CHAPTER 3
Basin Setting

3.1 HYDROGEOLOGIC CONCEPTUAL MODEL *(REG. § 354.14)*

This section describes the HCM of the Colusa Subbasin. The HCM supports development and implementation of a GSP pursuant to the requirements of the Sustainable Groundwater Management Act of 2014 (SGMA). This section was prepared through a coordinated effort between the GSAs responsible for managing the Colusa Subbasin: the Colusa Groundwater Authority and the Glenn Groundwater Authority.

3.1.1 Regulatory Requirements

Title 23 Section 354.14 of the CCR (23 CCR §354.14) requires that each GSP "shall include a descriptive hydrogeologic conceptual model of the basin based on technical studies and qualified maps that characterizes the physical components and interaction of the surface water and groundwater systems in the basin" and shall include written descriptions for the following HCM components:

- Regional geology and structure (Section 3.1.7)
- Lateral basin boundaries (Section 3.1.8.1)
- Definable bottom of the basin (Section 3.1.8.2)
- Principal aquifers and aquitards, including formation names, vertical and lateral extent, aquifer properties, restrictions to flow, water quality, and primary uses (Section 3.1.10)
- Any data gaps and uncertainties identified in the previously listed topics (Section 3.1.12)

In accordance with 23 CCR §354.14, the HCM shall also include maps of each of the following physical components of the HCM. All maps shall be informative, labeled, and include the datum (23 CCR §352.4(d)). Information regarding key data sources is also included on each of the maps.

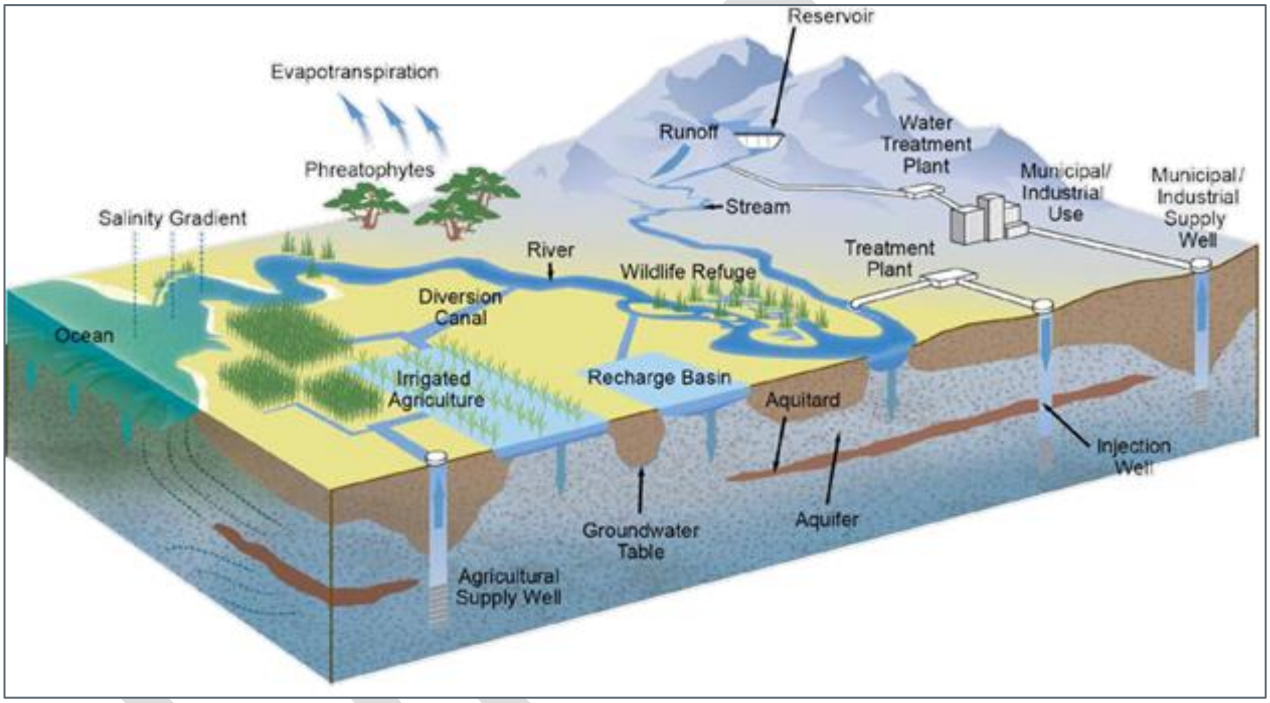
- Topography
- Surface geology and a minimum of two cross sections
- Soil properties
- Recharge and discharge areas
- Surface water features
- Sources and points of delivery of imported water

This report addresses these requirements using currently available data and information in accordance with the DWR BMPs for the Sustainable Management of Groundwater: Hydrogeologic Conceptual Model BMP (DWR, 2016). Additionally, components of this HCM have been compared to and updated based on information included in the California Central Valley Groundwater-Surface Water Simulation Model – Fine Grid (C2VSimFG), the selected integrated hydrologic model (IHM) chosen to support the Colusa Subbasin GSAs. This section provides a comparison of the HCM and IHM. Data gaps, uncertainties, and recommended actions are also presented in this section (Section 3.1.12).

3.1.2 Background Information

The HCM provides the general understanding of the hydrogeologic physical setting, characteristics, and processes that occur within the Colusa Subbasin and provides the foundation upon which the IHM and components of the water budget are based.

Figure 3-1 depicts a generalized HCM (DWR, 2016). The main components of the HCM include surficial and subsurface features. Surficial features include topography, hydrology, water supply features, land use, soil types, and geologic outcrops. Subsurface features of the HCM include geologic formations and structures and the presence and characteristics of aquifers and aquitards. These HCM components, except for land use, are discussed in this report section. Land use is discussed in both the Plan Area and Water Budget sections of the GSP.



Reference: California Department of Water Resources, 2016, Best Management Practices for the Sustainability Management of Groundwater: Hydrogeologic Conceptual Model: California Department of Water Resources, December 2016.

Figure 3-1. Hydrogeologic Conceptual Model Representation

The Colusa Subbasin HCM was developed using information provided in a variety of existing studies, dissertations, reports, and datasets. Table 3-1 and Section 3.5 document the data sources and references used to develop the HCM.

Table 3-1. Hydrogeologic Data Sources

File Content	File Format	Responsible Agency	Source Reference	Website
Base of Fresh Water	PDF	USGS	Olmsted, F.H. and Davis, G.H., 1961, Geologic Features and Ground-Water Storage Capacity of the Sacramento Valley, California: U.S. Geological Survey in cooperation with the California Department of Water Resources Water Supply Paper WSP-1497, plate 5.	https://pubs.er.usgs.gov/
Bulletin 118 Groundwater Basin	GIS Shapefile	DWR	DWR, 2019, Bulletin 118 Basin Boundary GIS Data, v.6.1: California Department of Water Resources (DWR).	https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118
Elevation DEM	GIS Raster	USGS	USGS, 2016, 1/3 arc-second National Elevation Dataset (NED) Digital Elevation Model (DEM): U.S. Geological Survey (USGS), 1x1-degree tiles N39W122, N39W123, N40W122, N40W123, downloaded 2016.	http://viewer.nationalmap.gov/
Geologic Structural Contours	PDF	USGS	Harwood, D.S. and Helley, E.J., 1987, Late Cenozoic Tectonism of the Sacramento Valley, California: U.S. Geological Survey Professional Paper PP-1359, plate 1.	https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
Geology	PDF	DWR	DWR, 2014, Geology of the Northern Sacramento Valley: prepared by the California Department of Water Resources Northern Region Office, Groundwater and Geologic Investigations Section.	https://www.water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Regional-Reports/Geology-of-the-Northern-Sacramento-Valley-California-June-2014.pdf
Geology	GIS Geodatabase	USGS	Helley, E.J. and Harwood, D.S., 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, scale 1:62,500.	Not Available Online
Geology	PDF	CGS(a)	Jennings, C.W. and Strand, R.G., 1960, Geologic Map of California, Olaf P. Jenkins edition, Ukiah Sheet: Department of Natural Resources Division of Mines and Geology (CDMG) Geologic Atlas Map GAM-24, third printing 1992, scale 1:250,000.	https://maps.conservation.ca.gov/cgs/publications/
Geology	PDF	CGS	Koenig, J.B., 1963, Geologic Map of California, Olaf P. Jenkins edition, Santa Rosa Sheet: California Department of Natural Resources Division of Mines and Geology Geologic Atlas Map GAM-22, scale 1:250,000.	https://maps.conservation.ca.gov/cgs/publications/
Geology	GIS Shapefile; PDF	DWR	DWR, 2009, Glenn-Colusa Irrigation District Test-Production Well Installation and Aquifer Testing: prepared by the California Department of Water Resources Northern District Groundwater Section in cooperation with Glenn-Colusa Irrigation District, March 2009, GIS shapefiles provided by DWR 2008.	http://wdl.water.ca.gov/pubs/geology/glenn-colusa_irrigation_district_test-production_well_installation_and_aquifer_testing__2009_/glenn-colusa_irrigation_district_test-production_well_installation_and_aquifer_testing__2009_.pdf
Groundwater Dependent Ecosystems	GIS Geodatabase; PDF	TNC	DWR, 2018, Summary of the "Natural Communities Commonly Associated with Groundwater" Dataset and Online Web Viewer: California Department of Water Resources, April 2018.	https://data.cnra.ca.gov/dataset/natural-communities-commonly-associated-with-groundwater
Hydrography - Hydrology and Watersheds	GIS Geodatabase	USGS	USGS, 2016, USGS National Hydrography Dataset (NHD) Downloadable Data Collection: U.S. Geological Survey National Geospatial Technical Operations Center (NGTOC), Region 1802.	http://viewer.nationalmap.gov/
Natural Communities Commonly Associated with Groundwater	GIS Shapefile	DWR	DWR, 2020, Natural Communities Commonly Associated with Groundwater (NCCAG) Dataset: California Department of Water Resources, California Department of Fish and Wildlife, and The Nature Conservancy.	https://gis.water.ca.gov/app/NCDatasetViewer/#
Soil Suitability for Recharge	GIS Shapefile	UCD &UC-ANR	University of California Davis (UCD) California Soil Resource Lab and University of California Division of Agriculture and Natural Resources (UC-ANR), 2017, Soil Agricultural Groundwater Banking Index (SAGBI), GIS shapefiles received 2017. O'Geen, A.T. et al, 2015, Soil Suitability Index Identifies Potential Areas for Groundwater Banking on Agricultural Lands: California Agriculture, Volume 69, Number 2, pp 75-84, April 2015.	https://casoilresource.lawr.ucdavis.edu/sagbi/
Soils	GIS Shapefile; Access Database	NRCS	NRCS, 2013 & 2017, Soil Survey Geographic Database (SSURGO): Natural Resources Conservation Service (NRCS) Web Soil Survey (WSS), Colusa County (CA011), Spatial Data V3 (2013), Tabular Data V11 (2017).	http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx
Soils	GIS Shapefile; Access Database	NRCS	NRCS, 2014 & 2017, Soil Survey Geographic Database (SSURGO): Natural Resources Conservation Service Web Soil Survey, Glenn County (CA021), Spatial Data V5 (2014), Tabular Data V12 (2017).	http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx
Soils	GIS Map Package	ESRI	ESRI, 2017, NRCS Compiled 2017 SSURGO Downloader: Environmental Systems Research Institute (ESRI), Big Chico Creek - Sacramento River, Butte Creek, Honcut Headwaters - Lower Feather, Sacramento - Stone Corral, Upper Cache, and Upper Stony watersheds.	http://esri.maps.arcgis.com/apps/View/index.html?appid=cdc49bd63ea54dd2977f3f2853e07fff
Stream Gauge and Reservoir Stations	Tabular	CDEC	DWR, 2017, California Data Exchange Center (CDEC): California Department of Water Resources, downloaded 2017.	http://cdec.water.ca.gov/index.html
Stream Gauges	Tabular	USGS	USGS, 2017, National Water Information System (NWIS) - Web Interface: U.S. Geological Survey, downloaded 2017.	https://waterdata.usgs.gov/nwis
Wetlands	GIS Geodatabase	FWS	U.S. Department of the Interior, 2014, Classification of Wetlands and Deepwater Habitats of the United States: U.S. Department of the Interior (USDI) Fish and Wildlife Service (FWS), Washington D.C., FWS/OBS-79-31.	https://www.fws.gov/wetlands/data/data-download.html

(a) California Division of Mines and Geology is now the California Geological Survey.

3.1.3 Climate and Precipitation

The Colusa Subbasin has a Mediterranean climate with cool, wet winters and hot, dry summers. Regionally, temperature and precipitation vary with elevation, with the lower temperatures and higher precipitation typically occurring at higher elevations. The region is subject to wide variations in annual precipitation, and experiences periodic dry periods. Summers can be hot at times with periods of 100-degree Fahrenheit temperatures.

Based on the historical data obtained from Western Regional Climate Center (WRCC) National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Network (COOP) stations in Colusa (Station 041948) and Orland (Station 046506), the recorded average monthly temperatures within the subbasin range from 46 to 80 degrees Fahrenheit, but the extreme low and high daily temperatures have been 15 and 120 degrees Fahrenheit, respectively (WRCC, 2020).

The average annual precipitation varies from about 21 inches in the northern portion of the subbasin to about 15 inches in the south. Due to the variable topographic relief of the subbasin, temperature and precipitation can vary greatly with location.

The Colusa station has recorded precipitation for water years 1949 through 2019 and the Orland station for 1905 through 2019. The water year starts October 1, ends on September 30, and is denoted by the calendar year of its end date. Figure 3-2 shows the annual water year precipitation measured at Colusa and Orland for water years 1949 through 2020. Water years missing more than 30 days of data during the rainy season were considered incomplete and were not included in this evaluation. The rainy season is interpreted to be October through April (Figure 3-2). Data was incomplete for water years 1952-1953, 1974, 1982, 1993-1998, and 2011-2013 at Colusa and water years 1906-1907, 1910, 1914, 1916-1920, 1941, 1981, 1994, 1996, and 2011-2012 at Orland. Historical precipitation shown on Figure 3-2 for these years is the minimum precipitation measured for the water year.

Multiple-year dry periods experienced in the Colusa Subbasin roughly correspond with state-wide multiple-year droughts. Multiple-year dry periods recorded within the Colusa Subbasin area include:

- 1949-1950
- 1954-1955
- 1959-1962
- 1964-1966
- 1971-1972
- 1976-1977
- 1987-1991
- 2007-2009
- 2012-2016

Figure 3-3 shows the exceedance curves for the Colusa and Orland precipitation data. The entire period of record except for water years with incomplete data was used for each station's exceedance curve. The figure shows the frequency at which a given level of annual precipitation was met or exceeded. The curve can be used to gauge how frequently the precipitation recorded in any given year was equaled or exceeded in the past. For example, the minimum historical precipitation of 8.15 inches recorded in Orland occurred in 1924 and was met or exceeded in 100 percent of years throughout Orland's period of record. Similarly, 90 percent of water years over Orland's period of record met or exceeded the 11.5 inches of precipitation measured in 2014.

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Figure 3-2. Historical Precipitation

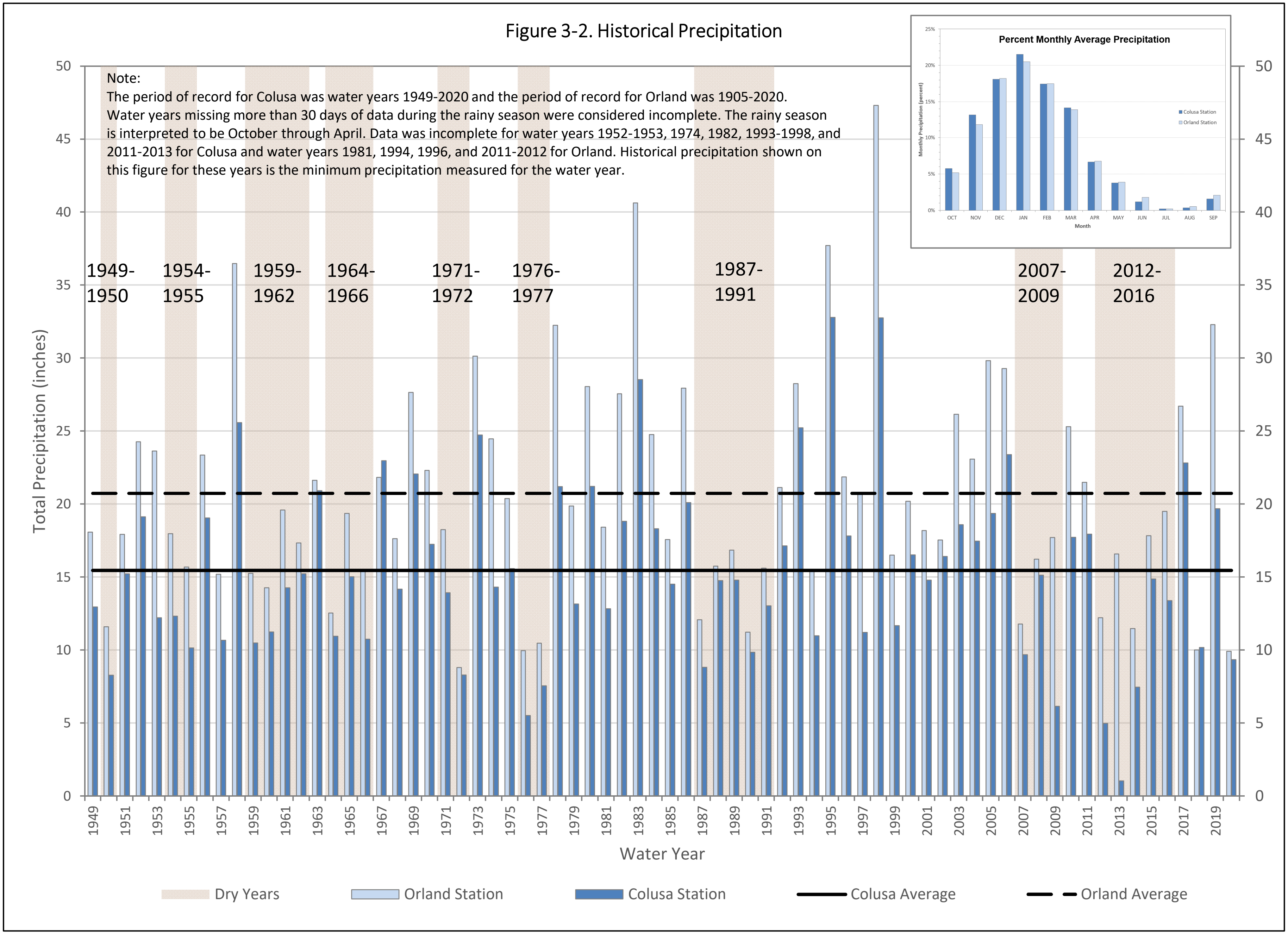

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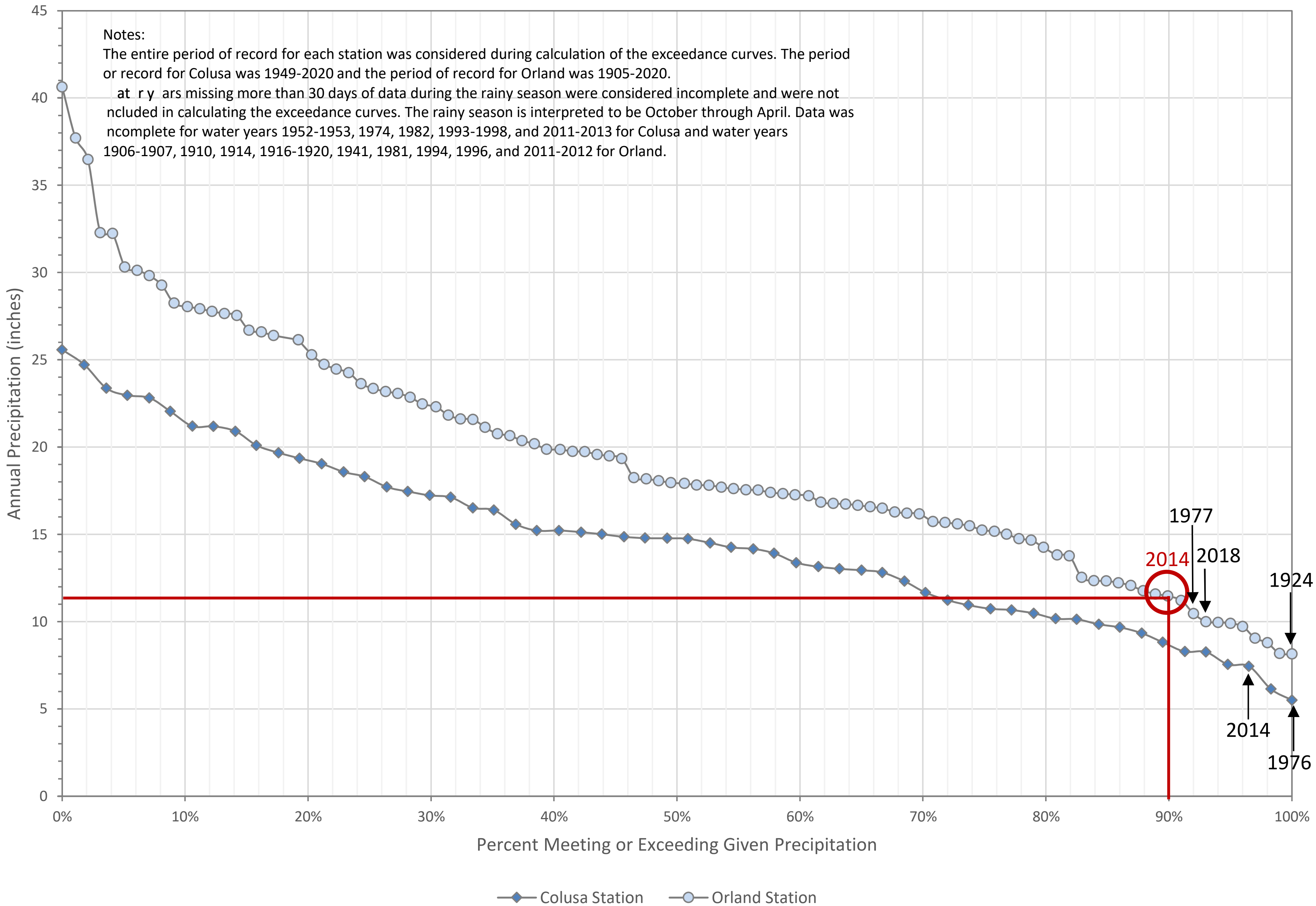
Figure 3-3. Precipitation Exceedance Curve



3.1.4 Topography

Figure 3-4 shows the topography of the Colusa Subbasin. The topography throughout the subbasin encourages drainage east towards the Sacramento River and south towards the San Joaquin Sacramento- River Delta (Delta). The western side of the subbasin is elevated and includes low foothills that transition to the higher elevation Coast Range. Streams from the Coast Range drain eastward through low alluvial plains towards Sacramento River flood basins.

Elevations greater than 1,000 feet North American Vertical Datum of 1988 (NAVD 88) occur within the northwestern and the southwestern portion of the subbasin. These areas of high terrain are associated with the foothills near Black Butte Lake and the northernmost extent of the Capay Hills. Minimum land surface elevations of less than 30 feet NAVD 88 occur in the southern portion of the subbasin between the Colusa Basin Drain and the Sacramento River. Land surface elevations along the Sacramento River range from about 150 feet NAVD 88 at the northeast boundary of the subbasin to about 40 feet NAVD 88 near the southeast boundary of the subbasin.

3.1.5 Hydrology

The hydrology of the Colusa Subbasin is influenced by the underlying geology, geomorphology and topography of the region and the Sacramento Valley's large agriculture industry.

The regional watersheds and natural waterways are shown on Figure 3-5. The Sacramento River is the principal stream in the subbasin and contributes significantly to the statewide water supply. Most of the streams within the region drain the Sierra Nevada to the east and the Coast Ranges to west and are tributary to the Sacramento River.

The watersheds of these tributary streams within the study area include:

- Big Chico Creek Sacramento River watershed (hydrologic unit code 08 [HUC08] 18020157), which drains into the Sacramento River at the northern boundary of the Colusa Subbasin;
- Upper Stony Creek watershed (HUC08 18020104), which drains into Stony Creek along the norther boundary of the Colusa Subbasin;
- Butte Creek watershed (HUC08 18020158), which drains into the west-central portion of the Colusa Subbasin, east of the Sacramento River;
- Honcut Headwaters – Lower Feather River watershed (HUC08 18020159), which drains into the Sacramento River south of the City of Colusa and flows along the Colusa Subbasin boundary; and
- Sacramento Stone Corral watershed (HUC08 18020104), which drains the Coast Ranges west of the Colusa Subbasin, as well as the majority of the Subbasin, itself.

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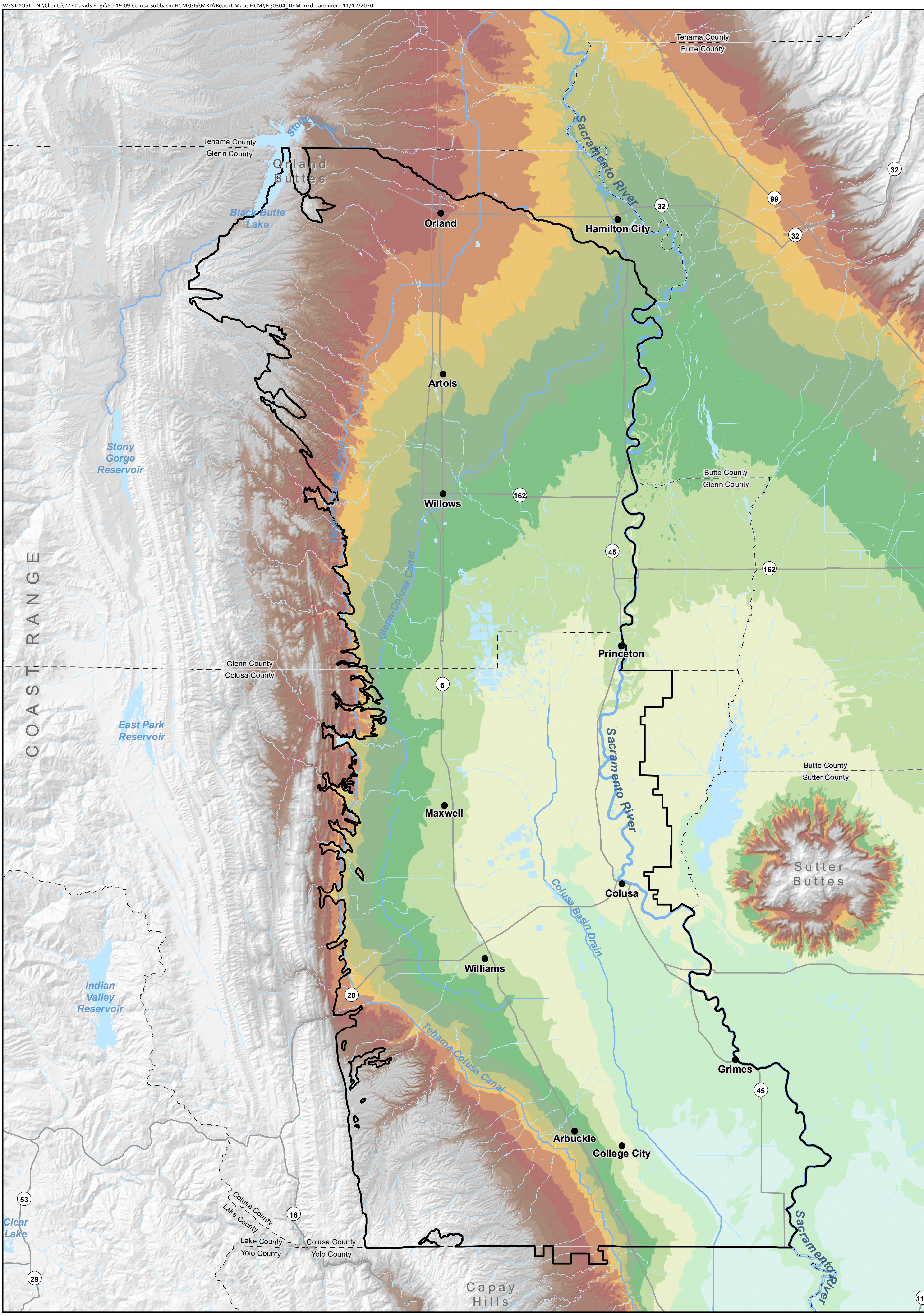

Source: USGS 1/3-arcsecond National Elevation Dataset (NED) Digital Elevation Model (DEM) N39W122, N39W123, N40W122, and N40W123.

Datums: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet. North American Vertical Datum of 1988, feet (NAVD 88).

Note:
1. Elevations greater than 1,000 ft NAVD 88 are shown as white on this map.

Colusa Subbasin

Land Surface Elevation (NAVD88, feet)

- < 30
- 30 - 50
- 50 - 75
- 75 - 100
- 100 - 125
- 125 - 150
- 150 - 175
- 175 - 200
- 200 - 250
- 250 - 300
- 300 - 350
- 350 - 400
- 400 - 450
- 450 - 500
- 500 - 750
- 750 - 1,000
- > 1,000

N

0 2.5 5
Scale in Miles

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Figure 3-4

Topography

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

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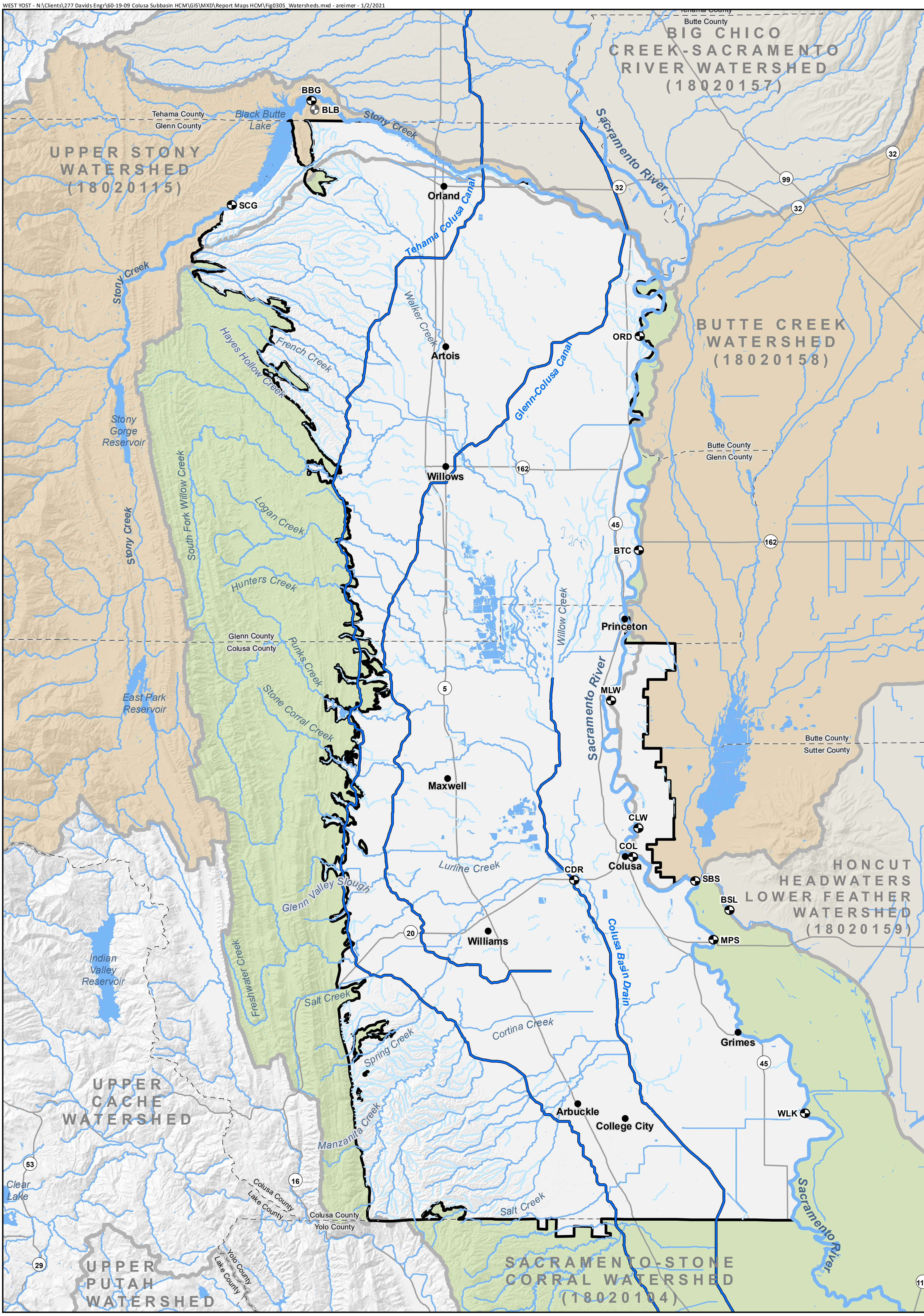

Source: Water features and watersheds boundaries are from the National Hydrography Dataset (NHD) for Region 1802. Watersheds shown are the Hydrologic Unit Code 8 watershed basins (HUC 8).

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

- Surface Water Flow Station
- Reservoir Station
- Major Waterways
- Minor Waterways
- Other Waterways
- Major Conveyance Infrastructure
- Water Bodies

- Colusa Subbasin
- Watersheds (HUC 8)

Inflow Watersheds (HUC 8)

- Big Chico Creek-Sacramento River; Honcut Headwaters-Lower Feather
- Sacramento-Stone Corral
- Butte Creek; Upper Stony Creek

N

0 2.5 5

Scale in Miles

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Figure 3-5

Watersheds and Natural Waters

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

The dominant north-northwesterly south-southeasterly structural trends in the Coast Range west of the Colusa Subbasin result in long narrow valleys and ridges. These topographic features have produced a drainage network that routes most of the Coast Range runoff to the Colusa Subbasin to Stony Creek, which flows north in the Coast Range through Stony Gorge Reservoir to Black Butte Lake before entering the Colusa Subbasin along its northern boundary and discharging into the Sacramento River. To the southwest in the Coast Range, similar geologic, geomorphic and topographic influences route most of the runoff through the Upper Cache Creek watershed in a southeasterly direction where it contributes to flows in Cache Creek. Cache Creek enters the Sacramento Valley south of the Colusa Subbasin in the Yolo Subbasin. As consequence of the dominance of the Upper Stony and Upper Cache Creek watersheds in capturing most of the runoff from the higher elevations in the Coast Range, the remainder of the other Coast Range streams influent to the subbasin have relatively small catchment areas in low elevation areas of the Coast Range. These streams are intermittent and drain the foothills that border the Coast Ranges to the west.

Canals and drains intersect streams and creeks to provide a water supply and drainage network, which is shown on Figure 3-6. Major water features and conveyance infrastructure that serve agencies within the Colusa Subbasin include the Sacramento River, Stony Creek, Black Butte Lake, the Tehama-Colusa Canal, Glenn-Colusa Canal, and the Colusa Basin Drain. The major water features and conveyance infrastructure are discussed in the following section. More detailed information regarding flows and volumes are discussed in the water budget section.

3.1.5.1 Natural Surface Waters and Conveyance Infrastructure

The major natural waterways flowing into, through, or along the boundary of the Colusa Subbasin include the Sacramento River and Stony Creek. Many smaller intermittent streams drain the foothills that abut the Coast Ranges west of the Colusa Subbasin. Three major water conveyance infrastructures also exist within the basin. These are the Tehama-Colusa Canal, the Glenn-Colusa Canal, and the Colusa Basin Drainage Canal system, otherwise known as the Colusa Basin Drain. Smaller canal and channel systems transport water between the natural waterways and conveyance infrastructure. The natural and man-made water channels within the Colusa Subbasin are interconnected. Figure 3-5 and Figure 3-6 show the surface hydrology of the Colusa Subbasin. The major waterways are discussed in the following subsections.

3.1.5.1.1 Black Butte Lake and Stony Creek

The Upper Stony Creek watershed drains an approximately 770 square mile area of the Coast Range, foothills, and uplands, most of which is situated west of the Colusa Subbasin. Stony Creek south of the Glenn-Tehama County line defines the boundary between the Colusa and Corning Subbasins. The Stony Creek headwaters are in the Coast Range terrain of western Colusa County. Stony Creek flows north toward Stony Gorge Reservoir. Water discharged from Stony Gorge Reservoir continues northeast to Black Butte Lake, where most of the drainage within the Stony Creek watershed is eventually captured. According to data listed on the CDEC website and shown on Figure 3-7, storage within Black Butte Lake has been between 1,200 af and 140,000 af since 1963. The lowest lake storage was recorded in Fall 1977, an extreme dry year. Releases from Black Butte Lake, monitored by the USBR and available on CDEC, from 1996 to 2020 fluctuated between 0 and 24,000 cubic feet per second (cfs) (CDEC, 2020). Discharges from Black Butte Lake flow into either Stony Creek or canals that irrigate agricultural lands of the Colusa and Corning Subbasins. Stony Creek eventually drains into the Sacramento River.

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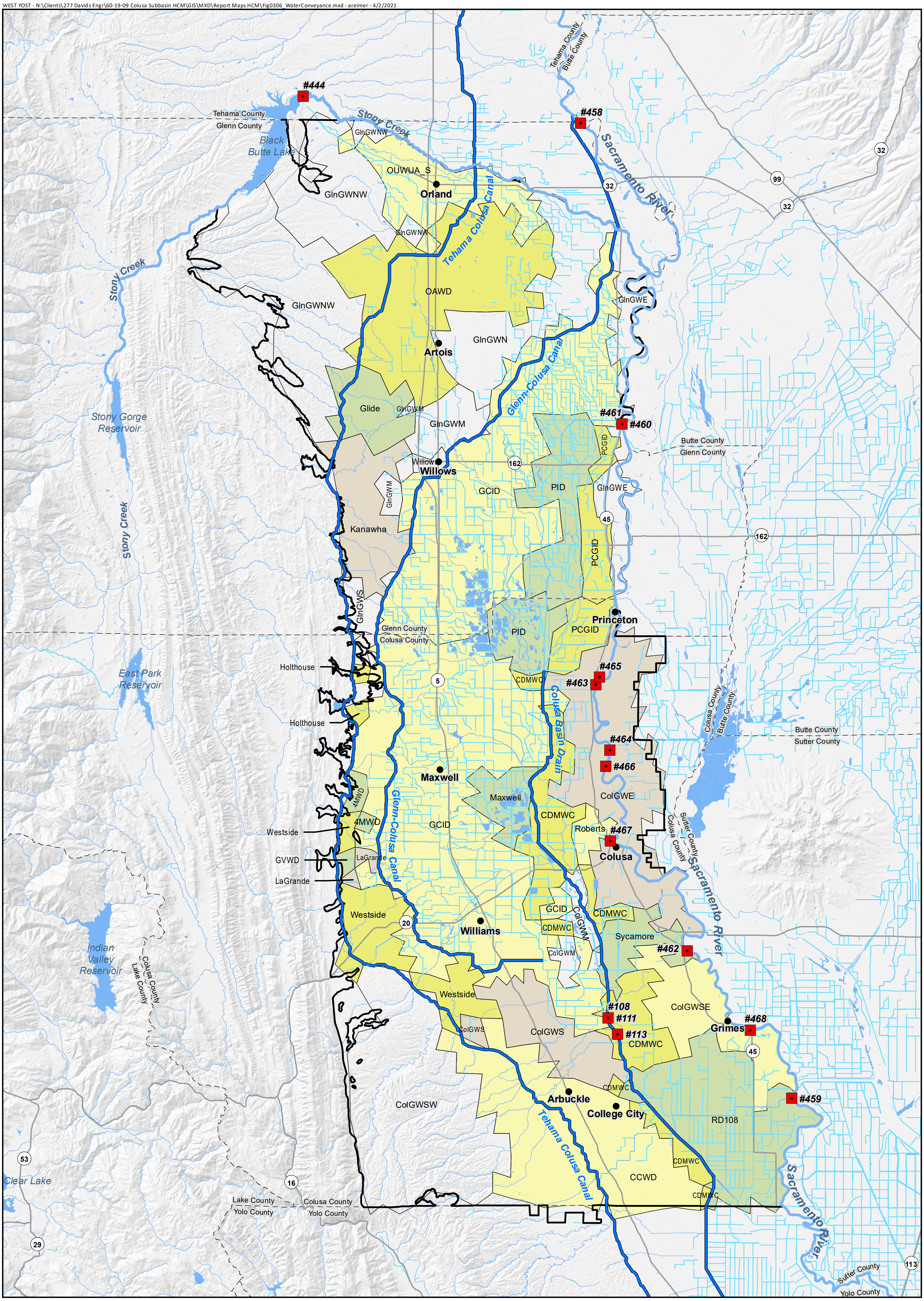

Source: Water features are from the National Hydrography Dataset (NHD) for Region 1802. Diversion points and model subareas were extracted from the C2VSimFG-Colusa hydrologic model.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Note:
1. Diversions 445 to 457 are located where the Tehama Colusa Canal diverts water from the Sacramento River and are not shown on this map.

