% of the MCL, and concentrations of hexavalent chromium and perchlorate are below 10% of the MCL, classifying each as low, as indicated by the green light.



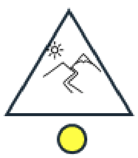
Vulnerability to Land Surface Contaminants: Average

Land surface contaminants include (but are not limited to): nitrate and perchlorate



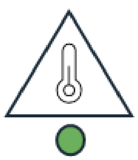
Age Vulnerability: Lower than average
The groundwater age is more than 75 years.

The groundwater age is based on laboratory analyses of the naturally occurring isotopes tritium and helium-3.



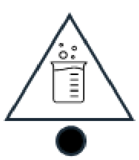
Recharge Source Vulnerability: **A**verage
The source of recharge to the well is mixed.

The recharge source is based on laboratory analyses of oxygen isotopes in the water. Oxygen isotopes in local rain are different from river water from high mountains.



Recharge Temperature Vulnerability: Lower than average
The temperature at the water table was more than 4 °F (2 °C) cooler than the mean annual air temperature.

Cool recharge temperatures are often caused by direct river water recharge which is not likely to bring contaminants from the land surface. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



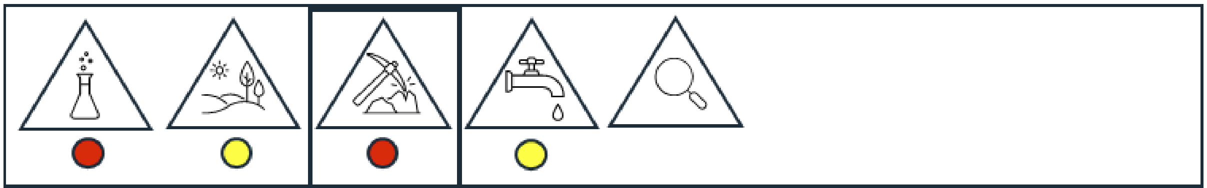
Redox Vulnerability: Anoxic
The redox condition of the groundwater is anoxic

The groundwater contains iron or manganese. In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

Tracer results and Well Vulnerability Stoplights

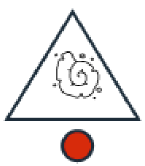
This well has a (top-level) *Vulnerability to Land Surface Contaminants* that is average, indicated by the yellow light. Recharge Source Vulnerability is classified as average with a yellow light Because the oxygen-18 isotope ratio of -9.0 per mil indicates a mixed recharge source. The Age and Recharge Temperature Vulnerabilities are classified as lower than average, indicated by green lights. The groundwater age is greater than75 years (the sample is devoid of tritium) which is typically associated with slower, deeper flowpaths with less exposure to land surface contaminants, giving the well a lower than average age-related vulnerability.

The Recharge Temperature vulnerability in this category is also lower than average because the recharge temperature, 10.9 °C is colder than the MAAT of 17.9 °C. The redox condition of the well water is anoxic, making denitrification conditions likely. Dissolved oxygen was not detected in the well water and the manganese concentration is 85.5 μg/L, greater than the threshold of 50 μg/L..



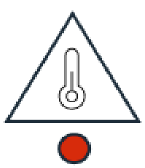
Vulnerability to Geological Contaminants: Higher than average

Geological contaminants include (but are not limited to): arsenic, uranium, and hexavalent chromium



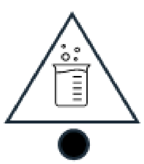
Fossil Groundwater Vulnerability: Higher than average
The fossil groundwater component in the well is: Higher than average

Fossil groundwater recharged more than a few hundred years ago and may contain geological contaminants that are released by rocks and sediments. Fossil groundwater is detected by laboratory analyses of dissolved helium. The helium concentration in groundwater increases slowly due to natural radioactive decay.



Geothermal Warming Vulnerability: Higher than average
The temperature of the water is more than 9 degrees F (5 C) warmer than the recharge temperature.

