FINAL REPORT

Antelope Subbasin

Sustainable Groundwater Management Act

Groundwater Sustainability Plan (Chapter 2B Basin Setting)

January 2022

Prepared For:

Tehama County Flood Control and Water Conservation District

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LIST OF ACRONYMS & ABBREVIATIONS

AB	Assembly Bill
bgs	Below Ground Surface
CASGEM	California Statewide Groundwater Elevation Monitoring
CCR	California Code of Regulations
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CDPH	California Department of Public Health
CE	Communications and Engagement
CFS	Cubic Feet per Second
CV-SALTS	Central Valley Salinity Alternatives
CVRWQCB	Central Valley Regional Water Quality Control Board
CWC	California Water Code
dS/m	Decisiemens per Meter
DAC	Disadvantaged Community
DDW	Division of Drinking Water
DOI	Department of the Interior
DWR	California Department of Water Resources
EC	Electrical Conductivity
ft^2/day	Square Feet Per Day
ft/day	Feet Per Day
ft/mile	Feet per Mile
ft bgs	Feet Below Ground Surface
ft msl	Feet Above Mean Sea Level
GAMA	Groundwater Ambient Monitoring and Assessment Program
GDE	Groundwater Dependent Ecosystem
GMP	Groundwater Management Plan
GPS	Global Positioning System
Gpm	Gallons per Minute

GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
HCM	Hydrogeologic Conceptual Model
iGDE	Indicators of Groundwater Dependent Ecosystems
ILRP	Irrigated Lands Regulatory Program
InSAR	Interferometric Synthetic Aperture Radar
IRWMP	Integrated Regional Water Management Plan
JPA	Joint Powers Authority
LLNL	Lawrence Livermore National Laboratory
LSCE	Luhdorff & Scalmanini, Consulting Engineers
MCL	Maximum Contaminant Level
mg/L	Milligrams per Liter
MO	Measurable Objective
MOA	Memorandum of Agreement
MT	Minimum Threshold
MTJ	Mendocino Triple Junction
MWELO	Model Water Efficient Landscape Ordinance
NCCAG	Natural Communities Commonly Associated with Groundwater
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
SAGBI	Soil Agricultural Groundwater Banking Index
SB	Senate Bill
SGMA	Sustainable Groundwater Management Act
SVWQC	Sacramento Valley Water Quality Coalition
SWRCB	State Water Resources Control Board
TAC	Technical Advisory Committee
TDS	Total Dissolved Solids
Tehama County FCWCD	Tehama County Flood Control and Water Conservation District
TM	Technical Memorandum
USBLM	United States Bureau of Land Management

USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
UWMPA	Urban Water Management Planning Act
WDL	Water Data Library
WDR	Waste Discharge Requirements
µg/L	Micrograms per Liter
µmhos/cm	Micromhos per Centimeter

2 SUBBASIN PLAN AREA AND BASIN SETTING (REG. § 354.8)

2.1 Description of Plan Area

2.2 Basin Setting

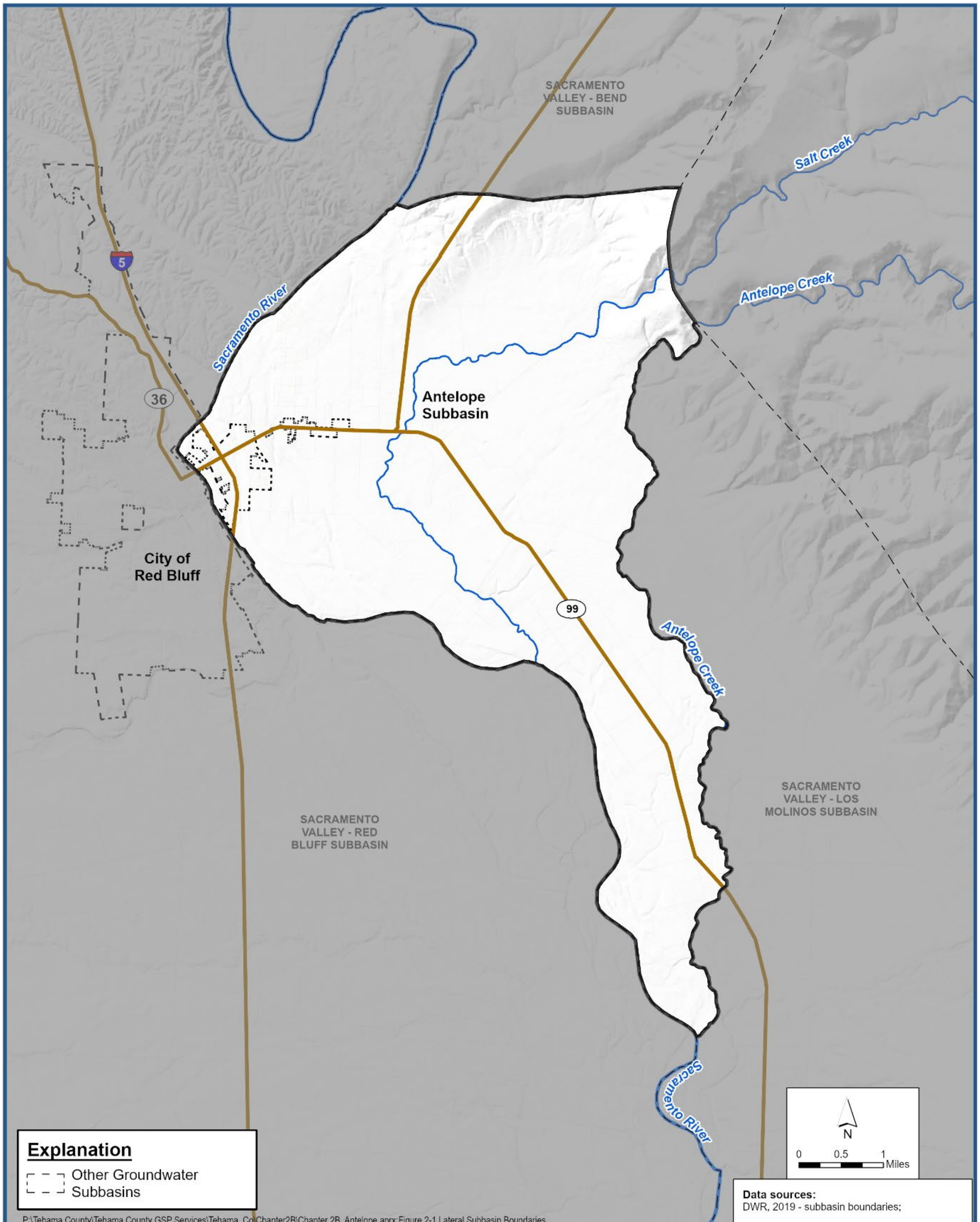
The Basin Setting section is a description of available information used as a background to develop the sustainability criteria for the Subbasin. It includes a detailed review of studies and historic groundwater conditions in the Subbasin. This information provides context about the quantity and movement of water in the Subbasin. The Basin supports numerical modeling used to define groundwater budgets.

2.2.1 Hydrogeologic Conceptual Model

The Hydrogeologic Conceptual Model (HCM) is the framework for the movement of water in the Subbasin. An HCM is developed through the use and interpretation of historical geologic, hydrogeologic, and hydrologic data and investigations to describe the geologic features, the water sources, and movement of surface water and groundwater. The HCM also describes groundwater quality and the origin and migration of chemicals of concern to beneficial users. The development of the HCM is based on the availability of data and is updated periodically as new hydrogeologic data is collected, analyzed, and interpreted. The development of an HCM begins with a review of historical reports and available data. The HCM presented herein of the Antelope Subbasin is the result of updating previous HCMs. The HCM is also the foundation for the numerical model used to produce the historic and current water budgets and the future projections of groundwater use. The components of the HCM including the Subbasin's lateral boundaries, topography, geologic setting, soil characteristics, principal aquifers, definable bottom of the aquifer system, surface water features, and recharge areas, are presented in the following sections.

2.2.1.1 Subbasin Boundaries

The lateral extent of the Antelope Subbasin is defined in the DWR Bulletin 118 and based on surface water and geologic features. Initial subbasin boundaries for California were published in 2004 with updates published in 2016 and 2018. No changes to the Antelope Subbasin boundary descriptions were included in the 2016 or 2018 Bulletin 118 updates. Surface water and geologic features are used as lateral bounds as they often control divergent groundwater flow (DWR, 2004). The Subbasin is bordered to the north by the Bend Subbasin separated by the low permeability mudflow deposits of the Tuscan Formation (Tehama County FCWCD, 2012). The western boundary is defined as the Sacramento River that separates the Subbasin from the Red Bluff Subbasin (DWR, 2004). The Subbasin is delineated to the east and southeast by the Cascade Range geologic province and Antelope Creek (DWR, 2004). Antelope Creek separates the Subbasin from the Los Molinos Subbasin. The bottom of the Subbasin is defined as the base of the post-Eocene continental deposits where the transition from marine derived sediments to terrestrial derived sediments corresponds to the transition from saline/brackish groundwater to fresh groundwater. Fresh groundwater is defined as water with an electrical conductivity (EC) of less than 3,000 micromhos per centimeter (µmhos/cm) as mapped by Berkstresser (1973) (DWR, 2014). This depth is corroborated by DWR's review of geophysical logs and water quality samples (DWR, 2014). The lateral subbasin boundaries are presented in **Figure 2-14** and the bottom of the basin is discussed further in section 2.2.1.6 and presented in **Figure 2-15** and **Figure 2-16**.



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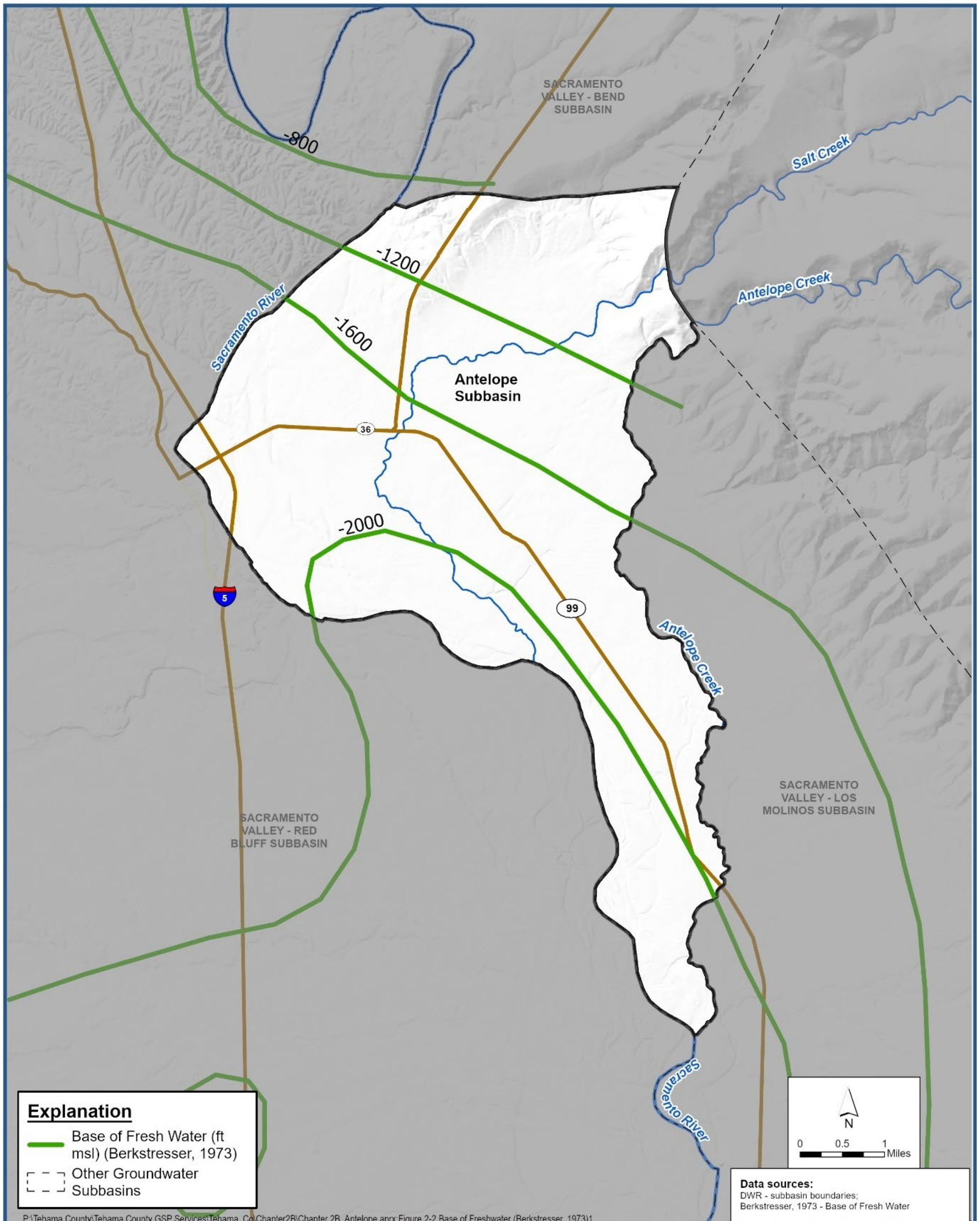
Lateral Subbasin Boundary

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-14



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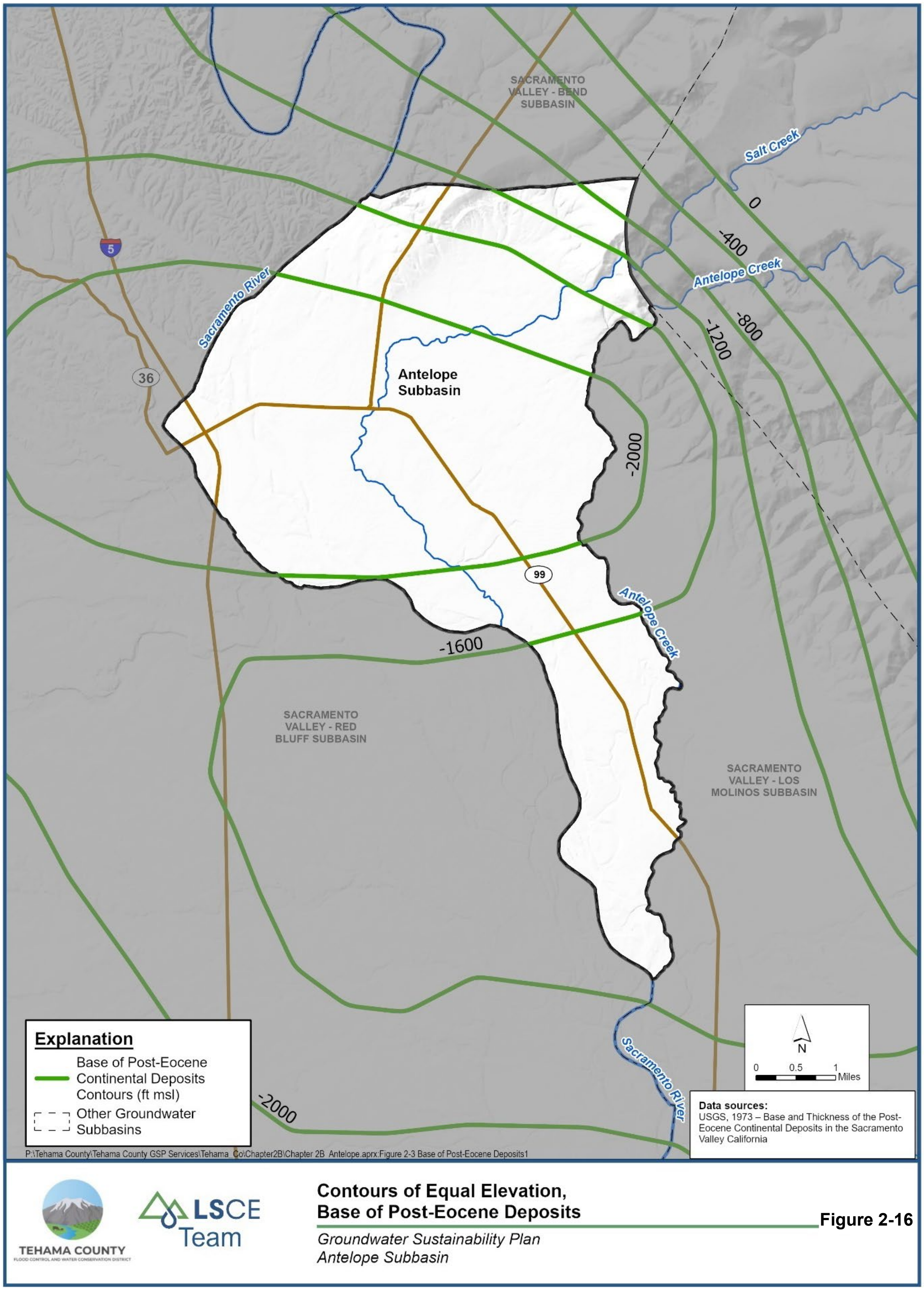
Contours of Equal Groundwater Elevation, Base of Freshwater

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-15



Contours of Equal Elevation, Base of Post-Eocene Deposits

Figure 2-16

Groundwater Sustainability Plan
Antelope Subbasin

2.2.1.2 Topographic Information

The Antelope Subbasin is characterized by a relatively flat topographic setting along the eastern side of the Sacramento Valley Basin. Topography is highest in the northeast corner of the Subbasin where the Chico Monocline borders the valley floor. The topographic slope is steep in the transition zone (10% - >50%) and is generally shallow throughout the rest of the Subbasin (<2%) (**Figure 2-17**). The ground surface elevation ranges from over 900 feet above mean sea level (ft msl) in the northeast corner of the Subbasin to less than 300 ft msl in the majority of the Subbasin (**Figure 2-18**).

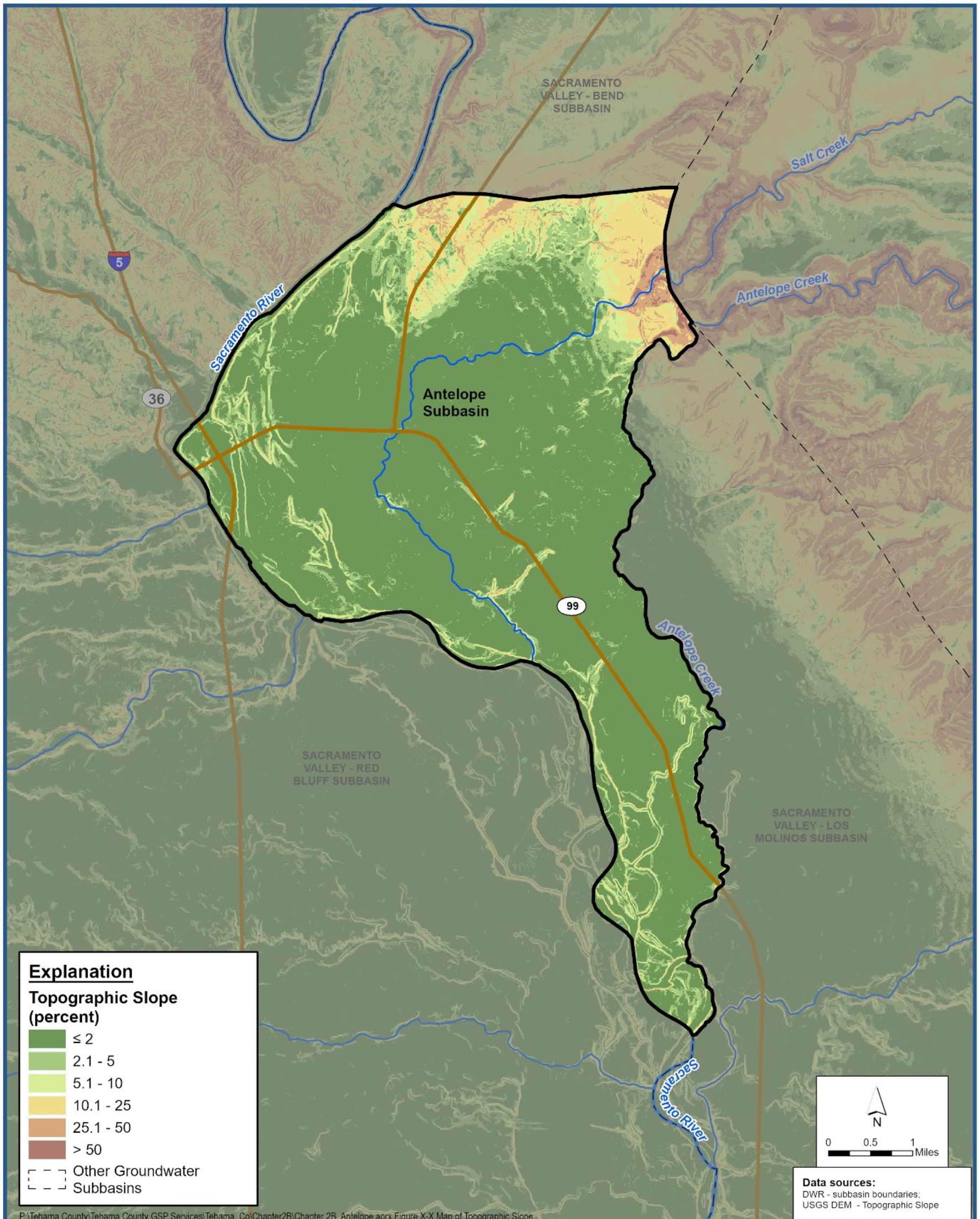
2.2.1.3 Geologic Setting

In the 1960s and 1970s, early studies of the geology in the northern Sacramento Valley were conducted for oil and gas exploration and characterization of geologic resources like groundwater. Studies by the USGS and independent researchers consolidated earlier work and conflicting nomenclature into more standardized and agreed upon definitions and characterized the water bearing potential and origin of the younger geologic units in the Sacramento Valley (Olmstead and Davis, 1961; Lydon, 1968; Ojakangas 1968). Depositional environments and geologic history of the older and deeper rocks were also characterized during the same period for oil and gas resources and academic purposes (Garrison, 1962; Bailey et al., 1970; Redwine, 1972; Dickinson and Rich, 1972; Mansfield, 1979).

In the 1980s and 1990s, further research was conducted on the older Great Valley Sequence geologic units (Ingersoll and Dickinson, 1981; Bertucci, 1983). Extensive mapping and seminal studies of the younger geologic formations were conducted by the USGS that further defined and separated the distribution and lithologic character of the geologic units in the Sacramento Valley (Marchand and Allwardt, 1981; Harwood et al., 1981; Helley and Jaworowski, 1985; Helley and Harwood, 1985; Harwood and Helley, 1987; Blake et al., 1999).

More recent studies in the 2000s and 2010s have attempted to further characterize the geologic material and contextualize the information as it relates to groundwater resources (DWR, 2004; DWR, 2008; Gonzalez, 2014). DWR conducted an extensive literature review and study to compile the most current geology and groundwater information in a 2014 report (DWR, 2014).

The geologic history of the northern Sacramento Valley, where the Subbasin is located, is dominated by a series of mountain building events leading to provenance changes in basin sedimentation. During the Mesozoic, a subduction zone created the plutonic emplacement of the Sierra Nevada. The uplift of the Sierra Nevada isolated the Pacific Ocean from its previous extent, moving the shoreline west (DWR, 2014). The uplifting mountains created a source of sediment that filled the forearc basin through erosional processes (Olmstead and Davis, 1961). On the western boundary of the forearc basin, the eastward dipping subduction resulted in accretionary forces forming the metamorphic rocks that would later make up the Franciscan Formation and Coast Range Ophiolite (DWR, 2014).



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Map of Topographic Slope

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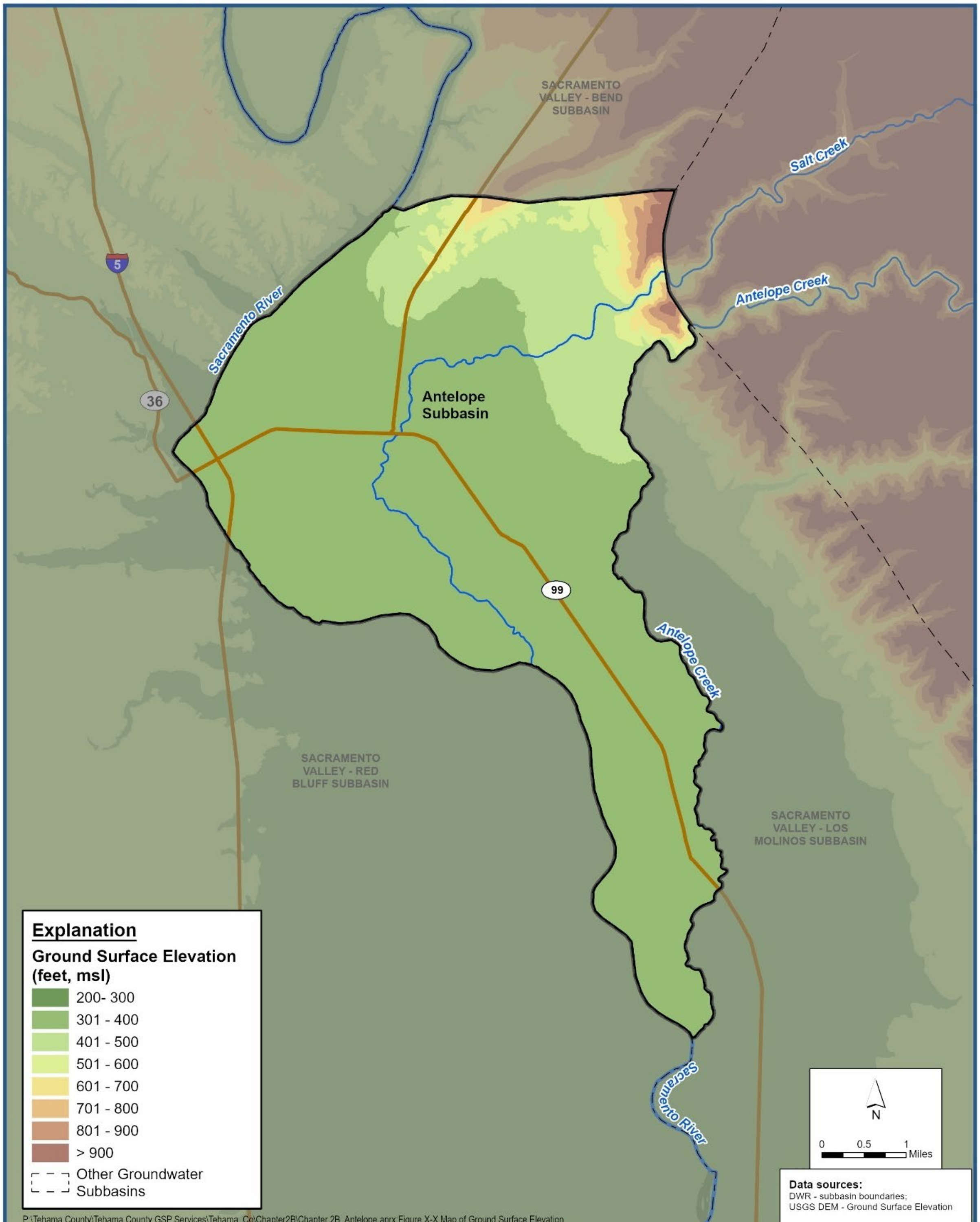
Antelope Subbasin

Figure 2-17



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Map of Ground Surface Elevation

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-18

During the early part of the Cenozoic Era in the Paleogene Period, the tectonic forces that dominated during the Mesozoic were still present (DWR, 2014). These tectonic forces resulted in periods of marine regression and transgressions that carved and subsequently filled a large canyon known as the lower Princeton Submarine Valley (DWR, 2014). Marine transgressions and regressions continued throughout the Paleogene and into the Miocene while older Cascade volcanism occurred on the eastern margins of the valley (DWR, 2014).

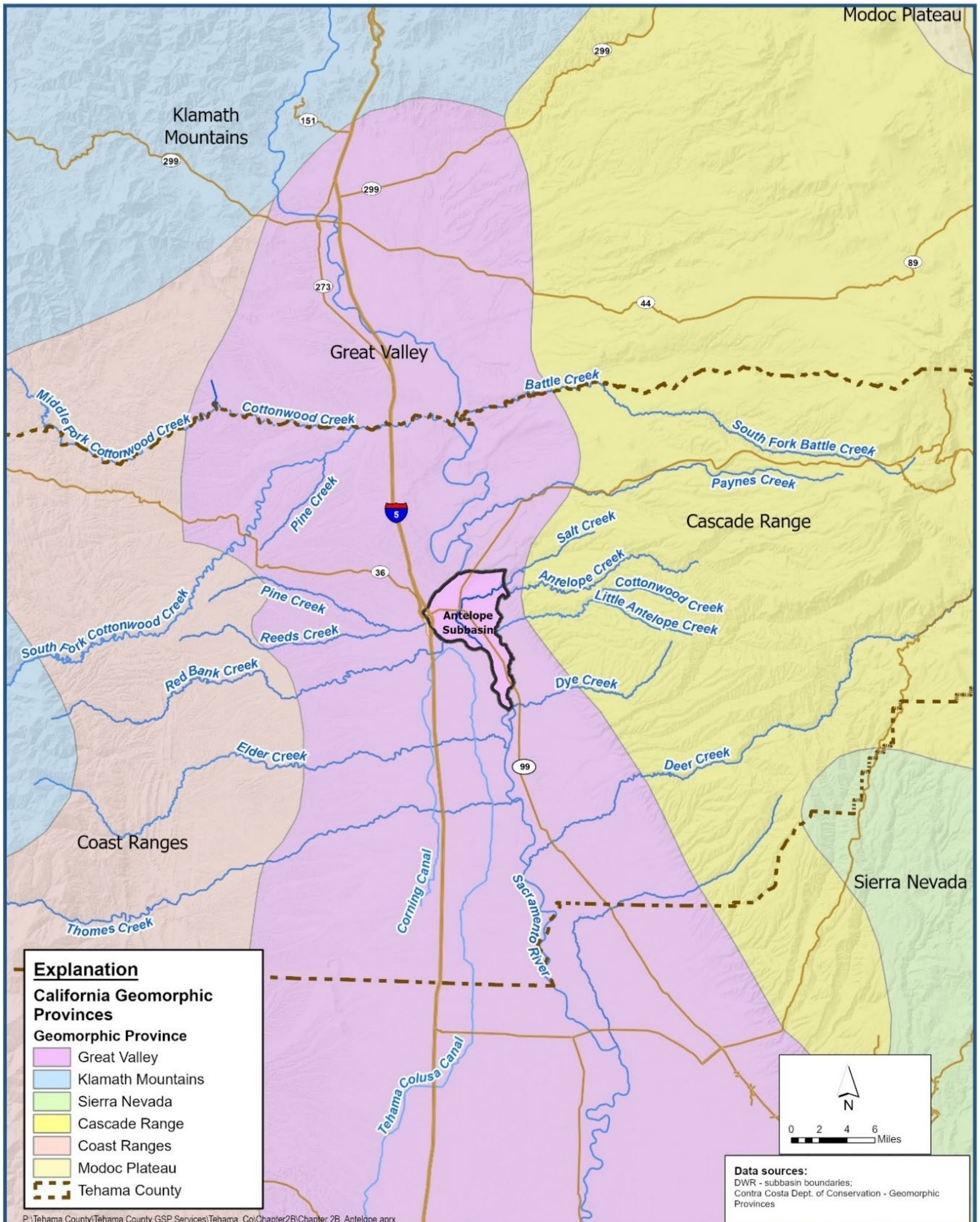
Continued sedimentation filled the valley throughout the Paleogene until a marine regression and sediment accumulation caused a transition from a marine to terrestrial depositional environment in the Neogene. During this period sedimentation sourced from the uplifting coast ranges, Klamath Mountains, and ancestral Cascades filled the basin (DWR, 2014). Throughout the Neogene epoch the tectonic regime was transitioning from subduction to transverse in a northward pattern until the present day where it is expressed as the Mendocino Triple Junction (MTJ). Tectonic forces associated with the northward migration of the MTJ resulted in geologic structures in the valley like the Chico Monocline, Red Bluff and Corning Faults, and the Los Molinos Syncline (DWR, 2014).