- Major Waterways
- Minor Waterways
- Major Conveyance Infrastructure
- Other Conveyance Infrastructure
- Water Bodies
- Colusa Subbasin

- Modeled Surface Water Diversion

Modeled Subareas that Receive Diverted Water
- 4MWD, GVWD, Glide, Maxwell, PID, RD108, Sycamore
- CCWD, ColGWSE, GCID, OUWUA_S, Roberts
- CDMWC, Holthouse, OAWD, PCGID, Westside
- ColGWE, ColGWS, Kanawha, LaGrande

Subareas that Do Not Receive Delivered Water: ColGWM, ColGWSW, GlnGWE, GlnGWM, GlnGWN, GlnGWNW, GlnGWS, Willows

N

0 2.5 5
Scale in Miles

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Figure 3-6

Water Conveyance Infrastructure

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

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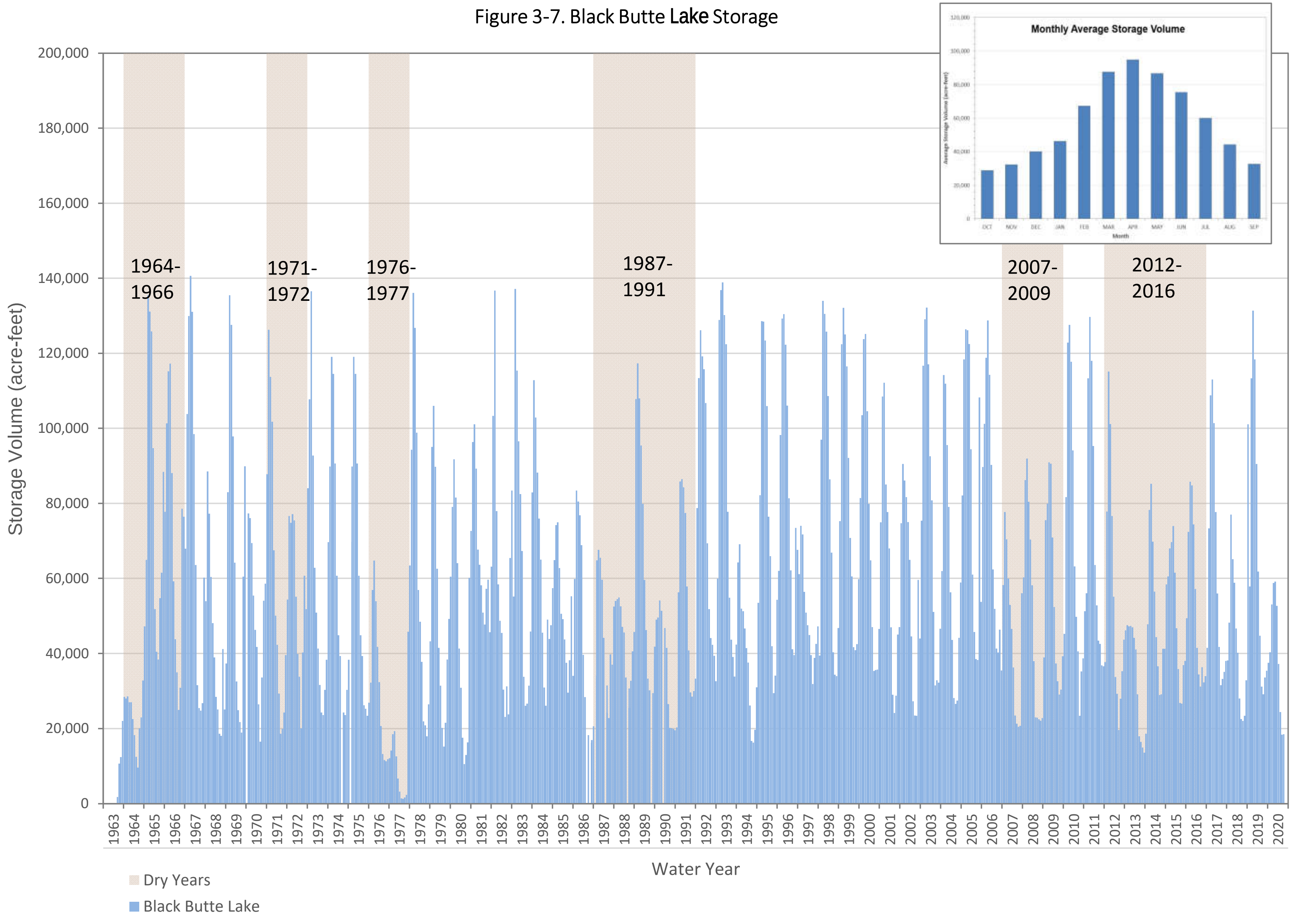
Figure 3-7. Black Butte Lake Storage



3.1.5.1.2 Sacramento River

The Sacramento River flows north to south along the eastern boundary of the Colusa Subbasin. The Sacramento River provides approximately 80 percent of the inflow to the Delta and is the largest and most important riverine ecosystem in the State of California (DWR, 2009a). In addition to providing flows to the Delta, the Sacramento River is the primary water source for irrigation water suppliers and certain landowners within the subbasin. Sacramento River stream flows measured at the Ord Ferry-Main Channel stream gauge, in the northern part of the Subbasin, varied between 200 and 160,000 cfs during the 1984 to 2020 time period, with extreme low flows measured in the spring of 1990. Stream flows measured at the stream gauge below Wilkins Slough (Station WLK), south of Grimes, varied between 2,400 and 33,000 cfs for the same period of record. Figure 3-8 depicts the historical flows at these two locations. During the rainy season, flows at Wilkins Slough are approximately a third those measured at Ord Ferry-Main Channel.

3.1.5.1.3 Tehama-Colusa Canal

The Tehama-Colusa Canal originates north of the study area at the Red Bluff Pumping Plant and Fish Screen in Tehama County, runs along the west side of the Colusa Subbasin, and terminates south of the subbasin near Dunnigan Water District, Yolo County. The Tehama-Colusa Canal is operated and maintained by the Tehama-Colusa Canal Authority (TCCA), located near Willows, Glenn County. The TCCA service area extends from Tehama to Yolo County and provides irrigation water to farmers growing a variety of permanent and annual crops within the study area.

3.1.5.1.4 Glenn-Colusa Canal

The Glenn-Colusa Canal system is situated east of the Tehama-Colusa Canal and west of the Sacramento River. The Glenn-Colusa Canal originates on the Sacramento River north of the Colusa Subbasin and extends south of Williams, Colusa County, where it flows into the local canal system. The Glenn-Colusa Canal is operated by the Glenn-Colusa Irrigation District (GCID), located in Willows. GCID covers approximately 175,000 acres; of which, approximately 140,000 acres are farmed, making it the largest irrigation district in the Sacramento Valley (GCID, 2017). In addition to serving agricultural lands, GCID services approximately 1,200 acres of private habitat land and 20,000 acres of protected federal wildlife. The main canal is approximately 65 miles long and conveys water into a complex system of nearly 1,000 miles of canals, laterals, and drains.

3.1.5.1.5 Colusa Basin Drain

The Colusa Basin Drain is a drainage system that transports rainfall runoff, agricultural runoff and return flows away from the agricultural lands in the study area to the Sacramento River and the Tule Canal near Knights Landing, Yolo County. Many of the smaller natural streams of the region, including Willow Creek, drain into the Colusa Basin Drain. Some of the water within the Colusa Basin Drain is captured and reused prior to being discharged into the Sacramento River.

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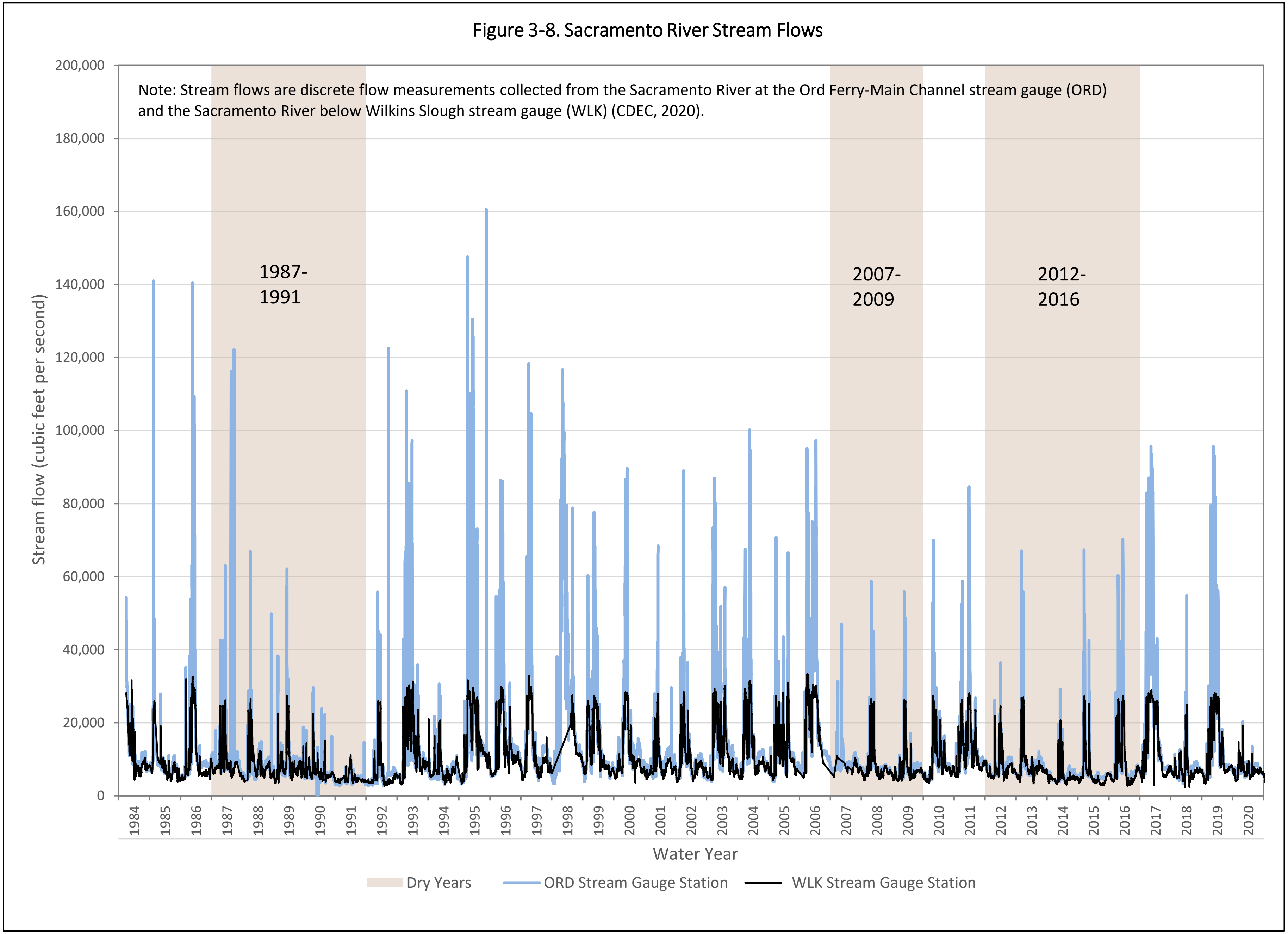
Figure 3-8. Sacramento River Stream Flows
Note: Stream flows are discrete flow measurements collected from the Sacramento River at the Ord Ferry-Main Channel stream gauge (ORD) and the Sacramento River below Wilkins Slough stream gauge (WLK) (CDEC, 2020).
1987-
1991
2007-
2009
2012-
2016
Stream flow (cubic feet per second)
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Water Year
Dry Years
ORD Stream Gauge Station
WLK Stream Gauge Station

3.1.5.1.6 Other Streams

Walker Creek (near Artois) and Willow Creek (near Willows) are north-south trending streams largely contained within the subbasin (Figure 3-5). There are many ephemeral and intermittent streams that flow into or through the subbasin. These include intermittent streams that drain the foothills between the Colusa Subbasin and the higher elevation areas of the Coast Ranges. These foothill drainages and their tributaries are classified as part of the Sacramento-Stone Corral Watershed, as defined by the National Hydrology Dataset (NHD). The following streams comprise the Sacramento Stone Corral watershed, which bounds most of the study area on its western side:

- Walker Creek
- Willow Creek
- French Creek
- Hayes Hollow Creek
- South Fork Willow Creek
- Logan Creek
- Hunters Creek
- Funks Creek
- Stone Corral Creek
- Lurline Creek
- Glenn Valley Slough
- Freshwater Creek
- Salt Creek (which flows past Williams, Colusa County)
- Spring Creek
- Manzanita Creek
- Cortina Creek
- Salt Creek (which flows past Arbuckle, Colusa County)

Runoff in these ephemeral and intermittent streams generally begins in late fall when the rainy season starts and may continue until late spring. Inter-annual runoff patterns from streams such as these are highly variable, and many of these streams flow into drainage canals within the subbasin. For example, Walker Creek and Willow Creek flow into the upstream end of the Colusa Basin Drain, and other creeks, including Stone Corral Creek and both Salt Creeks, flow into the Colusa Basin Drain’s lower reaches (Figure 3-5).

3.1.5.2 Imported Water Sources and Points of Delivery

The primary surface water bodies through, or from, which imported waters are delivered to entities within the Colusa Subbasin include the Sacramento River and Stony Creek, with the Tehama-Colusa Canal and the Glenn-Colusa Canal being the primary conveyances of Sacramento River water. These surface water features, along with the regional and local water conveyance infrastructure, are shown on Figure 3-6. Water delivered via the Tehama-Colusa Canal, Sacramento River, Stony Creek, and other Central Valley Project contracts are managed by USBR.

Modeled points of surface water diversions included in the C2VSimFG-Colusa model and their delivery areas are shown on Figure 3-6 and listed in Table 3-2. The sources and delivery points for imported waters are described in more detail in Section 3.5 and the model development and calibration Technical Memorandum prepared by Woodard and Curran (2021) (Appendix 3-D).

Table 3-2. Surface Water Diversions Delivered to Land

Model Diversion ID[(a)]	Description	Modeled Delivery Subarea	Data Source
444	Orland Unit Water Users' Association (OUWUA) (South Canal only)	OUWUA_S	USBR
445	Colusa County WD	CCWD	USBR
446	Orland-Artois WD (OAWD)	OAWD	USBR
447	Glenn-Colusa ID (Tehama-Colusa Canal)	GCID	USBR
448	Westside WD	Westside	USBR
449	Kanawha WD	Kanawha	USBR
450	Glide WD	Glide	USBR
451	La Grande WD	LaGrande	USBR
452	Davis WD	Westside	USBR
453	4-M WD	4MWD	USBR
454	Holthouse WD	Holthouse	USBR
455	Glenn Valley WD	GVWD	USBR
456	Cortina WD	CCWD; ColGWS	USBR
457	Myers-Marsh MWC	GCID; ColGWS	USBR
458	Glenn-Colusa ID Main Canal	GCID	USBR, GCIDWIS, and eWRIMS
459	Reclamation District #108	RD108	USBR
460	Princeton-Codora-Glenn ID	PCGID	USBR
461	Provident ID	PID	USBR
462	Sycamore MWC	Sycamore	USBR
463	Maxwell ID	Maxwell	USBR
464	Carter Mutual Water Company	ColGWE	USBR
465	Misc Sac River Riparian Diversions	ColGWE	USBR
466	Misc Sac River Riparian Diversions	ColGWE	USBR
467	Misc Sac River Riparian Diversions	ColGWE; Roberts	USBR
468	Andreotti, Arnold and Arthur, et al	ColGWSE	USBR
108	Colusa Basin Drain to Princeton-Cordua-Glenn ID, Provident ID, Maxwell ID for Ag (08N_SA1)	PID; PCGID	C2VSimFG Beta2
111	Colusa Basin Drain to Colusa NWR (08S_PR)	CDMWC	C2VSimFG Beta2
113	Colusa Basin Drain to Colusa Drain MWC for Ag (08S_PA)	CDMWC	C2VSimFG Beta2

(a) Diversion ID in the C2VsimFG-Colusa model. C2VsimFG-Colusa was adapted from the C2VSimFG Beta2 model.

3.1.6 Soils

According to DWR (1978), which summarizes work performed by the USGS (Bertoldi, 1974), most soils in the study area are either: 1) "soils containing hardpan or other consolidated horizons that restrict the vertical flow of water, including soils over bedrock", such as occur in the western upland areas; or 2) "soils containing clay in sufficient quantities to impede the vertical flow of water", such as occur in the former flood basins of the Sacramento River. Exceptions to this generalization are the soils in the vicinity of Stony Creek and stream channel deposits adjacent to the Sacramento River, which have "few barriers to the vertical flow of water" (DWR, 1978). These general patterns are supported by more recent soil surveys conducted by the Natural Resources Conservation Service (NRCS). Areas containing soils with few barriers to vertical flow have higher potential to recharge the underlying aquifers.

Figure 3-9 contains the NRCS Soil Survey Geographic Database (SSURGO) hydrologic soil group designations. Much of the study area is classified as hydrologic groups C and D, which are defined as soils with slow or very slow infiltration rates when saturated (NRCS, 1986). Slow infiltration rates, as defined by NRCS, can be due to the presence of fine-textured layers, clays with high shrink-swell potential, shallow water tables, or shallow soil layers underlain by near-impervious layers. The Stony Creek alluvial fan, the Sacramento River historic channel, and runoff areas of northern Dunnigan Hills contain hydrologic soil groups A and B, which are defined as areas with high and moderate infiltration rates when saturated, respectively, occasionally mixed with soil group D (NRCS, 1986). Soils classified as mixed D soils (A/D, B/D, or C/D) typically correspond to soils near shallow water tables. These mixed D soils exhibit very low infiltration rates when undrained (characteristic of soil group D), and the alternate level of infiltration when drained (characteristic of soil group A, B, or C).

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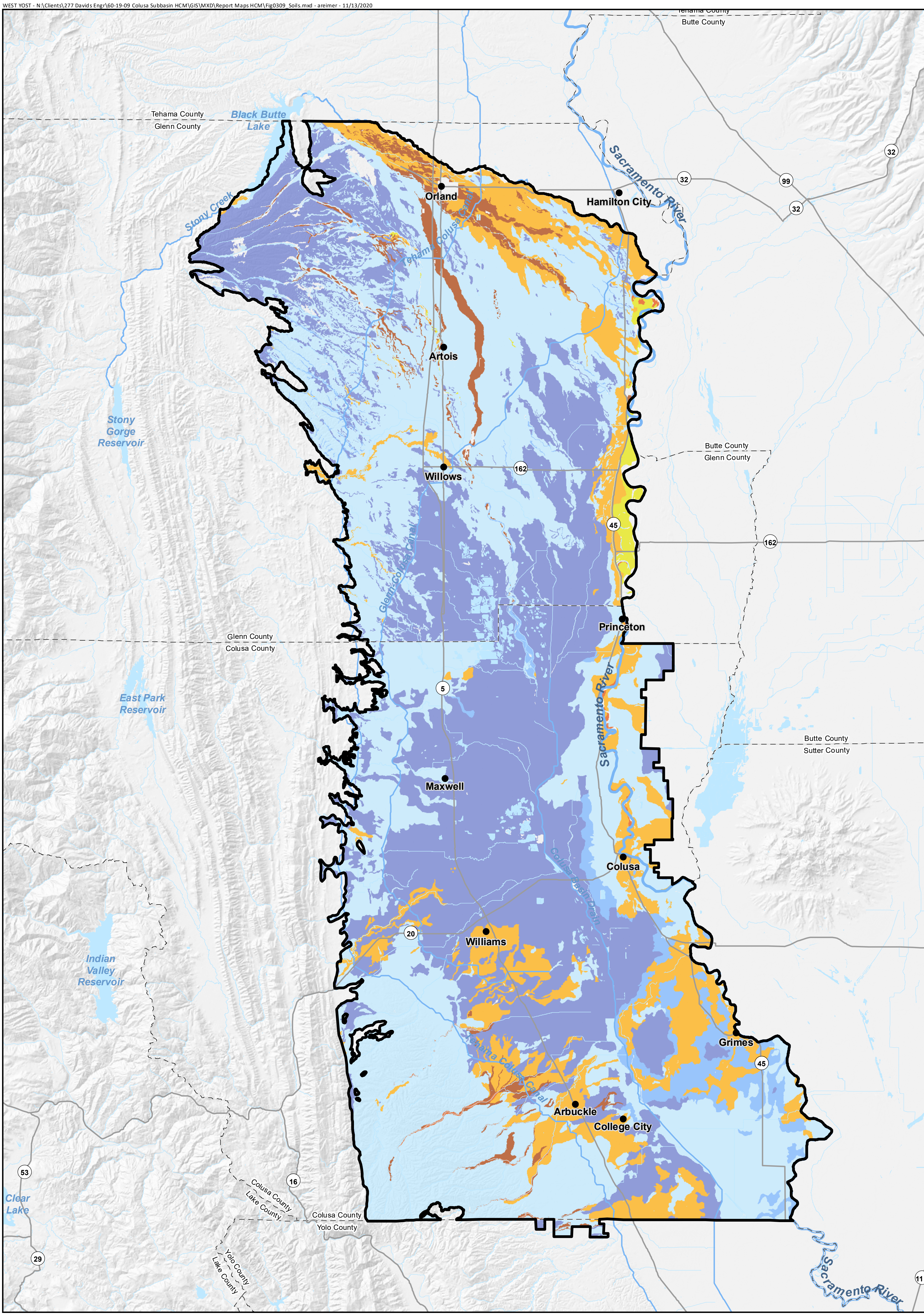

Source: Soil Survey Geographic Database (SSURGO) soils were downloaded via the 2014 SSURGO Downloader for the Big Chico Creek - Sacramento River, Butte Creek, Honcut Headwaters - Lower Feather, Sacramento Stone Corral, Upper Cache, and Upper Stony watershed subbasins.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Note:
1. SSURGO soil designations outside of the study area are not shown in this map.

Study Area

Hydrologic Soil Type

- A - Gravelly Sands to Sands
- A/D - Gravelly Sands to Clays
- B - Moderately Coarse to Moderately Fine Soils
- B/D - Moderately Coarse to Fine Soils
- C - Moderately Fine to Fine Soils
- C/D - Moderately Fine to Claypan Soils
- D - Claypan Soils

N

0 2.5 5
Scale in Miles

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Figure 3-9

Soils

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

3.1.7 Geologic Framework

This section describes the geologic framework for the study area, per the BMP (DWR, 2016) and 23 CCR §354.14(b). The regional geologic and structural setting of the basin and surrounding area are described, including faults and other geologic structures that may influence groundwater flow and quality.

3.1.7.1 Regional Geologic History

Table 3-3 lists the geologic units within the study area and characterizes their age, lithologic character, thickness, and water bearing character (WRIME, 2003). Figure 3-10 shows detailed surface geologic mapping for the study area and surrounding region, and the locations of five geologic cross sections through the study area. Cross sections are provided on Figure 3-11 through Figure 3-13, and a three-dimensional (3D) representation of the HCM is provided on Figure 3-14. Figure 3-15 shows the Tehama and Tuscan Formation surficial outcrops and subsurface extents, including an approximation of the subsurface Tehama-Tuscan Transition Zone, in which Tehama and Tuscan Formation deposits are intermixed (DWR, 2009b). Figure 3-16 includes elevation contours for the top of the Cretaceous rocks. These contours represent the structural base of the freshwater aquifer system (Harwood and Helley, 1987).

The cross sections were developed based on DWR's Geology of the Northern Sacramento Valley report (DWR, 2014). Some of the original DWR (2014) cross sections were expanded and new or extended cross sections were generated to provide a geologic representation of the subsurface throughout the entire study area (Figure 3-10). The revised and new cross sections were based on land surface information, well completion reports, and other geologic references for the region. References to the data used to generate the cross sections are provided in Table 3-1 and Section 3.5. The cross sections were used to generate a 3D model of the post-Cretaceous water bearing formations, and for assessment of the groundwater monitoring network.

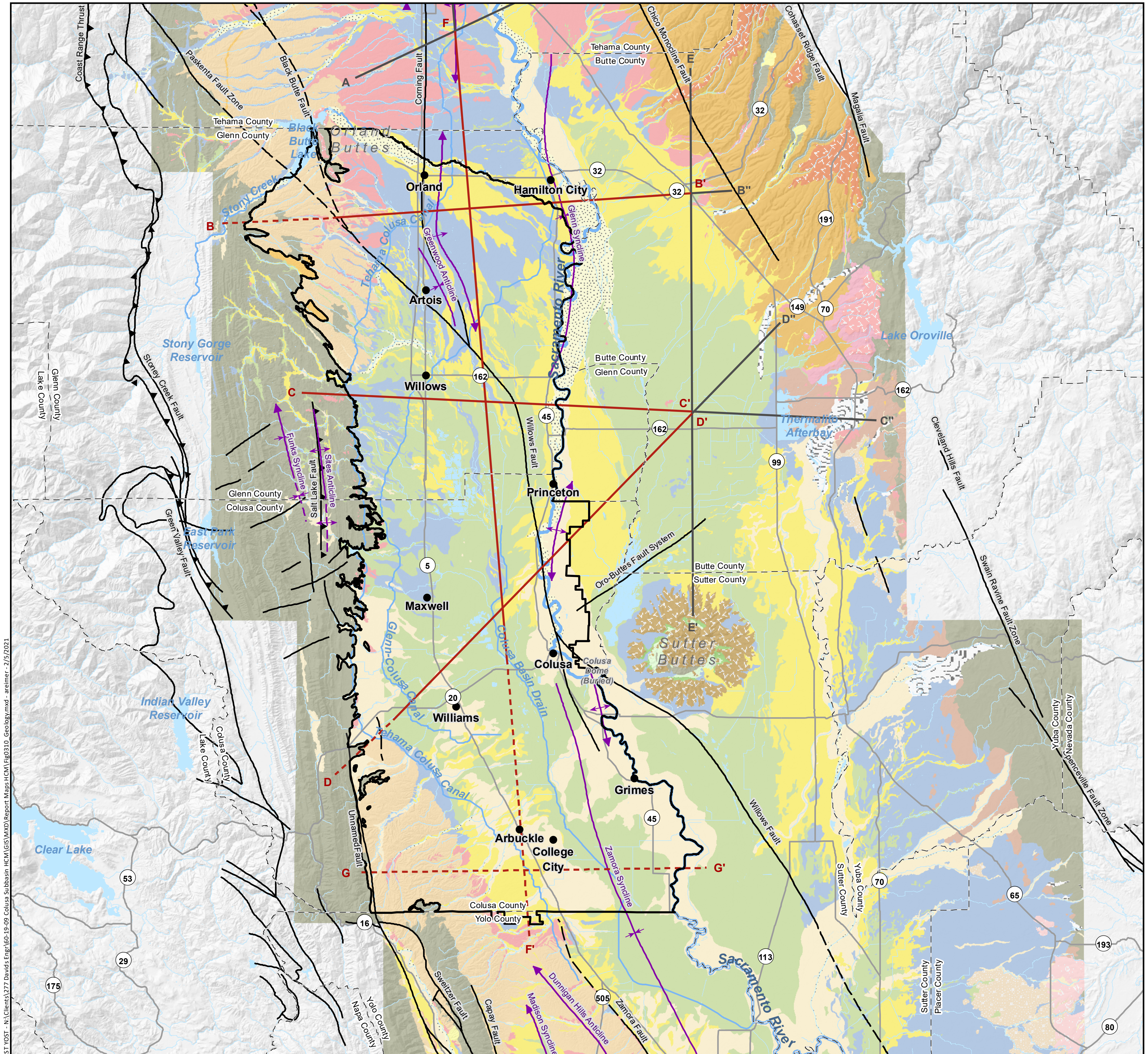
From the Late Jurassic (approximately 159 million years ago [Ma]) through the Miocene (~23 Ma), much of what is now the Northern Sacramento Valley was a marine basin created in the forearc of the Pacific-North American plate subduction zone. The western boundary of the basin was formed by uplifting of volcanic, metamorphic and sedimentary rocks of marine origin, which would later become the Coast Ranges. This marine basin was bounded to the east by the Klamath-Sierran terrane formed during the Nevadan orogeny (~155 Ma). Thick sequences of sediments eroded from the uplifted Klamath-Sierran terrane were deposited into the inland sea during the Cretaceous period. The resulting marine siltstones, sandstones, shales, and conglomerates comprise the Great Valley Sequence. Outcrops of the Great Valley Sequence define the western boundary of the study area (Figure 3-10). The fresh groundwater-bearing formations overlie the Great Valley Sequence in most of the study area, making it a major component of the structural base of the subbasin. The Great Valley Sequence is included in the pre-Paleogene and Cretaceous rocks referenced in the maps and within the report text. Figure 3-16 shows contours of the elevation of the top of the Cretaceous rocks in the study area.

Table 3-3. Description of Geologic Units

Series		Unit	Lithologic Character	Thickness[(a)], ft	Water-Bearing Character
Quaternary	Holocene	Alluvium, Qa	Unconsolidated unweathered gravel, sand, silt, and clay[(a)].	80	Deposits are moderately to highly permeable with high permeability gravelly zones yielding large quantities to shallow wells[(b)]. Although deposits along Stony, Chico, and Thomes Creeks are important recharge areas[(b)], extensive water-bearing capacity is restricted by thickness and areal extent[(a)].
Quaternary	Holocene	Basin Deposits, Qb	Unconsolidated[(e)] fine-grained silts and clays, locally interbedded with stream and channel deposits along the Sacramento River[(a)].	150	Deposits are typically saturated nearly to the ground surface[(b)]. The low to moderate permeability results in yields of small quantity and poor groundwater quality to domestic wells[(a,b)].
Quaternary	Pleistocene	Modesto Formation, Qm	Poorly sorted[(e)] unconsolidated weathered and unweathered gravel, sand, silt, and clay[(c)].	200	Moderately to highly permeable[(a)].
Quaternary	Pleistocene	Riverbank Deposits, Qr	Poorly sorted[(e)] unconsolidated to semi-consolidated[(c)] pebble and small cobble gravels interlensed with reddish clay, sand, and silt[(a)].	200	Water-bearing capability is limited by thickness. These poorly to highly permeable deposits supply moderate groundwater amounts to domestic and shallow irrigation wells. Deeper irrigation wells may be supplied if the wells contain multiple perforation zones[(a)].
Quaternary	Pleistocene	Red Bluff Formation, Qrb	Highly weathered, sandy gravels[(g)].	30(g)	Water-bearing capability is limited by thickness. Fresh groundwater may occur as a perched aquifer[(g)].
Neogene & Quaternary	Pliocene & Pleistocene	Tehama Formation, Tte	Fluviatile moderately consolidated pale green, gray, and tan sandstone and siltstone enclosing lenses of sand and gravel; silt and gravel; and cemented conglomerate derived from the Coast Ranges[(a,c)].	2,000	Local high permeability zones within this characteristically low to moderate permeability unit, widespread distribution, and deep thickness cause this formation to be the principal water bearing unit in the area. Deep well yields are typically moderate, but are highly variable[(b)].
Neogene	Pliocene	Tuscan Formation, Tt	This series of volcanic flows, consolidated tuff breccia, tuffaceous sandstone, and volcanic ash derived from the Cascade Range interfingers with the Tehama Formation as it westerly grades into volcanic sands, gravels, and clays[(a,b)]. The formation is divided by layers of thin tuff or ash units into four lithologically similar units A-D[(a)].	1,500	Within this formation, moderately to highly permeable volcanic sediments are hydraulically confined by layers of tuff breccias and clays[(b)]. Units A and B are the primary water-bearing zones and are composed of volcanic conglomerate, sandstone, and siltstone layers interbedded with lahars. Stratigraphically higher, the massive lahar deposits of unit C confine groundwater in the permeable beds of units A and B1.
Neogene	Pliocene	Nomlaki Tuff Member	Tuff breccias and white tuffs of dacitic composition. This member of the Tehama and Tuscan Formations serves as an important stratigraphical marker bed in northern Sacramento Valley[(e)].	60(e)	Poorly permeable.
Neogene	Miocene	Neroly Formation, Tn	Marine to non-marine tuffaceous andesitic sandstone interbedded with tuffaceous shales and tuff layers. Contains local conglomerate lenses[(c)].	500	This formation of variable permeability contains interstitial fresh water under confined conditions(d), however, deposits of the Neroly Formation are typically located below the base of fresh water.
Neogene	Miocene	Upper Princeton Valley Fill, Tupg	Non-marine sandstone containing mudstone, conglomerate, and sandstone conglomerate interbeds[(c)].	1,400	Largely non-water bearing or contains interstitial confined fresh to brackish water[(g)].
Neogene	Miocene	Lovejoy Basalt, Tl	Black, dense, hard microcrystalline basalt[(c)].	65	Largely non-water bearing.
Paleogene	Eocene	Ione Formation, Ti	Marine gravels[(f)], sandstone with claystone, and carbonaceous interbeds[(g)].	500(f)	Largely non-water bearing or contains interstitial confined fresh to brackish water.
Paleogene	Eocene	Lower Princeton Submarine Valley Fill, Tlpg	Marine conglomerate and sandstone interbedded with silty shale[(c)].	2,400	Largely non-water bearing or contains saline water.
Cretaceous		Great Valley Sequence, JKgvs	Marine siltstone, shale, sandstone, and conglomerate[(c)].	15,000	Largely non-water bearing or contains saline water[(b)].
Pre-Cretaceous		Basement Complex, pTb	Metamorphic and igneous rocks.	n/a	May contain groundwater, mainly saline, in fractures and joints.

Source: This table was originally included as part of the hydrogeologic conceptual model for the Stony Creek Fan IGSM (WRIME, 2003)[(h)]. The table has been revised and expanded to include the hydrogeologic conceptual model units for the study area represented in this report.

(a) Department of Water Resources web page (www.wq.water.ca.gov).
(b) Department of Water Resources, Bulletin 118-6, 1978.
(c) Department of Water Resources, Bulletin 118-7 (Draft, not published).
(d) Department of Water Resources, Sacramento River Basin-Wide Water Management Plan-Draft, 2000.
(e) Department of Water Resources, Groundwater Levels in the Sacramento Valley Groundwater Basin, Glenn County, 1997.
(f) Springhorn dissertation, 2008.
(g) Department of Water Resources, Geology of the Northern Sacramento Valley, 2014.
(h) WRIME, Stony Creek Fan Integrated Groundwater and Surface Water Model (SCFIGSM) Hydrogeology and Conceptual Model, 2003.



- Northern Sacramento Valley Geology Cross Section Used for the Hydrogeologic Conceptual Model
- Section Extension or New Cross Section
- Northern Sacramento Valley Geology Cross Section Not Used for the Hydrogeologic Conceptual Model
- Study Area

N

0 4 8

Scale in Miles

Geologic Structures

- Anticline
- Syncline
- Plunging Anticline
- Plunging Syncline
- Doubly Plunging Anticline
- Double Plunging Syncline
- Fault
- Thrust Fault

Geologic Units

- Stream Channel Deposits (Holocene)
- Alluvial Deposits (Holocene)
- Basin Deposits (Holocene)
- Landslides (Quaternary)
- Modesto Formation (Pleistocene)
- Riverbank Formation (Pleistocene)
- Red Bluff Formation (Pleistocene)
- Turlock Lake Formation (Pleistocene)
- Volcanic Rocks and Lacustrine Deposits of Sutter Buttes (Pleistocene - Pliocene)
- Basaltic Rocks (Pleistocene - Pliocene)
- Tehama Formation (Pliocene)
- Nomlaki Tuff Member (Pliocene)
- Putah Tuff Member (Pliocene)
- Tuscan Formation (Pliocene)
- Laguna Formation (Pliocene)
- Sutter Formation of Williams and Curtis (1977) (Pliocene - Oligocene)
- Channel Deposits (Pliocene - Miocene)
- Mehrten Formation (Pliocene - Miocene)
- Lovejoy Basalt (Miocene)
- Ione Formation (Eocene)
- Sedimentary Rocks in Sutter Buttes Area (Eocene)
- Metamorphic, Igneous, and Sedimentary Rocks (pre-Paleogene)
- Tailings

Source:

1. California Department of Water Resources, 2014, Geology of the Northern Sacramento Valley: prepared by the California Department of Water Resoures Northern Region Office, Groundwater and Geologic Investigations Section, updated September 2014.
2. Helley, E.J. and Harwood, D.S., 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, scale 1:62,500, GIS geodatabase.
3. Jennings, C.W. and Strand, R.G., 1960, Geologic Map of California, Olaf P. Jenkins Edition, Ukiah Sheet: Department of Natural Resources Division of Mines and Geology, third printing 1992, scale 1:250,000.
4. Koenig, J.B., 1963, Geologic Map of California, Olaf P. Jenkins Edition, Santa Rosa Sheet: California Department of Natural Resources Division of Mines and Geology, scale 1:250,000.
5. Springhorn, S.T., 2008, Stratigraphic Analysis and Hydrogeologic Characterization of Cenozoic Strata in the Sacramento Valley near the Sutter Buttes: Master of Science Dissertation, California State University, Chico, 2008.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Notes:

1. The Helley and Harwood mapping is used where available and is supplemented or revised using geologic mapping from the California Department of Natural Resources Division of Mines and Geology documents and information provided in the Springhorn dissertation (2008)
2. Geologic structures are dashed where approximated.

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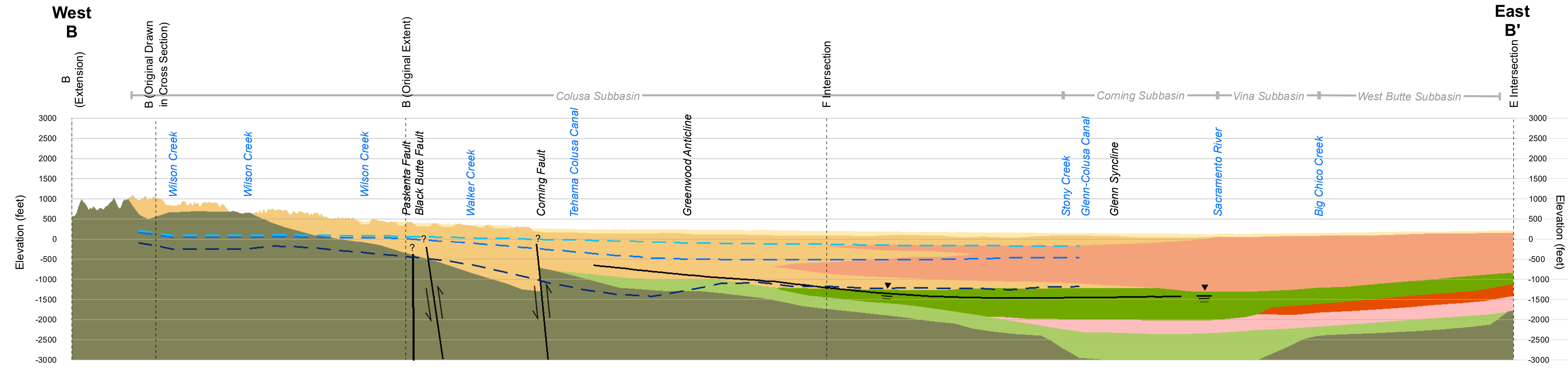
Figure 3-10

Geologic Map

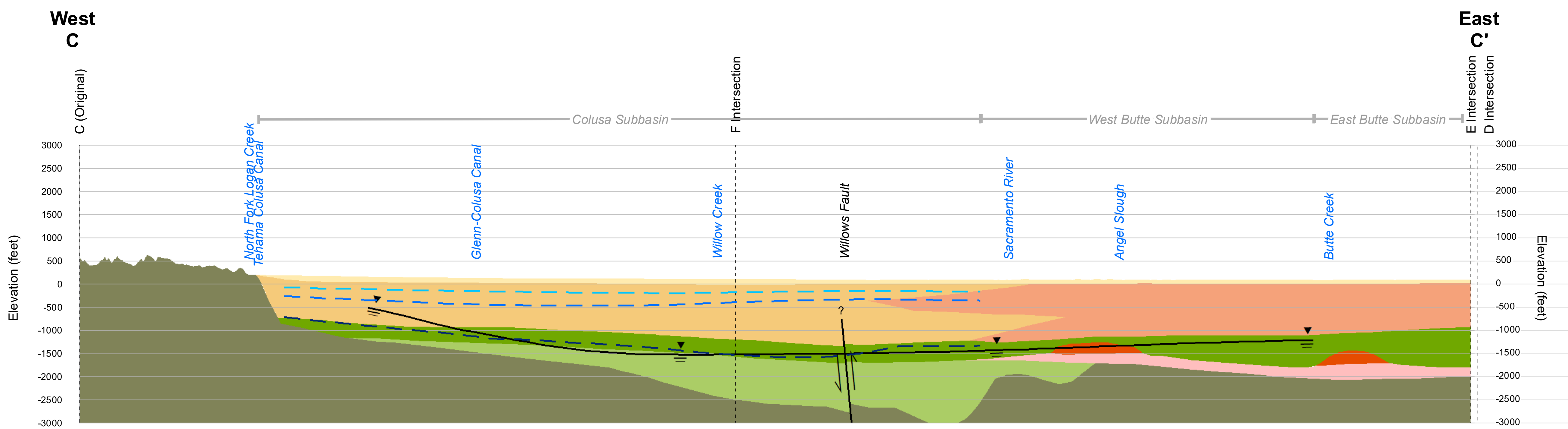
Colusa GSA and Glenn GSA

Colusa Subbasin

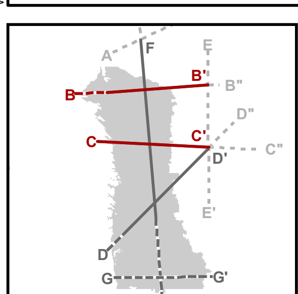
Groundwater Sustainability Plan



Cross Section B-B'



Cross Section C-C'



Inset Map Symbology

- Selected NSV Geology Cross Section Used for HCM
- Selected Section Extension or New Cross Section
- NSV Geology Cross Section Used for HCM
- Section Extension or New Cross Section
- NSV Geology Cross Section Not Used for HCM
- Colusa Subbasin

Cross Section Symbology

- Fault
- Base of Fresh Water (~2,000 mg/L TDS)
- Base of Model Layer 1 and Modeled Unconfined Aquifer
- Base of Model Layer 2 and Modeled Confined Aquifer Pumping
- Base of Model Layer 3 and Modeled Base of Fresh Water

Geologic Units

- Alluvium
- Tehama Formation
- Tuscan Formation
- Upper Princeton Valley Fill
- Lovejoy Basalt
- Ione Formation
- Lower Princeton Valley FIll
- Cretaceous Rocks (pre-Paleogene)

Notes:

1. Elevations are in North American Vertical Datum of 1988, feet (NAVD 88).
2. Cross sections shown are digitized versions of the cross sections included in the Department of Water Resources (DWR) Geology of the Northern Sacramento Valley, California report (DWR, 2014). Existing cross sections were extended and new cross sections were added, as needed, to provide coverage for the entire Colusa Groundwater Subbasin.
3. Cross sections B, C, and D were not digitized beyond their intersection with section E.
4. Base of fresh water was digitized from Olmsted and Davis (1961) and is not shown beyond the extent of the original base of freshwater contouring. Base of fresh water was defined by Olmsted and Davis as approximately 2,000 mg/L of total dissolved solids (TDS).
5. The preliminary approximation of the base of the groundwater subbasins within the study area is based on geologic formation boundaries.