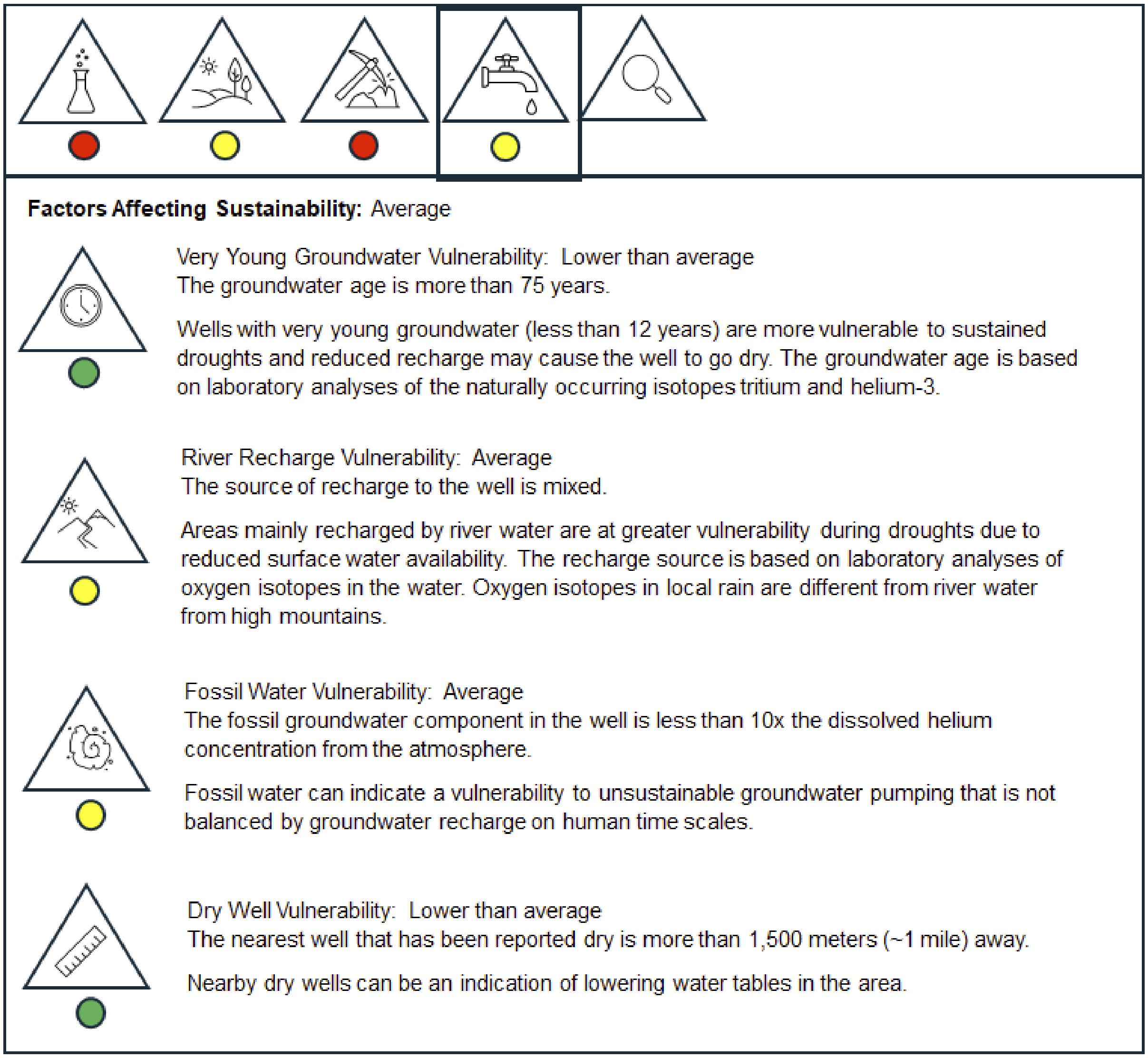
A well water temperature that is higher than the temperature at the water table indicates deep groundwater flow paths. Deep groundwater flow paths may contain geological contaminants that are released by rocks and sediments. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