2.2.1.3.1 *Regional Geology*

The terrane surrounding the Subbasin is the source for the sediments that are deposited in and comprise the Sacramento Valley. It is important to understand the surrounding geologic provinces to properly characterize and contextualize the stratigraphy of the subbasin. The Northern Portion of the Sacramento Valley where the Subbasin is located is bordered on the east by the Cascade Range Province and the Klamath and Coast Range Geologic Provinces are to the west (**Figure 2-19**).

Klamath Geologic Province

The mountains to the northwest of the Subbasin make up the Klamath Geologic Province. The mountain range is steep with peaks of approximately 6,000 ft to 8,000 ft. The Klamath Mountains are comprised of accreted terranes consisting of oceanic crust and accreted island arcs (Blake et al., 1999). To the northwest of the Subbasin, the province consists of Jurassic and older metamorphic-plutonic basement overlain by the east to southeast dipping Great Valley Sequence (Blake et al., 1999). Very few streams and tributaries drain the Klamath Geologic Province in the vicinity of the Subbasin.



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Map of Geologic Provinces

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Antelope Subbasin

Figure 2-19

Coast Range Geologic Province

West of the Sacramento Valley lies the northern portion of the Coast Range Geologic Province. The northern Coast Range Geologic Province in the vicinity of the Sacramento Valley is steeply sloped with peaks around 5,700 ft.

The mountains here form the boundary between the northern Sacramento Valley and the California Coast. Major creeks that that feed the Sacramento River drain the Coast Ranges.

The rocks exposed in the western area of the Coast Range Province are composed of metamorphosed deep sea marine sedimentary rocks (Franciscan Complex). The Franciscan rocks are subdivided into two separate terranes, the Pickett Peak terrane and the Yolla Bolly terrane, which are further divided into sub-groups separated by thrust faults (Blake, 1999). The Franciscan Complex is separated from Jurassic and Cretaceous sedimentary rocks of the Sacramento Valley western foothills by the Coast Range Fault.

The recent and Quaternary history of the basin is similar to present day conditions. The MTJ continued its migration north to its present location causing flexural structures to form like the Inks Creek Fold system (DWR, 2014). Sedimentation continues to occur along stream channels that feed the Sacramento River and is sourced from the surrounding terrane and reworking of emplaced sediment.

Sacramento Valley Western Foothills

Along the west side of the Sacramento Valley are the foothills of the Coast Ranges and the Klamath Mountains. These foothills form a transition from the steeply sloped peaks of the Coast Ranges to the shallower slopes of the Sacramento Valley. Many streams drain the western foothills and feed the streams and channels in the Sacramento Valley.

The Jurassic and Cretaceous rocks of the Great Valley sequence that are exposed in the western portion of the province consist of marine sourced sedimentary rocks (DWR, 2014). These deposits are exposed due to folding and tilting and form the west limb of a structural trough (DWR, 2014). In the northwest of the province the outcrops are in depositional contact with the Coast Range Ophiolite and in the southwest they are in fault contact (Blake, 1999). In the most northern areas of the western foothills the Great Valley Sequence is in contact with the Klamath Mountains (Blake, 1999). The marine origin of the Great Valley sequence causes the groundwater contained therein to be saline and brackish (connate water).

Cascade Range Province

The Cascade Range Province immediately borders the Subbasin to the east. The Cascade Range is a series of andesitic and basaltic-andesite volcanic cones that extend from Lassen Peak in the south through Washington and Oregon in the north (USGS, 2002; Clynne and Muffler, 2010). The ancestral southernmost volcano of the Cascade Range, Mt. Yana, was the principal source of sediment for the Tuscan Formation (Lydon, 1968). The Cascade Range is an active volcanic arc that is driven by the eastward subduction off the coast of Washington, Oregon, and Northern California. Streams and rivers drain the Cascade Range in the vicinity of the Subbasin, feeding the Sacramento River and transporting sediment to the Sacramento Valley Groundwater Basin.

Great Valley Province (Sacramento Valley Province)

The Great Valley Province encompasses the entire central valley of California. The northern region of the Great Valley Province where the Subbasin is located is referred to as the Sacramento Valley Province. The Sacramento Valley Province (Great Valley Province on **Figure 2-19**) is relatively flat and gently slopes on either side toward the south draining Sacramento River. Stream channels, flood plains, and natural levees dominate the interior of the province which is bordered by the Coast Ranges to the west and the foothills of the Cascades to the east. The underlying sediments are dominated by the freshwater bearing Tehama Formation in the west and the Tuscan Formation in the east (Blake et al., 1999).

The alluvial plains of the western side of the province were formed by the ancestral Sacramento River and its tributaries. The streams deposited large amounts of sediment sourced from the uplifting Coast Range and to a lesser extent, the Klamath Mountains, during the Pliocene (Blake et al., 1999). These Pliocene sediments were later cut and filled by younger streams and tributaries (Blake et al., 1999). Outcrops of these younger sediments occupy currently active streams and tributaries (Blake et al., 1999).

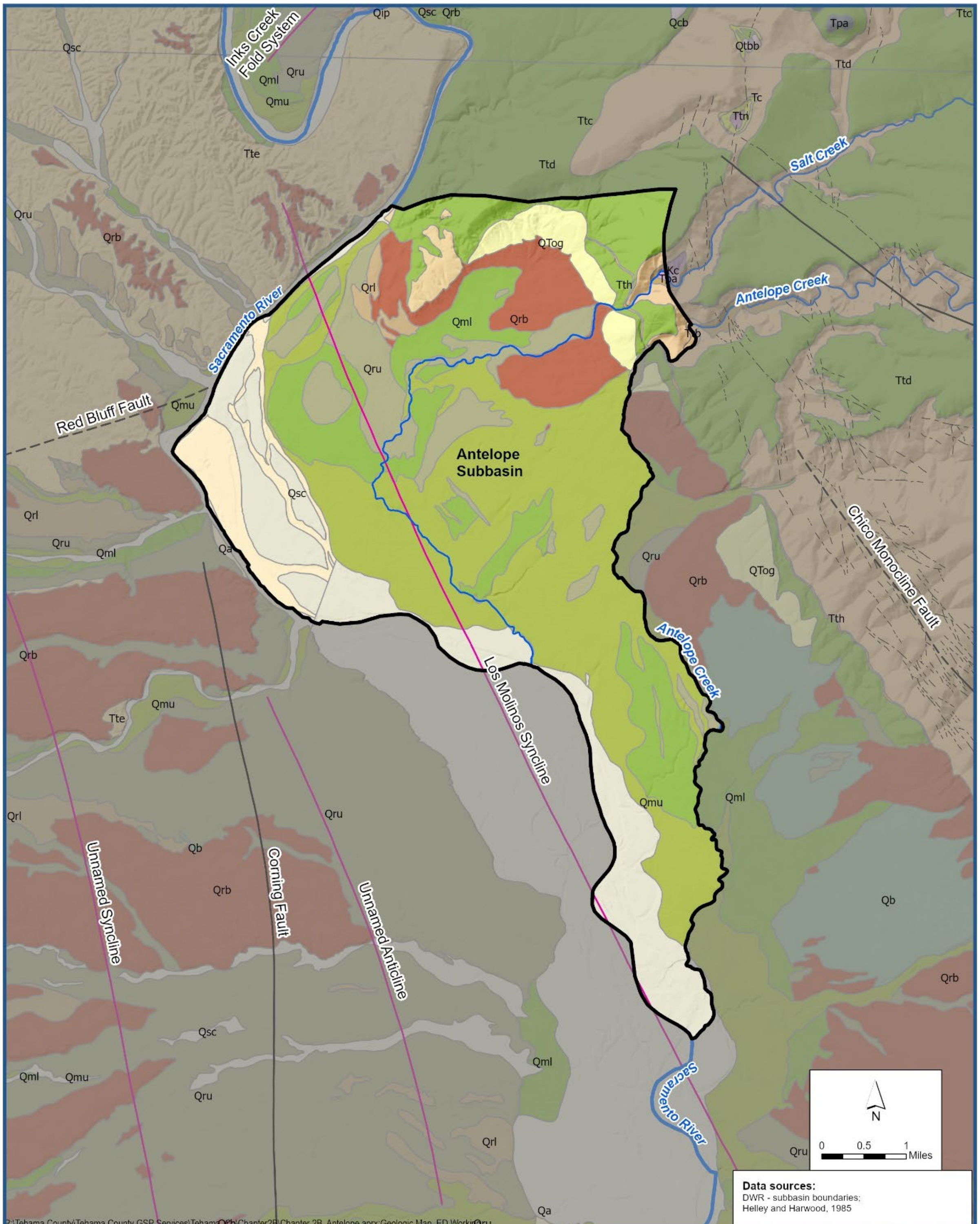
The topography on the east side of the Province is similar to that of the west. It has steeply sloping drainages in the east that shallow into alluvial fans in the vicinity of the Sacramento River. The major difference between the west and the east side is the provenance of the Pliocene sediments. The Pliocene sediments of the east side were sourced from the Cascade Range (DWR, 2014).

2.2.1.3.2 *Geologic Formations*

Geologic formations were mapped by Helley and Harwood (1985) and digitized by DWR (2014). The digitized maps were modified and are presented as **Figures 2-20** and **Figure 2-20B**. Geologic cross sections were constructed using available data, locations of cross sections are presented as **Figure 2-21** and **Figure 2-21B** and cross sections are presented as **Figure 2-22** and **Figure 2-23**. In addition, a DWR cross section (DWR, 2008) that includes the Subbasin, and extends several miles to the east into the Red Bluff Subbasin is presented as **Figure 2-24** and **Figure 2-24B**. A summary of stratigraphic relationships and water bearing character is presented as **Table 2-8**.

Great Valley Sequence

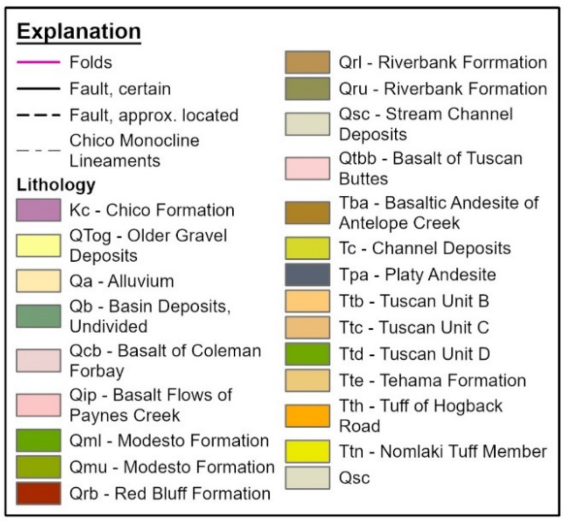
The Great Valley sequence is characterized by Late Jurassic and Cretaceous deep-marine turbidites comprised of interbedded marine sandstone, siltstone, and conglomerate (Bailey et al. 1970; Bertucci, 1983; DWR, 2014). The Great Valley sequence can be seen on the eastward edges of the northern Sacramento Valley and underly the younger deposits throughout the Subbasin (**Figure 2-20**). The deposits have been observed to be 45,000 feet thick (Ingersoll and Dickeson, 1981). The depth to the top of the Great Valley Sequence ranges from 2,800 ft bgs to over 3,000 ft bgs in the Subbasin (**Figure 2-24**). The source material was the ancestral Sierran-Klamath terrane (Ojakangas, 1968; Dickinson and Rich, 1972; Mansfield, 1979; Ingersoll and Dickerson, 1981; DWR, 2014). The eroded sediments were deposited off the continental shelf as turbidity flows and submarine fans. The groundwater contained in the Great Valley sequence is primarily saline due to the marine depositional environment (DWR, 2014).



Geologic Map with Faults

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-20



P:\Tehama County\Tehama County GSP Services\Tehama_Co\Chapter2B\Chapter 2B Antelope.aprx:Geologic Map_ED Working

Data sources:
DWR - subbasin boundaries;
Helley and Harwood, 1985

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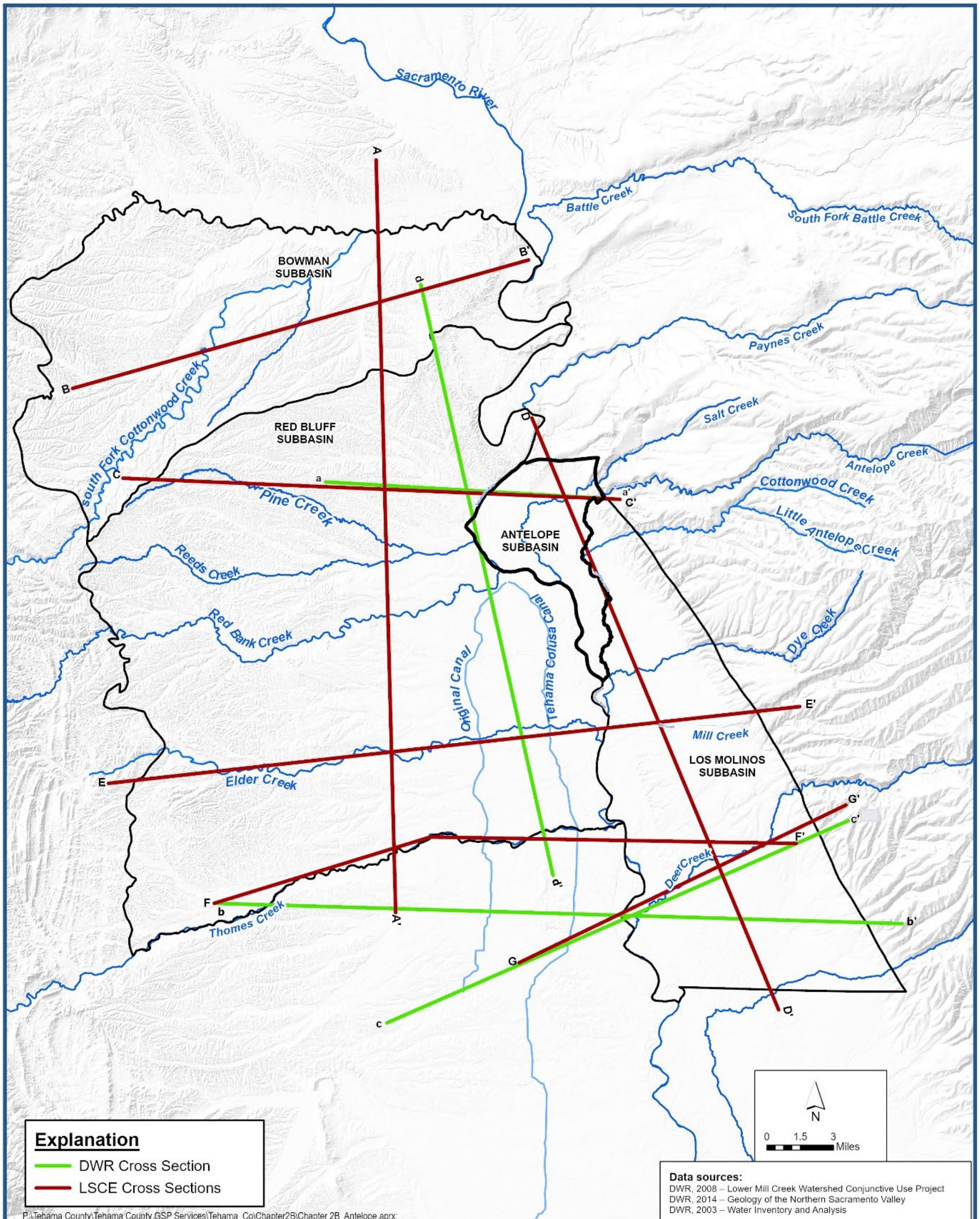
Geologic Map with Faults

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-20B



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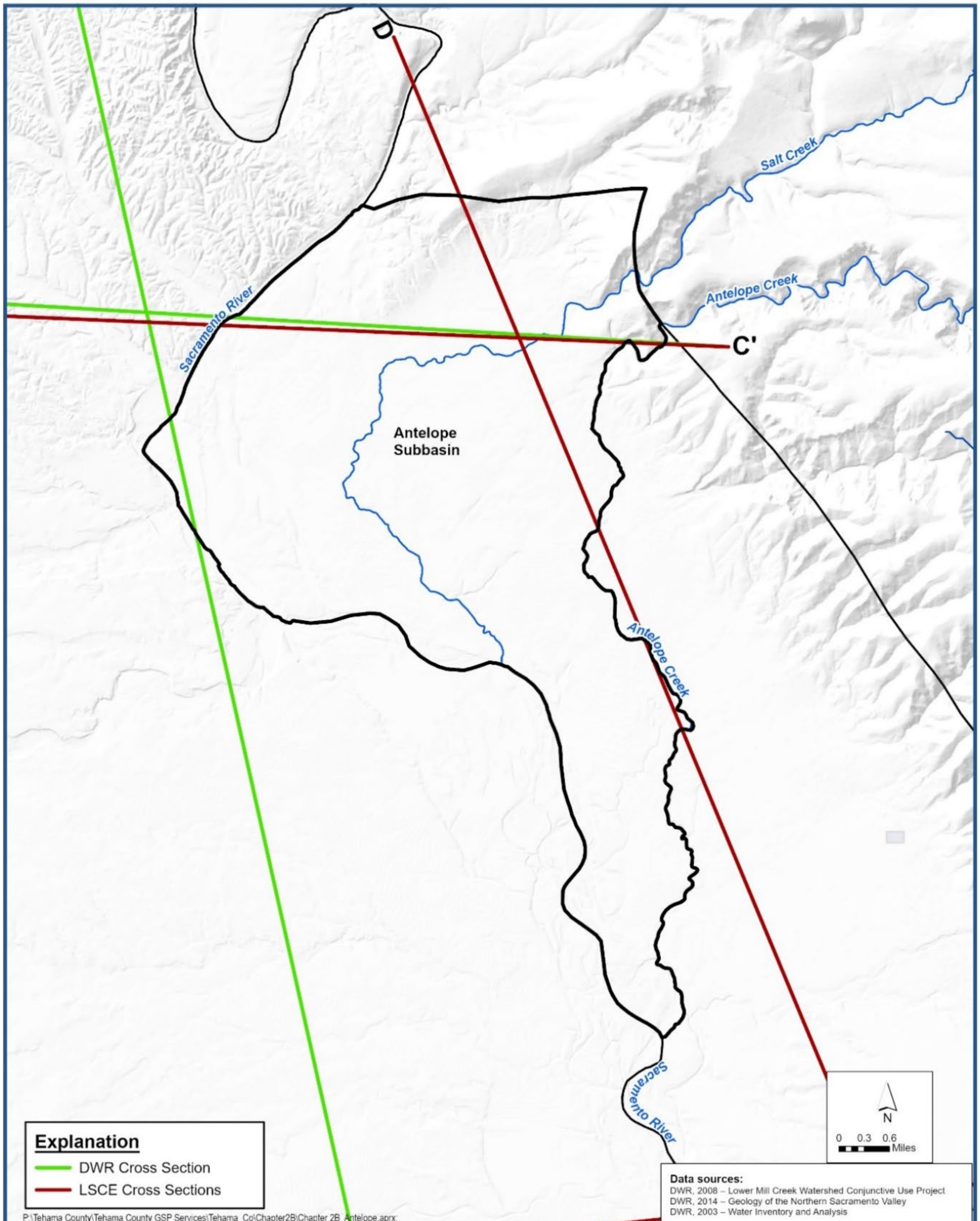
Map of Cross Section Locations

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-21



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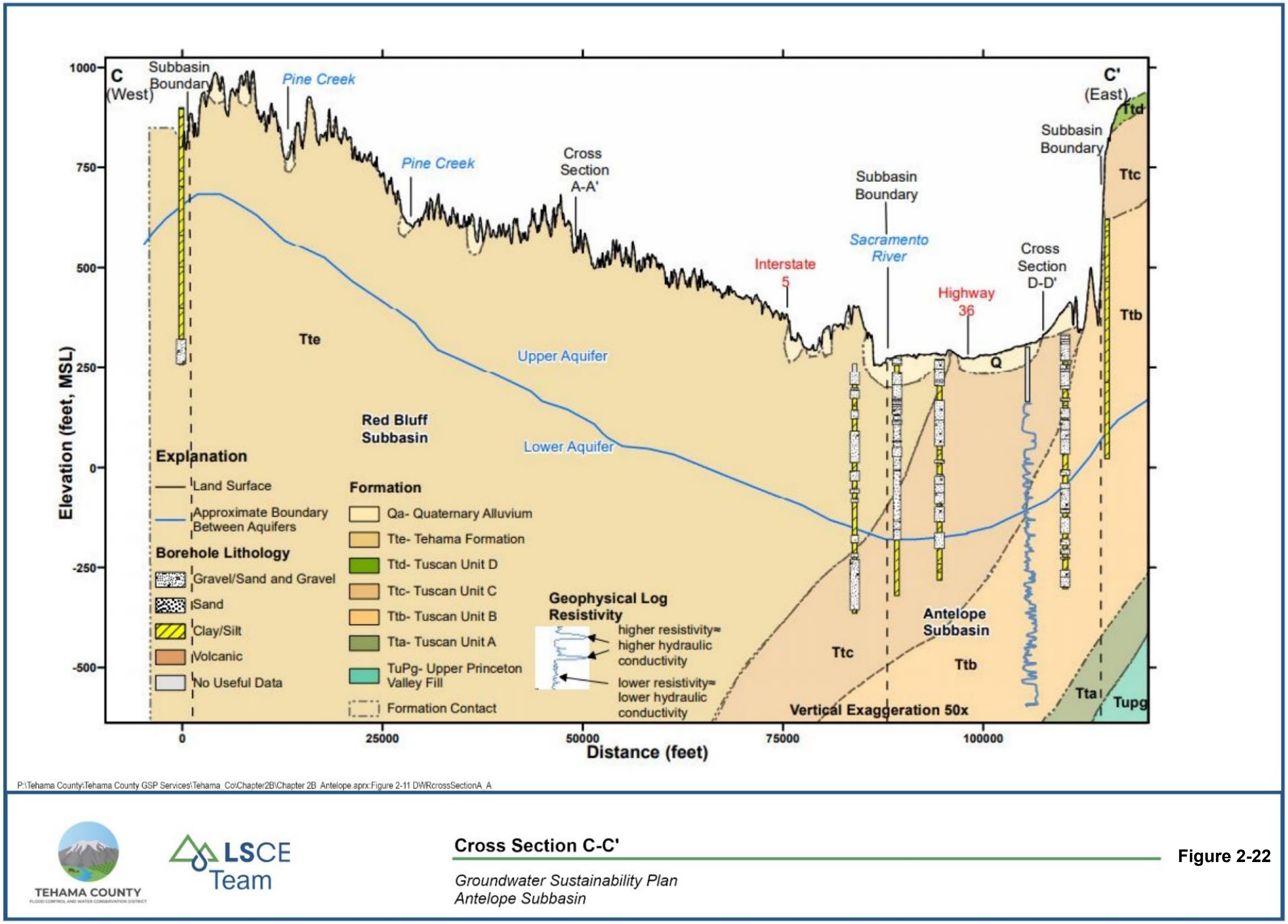
Map of Cross Section Locations

Groundwater Sustainability Plan
Antelope Subbasin

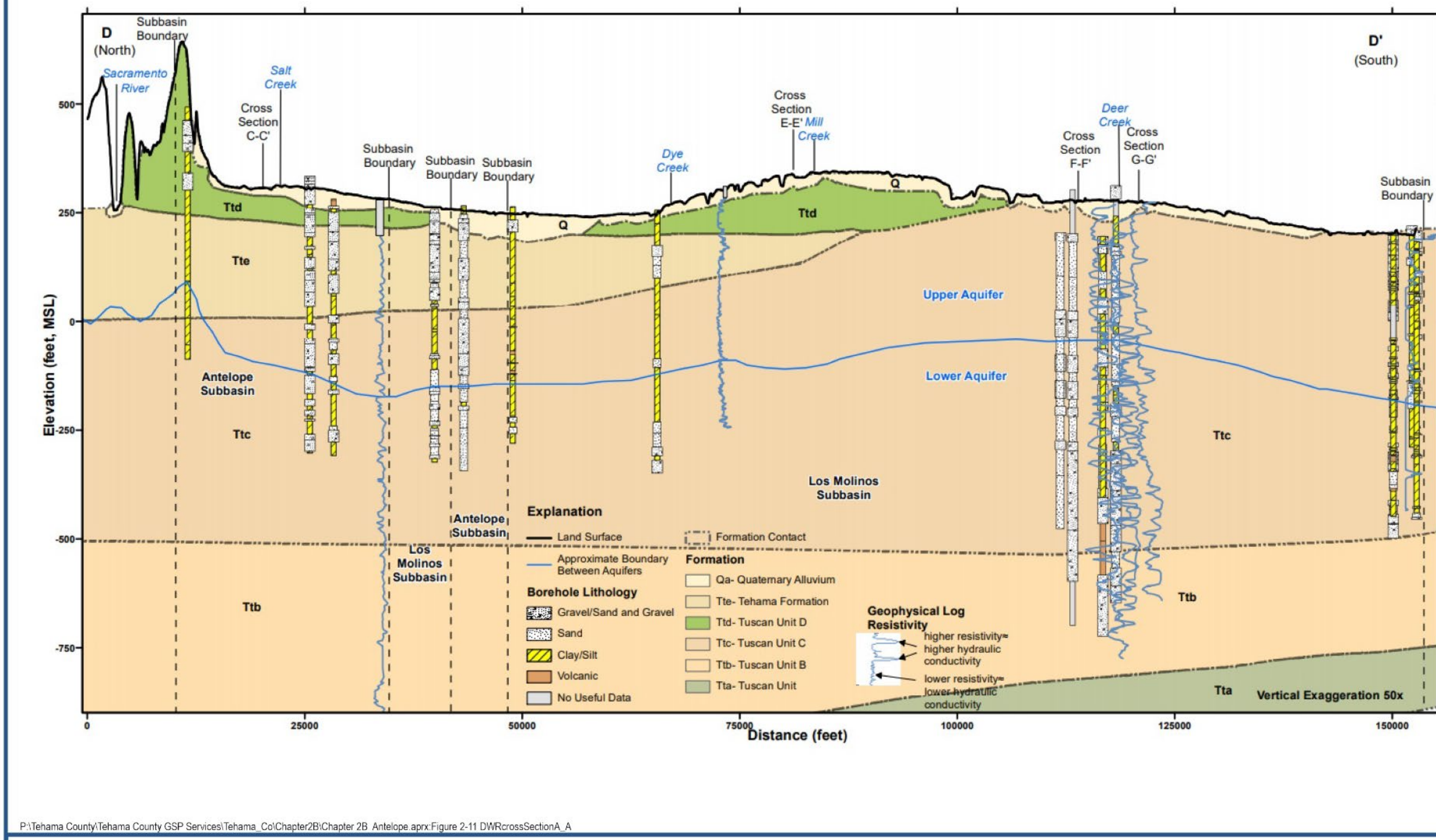
Figure 2-21B



Cross Section C-C'

Groundwater Sustainability Plan
Antelope Subbasin

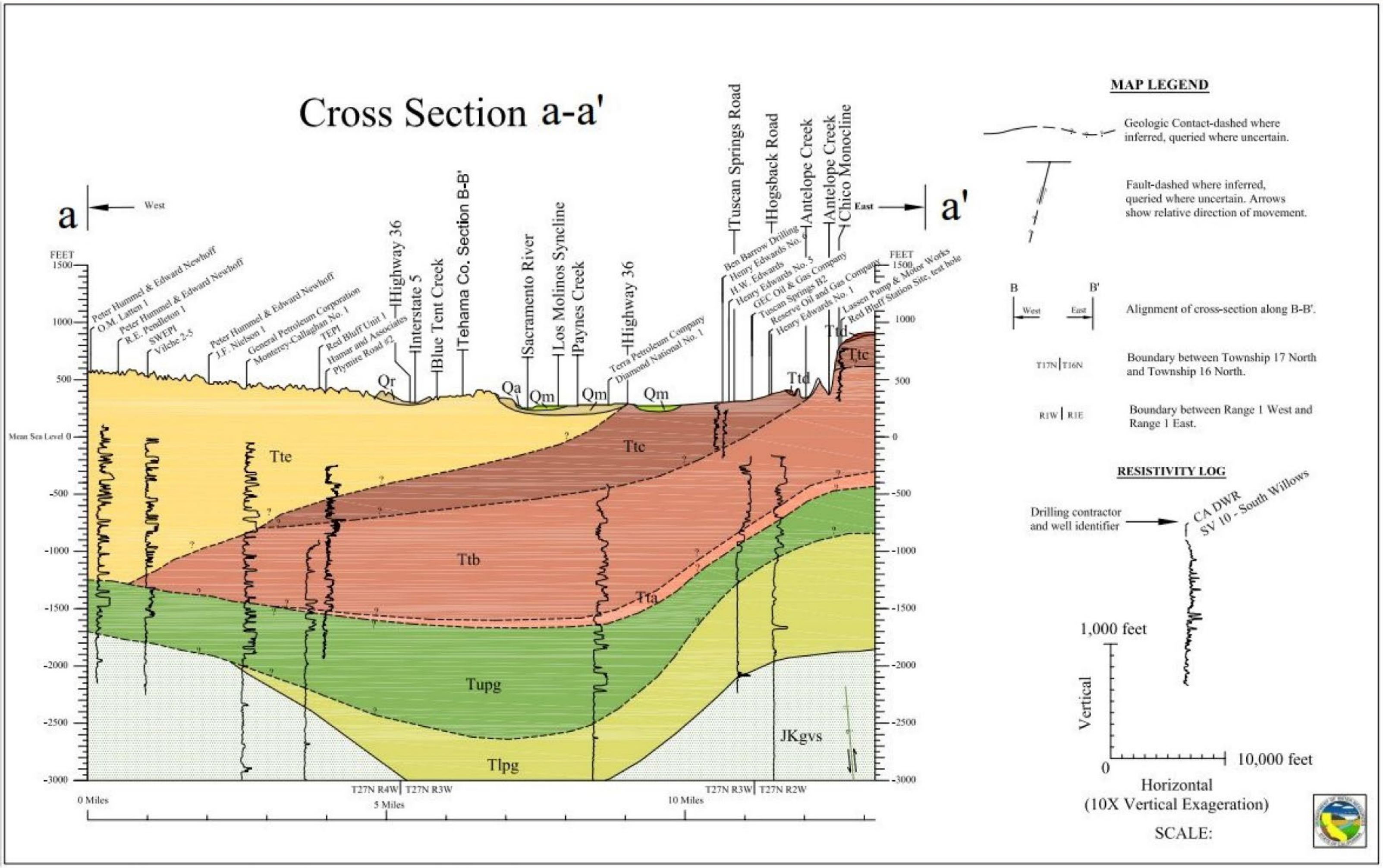
Figure 2-22



Cross Section D-D'

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-23



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Cross Section a-a'