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0 1.25 2.5

Scale in Miles

Vertical Exaggeration: 5.28

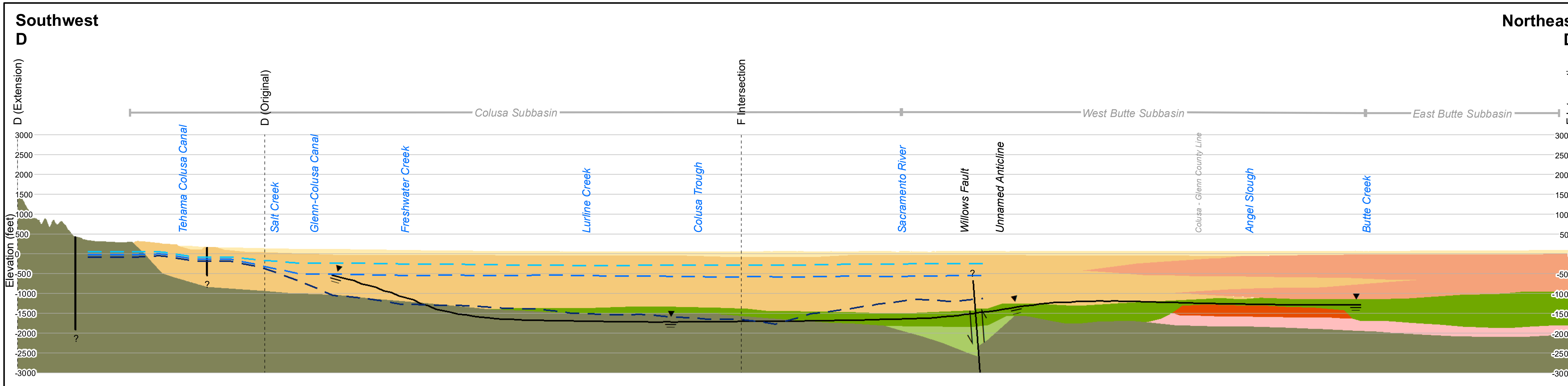
Figure 3-11

Cross Sections B-B' and C-C'

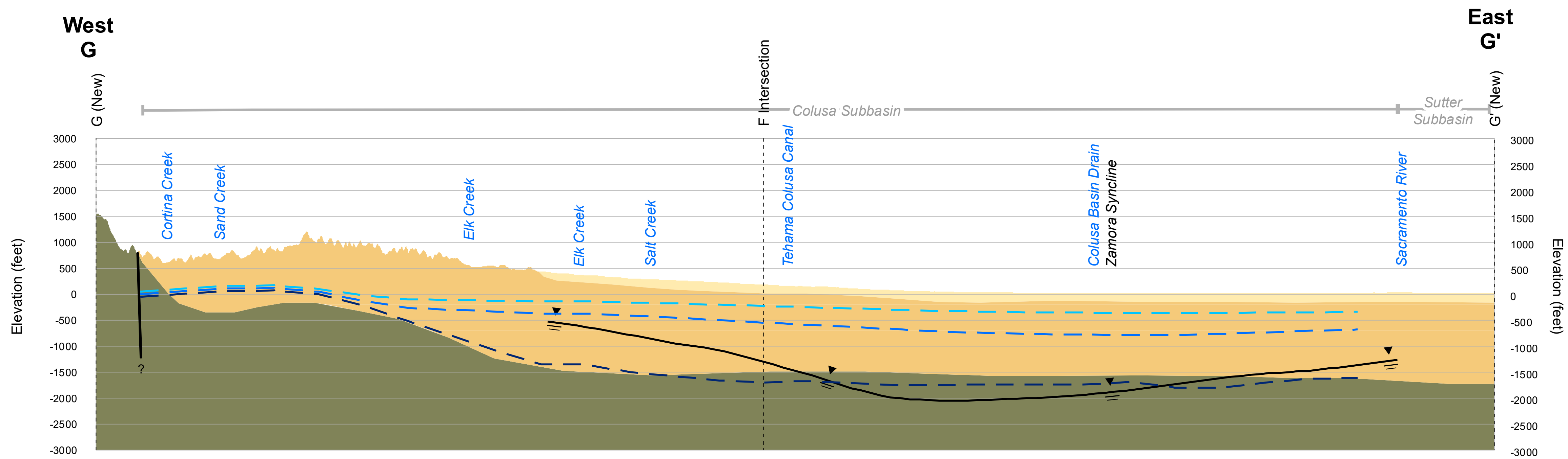
Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan



Cross Section D-D'



Cross Section G-G'

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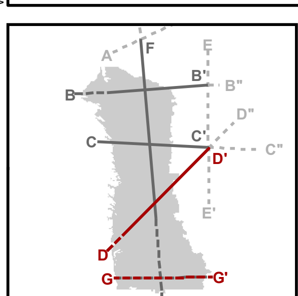

Inset Map Symbology

- Selected NSV Geology Cross Section Used for HCM
- Selected Section Extension or New Cross Section
- NSV Geology Cross Section Used for HCM
- Section Extension or New Cross Section
- NSV Geology Cross Section Not Used for HCM
- Colusa Subbasin

Cross Section Symbology

- Fault
- Base of Fresh Water (~2,000 mg/L TDS)
- Bottom of Model Layer 1 and Modeled Base of Unconfined Aquifer
- Bottom of Model Layer 2 and Modeled Base of Confined Aquifer Pumping
- Bottom of Model Layer 3 and Modeled Base of Fresh Water

Geologic Units

- Alluvium
- Tehama Formation
- Tuscan Formation
- Upper Princeton Valley Fill
- Lovejoy Basalt
- Ione Formation
- Lower Princeton Valley FIll
- Cretaceous Rocks (pre-Paleogene)

Notes:
1. Elevations are in North American Vertical Datum of 1988, feet (NAVD 88).
2. Cross sections shown are digitized versions of the cross sections included in the Department of Water Resources (DWR) Geology of the Northern Sacramento Valley, California report (DWR, 2014). Existing cross sections were extended and new cross sections were added, as needed, to provide coverage for the entire Colusa Groundwater Subbasin.
3. Cross sections B, C, and D were not digitized beyond their intersection with section E.
4. Base of fresh water was digitized from Olmsted and Davis (1961) and is not shown beyond the extent of the original base of freshwater contouring. Base of fresh water was defined by Olmsted and Davis as approximately 2,000 mg/L of total dissolved solids (TDS).
5. The preliminary approximation of the base of the groundwater subbasins within the study area is based on geologic formation boundaries.

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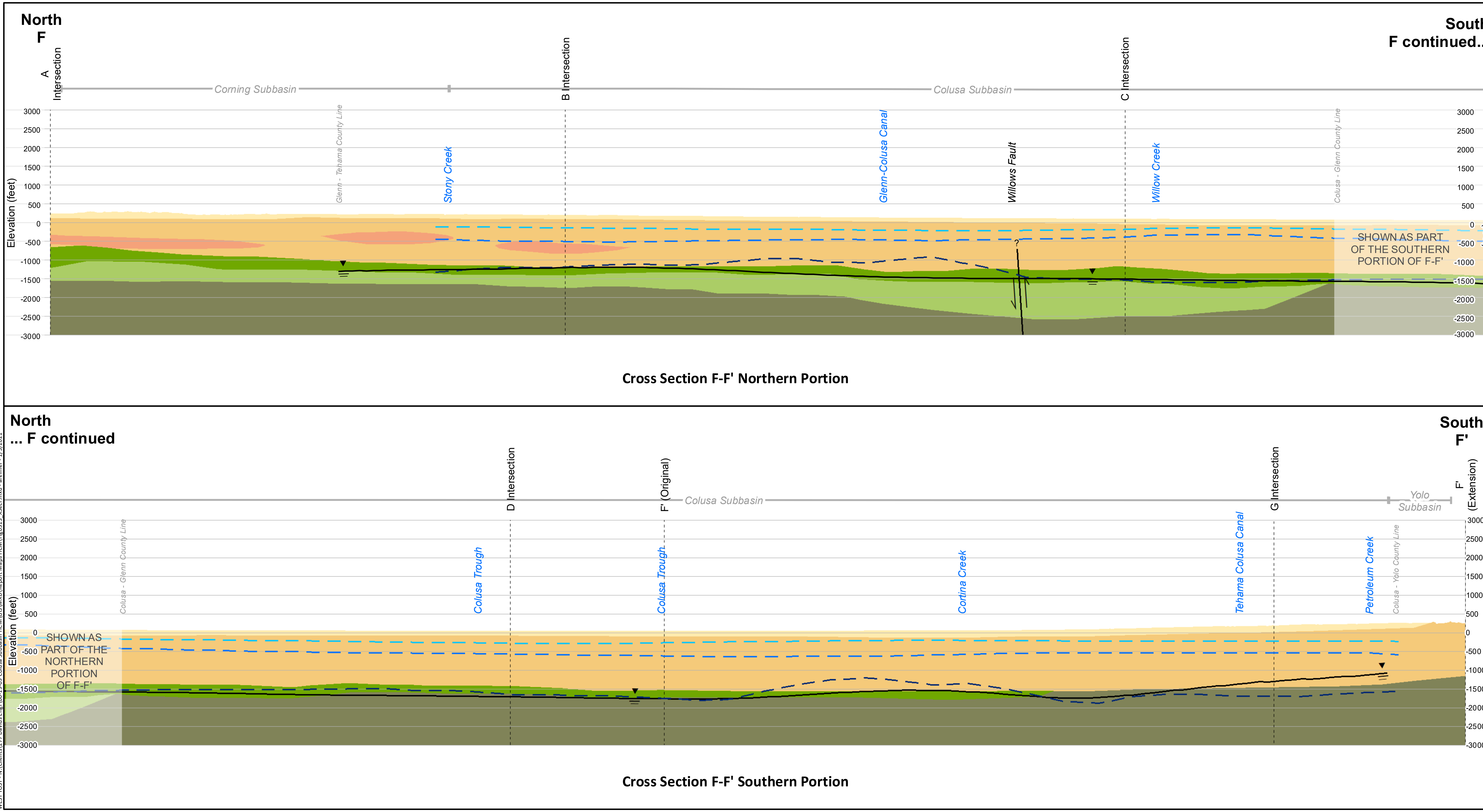
0 1.25 2.5
Scale in Miles

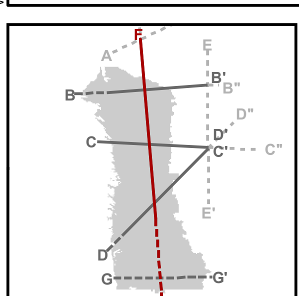
Vertical Exaggeration: 5.28

Figure 3-12

Cross Sections D-D' and G-G'

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan





Inset Map Symbology

- Selected NSV Geology Cross Section Used for HCM
- Selected Section Extension or New Cross Section
- NSV Geology Cross Section Used for HCM
- Section Extension or New Cross Section
- NSV Geology Cross Section Not Used for HCM
- Colusa Subbasin

Cross Section Symbology

- Fault
- Base of Fresh Water (~2,000 mg/L TDS)
- Bottom of Model Layer 1 and Modeled Base of Unconfined Aquifer
- Bottom of Model Layer 2 and Modeled Base of Confined Aquifer Pumping
- Bottom of Model Layer 3 and Modeled Base of Fresh Water

Geologic Units

- Alluvium
- Tehama Formation
- Tuscan Formation
- Upper Princeton Valley Fill
- Lovejoy Basalt
- Ione Formation
- Lower Princeton Valley FIll
- Great Valley Sequence

Notes:
1. Elevations are in North American Vertical Datum of 1988, feet (NAVD 88).
2. Cross sections shown are digitized versions of the cross sections included in the Department of Water Resources (DWR) Geology of the Northern Sacramento Valley, California report (DWR, 2014). Existing cross sections were extended and new cross sections were added, as needed, to provide coverage for the entire Colusa Groundwater Subbasin.
3. Cross sections B, C, and D were not digitized beyond their intersection with section E.
4. Base of fresh water was digitized from Olmsted and Davis (1961) and is not shown beyond the extent of the original base of freshwater contouring. Base of fresh water was defined by Olmsted and Davis as approximately 2,000 mg/L of total dissolved solids (TDS).
5. The preliminary approximation of the base of the groundwater subbasins within the study area is based on geologic formation boundaries.

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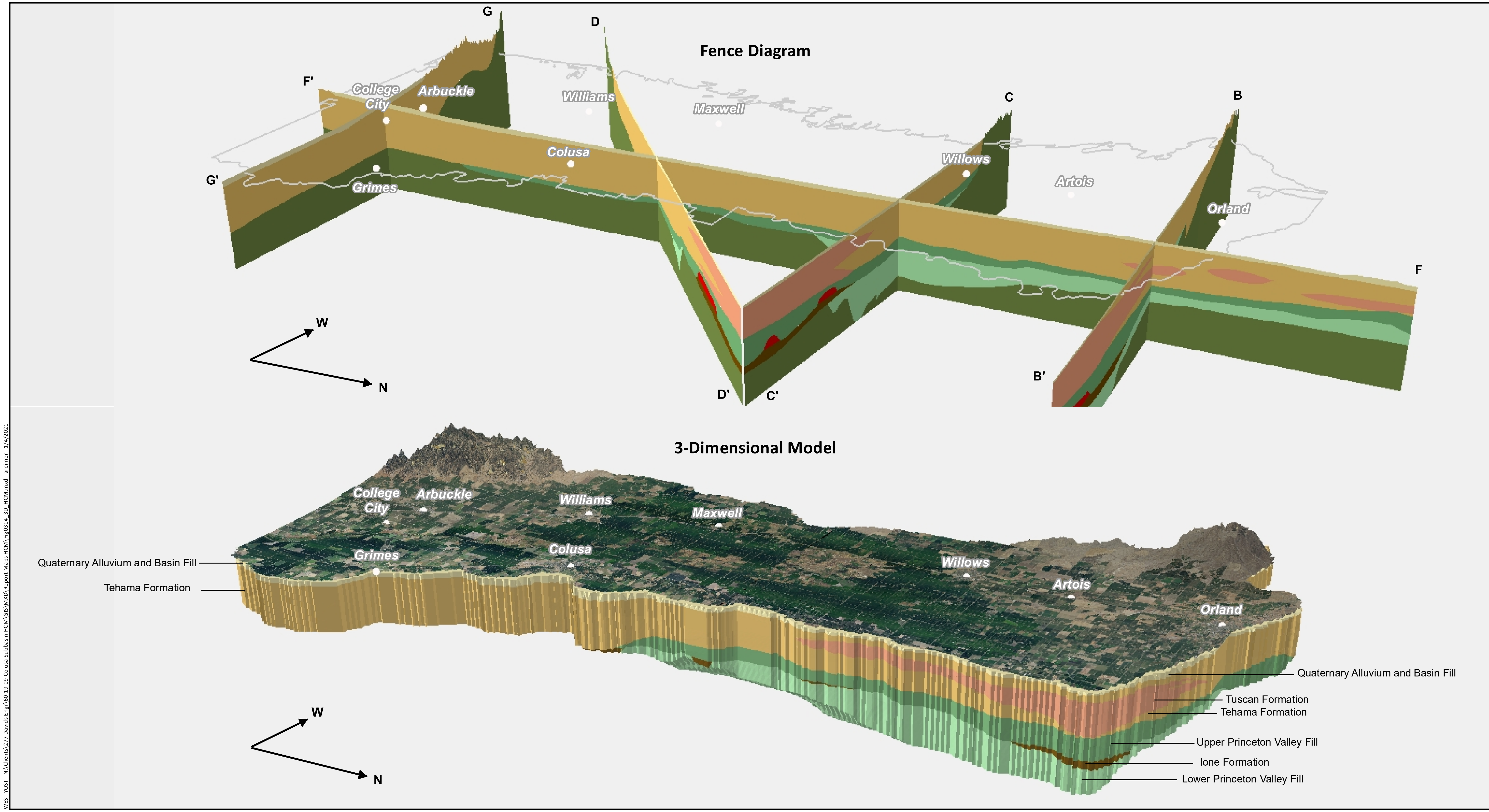
0 1.25 2.5
Scale in Miles
Vertical Exaggeration: 5.28

Figure 3-13

Cross Section F-F'

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan



Datums: North American Datum of 1983, California State Plane Zone II, feet. North American Vertical Datum of 1988, feet.

Notes:
1. Vertical exaggeration is 10x.
2. Elevations are in North American Vertical Datum of 1988, feet (NAVD 88).
3. The fence diagram and 3-dimensional (3D) model are based on the cross sections included in the California Department of Water Resources (DWR) Geology of the Northern Sacramento Valley, California report (DWR, 2014) and have been updated and expanded upon based on available well completion reports to represent the water-bearing formations.
4. The 3D model excludes the Lovejoy Basalt.

Hydrogeologic Formation

- Quaternary Alluvium and Basin Fill
- Tehama Formation
- Tuscan Formation
- Upper Princeton Valley Fill
- Lovejoy Basalt
- Ione Formation
- Lower Princeton Valley Fill
- Cretaceous Rocks (pre-Paleogene)

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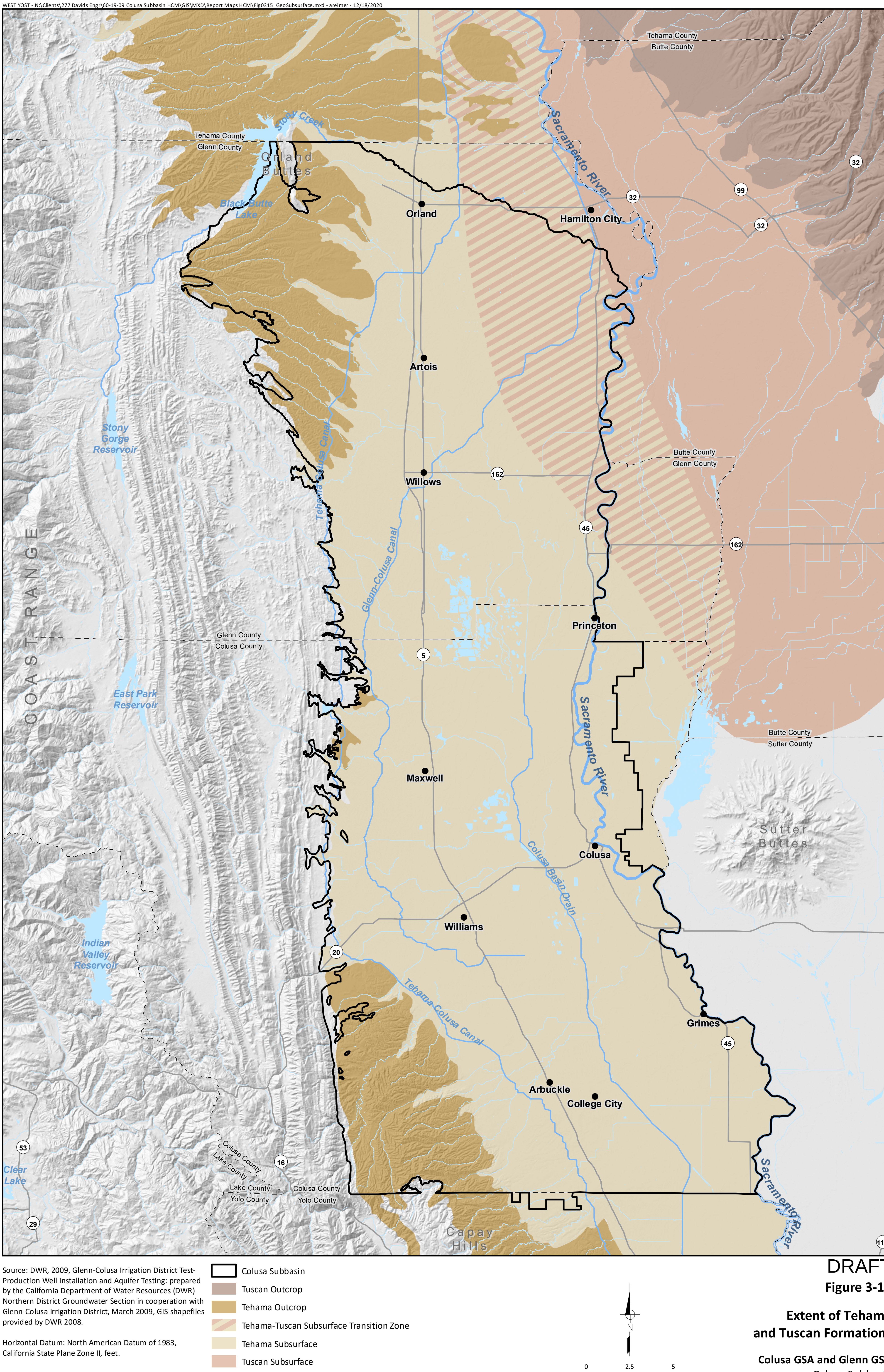
Figure 3-14

3D Hydrogeologic Conceptual Model

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan



Source: DWR, 2009, Glenn-Colusa Irrigation District Test-Production Well Installation and Aquifer Testing: prepared by the California Department of Water Resources (DWR) Northern District Groundwater Section in cooperation with Glenn-Colusa Irrigation District, March 2009, GIS shapefiles provided by DWR 2008.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

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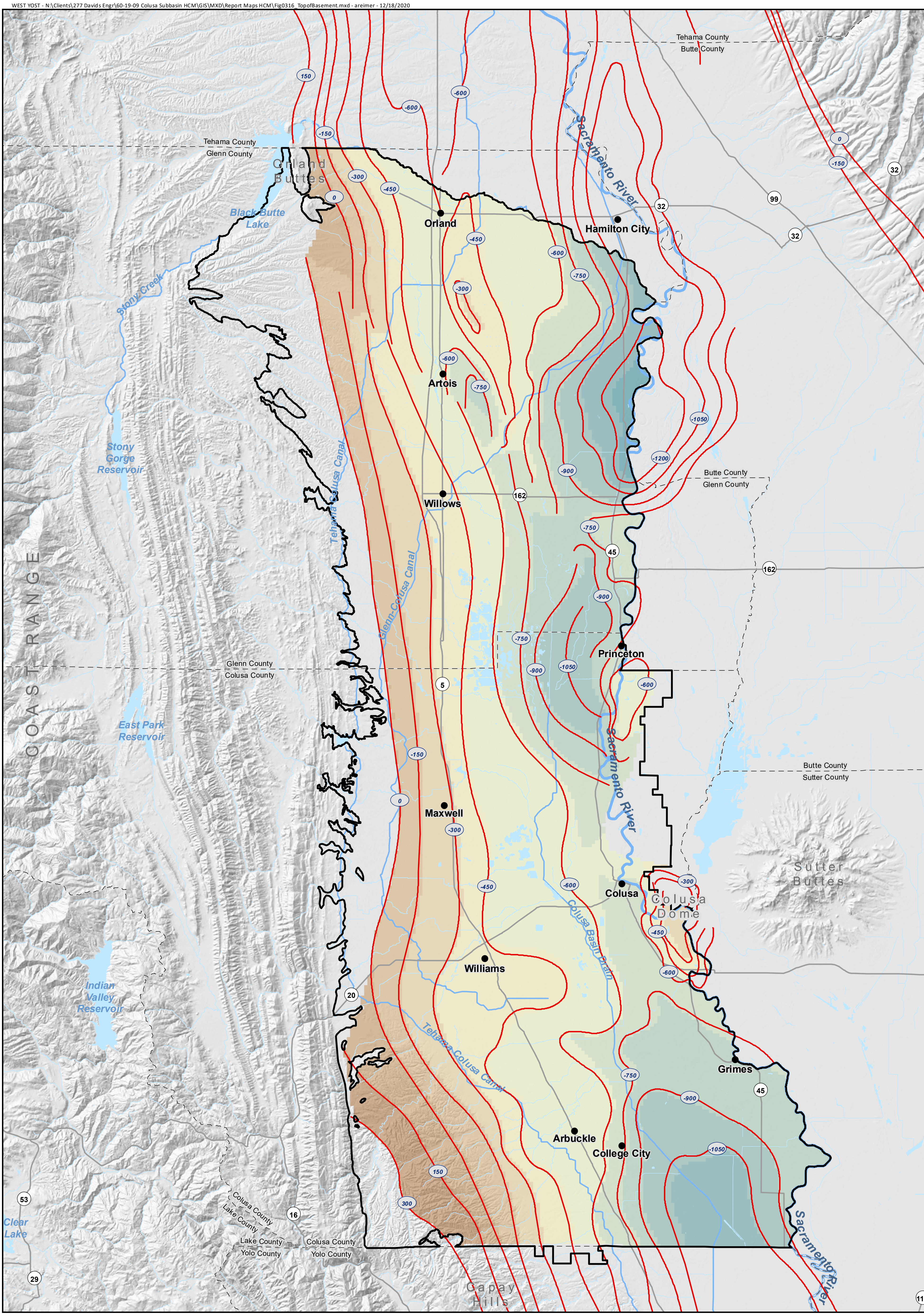
Figure 3-15

Extent of Tehama and Tuscan Formations

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan



Top of Cretaceous Rocks Elevation Contours (MSL, meters)

Colusa Subbasin

Top of Cretaceous Rocks Elevation (MSL, feet)

< -4000	-2500 - -2000	-500 - 0
-4000 - -3500	-2000 - -1500	0 - 500
-3500 - -3000	-1500 - -1000	500 - 1000
-3000 - -2500	-1000 - -500	> 1500

Source: Harwood, D.S. and Helley, E.J., 1987, Late Cenozoic Tectonism of the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1359, plate 1.

Datums: North American Datum of 1983, California State Plane Zone II, feet. Mean Sea Level (MSL).

Note:
1. Color floodmap of the top of Cretaceous rocks elevation was created using the top of Cretaceous rocks elevation contours in meters.

N

0 2.5 5
Scale in Miles

DRAFT

Figure 3-16

Top of Cretaceous Rocks Structural Contour Map

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

The shoreline of the sea migrated westward throughout the Paleogene period due to continued subduction of the Pacific plate beneath the North American plate. During this period of regression, drainage from ancestral mountain ranges located north of the study area eroded a submarine valley into the marine deposits (DWR, 2014; Redwine, 1984). This valley, called the Princeton Submarine Valley, extends from the northern end of what is now the Sacramento Valley towards the City of Woodland in Yolo County, south of the study area. Continued regression of the inland sea and ongoing drainage from the surrounding ancestral hills resulted in a mix of marine and continental deposits filling the Princeton Submarine Valley and surrounding basin. The incised nature of the Princeton Submarine Valley within the Great Valley Sequence can best be seen in the west to east trending Cross Sections B-B', C-C', and D-D' on Figure 3-11 and Figure 3-12. Cross Section F-F', on Figure 3-13, approximately follows the axis of the valley.

The lowest extents of the submarine valley were unconformably filled with Lower Princeton Valley Fill deposits during the Eocene. The Lower Princeton Valley Fill, deposited via turbidity flows, consists of interbedded sandstones and shale (DWR, 2014; Springhorn, 2008). The Lower Princeton Valley Fill was conformably overlain by the Ione Formation in the Eocene (~40 Ma) via stream drainage from the Sierra Nevada. The western extent of the Ione Formation is characterized by shallow marine deposition in the remnants of the inland sea, while the eastern extent of the formation is characterized by non-marine deltaic deposition (Redwine 1984; Springhorn, 2008). The Ione Formation unconformably overlies the Great Valley Sequence and crystalline and metasedimentary rocks near the eastern portion of the Sacramento Valley and is used as a marker bed to distinguish the Upper and Lower Princeton Valley Fill deposits.

Around this time, the tectonic regime of the northern Sacramento Valley began transitioning from a subduction zone to a transform zone as the Mendocino Triple Junction (composed of the Pacific, North America, and Juan de Fuca-Gorda plates) approached the study area from the south. The transition from subduction to transform movement resulted in the creation of faults and folds, many of which are north-south trending due to the direction of compression applied by the transform system.

Volcanic activity during the Miocene resulted in the deposition of the Lovejoy Basalt (~16.4 Ma), which unconformably overlies the Ione Formation and older formations, where they exist (Figure 3-11 and Figure 3-12). These basaltic flows originated near Honey Lake in the eastern Sierras and flowed westward, following channels towards and through what is now the northern Sacramento Valley (Helley and Harwood, 1985). Due to its distribution as flows in preexisting channels, the presence of Lovejoy Basalt is widespread but discontinuous.

Unconformably overlying the Lovejoy Basalt and older formations is the Upper Princeton Valley Fill. Upper Princeton Valley Fill was originally thought to have been deposited in Late Miocene to Oligocene, however age dating of the Lovejoy Basalt has constrained the age of the Upper Princeton Valley Fill to the Miocene epoch (~16.4 Ma) (Springhorn, 2008). Upper Princeton Valley Fill consists of sandstone, with occasional interbeds of mudstone and conglomerate deposited in a fluvial floodplain system (Redwine, 1984). Because of its depositional history, groundwater within the Upper Princeton Valley Fill is fresh to brackish in quality.

Uplift of the Coast Ranges in the Pliocene epoch eventually gave form to the Sacramento Valley as it exists today. Alluvial, fluvial, and floodplain deposits derived from the Coast Ranges eventually accumulated as the Tehama Formation along the western side of the valley, while volcanic activity within the southern Cascade Ranges produced basalt and andesite flows that would eventually become reworked into the Tuscan Formation. The Tehama and Tuscan Formations were deposited concurrently during the late Pliocene to Pleistocene, interfingering with one another beneath the valley floor in what is referred to as the Tehama-Tuscan Transition Zone (Figure 3-15). The interlayering of the Tehama and Tuscan Formations can be seen in Cross Sections B-B', C-C', D-D', and F-F' (Figure 3-11 through Figure 3-13). The Tuscan Formation appears as isolated lenses in north-south trending Cross Section F-F', but these lenses are integral with the main body of the Tuscan Formation, as depicted in the west-east trending cross sections. In the late Pliocene epoch, volcanic activity within the southern Cascade Range caused the widespread deposition of the Nomlaki Tuff across the northern Sacramento Valley. The Nomlaki Tuff has been radiometrically dated to 3.4 Million Years Ago (Ma) (Evernden, 1964) and provides an age constraint on the Tehama and Tuscan Formations because it is found in the basal deposits of both formations. The age of the upper boundary of the Tuscan Formation is further constrained to 1.5 Ma based on age dating of a rhyolite flow that overlies the Tuscan Formation near Mineral, Tehama County (Lydon, 1968).

Additional faults and folds were created as the Mendocino Triple Junction continued to move northward. These include the Corning Fault, Glenn Syncline, Greenwood Anticline, and an assortment of domes and buttes within the study area. The Sutter Buttes are thought to have formed in part due to the compressional tectonics associated with the migration of the Mendocino Triple Junction (Hausback and Nilsen, 1999). The most recent Sutter Buttes volcanism occurred approximately 2 Ma (Hausback and Nilsen, 1999).

Quaternary geologic deposits are characterized by alluvial pediments and fans, and basin floodplain deposits of the Red Bluff Formation (an erosional surface, or pediment), Riverbank Formation, Modesto Formation, and basin deposits. These are collectively referred to as "Alluvium" on the cross sections found on Figure 3-11 through Figure 3-13 because of their limited thicknesses relative to the older formations (Table 3-3).

The Red Bluff Formation is thin sand and gravel deposit resting on a pediment or erosional surface on the Tehama Formation (Figure 3-10). The Red Bluff Formation was formed when the Sacramento Valley was a closed drainage basin, which resulted in lacustrine depositional environments. The Red Bluff Formation is thought to represent the paleoshores of this ancient lacustrine system (DWR, 2014; Springhorn, 2008). The age of the Red Bluff Formation is constrained to 0.6 to 1.09 Ma by radiometrically determined ages of the Rockland ash bed and the Deer Creek basalt, respectively (Harwood et. al., 1981; Harwood and Helley, 1987; Lanphere et. al., 1999). This constrains the age of the Tehama Formation to be no younger than 0.6 to 1.09 Ma.

Lacustrine environments resulting from the basin's internal drainage during Red Bluff Formation time also resulted in the deposition of diatomaceous clays similar to the Corcoran Clay of the San Joaquin Valley. This indicates that potentially subsidence-prone compressible sediments of approximately 0.6 to 1.09 Ma age are located near the top of the Tehama Formation.

The limited fresh groundwater found within the Red Bluff Formation tends to be present under perched conditions (DWR, 2014). The Red Bluff Formation is therefore not further discussed in the following sections of this report.

Glacial activity during the Pleistocene epoch resulted in the Riverbank and Modesto Formations (Busacca et. al., 1989). The age of the Riverbank Formation ranges from 0.13 to 0.45 Ma and corresponds to the Illinoisan and older glacial stages. The age of the Modesto Formation ranges from approximately 0.01 to 0.042 Ma and correlates to the Wisconsin glacial stage.

The youngest deposits of the study area consist of Holocene-aged basin deposits and stream channel deposits.

3.1.7.2 Primary Freshwater-Bearing Formations

The geologic formations forming the freshwater aquifer comprise a single aquifer system. The geologic formations comprising the freshwater aquifer system are discussed below.

3.1.7.2.1 Tuscan Formation

Tuscan Formation deposits are characterized by their Cascade Range origin and volcanic signature. This extensive series of basaltic and andesitic volcanic flows, consolidated tuff breccia, tuffaceous sandstone, and volcanic ash is primarily located on the northeastern portion of the Sacramento Valley. Figure 3-10 and Figure 3-15 show the approximate surface and subsurface extents of the Tuscan Formation in the vicinity of the study area. The Tehama-Tuscan Transition Zone is also visible in the 3D hydrogeologic conceptual model shown on Figure 3-14. The Tuscan Formation comprises the oldest freshwater aquifer in the eastern half of the northern Sacramento Valley. The Tuscan Formation is exposed on the eastern side of the Sacramento Valley and occurs as interfingering layers with the Tehama Formation at depth near the center of the Sacramento Valley. This interfingering of the Tehama Formation with Tuscan Formation units is referred to as the Tehama-Tuscan Transition Zone (Figure 3-15). In the study area, these deposits occur at depths greater than the depths of most existing domestic wells.

Moderately to highly permeable volcanic sediments are hydraulically confined by layers of tuff breccias and clays within the Tuscan Formation. The Tuscan Formation contains four map units, which are designated A through D, with A being the oldest (DWR, 2006a). The low permeability lahar, or mudflow, deposits of Unit C are confining beds for the underlying older Tuscan Units A and B. Although Unit C contains permeable volcanic sandstone and conglomerate interbeds, this unit is characterized by an overall low yield of water to wells within the study area. Units A and B are much coarser-grained than the overlying Unit C, and they are the primary water-bearing zones of the eastern Sacramento Valley. The lower Tuscan Formation (Tuscan Units A and B) is present at depths below 700 feet in the eastern part of the study area and consists of volcanic conglomerate, sandstone, siltstone, and interbedded lahars overlain by tuffaceous breccias, sandstone and conglomerate. Tuscan Unit D is not present within the study area.

The permeability of the Tuscan Formation varies, and irrigation wells range in well yield from 7 to 4,000 gallons per minute (gpm). The average yield based on 46 wells within West Butte Subbasin was 1,833 gpm (DWR, 2004b).

3.1.7.2.2 Tehama Formation

Figure 3-10 and Figure 3-15 show the approximate surface exposures and subsurface extents of the Tehama Formation. The Tehama Formation forms the oldest, deepest, and thickest part of the freshwater aquifer in the western half of the northern Sacramento Valley. The Tehama Formation consists of up to nearly 2,000 feet of moderately compacted silt, clay, and silty fine sand enclosing thin, discontinuous lenses of sand and gravel deposited in a fluvial (river-borne) environment (DWR, 2006a; Olmsted and Davis, 1961). Based on the mineralogy of surface exposures, the sediments were derived from erosion of the Coast Ranges and Klamath Mountains to the west and northwest. They were deposited under floodplain conditions on the west side of a broad valley of low relief (Brown and Caldwell, 2007; Russell, 1931).

The Tehama and Red Bluff Formations are exposed at the land surface on the western side of the Sacramento Valley, in the northwest, and the southwest. The outcrop of the Tehama and Red Bluff Formations and pinchout of the younger valley sediments coincide with an increase in terrain, as seen in

Figure 3-4. There are few wells drilled in these areas and local residents report that existing wells yield little groundwater. Geologic mapping shows outcropping of older Cretaceous-aged sedimentary rocks in the northwestern portion of the subbasin near the Orland Buttes and west of the Tehama-Colusa Canal (Figure 3-10). Based on these observations, the Tehama Formation is relatively thin and has a low permeability where it outcrops. The Tehama Formation is buried beneath younger sediments to the east and interfingers with the Tuscan Formation throughout the Tehama-Tuscan Transition Zone in the northeast portion of the Colusa Subbasin (Figure 3-15).

The permeability of the Tehama Formation varies but is generally less than in the overlying unconsolidated alluvial deposits. Because of the thickness of the producing zones, production from the Tehama Formation can be up to several thousand gallons per minute per well (DWR, 2006a), but is typically less than that exhibited by the Tuscan Formation.

3.1.7.2.3 Riverbank and Modesto Formations

The late Pleistocene-aged Riverbank and Modesto Formations uncomfortably overlie the Tuscan and Tehama Formations. The thickness of the formation ranges from less than 10 feet to nearly 200 feet across the valley floor (DWR, 2006a; Helley and Harwood, 1985). These formations consist of loose to moderately compacted silt, silty clay, sand and gravel deposited in alluvial depositional environments during periods of world-wide glaciation (DWR, 2006a; Lettis, 1988; Weissmann et. al., 2002). The formations were deposited in response to changes in base level and increased precipitation during the glacial periods. The increased stream gradients and precipitation resulted in greater stream discharge and competency than observed today. The greater competency of the streams led to scouring of stream channels in preexisting geologic deposits, followed by transport, deposition and burial of sands and gravels in the channels as the glacial cycles progressed.

Figure 3-10 shows the spatial distribution of the Riverbank and Modesto Formation in the study area. The formations are exposed at the land surface along the channels of creeks and along the western margin of the study area, where they form a series of coalescing alluvial fans, emanating from the mouths of the creeks. The Riverbank and Modesto Formations typically form terraces along stream channels. The oldest terraces occur furthest from the channel and at the highest elevations. Successively younger terraces are incised into the next oldest deposit and, therefore, occur closer to the stream channel and at lower elevations. The Riverbank Formation forms the older terrace deposits that occur at a higher topographic level. In the Stony Creek Fan area, these terraces are well-defined, but they are absent or poorly defined along other minor streams in the study area.

The Riverbank Formation consists of poorly to highly permeable pebble and small cobble gravels interbedded with reddish clay, sand, and silt. The Modesto Formation consists of moderately to highly permeable gravels, sands, and silts. The Riverbank Formation is distinguished from the Modesto Formation by interbedded clay layers. These formations contain fresh water (DWR, 2006a; Harwood and Helley, 1987).

Wells penetrating the sand and gravel units of the Riverbank and Modesto Formations produce up to about 1,000 gpm; however, the production varies depending on local formation thickness (DWR, 2006a). Wells screened in the Riverbank and Modesto Formations are generally domestic and shallow irrigation wells (DWR, 2006a).

3.1.7.2.4 Stream Channel and Basin Deposits

Holocene stream channel and basin deposits are the youngest sediments in study area, with ages of roughly 10,000 years or younger (Helley and Harwood, 1985). The stream channel and basin deposits consist of up to 80-foot sections of unconsolidated clay, silt, sand, and gravel reworked from older formations by streams. According to DWR (2006), which also refers to these deposits as younger alluvium, these deposits form a shallow, unconfined aquifer of moderate to high permeability, but with limited capacity due to the relatively restricted lateral and vertical extents of the deposits.

Holocene flood basin deposits are very young surficial deposits formed during flood events when streams overtopped their natural levees, flooding the surrounding area. As the flood water spread, the current velocity and stream competency decreased, resulting in deposition of silts, clays, and fine sands. Flood basin deposits reach thicknesses of up to 150 feet and may be interbedded with stream channel deposits (DWR, 2006a). Because of their low permeability, limited extent, and generally poor water quality, flood basin deposits are typically not used for groundwater production (DWR, 2006a).

3.1.7.3 Geologic Structures

Figure 3-16, from Harwood and Helley (1987), shows the structural contours in meters delineating the top of the Cretaceous marine sedimentary rocks in the vicinity of the study area. The shaded color intervals on Figure 3-16 conform to the structural contours of the top of the Cretaceous rocks, but are represented in feet instead of meters to facilitate comparison to the other maps included in this report. The structural contours were based on the Cretaceous rocks because the resulting surface produces a single structural datum throughout the western Sacramento Valley. This datum helps reveal some of the geologic structures (folds and faults) that affect the groundwater basin.

Figure 3-10 shows the significant structural features near the study area, including, but not limited to the Willows Fault, Corning Fault, Glenn Syncline, and the Zamora Syncline in addition to other smaller unnamed geologic structures. These structural features affect geologic units at least as young as the Red Bluff Formation, which indicates that structural deformation was occurring as recently as 0.45 Ma – the oldest potential age of the overlying Riverbank Formation – and may be continuing at present (Harwood and Helley, 1987).

3.1.7.3.1 Faults

Faults may affect groundwater flow by bringing geologic materials with different hydraulic properties into contact across the fault plane or by fracturing the materials, which could either increase or decrease permeability, depending on the degree of fracturing and other geologic processes, such as mineralization, active within the fault zone. The fault might, therefore, act as a boundary or barrier affecting the lateral flow of groundwater between adjacent areas, and might act as a conduit allowing vertical or lateral flow within the fault zone. The faults that were analyzed as part of this report include the Willows Fault, Corning Fault, Black Butte Fault, and the Paskenta Fault. These faults are shown on Figure 3-10 and discussed in the following subsections.

3.1.7.3.1.1 Zamora Fault

The Zamora Fault is a northwest-trending, east-dipping normal fault mapped along the eastern edge of Dunnigan Hills, south of the Colusa Subbasin. The Dunnigan Hills escarpment is partially attributed to the displacement along the Zamora Fault (Harwood and Helley, 1987). Local topography and geology indicate that the fault may extend further northward towards Arbuckle.

3.1.7.3.1.2 Willows Fault

The Willows Fault is a north-south trending reverse fault that dips 74 degrees to the east and extends from near Stockton, San Joaquin County to the north end of the Sacramento Valley (Harwood and Helley, 1987). The reverse movement of the fault juxtaposes Mesozoic-aged marine formations against the Tehama Formation, as seen in portions of Cross Sections B-B', C-C', and D-D', and the northernmost portion of Cross Section F-F' (Figure 3-11 through Figure 3-13). Additionally, there is evidence that the Willows Fault influenced not only the position of the Lower Princeton Valley Fill thalweg, but also offset the fill during deposition (Redwine, 1984). Displacement along the Willows Fault is approximately 1,600 feet at the top of the Cretaceous rocks and approximately 1,560 feet at the top of the Eocene formations (Harwood and Helley, 1987). The most recent activity along the Willows Fault affects the lower Tehama Formation. The slip rate on the Willows Fault is estimated to be 0.00055 inches per year (McPherson and Garven, 1999).

Groundwater elevations exhibit a localized lowering of the water levels where the northern extent of the Willows Fault splits into the Black Butte and Paskenta Fault zones. This is discussed more in the Existing and Historical Groundwater Conditions sections of the GSP (Section 3.2).

3.1.7.3.1.3 Corning Fault

The Corning Fault is an offshoot of the Willows Fault that extends north of Artois, Glenn County. It is a north-trending reverse fault of similar structure to the Willows Fault, which has no surface expression, but offsets the Pleistocene-age Red Bluff Formation and the underlying Tehama Formation (Harwood and Helley, 1987). Additionally, Late Cretaceous deposits in the region exhibit offsets of approximately 1,000 feet due to the Corning Fault (Helley and Hardwood, 1985), which can be seen in Cross Section B-B' (Figure 3-11). William Lettis and Associates (2002) concluded that "the Corning Fault is an active seismic source" with an estimated slip rate between 0.0008 and 0.002 inches per year.

3.1.7.3.1.4 Black Butte Fault

The Black Butte Fault is a northwest trending fault that separates the Orland Buttes from Black Butte Lake. Movement along the fault may have caused the uplift of the Orland Buttes (Russell, 1931). Mapping by Helley and Harwood (1985) included on Figure 3-10 depicts the Black Butte Fault as a northward offshoot of the Willows Fault, much like the Corning Fault.

3.1.7.3.1.5 Paskenta Fault

Displacement along the Paskenta Fault impacts the Cretaceous rocks but has not been observed within the Tehama and younger formations, constraining its most recent activity to approximately 3.3 Ma (DWR, 2014). There are two main interpretations of the geologic nature of the Paskenta Fault zone. One interpretation is that the fault zone is a northwest trending, left lateral, transtensional strike slip fault (Moxon, 1990). The other interpretation is that the fault zone originated as an east-striking north-dipping normal fault zone that has been subjected to uplift and tilting to its current northwest trend (DWR, 2014; Jones et. al., 1969; Moxon, 1990). Additionally, some studies represent the fault zone as truncating near Black Butte Lake or transitioning into an anticlinal form while others have mapped the fault as a splay fault from the Willows Fault, as shown on Figure 3-10 (DWR, 2014).