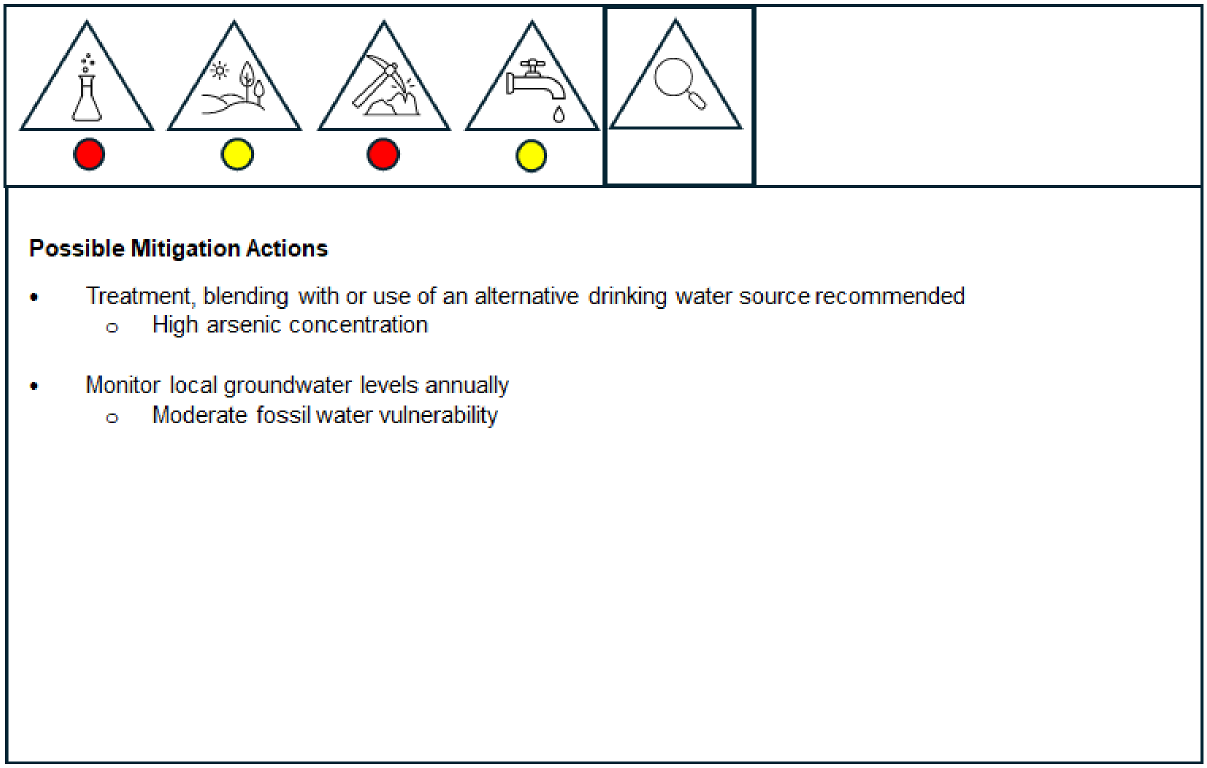
Redox Vulnerability: Anoxic
The redox condition of the groundwater is anoxic

The groundwater contains iron or manganese. In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

The well has a higher than average (top-level) *Vulnerability to Geological Contaminants*, indicated by the red light. Both subcategories Fossil Groundwater Vulnerability and Geothermal Warming Vulnerability are Higher than average. The terrigenic ^4He concentration is 1.78x10^{-7} cm^3(STP)/g, which is greater than the primary threshold of 4.65x10^{-8} cm^3(STP)/g, indicating a large proportion of fossil water is present, and leading to a red stoplight for the Fossil Water Vulnerability. The discharge temperature at the well is 26 °C and the difference between the recharge and discharge temperatures is 15.1 °C, which considerably higher than the primary threshold (5 °C) for the Geothermal Warming Vulnerability. As stated above, the redox condition of the well water is anoxic, which will likely cause mobilization of geological arsenic.



The well has an average (top-level) vulnerability to *Factors Affecting Sustainability*, indicated by the yellow light. The subcategories of Very Young Groundwater and Dry Well Vulnerability are both lower than average, indicated by green lights. The nearest reported dry well is more than 15 km away, indicating conditions in the nearby area are not vulnerable to lowering groundwater levels due to prolonged drought conditions. The River Recharge Vulnerability is average, indicated by the yellow light, because the oxygen-18 isotope ratio indicates a mixed source. The Fossil Water Vulnerability is average, also indicated by a yellow light, because the terrigenic helium-4 concentration is between the primary threshold of 4.65×10^{-7} cm^3(STP)/g and the secondary threshold (atmospheric equilibrium solubility concentration) of 4.65×10^{-8} cm^3(STP)/g.