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-24

DESCRIPTION OF MAP UNITS

Qa	**Alluvium** (Holocene)-Includes surficial alluvium and stream channel deposits of unweathered gravel, sand and silt, maximum thickness 80 ft. *(adapted from Helley & Harwood, 1985)*.
Qb	**Basin Deposits** (Holocene)-Fine-grained silt and clay derived from adjacent mountain ranges, maximum thickness up to 200 ft. *(adapted from Helley & Harwood, 1985)*.
Qm	**Modesto Formation**, undifferentiated (Pleistocene)-Alluvial fan and terrace deposits consisting of unconsolidated weathered and unweathered gravel, sand, silt and clay; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood , 1985).*
Qr	**Riverbank Formation**, undifferentiated (Pleistocene)-Alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand and silt; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood, 1985).*
Tte	**Tehama Formation** (Plio-Pleistocene)-Includes Red Bluff Formation on west side. Pale green, gray and tan sandstone and siltstone with lenses of pebble and cobble conglomerate; maximum thickness 2,000 ft. *(adapted from Helley & Harwood, 1985).*
Ttd	**Tuscan Unit D** (Plio-Pleistocene)-Fragmental flow deposits characterized by monolithic masses containing gray hornblende and basaltic andesites and black pumice, maximum thickness 160 ft. *(adapted from Helley & Harwood, 1985).*
Ttc	**Tuscan Unit C** (Plio-Pleistocene)-Includes Red Bluff Formation on east side. Volcanic lahars with some interbedded volcanic conglomerate and sandstone, and reworked sediments; maximum thickness 600 ft. *(adapted from Helley & Harwood, 1985, DWR Bulletin 118-7, 2001, draft report).*
Ttb	**Tuscan Unit B** (Pliocene)-Layered, interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone; maximum thickness 600 ft. *(adapted from Helley and Harwood, 1985; DWR Bulletin 118-7, 2001, draft report).*
Tta	**Tuscan Unit A** (Pliocene)-Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone containing metamorphic rock fragments; maximum thickness 400 ft. *(adapted from Helley & Harwood, 1985; DWR Bulletin 118-7 (in progress), 2001).*
Tl	**Lovejoy Basalt** (Miocene)-Black, dense, hard microcrystalline basalt; maximum thickness 65 ft. *(adapted from Helley & Harwood, 1985).*
Tupg	**Upper Princeton Valley Fill** (Late Oligocene to Early Miocene)-Non-marine sediments composed of sandstone with interbeds of mudstone and occasional conglomerate and conglomerate sandstone; maximum thickness 1,400 ft. *(adapted from Redwine, 1972).*
Ti	**Ione Formation** (Eocene)-Marine to non-marine deltaic sediments, light colored, commonly white conglomerate, sandstone and siltstone, which is soft and easily eroded; max. thickness 650 ft. *(adapted from DWR Bulletin 118-6, 1978; Creely, 1965).*
Tlpg	**Lower Princeton Submarine Valley Fill** (Eocene)-includes Capay Formation. Marine sandstone, conglomerate and interbedded silty shale, maximum thickness 2,400 ft. (*adapted from Redwine, 1972*)
JKgvs	**Great Valley Sequence** (Late Jurassic to Upper Cretaceous)-Marine clastic sedimentary rock consisting of siltstone, shale, sandstone and conglomerate; maximum thickness 15,000 ft.
JKf	**Franciscan Formation** (Jurassic to Cretaceous)-Dominated by greenish-grey greywackes with lesser amounts of dark shale, limestone and radiolarian chert, maximum thickness up to 25,000 ft. *(adapted from strand, 1962 and Norris & Webb, 1990).*

P:\Tehama County\Tehama County GSP Services\Tehama_Co\Chapter2B\Chapter 2B_Antelope.aprx:Figure 2-11 DWRcrossSectionA_A

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DWR Cross Section Legend

Antelope Subbasin Groundwater Sustainability Plan
Tehama County, California

Figure 2-24B

Table 2-8. Stratigraphic Summary with Hydrogeologic Properties

Age: Period	Age: Epoch	Geologic Unit	Lithology Description	Approximate Thickness Interpreted in Subbasin	Aquifer Unit	Hydrogeologic Character
Quaternary	Holocene	Surficial Alluvium	Unweathered gravel, sand, and silt (DWR, 2014)	25-50 ft (DWR, 2008)	Upper	Moderately permeable but not a significant source of groundwater in the Subbasin due to limited extent (DWR, 2004)
Quaternary	Pleistocene & Pliocene	Modesto Formation	Alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand, silt, and clay (DWR, 2014)	50 ft (DWR, 2004; DWR 2008)	Upper	Moderately to highly permeable. Limited source of groundwater due to limited thickness and extent in the Subbasin (DWR, 2004).
Quaternary	Pleistocene & Pliocene	Riverbank Formation	Alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand, and silt (DWR, 2014)	100 ft (DWR, 2008)	Upper	Moderately to highly permeable. Limited Source of groundwater due to limited thickness and extent in Subbasin (DWR, 2004)
Quaternary	Pleistocene & Pliocene	Red Bluff Formation	Thin veneer of highly weathered, bright red gravels (DWR, 2014)		Upper	Water is available only where local perched conditions exist. Provides limited water due to limited extent and thickness in the Subbasin (DWR, 2004).
Neogene	Pleistocene & Pliocene	Tehama Formation	Pale green, gray, and tan sandstone, and siltstone with lenses of pebble and cobble conglomerate (DWR, 2014)	750 ft (DWR, 2008)	Upper/Lower	Low to moderate permeability with localized areas of high permeability (DWR, 2003). Well yields can range from 475 gpm to 950 gpm (DWR, 2003)
Neogene	Pleistocene & Pliocene	Tuscan Formation	Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff (DWR, 2014)	1500 ft (DWR, 2004)	Upper/Lower	Low to high permeability and is the main water-bearing formation in the Subbasin (DWR, 2004)
Paleogene	Miocene	Upper Princeton Valley Fill	Non-marine sediments composed of sandstone with interbeds of mudstone, occasional conglomerate, and conglomerate sandstone (DWR, 2014)	1100 ft (DWR, 2008)	Brackish	
Paleogene	Eocene	Lower Princeton Submarine Fill	Marine Sandstone, conglomerate, and interbedded silty shale (DWR, 2014)	350 ft (DWR 2008)	Saline	
Cretaceous		Great Valley Sequence	Marine clastic sedimentary rock consisting of siltstone, shale, sandstone, and conglomerate (DWR, 2014)	1100 ft (DWR, 2008)	Saline	

Lower Princeton Submarine Valley Fill

The lower Princeton Submarine Valley Fill is composed of Eocene aged interbedded marine shale and sandstones (DWR, 2014; Redwine, 1972). The formation is not visible at the surface but has been observed to be approximately 1,500 ft deep in the Sacramento Valley based on the interpretation of lithologic logs from oil and gas wells (Redwine, 1972). The extent of the lower Princeton Submarine Valley Fill within the Subbasin is limited to the west and thins to the east; eventually pinching out near the Chico Monocline (**Figure 2-24;** DWR, 2014). The formation was deposited under marine conditions therefore formation groundwater is saline (Redwine, 1972). The formation is unconformably overlain by the upper Princeton Valley Fill in the Subbasin (DWR, 2014).

Upper Princeton Valley Fill

The upper Princeton Valley Fill is composed of Miocene-age sandstone with frequent interbeds of pelite (mudstone) and occasional conglomerate (Redwine, 1972). The formation is not observed on the surface but extends throughout the northern Sacramento Valley from Red Bluff to the Sutter Buttes with maximum thicknesses of 1,400 ft (DWR, 2014; Redwine 1972). Similar to the lower Princeton Submarine Valley Fill, the Upper Princeton Valley Fill is thickest in the west and thins to the east, eventually pinching out near the Chico Monocline (**Figure 2-24;** DWR, 2014). The formation sandstone contains interstitial brackish water and occasionally fresh water (DWR, 2014; Redwine, 1972). The formation sediments were deposited by a meandering stream, following a similar trajectory to the modern Sacramento River (Redwine 1972).

Tuscan Formation

The late Pliocene Tuscan Formation is comprised of interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous-tuff sourced from ancestral Cascade Volcanoes (DWR, 2014; Helley and Harwood, 1985; Lydon 1968). The formation can be seen in outcrops along the eastern side of the Sacramento Valley from the Redding area in the north to near Oroville in the south (DWR, 2014). In the subsurface, the volcanic sourced deposits of the Tuscan interfinger with the metamorphic sourced sediments of the Tehama Formation in the vicinity of the Sacramento River, forming the western extent of the Tuscan Formation (Garrison, 1962; Lydon, 1968). The westward extent of this interfingering can be west of the Sacramento River (DWR, 2014). Beneath the valley sediments, the Tuscan Formation is relatively flat lying, dipping 2 to 3 degrees on the western side of the valley (Olmstead and Davis 1962). Thicknesses of the formation ranges from 300 ft at the westward extent to 1,700 ft in the east (Lydon, 1968). In the Subbasin, the formation may be at its maximum thickness, 1,700 ft.

The Tuscan Formation was deposited by volcanic mudflows and stream channels carrying debris from the ancestral Cascade volcanic centers (Lydon, 1968). These volcanic mudflows and stream channels flowed westward and fanned out in the valley resulting in variation of the formation thickness (DWR, 2014). The volcanic mudflow deposits were cut over time by streams flowing from the east (DWR, 2014). Lastly, the stream channels were subsequently filled by reworked volcanic sand and gravel that now contain fresh groundwater in pore spaces (DWR, 2014; Lydon, 1968).

The depositional history resulted in a formation that is heterogeneous and is divided into four units (oldest to youngest: Unit A, Unit B, Unit C, and Unit D). Tuscan Unit A is composed of metamorphic clasts in interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone, and fractured tuff breccia (DWR, 2004). Groundwater in Unit A is associated with sandstone and conglomerate layers as well as the fractured tuff breccia (DWR, 2003). Unit B (Ttb on **Figure 2-20**) similarly yields water readily. Unit B is composed of lahars, tuffaceous sandstone, and conglomerate (DWR, 2004). Groundwater in Unit B is contained in the reworked sand and gravel layers and is the main source for Tuscan Formation groundwater in Tehama County (DWR, 2003). Unit C (Ttc on **Figure 2-20**) mainly consists of low permeability volcanic mudflow deposits that act as confining layers for groundwater contained in Unit B (DWR, 2004). Unit D is characterized by masses of andesite, pumice, and fragments of black obsidian in a mudstone matrix (Gonzalez, 2014). Tuscan Formation outcrops in the northeast portion of the Subbasin (**Figure 2-20**).

Tehama Formation

The Tehama Formation (Tte on **Figure 2-20**) is composed of Pliocene-age noncontiguous layers of sandstone and siltstone, with lenses of pebble and cobble conglomerate (Blake et al., 1999; Helley and Harwood, 1985). The sandstone and siltstone are predominately composed of metamorphic clasts with some volcanic clasts (Blake et al., 1999; Helley and Harwood, 1985). The formation is present from the foothills of the Coast Ranges in the west to the vicinity of the Sacramento River in the east where the Tehama Formation intermixes with the Tuscan Formation in the Subsurface (DWR, 2014). The northern-most outcrops of the Tehama Formation can be seen near Redding and stretch as far south as Vacaville (DWR, 2014). In the Subbasin, the Tehama Formation outcrops in the north in contact with the Tuscan Formation and the Red Bluff Formation (**Figure 2-20**). Thickness of the Tehama Formation can be up to 750 ft in the Subbasin (**Figure 2-24**).

The Tehama Formation was deposited by streams flowing eastward off the Coast Ranges and, to a lesser extent, south from the Klamath Mountains (DWR, 2014). The streams flowed and deposited sediment under floodplain conditions (DWR, 2014). This depositional environment resulted in non-continuous series of poorly sorted sediments cut by non-lenticular channels of coarser sediments (DWR, 2014; Russell, 1931). The Tehama Formation's maximum thickness over its entire mapped extent is 2,000 ft (Olmstead and Davis, 1961).

Saturated groundwater conditions exist in the gravel and sand layers of the Tehama Formation (DWR, 2014; Olmstead and Davis, 1961). The base to fresh water is widely reported to be at the base of the Tehama Formation or sometimes within the Tehama Formation (DWR, 2014; Olmstead and Davis, 1961; Springfield and Hightower, 2012). The Tehama Formation is overlain and cut by the younger Modesto, Red Bluff, and Riverbank Formations (DWR, 2014).

Red Bluff

The Red Bluff Formation (Qrb on **Figure 2-20**) is composed of sandy gravels that lie on 0.45 to 1.08 mega-annum (Ma) pediment surfaces. The Red Bluff Formation weathers to a bright-red color (Helley and Harwood, 1985; Helley and Jaworowski, 1985). The formation is discontinuously exposed in the northern Sacramento Valley overlying the Tehama and Tuscan Formations from the Redding area to the vicinity of Cache Creek (DWR, 2014; Russell, 1931; Olmstead and Davis, 1961; Helley and Harwood, 1985). Studies propose that the Red Bluff Formation is the result of alluvial fans depositing reworked metamorphic (Klamath origin) and volcanic (Cascade origin) sediments upon a pediment (Gonzalez, 2014; Harwood et al., 1981; Helley and Jaworowski, 1985). The pediment deposition has resulted in sparce perched aquifer conditions in the 3 ft to 33 ft thick formation (DWR, 2014; Olmstead and Davis, 1961). In the Subbasin, the Red Bluff Formation's extent is limited to the Northeast (**Figure 2-20**).

Riverbank

The Riverbank Formation (Qrl and Qru on **Figure 2-20**) is composed predominately of gravel, sand, and silt deposits that were deposited unconformably on the Tehama, Tuscan, and Red Bluff Formations (DWR, 2014; Marchand and Allwardt, 1981). The formation extends from Redding to Merced discontinuously (Marchand and Allwardt, 1981). It is generally found along higher-elevation terraces beneath the pediment surface of the western tributary systems including the Thomes, Elder, Oat, and Cottonwood Creeks (Tehama County FCWCD, 2012). The thickness varies from 1 ft to over 200 ft (Helley and Harwood, 1985). In the Subbasin the Riverbank is localized to the northwest and on the banks of Antelope Creek (**Figure 2-20**).

It is divided into upper and lower members that are lithologically similar but differ in stratigraphic position and degree of soil development (Helley and Harwood, 1985; Blake et al., 1999). Both members contain gravel, sand, silt, and clay derived from the surrounding mountain ranges (Klamath, Coast Ranges, and Cascades). The upper member occupies the lower terrace positions while the lower member occupies the higher positions (Helley and Harwood, 1985). The upper member consists of semi-consolidated sediments while the lower consists of unconsolidated but compact alluvium (Helley and Harwood, 1985). Both members display soil development with B horizons and local hardpans however, the soils are more developed in the lower member (Blake et al., 1999). The Riverbank formation yields limited water due to its aerial extent and limited thickness (1 to 200 feet) (Helley and Harwood, 1985). The thickness in the Subbasin has been interpreted to be up to 100 ft based on cross sections constructed by DWR (2008) (**Figure 2-24**). The Formation is overlain by the younger Modesto Formation, basin deposits, or surficial alluvium (DWR, 2014).

Modesto

The Modesto Formation is composed of 0.14 to 0.42 Ma stream channel deposits that were laid down in a manner similar to the Riverbank Formation (Marchand and Allwardt 1981). It can be seen on the ground surface from Redding to the San Joaquin Valley (DWR, 2014). The formation ranges in thickness from less than 10 ft to 200 ft (Helley and Harwood, 1985). The Modesto Formation is present at the surface in the majority of the Subbasin and at thicknesses up to 50 ft (**Figure 2-20; Figure 2-24)**. Groundwater occurs in the formation under unconfined conditions (DWR, 2014).

The Modesto Formation consists of a lower member (Qml on **Figure 2-20**) occupying higher topographic areas and an upper member (Qmu on **Figure 2-20**) visible at lower topographic areas (Helley and Harwood, 1985). Both the lower and the upper members are composed of unconsolidated gravel, sand, silt, and clay. The main difference between the two is that the lower member is slightly more weathered (Helley and Harwood, 1985). The Modesto Formation sedimentary deposits often border currently active stream channels and were likely deposited by the same streams they border (Helley and Harwood, 1985).

Basin Deposits

The Basin Deposits (Qb on **Figure 2-20**) are composed of fine silts and clays that were deposited under flood conditions by the sediment-laden streams in the Subbasin rising above the natural levees into the low-lying areas (DWR, 2014; Olmstead and Davis, 1961). Exposures of the Basin Deposits can be seen in Butte, Glenn, and Colusa Counties forming the soil conditions needed for farming in the area (DWR, 2014). Thickness of the deposits have been observed at a maximum of over 200 feet near the Sacramento River and at a minimum of 10 feet along the valley edges (Helley and Harwood, 1985). The formation provides limited groundwater due to its fine-grained nature (Olmstead and Davis, 1961). Basin Deposits have not been observed within the Antelope Subbasin but have been observed just past the eastern subbasin boundary (**Figure 2-20**).

Surficial Alluvium

The surficial alluvium (QTog, Qa, Qsc on **Figure 2-20**) is the youngest of the geologic units in the Subbasin. The alluvium consists of gravel, sand, and silt sourced from the Klamath, Coast Range, Cascade, and Sierra Nevada Ranges and transported and deposited by modern streams and rivers (Helley and Harwood, 1985). It is present throughout the northern Sacramento Valley forming natural levees and along current rivers and streams (DWR, 2014). The maximum thickness of the surficial alluvium has been observed up to 30 feet (Helley and Harwood, 1985). Based on cross sections from DWR (2008), the maximum thickness in the Subbasin is interpreted to be up to 25 ft (**Figure 2-24)**. It is not a major source of water due to its limited thickness and extent (DWR, 2014).

2.2.1.3.3 Geologic Structures

Geologic structures are a result of tectonic forces leading to deformation in the geologic material. The deformation can control direction and rate of groundwater flow. This section is a description of major geologic structures in the area. The Los Molinos Syncline is the only major structure observed in the Subbasin and the other structures are discussed for regional context (**Figure 2-20**).

Los Molinos Syncline

The Los Molinos Syncline is a 1.0 to 2.5 Ma north northwest-trending syncline that locally controls the Sacramento River (Blake et al., 1999). The syncline generally follows topographically low elevations and lies between the Chico Monocline and the Corning Fault. The Los Molinos Syncline may influence the direction of groundwater flow.

Red Bluff Fault

The Red Bluff Fault is a 15-mile-long south-dipping normal fault that has surface expressions northeast of the City of Red Bluff (DWR, 2014). Strike is generally 60 degrees east and has been observed to have late Cenozoic displacement as it affects the base of the Pliocene rocks, offsetting them about 500 feet (Blake et al., 1999).

Corning Fault

The Corning Fault is a north-trending reverse fault with no surface expression. It branches off the Willows Fault south of Tehama County. The main evidence for the fault is subsurface surveys performed by Harwood and Helley (1987). The fault has been observed at a dip of 74 degrees east with greater degrees of offset on older rocks (DWR, 2014; Helley and Harwood, 1985). The fault generally follows the trend of Interstate 5 until its terminus at the Red Bluff Fault and Chico Monocline north of Red Bluff (DWR, 2014).

Inks Creek Fold System

The Inks Creek Fold System is a series of northeast-trending folds that occur to the north of the Subbasin (DWR, 2004). The fold system is composed of a dome on the west side of the Sacramento River, and a southwest-plunging anticline and syncline that locally controls the major bends in the Sacramento River (Harwood and Helley, 1987). The system is a part of the Red Bluff Arch, a hydrologic drainage divide that separates the Redding Area groundwater basin and the Sacramento Valley groundwater basin (DWR, 2014).

Chico Monocline

The Chico Monocline is a flexure feature in the east side of the Subbasin that roughly follows the boundary of the valley. It is a northwest-trending feature that deforms the Tuscan Formation in the east, causing the beds to increase from a dip of 2 to 5 degrees in the middle of the valley to 25 degrees in the west (DWR, 2014).

Red Bluff Arch

The Red Bluff Arch is an area of regional compression that encompasses multiple tectonic features in the area (DWR, 2014). It is a northeast-trending feature that encompasses the Red Bluff fault, the Inks Creek Fold System; and the Seven Mile, Tuscan Springs, Salt Creek, and Hooker Creek domes (DWR, 2014). The collection of features regionally creates a barrier to groundwater flow separating the Sacramento Valley Groundwater Basin from the Redding Area groundwater Basin (DWR, 2014).

2.2.1.4 Soil Characteristics

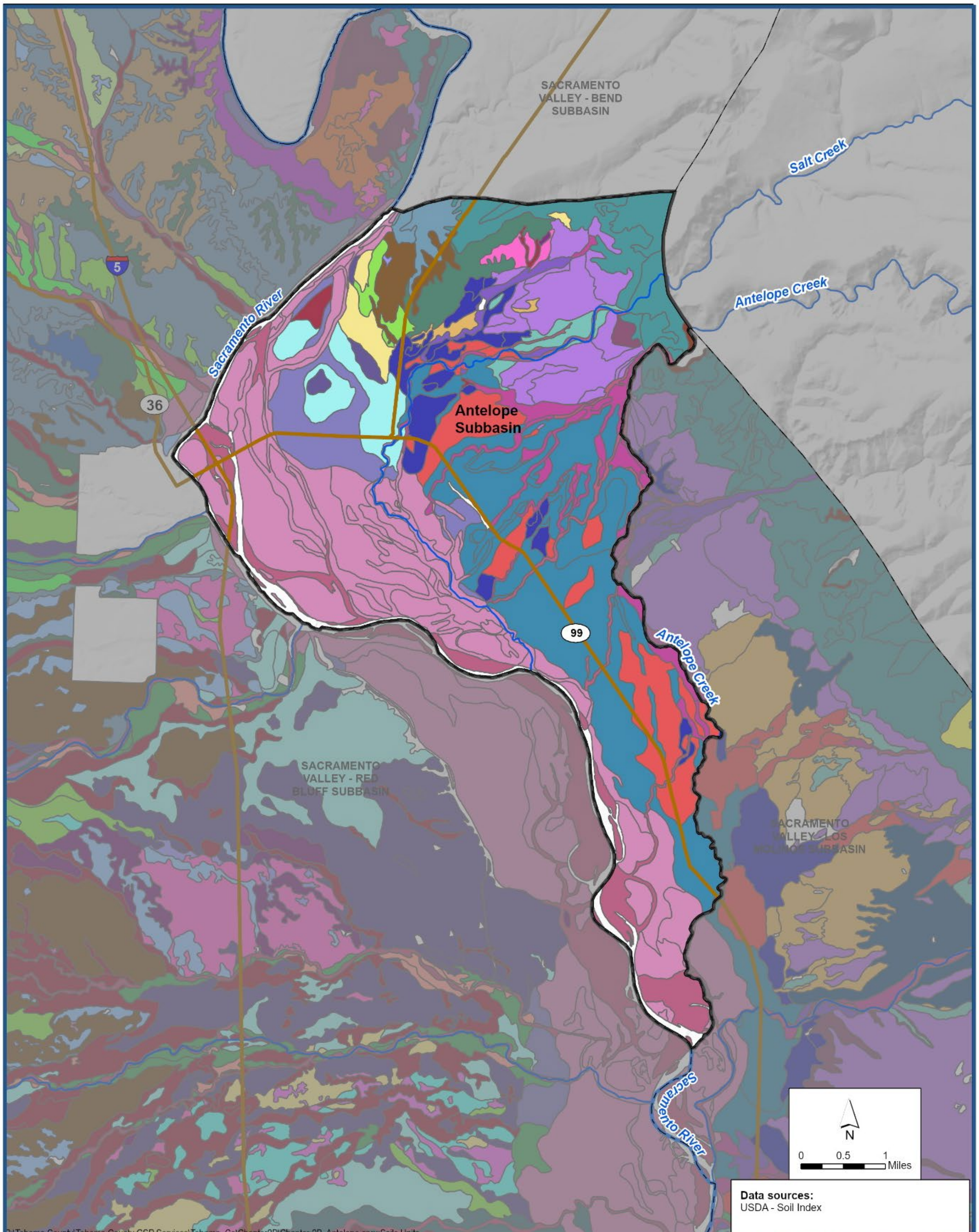
The characteristics of a soil influence the movement of surface water (e.g., water sourced from rainfall, stream flow, or anthropogenic activities such as irrigation). Coarse, porous soils promote infiltration of surface water, while relatively impermeable soils promote surface runoff. Chemical properties of a soil (e.g., salinity and pH) can alter the chemistry of water that percolates through it. Therefore, understanding the spatial variability of soil characteristics is important to conceptualize the hydrogeologic system of the Subbasin. Surficial soil property data were obtained from the Natural Resources Conservation Service (NRCS), US Department of Agriculture. NRCS soil surveys use soil "map units" to delineate geographical areas that have soils with similar characteristics. A "soil series" is a unique collection of map units. It represents a three-dimensional soil body that is composed of soils that have a relatively narrow set of properties. Detailed descriptions of soil map units and series are available in USDA Soil Survey Manual, Handbook No. 18 (Soil Science Division Staff, 2017).

Soils – Type

Surficial soil types that are present in the Antelope Subbasin belong to 58 unique map units. These soil types are grouped into 28 soil series and shown in **Figure 2-25** and **Figure 2-25B**. The two most dominant soil series in the Subbasin are Columbia and Vina, each of which covers about 20% of the Subbasin. The Columbia series soils exist on flood plains and natural levees of streams, thus commonly in the western and southern areas of the Subbasin. These soils are very deep and are moderately well drained. The Vina series, which consists of very deep, well drained soils, exist in alluvial fans in the western part of the Subbasin. Other dominant soil types in the Subbasin are Los Robles, Tuscan, Riverwash and Toomes series, as well as Columbia Complex. These soils are all well drained and each type covers about 6% to 7% of the Subbasin. The Los Robles soils exist on gently sloping fans and terraces. Tuscan soils exist on gently sloping alluvial terraces in the northeastern part of the Subbasin, while Toomes soils are on foothills of the same areas. Riverwash soils occur along stream valleys and drainage ways. Columbia Complex soils, which are a mixture of Riverwash and Columbia series soils, also occur along drainage ways. All other soil series that exist in the Subbasin collectively cover about 25% of the land surface, and the contribution of each series vary from less than 1% to 4%.

Soil Texture

Soil textural classes are defined based on relative percentages of sand, silt, and clay (Soil Science Division Staff, 2017). Spatial distribution of soil textural classes in the Antelope Subbasin are shown in **Figure 2-26**. Loam and different variations of loam are the dominant surficial soil textures in the Subbasin. Loam soil (a soil composed mostly of sand and silt with a small amount of clay) covers about 30% of mapped surface area and exists throughout the Subbasin, except in the northeastern part and along the western boundary. Clay loam, which is loam soil with abundant clay, also exists adjacent to loam soil covering about 10% of the mapped surface. Loam that contains relatively high amount of coarse materials (sandy loam, gravelly loam, stony loam and cobbly loam) covers over 40% of the land. These soils predominantly occur along the western boundary of the Subbasin and in the northern areas. Gravelly sand, which commonly occurs along drainage ways, covers over 10% of the land surface.



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Soils - Type by Soil Series

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-25

Explanation

Soils Type

Soil Series

- Alltamont
- Anita
- Anita-Galt
- Anita-Keefers
- Arbuckle
- Arbuckle-Tehama
- Berrendos
- Bosquejo
- Charger
- Clear Lake
- Colluvial Land
- Columbia
- Corning
- Corning-Newville
- Corning-Redding
- Cortina
- Dibble
- Dibble-Gullied
- Doemill-Jokerst
- Farwell
- Gianella
- Hillgate
- Inks
- Jokerst-Doemill-Typic
- Keefers
- Kimball
- Langlier
- Lodo-Millsholm
- Los Robles
- Maywood
- Millrace
- Millsap
- Millsholm
- Millsholm-Millsap
- Moda
- Molinos
- Munjar-Tuscan
- Myers
- Nacimiento
- Nacimiento-Altamont
- Nacimiento-Newville
- Newville
- Newville-Dibble
- Newville-Laniger
- Orland
- Perkins
- Perkins-Kimball
- Peters
- Peters-Newville
- Pleasanton
- Red Bluff
- Redding
- Redding-Newville
- Redsluff
- Redtough-Fallager-Anita
- Redtough-Redswale
- Reiff
- Riverwash
- Sehorn
- Sehorn-Millsholm
- Supan
- Tailings and Placer Diggings
- Tehama
- Toomes
- Toomes-Supan
- Tuscan
- Tuscan-Igo-Anita
- Vina
- Wafap-Hamslough
- Wyo
- Yolo
- Zamora
- Other Groundwater Subbasins

Data sources:
USDA - Soil Index

P:\Tehama County\Tehama County GSP Services\Tehama_Co\Chapter2B\Chapter 2B Antelope.aprx:Soils Units

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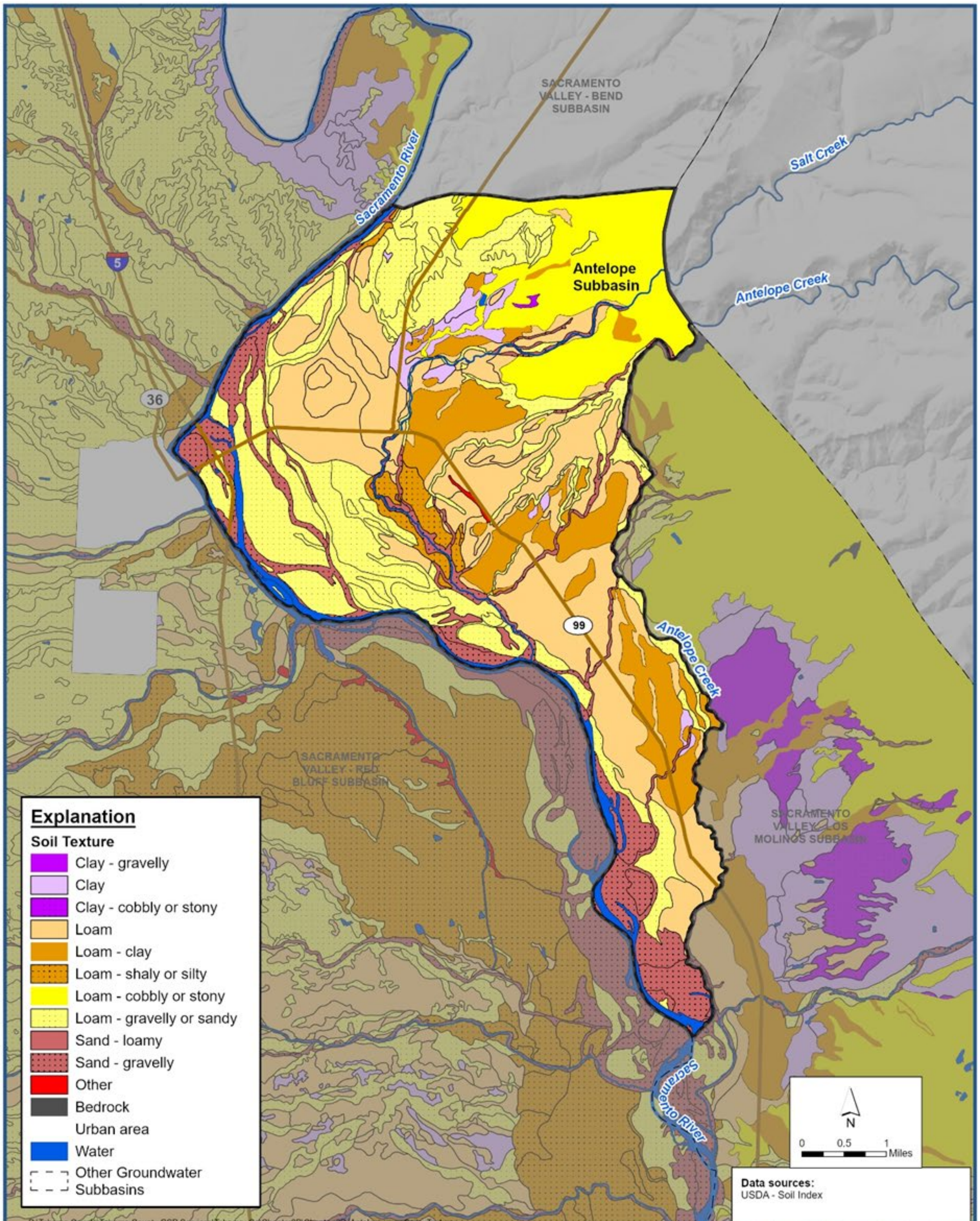
Soils - Type by Soil Series

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-25B



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Soils - Texture

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-26

Hydraulic Conductivity

The saturated hydraulic conductivity of surficial soils, which is a measure of a soil's ability to transmit water under a hydraulic gradient, ranges from approximately 0.5 feet per day (ft/day) to 7 ft/day in about 80% of the Antelope Subbasin. Saturated hydraulic conductivity can be up to 26 ft/day in the remaining 20% of the Subbasin (**Figure 2-27**). The spatial distribution of hydraulic conductivity throughout the Subbasin is related to the distribution of soil texture. Relatively fine textured soils such as clays, clay loam and loam have low hydraulic conductivities. Therefore, low hydraulic conductivity values are common in the northern part of the Subbasin. Coarse textured soils such as sandy, gravelly, or cobbly loams, and gravelly sand have high hydraulic conductivities. Therefore, high hydraulic conductivity values are common along drainage ways and in alluvial fan deposits.