3.1.7.3.2 Folds

Folds may affect groundwater conditions because folding causes the elevation and thickness of geologic units to vary from place to place. Synclines are typically characterized by thickening of younger units near the axis of the fold and potential exposure of older more consolidated units near the margins of the fold. Anticlines are the opposite and can expose less permeable rock formations along their axis and may exhibit thickening of younger less consolidated formations near their margins. Additionally, the permeability and other material properties of sedimentary rocks, such as the Tehama Formation, are typically naturally anisotropic due to the alignment of mineral grains along bedding planes during deposition of the sediments. This alignment of the mineral grains results in higher permeability along rather than across bedding planes, which typically results in a maximum permeability horizontally and a minimum permeability vertically. Subsequent folding of bedding planes causes a reorientation of the direction of the mineral grains, and therefore a reorientation of the maximum and minimum permeability direction, which may affect groundwater flow rates and directions. The folds that were analyzed as part of this report include the Zamora Syncline, the Glenn Syncline, and the Greenwood Anticline. These folds are shown on Figure 3-10 and discussed in the following subsections.

3.1.7.3.2.1 Zamora Syncline

The Zamora Syncline is located in the subsurface east of Arbuckle, Colusa County and extends into Yolo County (Figure 3-10). The Zamora Syncline has no topographic expression, which means that the thickness of post-Cretaceous sediments, including the Tehama Formation, is greater along the axis of the syncline than on the limbs. This means that the aquifer thickness is greatest along the axis of the syncline. The effects of the Zamora Syncline on the older Cretaceous formations can be seen on Figure 3-16, where the elevation of the top of the Cretaceous formations is depressed west and south of College City, Colusa County.

3.1.7.3.2.2 Glenn Syncline

The Glenn Syncline is located near Hamilton City, Glenn County and was formed during the same compressional regime as the Corning Fault (DWR, 2014). The Glenn Syncline roughly follows the direction of the Sacramento River (Figure 3-10). The effects of the Glenn Syncline on the Cretaceous formations can be seen in the elevation contours of the top of the Cretaceous rocks on Figure 3-10, where a depression in the top of the Cretaceous formations corresponds to the axis of the Glenn Syncline. Folding of the geologic formations along the Glenn Syncline can also be seen in Cross Section B-B’ (Figure 3-11). Due to the vertical exaggeration of the cross section, folding is not as evident as the presence of the Princeton Submarine Valley, but a slight depression can be seen in the Great Valley Sequence and Upper Princeton Valley Fill near the Glenn Syncline.

3.1.7.3.2.3 Greenwood Anticline

The Greenwood Anticline and an unnamed syncline are located near Artois, Glenn County. These structures are on opposing sides of the Corning Fault and mimic the change in strike directions displayed by the Corning Fault (Helley and Harwood, 1985). It is believed that the Greenwood Anticline and the unnamed syncline coincided with the formation of the Corning Fault, under the same tectonic stress regimes (DWR, 2014). Comparing Figure 3-10 and Figure 3-16, highs in the top of the Cretaceous formations are associated with the locations of the anticlines.

3.1.7.3.3 Orland Buttes

The Orland Buttes are located along the eastern shore of Black Butte Lake in Glenn County. The buttes are composed of Cretaceous rocks capped by Lovejoy Basalt, which were thought to have been uplifted due to movement along the Black Butte Fault (Russell, 1931). Seismic refraction data and a recent study by Williams Lettis and Associates (2002), however, suggest that the Orland Buttes were exposed via uplift and subsequent eastward tilting along a blind west-dipping thrust fault.

3.1.7.3.4 Sutter Buttes

The Sutter Buttes rise about 2,080 feet above the Sacramento Valley floor east of Colusa and are composed of igneous, metasedimentary and metavolcanic rocks about 2.4 to 1.4 Ma in age (Harwood and Helley, 1987). The formation of the Sutter Buttes occurred in two phases. The first phase caused Upper Cretaceous and Lower Paleogene formations to be arched into a dome rising above land surface during a period of magma injection. This was followed by rapid erosion and heavy faulting of the dome structure, causing the relatively older formations to be exposed prior to the second phase. The second phase consisted of explosive volcanism, producing the rampart tuffs and breccias surrounding the Sutter Buttes. Like many of the other geologic structures of the region, the Sutter Buttes express characteristics representative of the stress regime produced by the Mendocino Triple Junction (Harwood and Helley, 1987).

3.1.7.3.5 Colusa Dome

The Colusa Dome is a subsurface structure located approximately six miles west-southwest of the Sutter Buttes (Harwood and Helley, 1987). The dome is oblong in shape, approximately 12 miles long in the north-south direction and approximately 3 miles wide. Formation of the Colusa Dome, proposed by Harwood and Helley (1987), is due to both drag on the Willows Fault or a related south-trending fault splay and localized magmatic intrusion, potentially during the same period that the Sutter Buttes were forming. The Colusa Dome is characterized by uplift of its Eocene- to Cretaceous rocks. Uplift of the Cretaceous rocks can be seen on Figure 3-16. The Cretaceous rocks have been uplifted to approximately 1,500 feet below ground surface (bgs) while the Eocene deposits have been uplifted to approximately 500 feet bgs (Springhorn, 2008 and Williams and Curtis, 1977).

3.1.8 Basin Boundaries

Per the BMPs (DWR, 2016) and 23 CCR §354.14(b), the lateral basin boundaries can be defined as geologic, hydrologic, or structural features that significantly affect groundwater flow. The lower boundary of the basin can be defined based on physical properties (such as depth to bedrock) or geochemical properties (such as base of fresh water).

3.1.8.1 Lateral Boundaries

Historically, the lateral boundaries of the Colusa Subbasin were defined hydrologically and consisted of Stony Creek to the north, the Sacramento River to the east, Cache Creek to the south, and the foothills of the North Coast Ranges to the west. The hydrologic rationale for these boundaries is that the streams are, or may be, coincident with groundwater divides (boundary zones of either converging or diverging groundwater flow) and the low-permeability Coast Ranges rocks create a barrier to groundwater flow at their contact with the alluvial sediments of the basin.

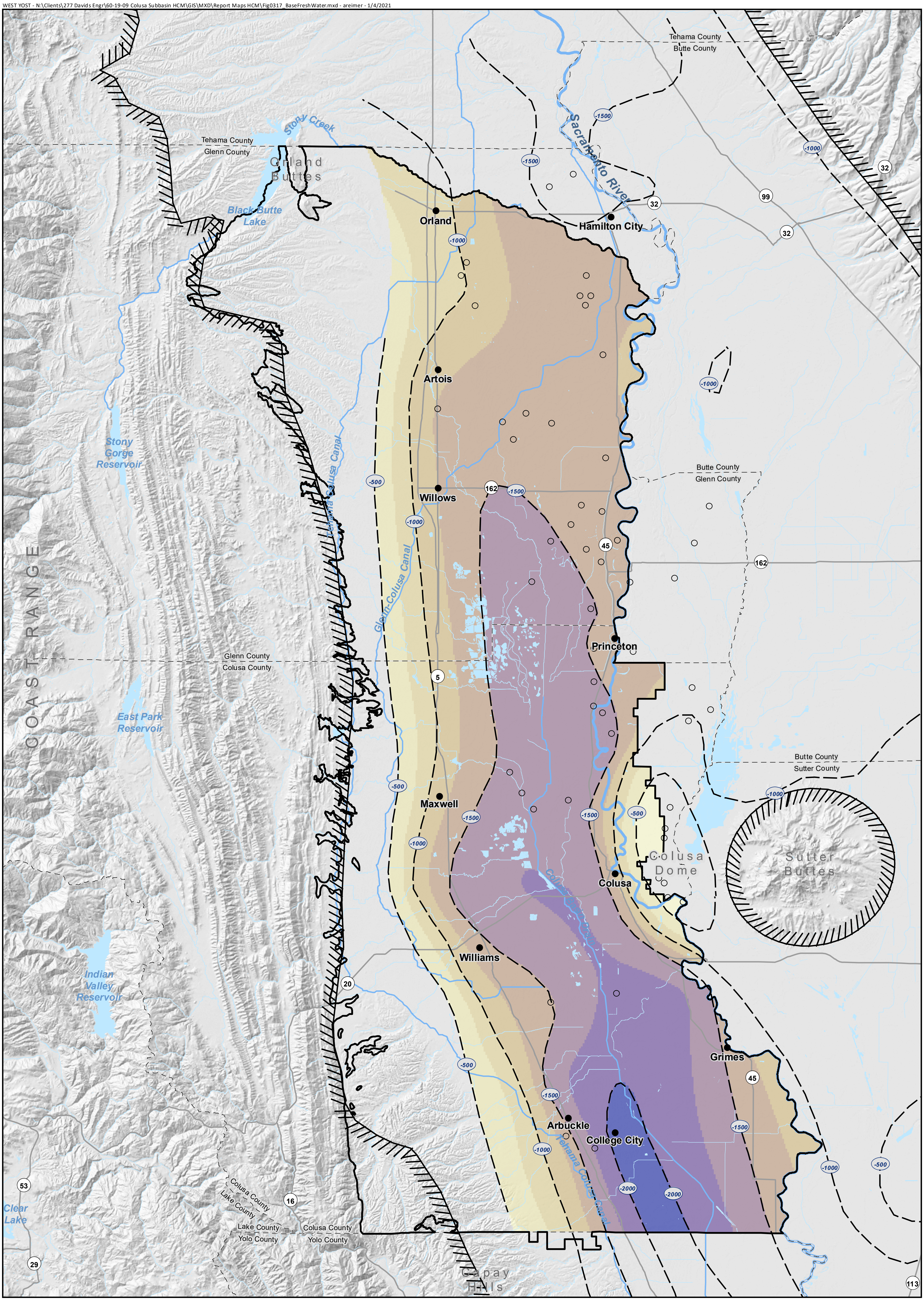
The modified Colusa Subbasin extents have defined the southern boundary to be the Colusa-Yolo County line, a jurisdictional boundary (DWR, 2016). The northern basin boundary is Stony Creek, where the Colusa Subbasin exists within Glenn County, and the Glenn-Tehama County line where Stony Creek exists in Tehama County. Stony Creek and the Coast Ranges comprise the western extent of the Colusa Subbasin. The Sacramento River demarks the eastern boundary of the Colusa Subbasin with the exception of lands within Colusa County east of the Sacramento River and west of Reclamation District 1004, which were added after the basin boundary modifications of 2018 (DWR, 2019).

3.1.8.2 Vertical Boundaries

Figure 3-16 provides elevation contours of the top of Cretaceous-age rocks in the Corning and Colusa Subbasins portion of the of the study area (Harwood and Helley, 1987). These contours provide one approximation of the physical base of the groundwater subbasins in the Colusa Subbasin (Harwood and Helley, 1987). Harwood and Helley (1987) contoured the top of the igneous crystalline and metasedimentary rocks where depth information was available and contoured the top of the Cretaceous rocks where wells were not deep enough to reach the crystalline and metasedimentary rocks. The contours on Figure 3-16 do not account for the post-Cretaceous Lower Princeton Valley Fill and Ione Formation, which were deposited in marine environments, or the Upper Princeton Valley Fill, which can contain fresh or brackish groundwater, and are therefore not considered part of the fresh groundwater basin (Redwine, 1984). These formations lie above the elevation contours shown on Figure 3-16.

The base of the groundwater subbasins can also be defined chemically as the base of fresh water. Figure 3-17 depicts the base of fresh water as defined by USGS (Olmsted and Davis, 1961). According to Olmsted and Davis (1961), the base of fresh water is where specific conductance of the water exceeds 3,000 micromhos, or approximately 2,000 milligrams per liter (mg/L) total dissolved solids (TDS). DWR is preparing an updated map of the base of freshwater within the Central Valley, which will be based on a TDS concentration of 1,000 mg/L, as defined the SWRCB maximum contamination level (MCL) for TDS (DWR, 2016). The base of fresh water defined by C2VSim is defined by a TDS concentration of 3,000 parts per million (ppm) (~3,000 mg/L) and was based on available geophysical logs (DWR, 2020). Data gaps and uncertainties associated with the base of freshwater are discussed in Section 3.1.12.

The cross sections shown on Figure 3-11 through Figure 3-13 contain an approximate delineation of the vertical extent of the subbasin. The physical base of the subbasin was defined as the base of the Tuscan or Tehama Formations. This definition excludes Cretaceous-age formations, post-Cretaceous age sediments of marine origin (Lower Princeton Valley Fill and the Ione Formation). The post-Cretaceous, non-marine Upper Princeton Valley Fill is excluded because it can contain brackish groundwater. This delineation is similar to the delineation based on the chemically defined basin extent, except near the western margins of the study area where brackish groundwater occurs above the Upper Princeton Valley Fill in the Tehama Formation.



Source: Olmsted, F.H. and Davis, G.H., 1961, Geologic Features and Ground-Water Storage Capacity of the Sacramento Valley, California: prepared by U.S. Geological Survey in cooperation with the California Department of Water Resources, Water Supply Paper 1497, plate 5.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Vertical Datum: Mean Sea Level (MSL).

Note:
1. Fresh water is defined as having a specific conductance less than 3,000 micromhos (approximately 2,000 mg/L of total dissolved solids)

○ Well Used for Contouring

Colusa Subbasin

Base of Fresh Water Elevation Contour (feet, dashed where approximate)

Edge of Sierra Nevada, Cascade Range, and Coast Range Province

Elevation of Base of Fresh Water (MSL, feet)

> -500
-750 - -500
-1000 - -750
-1,250 - -1,000
-1,500 - -1,250
-1,750 - -1,500
-2000 - -1,750
<-2,000

0 2.5 5
Scale in Miles

DRAFT

Figure 3-17

Base of Fresh Water

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

3.1.9 Stratigraphic and Structural Features Potentially Affecting Flow

Stratigraphic and structural features that could potentially impact groundwater flow were introduced in Section 3.1.7.3. The structures discussed below are not necessarily basin boundaries but may impede or enable groundwater flow within the aquifer system.

3.1.9.1 Topography

Topographic relief impacts flows at shallower depths in the aquifer system, for example where permeable beds pinch out on elevated topography and the older, less permeable units are exposed on the surface.

3.1.9.2 Faults

Geologic investigations have shown displacement of the hydrogeologic formations along the Willows and Corning Faults. This is evident in the cross sections of Figure 3-11 through Figure 3-13. These basin faults may act as barriers or conduits to fresh groundwater flows. Displacement along the Paskenta Fault zone has not been observed in the fresh groundwater bearing hydrogeologic formations, however, measured and interpolated water levels near the Paskenta and Willows Fault zones near Artois, Glenn County exhibit a consistent localized lowering of the groundwater elevations along the trace of the fault. Additional study of the groundwater conditions would be needed to determine if the fault is acting as a conduit for flow along the fault trace, is impeding flows traverse to the fault, or both.

3.1.9.3 Folds

Synclines are the folding in of the stratigraphic formations, deepening younger formations along the axis of the syncline and potentially exposing the older formations along the margins. Synclines can indicate locations of increased permeability or aquifer connectivity. This is seen within the basin near the Zamora Syncline where the Tehama Formation is characterized by highly pervious, loose, and well bedded layers (DWR, 2006a). Folds can also cause reorientation of naturally anisotropic units causing decreased permeability within the aquifer; however this effect on permeability has not yet been quantified within the subbasin.

3.1.9.4 Stratigraphic Pinchouts

Stratigraphic pinchouts can occur at different scales. At a geologic scale, pinchouts can be found at the lateral extents of the formation, where the formation thickness tapers out. Examples of this within the study include the overlapping fingers of the Tehama and Tuscan Formations throughout the transition zone (Figure 3-15) or where the alluvial and basin deposits truncate against the uplands of the Coast Ranges (Figure 3-10). Pinchout can also be seen in the cross sections on Figure 3-11 through Figure 3-13.

Pinchouts can also occur at a larger scale. Structured heterogeneity of a geologic formation can result in higher permeable sediment occurring within lower permeable material. The Tehama Formation is especially heterogeneous given its depositional history of alluvial and fluvial deposits and is composed of predominantly fine-grained sediments enclosing discontinuous lenses of sand and gravel, which by definition are pinchouts.

3.1.10 Principal Aquifers and Aquitards

There is one principal aquifer within the Colusa Subbasin, which consists of the freshwater-bearing sediments that underlie the Colusa Subbasin. Fresh water can be found in the Holocene basin and stream channel deposits, Modesto Formation, Riverbank Formation, Tehama Formation, and the Tuscan Formation where it exists in the Tehama-Tuscan Transition Zone.

Shallow groundwater in the study area occurs under unconfined conditions in the Holocene stream channel deposits, except where these units are overlain by Holocene basin deposits, creating semiconfined to confined conditions (DWR, 1978). At greater depths, groundwater occurs under semiconfined to confined conditions in a single heterogeneous aquifer system, composed of predominantly fine-grained sediments enclosing discontinuous lenses of sand and gravel. The aquifer properties, including hydraulic conductivity, vertical leakance, and degree of confinement are dependent on the properties of the fine-grained units (Bertoldi et. al., 1991; Williamson et. al., 1989). The physical, chemical, and hydraulic hydrogeologic properties of the principal aquifer are discussed in the following subsections.

Most of the fresh groundwater within the study area is contained within the Tehama Formation. The fraction of fresh groundwater contained within the Tehama Formation decreases in the northeastern portion of the study area, where the Tuscan Formation is more prevalent (Figure 3-15). The interface between the Tehama Formation Aquifer and Tuscan Formation Aquifer, referred to in this report as the Tehama-Tuscan Transition Zone, has been documented as mixed Tehama and Tuscan Formation sediments (DWR, 2009b). These mixed sediment zones grade into the Tehama and Tuscan Formations and probably result in continuity of flow between the Tehama Formation and the Tuscan Formation.

There are no defined principal aquitards within the Colusa Subbasin, however, the formations deposited under alluvial conditions or volcanic flows with lahars, such as the Tehama and Tuscan Formations, respectively, tend to consist of thick low-permeability sediments interbedded with interconnected channels or lenses of higher-permeability sediment. The low-permeability sediments may impede vertical groundwater flows, but generally do not separate the aquifer system into separate, definable principal aquifers.

3.1.10.1 Physical and Structural Properties

The lateral extent of the principal aquifer is the same as the lateral extent of the subbasin and is discussed in Section 3.1.8.1.

The principal aquifer extends to the base of fresh water, which is discussed in Section 3.1.8.2.

The unconfined to semi-confined portion of the principal aquifer primarily consists of Riverbank and Modesto Formations, as well as the overlying Holocene stream channel and basin deposits. These sediments are, at most, approximately 200 feet thick and are comprised of unconsolidated to semi-consolidated materials. These sediments are found throughout the subbasin but pinch out near the western margin of the basin where the foothills and uplands of the Coast Ranges commence, and the Tehama Formation outcrops. Geologic mapping and well records support that the Tehama Formation is relatively thin where it outcrops and does not produce much groundwater. This is discussed more in Section 3.1.7.2.2.

The confined portion of the principal aquifer consists of the Tehama Formation, Tuscan Formation, and to a lesser extent, the Upper Princeton Valley Fill. The Tehama Formation is the primary water-bearing formation within the principal aquifer. The Tehama Formation is heterogeneous with discontinuous sand and gravel lenses. Thicknesses of the Tehama Formation can be as much as approximately 2,000 feet

(Olmsted and Davis, 1961). The Tehama Formation exists throughout the Colusa Subbasin but pinches out along the western margin of the basin with the Coast Ranges and also to the east within the Tehama-Tuscan Transition Zone (Figure 3-15). The Tuscan Formation is composed of interbedded lahars, conglomerate, volcanic sandstone, and volcanic ash layers and can be found at depths greater than 700 feet bgs. The Tuscan Formation within the subbasin exists almost solely within the Tehama-Tuscan Transition Zone but can be found as far east as the foothills of the Sierra Nevada Mountain Range. The Upper Princeton Valley Fill is located at depths greater than 1,000 feet bgs where it exists within the subbasin and is predominantly composed of sandstone. Table 3-4 contains the ranges of vertical and horizontal hydraulic conductivity, transmissivity, storativity, and specific yield values for the principal aquifer's unconfined and confined hydrogeologic units as listed in published reports on aquifer testing. Analytical models such as the Theis or Hantush-Jacob methods commonly enable the estimation of transmissivity and storativity from aquifer test data. Transmissivities can then be used to determine hydraulic conductivity of a water-bearing unit. Hydraulic conductivities are a measure of the aquifer's ability to transmit water horizontally or vertically. Aquifer materials generally have higher horizontal hydraulic conductivity than vertical hydraulic conductivity. Confining units are generally the limiting factor when evaluating vertical movement of water through the aquifer system.

Horizontal hydraulic conductivity of the unconfined to semi-confined zone ranges from 10 to 229 feet per day (ft/day).

A typical horizontal hydraulic conductivity of the Tehama Formation is approximately 27 ft/day. Within the permeable units of the Tuscan Formation (Units A and B), horizontal hydraulic conductivities range from 11 to 88 ft/day. One study estimated horizontal hydraulic conductivity within the confining unit of the Tuscan Formation (Unit C) to be 321 to 571 ft/day (Brown and Caldwell, 2013), an order of magnitude larger than those estimated within the more permeable units. Typically, the horizontal hydraulic conductivity of low-permeability strata is lower than that of its more permeable counterparts. This discrepancy in hydraulic conductivity values may be due to aquifer testing conducted within highly permeable zones within Unit C. More investigation into the discrepancy is recommended, as discussed in Section 3.1.12.2.

Vertical hydraulic conductivity for the confining unit in the Tehama-Tuscan Transition Zone was estimated to be 0.0036 ft/day based on data obtained during an aquifer test using a multiple completion observation well with separate completions perforated above and below the confining unit (West Yost, 2012).

Water released from storage within confined aquifer systems is characterized by the storativity of the aquifer units. Storativity is estimated to range from 0.0003 to 0.001 for the Tehama Formation and 0.00004 to 0.003 for the Tuscan Formation. Storativity of Unit A of the Tuscan Formation (the deepest unit) is generally higher than that of Unit B (Brown and Caldwell, 2013), but still lower than that of the Tehama Formation. Storativity values are not reported for the unconfined portion of the Tuscan Formation.

Specific yield represents the water released from drainage from the pore space between the individual grains that comprise the aquifer sediment. Specific yield is only specified for the unconfined portion of the principal aquifer. Specific yield for the unconfined portion of the principal aquifer is approximately 0.034 to 0.185 (3.4 percent to 18.5 percent) (Olmsted and Davis, 1961).

Structural properties that could impact groundwater flows within the principal aquifer are discussed in more detail in Section 3.1.9.

Table 3-4. Hydraulic Properties

Hydraulic Property per Source	Unconfined to Semi-Confined	Confined (Tehama Formation)	Confined (Tuscan Formation)		
			Unit C	Unit B	Unit A
Transmissivity, ft^2/day					
Stony Creek Fan Aquifer Performance Testing[a]	--	2,466 - 4,727	--	2,705 - 8,902	2,705 - 8,902
Tuscan Aquifer Investigation[c]	--	--	11,550 - 20,540	2,322 - 3,078	12,230 - 23,650
Horizontal Hydraulic Conductivity, ft/day					
Stony Creek Fan Aquifer Performance Testing[a]	--	26.6	--	11.4 - 13.2	11.4 - 13.2
Stony Creek Fan Feasibility Study[b]	10 - 229	--	--	--	--
Tuscan Aquifer Investigation[c]	--	--	321 - 571	66 - 88	41 - 79
Vertical Hydraulic Conductivity, ft/day					
Stony Creek Fan Aquifer Performance Testing[a]	--	--	0.0036	--	--
Storativity, unitless					
Stony Creek Fan Aquifer Performance Testing[a]	--	0.0003 - 0.001	--	0.0009 - 0.003	0.0009 - 0.003
Tuscan Aquifer Investigation[c]	--	--	0.0003 - 0.0005	0.00004 - 0.00009	0.00004 - 0.001
Specific Yield, unitless					
USGS Water Supply Paper 1497[d]	0.034 - 0.185	--	--	--	--

(a) West Yost, 2012
(b) Montgomery Watson Harza (unpublished) via WRIME, 2003
(c) Brown and Caldwell, 2013
(d) Olmsted and Davis, 1961

3.1.10.2 Primary Uses

There are twenty (20) stakeholders within the Colusa Subbasin shown on Figure 3-6. These stakeholders include municipalities, water agencies, irrigation districts, wildlife refuges, and reclamation districts. Not shown on Figure 3-6 are private and domestic pumpers located in the “white-space” of the Colusa Subbasin. The primary uses of groundwater within the principal aquifer include irrigation, domestic, industrial, and municipal supply (DWR, 2006a).

3.1.10.3 Water Quality

Historical groundwater quality concerns within the study area include locally elevated levels of electrical conductivity (EC) and TDS, adjusted sodium absorption ratio, boron, nitrate, and manganese (DWR, 2006a; Wood Rodgers, 2008). Many of the entities within Glenn and Colusa Counties that monitor groundwater for quality either use wells that have multiple or long perforated intervals that access groundwater from both the unconfined and confined portions of the principal aquifer, or report water quality results from their wells collectively, without specifying what depth(s) the well was screened in. This data gap is discussed in more detail in Section 3.1.12 of this report.

Recent groundwater quality concerns within the Colusa Subbasin include salinity, boron, nitrate, heavy metals, including arsenic, and hexavalent chromium. High concentrations of sodium, chloride, and sulfate, all of which are related to salinity (TDS and EC) have been observed south of Maxwell (CH2MHILL, 2016; RD 108, 2008) and could negatively impact agricultural applications. Elevated concentrations of boron within Colusa County have already impacted agricultural practices (GCID, 1995). In contrast, boron concentrations measured in select groundwater wells within Glenn County have not exceeded the United States Environmental Protection Agency (USEPA) agricultural water quality goal for boron of 750 micrograms per liter (μg/L) (USEPA, 1986; USGS, 2018). Elevated salinity levels throughout much of Colusa County, nitrates near Orland and Willows, arsenic near Grimes, and iron and manganese near Williams and Colusa are of concern with respect to drinking water MCLs (CH2MHILL, 2016). Drinking water supply wells near Willows, Glenn County, have experienced high concentrations of hexavalent chromium (California Water Service, 2016).

There are also several active groundwater contamination cleanup sites in the study area. These primarily include leaky storage tanks and unauthorized releases of contaminants such as petroleum hydrocarbons, nitrate, pesticides and herbicides including dicamba, and solvents. Most of these cleanup sites impact the unconfined portion of the principal aquifer, but there is a risk that the contamination could migrate into the deeper, more heavily pumped portions of the aquifer. The largest contamination site is the Orland Dry Cleaner site, a tetrachloroethylene (PCE) plume that extends approximately two miles southeast of the source location in Orland, Glenn County (Department of Toxic Substances Control [DTSC], 2018; SWRCB, 2020b). In 2007, PCE contamination was recorded at depths of 127 feet bgs (DTSC, 2018.

More detail regarding existing and historical groundwater quality issues and trends is provided in Section 3.2 of this GSP.

3.1.11 Groundwater Inflows and Outflows

Groundwater underflows between the Colusa Subbasin and neighboring groundwater subbasins depend on fixed aquifer hydraulic properties and the prevailing groundwater gradients, which are influenced by time-dependent natural recharge and discharge patterns, aquifer interactions with streams, the effects of pumping, and the effects of managed and unmanaged recharge. These inflows and outflows are discussed further in the following subsections.

3.1.11.1 Groundwater Underflow

Groundwater underflow occurs across the boundary of the Colusa and Yolo Subbasins under the influence of the generally southeasterly to southerly groundwater flow gradient. The boundary between the Colusa and Yolo Subbasins is jurisdictional and has no influence on the flow of groundwater (Figure 3-4). Groundwater underflow may occur as either outflow or inflow across the northern and eastern hydrologic borders of the study area, where the Colusa Subbasin abuts neighboring subbasins. The magnitude of these underflows is not currently quantified but is anticipated to be a relatively small component of the water budget for the study area and neighboring groundwater subbasins. Significant influences on these inflows and outflows include groundwater gradients across subbasin boundaries, stream stage in the Sacramento River, Stony Creek and Butte Creek, and the timing, location, and magnitude of groundwater pumping, managed recharge, and unmanaged recharge, which includes recharge due to agricultural practices and precipitation.

Underflow across the western boundary of the study area is negligible due to the low permeability of the Coast Range rocks.

3.1.11.2 Groundwater Recharge Areas

The primary sources of groundwater recharge in the Colusa Subbasin are deep percolation – the movement of water from land surface to the aquifer – of precipitation and applied water. Other volumetrically less important sources include deep percolation resulting from domestic and municipal uses.

3.1.11.2.1 Agricultural Recharge

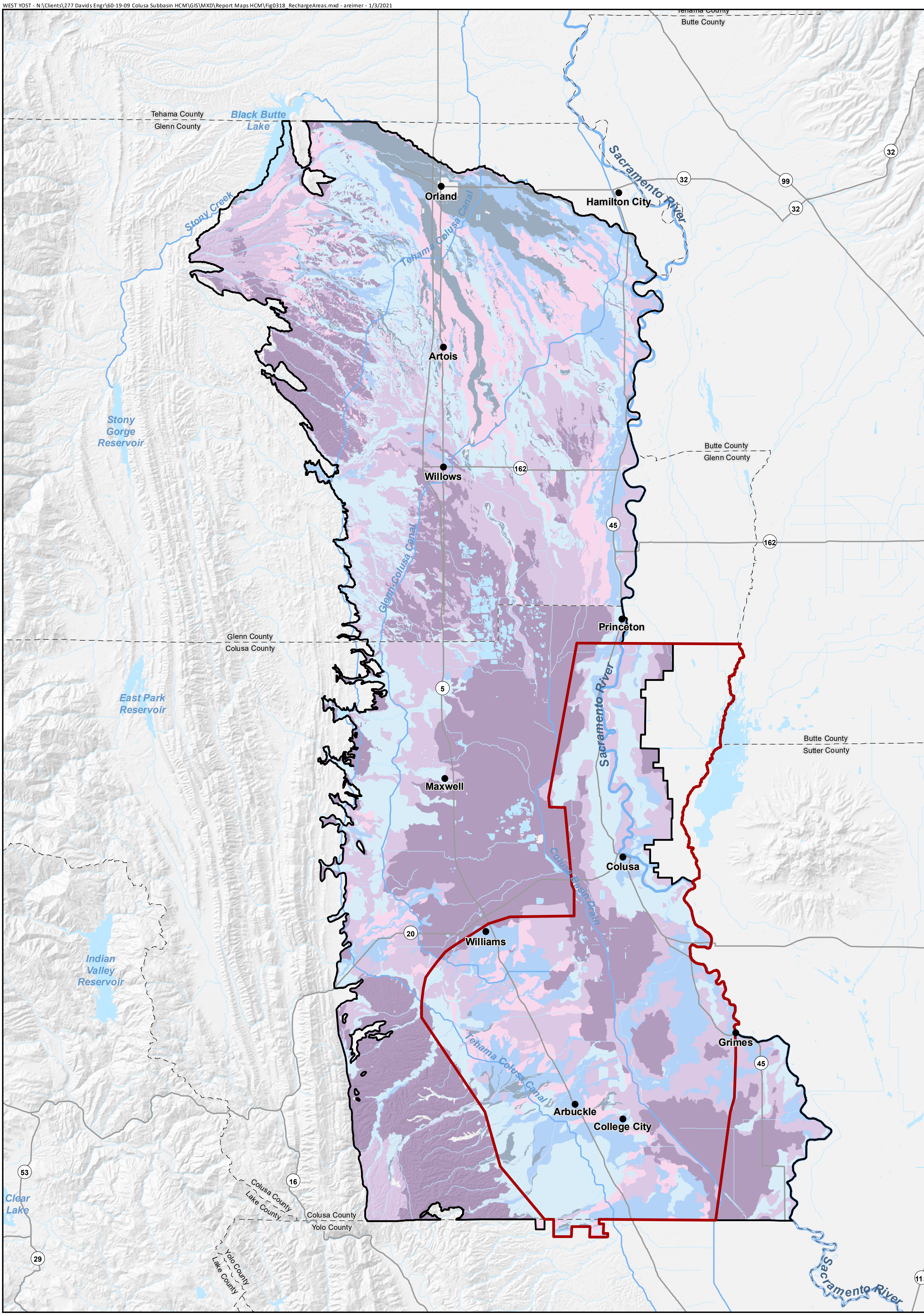
Much of the study area is devoted to agriculture; many of the agricultural fields are irrigated with surface water supplies from the Tehama-Colusa Canal, the Glenn-Colusa Canal, and other irrigation water supply systems, which provide Sacramento River water from outside of the basin boundaries (Figure 3-6). Water applied to agricultural lands has a significant contribution to groundwater recharge.

3.1.11.2.2 Soil Suitability for Groundwater Banking

Recharge occurs throughout the study area, but at variable rates depending on topography, soil properties and the underlying geology, as introduced in Sections 3.1.4, 3.1.6, and 3.1.7, respectively. Figure 3-18 shows potential recharge areas based on the Soil Agricultural Groundwater Banking Index (SAGBI) (O’Geen et. al., 2015). SAGBI was developed to provide a measure of soil suitability for recharge on agricultural lands while maintaining the viability of soils and crops, and groundwater quality. The index was developed considering five major factors (O’Geen et. al., 2015):

1. Deep percolation;
2. Root zone residence time;
3. Topography;
4. Chemical limitations; and
5. Soil surface conditions.

As depicted on Figure 3-18, the index also includes the assumption that soils with restrictive layers would be made more permeable through deep tillage. The index ranges from very poor to excellent over the study area.



Source: O'Geen, A.T. et. al., 2015, Soil Suitability Index Identifies Potential Areas for Groundwater Banking on Agricultural Lands: California Agriculture, Volume 69, Number 2, pages 75-84, April 2015, GIS files provided November 2017.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Note:
1. Modified Soil Agricultural Groundwater Banking Index (SAGBI) suitability groups assume that soils with restrictive soil layers have been modified by deep tillage.

Colusa Subbasin

Colusa Multi-Benefit Groundwater Recharge Project Area (2020)

Soil Agricultural Groundwater Banking Index with Assumed Deep Tillage Modification

Excellent
Good
Moderately Good
Moderately Poor
Poor
Very Poor

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Figure 3-18

Locations of Potential Recharge

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

Soils with indices in the moderately good to excellent range correspond to hydrologic soil groups A through C, as discussed in Section 3.1.6, and are mostly located over younger alluvial fan and stream channel deposits, including those of Stony Creek and other small streams draining the Coast Ranges, and younger stream channel deposits located along the Sacramento River (Figure 3-9 and Figure 3-10).

3.1.11.2.3 Multi-Benefit On-Farm Managed Aquifer Recharge Program

In 2018, the Colusa Groundwater Authority in cooperation with The Nature Conservancy (TNC) implemented a pilot managed aquifer recharge program. During this program, farmers worked with TNC to create temporary wetlands using existing water conveyance infrastructure and available flows during fall and winter migration periods. The program sought to increase groundwater recharge in severely disadvantaged communities while providing habitat for migratory birds. Various factors including water availability, soil suitability, and farming practices were evaluated for participating farmers. The pilot project areas are delineated on Figure 3-18.

3.1.11.3 Groundwater Discharge Areas

Groundwater discharges in the study area include:

- Discharges to streams, drains, seeps and springs;
- Losses to the atmosphere through uptake and consumption by wetland or riparian vegetation (phreatophytes), deeply rooted crops, and bare soil evaporation under shallow water table conditions; and
- Groundwater pumping.

Figure 3-19 and Figure 3-20 show depth to groundwater during the spring of 2006 (prior to the multiple year droughts of 2007-2009 and 2012-2015) and the spring of 2017 (after the multiple year droughts), respectively.

Areas with depth to groundwater close to land surface may indicate potential zones of groundwater discharge that can be expressed as flowing artesian wells, or through discharge to ponds, springs wetlands, streams and canals. Discharges can also occur through evapotranspiration from riparian or phreatophytic vegetation, and from bare soil evaporation.

In the spring of 2006, the largest of these potential discharge zones was in a low elevation area of the Colusa Subbasin aligned along a north-northwesterly trend extending from the Colusa-Yolo County line into the southern half of Glenn County (Figure 3-19). The axis of the southerly part of this zone was aligned with the Colusa Basin Drain, which is an indication that the Colusa Basin Drain received groundwater discharge in spring 2006. Shallow depths to water in spring of 2006 also were evident along the Sacramento River, indicating that some reaches of the Sacramento River may have received groundwater discharges in spring 2006.

The extent of potential groundwater discharge areas in the spring of 2017 was similar but more limited.

Comparison of the depth to groundwater contours to land use shows that many areas with shallow depths to groundwater correspond to the areas of rice cultivation and wildlife refuges. Ponded agricultural fields tend to be in areas that contain a high percentage of silts and clays, which restrict, yet do not negate the vertical flow of water into or out of the groundwater system. A portion of the groundwater would therefore discharge into the ponded water and a portion would discharge into unlined irrigation canals, drains, or ephemeral stream channels.

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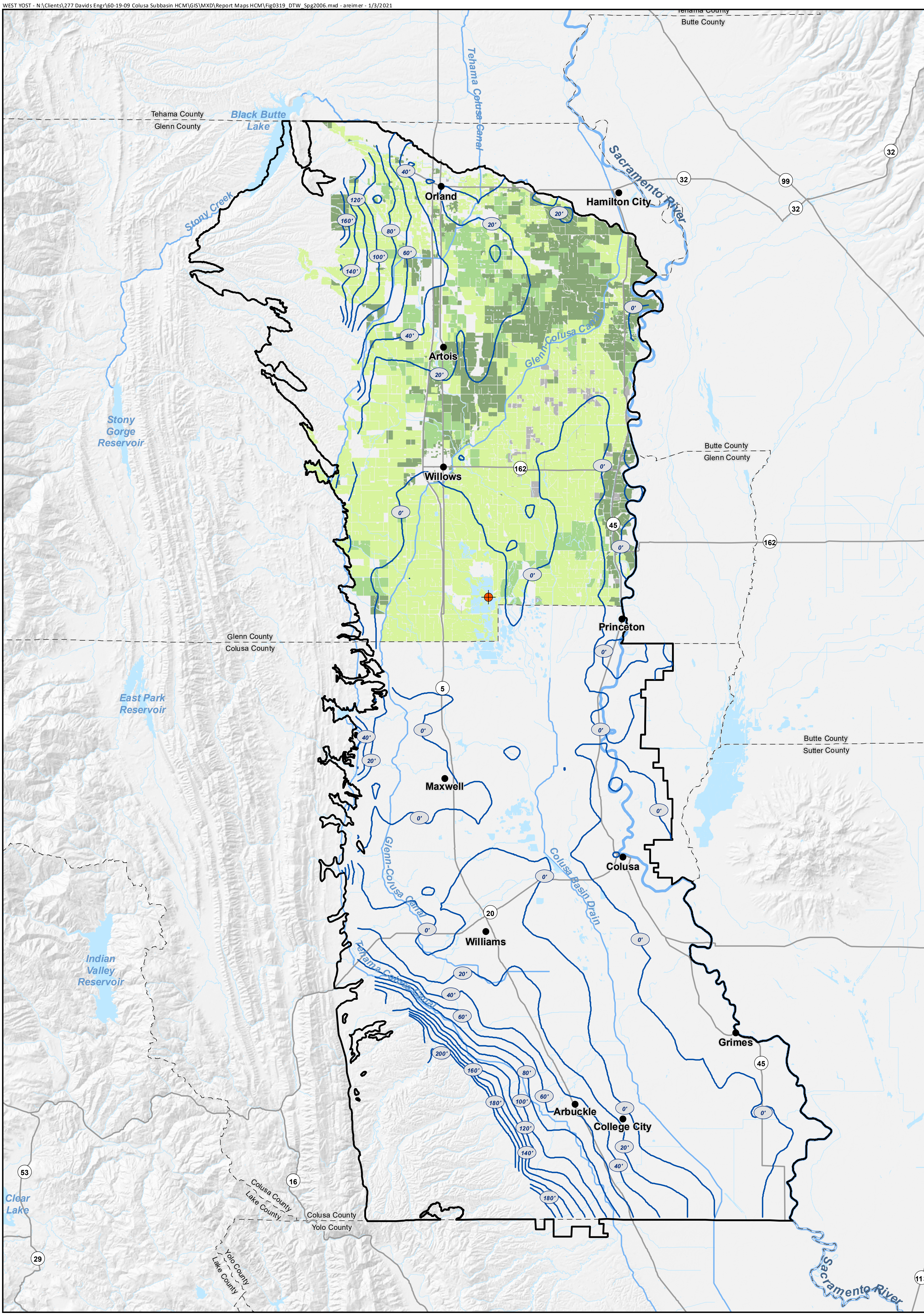

Source: Water levels were obtained from the California Department of Water Resources Water Data Library. Water source information was obtained from DWR Land Use Survey. Water source data for Glenn County was surveyed in 2003. Colusa County was surveyed in 2003 for land use but not water use.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Well 18N02W18D001-004M

Spring 2006 Depth to Water Contours (feet, 20-foot Interval)

Colusa Subbasin

Water Source (2003)

Surface Water

Mixed Surface and Groundwater

Groundwater

Unknown

0 2.5 5

Scale in Miles

DRAFT

Figure 3-19

Depth to Groundwater Contours Spring 2006

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

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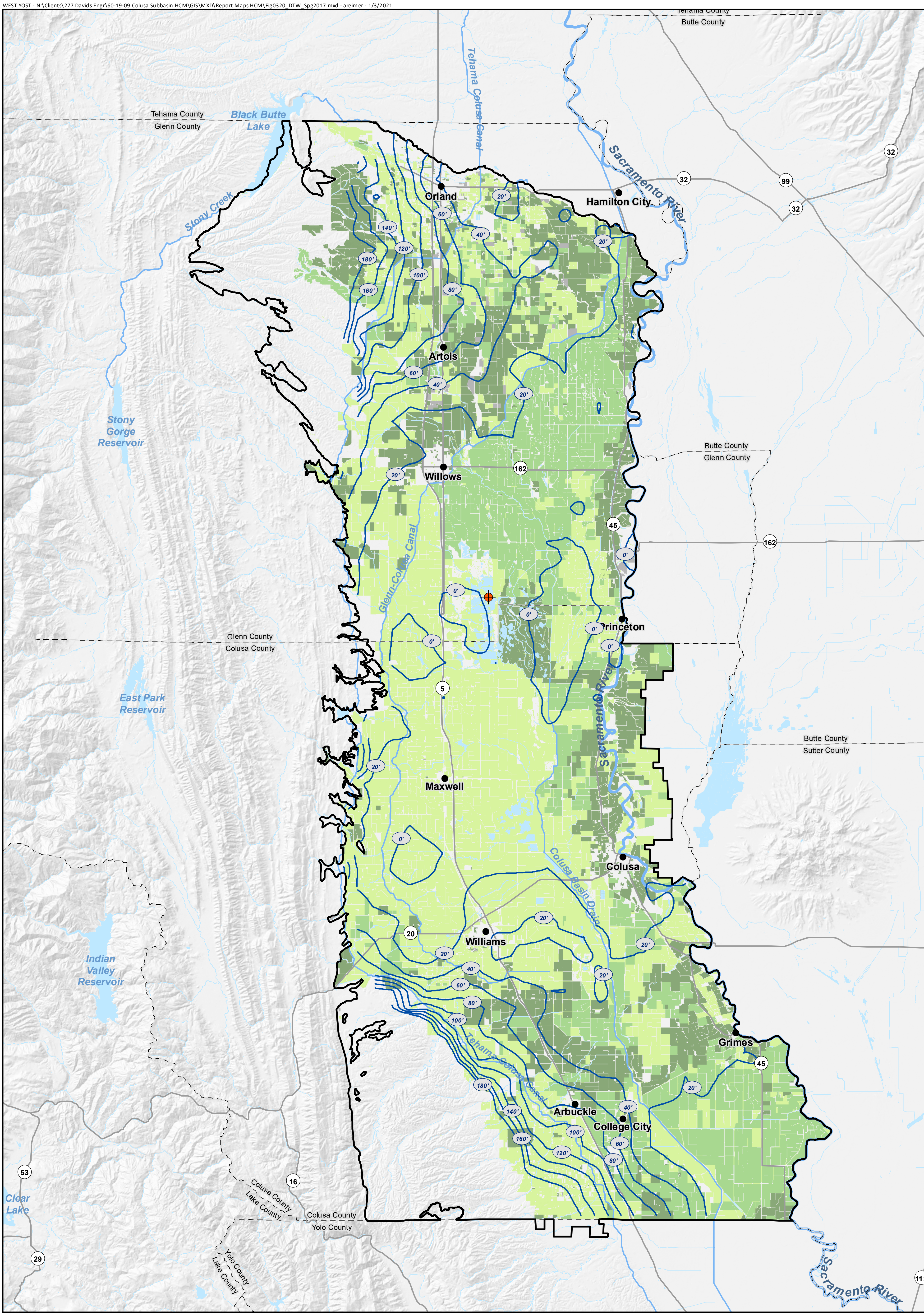


Source: Water levels were obtained from the California Department of Water Resources Water Data Library. Water source information was obtained from DWR Land Use Survey. Water source data for Glenn and Colusa Counties were marked as provisional, 2014.