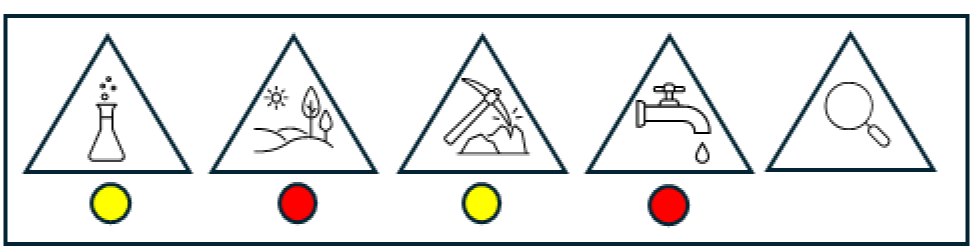
The tool displays possible mitigation actions for this well, based on the various stoplights.

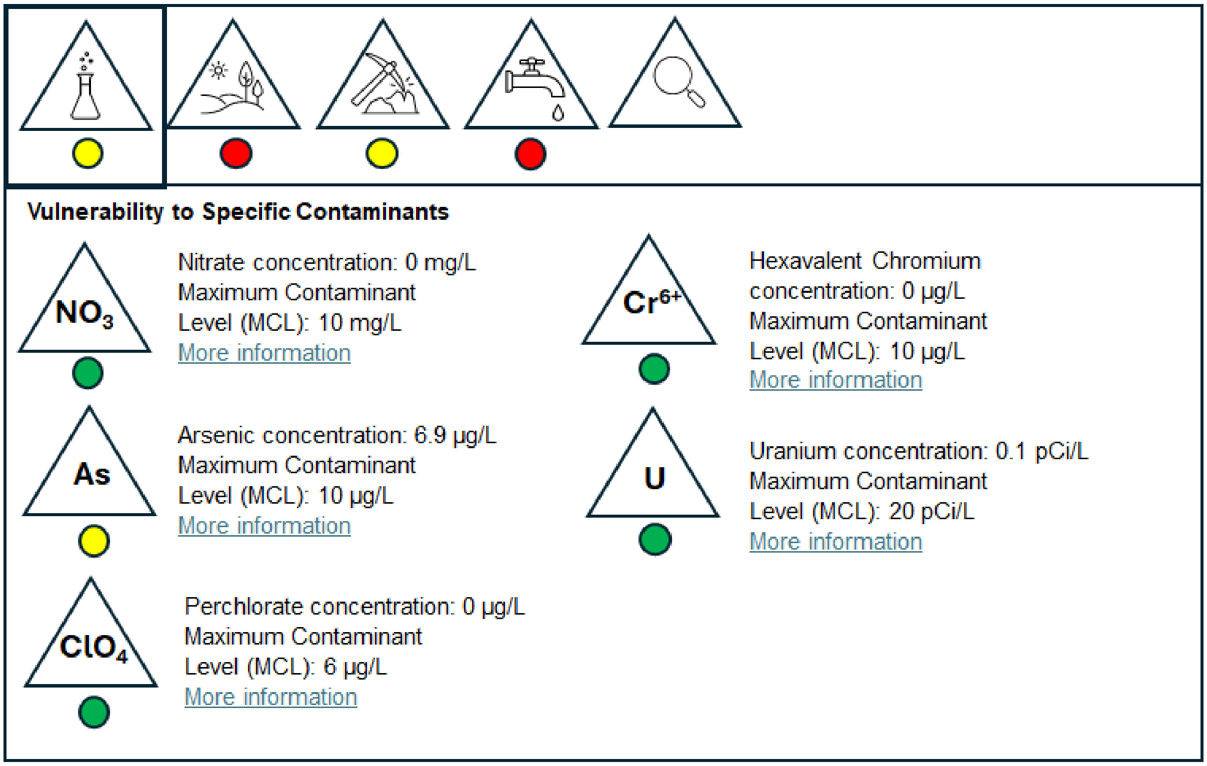
- Red light for arsenic: Treatment to remove arsenic, blending with or use of an alternate water source
- Yellow light for Fossil Water Vulnerability under Factors Affecting Sustainability: Monitor local groundwater levels quarterly

Overall, the VAT highlights the vulnerability of this well to geological contaminants (already manifest in the high arsenic concentration) and a tritium-helium age-related vulnerability to contaminants from the surface that is lower than average due to the old groundwater age. The groundwater likely has a deep flowpath considering the large difference between recharge and discharge temperatures, yet the accumulation of terrigenic helium-4 did not surpass the sustainability threshold for high Fossil Water Vulnerability.