Drainage

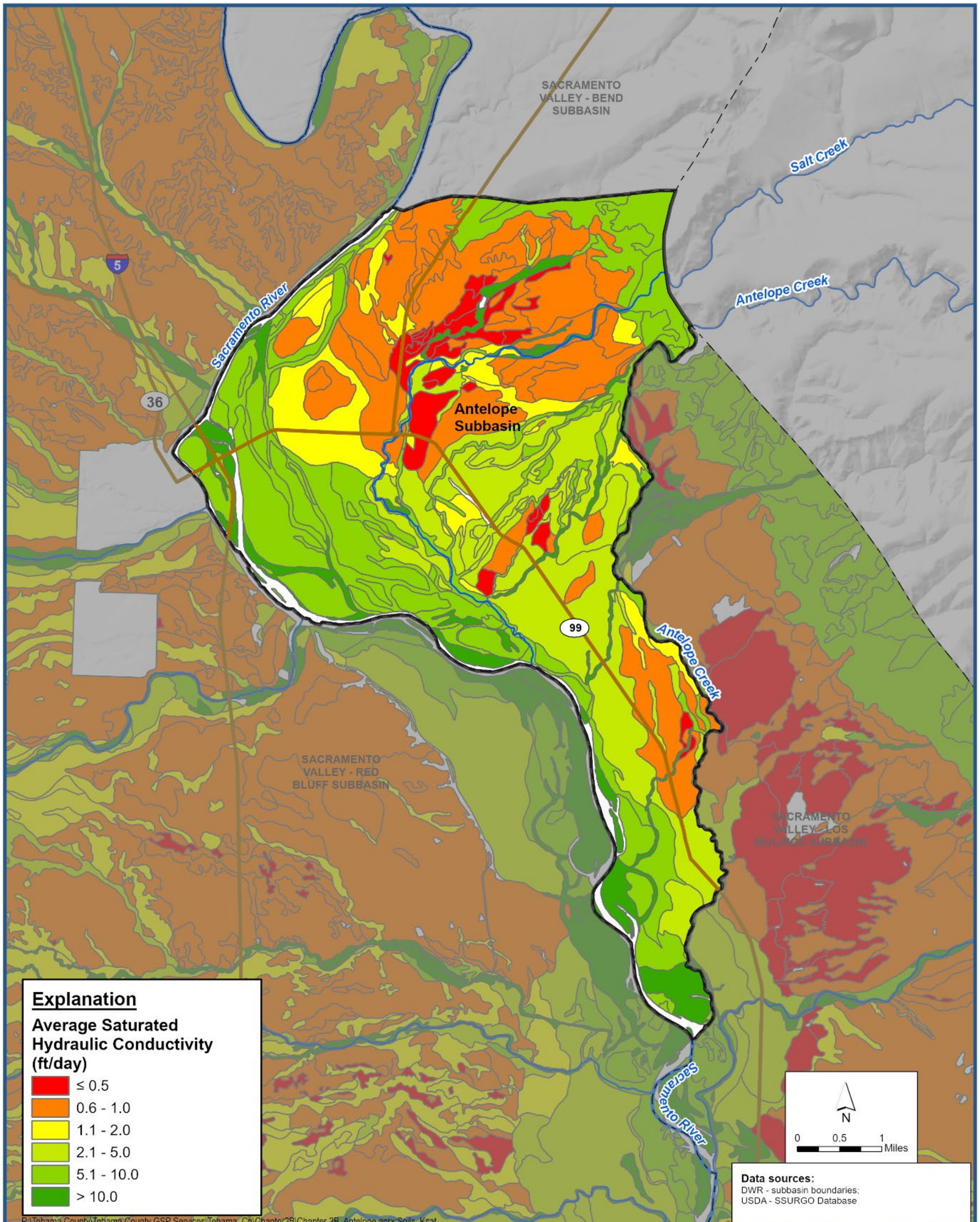
Soil drainage classes indicate the ability of a soil to drain water. Spatial distribution of soil drainage properties in the Antelope Subbasin closely resembles the distribution of saturated hydraulic conductivity and soil texture (**Figure 2-28**). More than 82% of the Subbasin area is categorized as well drained soils. Small patches of poorly drained and somewhat poorly drained soils, as well as moderately well drained soils mostly occur in the northern part of the Subbasin. Excessively drained soils occur along and adjacent to drainage ways, where coarse soils are abundant.

Electrical Conductivity

Electrical conductivity of a soil is an indirect measure of the amount of salt present in that soil. Percolating water can leach and transport salts from saline soils to groundwater, resulting in the increase of the salinity of groundwater. All surficial soils in the Antelope Subbasin fall into non-saline class, where EC values are less than 2 decisiemens per meter (dS/m) (2,000 µmhos/cm). As per NRCS soil data, EC of surficial soils in more than 90% of the Subbasin is zero dS/m, while that of soils in the remaining areas is 1 dS/m (1,000 µmhos/cm) (**Figure 2-29**).

pH

Soil pH is a measure of the acidity or alkalinity of that soil, which influences chemical interactions between soil minerals and percolating water. A pH of 7 is considered neutral. Increasing pH values indicate more alkaline soil conditions and decreasing pH values indicate more acidic soil conditions. Soil pH in the Antelope Subbasin is slightly acidic. It ranges between 6.6 and 7.0 throughout the Subbasin except in the north and northeast areas, where the pH range is predominantly between 5.1 and 6.5 (**Figure 2-30**). In general, solubility of minerals increases with acidity of the soil and water. Acidity of surficial soils in the Subbasin are not expected to adversely alter water quality.



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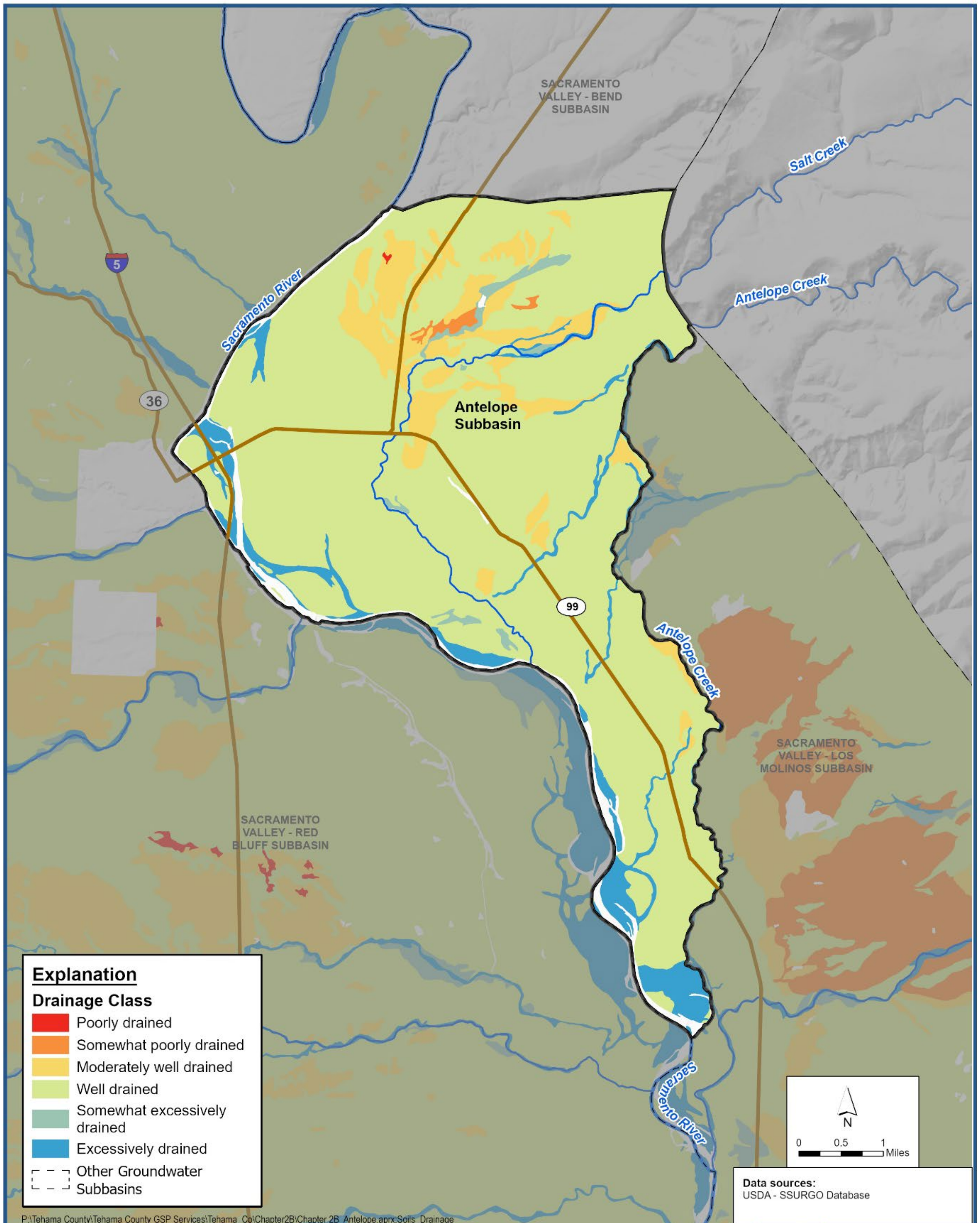
Soils - Saturated Hydraulic Conductivity

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-27



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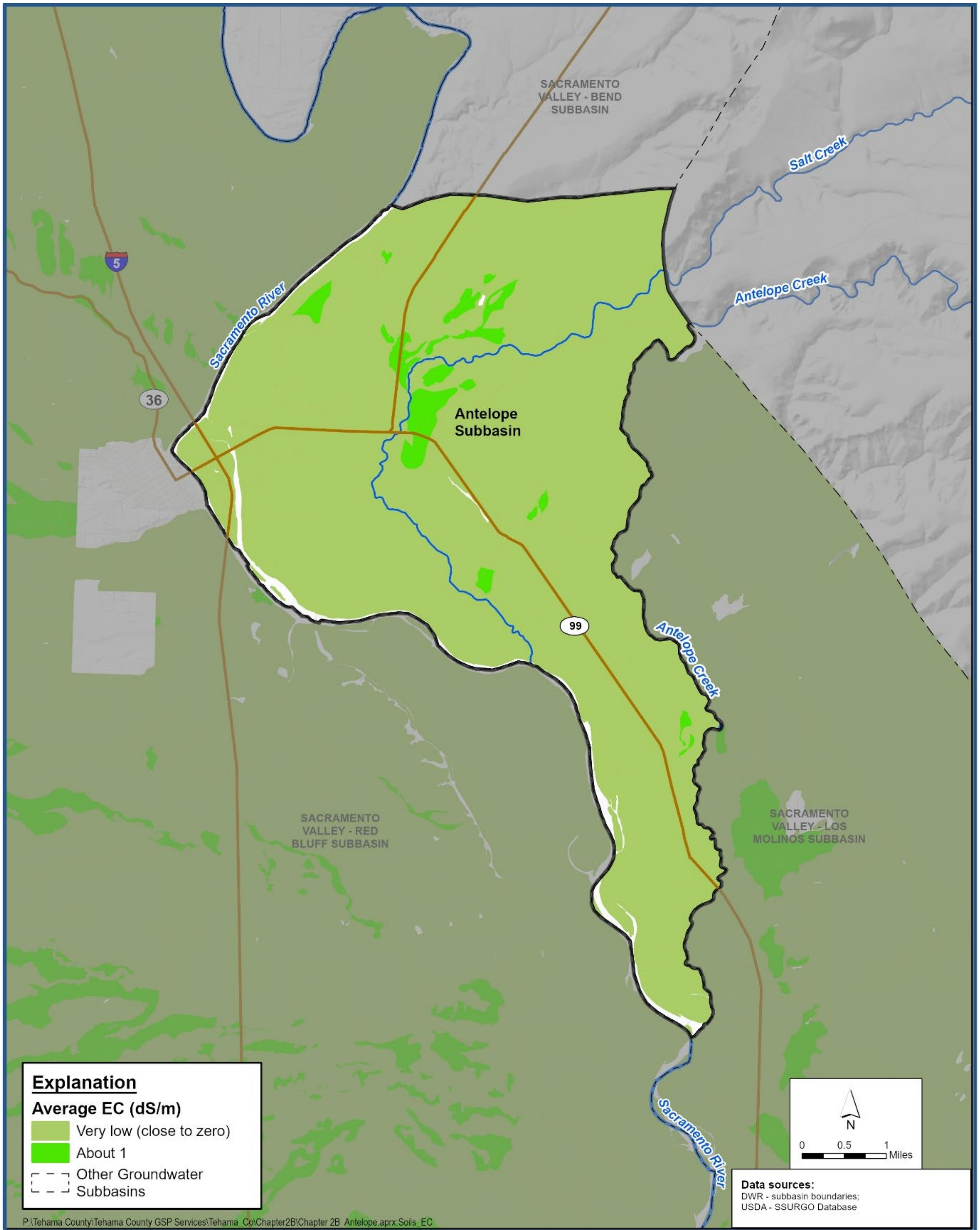
Soils - Drainage Class

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-28



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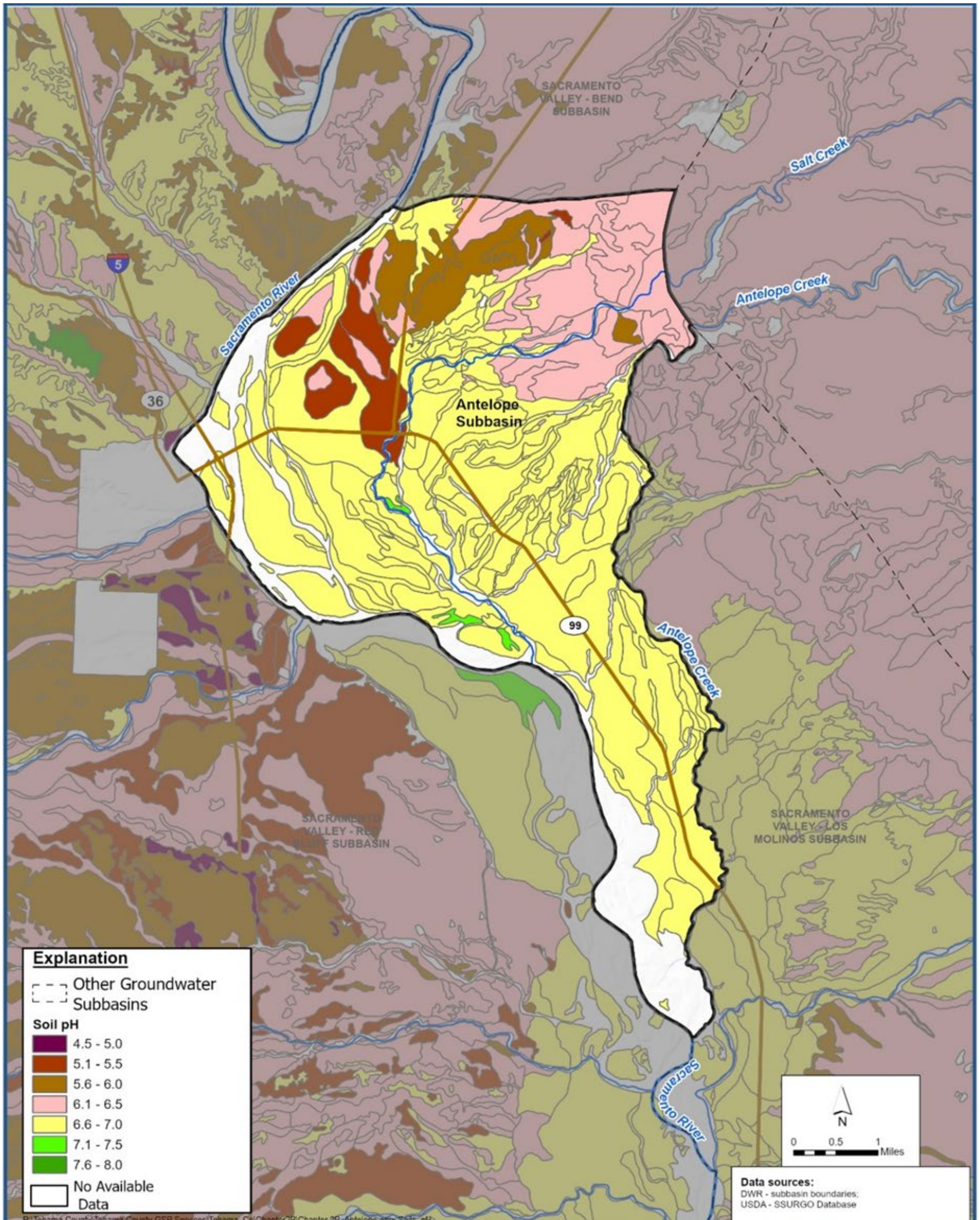
Soils - Electrical Conductivity

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-29



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Soils - pH

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-30

2.2.1.5 Identification/Differentiation of Principal Aquifers

Two principal aquifer units are defined in the Subbasin: Upper Aquifer and Lower Aquifer. The two-aquifer designation is based on an examination of time-series groundwater elevation hydrographs, electric resistivity data from geophysical logs, lithologic logs, well construction details, and review of previous studies in the Subbasin. The northern Sacramento Valley depositional environment is dominated by fluvial and alluvial deposition after the Eocene marine depositional environment transitioned to a subaerial one. The Pliocene depositional environment is similar to the current depositional conditions, with eastern depositional streams sourced from the Cascade Range and western depositional streams sourced from the Coast Ranges draining onto a central floodplain. This depositional environment resulted in a complex and varied series of water bearing sedimentary deposits and the Tuscan / Tehama Formations that collectively form a two-aquifer system in the Subbasin and beyond. Within singular water bearing formations there are areas where confined or unconfined conditions can be dominant. Generally, confined aquifer conditions are encountered at depth and unconfined conditions are seen in the shallower porous media. The complexity of the geologic materials and the formations makes it difficult to define a singular widespread aquitard or distinctive change in geologic materials separating an upper and lower aquifer. To delineate between areas with a higher likelihood of confined conditions, well construction data throughout the Subbasin were examined. Most of the wells in the Subbasin are screened or completed above 400 feet below ground surface (ft bgs). The bottom of numerical model layer 5 best corresponds with this depth. The bottom of model layer 5 is used as the delineation between the Upper and the Lower Aquifer. This model layer boundary also generally corresponds to fine grained lithology from available well completion reports (**Figure 2-22**; **Figure 2-23**). Lastly, the degree of heterogeneity and anisotropy (directional preferable flow) is likely significant, but not easy to define based on current information.

Upper Aquifer

The Upper Aquifer is defined as the water bearing material from ground surface to the bottom of model layer 5 (approximately 350-450 ft bgs in the Subbasin). The Upper Aquifer has unconfined to semi-confined water conditions. Water bearing geologic units in the Upper Aquifer include the Quaternary formations and the upper portions of the Tehama and Tuscan Formations. Wells screened in the Upper Aquifer are largely for domestic purposes. The depth to the bottom of the Upper Aquifer is approximately 350-450 ft bgs (**Figure 2-22 and Figure 2-23**). The storage capacity of the Antelope Subbasin Upper Aquifer is estimated to be approximately 270,000 acre-feet to a depth of 200 feet (DWR, 2004).

Site-specific Aquifer properties obtained from aquifer tests were not readily available for the Subbasin, however, aquifer tests were conducted in surrounding subbasins. Hydraulic conductivity (rate at which water moves through an aquifer), transmissivity (hydraulic conductivity multiplied by aquifer thickness), and storage coefficients (ability of the aquifer to store water, commonly expressed as specific yield for water table/unconfined aquifers and storativity for confined aquitards) have been estimated near the Subbasin.

In the Los Molinos Subbasin, to the south, estimated transmissivity of the upper portion of the Tuscan Formation (70-530 ft bgs) is approximately 14,000 square feet per day (ft^2/day) to approximately 55,000 ft^2/day (DWR, 2003). This depth interval covers a portion of the Lower Aquifer but is mostly within the Upper Aquifer. In the neighboring Red Bluff Subbasin, the Tehama Formation has an average transmissivity of approximately 4,000 ft^2/day, an average storativity of 0.00089, and an average hydraulic conductivity of 120 ft/day based on a 1989 constant discharge aquifer test at the Rancho Tehama Reserve (McManus, 1993; DWR, 2003).

Lower Aquifer

The Lower Aquifer is defined as the freshwater bearing geologic units throughout the Subbasin from the bottom of model layer 5 at approximately 350-450 ft bgs, to the bottom of the Subbasin. The aquifer has confined to semi-confined conditions. Water bearing geologic units include the lower portions of the Tehama and Tuscan Formations. Wells screened in the Lower Aquifer are largely for non-domestic purposes.

The lack of wells screened in the Lower Aquifer in the Subbasin creates a data gap for hydraulic properties. Hydraulic conductivity has not been directly measured in the Subbasin; however, the lower Tuscan Formation (Units A and B) has a hydraulic conductivity estimate (via an aquifer test south of Deer Creek and North of Little Chico Creek) of 41-88 ft/day (Brown and Caldwell, 2013). Transmissivity of the lower parts of the Tuscan Formation (340-920 ft bgs) ranges from 5,415 ft^2/day to 49,986 ft^2/day south in the Los Molinos Subbasin (DWR, 2003). Storativity in the Los Molinos Subbasin is estimated to be 0.0025 and hydraulic conductivity is estimated to be 40 ft/day to 60 ft/day (Harrison, 1989; Ely, 1994; DWR, 2003). The Tehama Formation has an average transmissivity of 4,341 ft^2/day, an average storativity of 0.00089, and an average hydraulic conductivity of 120 ft/day based on a 1989 constant discharge aquifer test at the Rancho Tehama Reserve in the Red Bluff Subbasin (McManus, 1993; DWR, 2003).

2.2.1.6 Definable Bottom of Basin

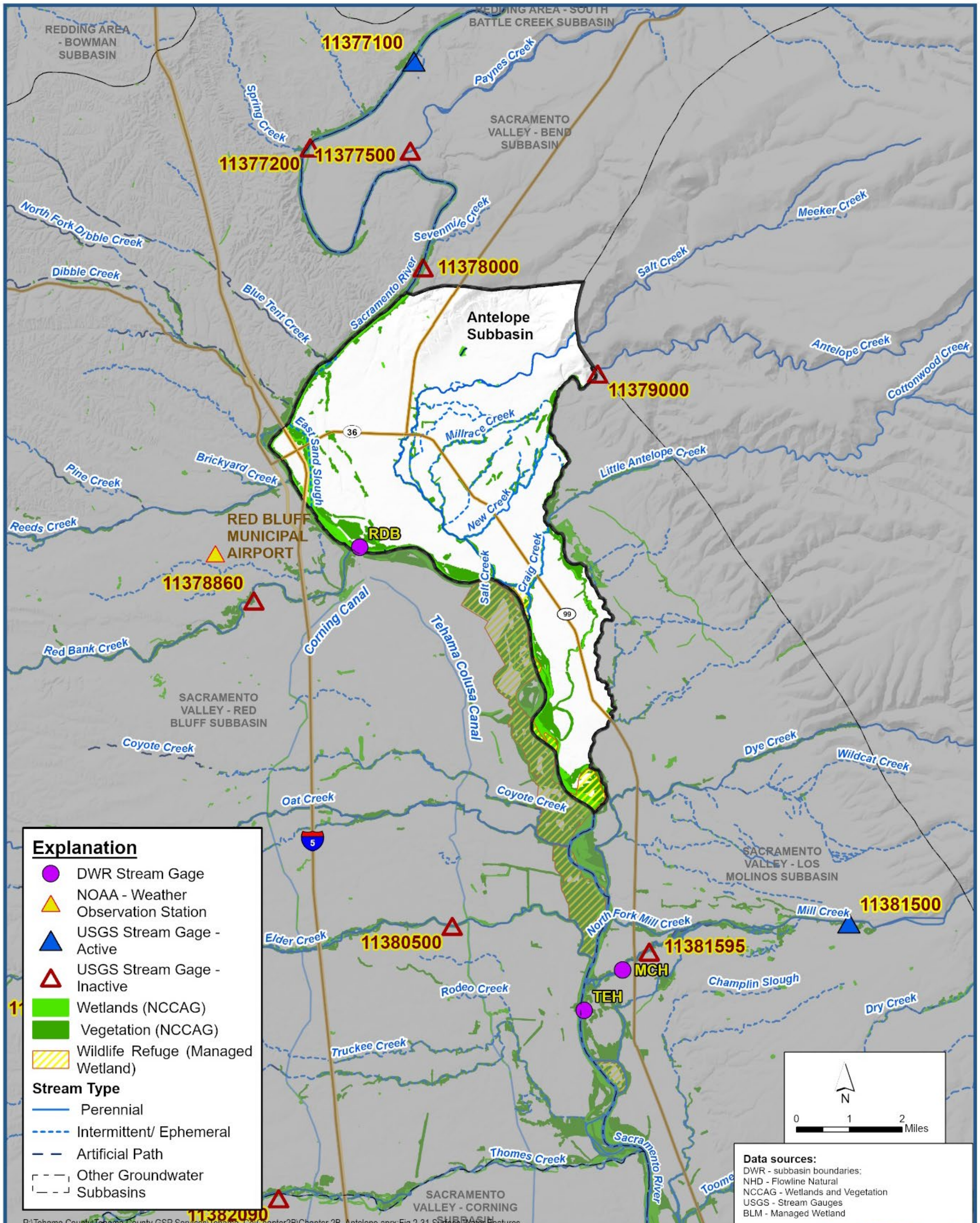
The base of the post-Eocene continental deposits is defined as the bottom of the basin. The post-Eocene deposits are the deepest locations where fresh water may exist. Contours of the base of post-Eocene deposits (**Figure 2-16)** are on the base of the Upper Princeton Valley Fill in the majority of the Subbasin. The Upper Princeton Valley Fill is a transitional formation from marine to terrestrial deposition. Interstitial fresh and brackish water is contained in the Upper Princeton Valley Fill and fresh water can intersect with the formation in places (USGS, 1974; TFCWCD, 2012). Fresh water is defined as having a maximum EC of 3,000 µmhos/cm (Berkstresser, 1973). The base of fresh water is the shallowest in the north at elevations of near -800 to -1,200 ft msl and deepest in the west at elevations deeper than -2,000 ft msl (**Figure 2-15;** Berkstresser, 1973). The elevation of the base of fresh water, as depicted by the equal elevation contour lines, is interrupted in the northeast where the Chico Monocline possibly affects the depth to fresh water (**Figure 2-15**). Fresh water depth based on electrical conductivity is corroborated by studies by DWR (2014).

2.2.1.7 Surface Water Features and Areas of Recharge

The primary surface water features in the Subbasin are the Sacramento River, Antelope Creek, Salt Creek, Craig Creek, and New Creek (**Figure 2-31**). Flow of all these waterways occur throughout the year (perennial). The Sacramento River flows southward along the western boundary of the Subbasin, while Antelope Creek flows southward along the eastern boundary. The New Creek and several other tributaries in the northern part of the Subbasin contribute flow to Salt Creek, which enters the Sacramento River about two miles downstream of the Red Bluff Diversion Dam. Craig Creek is a distributary channel flowing from Antelope Creek. It has a relatively small drainage area and enters the Sacramento River slightly downstream of where Salt Creek enters the Sacramento River. There are several intermittent or ephemeral streams in the Subbasin. These streams are tributaries of the Sacramento River and have a general flow direction of north to south. Several small seasonal ponds (surface area less than 10 acres) occur along streams, but there are no natural lakes or reservoirs within the Subbasin.

Groundwater recharge of the Subbasin primarily occurs from the flow of the Sacramento River and the other streams and tributaries in the Subbasin (DWR, 2004). Some of the groundwater recharge contributions from smaller streams and tributaries likely support low flow conditions in the Sacramento River as baseflow. Relatively high hydraulic conductivity of streambeds and soils located adjacent to these streams create favorable conditions for percolation of surface water (**Figure 2-27**). However, the Soil Agricultural Groundwater Banking Index (SAGBI; O'Geen et al., 2015), which indicates the suitability of land for groundwater recharge by flooding, gives “poor” deep percolation rating to many areas of flood plains and natural levees of streams despite the presence of highly conductive surficial soils (**Figure 2-32**). The poor rating in these areas can be attributed to the presence of low-permeable soil layers and a relatively shallow groundwater table, which are unfavorable for groundwater banking operations or managed aquifer recharge. Lastly, recharge likely also occurs along 1) the mountain front due to runoff and groundwater movement down into the valley, 2) disperse aerial recharge from natural precipitation, and 3) irrigation water.

Seasonal wetlands exist adjacent to many streams, and most notably along the Sacramento River (**Figure 2-33**). A small portion of the Sacramento River National Wildlife Refuge, a managed wetland, also exists at the southern part of the Subbasin (**Figure 2-31**). These wetlands may indicate the seasonal occurrence of groundwater discharge when the groundwater table rises to the land surface. However, data are not available to distinguish between wetlands fed by groundwater and those fed by surface water (from streams and precipitation run-off). A direct source of recharge to deeper geologic formations like Tuscan Unit B occurs where the formations outcrop on the eastern edge of the Subbasin (DWR, 2003).