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, feet.

Well 18N02W18D001-004M

Spring 2017 Depth to Water Contours (feet, 20-foot Interval)

Colusa Subbasin

Water Source (2014)

Surface Water

Mixed Surface and Groundwater

Groundwater

Unknown

N

0 2.5 5

Scale in Miles

DRAFT

Figure 3-20

Depth to Groundwater Contours Spring 2017

Colusa GSA and Glenn GSA

Colusa Subbasin

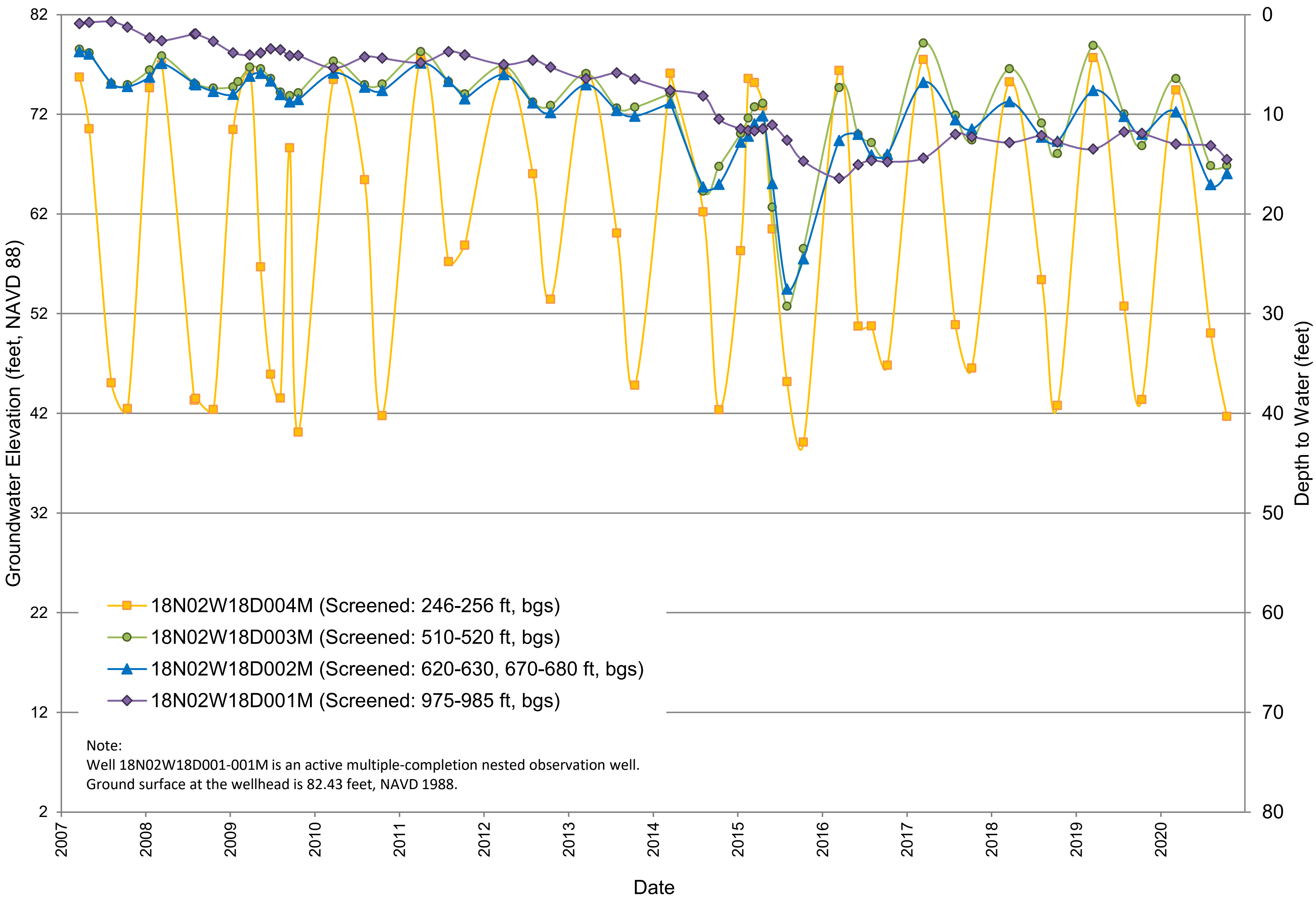
Groundwater Sustainability Plan

The potential for flowing artesian conditions is evident in the historical groundwater level measurements for some monitoring wells in the Colusa Subbasin. Figure 3-21 is a hydrograph for a multiple completion well located north of the Sacramento National Wildlife Refuge, west of Princeton. As seen on the hydrograph, the groundwater within the deep completion (18N02W18D001) historically has a higher potentiometric head than the groundwater within the shallower completions. This indicates a potential for upward flow of groundwater from the deeper confined water-bearing units to the shallower confined water-bearing units. Starting in 2014 and continuing through the first half of 2020, however, the depth to groundwater within the deepest completion has decreased significantly, indicating a reversal in the vertical flow direction. This period corresponds to the multiple year droughts of 2007 to 2009 and 2012 to 2016. Although the overall depths to groundwater were greater in the latter half of 2020, the vertical flow direction reverted back to pre-2014 conditions.

Groundwater pumping within the basin serves municipal, domestic, irrigation, and environmental needs. Figure 3-19 and Figure 3-20 show the irrigation districts, reclamation districts, municipal water agencies, and wildlife refuges within the study area and the water supply source identified by DWR (2014). DWR surveys of groundwater extraction for the Colusa Subbasin reported approximately 310,000 af for agricultural applications, 14,000 af for municipal and industrial consumption, and 22,000 af for environmental wetland use (DWR, 2006a). There are also many unmetered domestic wells located throughout the study area. Colusa County estimates approximately 1,200 af of groundwater extraction from domestic wells (Wood Rodgers, 2008) within County lines. A more detailed discussion of the water budget is discussed in Section 3.3 of this GSP.

While the municipalities rely on groundwater to serve their residents, much of the agricultural lands within the study area divert surface water supplies for irrigation. Some of the farmlands use a mix of surface water supplies and groundwater (Figure 3-19 and Figure 3-20. The primary groundwater pumping areas for irrigation correspond to farmlands that do not receive surface water supplies. An example of this includes farmlands that are not part of an existing irrigation district.

Figure 3-21. Hydrograph for Well 18N02W18D001-004M



3.1.12 Data Gaps, Uncertainty, and Recommended Actions

BMPs for the HCM (DWR, 2016) state that "the HCM should be developed and periodically updated as part of an iterative process as data gaps are addressed and new information becomes available". The different components of the HCM were evaluated for data gaps, uncertainty, and unresolved discrepancies identified through comparison with the C2VSimFG. These topics and recommended future actions are discussed in more detail in the following subsections. More information regarding C2VSimFG and how it was used for the Colusa Subbasin can be found in an accompanying technical memorandum.

3.1.12.1 Extent of Geologic Units, Principal Aquifer, and Base of Fresh Water

Uncertainties in the thickness and extent of the principal aquifer, geologic formations, and base of fresh water have been identified in the following areas of the subbasin:

1. Tehama-Tuscan Transition Zone;
2. Northwestern upland area, west of Orland;
3. Southwestern upland area, west of Arbuckle; and
4. Near the Zamora Syncline, east of Williams and College City.

There is uncertainty regarding the extent and depths of the Tehama and Tuscan Formations within the Tehama-Tuscan Transition Zone. Previous geologic mapping shown on the cross sections (Figure 3-11 through Figure 3-13) and Figure 3-15 depict thick depositions of Tehama and Tuscan within the Transition Zone, but the borehole data delineating the thickness and extent of units and the degree to which Tehama and Tuscan Formation sediments are intermixed is limited.

The base elevation of the uppermost three C2VsimFG model layers is overlain on the cross sections (Figure 3-11 through Figure 3-13). The modeled layers for C2VSimFG are based on groundwater conditions and pumping, not geologic units, but can be compared with the extent of the geologic units comprising the principal aquifer. The principal aquifer is also characterized by the extent and thickness of the freshwater-bearing geologic formations within the subbasin. Therefore, the extent of the geologic formations, principal aquifer, mapped base of freshwater and extent of the model layers are all related. Discrepancies between these datasets highlight uncertainty in the underlying datasets, the methods used to interpolate the base of fresh water, and the methods used to interpolate the thicknesses of geologic formations between locations with known data. Available information in the northwest uplands indicate that the Tehama Formation in that area is relatively thin compared to the rest of the subbasin and has low groundwater yield. The geologic mapping and cross section B-B' shown on Figure 3-10 and Figure 3-11 support this theory. The modeled base of fresh water, however, shows the principal aquifer as approximately 1,000 feet thick. This contradicts the available geologic data and verbal reports from residents of the area. Olmsted and Davis (1961) did not map the base of fresh water in this area. Table 3-5 provides a comparison of the four model layers with the principal aquifer and geologic formations.

Table 3-5. Comparison of Modeled Layers with Principal Aquifer and Geologic Units			
C2VSimFG Model Layer Number	C2VSimFG Model Layer Description	Principal Aquifer	Geologic Formation
1	Unconfined Freshwater Aquifer Zone with Pumping	Unconfined Zone	Holocene Basin Fill and Stream Channel Deposits Modesto Formation Riverbank Formation Tehama Formation (minimal)
2	Confined Freshwater Aquifer Zone with Pumping	Confined Zone	Tehama Formation Tuscan Formation
3	Confined Freshwater Aquifer Zone with Little Pumping	Confined Zone	Tehama Formation Tuscan Formation Upper Princeton Valley Fill (partial)
4	Confined Saline Aquifer	--	Upper Princeton Valley Fill (partial) Ione Formation Lower Princeton Valley Fill

Uncertainty is even greater in the southwestern upland area than the northwest upland area. In addition to minimal available well logs, there are no mapped isolated outcrops of older Cretaceous-aged rocks within the southern uplands to indicate uplift of older bedrock formations. Cross sections D-D’ and G-G’, which cut through the southwestern upland area, show the reverse discrepancy along the west margin of the basin (Figure 3-12). Cross sections D-D’ and G-G’ show the modeled base of the aquifer to be much shallower than the mapped freshwater-bearing geologic units.

The Tehama Formation thickens near the Zamora Syncline, however available data that identifies the base of the Tehama Formation in this area is scarce. The modeled based of fresh water from C2VSimFG and the mapped base of fresh water from Olmsted and Davis (1961) both indicate that fresh water exists at depths greater than those shown on cross section G-G’ (Figure 3-12).

Other locations where the modeled or mapped base of fresh water does not coincide with the freshwater-bearing formations can be seen on the cross sections (Figure 3-11 through Figure 3-13). For example, near the Corning Fault on cross section B-B’, near Sacramento River on cross section D-D’, or between Cortina Creek and the Tehama-Colusa Canal on cross section F-F’.

Additional subsurface data will be collected to help delineate the base of the geologic formations in the aforementioned areas. The vertical extents of these geologic units will be updated through evaluation of DWR’s forthcoming texture model developed as part of the Sacramento Valley Simulation Model (SVSim); inspection of geophysical logs from oil and gas wells; aeromagnetic surveys; in-depth evaluation of available well completion reports (most of which may not be deep enough to characterize the base of the Tehama and Tuscan Formations, but may be sufficient to better define the Tehama-Tuscan Transition Zone); information from new boreholes; and/or other methods or data sources that may characterize the subsurface stratigraphy.

Different agencies have chosen different TDS concentration thresholds to define the base of fresh water. These different threshold concentrations used to classify fresh water versus saline water may be a contributing factor in the discrepancy. Olmsted and Davis (1961) used a threshold of approximately 2,000 mg/L while C2VSimFG assumes a threshold of 3,000 ppm (approximately 3,000 mg/L of TDS, DWR, 2020), and DWR is preparing an updated map of the base of freshwater within the Central Valley, which will be based on a TDS concentration of 1,000 mg/L, the MCL for TDS (DWR, 2016).

Once additional information is evaluated, either the geologic extents in the HCM can be updated and the relevant C2VSimFG model inputs can be adjusted to better represent the principal aquifer in these areas.

3.1.12.2 Hydraulic Parameters

Hydraulic parameter estimates will be updated and refined by performing additional pumping tests, and reanalyzing existing test data in cases in which parameter estimates are outside of expected ranges. Pumping tests will use pumping wells and dedicated monitoring wells discretely screened in either the unconfined or confined portion of the principal aquifer in order to better quantify hydraulic parameters per the principal aquifer's unconfined or confined condition.

The hydraulic properties of Tuscan Formation Unit C will be further investigated to verify the high hydraulic conductivities reported for Unit C and their applicability in the Colusa Subbasin.

3.1.12.3 Groundwater Quality

23 CCR §354.14(b)(4)(D) states that "general water quality of the principal aquifers" shall be included in the HCM. Future groundwater quality characterization efforts will utilize wells with known construction. The wells used to characterize groundwater quality discussed in this report are all drilled within the principal aquifer but have not been identified as representing the unconfined or confined conditions. Identifying well depths and construction information would be beneficial in order to better understand groundwater quality and the potential spatial trends and movement of contaminants within the principal aquifer.

3.1.12.4 Groundwater Level Measurements

Groundwater elevation contours shown on Figure 3-19 and Figure 3-20 imply that the faulting could be impacting the localized groundwater flow regime. Additional water level measurements collected from the greater Artois area and westward would allow better evaluation of groundwater conditions in the area. More data could shed light on if the localized groundwater lows are due to the fault zone or some other factor such as localized pumping.

3.2 EXISTING & HISTORICAL GROUNDWATER CONDITIONS *(REG. § 354.16)*

This section describes the existing and historical groundwater conditions of the Colusa Subbasin to support development and implementation of the GSP pursuant to the requirements of SGMA. This report section was prepared through a coordinated effort between the GSAs responsible for managing the Colusa Subbasin: the Colusa Groundwater Authority and the Glenn Groundwater Authority.

3.2.1 Regulatory Requirements

Title 23 Section 354.16 of the California Code of Regulations (23 CCR §354.16) requires that the GSP "shall provide a description of current and historical groundwater conditions in the basin, including data from January 1, 2015, to current conditions, based on the best available information" and shall include descriptions for conditions related to the six undesirable results listed under SGMA:

- Groundwater elevations (Section 3.2.2)
- Groundwater storage (Section 3.2.3)
- Seawater intrusion (Section 3.2.4)
- Groundwater quality issues (Section 3.2.5)
- Land subsidence (Section 3.2.6)
- Interconnected surface water systems (Section 3.2.7)
- Groundwater-dependent ecosystems (Section 3.2.8)

This section addresses these requirements using currently available data and information in accordance with the information provided by DWR and listed in the California Code of Regulations.

3.2.2 Groundwater Elevations

Appendix 3-A contains the location map and historical hydrographs for the 50 wells identified as part of the Colusa Subbasin groundwater monitoring network. The monitoring network contains a mix of active water supply wells and dedicated observation wells. The monitoring network wells are constructed to different depths within the principal aquifer and represent conditions within the unconfined to confined zones. Appendix 3-B contains historical groundwater elevation contour maps for spring and fall of calendar years 2006 (wet conditions), 2015 (critical conditions), 2017 (wet conditions), and 2020. Most of the wells used in contouring are screened at depths greater than 100 feet and represent groundwater levels in the semiconfined to confined part of the principal aquifer.

3.2.2.1 Temporal and Spatial Trends

Figure 1 of Appendix 3-A shows the locations of the monitoring wells within the subbasin. A hydrograph representative of typical historical and seasonal groundwater level trends within the Colusa Subbasin is shown on Figure 3-22. The Colusa Subbasin has a Mediterranean-type climate with wet winters and dry summers. Seasonal trends in groundwater elevations reflect these seasonal climatic changes. During the dry season when there is an increase in groundwater pumping, depth to groundwater increases, and during the rainy season when there is a decrease in demand and groundwater recharge rates are higher, groundwater levels decrease. These seasonal fluctuations in groundwater elevations can be seen in the hydrograph on Figure 3-22. The magnitude of the seasonal drawdown and recovery depends on hydrologic conditions (e.g. dry or wet years) and human influence such as demand and available water supply sources.

Well 13N01W07G001M (Figure 3-22) is screened in the unconfined to semi-confined portion of the principal aquifer. Groundwater levels declined during the droughts of 1976 to 1977, 1987 to 1991, 2007 to 2009, and 2012 to 2016 and either stabilized or recovered after these dry years. The most notable recovery period occurred around 1983, which was both a wet year and when water users added more surface water to their supply portfolios. Groundwater recharge increased after the introduction of surface waters due to a decrease in groundwater pumping and the addition of applied surface waters for agricultural use. Event signatures such as these are less notable in shallow wells located near surface waters, where flows in perennial streams or irrigation canals may smooth out impacts to groundwater levels.

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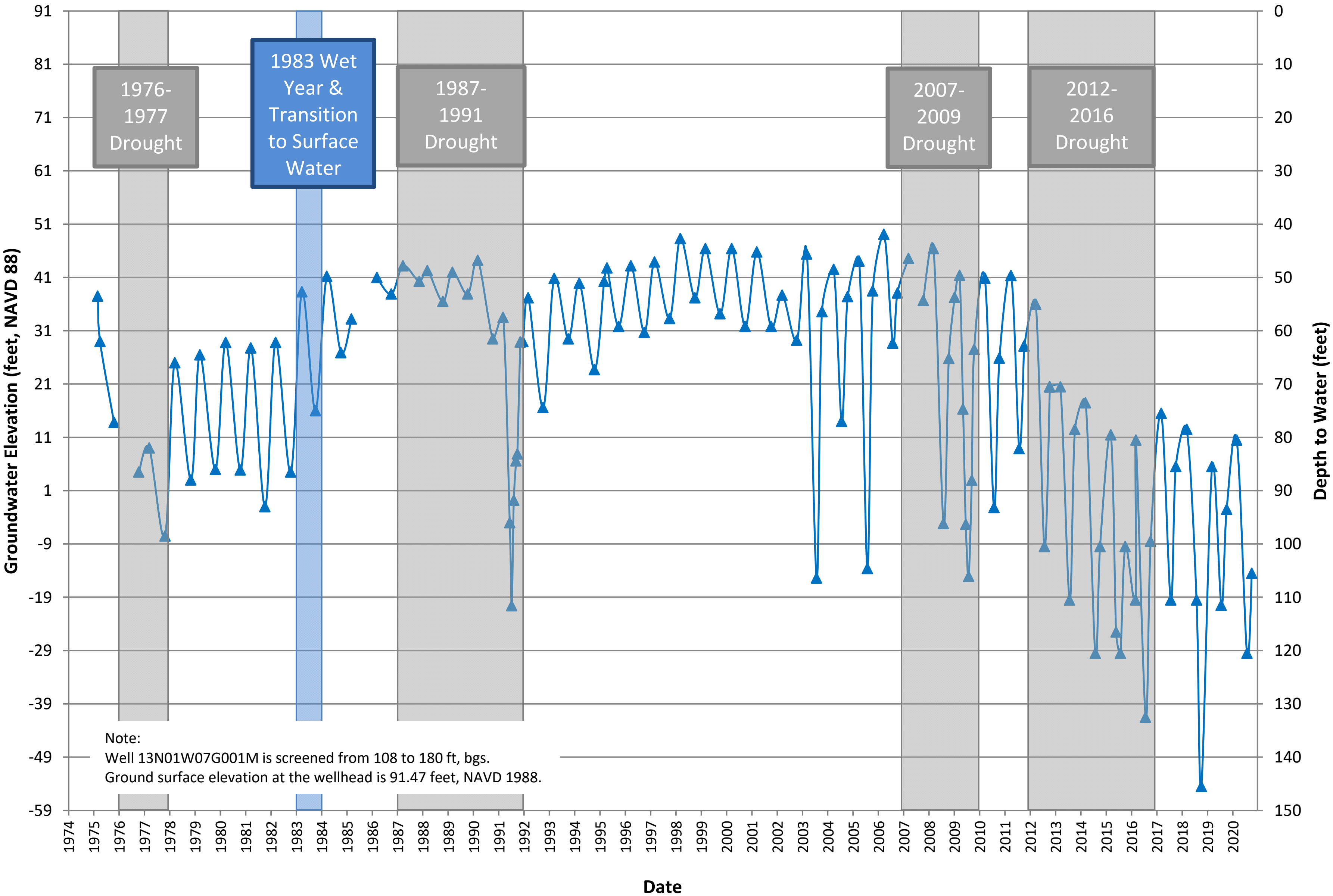
Figure 3-22. Hydrograph for Well 13N01W07G001M



Regional groundwater flow within the Colusa Subbasin is generally eastward from the margins of the Sacramento Valley toward the Sacramento River and southward towards the Sacramento-San Joaquin Delta. The regional groundwater flow trends are typified by groundwater conditions in 2006. Figures 1 and 2 of Appendix 3-B shows the groundwater elevations in spring and fall of 2006, before the onset of the multiple-year droughts of 2007 to 2009 and 2012 to 2016. For most of the Subbasin, the groundwater flows in a southeasterly direction, consistent with typical regional trends. South of Arbuckle, however, groundwater flows northeast down from the uplands before turning southeast and down the valley. This flow pattern is repeated in spring and fall 2015, which represent conditions during a multiple-year drought period (Figure 3 of Appendix 3-B).

Groundwater pumping has resulted in cones of depression that disrupt the regional groundwater flow trends. Changes in land use and multiple-year droughts have led to increased groundwater pumping. These changes in groundwater pumping have created new cones of depression and enlarged existing cones of depression. The regional groundwater gradient and direction were affected by cones of depression in areas of heavy groundwater pumping, which can be seen on the spring and fall 2015 contour maps (Figures 3 and 4 of Appendix 3-B).

Groundwater elevations throughout the study area declined over the prolonged dry period after 2006 but recovered in 2017. Figure 3-23 is a groundwater elevation change map that compares spring 2006 (pre-drought) to spring 2017 (post-drought) conditions. Negative changes in groundwater elevations indicate decreases in the spring groundwater elevations from 2006 to 2017, which highlights areas that had not fully recovered from the multiple-year drought between 2007 and 2016. The primary areas with groundwater declines were in the northwestern part of the study area near, and west of, the Glenn County communities of Orland and Artois, and in the southern part of the study area near the Colusa County communities of Williams, Arbuckle, and College City.

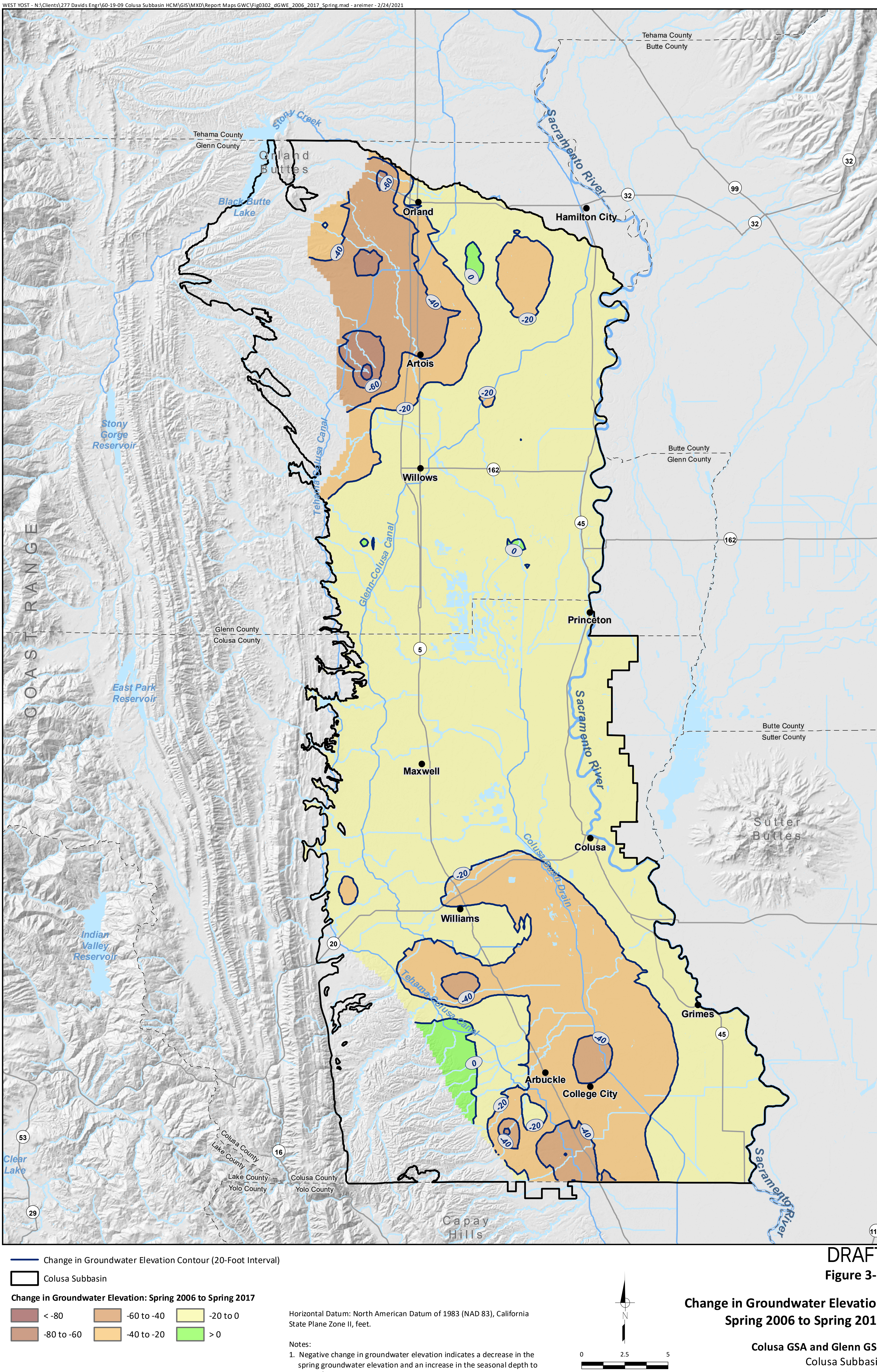
Current groundwater elevations are shown on Figure 3-24 and Figure 3-25 for spring and fall 2020, respectively. Current groundwater levels are similar to those measured in 2017, indicating that regional groundwater levels have been relatively stable since the end of the previous multiple-year drought.

3.2.2.2 Lateral and Vertical Flow Gradients

The lateral groundwater gradient has historically been relatively stable over time and typically increases with increasing terrain slope. Typical lateral flow gradients within the Colusa Subbasin are approximately 0.001 in the valley and approximately 0.01 in the uplands. Impacts due to pumping are the exception to the typical gradients and disrupt both local and regional gradients.

The vertical groundwater gradients within the principal aquifer provide insight into pumping stresses within the aquifer. Vertical groundwater gradient also helps in the identification and assessment of areas where groundwater discharge and recharge may occur, and supports the understanding of interconnections between the surface water features and the groundwater system. Figure 3-26 through Figure 3-28 contain hydrographs for multiple-completion nested monitoring wells in order from north to south. The well locations are shown on Figure 1 of Appendix 3-A. Well 22N03W24E001-003M is located just south of Stony Creek near the Tehama Colusa Canal. A downward vertical gradient has consistently been observed at 22N03W24E001-003M (Figure 3-25), indicating that there is potential groundwater recharge from surface sources. This is consistent with other multiple-completion wells in the area.

WEST YOST - N:\Clients\277 Davids Engr\60-19-09 Colusa Subbasin HCM\GIS\MXD\Report Maps GWC\Fig0302_dGWE_2006_2017_Spring.mxd - areimer - 2/24/2021



Change in Groundwater Elevation Contour (20-Foot Interval)

Colusa Subbasin

Change in Groundwater Elevation: Spring 2006 to Spring 2017

< -80	-60 to -40	-20 to 0
-80 to -60	-40 to -20	> 0

Horizontal Datum: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Notes:
1. Negative change in groundwater elevation indicates a decrease in the spring groundwater elevation and an increase in the seasonal depth to water, from 2006 to 2017.

N

0 2.5 5

Scale in Miles

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Figure 3-23

Change in Groundwater Elevation Spring 2006 to Spring 2017

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

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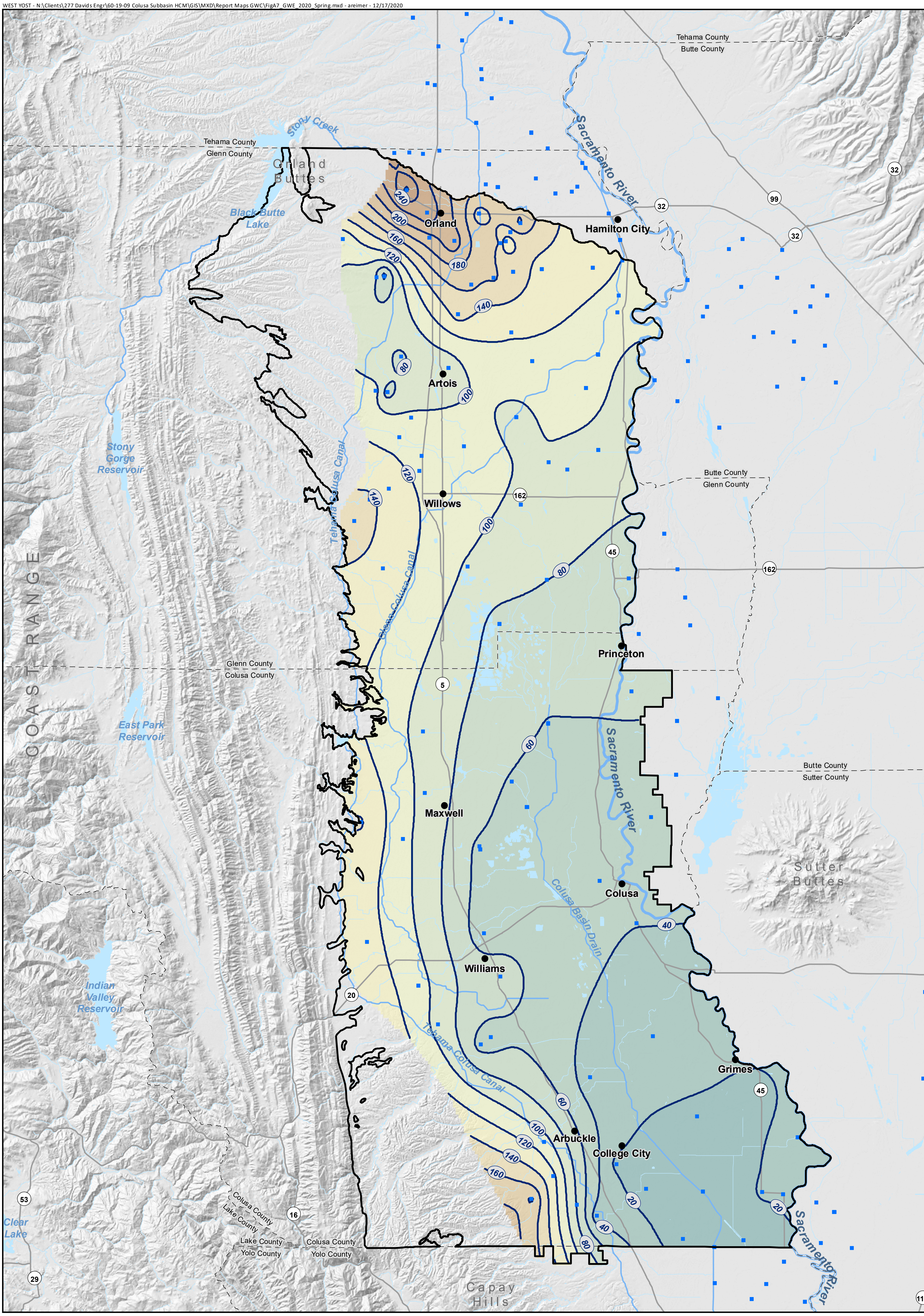

Groundwater Elevation (ft)

260 - 280	140 - 160	20 - 40
240 - 260	120 - 140	0 - 20
220 - 240	100 - 120	-20 - 0
200 - 220	80 - 100	-40 - -20
180 - 200	60 - 80	
160 - 180	40 - 60	

Well Used for Contouring

Groundwater Elevation Contour (20-Foot Interval)

Colusa Subbasin

Horizontal Datum: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Vertical Datum: North American Vertical Datum of 1988, feet (NAVD 88).

N

0 2.5 5

Scale in Miles

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Figure 3-24

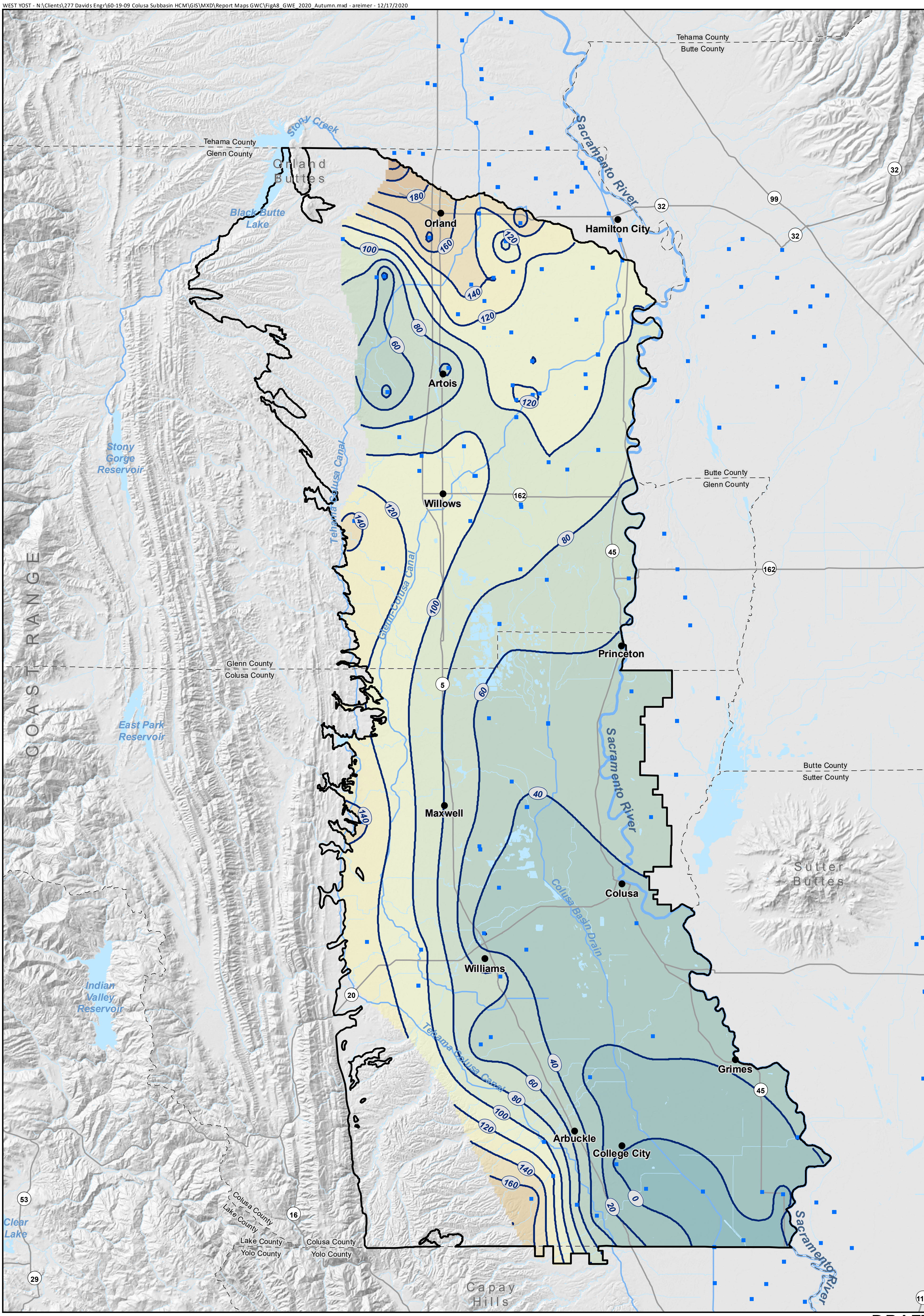
Groundwater Elevation Contours Spring 2020

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

WEST YOST - N:\Clients\277 Davids Engr\60-19-09 Colusa Subbasin HCM\GIS\MXD\Report Maps GWC\FigA8_GWE_2020_Autumn.mxd - areimer - 12/17/2020



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Groundwater Elevation (ft)

260 - 280	140 - 160	20 - 40
240 - 260	120 - 140	0 - 20
220 - 240	100 - 120	-20 - 0
200 - 220	80 - 100	-40 - -20
180 - 200	60 - 80	
160 - 180	40 - 60	

- Well Used for Contouring
- Groundwater Elevation Contour (20-Foot Interval)
- Colusa Subbasin

Horizontal Datum: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Vertical Datum: North American Vertical Datum of 1988, feet (NAVD 88).