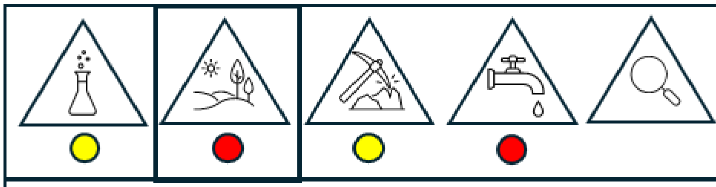
4.4.3. Example Well 3: S7-SAC-NA07

S7-SAC-NA07, is a 132 ft deep domestic well north of Sacramento, near the Sacramento River, screened from 58 to 118 feet bgs, and sampled by the U.S. Geological Survey under the GAMA program.



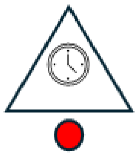


This well is similar to the previous example in that arsenic is the only contaminant detected at a level above a threshold. In this case, the arsenic concentration is 6.9 mg/L, above the secondary threshold of 5 mg/L (50% of the MCL)), so it has a yellow light for Vulnerability to Specific Contaminants, and for arsenic specifically, while all other contaminants have green lights.



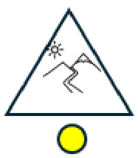
Vulnerability to Land Surface Contaminants: Higher than average

Land surface contaminants include (but are not limited to): nitrate and perchlorate



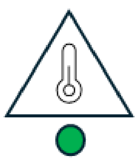
Age Vulnerability: Higher than average
The groundwater age is 8 years.

Young groundwater, less than 30 years old, can bring contaminants from the land surface. The groundwater age is based on laboratory analyses of the naturally occurring isotopes tritium and helium-3.



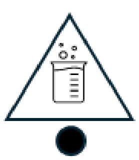
Recharge Source Vulnerability: Average
The source of recharge to the well is mixed.

The recharge source is based on laboratory analyses of oxygen isotopes in the water. Oxygen isotopes in local rain are different from river water from high mountains.



Recharge Temperature Vulnerability: Lower than average
The temperature at the water table was more than 4 °F (2 °C) cooler than the mean annual air temperature.

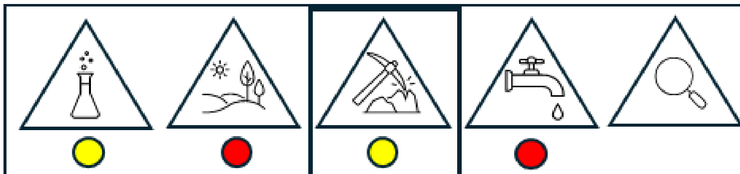
Cool recharge temperatures are often caused by direct river water recharge which is not likely to bring contaminants from the land surface. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



Redox Vulnerability: Anoxic
The redox condition of the groundwater is anoxic

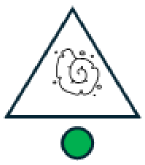
The groundwater contains iron or manganese. In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

The groundwater age of 8 years results in higher than average classifications for Vulnerability to Land Surface Contaminants and Factors Affecting Sustainability, despite land surface contaminant concentrations all being classified as low and the well not being located in an area that has had many reported dry wells. The oxygen-18 isotope ratio value of –10.2 per mil is between the two thresholds but very near the primary threshold for river water (-10.3 per mil) so the related stoplights reflect a mixed recharge source. The recharge temperature (12.2 °C) is cooler than the MAAT (16.4 °C) leading to a lower than average Recharge Temperature Vulnerability.



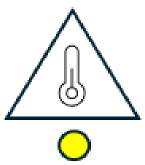
Vulnerability to Geological Contaminants: Average

Geological contaminants include (but are not limited to): arsenic, uranium, and hexavalent chromium



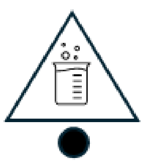
Fossil Groundwater Vulnerability: Lower than average
The fossil groundwater component in the well is: Lower than average

Fossil groundwater recharged more than a few hundred years ago and may contain geological contaminants that are released by rocks and sediments. Fossil groundwater is detected by laboratory analyses of dissolved helium. The helium concentration in groundwater increases slowly due to natural radioactive decay.



Geothermal Warming Vulnerability: Average
The temperature of the water is more than 5 degrees F (3 C) warmer than the recharge temperature.