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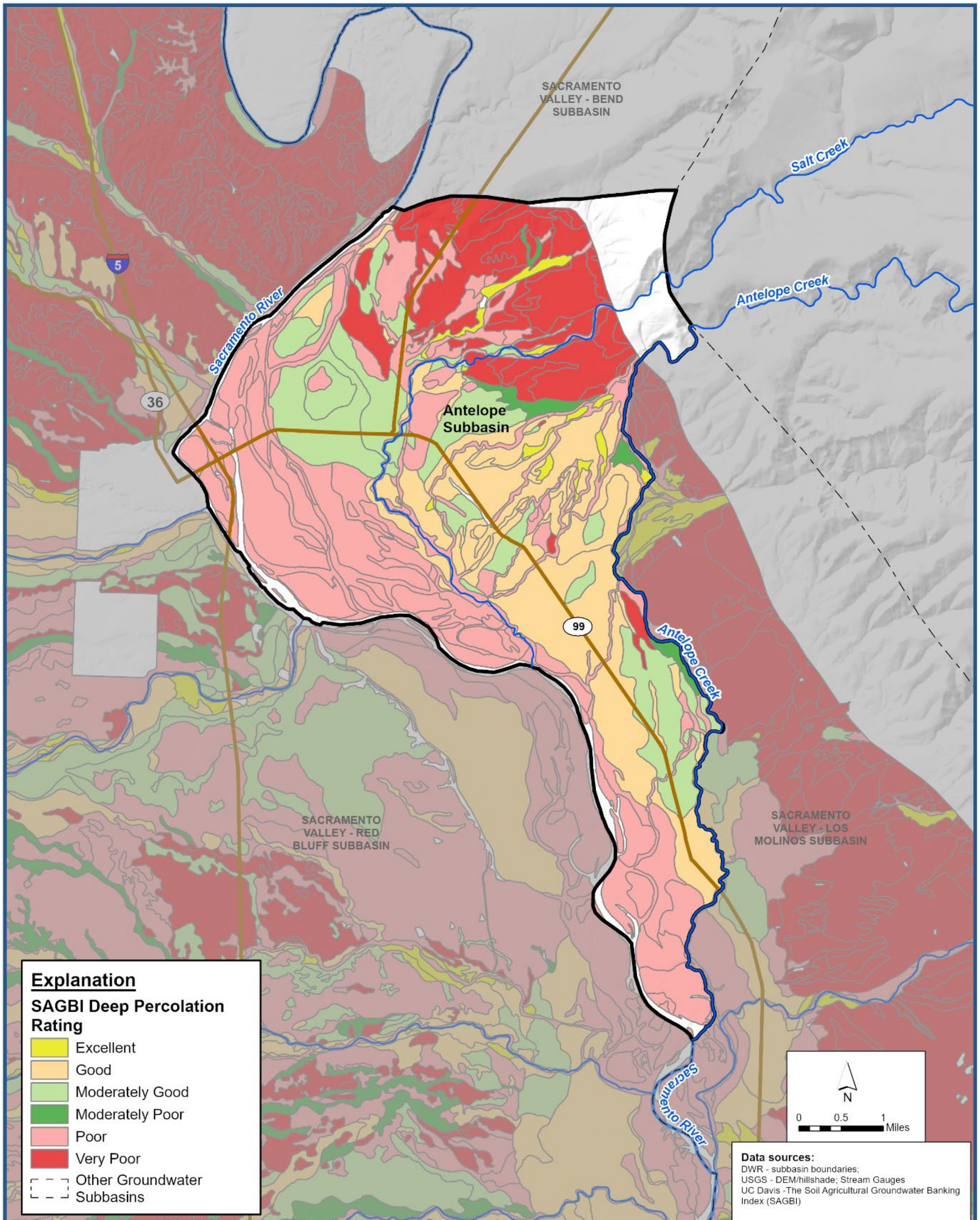
Map of Surface Water Features

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-31



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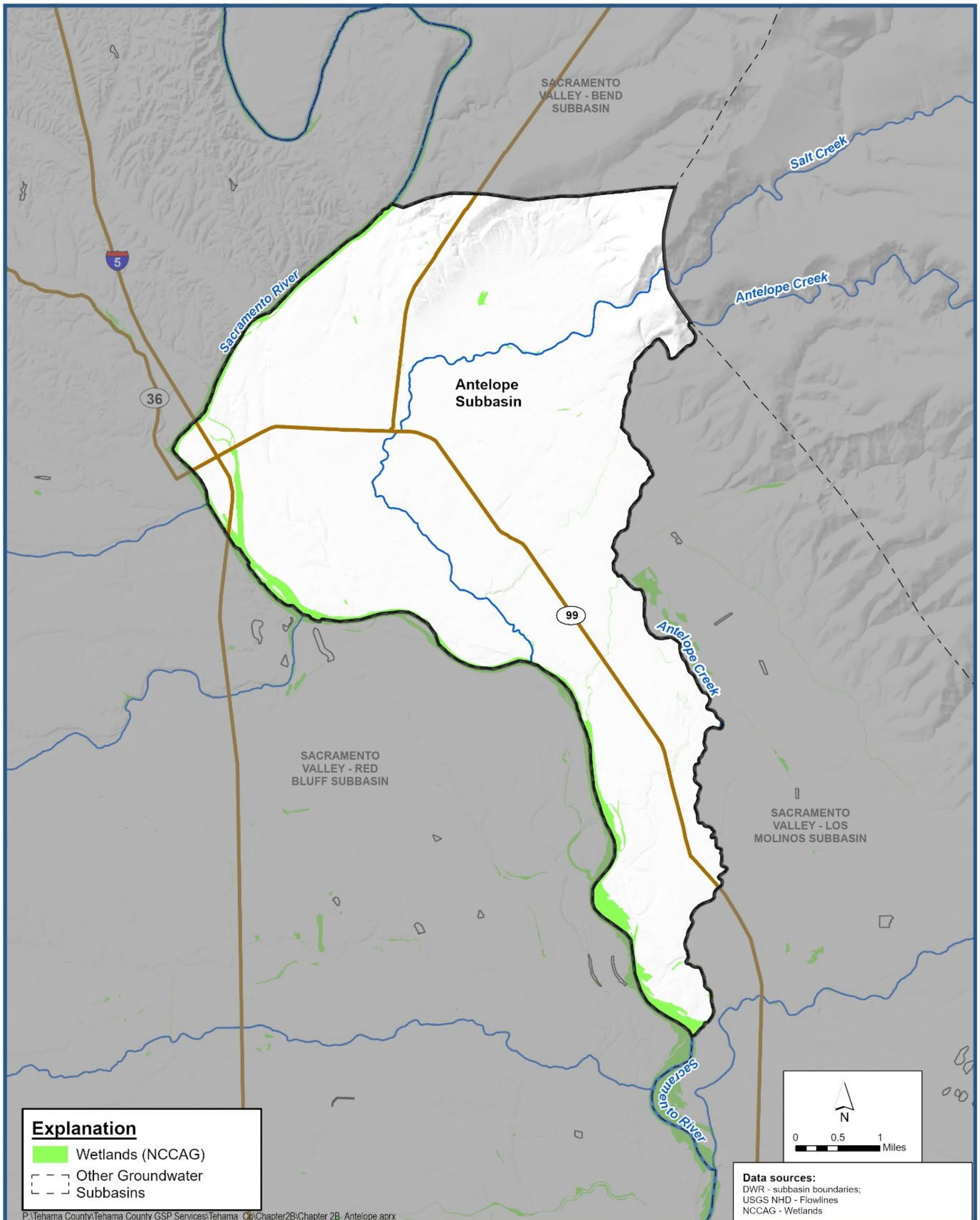
SAGBI Groundwater Recharge Rating

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-32



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Map of Discharge Areas – Wetlands, Springs, Seeps

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-33

2.2.1.8 Data Gaps and Uncertainty

Stratigraphy

The general stratigraphy of the subsurface within the Subbasin is characterized based on past studies and LSCE's interpretation of well completion reports and geophysical logs, however, specific thicknesses and lateral extent of formations is poorly understood. The western extent of the Tuscan Formation in the vicinity of the Sacramento River is poorly defined and the extent of the interfingering between the Tuscan and Tehama Formations in the subsurface is not known. The Hydrogeologic properties differ between the two formations, and it would be beneficial to know where the properties change so aquifer zones could be better constrained and future wells could be screened in targeted intervals.

Hydrogeologic Parameters

Estimates of hydrogeologic parameters are not available in the Subbasin. Parameters have been estimated for geologic formations outside of the Subbasin; however, the formations vary with extent and may be different in the Subbasin. Parameters like storativity, transmissivity, and hydraulic conductivity can be estimated based on geology however, without field and lab measurements the range of values is significant. Future pump tests and testing of soil collected from drilling will help characterize the parameters specific to the Subbasin.

Surface Water and Recharge

Surface water and groundwater interconnectivity is based on observable relationships between streams and shallow groundwater. There is a lack of shallow wells near active stream gages, a condition needed to establish the relationship. Future frequent monitoring from the existing- and from new- stream gauges along the major waterways and from new proximal shallow monitoring wells would help to describe interaction between surface water and groundwater.

2.2.2 Current and Historical Groundwater Conditions

An understanding of groundwater levels and the direction of flow is essential to sustainable groundwater management. This includes both the spatial and temporal variation of groundwater levels which are a function of geology, groundwater management, land use, and climatic conditions. Historical and current groundwater levels of the Subbasin were evaluated using data obtained from public databases (DWR, SWRCB, and USGS) and information available in the literature. LSCE performed a quality assurance/quality control (QA/QC) process on compiled data, which included evaluation of data for completeness and duplication, as well as identification of questionable data.

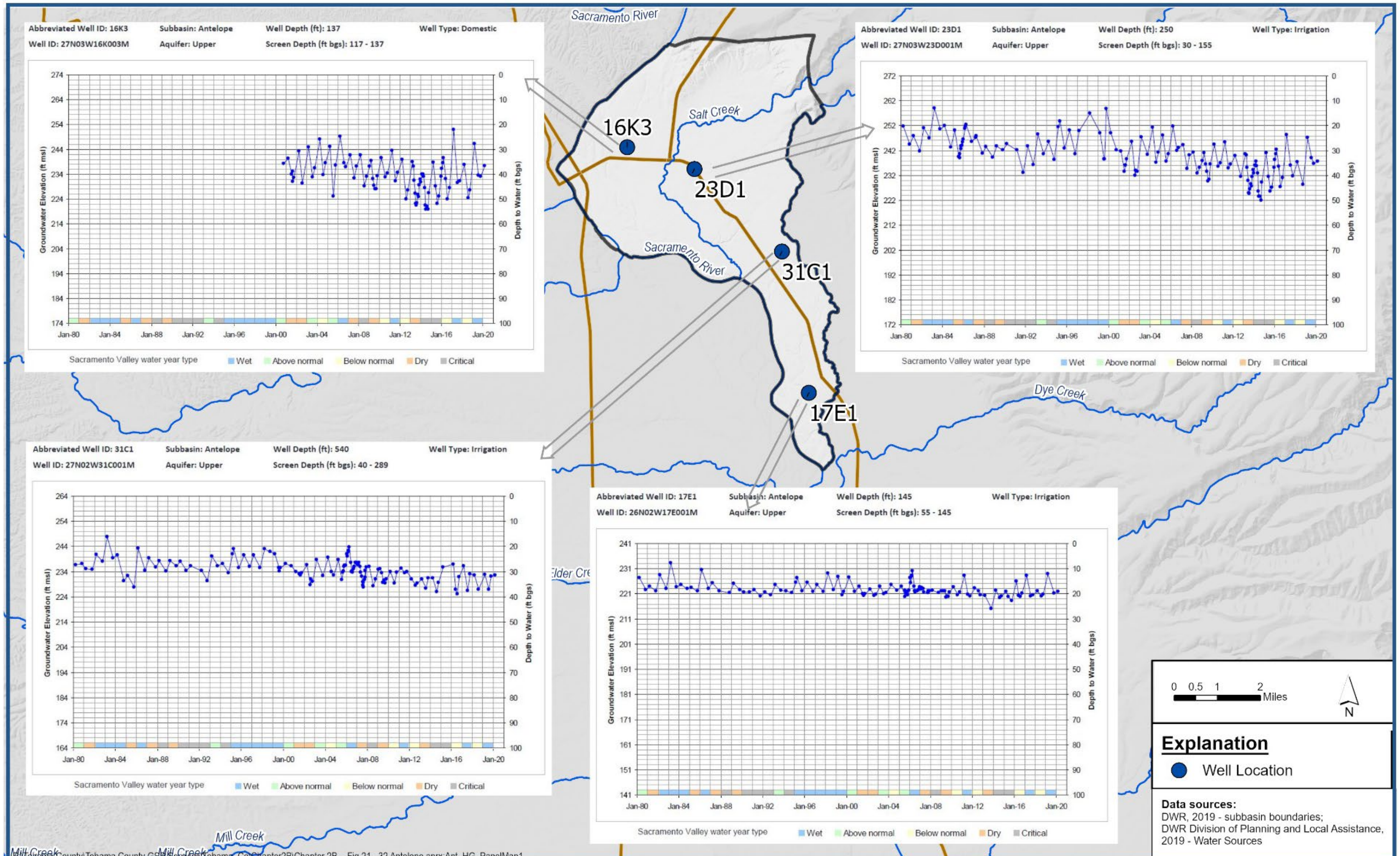
The following discussion on groundwater levels, flow directions, and groundwater quality are limited to the Upper Aquifer due to the lack of data from the Lower Aquifer. Data from wells that were completed or screened entirely within the Upper Aquifer were selected to characterize groundwater conditions of the Upper Aquifer. Groundwater level or quality data were not available from wells that were completely or partially constructed in the Lower Aquifer. Lack of data to characterize conditions in the Lower Aquifer is identified as a data gap.

2.2.2.1 Groundwater Levels and Flow Direction

2.2.2.1.1 *Groundwater Levels*

To gain a historical perspective of trends in groundwater levels in the Upper Aquifer, groundwater level hydrographs were generated for wells with historical time series data of sufficient period of record. Representative hydrographs and the locations of corresponding wells are shown in **Figure 2-34**, while all hydrographs used for the groundwater level evaluation are in **Appendix 2-F**. A graphical illustration that describes information shown on a hydrograph is also included in **Appendix 2-F**. Trends of groundwater levels can be observed over various time periods when data is available. The time-series data also show seasonal variations and changes that correspond to wet and dry periods of the Subbasin. The total annual precipitation measured at the Red Bluff Municipal Airport (RBF) shows a strong positive correlation with the Sacramento Valley Water Year Index (Pearson's correlation coefficient = 0.72). **Figure 2-31** shows the location of the rain gage, and **Figure 2-35** shows the annual precipitation and cumulative departure curve of precipitation. Between water years of 1990 and 2018 (representative base period of this GSP that represents long-term average annual hydrologic conditions), multi-year wet periods occurred in 1995-1999, while multi-year dry periods occurred in 1990-1992 (started in 1987), 2007-2009 and 2013-2015 in the Sacramento Valley (**Table 2-9**). Seasonal high-water levels in the Subbasin (in winter/spring seasons) during wet periods range between about 10 and 45 ft bgs. Groundwater levels decreased during dry periods likely due to the combined effect of increased withdrawal from wells and reduction in recharge. The lowest groundwater levels in recent history (since 1980) occurred during the 2013-2015 drought. During that period, seasonal highwater levels ranged between 20 and 60 ft bgs. Recent data indicate that the groundwater levels partially or completely recovered to pre-drought levels since then. Seasonal water level fluctuation at any well during a water year ranges from a few feet to about 25 ft depending on well location, construction, and local water use. In general, depth to water and magnitude of seasonal fluctuations decreases towards the south and southwest side of the Subbasin.

Statistical analysis of data from three wells, that have data that span the entirety of the 1990 through 2018 hydrologic base period, show very small declines in seasonal high groundwater levels. These declines ranged from approximately nine feet (about 0.30 ft/year) in the northcentral area of the Subbasin (area around the intersection of State Highway 99E and Highway 36E) to generally stable groundwater levels in the southern areas of the Subbasin (about one to two feet total or less than 0.05 ft/year) during the 1990-2018 period. Results of the groundwater level trend analysis, which used both parametric (Ordinary least squares regression) and nonparametric (Mann-Kendall and Theil–Sen) methods, are included in **Appendix 2-F**. The trend of groundwater levels is not an indication of overdraft, but likely due to removal of temporary surplus of groundwater. Temporary surplus removal is the extraction of a volume of aquifer storage to enable the capture of recharge and reduction in subsurface outflow from the Subbasin without impacting beneficial users of groundwater to an unreasonable degree.



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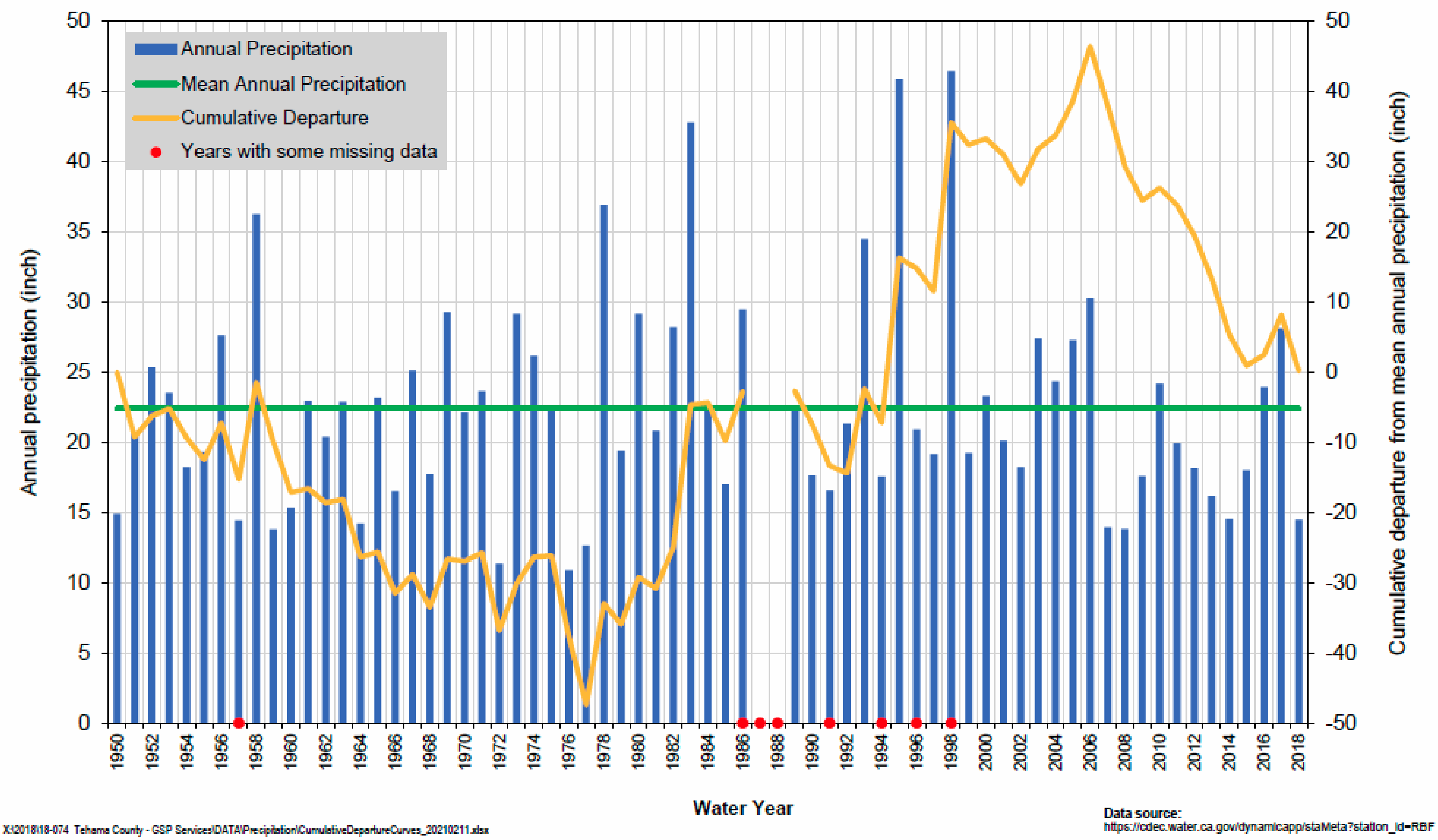
Panel Map of Selected Groundwater Elevation Hydrographs

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-34



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Annual Precipitation and Cumulative Departure at Red Bluff Municipal Airport

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-35

A factor in trends observed in groundwater elevation change is the potential gradual increase of groundwater withdrawal. Even though the actual amount of extracted groundwater from wells is not metered or directly measured, changes in land use and the number of wells constructed over time could be used to indicate an increase in groundwater withdrawal in the Subbasin. Well completion reports obtained from DWR show that about 750 new wells (all types, domestic, irrigation and public supply) were constructed from 1970 to 1999. Construction continued into the last two decades, 2000-2009 and 2010-2019, with 280 and 210 new wells, respectively. The increase of total wells in the Subbasin suggests increased total pumping (withdrawal) contributing to observed declining groundwater level trends. Land use practice probably is another factor (see Section 2.2.2.1, Land Use). Water budgets are discussed in detail in Section 2.3.

Decline of groundwater levels since 2008, especially in west/northwest areas, may be partially attributed to changing operation of the Red Bluff diversion dam. Between 1966 and 2008, the Sacramento River water level was elevated for a large part of the year by closing gates of the Red Bluff dam and creating “Lake Red Bluff” to facilitate gravity-diversion of water to Tehama-Colusa and Corning canals. Seepage from this lake raised groundwater levels in its vicinity by up to 10 ft compared to pre-construction levels (DWR, 1987). From 2008 to 2011, gates of the dam were opened to allow the river to flow through the dam in all months except from May to September. All gates were permanently opened in September 2011. At present, river water is diverted to the canals via a pumping plant. These changes have reduced the impounded water behind the dam, potentially reducing the groundwater recharge from the river seepage (Tehama County FCWCD, 2012). Hydrographs of two wells located within three miles from the Red Bluff dam (27N03W20C001M1 and 27N03W23D001M in **Figure 2-34**) do not show rapid water level changes in response to these operation changes. Therefore, we can expect that the extent of area influenced by the operation changes of the dam is limited (less than 3 miles from the dam).

2.2.2.1.2 *Groundwater Elevation Contours and Flow Directions (§354.16(a)(1))*

Groundwater elevation contour maps were created to evaluate general groundwater flow directions. Seasonal high and seasonal low water elevations of Upper Aquifer wells were used to develop contours of equal groundwater elevation (“Contours”). Water levels of wells that are entirely screened within the top 50 ft bgs and wells without construction details were excluded from contouring, since these wells are likely not representative of the areas of the aquifer where groundwater pumping occurs. Contours were initially developed using spatial analyst tools in ArcGIS software, and then modified based on professional judgement. Contours were not developed for those areas of the Subbasin where data was lacking.

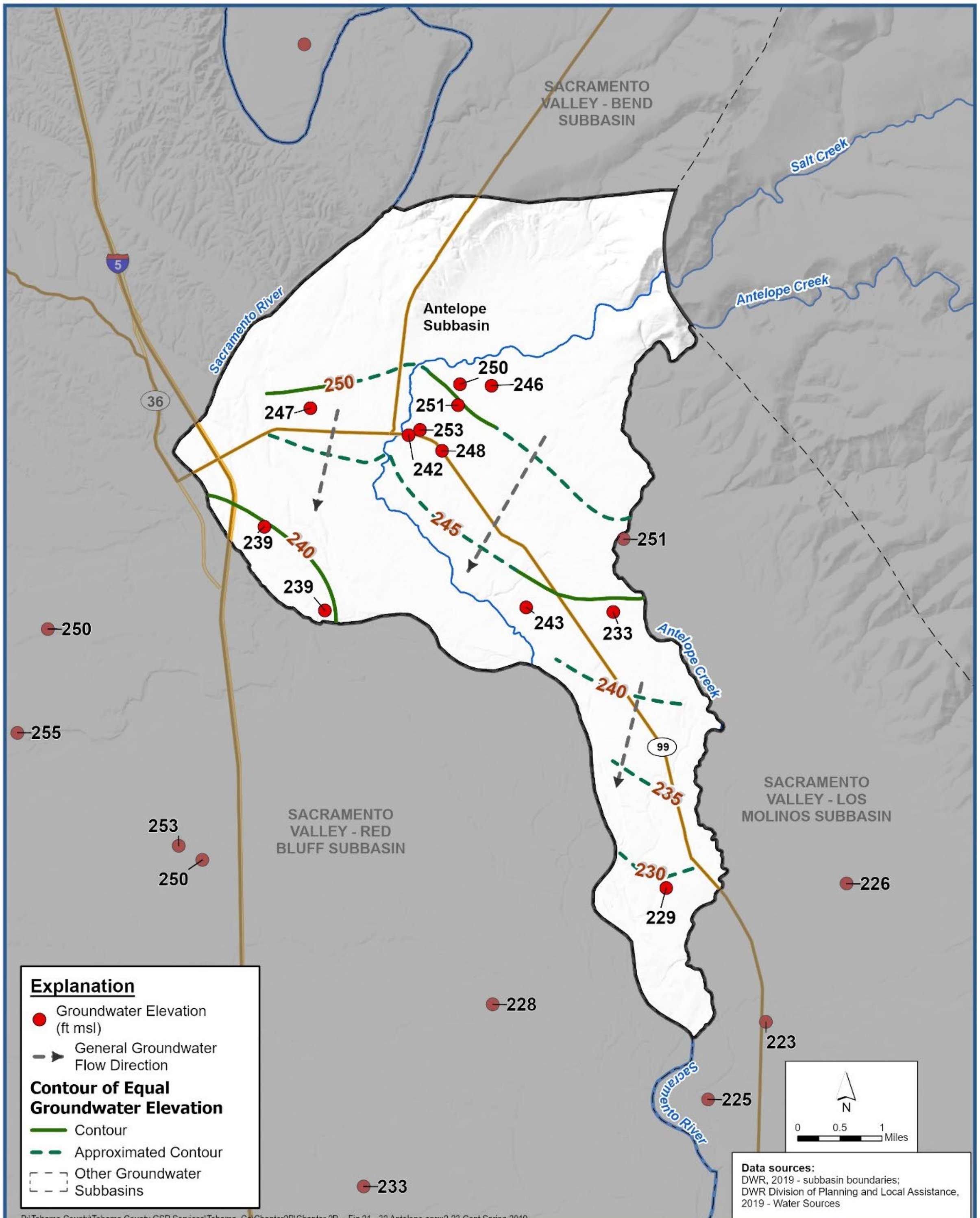
Contour maps were created to evaluate seasonal high and seasonal low groundwater conditions in multiple years that included wet, dry, and critical water year types between 1990 and 2019. Contours of current groundwater conditions are represented using the seasonal high and seasonal low groundwater elevation of water year 2019 (**Figures 2-36 and 2-37**). After evaluation of groundwater level hydrographs with long-term data and the Sacramento Valley water year type record (**Table 2-9**), water years 2017, 2013 and 2015 were considered to represent groundwater conditions in wet, dry, and critical years, respectively (**Figures 2-38 through 2-43**).

Groundwater elevations are highest in the northern areas of the Subbasin and lowest in the south in all time periods. During a wet year, seasonal high groundwater elevations range from about 230 ft msl (in south) to 250 ft msl (in north) (**Figure 2-38**). However, during seasonal low conditions **(Figure 2-39)**, groundwater elevations in the western area decrease by over 10 ft, but in the northern and southern areas the decrease is about 5 ft. In a dry year, groundwater elevations are about 10 ft deeper in the west side compared to a typical wet year (**Figures 2-40 and 2-41)**, but the elevation decrease in the other areas of the Subbasin are less than 10 ft. Seasonal high groundwater elevations in a critical year compared to seasonal high conditions of a dry year are about 5 ft lower (**Figure 2-42**). Lastly, seasonal low groundwater elevations in both a critical year and a dry year are similar (**Figure 2-43**).

All groundwater contour maps of the Upper aquifer indicate a southwesterly general flow from the elevated areas of the valley towards the Sacramento River in the valley floor. General groundwater flow directions in the Subbasin are primarily determined by the topography and influenced by local-scale groundwater withdrawal and recharge. Influence of groundwater withdrawal on flow direction is noticeable in the northcentral area, where contours indicate a predominantly westward flow during seasonal low conditions (in the fall) compared to southward flow during seasonal high conditions (in the winter/spring). A similar westward flow is indicated during seasonal high conditions in 2015, when the groundwater levels were low in the northcentral area due to drought conditions.

Groundwater contour maps show that the general horizontal hydraulic gradient in the central area of the Subbasin increases from the winter/spring to fall during a year, as well as from a wet year to a dry or critical year. In a wet year, hydraulic gradient in this area ranges from about 4 to 7 feet per mile (ft/mile) during the winter/spring, and from about 10 to 13 ft/mile during the fall. In the southern area, the gradient remains between about 2 and 3 ft/mile throughout the year. During the winter/spring of a dry or critical year, horizontal gradient ranges from about 6 to 10 ft/mile in the central area and 2 to 5 ft/mile in the southern portion of the Subbasin. The gradients throughout the Subbasin appear to slightly increase in the fall of a dry and critical year, but the change cannot be reliably quantified due to the uncertainty associated with contour locations.

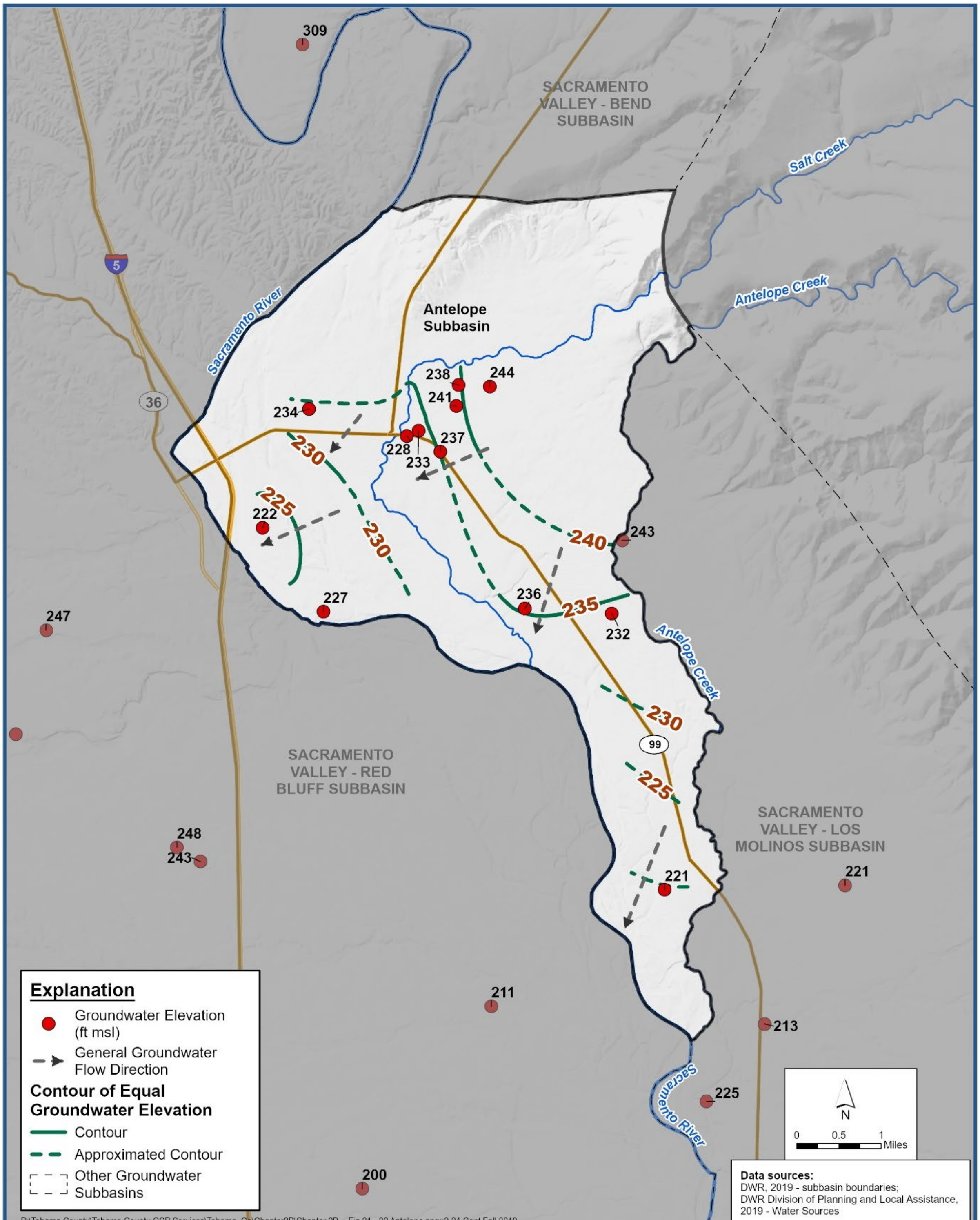
Water level data indicate a consistent, vertically downward hydraulic gradient in the Upper aquifer. However, accurate quantification of vertical gradients is difficult because of lack of data from nested or clustered monitoring wells in the Subbasin. Vertical hydraulic gradient was evaluated using two closely located individual wells (distance less than 1,000 ft) in the northcentral area of the Subbasin. Locations and water level hydrographs of these two wells, 27N03W14N001M (screened from 40 to 75 ft bgs) and 27N03W23D001M (screened from 30 to 155 ft bgs), are presented in **Appendix 2-F**. The gradient cannot be quantified for a meaningful use because of the long well screens. However, water level data indicate that the gradient is higher in the fall compared to that in the winter/spring.



Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal High of 2019

Figure 2-36

Groundwater Sustainability Plan
Antelope Subbasin



Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal Low of 2019

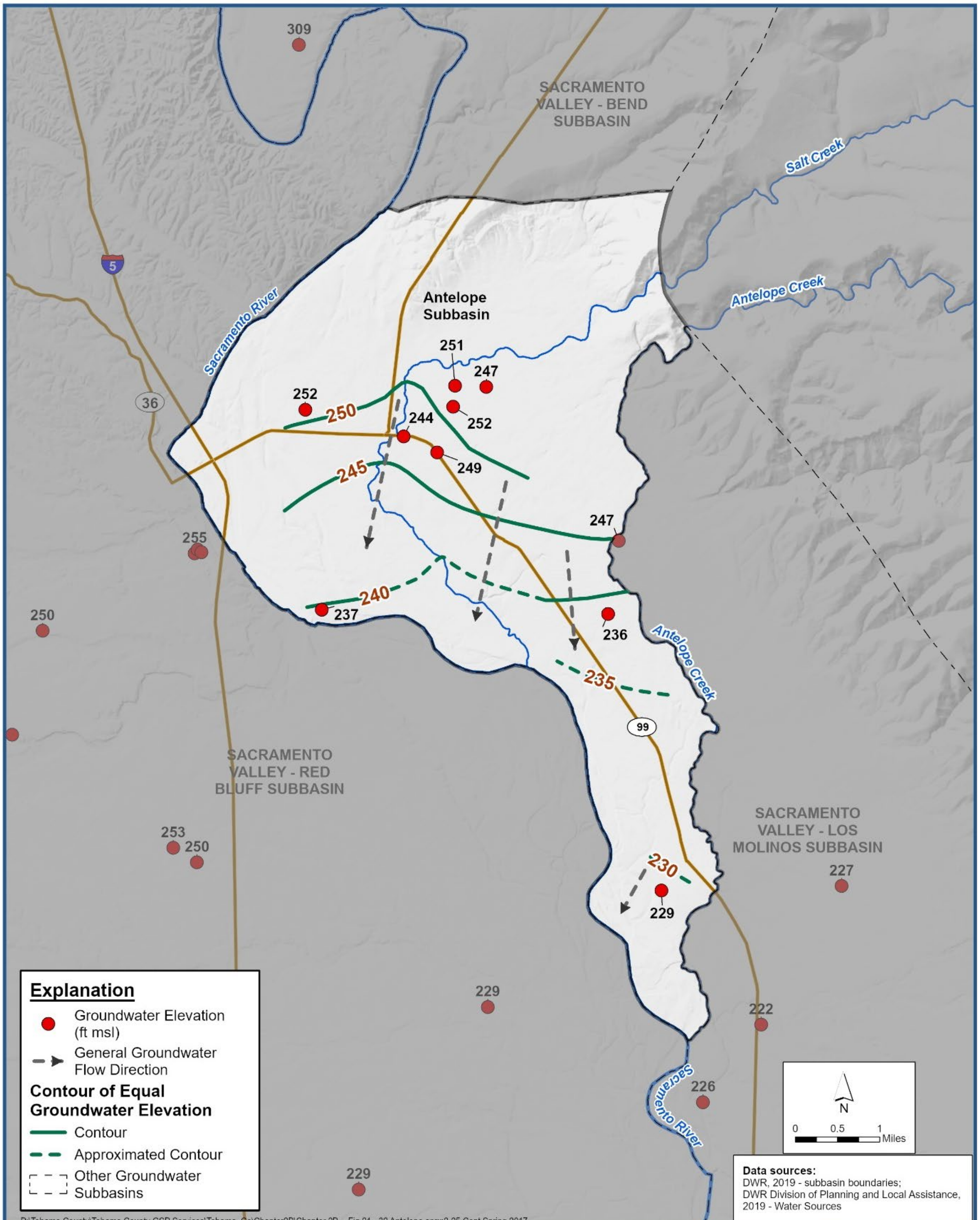
Figure 2-37

Groundwater Sustainability Plan
Antelope Subbasin

Table 2-9. Sacramento Valley Water Year Types since 1980

WATER YEAR	WATER YEAR INDEX	WATER YEAR TYPE
1980	9.04	Above Normal
1981	6.21	Dry
1982	12.76	Wet
1983	15.29	Wet
1984	10.00	Wet
1985	6.47	Dry
1986	9.96	Wet
1987	5.86	Dry
1988	4.65	Critical
1989	6.13	Dry
1990	4.81	Critical
1991	4.21	Critical
1992	4.06	Critical
1993	8.54	Above Normal
1994	5.02	Critical
1995	12.89	Wet
1996	10.26	Wet
1997	10.82	Wet
1998	13.31	Wet
1999	9.80	Wet
2000	8.94	Above Normal
2001	5.76	Dry
2002	6.35	Dry
2003	8.21	Above Normal
2004	7.51	Below Normal
2005	8.49	Above Normal
2006	13.20	Wet
2007	6.19	Dry
2008	5.16	Critical
2009	5.78	Dry
2010	7.08	Below Normal
2011	10.54	Wet
2012	6.89	Below Normal
2013	5.83	Dry
2014	4.07	Critical
2015	4.00	Critical
2016	6.71	Below Normal
2017	14.14	Wet
2018	7.14	Below Normal
2019	10.34	Wet

Source - https://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST
Accessed in January 2021



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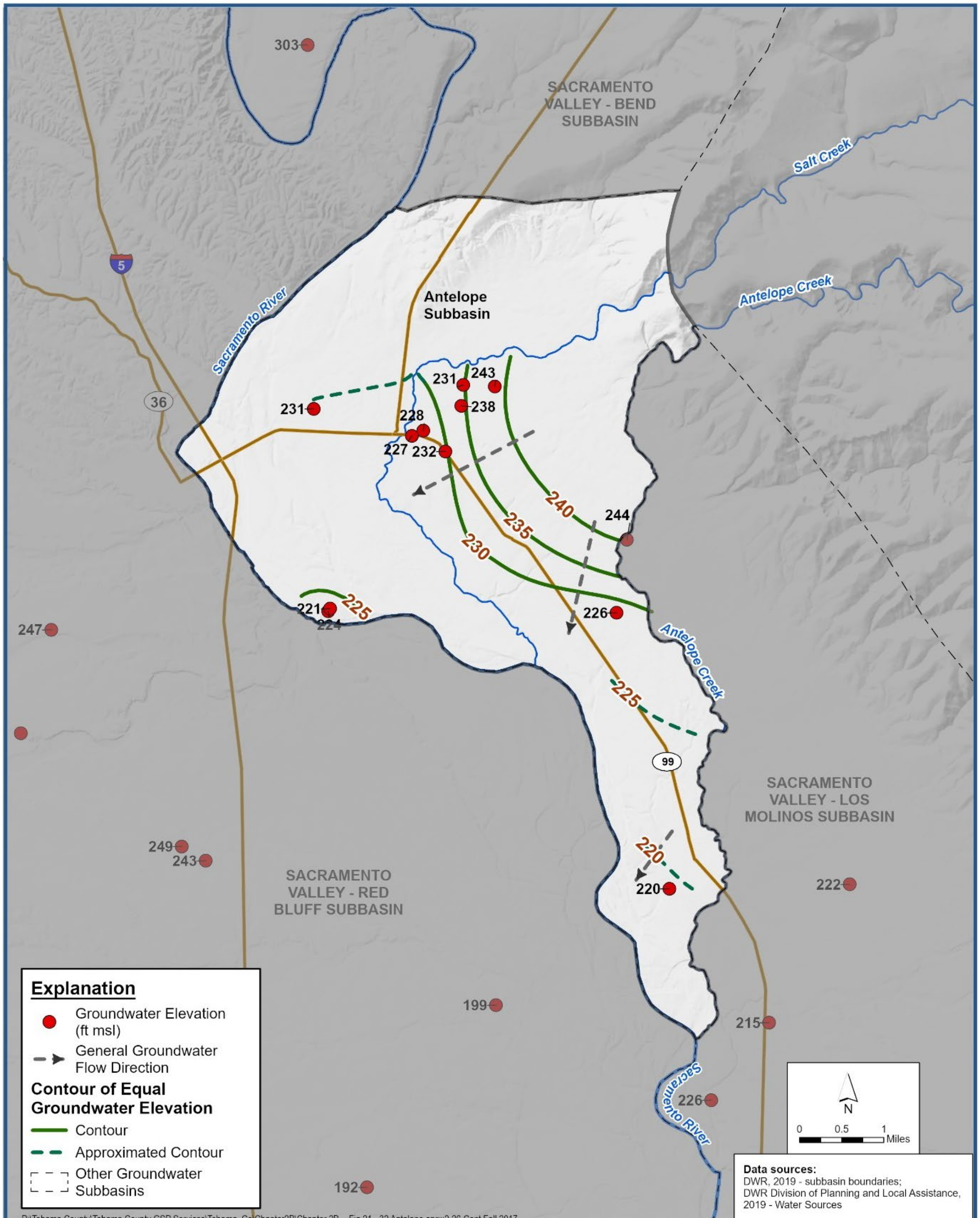
Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal High of 2017

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-38



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Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal Low of 2017

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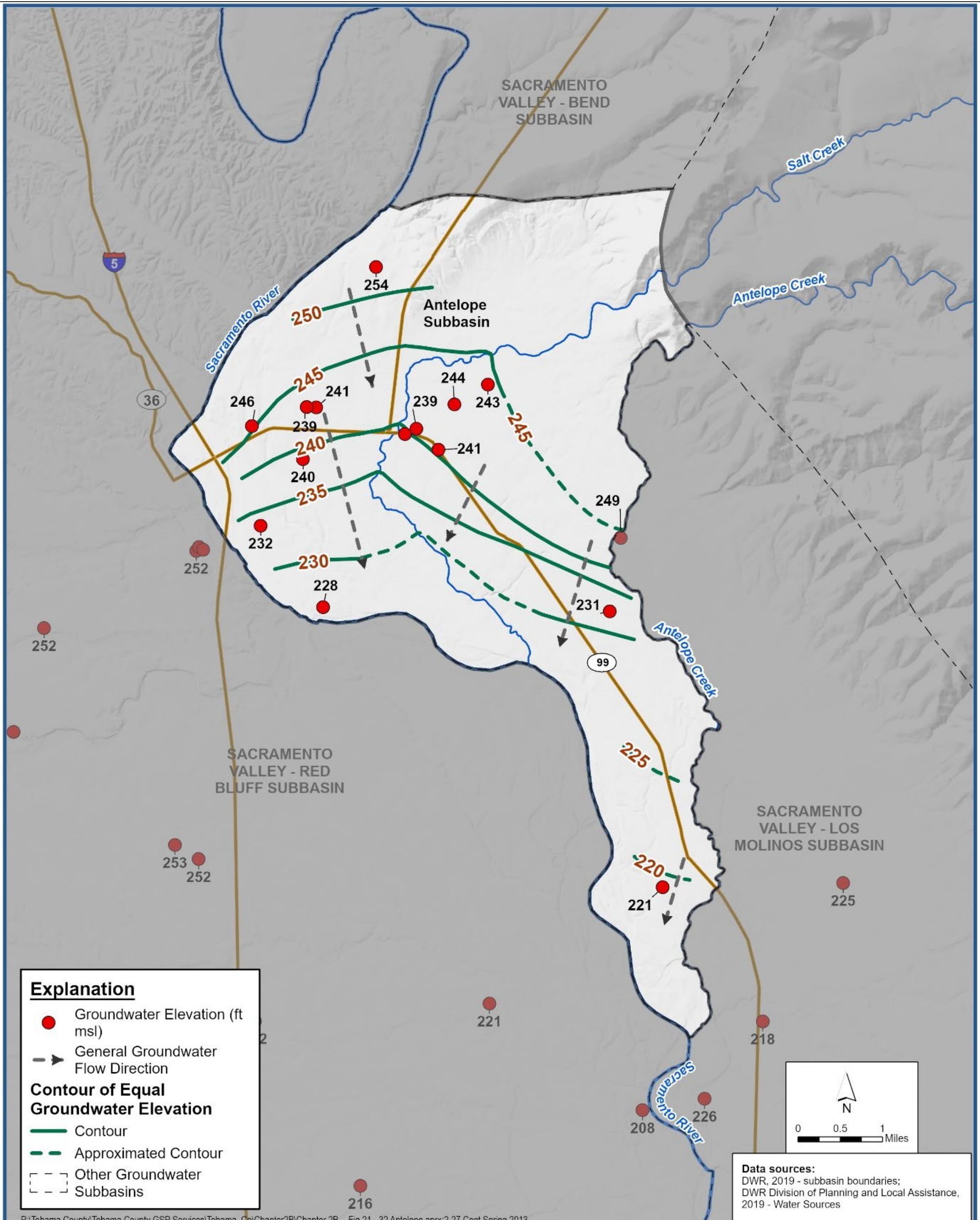
Antelope Subbasin

Figure 2-39



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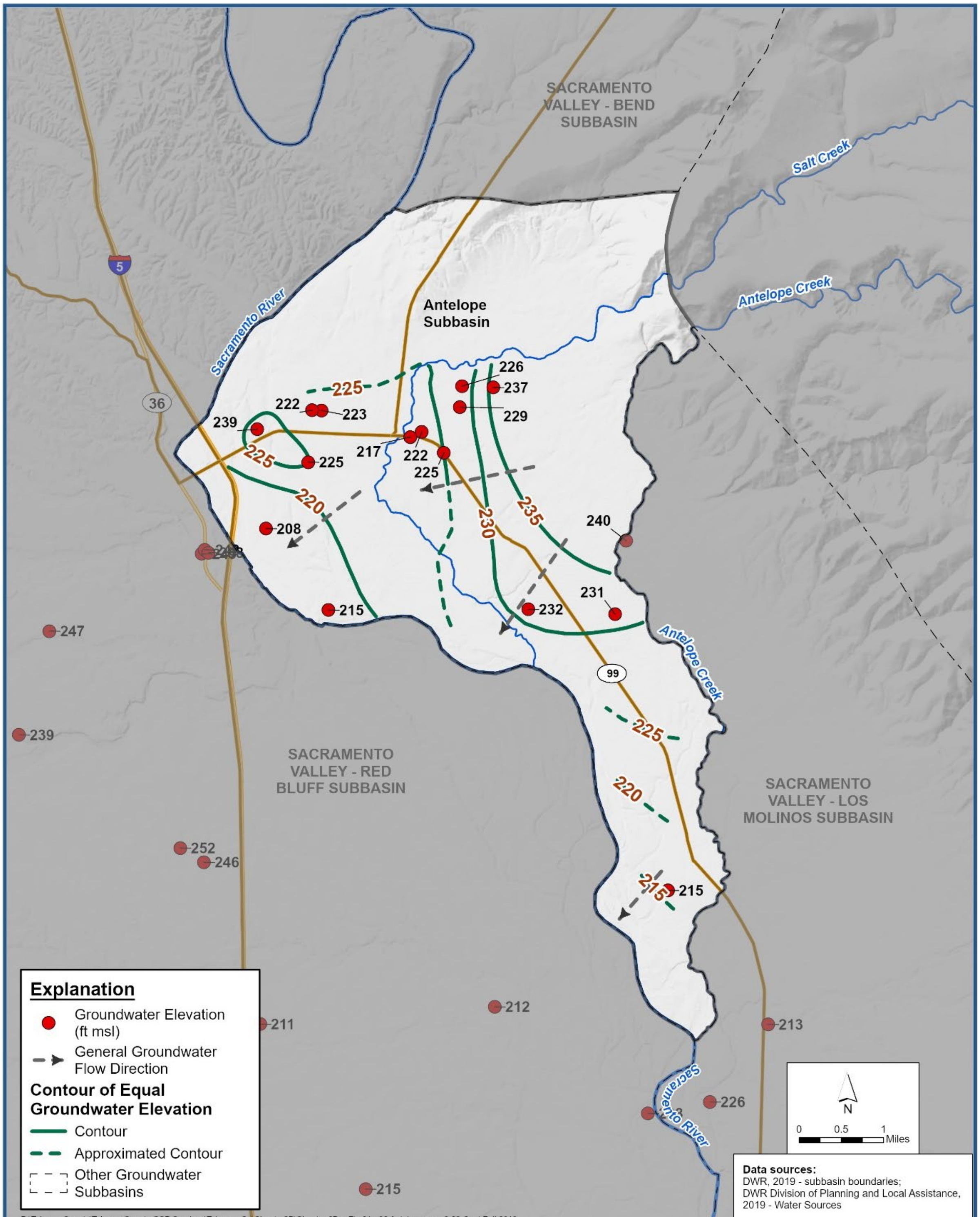
Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal High of 2013

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-40



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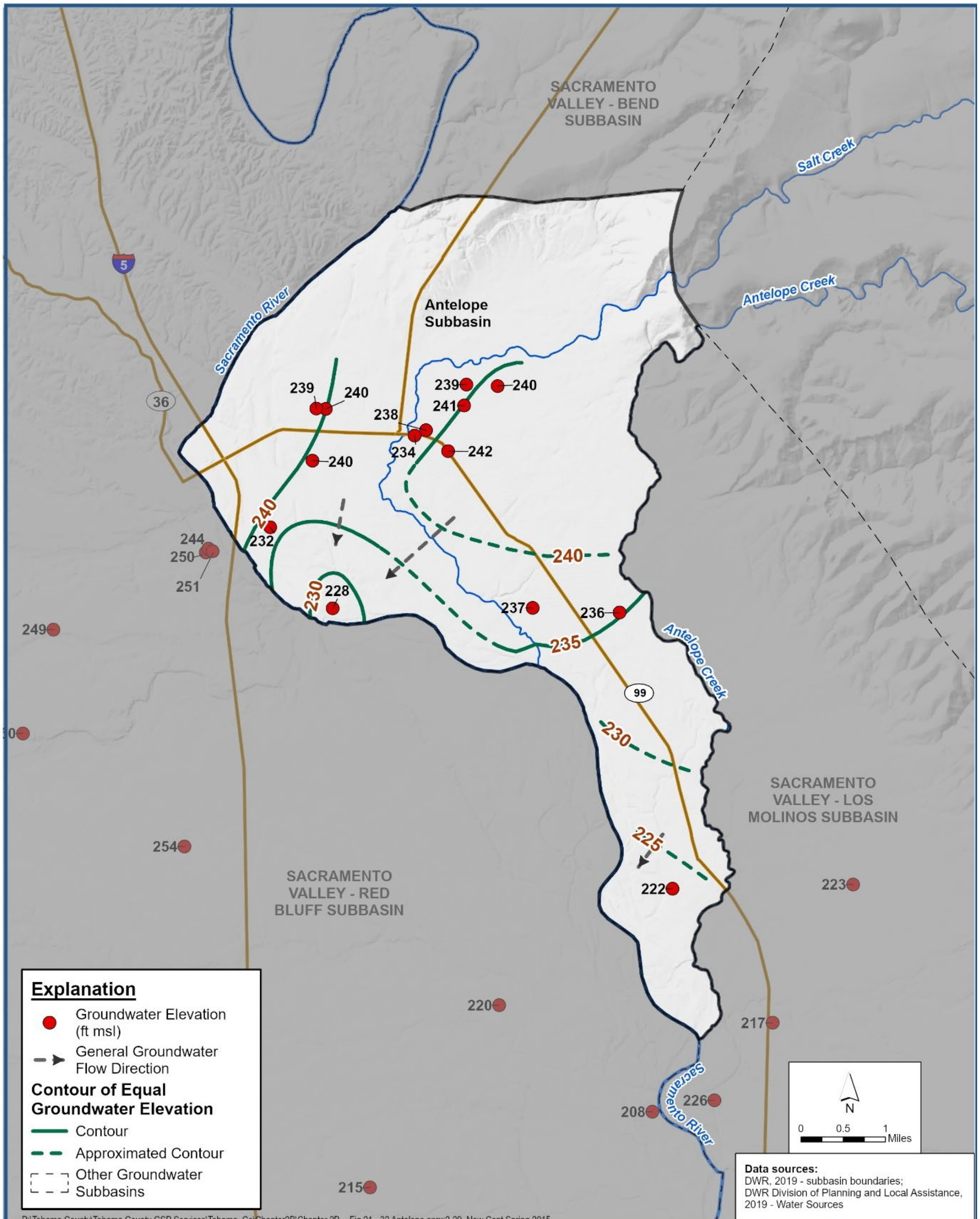
Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal Low of 2013

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-41



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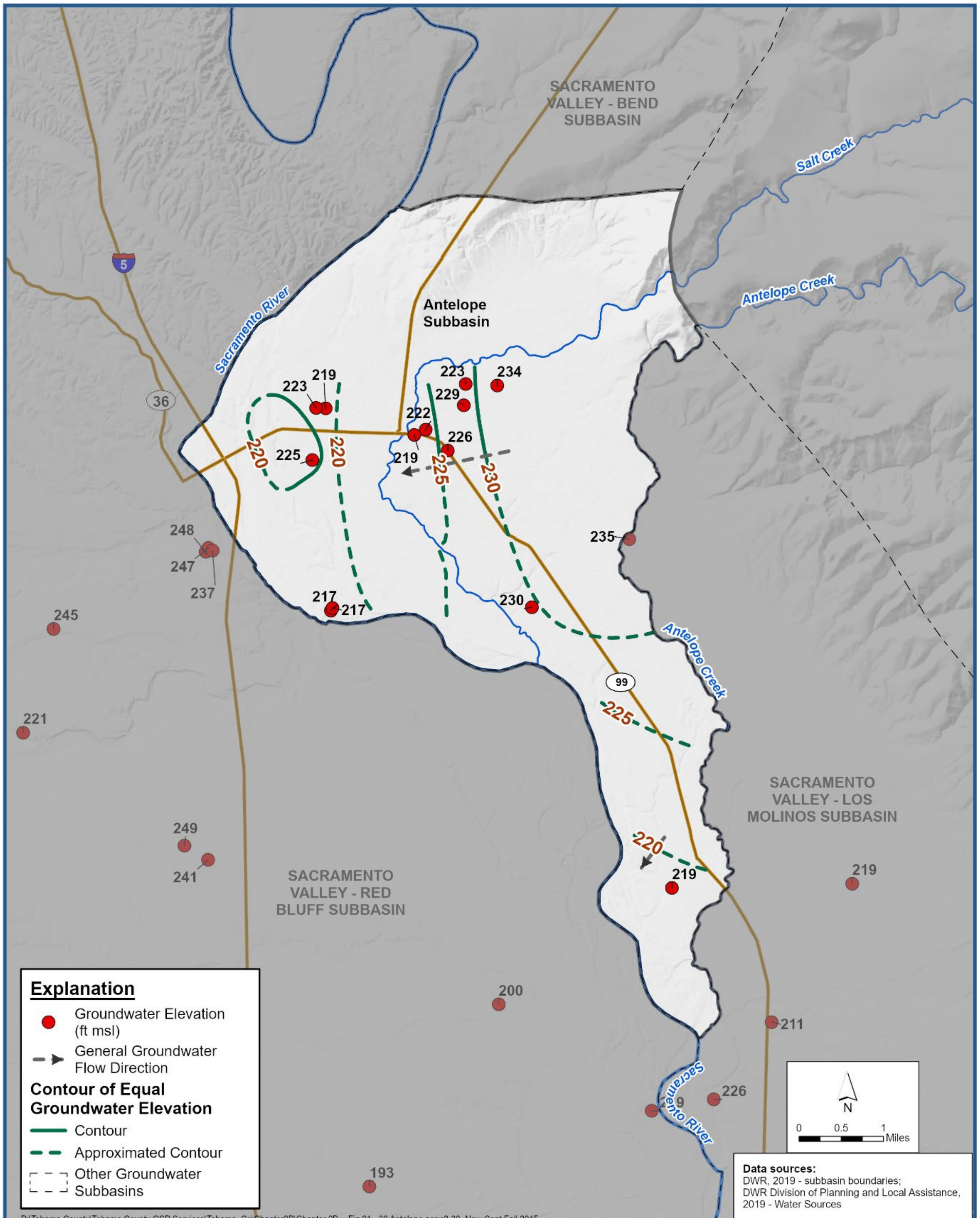
Contours of Equal Groundwater Elevation upper Aquifer - Seasonal High of 2015

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-42



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Contours of Equal Groundwater Elevation
Upper Aquifer - Seasonal Low of 2015

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-43

2.2.2.2 Change in Groundwater Levels and Storage

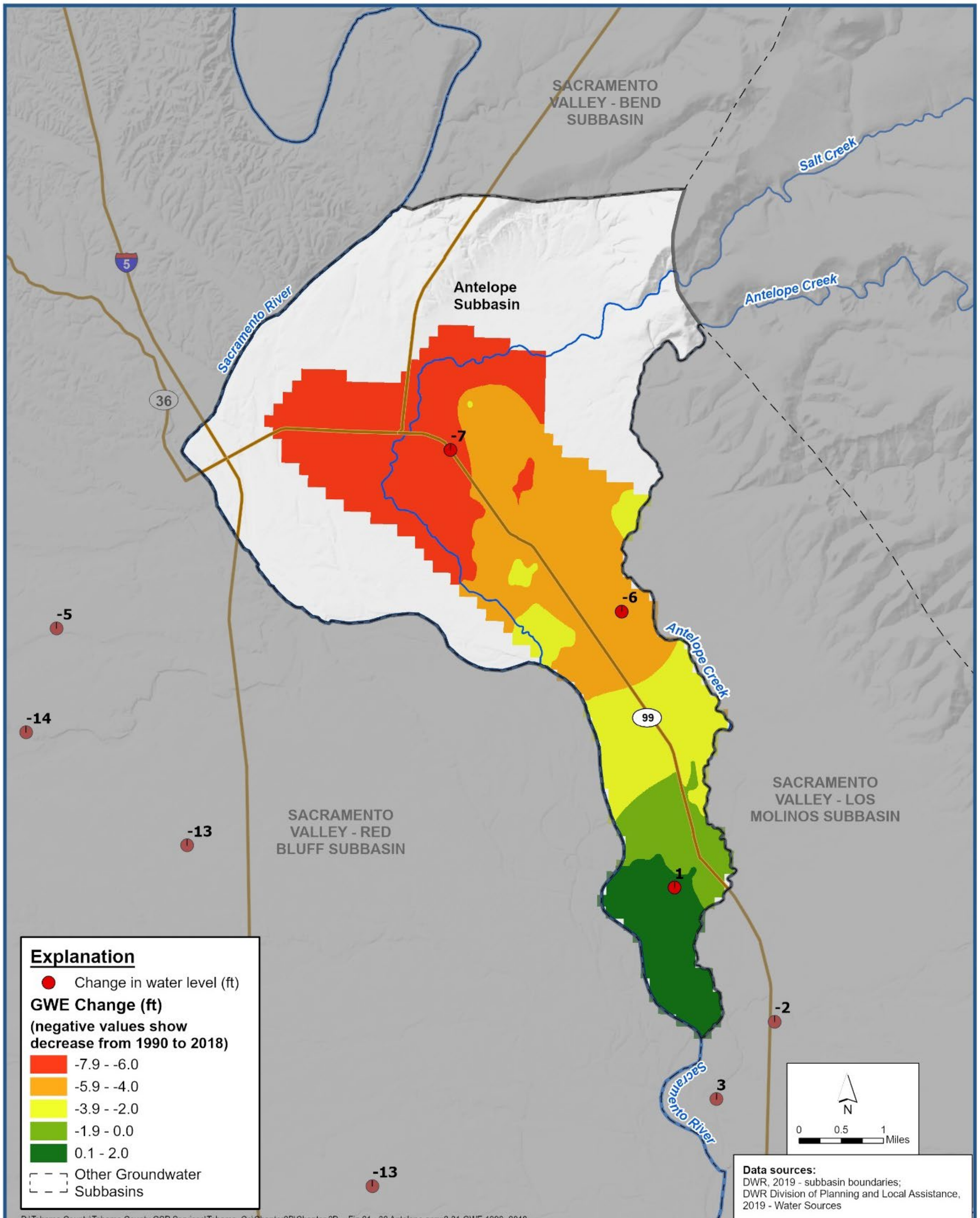
Change in seasonal high groundwater elevations (spring to spring) from 1990 to 2018 was estimated to evaluate changes in groundwater storage during the hydrologic base period. Groundwater elevation surfaces for 1990 and 2018 were separately created by interpolating available water levels in each year, the difference between these two surfaces (**Figure 2-44)**, which encompasses a volume of both water and porous media, was calculated. Groundwater elevation change is not shown in **Figure 2-44** in the northern and northeastern parts of the Subbasin since water level data were unavailable. Between 1990 and 2018, groundwater elevations decreased by approximately 10 ft in the northcentral area of the Subbasin (mainly areas west and south close to the intersection of State Highway 99E and Highway 36E), but the elevations increased by over two ft in the southern portion. The area where groundwater elevation change was estimated is approximately 9,700 acres, which is about 51% of the Subbasin area. However, this area includes about 73% of all irrigated lands in the Subbasin (2018 land use data). The change of groundwater elevations corresponds to a decrease of approximately 5,000 acre-feet of groundwater in the Upper Aquifer of this area, using the volume between the two groundwater surfaces and a specific yield of 0.072 (DWR, 2004). The specific year-to-year historical groundwater storage changes are also estimated using a surface water-groundwater flow model discussed in the section 2.3.

2.2.2.3 Groundwater Quality

The evaluation of groundwater quality in the Subbasin included a literature review (e.g., Bennett et al., 2011 and Tehama County FCWCD, 2012) and evaluation of groundwater quality data collected from SWRCB GeoTracker and GeoTracker GAMA databases. Previous studies documented occurrences of undesirable concentrations of nitrate, boron, and arsenic in the Subbasin. Currently, all groundwater clean-up sites (including leaking underground storage tanks) within the Subbasin are closed or inactive. Occurrences of unregulated chemicals associated with pesticides at concentrations higher than the USGS "Health Based Screening Level" have been reported six times since 2007 at six different municipal wells. Widespread presence of contaminants at undesirable levels, except nitrate, have not been reported in groundwater samples in the Subbasin. Therefore, the following discussion focuses on total dissolved solid (TDS), nitrate, arsenic, and boron concentrations of the Upper Aquifer of the Subbasin. We assume that all available water quality data represent water quality of the Upper Aquifer. Wells that have water quality data without construction details are expected to be completely or mostly screened in the Upper Aquifer, because wells screened in the Lower Aquifer are rare in the Subbasin.

Total Dissolved Solid (TDS)

The occurrence of TDS at undesirable concentrations is not a concern at present. Historically, TDS concentrations have not exceeded 800 milligrams per liter (mg/L) in groundwater in the Subbasin. Long term TDS records show temporal fluctuations within narrow ranges without any noticeable trend. A total of 361 groundwater samples were tested for TDS since 1957; only seven sample results exceeded the Secondary Maximum Contaminant Level (500 mg/L). These seven samples were collected from seven individual wells that are scattered in the northern part of the Subbasin (**Figure 2-45**).