N

0 2.5 5

Scale in Miles

Figure 3-25

Groundwater Elevation Contours Fall 2020

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

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Figure 3-26. Hydrograph for Well 22N03W24E001-003M

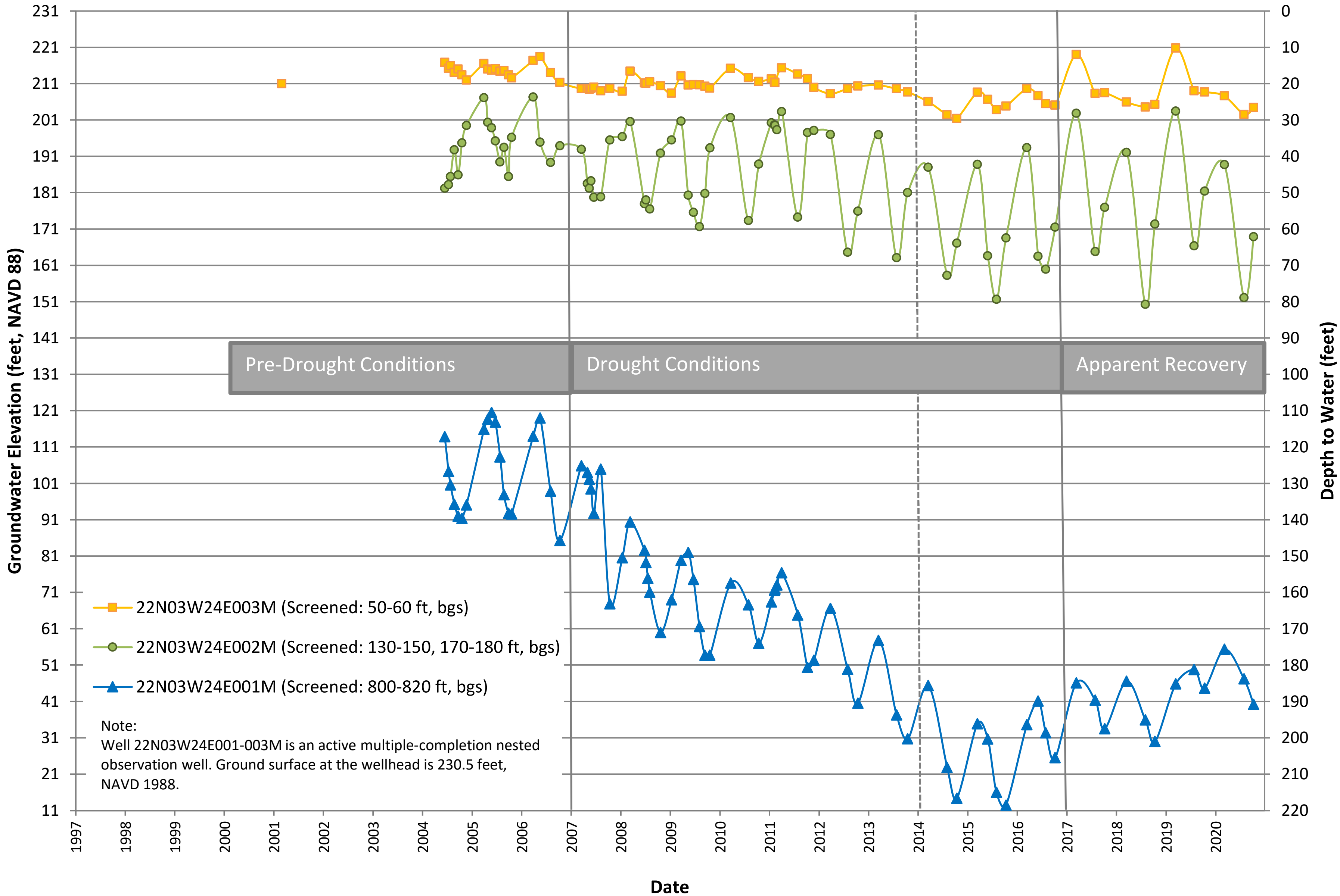

Figure 3-27. Hydrograph for Well 18N02W18D001-004M

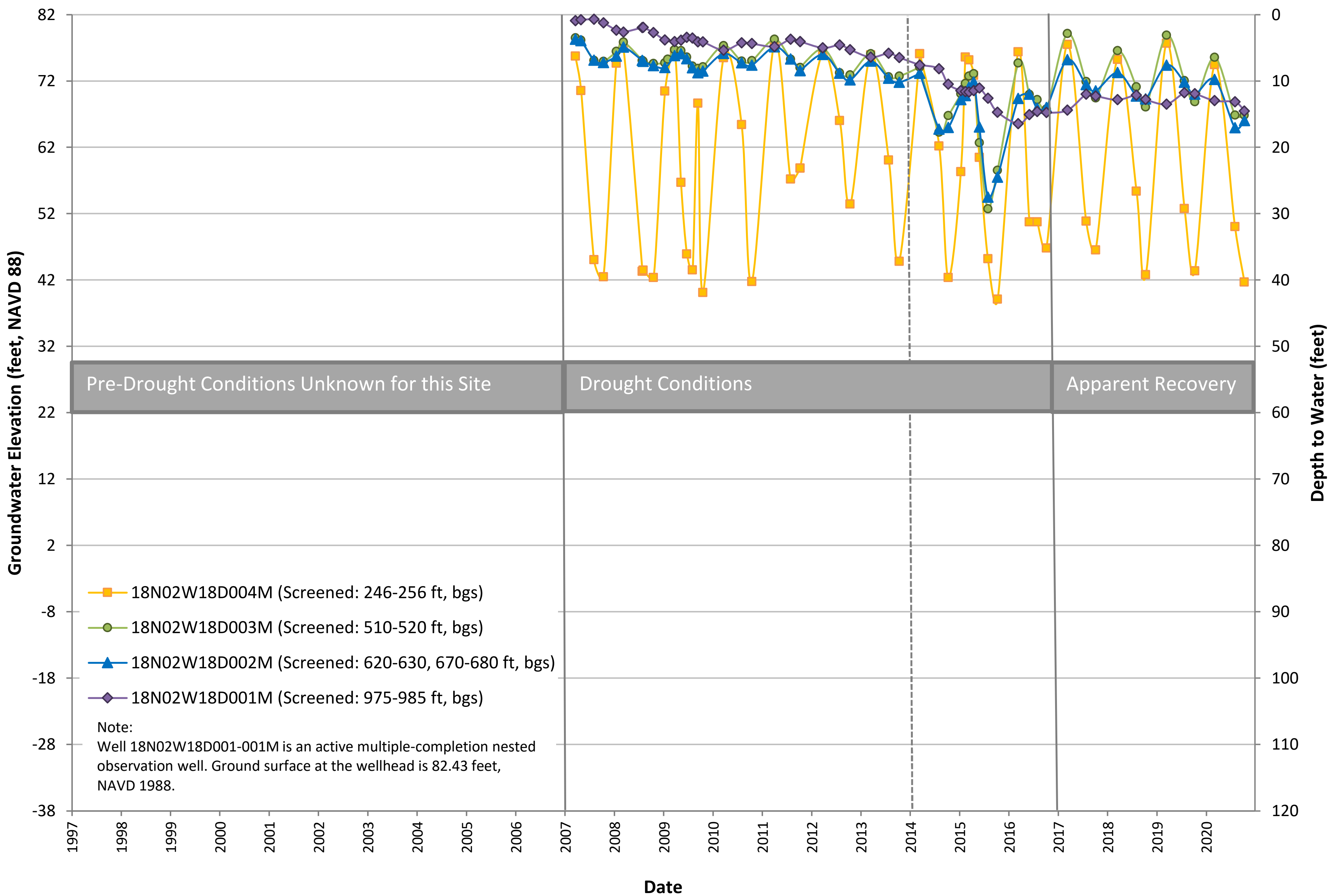

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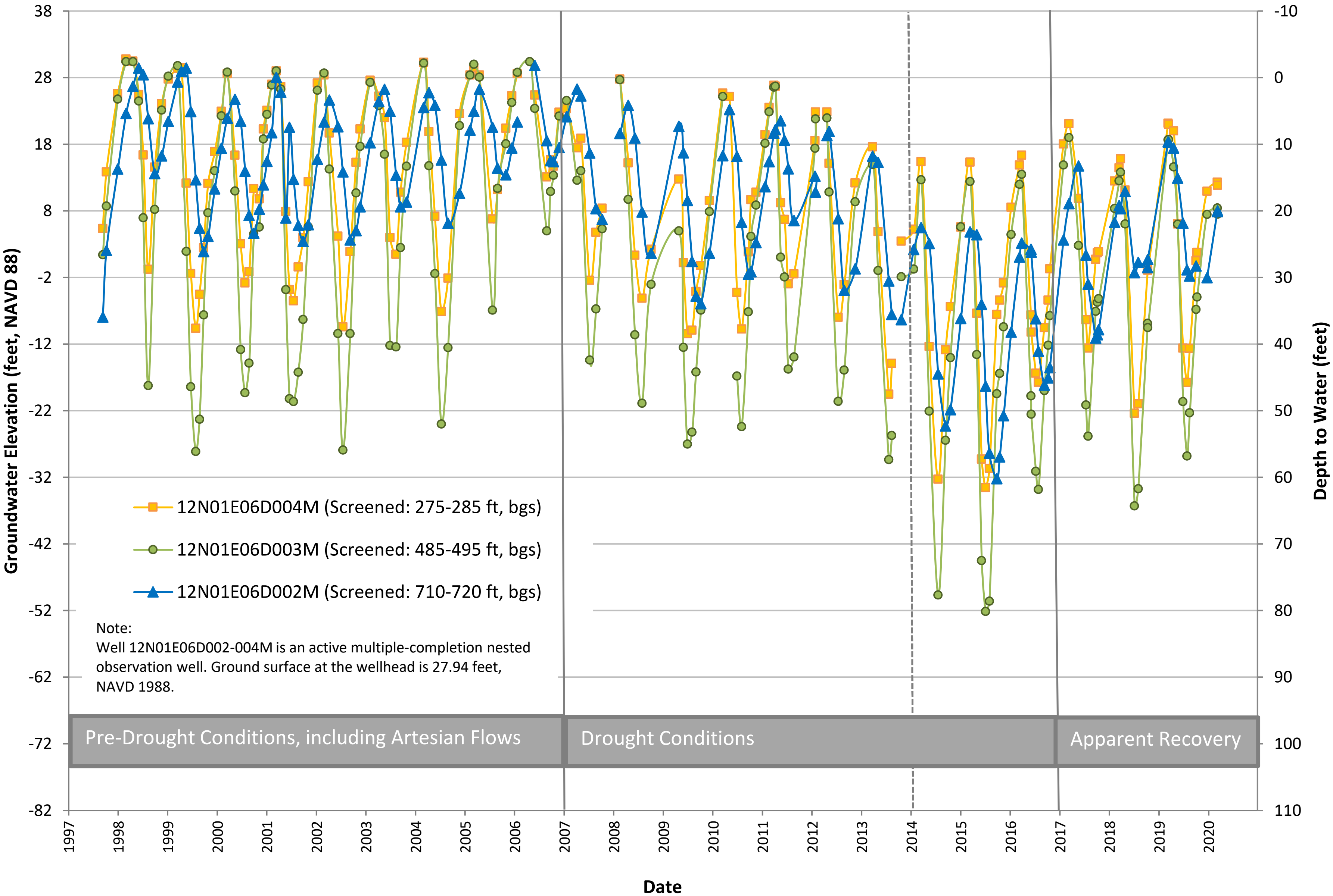
Figure 3-28. Hydrograph for Well 12N01E06D002-004M



Well 18N02W18D001-004M, shown on Figure 3-27, is located just north of the Glenn and Colusa County border. Before 2014, the well exhibited an upward flow gradient, with potential for upward groundwater from the deeper confined aquifer zone towards a shallower semi-confined aquifer zone. After 2014, in the midst of the prolonged dry period, the gradient began to transition. The vertical gradients in 18N02W18D001-004M after 2014 show potential for downward flow during the rainy season and upward flow during the dry season.

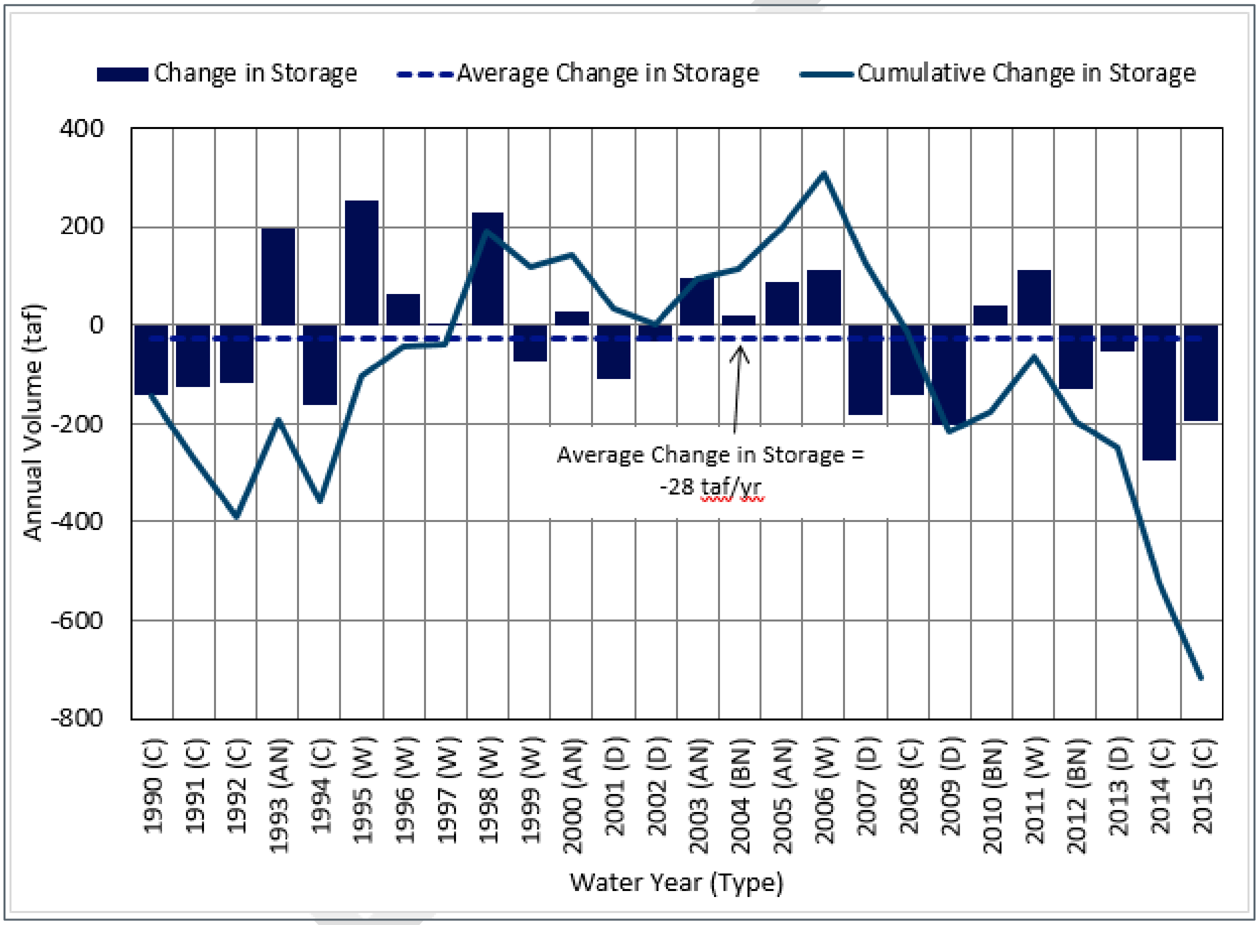
Variable vertical gradients also occurred in well 12N01E06D002-004M (Figure 3-28), located on the Colusa and Yolo County line. Prior to the prolonged dry period between 2007 and 2016, the vertical gradients and groundwater elevations measured in the well showed potential for seasonal flowing artesian conditions. The potentiometric head of the confined aquifer system rose above land surface during the wet season. During the start of the multiple-year drought, the vertical gradient was upward from the deep zone and downward from the shallow zone towards the middle zone. This may have been due to the majority of groundwater pumping occurring at depths similar to the middle completion of the monitoring well. During the latter half of the multiple-year drought, the vertical gradient reversed during the wet season, with vertical gradients showing potential for flow from the shallow towards the deeper zones. After 2016, the vertical gradients returned to pre-drought conditions, but at generally lower groundwater elevations.

3.2.3 Estimate of Groundwater Storage

The current groundwater storage volume within the Colusa Subbasin, above the crystalline basement rocks and base of freshwater, is estimated to be between about 26 million acre-feet (maf) and 140 maf based on an analysis using contouring of Spring 2020 groundwater levels, an average saturated thickness, and an assumed average specific yield range of 0.034 to 0.185, taken from Olmsted and Davis (1961). This range in groundwater storage volume reported in this GSP is low due the lack of groundwater elevation and groundwater quality data within the upland areas of the subbasin and uncertainty regarding the depth to the base of freshwater. Recent groundwater modeling conducted to support development of this GSP suggests average specific yield values for the full saturated thickness in the subbasin (i.e., from the regional water table to the base of fresh water) fit within the range provided by Olmsted and Davis (1961).

Prior to the groundwater basin modification process concluded by DWR in 2018, DWR Bulletin 118 estimated the aquifer storage capacity within the upper 200 feet of the Colusa Subbasin to be approximately 13 maf (DWR, 2006). The Colusa Subbasin at the time was bounded by Stony Creek to the north, Sacramento River to the east, Cache Creek to the south, and the uplands of Dunnigan Hills and the foothills of the Coast Ranges to the west. Currently, the Colusa Subbasin excludes the areas south of the Colusa-Yolo County boundary and includes a portion of the former West Butte Subbasin east of the Sacramento River within Colusa County. Taking into account the area of the current Colusa Subbasin and a specific yield estimate of 0.071 within the unconfined zone, as reported in Bulletin 118 (2006), approximately 10.3 maf of storage capacity is estimated within the upper 200 feet of the current subbasin extent. Given that the base of freshwater can be found at depths of more than 2,000 feet, the storage estimate of 26 maf to 140 maf is likely to be low.

The average annual change in storage was -28 thousand acre-feet per year (taf/yr) over the historical water budget period of 1990 to 2015. This indicates that, on average, more groundwater has left the Colusa Subbasin than entered, resulting in an average net reduction in groundwater stored in the Colusa Subbasin. Figure 3-29 summarizes the annual change in storage and the cumulative change in storage in the Colusa Subbasin aquifer system over the historical water budget period. A decrease in groundwater storage occurred during critically dry (C), dry (D), and below normal (BN) water years. This is most evident between 2007 and 2015, when the region experienced a series of consecutive, multiple-year droughts. While critically dry, dry, and below normal water years almost always correspond with a decrease in storage, above normal (AN) and wet (W) water years do not always result in an increase in groundwater storage. On average, the Colusa Subbasin's storage volume is influenced more by dry years than wet years. This is likely due to both a greater reliance on groundwater supply during dry years when surface water is less readily available and the relatively slow nature of deep percolation to recharge the groundwater system during wet years. Most of the groundwater inflows and outflows within the Colusa Subbasin are exchanged directly with the land and surface water system overlying the Colusa Subbasin groundwater system. More information regarding the groundwater storage calculations can be found in the water budget section of this GSP (Section 3.3) and the model development and calibration Technical Memorandum prepared by Woodard and Curran (2021) (Appendix 3-D).



Reference: Woodard and Curran. 2021. C2VSimFG-Colusa Model Development and Calibration Technical Memorandum: prepared as part of the Groundwater Sustainability Plan for the Colusa Subbasin.

Figure 3-29. Change in Groundwater Storage

3.2.4 Seawater Intrusion

The study area is located approximately 30 miles from the legal Sacramento-San Joaquin River Delta boundary, and even farther from the brackish delta estuaries. Additionally, the 2019 Basin Prioritization study by DWR found that the Colusa Subbasin has not exhibited any impacts of seawater intrusion within the past 20 years (DWR, 2020a). Seawater intrusion is neither occurring nor anticipated to occur in the Subbasin. Further discussion of seawater intrusion is not included in this GSP.

3.2.5 Groundwater Quality

Groundwaters within the Subbasin are mixed calcium, magnesium, and sodium bicarbonate waters (DWR, 2004, 2006). The northern portion of the Subbasin is dominated by calcium bicarbonate water, while increased sodium content has been observed near the Sutter Buttes and west towards Williams, resulting in localized occurrences of mixed sodium and magnesium bicarbonate waters south of Princeton, near Williams, Colusa, Grimes, and Arbuckle, and south towards Yolo County (DWR, 2006).

Groundwater quality concerns within the Colusa Subbasin include locally elevated levels of EC and TDS, adjusted sodium absorption ratio, arsenic, boron, hexavalent chromium, iron, manganese, and nitrate (DWR, 2006; Wood Rodgers, 2008; California Water Service, 2016; SWRCB, 2020a). The following subsections discuss the occurrence of these constituents of concern within the Subbasin.

Monitoring and regulatory programs exist for the major constituents of concern within the Colusa Subbasin. These include programs managed by the U.S. Geological Survey, State of California Department of Water Resources and the State Water Resources Control Board, Central Valley Salinity Coalition, and Central Valley Regional Water Quality Control Board. This section summarizes groundwater quality information from these existing programs. Chapter 4 provides describes the proposed monitoring network for monitoring the potential mobilization of saline connate water from below the freshwater aquifer or along faults in the vicinity of the Sutter Buttes.

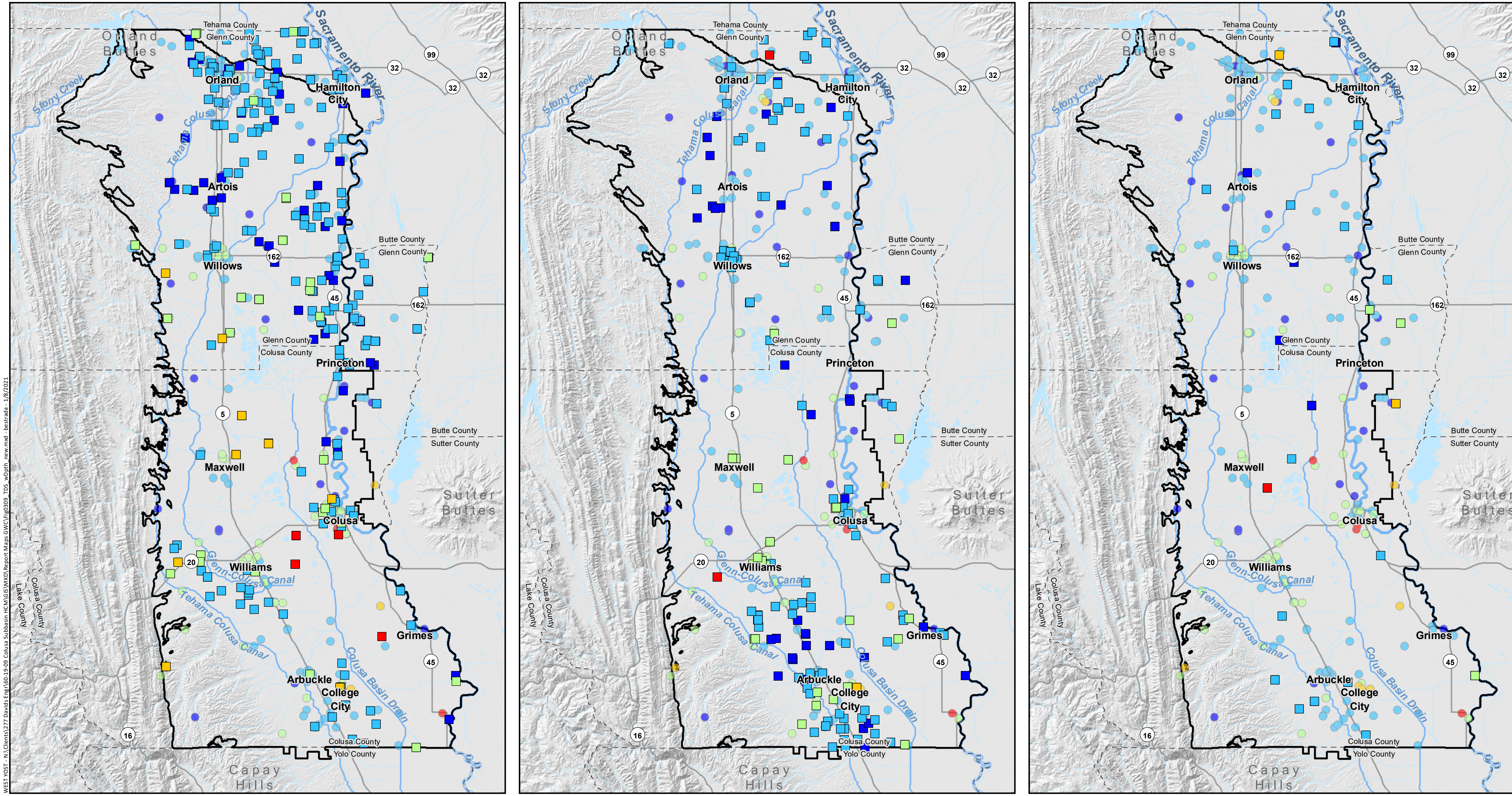
3.2.5.1 Major Naturally Occurring Constituents

All groundwater contains dissolved constituents that are products of natural processes of the hydrologic cycle. Rainfall contains only small concentrations of dissolved constituents. Upon reaching the land surface, dissolution of minerals contributes dissolved ions to the water. Calcium, magnesium, and sodium are the major cations (positively charged ions) typically found in groundwater, and sulfate and chloride, which, along with bicarbonate, are the major anions (negatively charged ions). The bicarbonate ion is formed by dissolution of carbon dioxide from the atmosphere and released by organic processes in the soil. Dissolved carbon dioxide contributes to the dissolution of minerals as water is recharged. The quantity of dissolved salts depends on the specific surface area of the aquifer material, the solubility of the minerals present, the pH and Eh of the system, and the residence time of the water in the subsurface aquifer.

3.2.5.1.1 Salinity

Salinity of groundwater can be characterized by the measured TDS concentration and/or the EC value. TDS concentrations throughout the Subbasin range from less than 100 mg/L to more than 1,500 mg/L, the short-term secondary MCL defined by Title 22 California Code of Regulations (SWRCB, 2018b). Figure 3-30 shows TDS concentrations detected in wells of varying depths. Wells with unknown depth and construction information are shown on all three panels of Figure 3-30. TDS concentrations of more than 500 mg/L, the recommended secondary MCL, have been detected in wells throughout the Subbasin, but mostly in wells south of Artois. The highest concentrations of TDS have been measured in the area surrounding the cities of Maxwell, Colusa, and Williams.

Wells Less Than 200 ft Deep | **Wells 200 to 700 ft Deep** | **Wells Greater Than 700 ft Deep**



Source: Total dissolved solid (TDS) concentration and well depth information was downloaded from GeoTracker Groundwater Ambient Monitoring and Assessment Program (GAMA) and U.S. Geological Survey (USGS) National Water Information System (NWIS), 2020.

Horizontal Datum: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Note:
1. TDS concentrations shown are the maximum detected at that location.
2. The drinking water standards (2018) secondary maximum contaminant level for TDS is 500 mg/L (recommended), 1,000 mg/L (upper limit), and 1,500 mg/L (short term).

Colusa Subbasin

Maximum TDS Concentration (mg/L) in Wells with Known Depth
- < 250
- 250 - 500
- 500 - 1,000
- 1,000 - 1,500
- > 1,500

Maximum TDS Concentration (mg/L) in Wells with Unknown Depth
- < 250
- 250 - 500
- 500 - 1,000
- 1,000 - 1,500
- > 1,500

N

0 4 8
Scale in Miles

DRAFT

Figure 3-30

Historical Concentrations Total Dissolved Solids

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

Wells screened in the unconfined to semi-confined zone of the aquifer (i.e. in wells less than 200 feet deep) had the highest number of wells with elevated TDS concentrations. TDS concentrations in the shallow wells southwest of Colusa have consistently been greater than 2,000 mg/L over a 20-year period. The wells southwest of Colusa with unknown depth have historically had TDS concentrations between 649 mg/L and 1,820 mg/L between 1957 and 2011. The wells northeast of Maxwell have consistently had TDS concentrations above 1,000 mg/L over 20-year period.

Wells with depths greater than 200 feet in these areas have historically had TDS concentrations less than 1,000 mg/L, with the exception of the deep well southeast of Maxwell. This well is a multiple-completion nested monitoring well with completions set at 378 feet, 775 feet, 1,236 feet, and 1,481 feet deep. In 2011, TDS concentrations in the deepest completion had the lowest TDS concentration (approximately 260 mg/L) while the second-deepest completion well had the highest TDS detection (approximately 930 mg/L). The two shallowest completions in the well had TDS concentrations of approximately 520 mg/L. In 2016, the second-shallowest completion well had the highest TDS concentration (approximately 1,640 mg/L), while the shallowest completion well had the lowest concentration (approximately 530 mg/L). The deepest completion was not measured in 2016.

The shallow well west of Grimes shown on Figure 3-30 is shown with an elevated TDS symbol because of a single TDS measurement of 2,040 mg/L taken in 1975. This older measurement may not be representative of current conditions in the area. Similarly, the wells near College City and other locations with TDS detections greater than 1,000 mg/L tend to be wells with a single measurement and may not represent current or consistent TDS concentrations for those locations.

Many of the wells located in or near urban areas exhibit TDS concentrations above the 500-mg/L recommended secondary MCL. This includes wells with unknown depths in the areas of Williams, Maxwell, Williams, Colusa, Arbuckle, and College City. Public supply wells deeper than 200 feet near Williams and Willows exhibited an increasing trend in TDS concentrations (Dupuy, et. al., 2019 and Jurgens, et. al., 2020).

3.2.5.1.2 Major Cations and Anions

The primary cations within the Subbasin are calcium, magnesium, and sodium. The highest calcium concentrations within the Subbasin have been measured in wells between Colusa and Williams, where concentrations have been recorded above 100 mg/L. Elevated sodium concentrations have been detected in wells throughout the Subbasin, but tend to be higher in the area surrounding Williams and Colusa. In Colusa, sodium concentration levels are often an order of magnitude greater that of magnesium or calcium. Magnesium concentrations are typically between 10 and 30 mg/L. Wells near Willows, Williams, and Arbuckle have shown an increasing trend in magnesium concentrations over the past decade (DWR, 2021; SWRCB, 2020a; USGS, 2020).

The ratio of calcium to sodium is much higher in the northern part of the Subbasin compared to the southern part of the Subbasin. This aligns with the spatial trend in water type, with calcium bicarbonate waters being characteristic of northern Glenn County and sodium bicarbonate waters generally characterizing Colusa County.

As a general rule, the ratio of sodium to calcium and magnesium concentrations in groundwater increases with residence time. This is due to cation exchange, which can be thought of as a natural water softening process that occurs when groundwater containing calcium and magnesium comes in contact with clay containing exchangeable sodium. The longer the water is in contact with the aquifer, the higher the ratio of sodium to calcium and magnesium, and the softer the water. This relationship may be obscured by other factors, including geologic heterogeneities that may cause variation in the sodium concentrations, independent of the residence time of the groundwater, and saline water intrusion. These factors, notwithstanding the relative concentrations of sodium, calcium and magnesium in the wells, may also help to delineate recharge and discharge zones, and potential mobilization of connate water.

The Subbasin waters are mixed bicarbonate waters. Other major anions distributed throughout the Subbasin include chloride and sulfate. The spatial distribution of the high concentrations of chloride and sulfate is similar to that of elevated concentrations of TDS and sodium, with the highest concentrations detected in the general Maxwell-Colusa-Williams area and south towards Arbuckle (Figure 3-30). Sulfate concentrations in this area have been measured above the 250-mg/L recommended secondary MCL, with the southern wells showing a long-term increasing trend in sulfate concentrations (SWRCB, 2020a). Groundwater samples in the past decade have generally contained chloride concentrations below the 250-mg/L recommended secondary MCL throughout the Subbasin (DWR, 2021; SWRCB, 2020a).

3.2.5.2 Other Naturally Occurring Constituents

Naturally occurring constituents that could constrain the use of groundwater within the Subbasin for potable supply, and which have been detected in the Colusa County's wells, include arsenic, boron, iron, manganese, and hexavalent chromium. Boron can also be detrimental to plants.

3.2.5.2.1 Arsenic

Arsenic is a naturally occurring constituent in groundwater and commonly occurs at concentrations ranging from 10 to 50 µg/L in the western United States, where it is typically associated with alluvial-lacustrine basin-fill deposits and volcanic rocks and sediments (Welch, et. al., 1988). The primary MCL for arsenic in drinking water is 10 µg/L (SWRCB, 2018a).

Arsenic has been detected near Grimes at concentrations of approximately 200 µg/L. A federal program was initiated to install filters on water connections and reduce the arsenic concentration (Glenn County, 2005). Recent concentrations of arsenic in wells near Grimes have been less than 20 µg/L. The elevated arsenic concentrations near Grimes were determined to be due to natural conditions (Glenn County, 2005), and is potentially impacted by Sacramento River stream channel and its proximity of the Sutter Buttes and the Colusa Dome.

3.2.5.2.2 Boron

Boron is a naturally occurring element that is associated with the marine deposits of the Coast Ranges. Anthropogenic sources of boron include industrial waste discharges, municipal wastewater, and agricultural practices (SWRCB, 2017). Boron in groundwater is most likely in the form of boric acid. Boron is a necessary component to plant growth in small amounts, but some plants are sensitive to the presence of boric acid in waters and may exhibit adverse effects if exposed to boron concentrations higher than the plant's tolerance.

Elevated concentrations of boron reported by GCID within Colusa County have impacted agricultural practices (GCID, 1995). According to GCID (1995), groundwater underlying the northern portion of the GCID service area has boron concentrations suitable for irrigation. Additionally, boron measured in select groundwater wells within Glenn County has not exceeded the USEPA agricultural water quality goal for boron of 750 µg/L (USEPA, 1986; USGS, 2020). In contrast, elevated levels of boron have been detected in the southern portion of the GCID service area (GCID, 1995).

3.2.5.2.3 Iron and Manganese

Iron concentrations exceeding the 300-µg/L secondary MCL have been reported in water supply wells near Orland, Willows, Delevan, Williams, Colusa, and Arbuckle within the past decade (DWR, 2021; SWRCB, 2020a). Williams and Colusa have experienced long-term increasing trends in iron concentrations, although the most recent concentrations have been lower than during previous years (USEPA, 2020; CH2MHILL, 2016).

Elevated manganese concentrations above the 50-µg/L secondary MCL have been reported near the cities of Williams and Colusa, and northeast of Artois, near the Sacramento River (USEPA, 2020). According to the Northern Sacramento Valley (Four Valley) Drinking Water Strategy Document (Glenn County, 2005), there have been customer complaints near Williams and Colusa related to iron and manganese in drinking water.

3.2.5.2.4 Hexavalent Chromium

Chromium typically occurs in in the trivalent state, which is nearly insoluble. Geochemical conditions in recharge zones or the aquifer can oxidize trivalent chromium to hexavalent chromium, which is soluble, mobile in groundwater, and a carcinogen. Naturally occurring chromium minerals are associated with serpentinite and other Coast Range rocks. Over geologic time, these rocks have been eroded, transported by streams, and incorporated in the basin fill sediments of the Colusa Subbasin.

There is currently no MCL for hexavalent chromium. The SWRCB implemented a 10-µg/L primary MCLs for hexavalent chromium on July 1, 2016. On May 31, 2017, the Sacramento Superior Court ruled that the SWRCB must withdraw the 10-µg/L hexavalent chromium MCL and develop a new MCL after assessing the economic feasibility of compliance, especially for smaller public water systems. The 10-µg/L hexavalent chromium MCL was withdrawn on September 11, 2017. The SWRCB has not published a timeline for issuing the new MCL, but the new MCL is anticipated to be announced in late 2021.

Drinking water supply wells near Willows have experienced high concentrations of hexavalent chromium (California Water Service, 2016). Hexavalent chromium in a well west of Willows has not been detected at concentrations below 20 µg/L since 2016 and was detected at 40.1 µg/L in July 2020 (SWRCB, 2020a). Hexavalent chromium concentrations greater than 20 µg/L have also been detected in wells midway between Williams and Arbuckle, and near Colusa, within the past decade (DWR, 2021; SWRCB, 2020a).

3.2.5.3 Non-Point Sources of Groundwater Pollution

Non-point sources of groundwater pollution are diffuse discharges that occur over a wide area. The major non-point source groundwater constituent of concern in the Colusa Subbasin is nitrate.

3.2.5.3.1 Nitrate

Nitrate is a naturally occurring compound that forms when nitrogen and oxygen combine in the soil. Nitrate occurs naturally in groundwater or can be introduced through a variety of land uses, including row crop agriculture, irrigated agriculture, and various waste disposal practices. Typical waste materials resulting in nitrate pollution include animal manures from commercial poultry, dairy, hog and beef operations; wastewater treatment plant effluent applied to land; household wastes disposed of in septic systems; and landfill leachate.

Small amounts of nitrate in groundwater are normal, but larger concentrations can result in serious health problems. The 45-mg/L MCL for nitrate (quantified as nitrate) is considered by the State and Federal governments to be the maximum concentration that can be safely consumed from a public water system. Excessive nitrate consumption can lead to health problems, including irritation of gastrointestinal tract and bladder, and methemoglobinemia, or blue baby syndrome, so named because affected infants take on a bluish tinge. Blue baby syndrome is caused when nitrate is converted to nitrite by bacterial activity in the stomach. Typically, in adults, this bacteria is destroyed by stomach acid. The stomachs of infants (especially less than 3 months of age in humans) are not fully developed and do not produce strong acids. This allows the bacteria to survive, leading to the buildup of nitrite in the blood. The nitrite oxidizes the ferrous iron in the blood to ferric iron, thereby limiting its ability to carry oxygen to the cells. The syndrome is readily treated if diagnosed.

Nitrate detections are widespread in the Colusa Subbasin but are mostly low concentrations, typically meeting drinking water standards, with the exception of the northern portion of Glenn County and the area near Willows (CH2MHILL, 2016; Wood Rodgers, 2008). According to the Sacramento Valley Water Quality Coalition Groundwater Quality Report (CH2MHILL, 2016), only 2 percent of the 359 total wells analyzed within Glenn and Colusa Counties had nitrate concentrations above the 45-mg/L MCL and the average nitrate concentration was 8.3 mg/L.

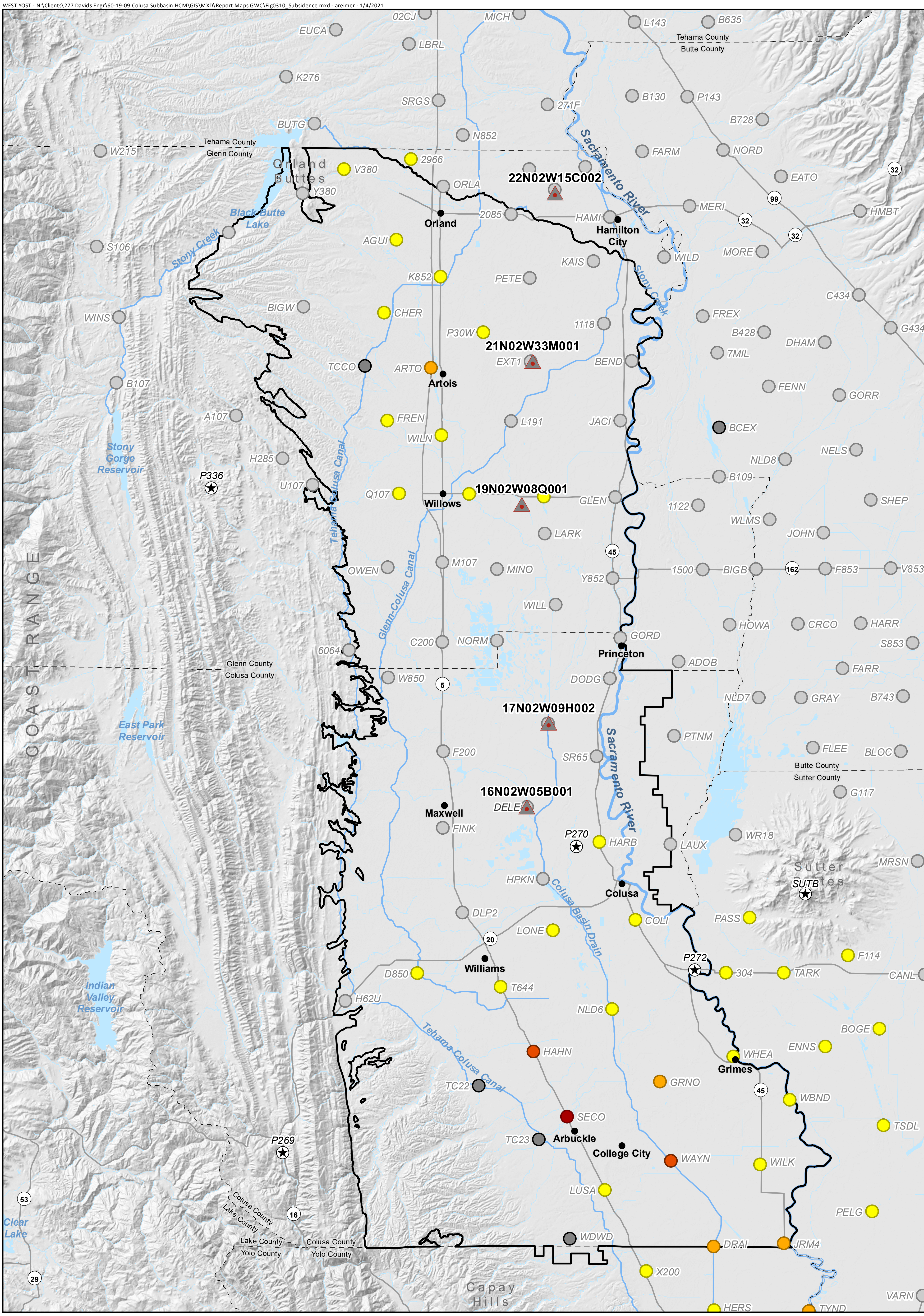
3.2.5.4 Point Sources of Groundwater Pollution

Point sources of groundwater pollution are discrete discharges that occur at a single identified location. Discharges from point sources can be either a single discharge event or have occurred continuously over a period of time. Point sources of groundwater pollution often require monitoring and cleanup programs.

There are several active groundwater contaminant cleanup sites in the Colusa Subbasin. These mostly include leaky storage tanks and unauthorized releases of contaminants such as petroleum hydrocarbons, nitrate, pesticides and herbicides. The largest contamination site is the Orland Dry Cleaner site, a perchloroethylene (PCE) plume within the Colusa Subbasin that extends approximately two miles southeast of the source location in Orland (DTSC, 2020 and URS Corporation Americas, 2020). PCE is a dense non-aqueous phase liquid, meaning it is denser than water, with a moderate to high mobility rating (SWRCB, 2017). Long-term temporal trends of PCE concentrations in most of the monitoring wells show concentrations stabilizing or decreasing since the start of sampling in 2003 (URS Corporation Americas, 2020).

3.2.6 Land Subsidence

Land subsidence can cause structural damage to wells, foundations, roads, bridges, and other infrastructure. The change in topography can also impact surface water flows by reducing conveyance capacity and potentially changing flow gradients within canals, natural streams, and floodplains. Inelastic land subsidence may also negatively impact groundwater storage capacity; however, it is yet to be determined if the subsidence measured within the Subbasin has measurably impacted storage capacity. Figure 3-31 shows the measured land surface displacement from resurvey of Sacramento Valley benchmarks between 2008 and 2017 (DWR, 2018a). Figure 3-32 includes the annual rate of subsidence from 2018 to 2019, as calculated from interferometric synthetic aperture radar (InSAR) imagery surveys (TRE ALTAMiRA, 2020). Appendix 3-C contains the location map and ground surface displacement charts measured in five extensometers located within the counties of Colusa and Glenn.



Source: Extensometers and continuous GPS stations were obtained from DWR and USGS. Benchmarks and displacement data were obtained from a resurvey report puublished by DWR (2020).

Datums: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Extensometer

Continuous GPS Station

Colusa Subbasin

Sacramento Valley Benchmark Subsidence Measured Between 2008 and 2017

- > 2 ft
- 1 - 2 ft
- 0.5 - 1 ft
- 2 inches - 0.5 ft
- < 2 inches
- New Benchmark or Not Surveyed

N

0 2.5 5

Scale in Miles

DRAFT

Figure 3-31

Measured Subsidence 2008 to 2017

Colusa GSA and Glenn GSA

Colusa Subbasin

Groundwater Sustainability Plan

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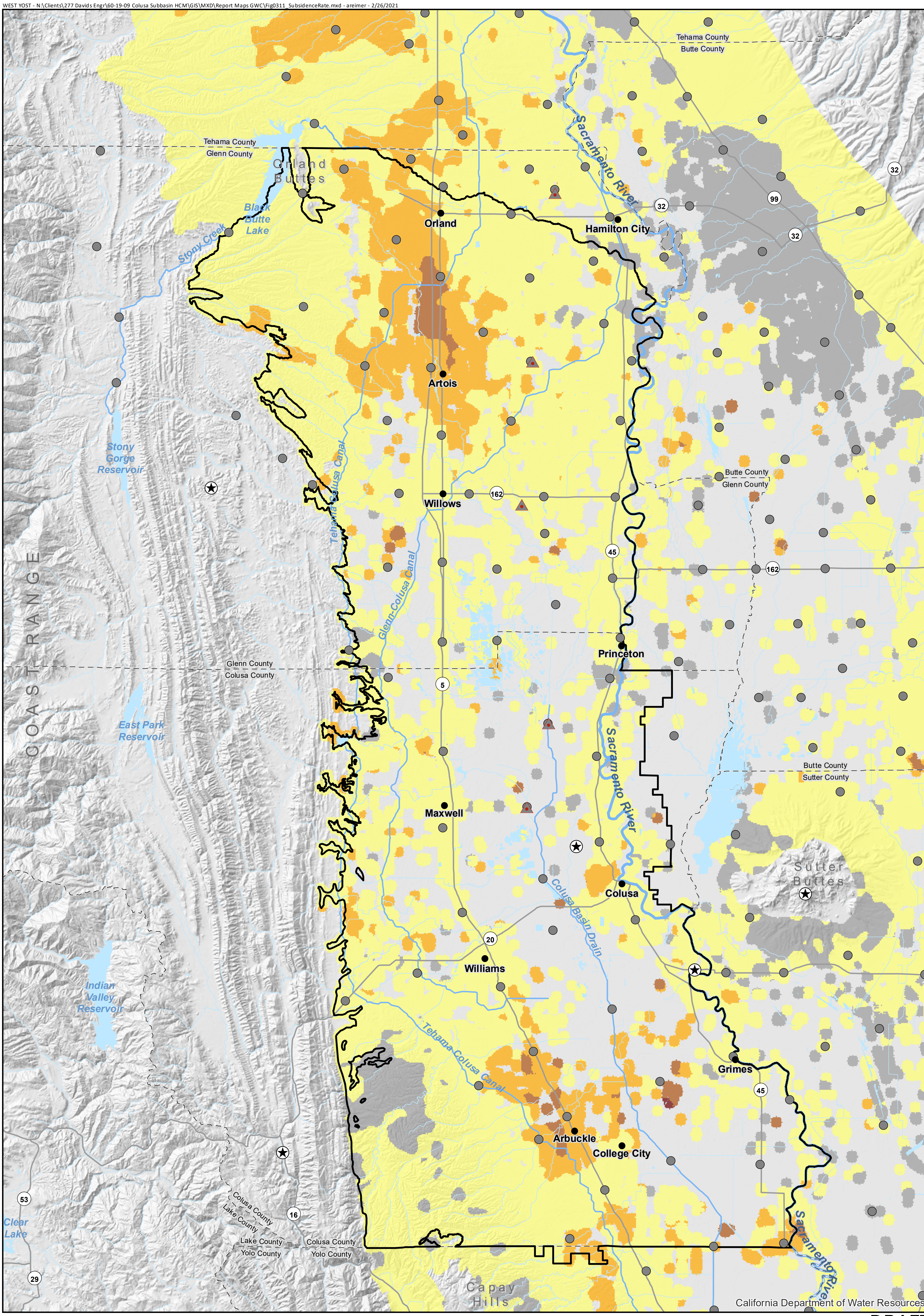


Source: TRE ALTAMiRA, 2020, InSAR Land Surveying and Mapping Services in Support of the DWR SGMA Program, Vertical Displacement v2019 Annual Rate 2018-09-01 to 2019-09-01, March 2020.