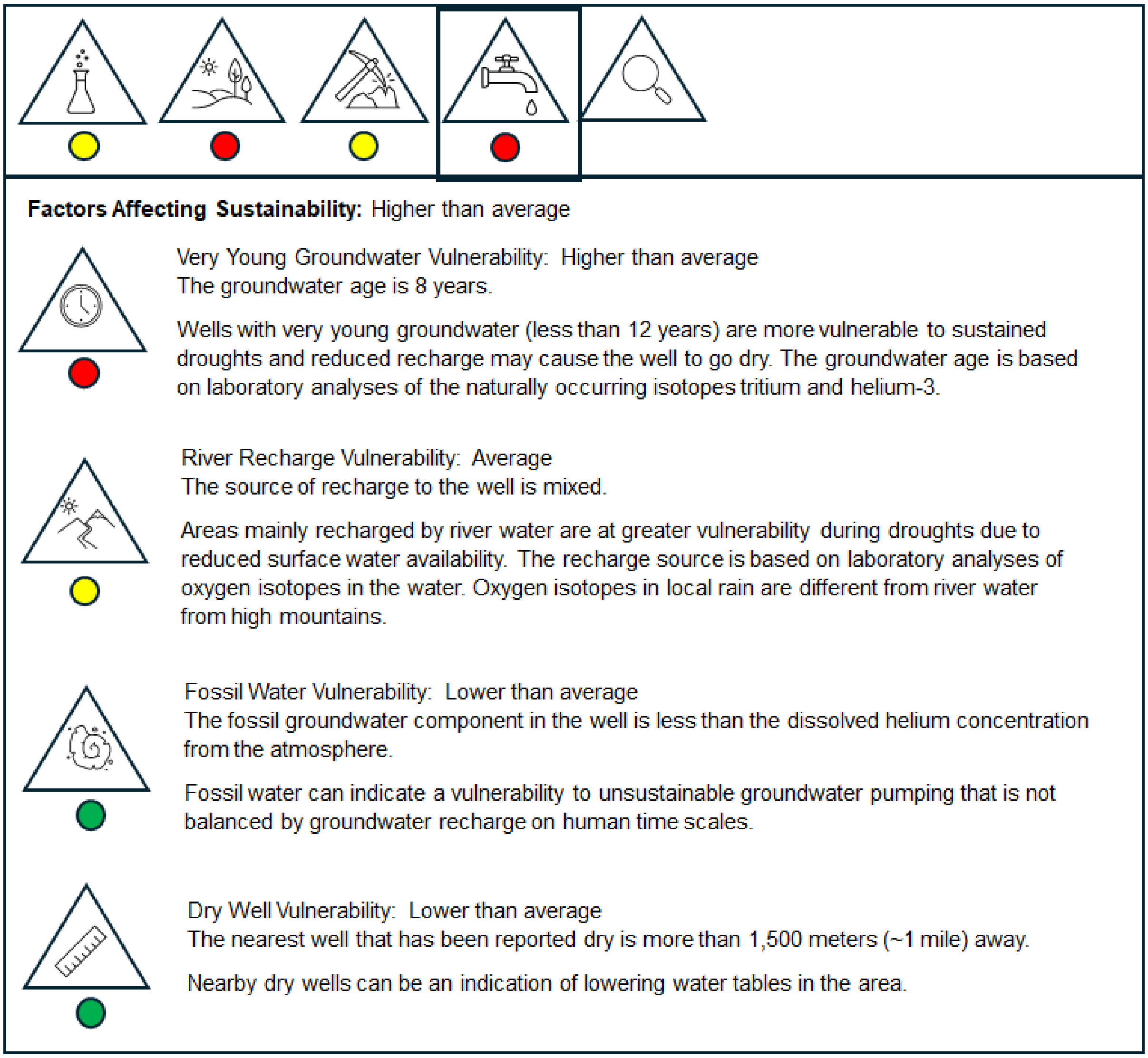
A well water temperature that is higher than the temperature at the water table indicates deep groundwater flow paths. Deep groundwater flow paths may contain geological contaminants that are released by rocks and sediments. The recharge temperature is based on laboratory analyses of dissolved noble gases in the water. Argon, krypton, and xenon dissolve more easily when the water is cold.