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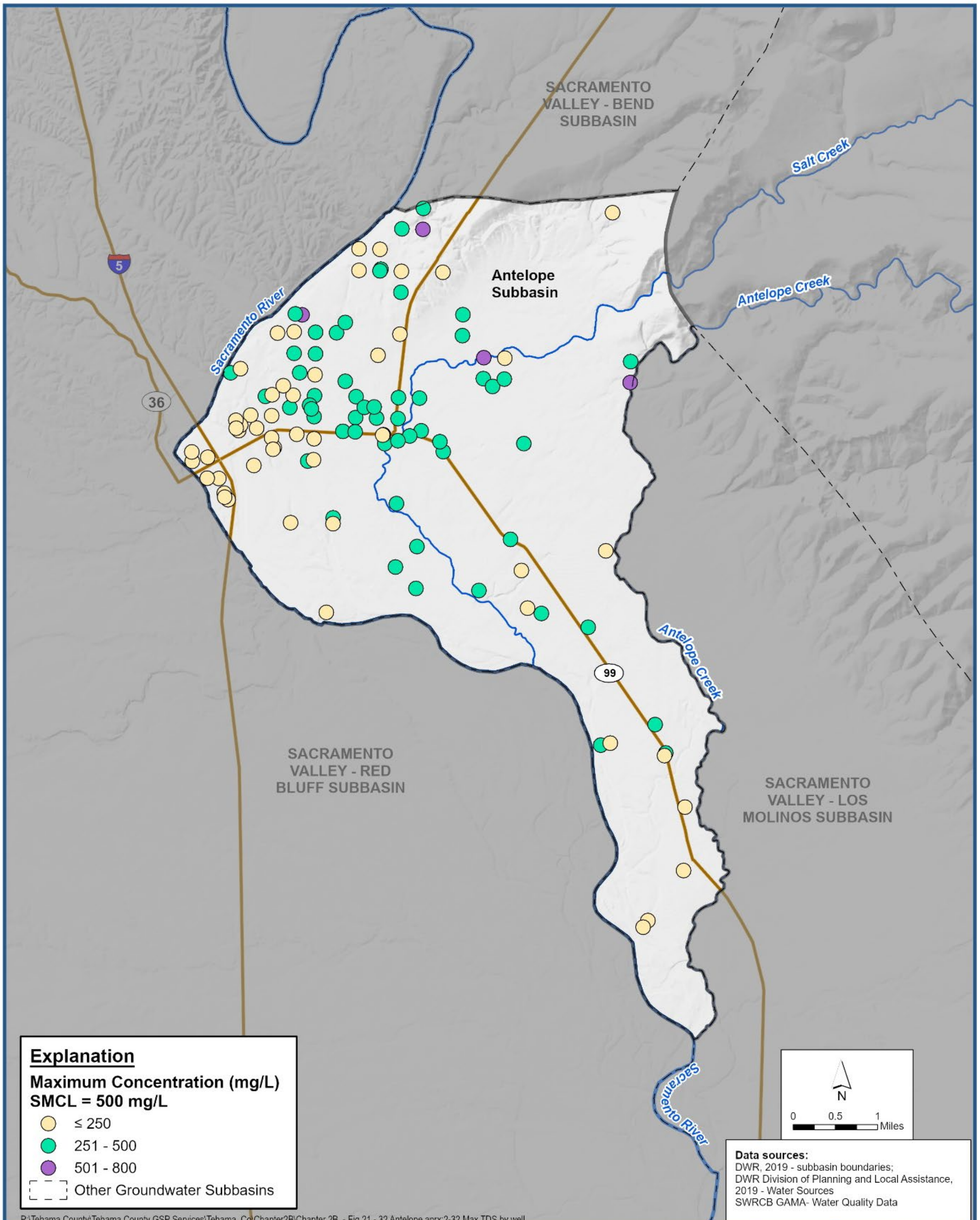
Change of Groundwater Elevation from Spring 1990 to Spring 2018

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-44



Maximum Historical TDS Concentration by Well

Groundwater Sustainability Plan
Antelope Subbasin

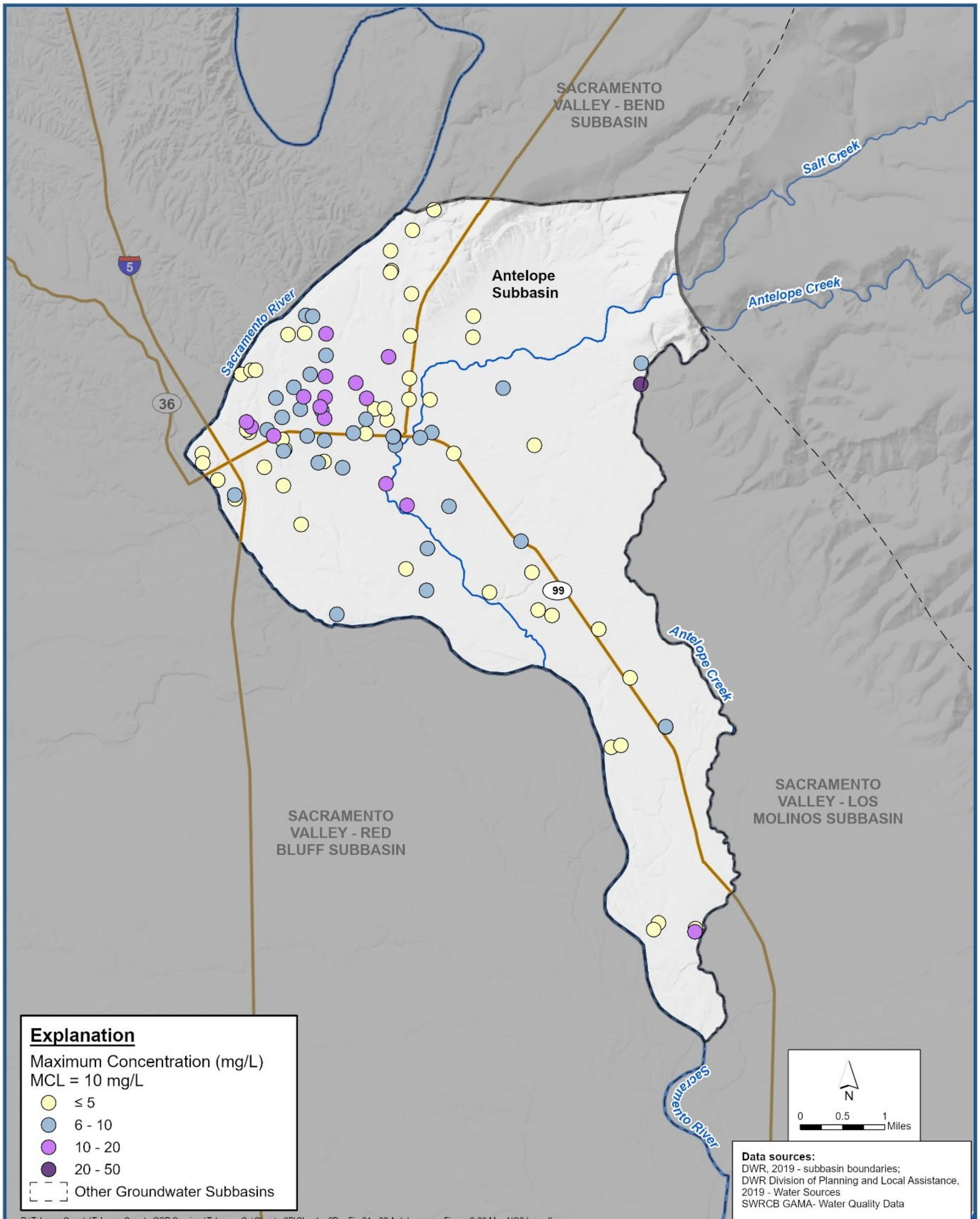
Figure 2-45

Nitrate

Nitrate (nitrate, expressed as nitrogen) concentrations that exceed the Maximum Contaminant Level (MCL) of 10 mg/L have been reported at least once at 10% of tested wells in the Subbasin (18 of 180 tested wells since 1950; **Figure 2-46**). The highest nitrate concentration in the Subbasin, 44.1 mg/L, occurred in 1963, and the highest concentration since then is 17 mg/L. Most of the wells with high nitrate concentrations are in the northwestern area of the Subbasin. Wells with long term data, primarily municipal wells in this area, show consistently high nitrate levels with gradually increasing trends (**Appendix 2-G**). For instance, the nitrate (as N) concentration of municipal well 5200598-001 mostly fluctuated between 8 and 10 mg/L since 2003 and it exceeded the MCL multiple times. Test results show an apparent increasing trend at this well and 60% of results (12 of 20) since 2015 are above 9 mg/L. Nitrate test results are below the MCL for samples from the central and southern areas of the Subbasin, except in samples from a municipal well (Well 5200015-001) located close to the southern boundary of the Subbasin. Nitrate concentration at this well exceeded the MCL twice since 2018. Sufficient data on well construction (screen depths) are not available to evaluate the vertical variability of nitrate in the aquifer. Abundant nitrate concentrations that exceed the MCL in the Subbasin suggests the necessity of regular monitoring of nitrate, especially in the northwestern part of the Subbasin. Elevated levels of nitrate in drinking water pose a serious health risk for infants. Potential sources of nitrate in the Subbasin include sewage disposal systems and fertilizer used in agriculture.

Arsenic

Available water quality data suggest that arsenic is currently not a groundwater quality concern in the Subbasin. Only one groundwater sample collected since 1960 from the Subbasin exceeded the arsenic MCL of 10 micrograms per liter (µg/L). This concentration of 17 µg/L is associated with a sample collected in 2002 from a municipal well located in the northwestern area of the Subbasin (Well 5200510-001). Test results of five other samples (27 samples in total) from this well and three other municipal wells in the same area (Wells 5200507-001, 5200510-002, and 5800913-001) since 2000 were between 8 and 10 µg/L. However, data do not show an identifiable trend of arsenic concentrations. All wells with historical test results over 5 µg/L are in the northwestern area of the Subbasin (north of Antelope Blvd and mostly west of Highway 36E; **Figure 2-47**). Arsenic is a naturally occurring chemical that originates from volcanic rocks of the Tuscan Formation (Tehama County FCWCD, 2012).



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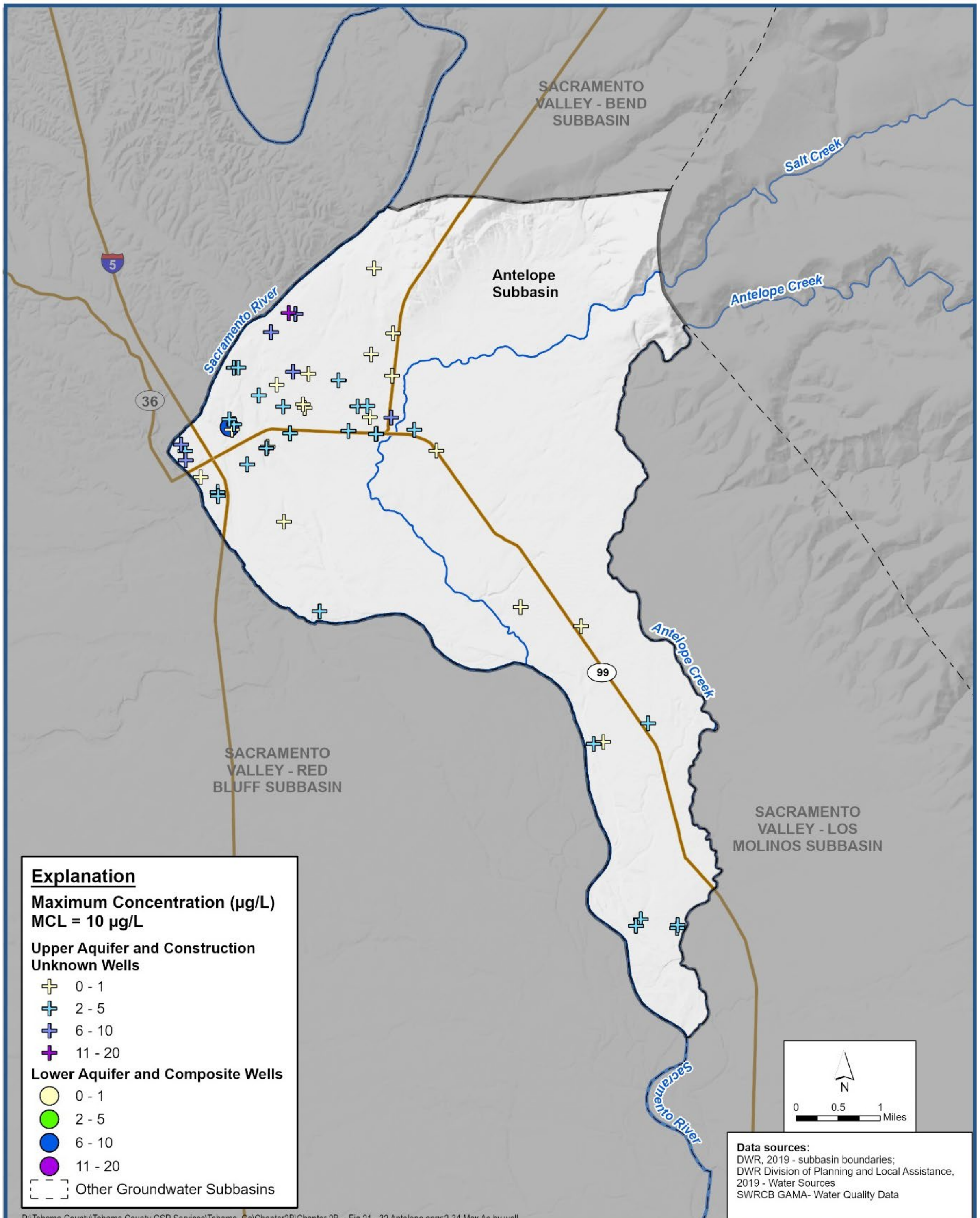
Maximum Historical Nitrate Concentration by Well

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-46



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Maximum Historical Arsenic Concentration by Well

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-47

Boron

Boron concentrations over 1.0 mg/L have been reported in groundwater samples collected from the northcentral part of the Subbasin, mostly in areas north of Antelope Blvd and east of Highway 36E, as well as in some areas along Salt Creek (**Figure 2-48**). Boron is an unregulated chemical for drinking water, but it has a California State Notification Level of 1.0 mg/L which applies to groundwater wells used for public drinking water. Approximately one fourth of groundwater samples tested for boron since 1952 (112 of 424 samples) had concentrations that exceeded this threshold. The two highest boron concentrations in the Subbasin, 10.1 and 9.4 mg/L, were reported at one well in 1983 and 1984, respectively. Samples from all other wells were below 4.0 mg/L. Boron is a naturally occurring chemical, most likely sourced from minerals in Cretaceous marine sedimentary rocks (DWR, 1987). Certain crops are sensitive to boron over 0.50 mg/L. Historical water quality data suggest that groundwater water used for irrigation of sensitive crops, especially in the northcentral areas of the Subbasin, should be monitored for boron to avoid negative impacts on crop yield.

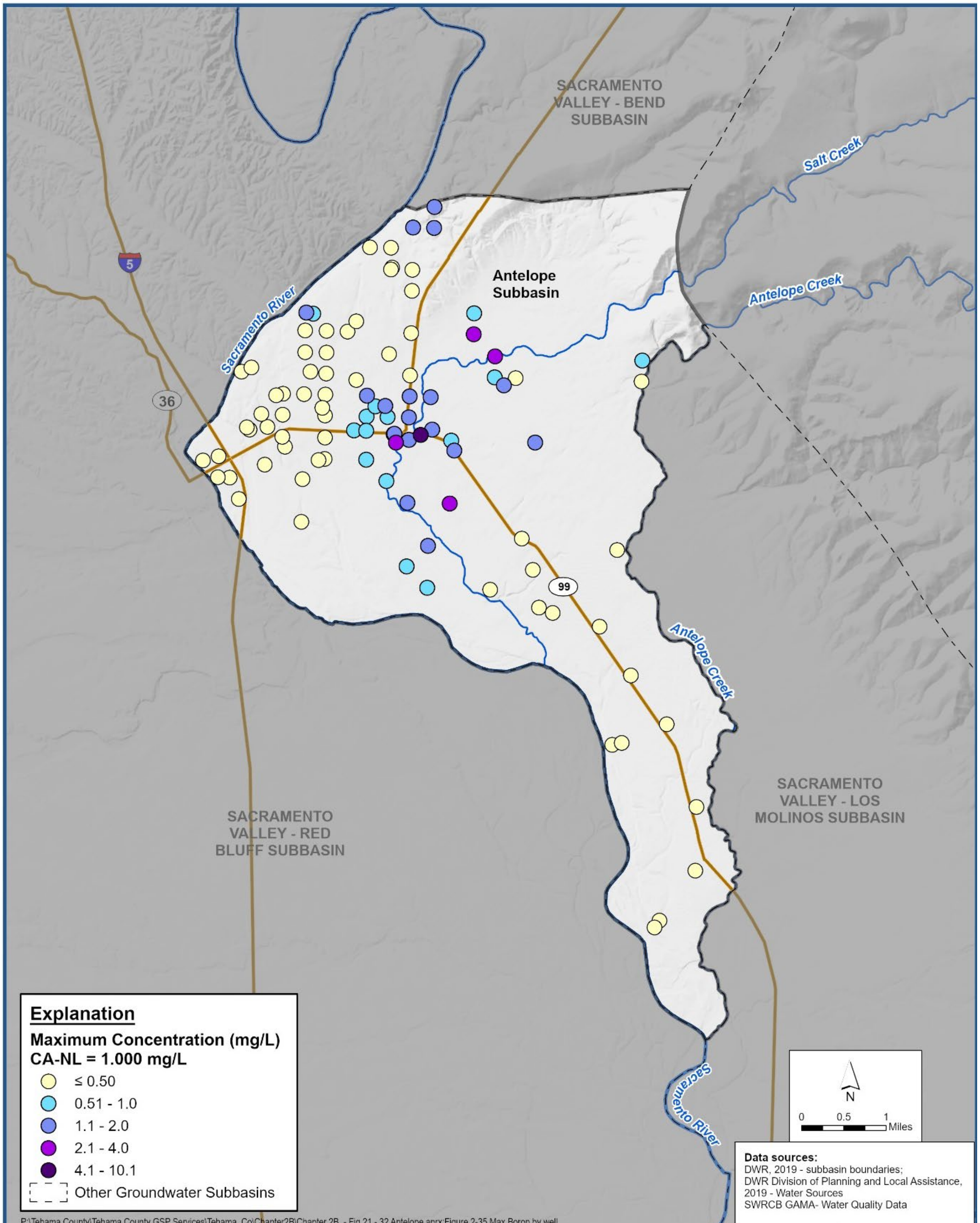
2.2.2.4 Seawater Intrusion

Seawater intrusion is not an applicable sustainability indicator for the Antelope Subbasin because it is not likely to occur in the Subbasin due to its distance from the Pacific Ocean (about 90 miles).

2.2.2.5 Subsurface Compaction and Land Subsidence

Antelope Subbasin has little to no reported evidence of subsidence. Subsidence occurs when groundwater is extracted from the pore spaces in the geologic material leading to compaction. The compaction causes the ground surface elevation to drop. In addition to groundwater extraction, oil and gas extraction can lead to subsidence. There are no active oil or gas wells in the Subbasin (**Figure 2-49**). Subsidence monitoring in the Subbasin is limited to two main surveys both conducted by DWR. The subsidence measured in these studies is likely elastic, meaning the land surface can recover (rise) if groundwater is recharged and again fills the pore spaces. Negative subsidence measurements indicate a downward vertical movement of the land surface and positive values indicate an upward movement.

In 2018 DWR released a report on land subsidence from 2008-2017 using Global Positioning Systems (GPS) survey methods. In 2008, DWR contracted the installation of a series of survey monuments across 11 counties; two survey monuments are within the Subbasin boundaries (**Figure 2-50**). These monuments were surveyed using GPS to establish a baseline elevation and then resurveyed in 2017. Results from 2008 and 2017 were compared to establish an average change in ground surface elevation over the almost ten-year study period. In the Subbasin, measured ground surface elevation decreased by 0.016 ft at the northern station and decreased by 0.021 ft at the southern station (**Figure 2-50**). On average, subsidence in the Subbasin was -0.00185 feet per year over the duration of the study.



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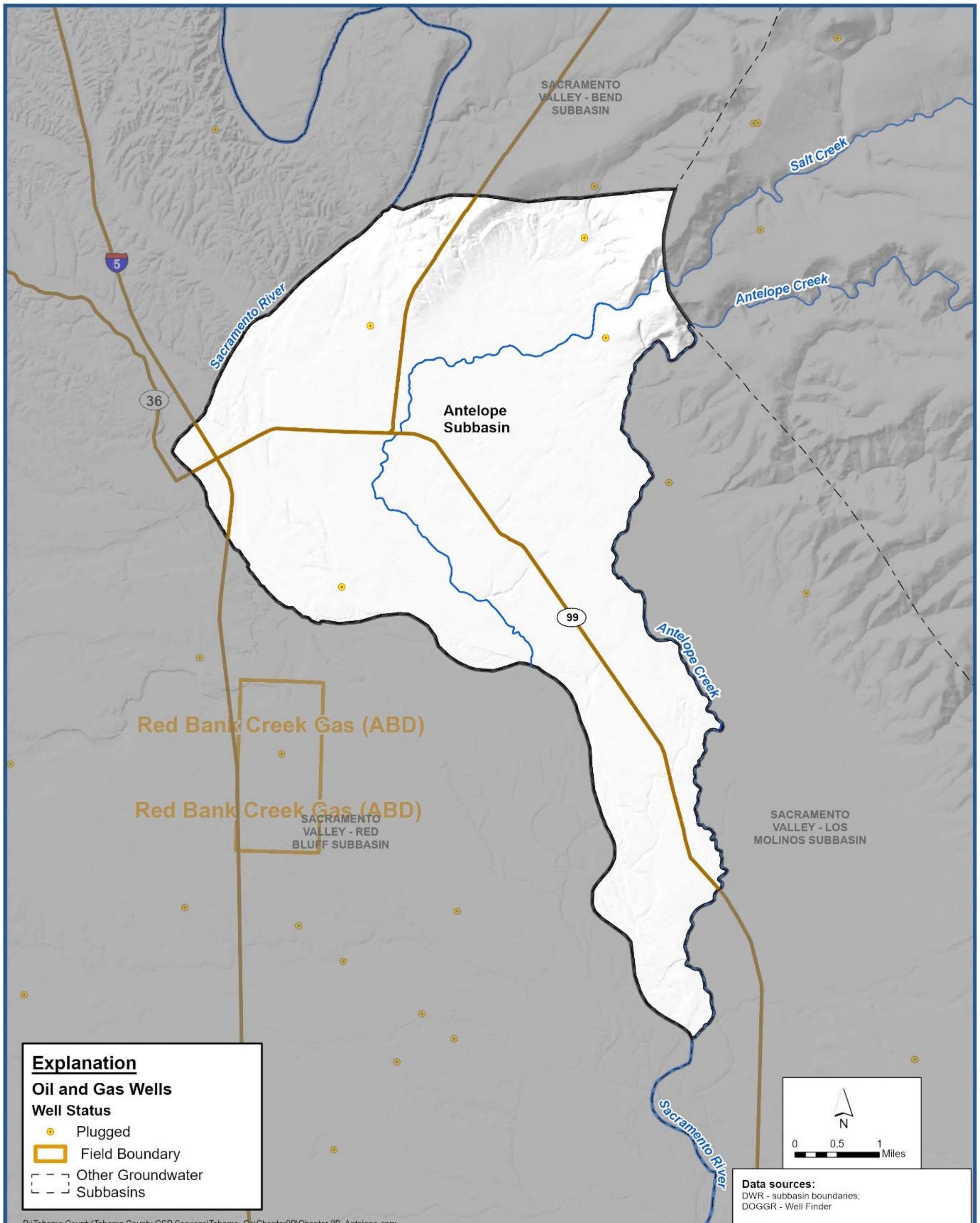
Maximum Historical Boron Concentration by Well **Figure 2-48**

Groundwater Sustainability Plan
Antelope Subbasin



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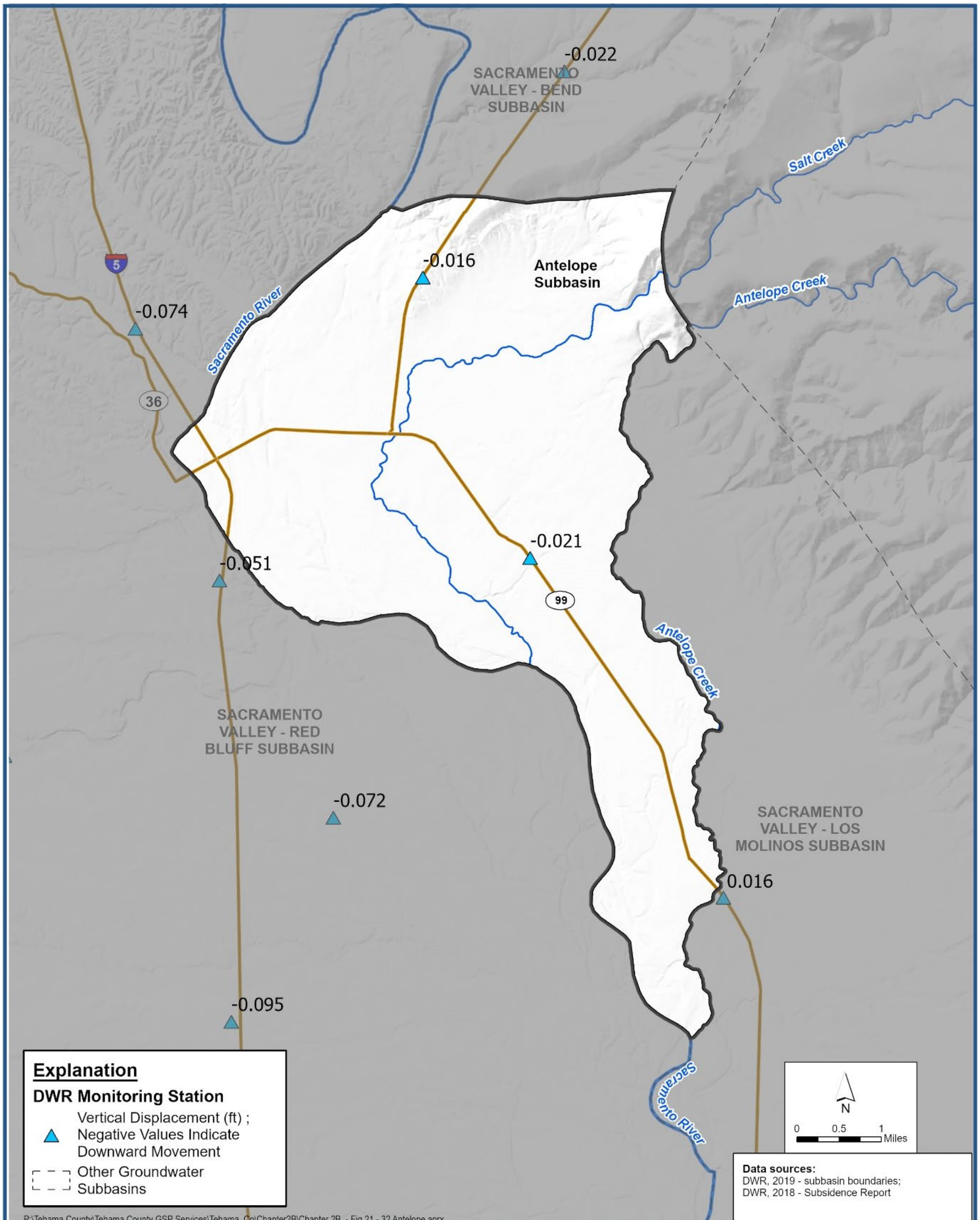
Map of Oil and Gas Fields and Wells

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-49



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Subsidence Measurements Between 2008 and 2017

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-50

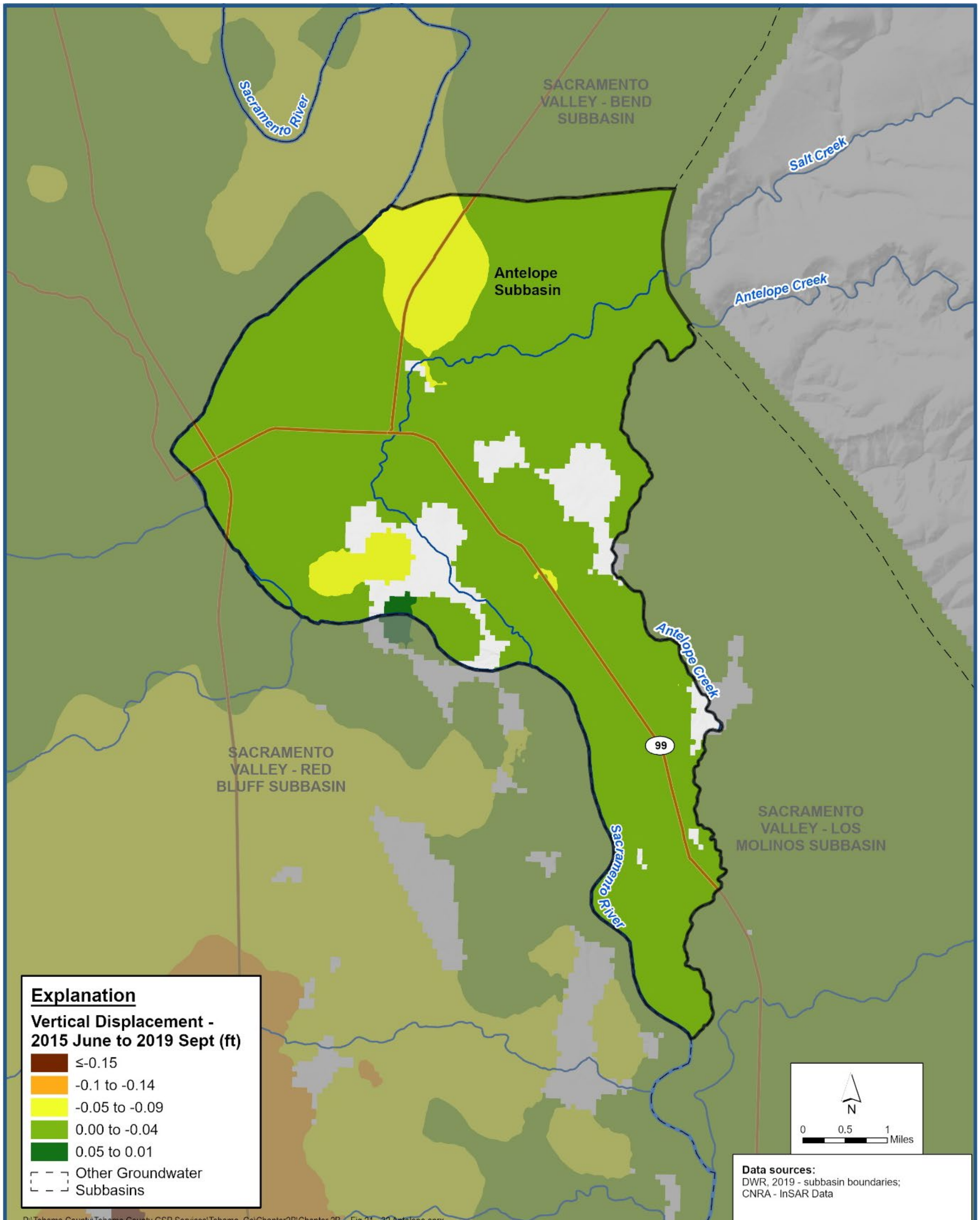
In 2015 DWR began reporting Interferometric Synthetic Aperture Radar (InSAR) surveys to assist with subsidence studies related to SGMA. Vertical measurements are collected by the European Space Agency Sentinal-1A satellite and compared to previous measurements to establish a change in surface elevation. The vertical measurements are collected as point data sets that represent 100-meter by 100-meter areas and are used to interpolate GIS rasters (**Figure 2-51**). Maximum vertical displacement measured using the InSAR approach from July 2015 to June 2019 was -0.05 to -0.09 ft in the Subbasin (**Figure 2-51**). On average, subsidence in the Subbasin was -0.01 feet per year to -0.018 feet per year from January 2015 to September 2019. The subsidence is likely elastic, meaning the land surface can recover (rise) if groundwater is recharged and again fills the pore spaces.

2.2.2.6 Surface Water Conditions

Historic and current surface water flow data is limited in the Subbasin. As discussed in Section 2.2.1.7, the Sacramento River, Antelope Creek, Salt Creek, Craig Creek (distributary stream off Antelope), and New Creek (tributary of Salt Creek) are the main surface water features in the Subbasin and are all perennials. Little Salt Creek, Millrace Creek, Butler Slough (distributary system off Antelope Creek), Paynes Creek Slough, and other smaller streams also flow through the Subbasin. Only the Sacramento River and Antelope Creek, have historical or current flow data.