Datums: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Extensometer
Continuous GPS Station
Sacramento Valley Subsidence Benchmark
Colusa Subbasin

Annual Subsidence Rate (inches per year) Between September 2018 and September 2019

> 2
1 - 2
0.5 - 1
0 - 0.5
Uplift or No Subsidence

N

0 2.5 5
Scale in Miles

DRAFT

Figure 3-32

Annual Land Subsidence Rate 2018 to 2019

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

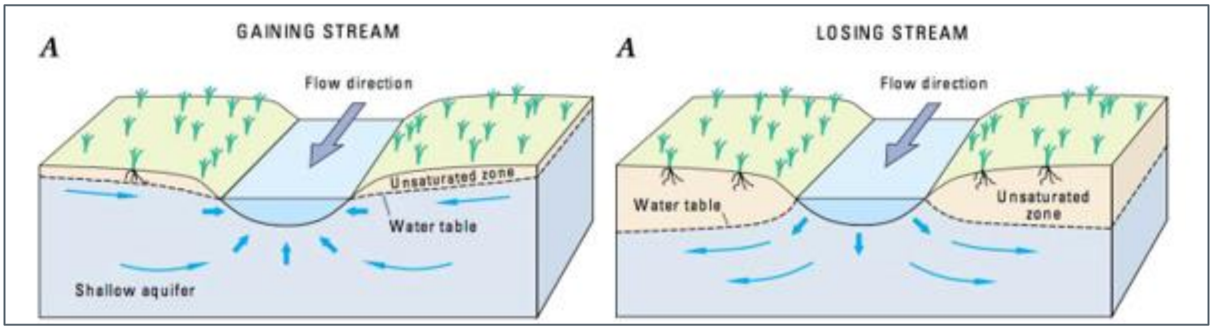
Damage to infrastructure as a result of land subsidence has been observed and reported in the Arbuckle area of Colusa County. A 2015 NASA report based on InSAR survey evaluation showed isolated land subsidence of up to approximately 0.5 feet west of Arbuckle (Farr et. al., 2015). Data from a repeat survey of the Sacramento Valley Height-Modernization Project benchmarks also indicates a decrease in land surface elevation by as much as two feet between 2008 and 2016 near Arbuckle (Ehorn, 2016). A resurvey of those benchmarks conducted in 2017 showed a total displacement of 2.14 feet since 2008. This equates to approximately 0.24 feet, or approximately 3 inches, of subsidence per year between 2008 and 2017, on average. Subsidence calculated by TRE ALTAMiRA from InSAR imagery showed up to more than 2 inches of subsidence occurring between 2018 and 2019 within the greater Arbuckle area (Figure 3-32).

Land subsidence is not exclusive to the Colusa County portion of the subbasin; repeat surveys of benchmarks in Glenn County showed small amounts of land subsidence southwest of Orland occurring between 2008 and 2017 (Ehorn, 2016 and DWR, 2018a). One benchmark located near Artois had a measured displacement of 0.59 feet, or approximately 7 inches. InSAR imagery from 2018 to 2019 showed approximately 1.5 inches of subsidence occurring between Orland and Artois.

Extensometer measurements have also recorded ground displacement in the Colusa Subbasin. Appendix 3-C contains a map of the extensometer locations (Figure 1 of Appendix 3-C) and ground displacement measured within extensometers in or near the subbasin. Seasonal displacements of ±0.3 inches have been recorded in these extensometers. Most of the subsidence measured in the extensometers has been elastic. Potential inelastic displacement may have occurred in extensometers 21N02W33M001M, northeast of Artois, and 16N02W05B001M, east of Maxwell, during the multiple-year droughts (Figure 5 and Figure 2 of Appendix 3-C, respectively). Potential inelastic subsidence occurred in 21N02W33M001M between 2007 and 2010, and between 2008 and 2016 in 16N02W05B001M. Measured seasonal fluctuations in displacement within both of these boreholes have since stabilized.

3.2.7 Interconnected Surface Waters

Surface water is typically managed separately from groundwater; however, surface waters interact with the underlying groundwater system. Stream-aquifer interactions are typically classified in two categories: gaining and losing. Figure 3-33 shows a conceptual example of gaining and losing streams. Gaining streams “receive” water from the underlying aquifer system, thereby increasing the flow or stage within the stream. This is also referred to as stream accretion. Losing streams “give” water to the underlying aquifer system. This is also referred to as stream seepage. Stream stage and groundwater levels provide evidence on whether a stream is gaining or losing.



Reference: U.S. Geological Survey. 2021.

Figure 3-33. Conceptual Example of Gaining and Losing Streams

The Colusa Subbasin integrated hydrologic model, C2VsimFG-Colusa, was used to analyze historical stream gains and losses. The modeled streams include the Sacramento River, Stony Creek, and the Colusa Basin Drain. On average, the subbasin experienced 336 taf/yr of stream gains from groundwater and 345 taf/yr of stream losses to groundwater between 1990 and 2015 (Woodard and Curran, 2020).

While Stony Creek, Sacramento River, and the Colusa Basin Drain all experience gaining and losing conditions throughout the year, the modeled surface waters within Colusa Subbasin are overall net gaining. Table 3-6 includes the breakdown of the modeled stream gains and losses for stream reach by water year type. Table 3-7 includes stream gain and loss statistics for the modeled streams.

Simulated Sacramento River conditions were also mostly net gaining, with the exception of 1998, where the Sacramento River experienced net loss of approximately 13 taf. The median net gain along the Sacramento River was approximately 72 taf/yr. The net gains in the Sacramento River were lower during wet years, when there would be more surface flow, and higher in the dry years, when surface waters would be in short supply. The Colusa Basin Drain was simulated with net gains of more than 82 taf/yr between 1990 and 2015, and never experienced net losing conditions, even during critically dry years. Contrary to what was simulated for the Sacramento River, net gains in the Colusa Basin Drain were higher during wet years than during dry conditions. Stony Creek always experienced annual net losses between 1990 and 2015. Stream losses were greatest during critically dry and dry years.

Table 3-6. Modeled Net Stream Gain 1990-2015 by Water Year Type

Water Year Type	Number of Years Evaluated	Net Stream Gain, taf Colusa Basin Drain	Net Stream Gain, taf Stony Creek	Net Stream Gain, taf Sacramento River
Critical Dry	7	109	-38	91
Dry	5	109	-30	86
Below Normal	3	104	-31	57
Above Normal	4	121	-33	47
Wet	7	127	-28	26

Note: Total gains, losses and net gains will not exactly match values reported elsewhere in this GSP due to different methods of extracting data from C2VSimFG-Colusa.

Table 3-7. Modeled Net Stream Gain 1990-2015 Statistics

	Colusa Basin Drain		Stony Creek		Sacramento River	
	Net Gain, taf	Year	Net Gain, taf	Year	Net Gain, taf	Year
Minimum	82	2010	-55	1992	-13	1998
Maximum	152	1999	-21	2006	117	2007
Median	115	1997	-31	2011	72	2000
Average	115	--	-32	--	62	--

Note: Total gains, losses and net gains will not exactly match values reported elsewhere in this GSP due to different methods of extracting data from C2VSimFG-Colusa.

3.2.8 Groundwater Dependent Ecosystems

GDE are defined as “ecological communities of species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface” (23 CCR § 351(m)). As described in TNC’s guidance for GDE analysis (Rohde et al. 2018), a GDE’s dependence on groundwater refers to reliance of GDE species and/or communities on groundwater for all or a portion of their water needs. Natural communities commonly associated with groundwater (NCCAG) within the State of California were mapped by TNC (DWR, 2018b) and Klausmeyer, et. al. (2018). The NCCAG mapping provided an initial indication of the location, habitat type, and impacted vegetation for potential GDE areas within the Colusa Subbasin. The majority of the potential GDE vegetation areas include cottonwood (31 percent), bulrush (21 percent), willow (15 percent), and oak (13 percent) habitat areas. Arundo, or giant reed, accounts for four percent of NCCAGs initially identified within the Colusa Subbasin.

The potential GDEs areas were screened to evaluate their likelihood of being a Colusa Subbasin GDE. A score of 1 (less likely to be a GDE) to 4 (more likely to be a GDE) was applied to the NCCAG areas based on depth to groundwater, proximity to surface waters, and proximity to irrigated croplands. Figure 3-34 outlines the scoring criteria and how the scores were determined. Figure 3-35 shows the spatial representation of the scoring and ranking criteria.

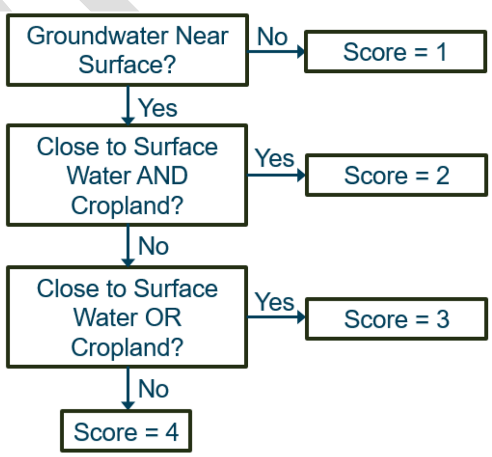


Figure 3-34. GDE Scoring Criteria

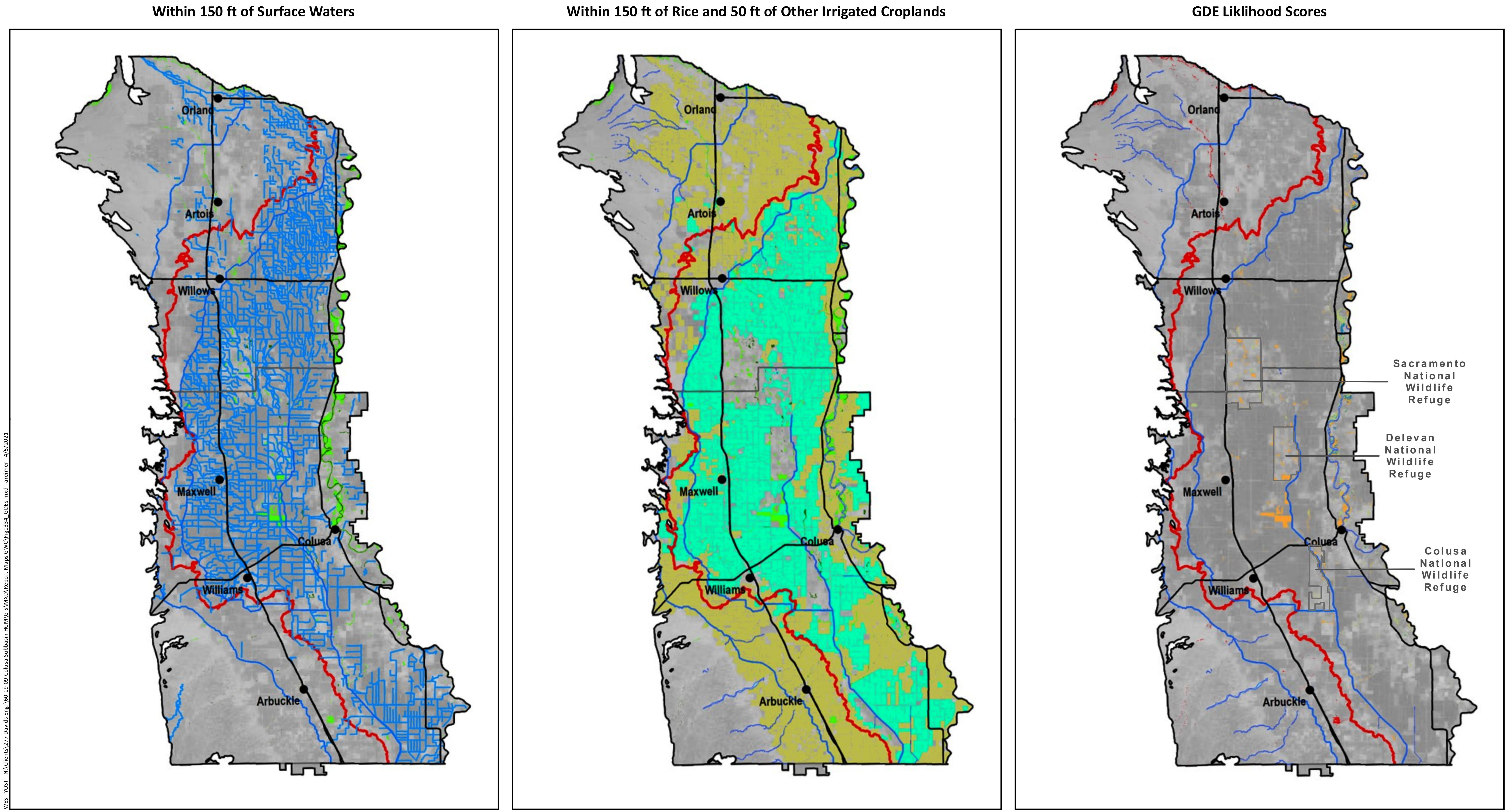
Review of available spring groundwater level data from 2014 to 2018 indicates that shallow groundwater levels (i.e., within 30 feet of ground surface) exist throughout much of the subbasin. A DTW of 30 feet was used as one of the primary criteria in the initial screening of potential GDEs. The use of a 30-foot DTW criterion to screen potential GDEs is based on reported maximum rooting depths of California phreatophytes and is consistent with guidance provided by TNC (Rohde et al., 2018) for identifying GDEs. The use of shallow groundwater data over the 5-year 2014 to 2018 time period was deemed appropriate because it provided a more conservative (i.e., more inclusive) indicator of potential GDEs than the use of a data from a single year. The 30-foot DTW contour is shown on Figure 3-35. Depths to shallow groundwater east of the contour are less than 30 feet.

Areas within 150 feet of surface waters, including canals, ditches, and perennial streams, were considered to have access to surface waters. Additionally, areas within 150 feet of irrigated rice paddies and 50 feet of other irrigated croplands were considered to have access to surface waters. The leftmost and middle panels of Figure 3-35 include the areas within 150 feet of surface waters, 150 feet of rice croplands, and 50 feet of other irrigated croplands. These areas were scored lower than areas farther away (i.e. less likely to be a GDE). GDEs are areas that are dependent on groundwater. Closer proximity to available surface waters decreases the likelihood that a vegetated wetland or potential GDE habitat area is a GDE. The exception to this could be locations where surface waters gain a significant amount of water from groundwater. The Sacramento River and the Colusa Basin Drain are both under net-gaining conditions, where surface waters annually gain water from the aquifer system (Section 3.2.7). These net-gaining conditions along surface water corridors could increase the likelihood of GDEs.

The rightmost panel of Figure 3-35 shows the scores for the potential GDE areas within the Colusa Subbasin. Table 3-8 includes the acreages per GDE score. Most of the NCCAG lands within the Subbasin were designated a score of 2, which is on the lower end of likelihood of being classified as a GDE due to proximity to both surface waters and irrigated croplands. The majority of the high scores (i.e. score of 3 or 4, or a high likelihood of being a GDE) occur along the Sacramento River corridor, within the wildlife refuges, and in non-agricultural lands surrounding some of the streams, such as along Willows Creek and south of Delevan Wildlife Refuge.

Table 3-8. GDE Likelihood Scores

Score	Score Description	Approximate Acreage
1	Less Likely	2,540
2	--	8,710
3	--	5,580
4	More Likely	920



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Source: Wetland and vegetation areas are from the Natural Communities Naturally Associated with Groundwater (NCCAG) datasets and associated reports prepared by The Nature Conservancy (2018).

Horizontal Datum: North American Datum of 1983 (NAD 83), California State Plane Zone II, feet.

Note:
1. GDE liklihood scores were obtained via comparison of NCCAG ares with proximity to surface waters and irrigated croplands.

- Colusa Subbasin
- Spring Depth to Water 30 ft Contour
- Proximity to Surface Waters (Within 150 ft)
- Proximity to Irrigated Rice Croplands (Within 150 ft)
- Proximity to Other Irrigated Croplands (Within 50 ft)
- NCCAG Vegetation and Wetlands

GDE Liklihood Score
- 4 (High Liklihood)
- 3
- 2
- 1 (Low Liklihood)

N

0 4 8
Scale in Miles

DRAFT

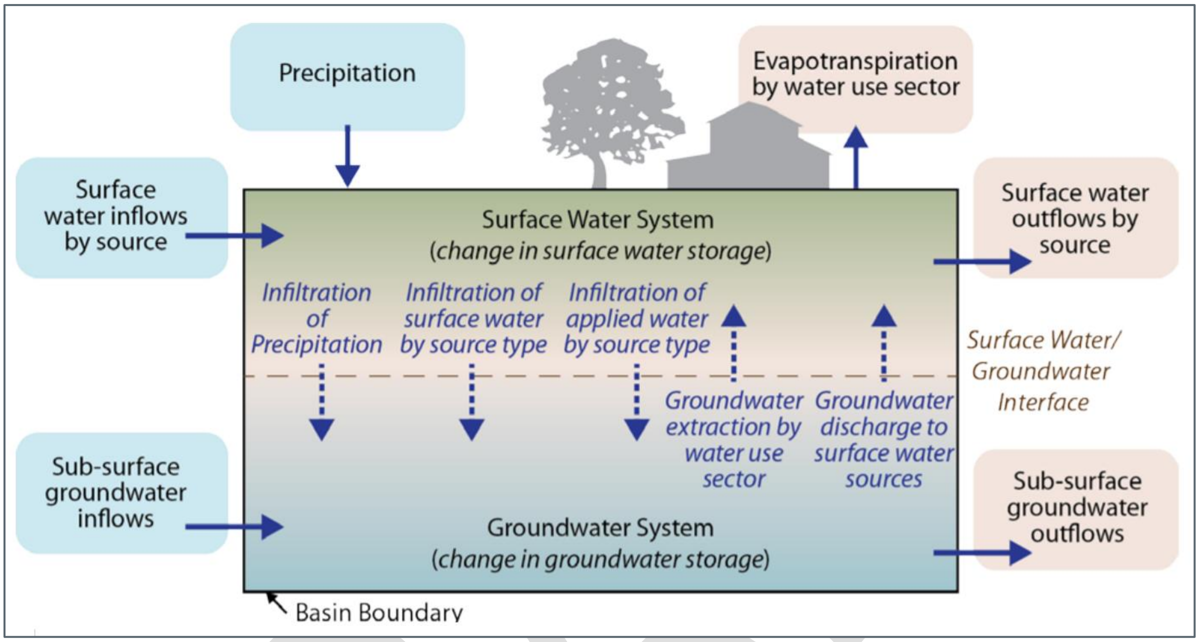
Figure 3-35

Groundwater Dependent Ecosystems

Colusa GSA and Glenn GSA
Colusa Subbasin
Groundwater Sustainability Plan

3.3 WATER BUDGET INFORMATION *(REG. § 354.18)*

This section describes historical, current, and projected water budgets in accordance with §354.18 of the GSP Emergency Regulations, including quantitative estimates of inflows to and outflows from the Colusa subbasin over time and changes in water storage within the basin. Components of the water budgets are depicted in Figure 3-36.



Notes: Boundary fluxes are shown as solid blue arrows, with inflows and outflows indicated by blue and red captions, respectively. Internal fluxes are indicated by dashed blue arrows. The two primary storage mechanisms are the surface water storage and groundwater storage systems.

Figure 3-36. Water Budget Components (DWR 2016)

Water budgets were developed considering hydrology, water demand, water supply, land use, population, climate change, surface water – groundwater interaction, and subsurface groundwater inflows and outflows to and from neighboring basins. Water budget results are reported on a water year basis spanning from October 1 of the prior year to September 30 of the current year. All water budget values are expressed in average annual volumes, with annual volumes presented in tabular form in Appendix 3E.

3.3.1 Selection of Hydrologic Periods

The GSP Emergency Regulations require evaluation of water budgets over a minimum of 10 years for the historical water budget, using the most recent hydrology for the current water budget, and 50 years of hydrology for the projected water budget. Hydrologic periods were selected for each water budget category listed below based on consideration of the best available information and science to support water budget development and consideration of the ability of the selected periods to provide a representative range of wet and dry conditions:

- **Historical** – The 26-year period from water years[1] 1990 to 2015 was selected based on the level of confidence in historical input data and information to support water budget development considering land use, surface water availability, hydrology, and other factors.
- **Current Conditions** – Historical water budget information for 2015 represents the most recent hydrology developed for GSP analysis (i.e. precipitation, evapotranspiration, stream inflows). To provide a broader basis for understanding current water budget conditions, a water budget scenario combining most recently available land use (2013 and 2015, representing non-curtailment [Shasta Non-Critical] and curtailment [Shasta Critical] years, respectively) and urban demands (average of 2006-2015) over 50 years of historical hydrology was developed. The period selected was 1966 to 2015. An advantage of evaluating the current conditions water budget over a representative 50-year period is that the results provide a baseline for evaluation of the projected water budgets.
- **Future Conditions** – Consistent with the current conditions water budget, the hydrologic period selected as the basis for the projected water budgets was 1966 to 2015.

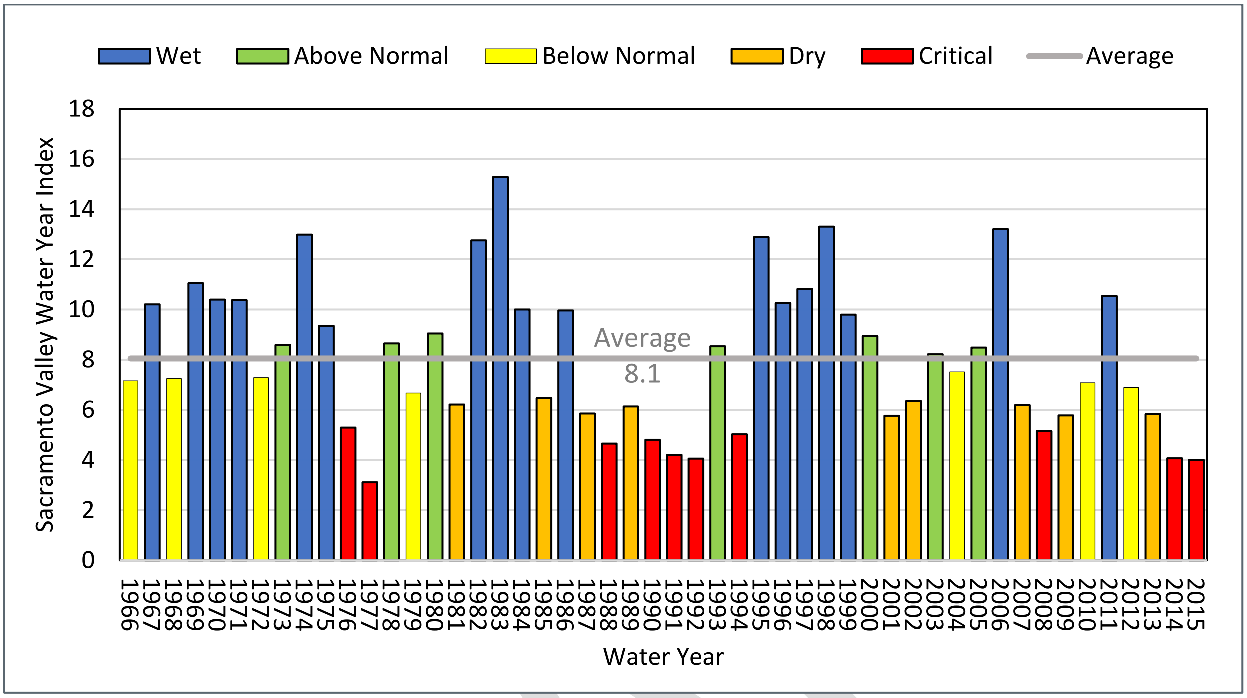
Selection of the 50-year hydrologic period for the current and projected water budget scenarios was based primarily on three considerations:

- C2VSimFG, the primary tool used to develop the water budgets, has hydrologic information from water years 1922 to 2015.
- The average Sacramento Valley Water Year Index[2] values for the 50-year period from 1966 to 2015 and the 104-year period from 1906 to 2019 (1906 is the first year for which the index is available) are both 8.1. This indicates that the selected 50-year period is similar on average to the entire period of record for the Sacramento Valley watershed. (Figure 3-37). This is important because the major source of surface water in the Colusa subbasin is the Sacramento River.
- The selected period includes a combination of wet and dry cycles, including relatively wet periods in the early 1970’s, mid 1980’s, and late 1990’s and dry periods in the late 1970’s, early 1990’s, and from approximately 2007 to 2015.

[1] A water year is defined as the period from October 1 of the prior year to September 30 of the current year. For example, water year 2000 refers to the period from October 1, 1999 to September 30, 2000.

[2] The Sacramento Valley Water Year Index classifies water years as wet, above normal, below normal, dry, or critical based on Sacramento River unimpaired flows. Additional details describing the Sacramento Valley Water Year Index are available from the California Data Exchange Center .

Additionally, annual precipitation for the 1966 to 2015 period averaged approximately 19.4 inches per year, as compared to 18.0 inches for the 1906 to 2018 period indicating slightly wetter conditions than the entire period of record for the Sacramento Valley Index.



Notes: The average index is 8.1, which is the same as the average for the entire period of record from 1906 through 2019.

Figure 3-37. Sacramento Valley Water Year Index and Water Year Types for a 50-year Period from 1966 to 2015

3.3.2 Use of the C2VSimFG Integrated Hydrologic Model

Development of the Integrated Water Flow Model (IWFM) began under the direction and funding of the California Department of Water Resources (DWR) in 2001. The fine-grid application of IWFM, the California Central Valley Groundwater-Surface Water Simulation Model (C2VSimFG), became publicly available in 2012. The model has been updated over time to simulate historical conditions through water year 2015. The model performs calculations on a monthly time step with monthly input data (i.e., precipitation, stream inflow, surface water diversions) and some annual input data (i.e., land use). Refinements to the model over time include additional crop types to better represent ponded crops (i.e., rice and wetlands), recalibrated soil parameters, and elemental land use. Development and calibration of the C2VSimFG-Colusa[3] model used for water budget analyses in the Colusa subbasin are described in more detail in Appendix 3D.

To prepare water budgets for this GSP, historical C2VSimFG-Colusa results for water years 1990 to 2015 have been relied upon, and four additional baseline scenarios have been developed to represent current and projected (future) conditions utilizing 50 years of hydrology (described previously). Specific assumptions associated with these scenarios are described in the following section.

[3] Version BETA2 of C2VSimFG was used for C2VSimFG-Colusa.

3.3.3 Water Budget Assumptions

Assumptions utilized to develop the historical, current, and projected water budgets are described below and summarized in Table 3-9.

Table 3-9. Summary of Water Budget Assumptions Used for Historical, Current Conditions, Future Conditions, and Future Conditions With Climate Change at Two Times in the Future (i.e., 2030 and 2070)

Water Budget	Analysis Period1	Hydrology	Land Use	Water Supplies
Historical Simulation	1990-2015	Historical	Historical	Historical
Current Conditions Baseline	2016-2065	Historical (1966-2015)	Current (2013 and 2015) used for Shasta non-critical and Shasta Critical, respectively	Current (2013 and 2015) used for Shasta non-critical and Shasta Critical, respectively, for water diversions; 2006-2015 average for urban demands
Future Conditions, No Climate Change Baseline	2016-2065	Historical (1966-2015)	Current (2013 and 2015) used for Shasta Non-critical and Shasta Critical, respectively	Current (2013 and 2015) used for Shasta Non-critical and Shasta Critical, respectively, for water diversions; 2006-2015 average for urban demands
Future Conditions, 2030 Climate Change Baseline	2016-2065	Historical (1966-2015), adjusted based on 2030 climate change with central tendency	Current (2013 and 2015) used for Shasta non-critical and Shasta Critical, respectively	Same as Current (see above), adjusted for 2030 climate change
Future Conditions, 2070 Climate Change Baseline	2016-2065	Historical (1966-2015), adjusted based on 2070 climate change with central tendency	Current (2013 and 2015) used for Shasta non-critical and Shasta Critical, respectively	Same as Current (see above), adjusted for 2070 climate change

3.3.3.1 Historical

A historical water budget was developed to support understanding of past aquifer conditions, considering surface water and groundwater supplies utilized to meet demands. The historical water budget was developed using C2VSimFG-Colusa and incorporates the best available science and information. Historical water supplies and aquifer response have been characterized by water year type based on DWR's Sacramento Valley Water Year Index.

As described previously, water years 1990 to 2015 were selected to provide a minimum of ten years across a range of hydrologic conditions. This period includes relatively wet years in 1995, 1998, 2006, and 2011 as well as dry conditions between 1990 and 1992, in 1994, and between 2007 and 2009 and between 2013 and 2015.

Development of the historical water budget is described in greater detail in Appendix 3-E.

Information utilized to develop the historical water budget includes:

- **Analysis Period** – Water years 1990 to 2015
- **Stream Flows** – Data from C2VSimFG-Colusa were used as best-estimates for inflows and outflows from rivers, streams, and other waterways traversing the basin or along the boundary. The Sacramento River is the major surface water inflow to the subbasin. Stony Creek also provides inflow to the region along the northern boundary. Flows were estimated using C2VSimFG-Colusa which simulates the Sacramento River, Stony Creek, and Colusa Basin Drain in the basin.
- **Land Use** – Land use characteristics for agricultural, native, and urban (including rural residential) lands were estimated annually based on a combination of DWR land use surveys and county agricultural commissioner cropping reports. DWR land use data were available for 1993, 1998, 2003, 2009, and 2014.
- **Agricultural Water Demand** – Agricultural irrigation demands were estimated using C2VSimFG-Colusa, which simulates crop growth and water use on a monthly basis, considering crop type, evapotranspiration, root depth, soil characteristics, and irrigation practices. For ponded land uses (rice and managed wetlands), pond depths and pond drainage are also considered to simulate demands.
- **Urban and Industrial Water Demand** – Urban and industrial demands and per capita water use over time were estimated based on a combination of pumping data provided by the State Water Resource Control Board (Small Supplier Conservation Reports) and Urban Water Management Plans (UWMPs). Estimates of population were based on data from the Department of Finance and from UWMPs. Urban land use was estimated from Colusa County General Plans.
- **Surface Water Diversions** – Surface water diversions were estimated based on a combination of reported diversions by water suppliers and Bureau of Reclamation records. In some cases, agricultural water demand was estimated for areas known to receive surface water but for which reported diversion data were not available.
- **Groundwater Pumping** – For urban water suppliers, historical pumping was estimated from reported pumping volumes over time. Pumping for large irrigation districts was developed from reported data and private pumping for landowners was calculated automatically within the model by first estimating the total demand and then subtracting surface water deliveries to calculate estimated groundwater pumping required to meet the remaining demand.

3.3.3.2 Current Conditions

The current conditions water budget was developed as a baseline to evaluate projected water budgets considering future conditions and is based on 50 years of hydrology along with the most recent information describing land use, urban demands, and surface water supplies. The 50-year hydrologic period was selected rather than the most recent year for which historical water budget information is available to allow for direct comparison of potential future conditions to current conditions. The use of a representative hydrologic period containing wet and dry cycles supports the understanding of variability and uncertainty in groundwater conditions over time, establishment of sustainable management criteria, and development of projects and management actions to avoid undesirable results.

The current water budget estimates current inflows, outflows, and change in storage for the basin using 50 years of representative hydrology and the most recent water supply, water demand, and land use information.

Information utilized to develop the current conditions baseline water budget include:

- **Analysis Period** – 50-years of hydrology were utilized representing the period from 1966 to 2015.
- **Stream Inflows** – Inflows of surface water into the basin were estimated utilizing the same information as for the historical water budget.
- **Land Use** – Land use for agricultural, native, and urban (including rural residential) lands was estimated annually using the most recent land use information. Specifically, 2013 and 2015 land use were mapped to the 50-year analysis period, with 2015 land use applied to critically dry years corresponding to Shasta Critical years and 2013 land use applied to all other years. Shasta Critical years were identified based on annual inflow to Shasta Lake. Annual inflow to Shasta Lake is a reasonable indicator of surface water supplies and associated changes in diversion curtailments within the basin, which are primarily associated with Sacramento River.
- **Agricultural Water Demand** – Agricultural irrigation demands were estimated using C2VSimFG-Colusa, in the same manner as the historical water budget.
- **Urban and Industrial Water Demand** – Urban and industrial demands were estimated based on recent per capita water use and projected 2050 population. Specifically, average per capita water use for recent years (2006-2015) was reduced based on projected 2050 values in the Willows UWMP.
- **Surface Water Diversions** – For the current conditions scenario, historical diversions were applied to the future, with 2015 diversions used in Shasta Critical years and 2013 diversion used in non-critical years. Critical conditions occurred in nine years within the 50-year simulation period: 2016, 2027, 2028, 2041, 2042, 2044, 2045, 2064, 2065. Diversions in those years were on average 22% less than in non-critical years.
- **Groundwater Pumping** – Pumping to meet urban demands was estimated based on an average of recent years, as described above. Pumping to meet agricultural and managed wetlands demands was estimated using C2VSimFG-Colusa as described previously for the historical water budget.

3.3.3.3 Future Conditions Scenarios

Three projected (future conditions) baseline water budgets were developed considering a range of future conditions that may occur. The scenarios consider future planned land use changes (i.e., development), along with changes in climate, including precipitation, surface water inflows, and evapotranspiration. These baselines provide information regarding changes in basin conditions (e.g. groundwater storage) that may occur in the future over a series of wet and dry cycles.

The projected water budget estimates potential future inflows, outflows, and change in storage for the basin using 50-years of representative hydrology (including modifications based on climate change projections), the most recent water supply and water demand, and planned future land use information.

Information utilized to develop the future conditions baseline water budgets include:

- **Analysis Period** – 50-years of hydrology were utilized representing the period from 1966 to-2015.
- **Stream Inflows**
  - Future Conditions, No Climate Change – Inflows of surface water into the basin were estimated utilizing the same information as for the historical water budget.
  - Future Conditions, 2030 Climate Change – Precipitation, evapotranspiration, and surface water supplies were adjusted to reflect climate change based on the 2030 Central Tendency climate change datasets provided by DWR to support GSP development.
    - For precipitation and evapotranspiration, monthly change factors were applied to historical values to estimate potential future conditions.
    - For stream flows, DWR estimates of stream inflows were utilized where available; for streams without direct estimates of inflows, inflows were estimated using streamflow change factors applied at the watershed scale.
  - Future Conditions, 2070 Climate Change – Precipitation, evapotranspiration, and surface water supplies were adjusted to reflect climate change based on the 2070 Central Tendency climate change datasets provided by DWR to support GSP development.
    - For precipitation and evapotranspiration, monthly change factors were applied to historical values to estimate potential future conditions.
    - For stream flows, DWR estimates of stream inflows were utilized where available; for streams without direct estimates of inflows, inflows were estimated using streamflow change factors applied at the watershed scale.
- **Land Use** – Land use for agricultural, native, and urban (including rural residential) lands was estimated annually using the most recent land use information and modified based on planned development according to the Colusa County 2030 General Plan.
  - Future Conditions, No Climate Change – Land use was assumed to be similar to the current conditions water budget scenario.
  - Future Conditions, 2030 Climate Change – 2013 and 2015 land use data were mapped to the 50-year analysis period considering 2030 central tendency climate change projections. 2015 land use was applied to extreme dry years and 2013 land use applied to all other years. 2013 and 2015 land use data were modified to reflect planned development, generally resulting in an increase in urban land through development of previously undeveloped (i.e., native) lands.
- **Future Conditions, 2070 Climate Change** – 2013 and 2015 land use data were mapped to the 50-year analysis period considering 2070 central tendency climate change projections. 2015 land use was applied to Shasta Critical years and 2013 land use applied to all other (Shasta Non-critical) years. 2013 and 2015 land use data were modified to reflect planned development, generally resulting in an increase in urban land through development of previously undeveloped (i.e., native) lands.
- Agricultural Water Demand – Agricultural irrigation demands were estimated using C2VSimFG-Colusa and modified from the current conditions scenario as described below.
  - Future Conditions, No Climate Change – Agricultural water demand was assumed to be similar to the current conditions water budget scenario.

- Future Conditions, 2030 Climate Change – Agricultural water demand was increased from current conditions based on 2030 central tendency climate change projections.
- Future Conditions, 2070 Climate Change – Agricultural water demand was increased from current conditions based on 2070 central tendency climate change projections.

- **Urban and Industrial Water Demand** – Urban and industrial demands were estimated based on projected urban demands. Specifically, future urban demands were estimated based on preliminary draft demands for 2050 provided as part of the 2020 Urban Water Management Plan (UWMP) for Willows. Estimates for other urban demand areas were based on population growth rates and per capita water use similar to Willows.
- **Surface Water Diversions** – Climate change estimates are based on current diversions with reduced diversions in some years to simulate drought periods. For both the 2030 and 2070 central tendency scenarios, reductions occurred in eight years within the 50-year simulation period: 2016, 2026, 2027, 2028, 2041, 2042, 2064, 2065. Diversions were on average about 25 percent less than full supply years.
- **Groundwater Pumping** – Pumping to meet urban demand was estimated based on draft projections from UWMPs currently under development, as described above. Pumping to meet agricultural and managed wetlands demand was estimated using C2VSimFG-Colusa as described previously for the historical water budget.

3.3.4 Water Budget Estimates

As described previously, water budget estimates were developed using C2VSimFG-Colusa. Primary components of the land and surface water system water budget include the following:

- **Inflows**
  - Surface Water Inflows – Inflows at the land surface through rivers, streams, canals, or other waterways. These inflows may also include overland flow from upslope areas outside of the basin. Note that although interactions with streams along the boundary of the basin (i.e., diversions and stream-aquifer interaction) are accounted for, the flow in the stream is not considered an inflow to the basin. Inflows from streams that traverse the basin, primarily the Sacramento River near the eastern edge of the subbasin where the river is within the subbasin, are accounted for explicitly.
  - Precipitation – Rainfall on the land surface within the basin boundary.
  - Groundwater pumping – Extraction of groundwater to meet agricultural, urban, managed wetlands, or other beneficial uses.
  - Stream Accretions – Gains in streamflow from shallow groundwater occurring when the water level in the aquifer adjacent to the stream is greater than the water level in the stream.
- **Outflows**
  - Surface Water Outflows – Outflows at the land surface through rivers, streams, canals, or other waterways. These outflows may also include overland flow to downslope areas outside of the basin.
  - Evapotranspiration – Consumptive use of water including both evaporation and transpiration components.

- Deep Percolation – Recharge of the groundwater system through the vertical movement of precipitation and applied irrigation water below the root zone.
- Seepage (also referred to as losses or leakage) – Recharge of the groundwater system from streams, canals, or other water bodies.

- **Change in Storage** – Changes in soil moisture storage within the upper several feet of soil in the root zone, as well as changes in storage in surface water bodies within the basin. These changes are generally negligible on an annual basis but vary over the course of a year based on precipitation patterns and other factors.

Primary components of the groundwater system water budget include the following:

- **Inflows**
  - Deep Percolation – Described above.
  - Subsurface Inflows – Groundwater inflows from adjacent basins or from the foothills on the west side of the subbasin.
  - Seepage – Described above.
- **Outflows**
  - Groundwater Pumping – Described above.
  - Subsurface Outflows – Groundwater outflows to adjacent basins.
  - Accretions – Described above.
- **Change in Storage** – Changes in water storage in the aquifer system. These changes tend to be large compared to changes in root zone soil moisture storage and can vary substantially from year to year.

Many components of the water budget can be estimated based on measured data (e.g. precipitation, diversions, evapotranspiration, etc.) and are used to develop inputs to C2VSimFG-Colusa to support water budget development. Other components are more difficult to measure or do not have measured values readily available (e.g. deep percolation, subsurface flows, groundwater pumping, surface water-groundwater interaction, etc.) and are estimated using C2VSimFG-Colusa. Additional detail describing the C2VSimFG is available in DWR Technical Memorandum entitled Integrated Water Flow Model: IWFM-2015 Theoretical Documentation[4].

Average annual water budget estimates for the historical water budgets and for the current and projected water budget scenarios are summarized in Table 3-10 for the land and surface water system and in Table 3-11 for the groundwater system. Additional information and discussion regarding the water budgets is provided in the following subsections. It is anticipated that the water budgets will be refined and updated over time as part of GSP implementation in the basin.