Redox Vulnerability: Anoxic
The redox condition of the groundwater is anoxic

The groundwater contains iron or manganese. In oxic groundwater, the contaminants nitrate, hexavalent chromium and uranium are mobile and stable. Nitrate and perchlorate can degrade, uranium can become less mobile, and chromium can become less toxic under anoxic conditions. Anoxic groundwater is more likely to contain geological contaminants that are soluble in anoxic conditions, like arsenic. Mixed redox conditions are likely the result of groundwater mixing along long screened wells.

Vulnerability to Geological Contaminants and Fossil Water Vulnerability (under Sustainability) are lower than average because the terrigenic helium-4 concentration is below all thresholds at 5.6 x10^{-10} cm^3(STP)/g. The groundwater is anoxic, which likely affects arsenic mobility, increasing the concentration into the moderate classification.



Factors Affecting Sustainability: Higher than average

Very Young Groundwater Vulnerability: Higher than average
The groundwater age is 8 years.

Wells with very young groundwater (less than 12 years) are more vulnerable to sustained droughts and reduced recharge may cause the well to go dry. The groundwater age is based on laboratory analyses of the naturally occurring isotopes tritium and helium-3.

River Recharge Vulnerability: Average
The source of recharge to the well is mixed.

Areas mainly recharged by river water are at greater vulnerability during droughts due to reduced surface water availability. The recharge source is based on laboratory analyses of oxygen isotopes in the water. Oxygen isotopes in local rain are different from river water from high mountains.

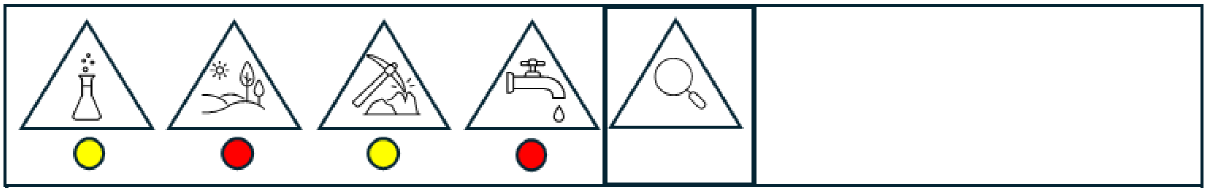
Fossil Water Vulnerability: Lower than average
The fossil groundwater component in the well is less than the dissolved helium concentration from the atmosphere.

Fossil water can indicate a vulnerability to unsustainable groundwater pumping that is not balanced by groundwater recharge on human time scales.

Dry Well Vulnerability: Lower than average
The nearest well that has been reported dry is more than 1,500 meters (~1 mile) away.

Nearby dry wells can be an indication of lowering water tables in the area.

As stated above, this well is not in an area of concern with high numbers of wells reported dry, but the groundwater age factor indicates the vulnerability is higher than average. The recharge source is mixed and there is a low proportion of fossil water.



Possible Mitigation Actions

- Quarterly water quality testing
  - Moderate arsenic concentration and anoxic groundwater
- Monitor local groundwater levels annually
  - Very young groundwater (age <12 years)

The tool displays possible mitigation actions for this well, based on the various stoplights.

- Yellow light for arsenic: Quarterly water quality testing
- Red light for Young Groundwater under Factors Affecting Sustainability: Monitor local groundwater levels quarterly

Overall, this well does not fit some of the patterns expected for relationships between contaminants and tracers. In particular, the occurrence of an elevated concentration of a geological contaminant in young groundwater does not fit the overall conceptual model. The close proximity of this well to the Sacramento River suggests that river floodplain sediments with high organic content affect the arsenic concentration, but the well's proximity to the river also likely results in cool river recharge and a young groundwater age. Although the likely source of recharge to the well is almost entirely river water, it is in the downstream portion of the Sacramento River, where somewhat isotopically heavier water is observed; the value is very close to the threshold value, so a mixed recharge source is indicated. Some of the limitations of the VAT are evident for this well, where hydrogeologic conditions, dominated by the proximity of a major river, are unlike the conditions over much of the Central Valley. Still, the VAT brings out useful information for the well owner, including the connection between reducing conditions and arsenic, and the potential for land surface contaminants to reach the well relatively quickly because of the young groundwater age.