The Sacramento River has three currently active gaging stations close to the Subbasin; USGS/USBR station #11377100 at Bend Bridge, USBR station at Red Bluff Diversion Dam (RDB), and DWR station at Tehama Bridge (TEH). Station RDB is located at the western boundary of the Subbasin and TEH is located about nine miles downstream from the southern boundary of the Subbasin (**Figure 2-31**). USGS/USBR station BND is located about 4.5 miles upstream from the northern boundary of the Subbasin with a daily record since 1963. Based on historical data from BND, the mean annual flow rate is about 12,500 cubic feet per second (CFS) with highest flows from January through March (historical mean over 16,800 CFS), and lowest flows in October (historical mean about 7,000 CFS) (USGS NWIS stream flow data). Stations RDB and TEH are only equipped with stage sensors and only directly monitor stage; however, CDEC's website presents flow data (assumed to be calculated from stage).

Antelope Creek is not currently measured in the vicinity of the Subbasin; however, historical flow data (1940 to 1982) are available from a USGS station close to the northeastern boundary of the Subbasin (station #11379000 in **Figure 2-31**). The mean annual flow rate for the period of 1940-1982 is about 150 CFS (USGS NWIS stream flow data). In general, the flow is highest in January and February (mean of over 300 CFS), and it is lowest in August and September (mean of about 38 CFS) (USGS NWIS stream flow data).



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DWR InSAR Subsidence Map

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-51

2.2.2.6.1 *Interconnected Surface Water Systems*

Characterizing the connectivity of the surface water systems in the Subbasin is challenging due to limited data. Modeling surface water and groundwater interaction is another means to address the connectivity and is discussed in section 2.3. When a stream stage is higher than the groundwater table the stream will lose water to the ground via infiltration of water through the streambed (losing conditions). If losing conditions are present but the depth of the water table is too deep, the stream is considered losing and disconnected, however if groundwater is just below the stream, then they are connected. When the water table elevation is higher than the stream stage, groundwater will infiltrate into the stream causing the stream to gain water (gaining conditions). Groundwater and surface water are always connected under gaining conditions. Installation of shallow monitoring wells near currently active stream gages would help to characterize the interconnectivity of the streams and the groundwater in the Subbasin.

The Subbasin does not have active stream gages near shallow monitoring wells needed to accurately define the volume of water moving between the surface water and groundwater systems where interconnected. As discussed in section 2.2.2.6, station RDB is the only currently active source of stream stage data in the Subbasin. Data from inactive stations was examined and no data was found to overlap (in time) with data available from nearby shallow monitoring wells. There are three currently monitored shallow CASGEM wells in the Subbasin. The closest CASGEM well to station RDB is 2.5 miles away (**Figure 2-52**). Installation of a shallow monitoring well near station RDB would help to characterize the interconnectivity of the Sacramento River and the groundwater in the Subbasin.

Figure 2-52 shows likely interconnected, likely disconnected and interconnectivity uncertain stream reaches based on a dataset developed by The Nature Conservancy (TNC, 2021). This dataset categorizes the likelihood of the interconnectivity based on approximated streambed elevation at a selected point and the minimum depth to groundwater at a nearby well recorded between 2011 and 2018. A stream segment that was hydraulically connected to groundwater at any time during that period is categorized as likely interconnected. Therefore, a large uncertainty exists about the seasonal and year-to-year variability of interconnectivity of streams. Losing and gaining stream segments categorized using the calibrated Tehama Integrated Hydrologic Model are included in **Sub-appendix G** of **Appendix 2-J**.

2.2.2.7 Identification of Groundwater Dependent Ecosystems

Groundwater dependent ecosystems (GDEs) are defined in the GSP regulations as, "ecological communities or species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" (23 CCR § 351(m)). Freshwater species in Antelope Subbasin are listed in **Appendix 2-H**. These species were geographically selected from the California Freshwater Species Database (CDFW, 2015). The approach used to both identify and prioritize GDE's was modified from the guidance document *Groundwater Dependent Ecosystems under the Sustainable Groundwater Management Act – Guidance for Preparing Groundwater Sustainability Plans* (The Nature Conservancy, 2018). The guidance document was produced by The Nature Conservancy (TNC), an environmental stakeholder who has been actively involved in GSP development and review throughout the state. The dataset of Natural Communities Commonly Associated with Groundwater (NCCAG) provides indicators of potential groundwater dependent ecosystems (iGDEs). This dataset, provided by DWR, is a compilation of

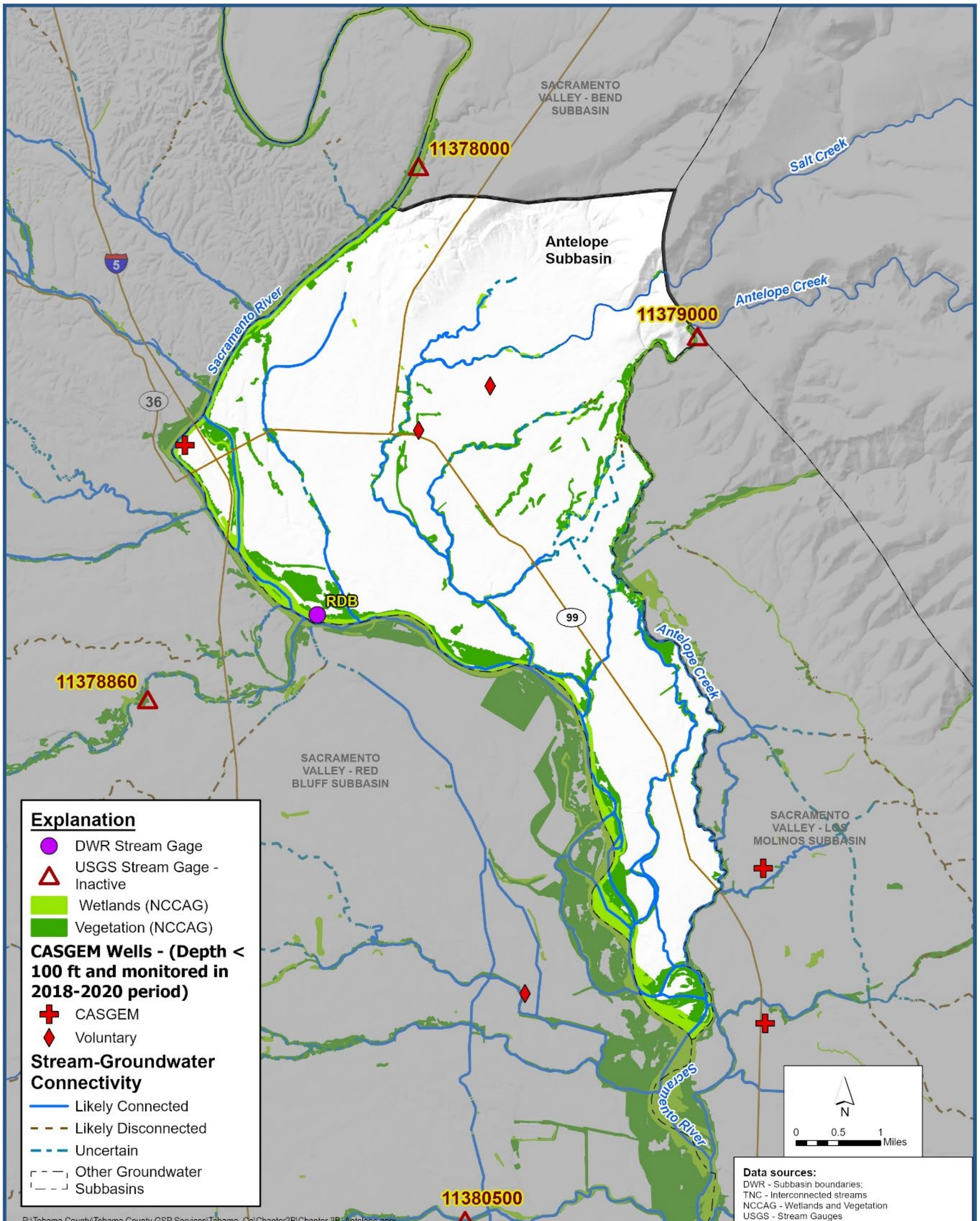
48 publicly available state and federal agency datasets that map vegetation, wetlands, springs, and seeps in California (Klausmeyer et al., 2018). NCCAG data show the occurrence of iGDEs adjacent to perennial and intermittent streams, as well as seasonally flooded wetlands in the Subbasin (**Figure 2-52**). The process used to identify potential GDEs in the Subbasin was accomplished by:

- a comparison of iGDEs with recent land cover data to update the map of iGDEs. This step is required because some iGDEs given in the NCCAG dataset are sourced from datasets mapped many years before 2015, which is the baseline year of SGMA. IGDEs found to exist within developed or irrigated lands were excluded during this step.
- an evaluation of groundwater conditions that can support GDEs. GDEs are likely to exist in areas where the seasonal high groundwater levels do not fall deeper than 30 ft bgs (TNC, 2019). Therefore, identifying areas with shallow groundwater that can support GDEs is important to identify GDEs. IGDEs within 1 mile of wells and with 2015-seasonal-high water deeper than 30 ft were excluded in this step.

A detailed description of methodology of GDE identification and prioritization is presented in a separate Technical Memorandum in **Appendix 2-I,** Surface Water Depletion and GDE Methodology and Analysis. The steps above reduce the original NCCAG dataset of iGDEs from an area of 1,457 acres to 1,212 acres of GDEs, a reduction of 17%.

Identified GDEs were then prioritized for future monitoring using two vegetation metrics available at the GDE Pulse web application developed by TNC; Normalized Derived Vegetation Index (NDVI) that indicates vegetation greenness and Normalized Derived Moisture Index (NDMI) that indicates vegetation moisture (Klausmeyer et al., 2019). An annual NDVI value based on summer conditions was assigned to each individual GDE. Then a linear regression was performed to determine the trend of NDVI values between 1990 and 2018 (representative base period of this GSP). A negative trend of NDVI indicates a decrease in vegetation greenness during this period. GDEs with negative NDVI trends were classified as high priority (trend less than -0.1) and low priority (trend between -0.1 and zero) for future monitoring. High priority GDEs cover an area of about 72 acres within the Subbasin (**Figure 2-53**). In the future, low priority GDEs will be observed outside of the established monitoring program and may be reclassified as high priority depending on future conditions.

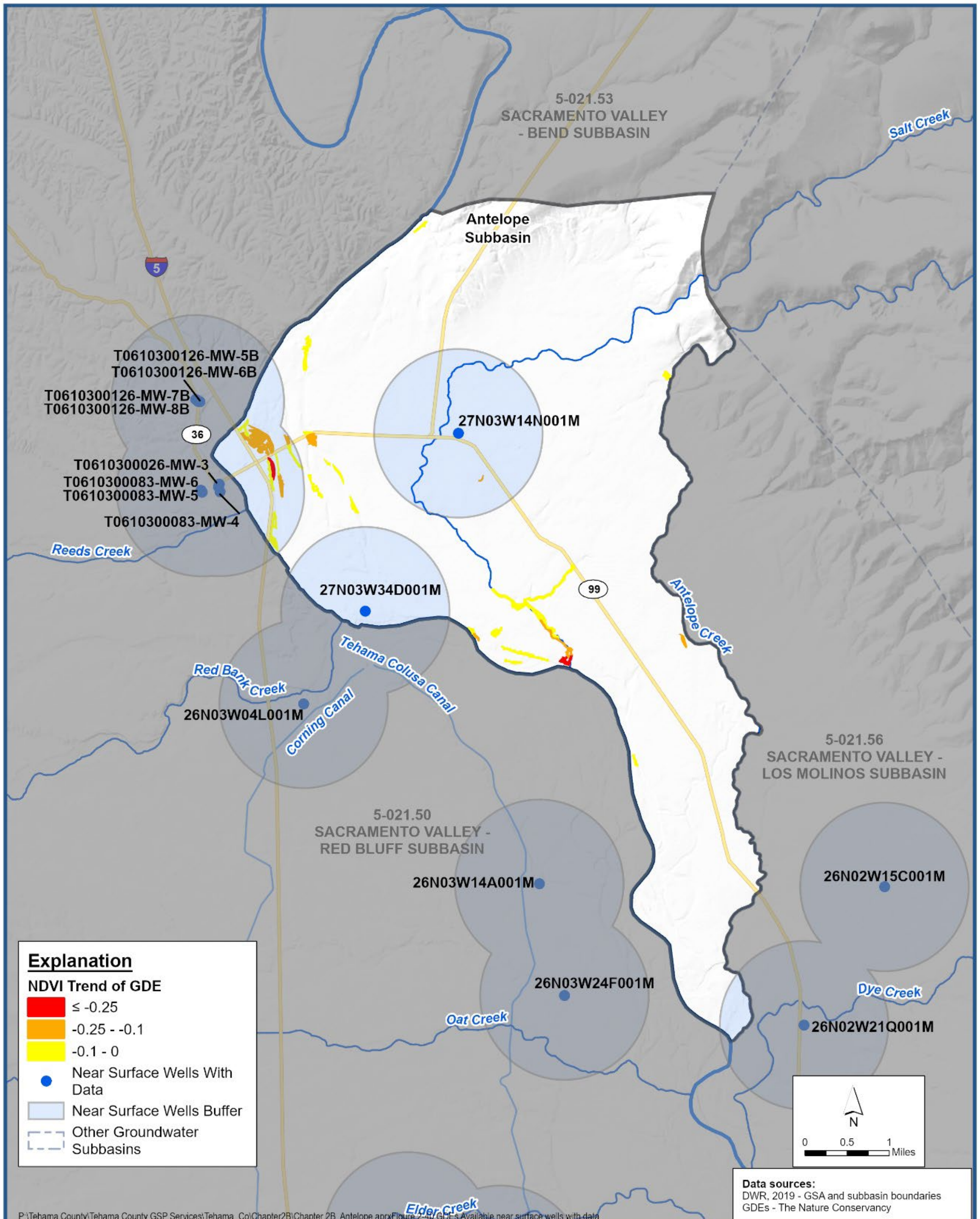
High priority GDEs were further evaluated to determine if temporal changes of vegetation metrics and local groundwater levels were correlated. Identifying such correlations would be useful to establish groundwater levels that can sustain GDEs. Only wells that were perforated within the top 100 feet below ground surface (near surface wells) and located within approximately one mile from the GDEs were included in this analysis. Vegetation metrics of high priority GDEs and groundwater levels of 12 wells that met above criteria (**Figure 2-53**) were analyzed, but 11 of these wells did not have sufficient water level data to identify correlations. Water levels of the other well (T0610300026 MW-3 in **Figure 2-53**) and vegetation metrics of an adjacent GDE had a poor (insignificant) correlation (**Figure 2-54**). It was found that negative NDVI trends of approximately 50 acres of “high priority” GDEs close to the Red Bluff Diversion Dam was primarily caused by the draining of Lake Red Bluff in 2011. Considering the lack of groundwater level monitoring close to high priority GDEs at present, installation of shallow groundwater monitoring wells near or within these GDEs is recommended.



Surface Water and Shallow Groundwater Monitoring Stations

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-52



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NDVI of GDEs

Groundwater Sustainability Plan
Antelope Subbasin

Figure 2-53

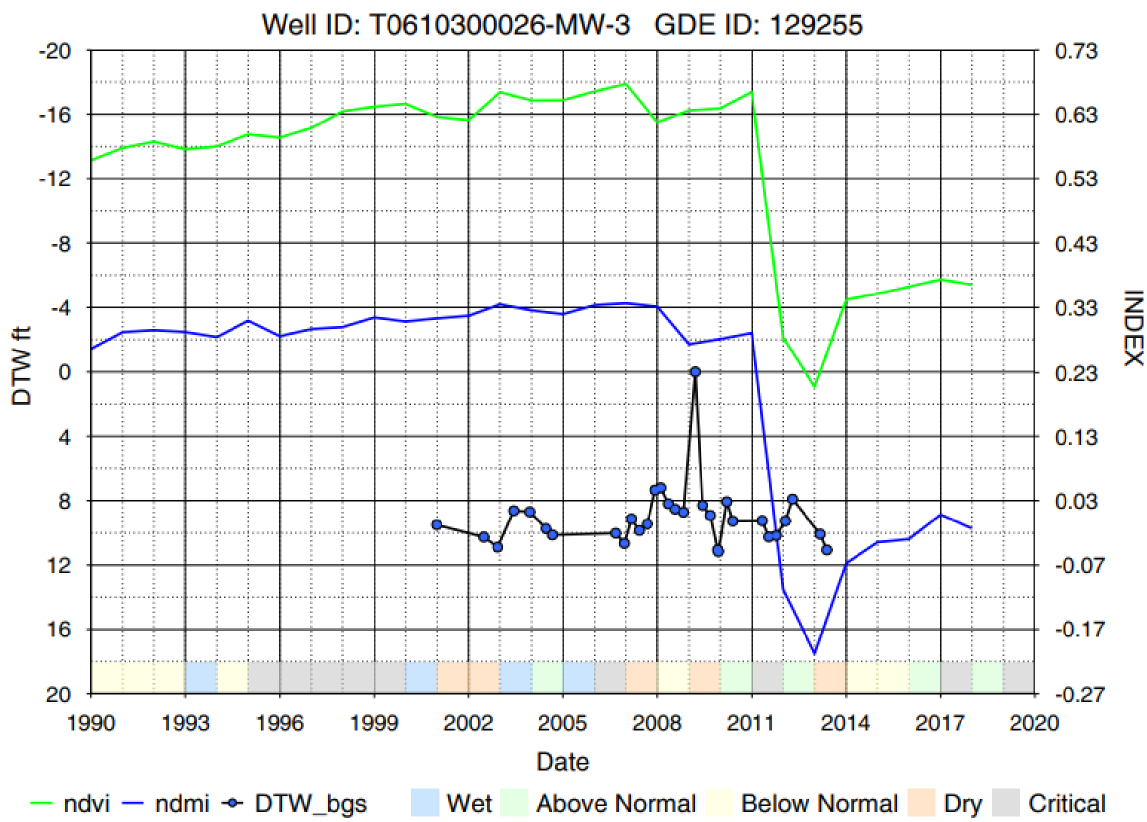

Figure 2-54. Timeseries graph of NDVI and NDMI of a GDE and depth to water at an adjacent well

2.2.3 Basin Setting Summary

In the Antelope Subbasin, water generally flows in a west to southwestern direction with downward vertical movement in the Upper Aquifer driven by natural recharge. Water typically follows topography flowing from high elevation areas in the east toward low elevations near Sacramento River in the west. Recharge contributions to the deeper geologic formations occurs on the eastern side of the Subbasin where the formations outcrop at the surface. Aquifer recharge also generally occurs along the Sacramento River and perennial streams where saturated hydraulic conductivity of soils is high. Proximal to these surface water features groundwater likely flows outward when groundwater elevations are lower (losing conditions). Discharge from the groundwater also occurs in these areas when the water table rises to the ground surface elevation (gaining conditions). The larger source of discharge is likely from production of water wells. A portion of applied water (irrigation) also contributes to recharge.

There is a two-aquifer system in the Subbasin with unconfined to semi-confined conditions in the Upper Aquifer and semi-confined to confined conditions in the Lower Aquifer. Nitrate contamination from sewage disposal systems and agricultural fertilizer are a concern in the northwestern area of the Subbasin. In the northcentral portion of the Subbasin, elevated boron levels have been observed, sourced from the marine cretaceous sedimentary rocks. These chemical sources dilute with groundwater and likely decrease with vertical and horizontal distance.

The concepts discussed in Chapter 2.2 will be further discussed and refined in Chapter 2.3, the Water Budget. Chapter 2.2 provided basic concepts needed to understand the geometry of the Subbasin, distribution and character of water bearing material, distribution and movement of groundwater and surface water, and historic and current groundwater conditions including water quality. Basic physical Properties of the Subbasin include:

- The Antelope Subbasin is bounded to the north by the low permeability mud flow deposits of the Tuscan Formation, to the west and southwest by the Sacramento River, to the southeast and east by Antelope Creek, and to the northeast and east by the Cascade Range Geologic Province.
- Fresh water occurs as groundwater to a maximum depth of over -2,000 ft msl in the west of the Subbasin.
- The bottom of the Subbasin is defined as the base of the post-Eocene continental deposits.
- The more recent geologic history is dominated by fluvial and alluvial deposition.
- The major water bearing formations are the Tuscan and Tehama Formations with some contribution from the shallower Quaternary sedimentary deposits.
- The ground surface generally slopes from the east to west with steeper slopes in the northeast of the Subbasin.
- Antelope Subbasin has little to no reported evidence of subsidence, with recent rates of 0.018 feet/year or less.

Based on available data, a two-aquifer system is defined in the Subbasin. Groundwater conditions in the Subbasin include:

- The Upper Aquifer is defined as model layers 1-5 (approximately 350-450 ft bgs) and the Lower Aquifer is defined as model layers 6-9. The model layers will be further discussed in section 2.3.
- Recharge of the Subbasin primarily occurs from the flow of the Sacramento River, Antelope Creek, Salt Creek, and other streams.
- Subsurface geologic formations can be recharged directly where they outcrop in the east.
- Groundwater contour maps of the Upper aquifer indicate a southwesterly general flow from the elevated areas of the valley towards the Sacramento River in the valley floor.
- Horizontal groundwater gradient magnitude ranges from 2 ft/mile to 13 ft/mile.

- In general, depth to water and magnitude of seasonal fluctuations decreases towards the south and southwest side of the Subbasin.
- Seasonal high-water levels during wet periods ranged between about 10 and 45 ft bgs.
- During seasonal low conditions of a wet year, groundwater elevations in the western area decrease by over 10 ft, but the decrease in the northern and southern areas is about 5 ft.
- Dry year to a wet year comparison indicates groundwater elevations are about 10 ft deeper in the west side of the Subbasin, however, the elevation decreases in other areas is less than 10 ft.
- Sufficient data are not available to quantify vertical hydraulic gradients within each primary aquifer, or between the two primary aquifers. However, available data indicate that it is consistently downward in the Upper Aquifer.
- Wells with long-term water level data show a general trend of decreasing groundwater levels over time (1990 to 2018) with rates up to about 0.30 ft/year in the western and northwestern areas of the Subbasin and less than 0.05 ft/year in the southern areas of the Subbasin.
- At present, groundwater quality is good with few exceptions most notably undesirable concentrations of nitrate in some areas of the Subbasin, which can be a health concern for very young children.

2.2.4 References

Bailey EH, MC Blake, and DL Jones. 1970. "On-land Mesozoic oceanic crust in California coast ranges." U.S. Geological Survey Professional Paper 700-C:C70-C81. https://books.google.com/books?hl=en&lr=&id=mwQlAQAAIAAJ&oi=fnd&pg=SL3-PA70&dq=Onland+Mesozoic+oceanic+crust+in+California+coast+ranges&ots=KFmxOU0dfe&si=-6g6JwC7hGvNlZKexz7JHPzC8A#v=onepage&q=Onland%20Mesozoic%20oceanic%20crust%20in%20California%20coast%20ranges&f=false

Bertucci PF. 1983. Petrology and provenance of the Stony Creek Formation, northwestern Sacramento Valley, California. Concord, CA: Chevron U.S.A. Exploration Department. 1-22 http://archives.datapages.com/data/pac_sepm/048/048001/pdfs/1.htm

Blake MC, DS Harwood, EJ Helley, WP Irwin, AS Jayko, and DL Jones.1999. "Geologic Map of the Red Bluff 30' X 60' Quadrangle, California." U.S. Geological Survey Miscellaneous Investigations Series Map I-2542, scale 1:100000.https://pubs.usgs.gov/imap/2542/

Brown and Caldwell, 2013. Lower Tuscan Aquifer Monitoring, Recharge, and Data Management Project https://www.buttecounty.net/Portals/26/Tuscan/LTAFinalReport.pdf

California Department of Fish and Wildlife, 2015, Biographic Information and Observation System https://wildlife.ca.gov/Data/BIOS

California Department of Water Resources, 1987, Antelope Groundwater Study

California Department of Water Resources, 2003, Tehama County Groundwater Inventory, Pre-Publication Draft

California Department of Water Resources, 2004, Sacramento Valley Groundwater Basin, Antelope Subbasin, California's Groundwater, Bulletin 118. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Bulletin-118/Files/2003-Basin-Descriptions/5_021_54_AntelopeSubbasin.pdf

California Department of Water Resources, 2008, Lower Mill Creek Watershed Project Conjunctive Use Study. https://cawaterlibrary.net/wpcontent/uploads/2017/11/lower_mill_creek_watershed_conjunctive_use_project__2008_.pdf

California Department of Water Resources, 2014, Geology of the Northern Sacramento Valley. https://cawaterlibrary.net/wp-content/uploads/2017/05/Geology-of-the-Northern-Sacramento-Valley.pdf

California Department of Water Resources, 2017, GPS Survey of the Sacramento Valley Subsidence Network.http://www.yolowra.org/documents/2017_GPS_Survey_of_the_Sacramento_Valley_Subsidence_Network.pdf

California Geological Survey. 2002. "California Geomorphic Provinces." Note 36. 4 pp. https://www.contracosta.ca.gov/DocumentCenter/View/34134/CGS-2002-California-Geomorphic-ProvincesNote-36-PDF

Clynne, M.A., and Muffler, L.J.P., Geologic map of Lassen Volcanic National Park and vicinity, California: U.S. Geological Survey Scientific Investigations Map 2899, scale 1:50,000. https://pubs.usgs.gov/sim/2899/

Dickinson WR and EI Rich. 1972. Petrologic intervals and petrofabrics in the Great Valley sequence, Sacramento Valley, California. Geological Society of America bulletin 83(10):3007-3024. https://pubs.geoscienceworld.org/gsa/gsabulletin/article-abstract/83/10/3007/7369/Petrologic-Intervals-and-Petrofacies-in-the-Great?redirectedFrom=fulltext

Ely, K.E., 1994, An Evaluation of Aquifer Characteristics Within The Tuscan Formation, Northeastern Sacramento Valley, Tehama County, California [Master's Thesis]: CSU, Chico, 292 p. Garrison, Lowell E. "The Marysville (Sutter) Buttes." *Sutter County, California: California Division of Mines and Geology Bulletin* 181 (1962): 69-72. http://pubs.geothermal-library.org/lib/grc/1021051.pdf

Gonzalez, M., 2014, Stratal Geometries of Tuscan Deposits In Big Chico Creek Canyon Outcrops And In The Subsurface Underlying Chico, California [Master's Thesis]: CSU, Chico, 125 p. https://www.csuchico.edu/bccer/_assets/documents/research-docs/tuscan-geology-11-30-2014-marisol-gonzalez.pdf

Harrison, K., 1991, Mill Creek Project, Test Well Installation Draft Report, Northern District, 29 p.

Harwood DS, EJ Helley, and MP Doukas. 1981. "Geologic Map of the Chico Monocline and Northeastern Part of the Sacramento Valley, California." U.S. Geological Survey Miscellaneous Investigations Series Map I-1238, scale 1:62,500. https://pubs.er.usgs.gov/publication/i1238

Helley, E., and Harwood, D., 1985, Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1790: 24 pp., 5 sheets, scale 1:62,500. https://pubs.er.usgs.gov/publication/mf1790

Helley EJ and C Jaworowski. 1985. The Red Bluff pediment, a datum plane for locating Quaternary structures in the Sacramento Valley, California. Washington, DC: U.S. Government Printing Office. U.S. Geological Survey Bulletin 1628: 13 pp. https://pubs.usgs.gov/bul/1628/report.pdf

Ingersoll RV and WR Dickinson. 1981. “Great Valley Group (Sequence), Sacramento Valley, California,” in V Frizzell, ed., Upper Mesozoic Franciscan rocks and Great Valley Sequence, Central Coast ranges, California. Society of Economic Paleontologists and Minerologists, Pacific Section, Los Angeles, CA: p. 1-33. http://archives.datapages.com/data/pac_sepm/033/033001/pdfs/1.htm

Klausmeyer, K., Howard J., Keeler-Wolf T., Davis-Fadtke K., Hull R., and Lyons A. 2018. Mapping Indicators of Groundwater dependent ecosystems in California

Klausmeyer, Kirk R., Tanushree Biswas, Melissa M. Rohde, Falk Schuetzenmeister, Nathaniel Rindlaub, Ian Housman, and Jeanette K. Howard. 2019. GDE Pulse: Taking the Pulse of Groundwater Dependent Ecosystems with Satellite Data. San Francisco, California. Available at https://gde.codefornature.org.

Lydon, Philip A. "Geology and lahars of the Tuscan Formation, northern California." *Geological Society of America Memoir* 116 (1968): 441-475. https://pubs.geoscienceworld.org/books/book/128/chapter/3789088/Geology-and-Lahars-of-the-Tuscan-Formation

Mansfield CF. 1979. “Upper Mesozoic subsea fan deposits in the southern Diablo Range, California: Record of the Sierra Nevada magmatic arc.” Geologic Society of America Bulletin 90(11) (November):1025-1046. https://pubs.geoscienceworld.org/gsa/gsabulletin/article-abstract/90/11/1025/189567/Upper-Mesozoic-subsea-fan-deposits-in-the-southern?redirectedFrom=fulltext

Marchand DE and A Allwardt. 1981. Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California. Washington: U.S. Government Printing Office. U.S. Geological Survey Bulletin 1470:1- 70. https://pubs.er.usgs.gov/publication/b1470

O'Geen, A., Saal, M., Dahlke, H., Doll, D., Elkins, R., Fulton, A., Fogg, G., Harter, T., Hopmans, J., Ingels, C., Niederholzer, F., Sandoval, S., Verdegaal, P., and Walkinshaw, M., 2015, Soil suitability index identifies potential areas for groundwater banking on agricultural lands, California Agriculture, 69(2):75-84. http://calag.ucanr.edu/Archive/?article=ca.v069n02p75

Ojakangas RW. 1968. “Cretaceous Sedimentation, Sacramento Valley, California.” Geological Society of America Bulletin 79(8):973-1008. https://pubs.geoscienceworld.org/gsa/gsabulletin/article-abstract/79/8/973/6386/Cretaceous-Sedimentation-Sacramento-Valley?redirectedFrom=fulltext

Olmstead, F. H., and Davis, G. H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U.S. Geological Survey Water Supply Paper 1497, 241 p. https://pubs.usgs.gov/wsp/1497/report.pdf

Page, R.W., United States Geological Survey, 1974, Base and Thickness of the Post-Eocene Continental Deposits in the Sacramento Valley, California. https://pubs.usgs.gov/wri/1973/0045/report.pdf

Redwine LE. 1972. "The Tertiary Princeton submarine valley system beneath the Sacramento Valley, California." University of California, Los Angeles, unpublished Ph.D. thesis. 480 pp. http://archives.datapages.com/data/pacific/data/069/069001/53_ps0690053.htm

Soil Science Division Staff. 2017. Soil survey manual. C. Ditzler, K. Scheffe, and H.C. Monger (eds.). USDA Handbook 18. Government Printing Office, Washington, D.C. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/scientists/?cid=nrcs142p2_054262

Tehama County Flood Control and Water Conservation District, 2012. Coordinated AB 3030 Groundwater Management Plan 2012. https://tehamacountywater.org/wp-content/uploads/2020/09/ab3030-groundwater-management-plan.pdf

The Nature Conservancy (TNC). 2021. Interconnected Surface Water in California's Central Valley, Version 1.0.1. https://icons.codefornature.org/

The U.S. Geological Survey's National Water Information System (USGS NWIS) stream flow data (accessed in January 2021)
USGS/USBR station #11377100 Sacramento River at Bend Bridge (BND):
https://waterdata.usgs.gov/nwis/inventory/?site_no=11377100&agency_cd=USGS
USGS station #11379000 Antelope Creek near Red Bluff:
https://waterdata.usgs.gov/nwis/inventory/?site_no=11379000&agency_cd=USGS