4.5. Caveats and Limitations

This tool is intended to give well owners and water managers possible reasons for the occurrence of certain contaminants and to highlight potential sustainability issues, based on broadly applied statistical interpretations of geochemical and isotopic tracers. While categorizing contaminant concentrations according to health-based benchmarks is straightforward, assigning vulnerabilities based on environmental tracers of groundwater flow and transport is accompanied by significant uncertainty. The derived parameters upon which the assessments are based are inherently 'noisy' because of complex recharge patterns, dispersion in heterogeneous aquifer systems, mixing of flowpaths in wells, and complex water-rock interaction. As quantified in Section 4.1 and 4.3 and in Table 7, categorization of vulnerabilities results in many instances where contaminant concentrations do not follow the expected patterns based on vulnerability indicators.

There are many instances of 'false positives', whereby e.g., a young groundwater age indicates a higher than average Vulnerability to Land Surface Contaminants, but no contaminant concentrations are above benchmark levels. A likely explanation is that contaminant sources are not present in the area. This type of false positive still imparts useful information, since the well is likely vulnerable if sources materialize. The tool also generates 'false negatives', whereby e.g., the Vulnerability to Geological Contaminants is lower than average because of a lower than average fossil groundwater component and lower than average geothermal warming, but arsenic is detected at a concentration above benchmark levels. A possible explanation is that the arsenic has an anthropogenic rather than geological source, or, as in the example well 3 (Section 4.4.3), a shallow source of arsenic in young groundwater is accompanied by reducing conditions. Again, the results may impart useful information, but the information does not follow from the tracer-related stoplight colors. Sustainability indicators do not have accuracy testing methods that are analogous to those that use contaminant concentrations.

Other limitations of the tool come about because of incomplete data for either contaminants or for tracers. Tables 1 and 2 show the number of wells with results for the various parameters, but individual wells may be missing more than one parameter. Only 410 wells of the 3095 included in the tool have data populating all 16 parameters (raw and derived) applied in the assessment. Dissolved oxygen, perchlorate, and hexavalent chromium are the most frequently missing parameters, as shown in Table 2. For example, a low number of detections above the MCL for perchlorate does not allow for meaningful accuracy testing (Table 6).

Since the stoplights may generate inaccurate results, the general recommendations for mitigation actions that are tied to the stoplight colors should be taken as initial suggestions and not required remedial activities. The recommendations could lead to further information gathering, further water quality or tracer testing, examination of alternate drinking water sources, or examination of possible physical changes to a well so that contamination is avoided.

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6. Appendix

Accuracy Testing Table

Concentration	Level	Age Vulnerability			Recharge Source Vulnerability			Recharge Temperature Vulnerability			Fossil Groundwater Vulnerability			Discharge Temperature Vulnerability		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Nitrate Concentration	Low	372	269	260	278	720	669	413	256	356	469	140	438	248	205	230
	Moderate	27	85	64	34	198	122	43	70	97	115	33	64	62	45	34
	High	9	66	111	29	236	249	38	61	119	152	35	35	61	45	26
		2%		26%	9%		24%	8%		21%	21%		7%	16%		9%
Arsenic Concentration	Low	260	302	340	225	787	728	344	267	434	575	148	342	272	217	173
	Moderate	61	62	40	46	150	137	76	53	68	67	37	95	51	40	52
	High	88	42	24	56	153	135	60	48	50	46	21	97	33	24	58
		22%		6%	17%		14%	13%		9%	7%		18%	9%		20%
Perchlorate Concentration	Low	209	187	186	112	350	292	197	187	294	341	95	255	270	193	210
	Moderate	29	65	64	8	114	84	21	52	113	106	35	48	84	73	24
	High	0	7	4	0	6	10	5	6	5	7	3	6	4	1	2
		0%		2%	0%		3%	2%		1%	2%		2%	1%		1%
Hexavalent Chromium Concentration	Low	116	96	134	100	220	273	166	90	146	203	51	157	121	82	108
	Moderate	123	171	127	43	277	237	160	151	206	248	85	191	150	106	78
	High	14	11	8	0	20	36	10	10	21	22	7	13	15	9	11
		6%		3%	0%		7%	3%		6%	5%		4%	5%		6%
Uranium Concentration	Low	342	311	282	210	656	565	382	282	421	511	165	427	295	237	242
	Moderate	9	40	36	16	94	32	38	26	35	52	13	35	25	21	20
	High	7	31	48	27	101	46	17	31	51	64	14	23	31	19	14
		2%		13%	11%		7%	4%		10%	10%		5%	9%		5%