[4] https://data.cnra.ca.gov/dataset/5c4b82c9-d219-4d71-a6cc-7ea6ccbaa54b/resource/a94dda67-4d90-418d-8c10-f403626b0f8d/download/iwfm-2015.0.1129_theoreticaldocumentation.pdf

Table 3-10. Average Annual Land and Surface Water System Inflows, Outflows, and Changes in Storage in taf/yr for the Water Budget Analysis Periods Listed in Table 3-9

Component	Historical Simulation	Current Conditions Baseline	Future Conditions, No Climate Change Baseline	Future Conditions, 2030 Climate Change Baseline[a]	Future Conditions, 2070 Climate Change Baseline[b]
Inflows					
Surface Water Inflows	11746.5	12556.2	12556.3	12596.6	12714.6
Sacramento River Diversions	1076.1	1196	1196	1196.3	1195.9
Stony Creek Diversions	92.3	90.7	90.7	90.7	90.7
Sacramento River Inflows	10499.7	11188.1	11188.2	11228.4	11335.5
Other Inflows from Boundary Streams	78.4	81.4	81.4	81.1	92.5
Precipitation	1210.4	1182.5	1182.5	1198.3	1257.5
Groundwater Pumping	502	499.4	498.8	525.4	558.6
Agricultural	463.1	458.3	458.3	484.4	516
Urban and Industrial	11.2	10.7	10.1	10.1	10.1
Managed Wetlands	27.7	30.4	30.4	31	32.5
Stream Gains from Groundwater	365.5	348.8	348.8	337.4	322.7
Total Inflow	**13824.4**	**14587**	**14586.4**	**14657.7**	**14853.3**
Outflows					
Evapotranspiration	1739.8	1790.3	1790.1	1840.6	1900.9
Agricultural	1430	1494.3	1494.3	1541.6	1596.2
Urban and Industrial	21.7	28	27.9	28.1	28.4
Managed Wetlands	68.7	68.7	68.7	70.4	73.3
Native Vegetation	179.7	163.3	163.3	164.6	167.1
Canal Evaporation	39.6	35.9	35.9	35.9	35.9
Deep Percolation	441.2	415.7	415.4	415.3	411
Precipitation	173.7	162.3	162.2	160	156.1
Applied Surface Water	195.8	161.7	161.7	161	158.1
Applied Groundwater	71.6	91.6	91.4	94.2	96.9
Seepage	345	378.6	378.5	387.1	400.7
Streams	205.8	230.8	230.6	239.2	252.9
Canals and Drains	139.2	147.9	147.9	147.9	147.8
Surface Water Outflows	11301.8	12002.5	12002.5	12014.9	12140.8
Precipitation Runoff	54.7	50.6	50.6	52.3	59.8
Applied Surface Water Return Flows	96	93.4	93.3	92.1	90
Applied Groundwater Return Flows	21.6	18.5	18.5	19.3	20.4
Sacramento River	9371.1	11049.4	11049.5	11085.7	11186.7

Table 3-10. Average Annual Land and Surface Water System Inflows, Outflows, and Changes in Storage in taf/yr for the Water Budget Analysis Periods Listed in Table 3-9

Component	Historical Simulation	Current Conditions Baseline	Future Conditions, No Climate Change Baseline	Future Conditions, 2030 Climate Change Baseline[(a)]	Future Conditions, 2070 Climate Change Baseline[(b)]
Colusa Basin Drain	709.2	758.7	758.6	742.4	773.8
Colusa Weir to Sutter Bypass	993.8	0	0	0	0
Other Outflows to Boundary Streams	55.7	31.9	32	23.1	10.1
Total Outflow	**13827.8**	**14587.1**	**14586.5**	**14657.8**	**14853.5**
Change in Storage (Inflow - Outflow)	**-3.4**	**-0.1**	**-0.1**	**-0.1**	**-0.1**

(a) Central Tendency Climate Change Projections
(b) Sacramento River Diversions and Stony Creek Diversions are diversions from boundary streams outside the subbasin. About 20 percent of the total diversions come from streams within the subbasin and are included in the Sacramento River Inflow.

Table 3-11. Average Annual Groundwater System Inflows, Outflows, and Changes in Storage in taf/yr for the Water Budget Analysis Periods Listed in Table 3-9

Component	Historical Simulation	Current Conditions Baseline	Future Conditions, No Climate Change Baseline	Future Conditions, 2030 Climate Change Baseline[(a)]	Future Conditions, 2070 Climate Change Baseline[(b)]
Inflows					
Subsurface Water Inflows	200.2	203	202.9	205.5	208.9
Deep Percolation	441.2	415.7	415.4	415.3	411
Precipitation	173.7	162.3	162.2	160	156.1
Applied Surface Water	195.8	161.7	161.7	161	158.1
Applied Groundwater	71.6	91.6	91.4	94.2	96.9
Seepage	345	378.6	378.5	387.1	400.7
Streams	205.8	230.8	230.6	239.2	252.9
Canals and Drains	139.2	147.9	147.9	147.9	147.8
Total Inflow	**986.4**	**997.4**	**996.8**	**1007.9**	**1020.6**
Outflows					
Subsurface Water Outflows	146.4	148.5	148.6	147.7	146.6
Groundwater Pumping	502	499.4	498.8	525.4	558.6
Agricultural	463.1	458.3	458.3	484.4	547.8
Urban and Industrial	11.2	10.7	10.1	10.1	10.1
Managed Wetlands	27.7	30.4	30.4	31	34.7
Stream Gains from Groundwater	365.5	348.8	348.8	337.4	322.7
Total Outflow	**1013.9**	**996.7**	**996.2**	**1010.6**	**1027.9**
Change in Storage (Inflow - Outflow)	**-27.5**	**0.6**	**0.6**	**-2.7**	**-7.3**

(a) Central Tendency Climate Change Projections
(b) Sacramento River Diversions and Stony Creek Diversions are diversions from boundary streams outside the subbasin. About 20 percent of the total diversions come from streams within the subbasin and are included in the Sacramento River Inflow.

3.3.4.1 Historical Simulation

The historical water budget provides a foundation for understanding how the basin has behaved, including insight into historical groundwater conditions (e.g. observed water levels). Also, in accordance with the GSP Emergency Regulations, the historical water budget covers a period of at least ten years (25-year period from 1990 to 2015). The historical water budget is used to evaluate the availability and reliability of historical surface water supplies and provides insight into the ability to operate the basin within the sustainable yield. Note that the historical analysis period experienced slightly more precipitation than the long-term average and included historic drought conditions from approximately 2007 to 2015.

Average annual inflows to and outflows from the basin for the historical land and surface water system water budget were estimated to be 13.8 million acre-feet per year (maf/yr). Average annual values were presented previously in Table 3-10 and are shown graphically in Figure 3-38.

Primary inflows to the land and surface water system include surface water inflows (11,747 taf/yr), precipitation (1,210 taf/yr), groundwater pumping (502 taf/yr), and stream gains from groundwater[5] (366 taf/yr). Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are major sources of surface water inflows.

Primary outflows from the land and surface water system include surface water outflows (11,302 taf/yr), evapotranspiration (1,740 taf/yr), deep percolation (441 taf/yr), and stream losses[6] (345 taf/yr). Surface water outflows include outflows through the Sacramento River, Colusa Basin Drain, Colusa Weir to Sutter Slough, and outflows to boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water to downslope lands. Evapotranspiration is primarily from agricultural lands but also from managed wetlands, canal evaporation, native vegetation, and urban and industrial lands. Deep percolation is primarily from precipitation, but also from applied water. Stream losses include a combination of stream seepage and seepage from canals and drains.

[5] i.e. stream accretions

[6] i.e. seepage

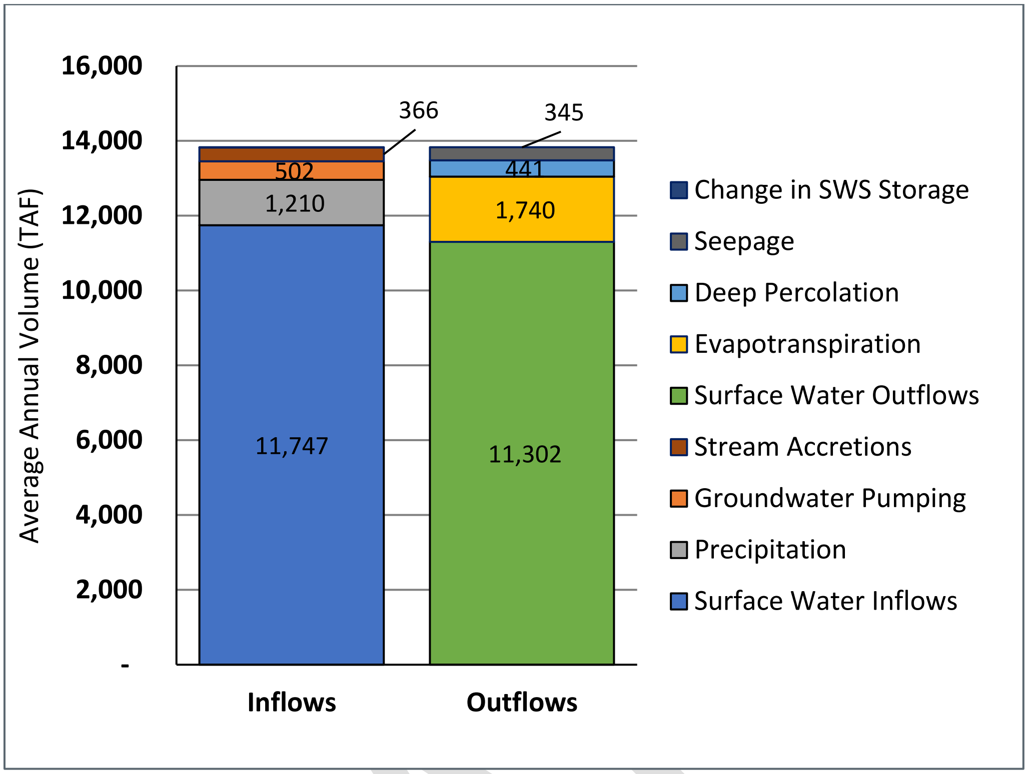


Figure 3-38. Average Annual Historical Land and Surface Water System Water Budget Summary

The average annual change in storage in the land and surface water system (3 taf/yr) is negligible due to similar soil moisture content in the root zone, on average, across water years.

Annual historical land and surface water system water budgets for 1990 to 2015 are provided in Table 3E-1 of Appendix 3E.

Average annual historical inflows to and outflows from the groundwater system were estimated to be 986 taf and 1,014 taf, respectively. Average annual values were presented previously in Table 3-11 are shown graphically in Figure 3-39 Inflows to the groundwater system include deep percolation (441 taf/yr), subsurface inflows from the Corning, Butte, Sutter, and Yolo subbasins (200 taf/yr), stream losses (345 taf/yr), and changes in groundwater storage (28 taf/yr). Outflows from the groundwater system include groundwater pumping (502 taf/yr), subsurface outflows to the Corning, Butte, Sutter, and Yolo subbasins (146 taf/yr), and stream gains from groundwater (366 taf/yr).

Annual historical groundwater system water budgets for 1990 to 2015 are provided in Table 3E-2 of Appendix 3E.

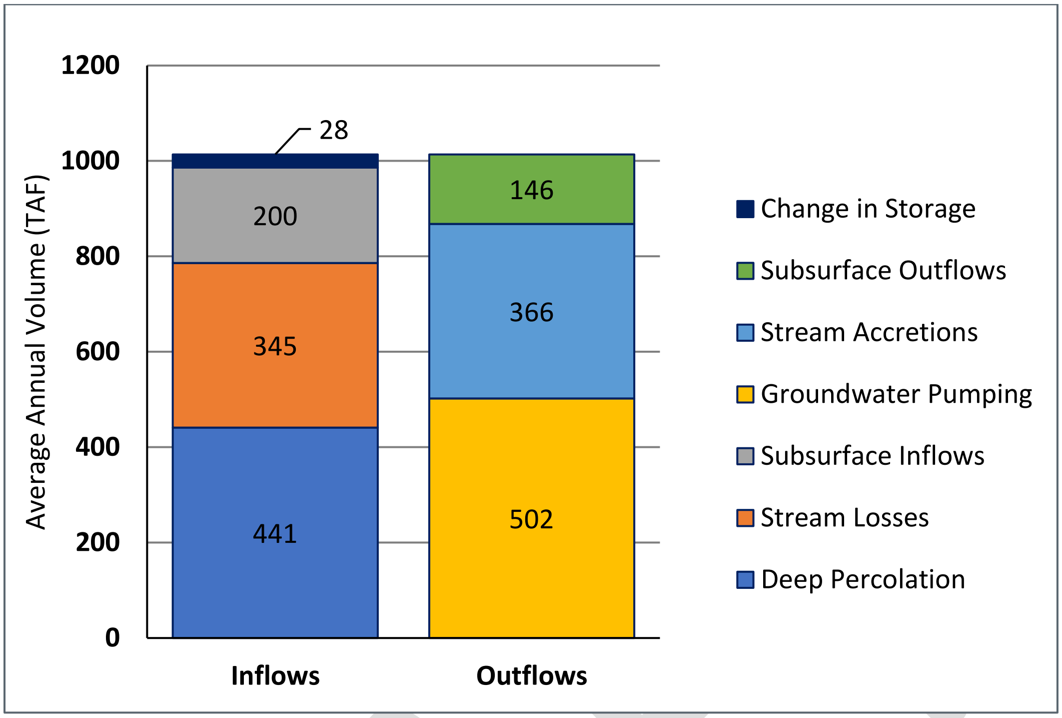


Figure 3-39. Average Annual Historical Groundwater System Water Budget Summary

Historical water supplies and change in groundwater storage are summarized by water year type in Table 3-12 based on the Sacramento Valley Water Year Index. Between 1990 and 2015, there were seven wet years, four above normal years, 3 below normal years, 5 dry years, and 7 critical years. Historical surface water deliveries were greatest in dry years and least in critical years. Groundwater pumping was greatest in dry years and least in wet years. Historically, groundwater storage in the basin has tended to increase in wet and above normal years and to decrease in below normal, dry, and critical years, with reductions in storage in below normal years less than reductions in dry and critical years. The average annual change in storage over the 1990-2015 historical period was -28 TAF.

Table 3-12. Historical Water Supplies and Change in Groundwater Storage by Hydrologic Water Year Type, taf/yr

Water Year Type	Surface Water Deliveries[a]	Groundwater Pumping	Total Supply	Change in Groundwater Storage
Wet	1,380.9	434.5	1,814.4	99.3
Above Normal	1,473.5	435.1	1,908.5	101.1
Below Normal	1,592.1	545.6	2,137.7	-24.2
Dry	1,597.6	570.3	2,167.8	-116.4
Critical	1,228.2	540.1	1,768.3	-165.8
Average	**1,419.8**	**502.0**	**1,921.7**	**-27.5**

(a) Surface Water Deliveries represents the volume of water delivered to agricultural and urban lands. It is an internal flow path and is different than Surface Water Inflow in the subbasin boundary balance summarized in Table 3-10.

3.3.4.1.1 Availability or Reliability of Historical Surface Water Supplies

As indicated in Table 3-12, historical surface water supplies for delivery to agricultural land vary based on water year type. The primary sources of surface water in the basin are the Sacramento River and Stony Creek. Surface water supplies are relatively reliable in the basin and represent approximately 74 percent of the total water supplies. Under 2030 and 2070 climate change conditions there may be an increase in the availability of surface water for irrigation in the basin due to increased precipitation from climate change effects. Potential effects of these changes are evaluated as part of the projected water budgets in the following sections.

Under diversion agreements between Sacramento River Settlement Contractors and the State, Sacramento River diversions can be reduced under the following conditions:

- DWR forecasted annual inflow into Lake Shasta is less than 3,200 taf[7], or
- There is a cumulative deficit of inflows below 4,000 TAF of greater than 800 TAF for any year or consecutive series of years.

3.3.4.1.2 Suitability of Tools and Methods for Planning

The water budgets presented herein have been developed using the best available information and best available science and structured in a manner consistent with the hydrogeologic conceptual model of the basin. The IWFM application C2VSimFG-Colusa, which is used to organize information for the water budgets, develop water budget scenarios, and perform water budget calculations, is currently the best available tool and is suitable for GSP development for the subbasin. The IWFM has been developed over the past several decades and updated over time to use updated model code, updated datasets, and updated input parameters through a series of efforts by DWR. Refinements to C2VSimFG specific to the Colusa basin are described Appendix 3D.

The water budgets developed using C2VSimFG-Colusa support the development of sustainable management criteria, evaluation of the monitoring network, and development of projects and management actions as part of GSP development. It is anticipated that the C2VSimFG-Colusa will continue to be updated and refined in the future as part of GSP implementation. Additional information describing C2VSimFG is available in DWR's Theoretical Documentation and User's Manual[8].

3.3.4.1.3 Ability to Operate the Basin within the Sustainable Yield

Sustainable yield refers to the maximum quantity of water, calculated over a base period representative of long-term conditions in the basin, and including any temporary surplus that can be withdrawn annually from a groundwater supply without causing an undesirable result. As a result, determination of sustainable yield requires consideration of SGMA's six sustainability indicators. Historical water budget estimates indicate an average annual decrease in storage of 28 taf/yr for the period from water year 1990 to 2015. Operation of the basin within the sustainable yield will likely require implementation of projects and management actions over the 20-year SGMA planning and implementation horizon. Projects and management actions are discussed in Chapter 6. The estimated sustainable yield of the basin is described in greater detail in Section 3.3.7.

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[7] The final, official forecast must be made by April 10 of each year.

[8] https://data.cnra.ca.gov/dataset/c2vsimfg_beta2

3.3.4.2 Current Conditions Baseline

The current conditions baseline water budget provides a foundation to understand the behavior of the basin considering current land use and urban demands over a broad range of hydrologic conditions as well as a basis for evaluating how groundwater conditions may change in the future based on comparison of water budget results to projected water budgets presented in the following section. A 50-year hydrologic period was selected, rather than a single, recent year to improve the basis for estimation of sustainable yield under current conditions.

Average annual inflows to and outflows from the basin for the current conditions land and surface water system baseline water budget were estimated to be 14,600 taf/yr. Average annual values were presented previously in Table 3-10 and are shown graphically in Figure 3-40.

Primary inflows to the land and surface water system include surface water inflows (12,556 taf/yr), precipitation (1,183 taf/yr), groundwater pumping (499 taf/yr), and stream gains from groundwater (349 taf/yr). Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are primary sources of surface water inflows.

Primary outflows from the land and surface water system include surface water outflows (12,002 taf/yr), evapotranspiration (1,790 taf/yr), deep percolation (416 taf/yr), and stream losses (379 taf/yr). Surface water outflows include outflows through Sacramento River, Colusa Basin Drain, Colusa Weir to Sutter Slough, and outflows to boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water to downslope lands. Evapotranspiration is primarily from agricultural lands but also from managed wetlands, canal evaporation, native vegetation, and urban and industrial lands. Deep percolation is primarily from precipitation, but also from applied water. Stream losses include a combination of stream seepage and seepage from canals and drains.

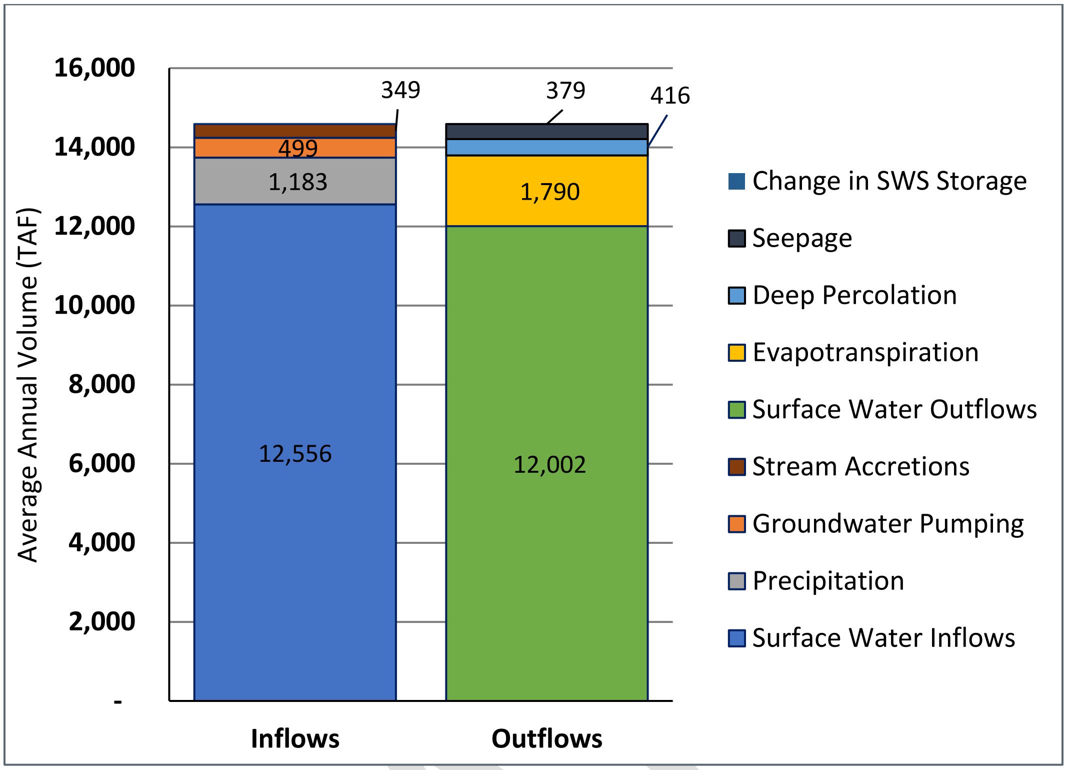

Figure 3-40. Average Annual Current Conditions Baseline Land and Surface Water System Water Budget Summary

The average annual change in storage in the land and surface water system (0.1 taf/yr) is negligible due to similar soil moisture content in the root zone, on average, across water years.

Average annual inflows to and outflows from the groundwater system were estimated to be 997 taf/yr during the current conditions baseline simulation period. Average annual values were presented previously in Table 3-11 and are shown graphically in Figure 3-41.

Inflows to the groundwater system include deep percolation (416 taf/yr), stream losses (379 taf/yr), and subsurface inflows from the Corning, Butte, Sutter, and Yolo subbasins (203 taf/yr). Outflows from the groundwater system include groundwater pumping (499 taf/yr), stream gains from groundwater (349 taf/yr), subsurface outflows to Corning, Butte, Sutter, and Yolo subbasins (149 taf/yr), and change in groundwater storage (1 taf/yr).

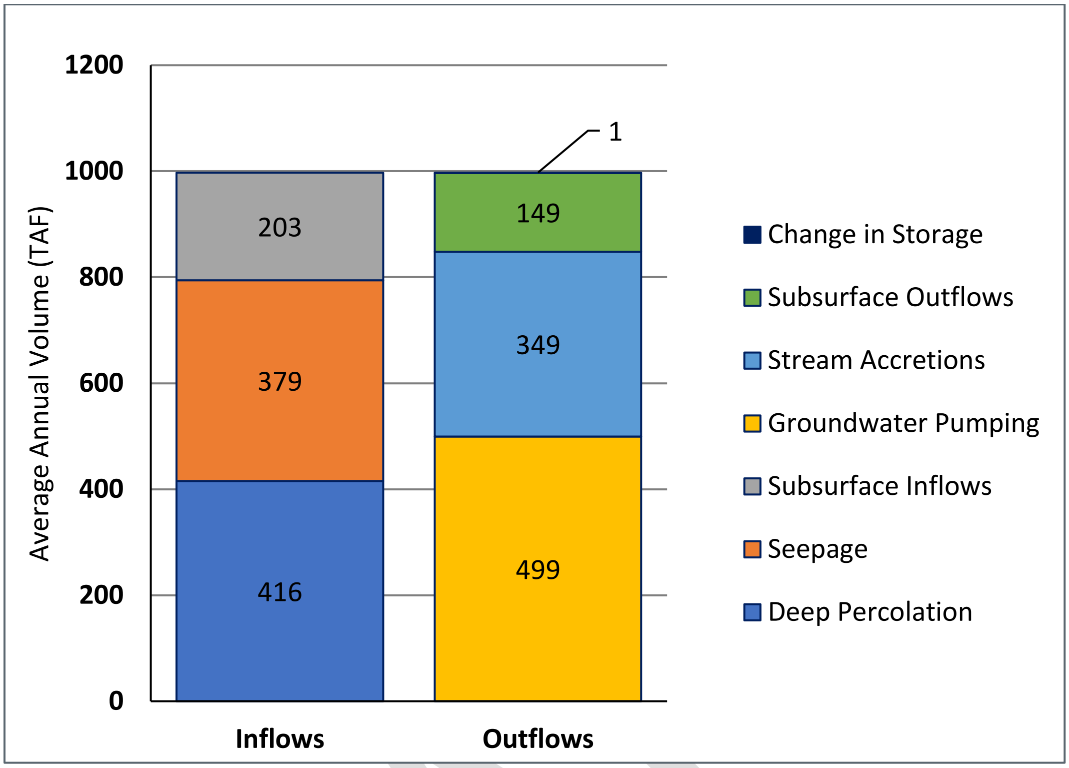

Figure 3-41. Average Annual Current Conditions Baseline Groundwater System Water Budget Summary

3.3.4.3 Future Conditions Scenarios

Three projected water budgets were developed for the basin to provide baseline scenarios representing potential future conditions considering planned development under the Colusa County 2030 General Plan and climate change centered around 2030 and 2070 based on central tendency climate change datasets provided by DWR. The projected water budget scenarios provide a foundation to understand the behavior of the basin considering potential future land use and urban demands over a broad range of hydrologic conditions, modified based on climate change projections. Use of a 50-year hydrologic period provides a basis for estimation of sustainable yield under potential future conditions.

3.3.4.3.1 Future Conditions, No Climate Change Baseline

Average annual inflows to and outflows from the basin for the future conditions without climate change projected land and surface water system baseline water budget were estimated to be 14.6 maf/yr. Average annual values were presented previously in Table 3-10 and are shown graphically in Figure 3-42.

Primary inflows to the land and surface water system include surface water inflows (12,556 taf/yr), precipitation (1,183 taf/yr), groundwater pumping (499 taf/yr), and stream gains from groundwater (349 taf/yr). Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are a primary source of surface water inflows. Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are a key source of surface water inflows.

Primary outflows from the land and surface water system include surface water outflows (12,003 taf/yr), evapotranspiration (1,790 taf/yr), deep percolation (415 taf/yr), and stream losses (379 taf/yr). Surface water outflows include outflows through Sacramento River, Colusa Basin Drain, Colusa Weir to Sutter Slough, and outflows to boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water to downslope lands. Evapotranspiration is primarily from agricultural lands but also from managed wetlands, canal evaporation, native vegetation, and urban and industrial lands. Deep percolation is primarily from precipitation, but also from applied water. Stream losses include a combination of stream seepage and seepage from canals and drains.

The average annual change in storage in the land and surface water system (0.1 taf/yr) is negligible due to similar soil moisture content in the root zone, on average, across water years.

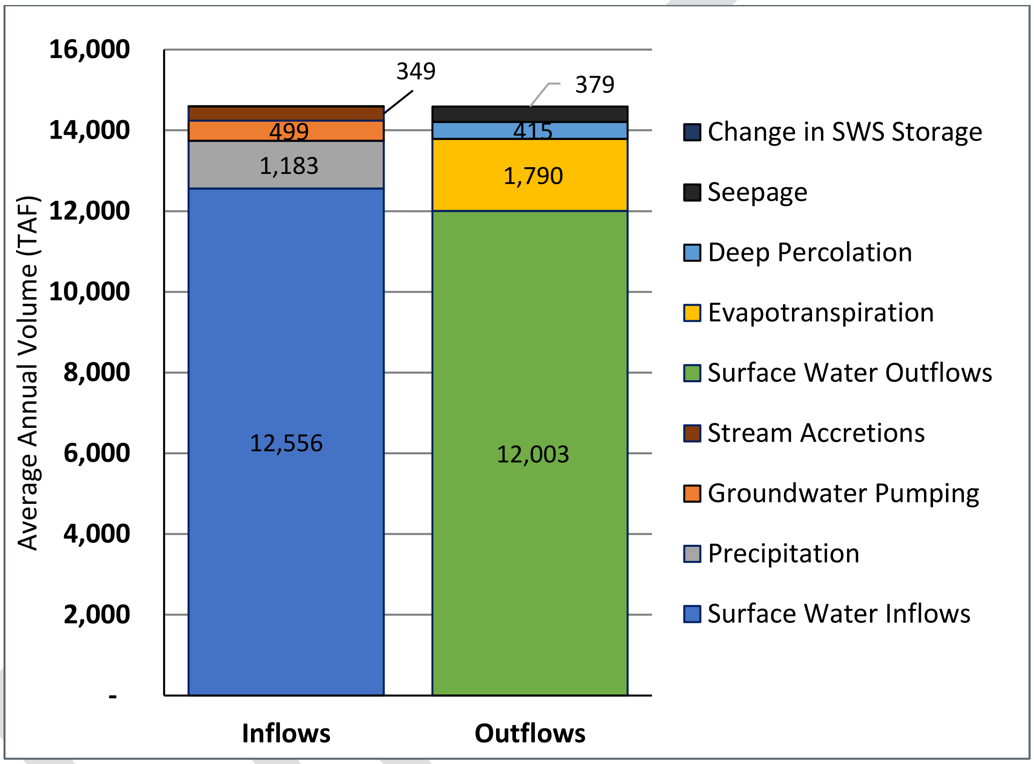

Figure 3-42. Average Annual Future Conditions, No Climate Change Baseline Land and Surface Water System Water Budget Summary

Average annual inflows to and outflows from the groundwater system were estimated to be 997 taf/yr for the future conditions without climate change simulation. Average annual values were presented previously in Table 3-11 are shown graphically in Figure 3-43**.**

Inflows to the groundwater system include deep percolation (415 taf/yr), stream losses (379 taf/yr), and subsurface inflows from the Corning, Butte, Sutter, and Yolo subbasins (203 taf/yr). Outflows from the groundwater system include groundwater pumping (499 taf/yr), stream gains from groundwater (349 taf/yr), and subsurface outflows to the Corning, Butte, Sutter, and Yolo subbasins (149 taf/yr).

There is negligible change in groundwater storage under the future condition, no climate change baseline water budget.

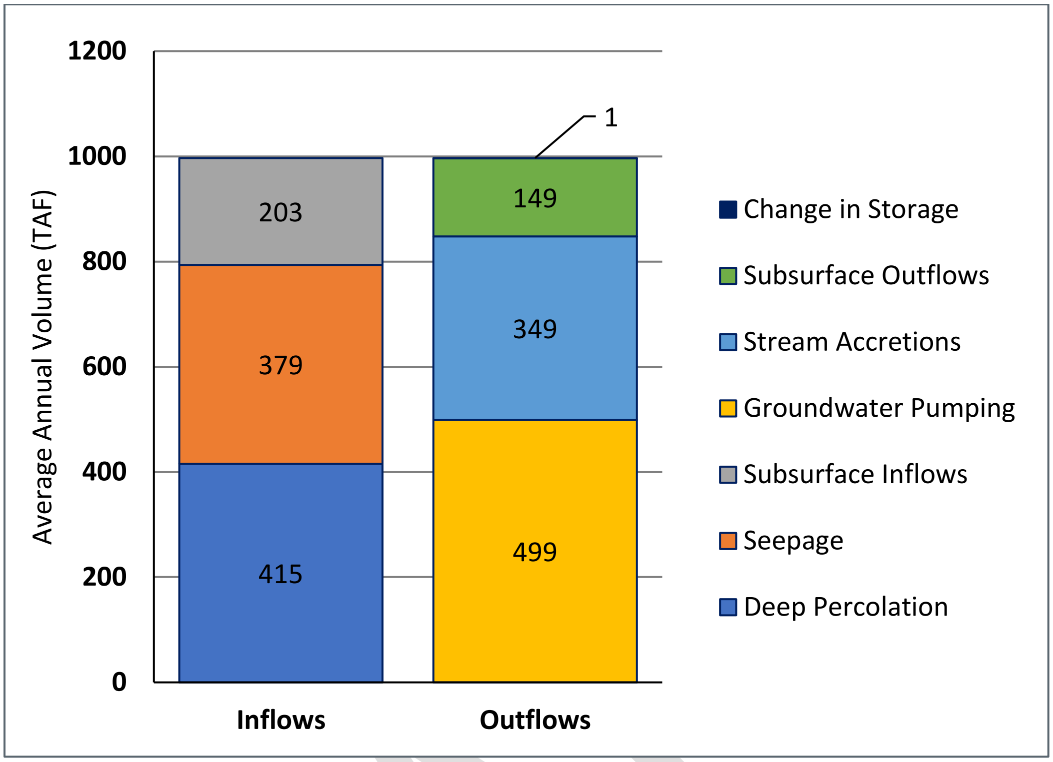

Figure 3-43. Average Annual Future Conditions, No Climate Change Baseline Groundwater System Water Budget Summary

3.3.4.3.2 Future Conditions, 2030 Climate Change Baseline

Average annual inflows to and outflows from the basin for the future conditions with 2030 climate change projected land and surface water system baseline water budget were estimated to be 14.7 maf/yr. Average annual values were presented previously in Table 3-10 and are shown graphically in Figure 3-44.

Primary inflows to the land and surface water system include surface water inflows (12,597 taf/yr), precipitation (1,198 taf/yr), groundwater pumping (525 taf/yr), and stream gains from groundwater (337 taf/yr). Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are a key source of surface water inflows.

Primary outflows from the land and surface water system include surface water outflows (12,015 taf/yr), evapotranspiration (1,841 taf/yr), deep percolation (415 taf/yr), and stream losses (387 taf/yr). Surface water outflows include outflows through Sacramento River, Colusa Basin Drain, Colusa Weir to Sutter Slough, and outflows to boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water to downslope lands. Evapotranspiration is primarily from agricultural lands but also from managed wetlands, canal evaporation, native vegetation, and urban and industrial lands. Deep percolation is primarily from precipitation, but also from applied water. Stream losses include a combination of stream seepage and seepage from canals and drains.

The average annual change in storage in the land and surface water system (0.1 taf/yr) is negligible due to similar soil moisture content in the root zone, on average, across water years.

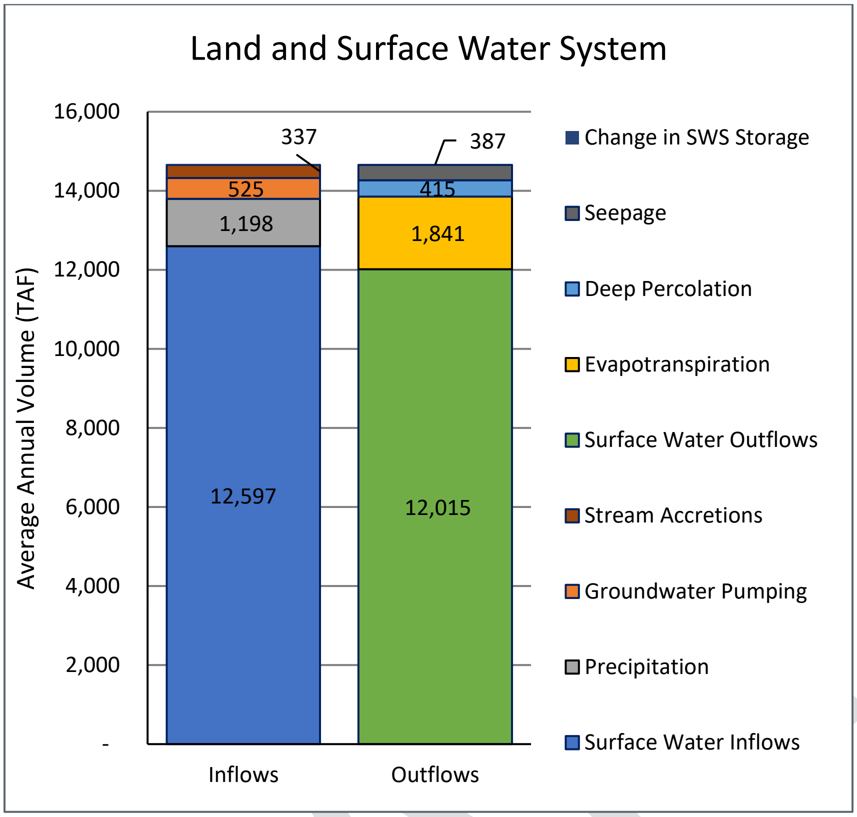

Figure 3-44.Average Annual Future Conditions, 2030 Climate Change Baseline Land and Surface Water System Water Budget Summary.

Average annual inflows to and outflows from the groundwater system were estimated to be 1.0 maf/yr during the 50-year simulation period. Average annual values were presented previously in Table 3-11 are shown graphically in Figure 3-45.

Inflows to the groundwater system include deep percolation (415 taf/yr), stream losses (387 taf/yr), subsurface inflows from the Corning, Butte, Sutter, and Yolo subbasins (205 taf/yr), and change in storage (3 taf/yr). Outflows from the groundwater system include groundwater pumping (525 taf/yr), stream gains from groundwater (337 taf/yr), and subsurface outflows to the Corning, Butte, Sutter, and Yolo subbasins (148 taf/yr).

There is a very small (-2.7 taf/yr) change in groundwater storage under the Future Condition, 2030 Climate Change water budget.

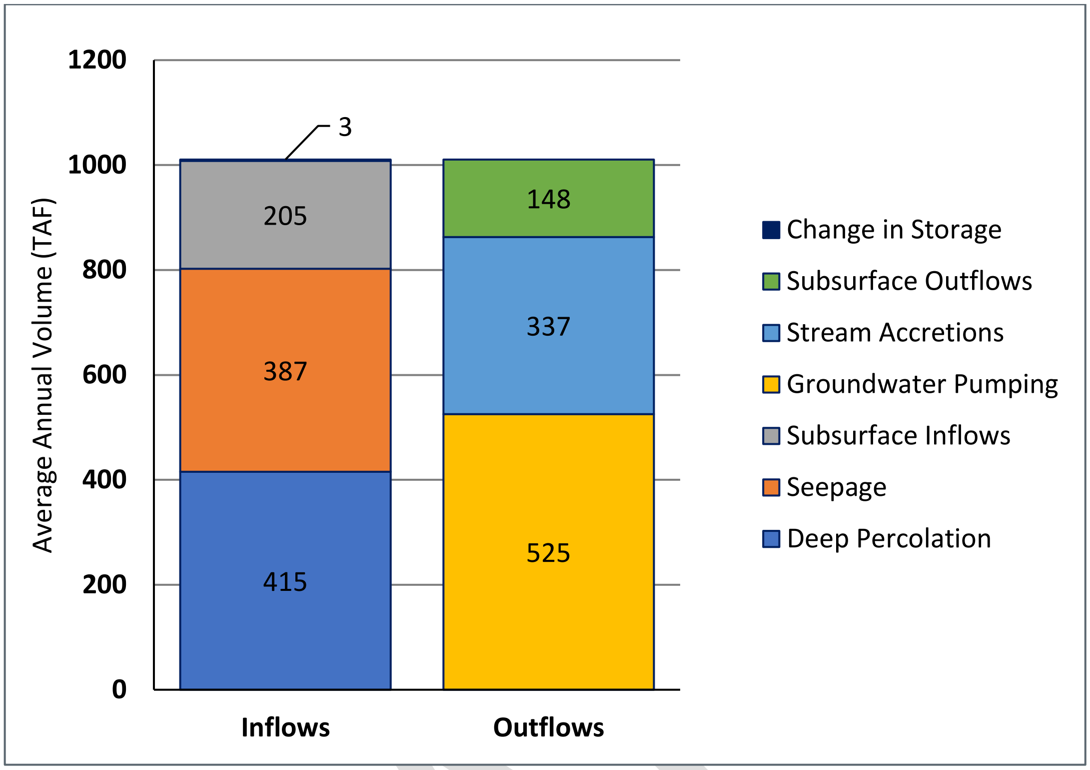

Figure 3-45. Average Annual Future Conditions, 2030 Climate Change Baseline Groundwater System Water Budget Summary

3.3.4.3.3 Future Conditions, 2070 Climate Change Baseline

Average annual inflows to and outflows from the basin for the future conditions with 2070 climate change projected land and surface water system baseline water budget were estimated to be 14,853 taf/yr. Average annual values were presented previously in Table 3-10 and are shown graphically in Figure 3-46.

Primary inflows to the land and surface water system include surface water inflows (12,715 taf/yr), precipitation (1,258 taf/yr), groundwater pumping (559 taf/yr), and stream gains from groundwater (323 taf/yr). Surface water inflows include the Sacramento River, other inflows from boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water from upslope lands. Additionally, diversions from the Sacramento River and from Stony Creek are a key source of surface water inflows.

Primary outflows from the land and surface water system include surface water outflows (12,141 taf/yr), evapotranspiration (1,901 taf/yr), deep percolation (411 taf/yr), and stream losses (401 taf/yr). Surface water outflows include outflows through Sacramento River, Colusa Basin Drain, Colusa Weir to Sutter Slough, and outflows to boundary streams including Stony Creek, as well as overland runoff of precipitation and applied water to downslope lands. Evapotranspiration is primarily from agricultural lands but also from managed wetlands, canal evaporation, native vegetation, and urban and industrial lands. Deep percolation is primarily from precipitation, but also from applied water. Stream losses include a combination of stream seepage and seepage from canals and drains.

The average annual change in storage in the land and surface water system (0.1 taf/yr) is negligible due to similar soil moisture content in the root zone, on average, across water years.

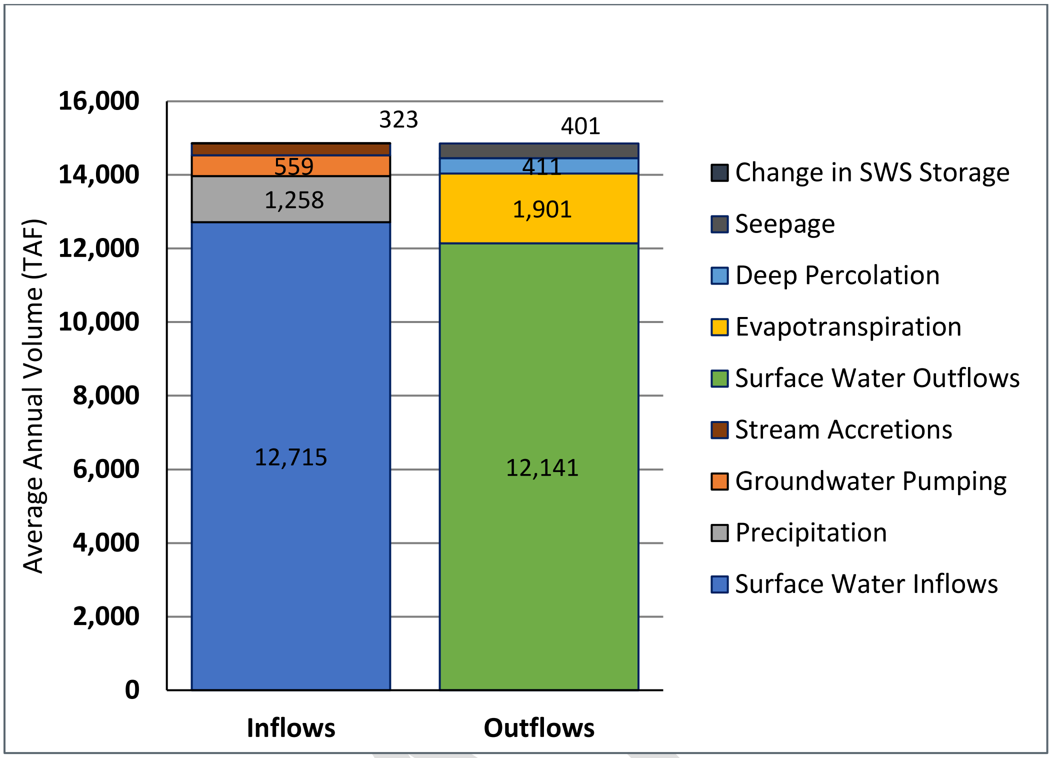

Figure 3-46. Average Annual Future Conditions, 2070 Climate Change Baseline Land and Surface Water System Water Budget Summary

Average annual inflows to and outflows from the groundwater system were estimated to be 1.0 maf/yr during the 50-year simulation period. Average annual values were presented previously in Table 3-11 are shown graphically in Figure 3-47.

Inflows to the groundwater system include deep percolation (411 taf/yr), stream losses (401 taf/yr), subsurface inflows from the Corning, Butte, Sutter, and Yolo subbasins (209 taf/yr), and change in groundwater storage (7 taf/yr). Outflows from the groundwater system include groundwater pumping (559 taf/yr), stream gains from groundwater (323 taf/yr), and subsurface outflows to the Corning, Butte, Sutter, and Yolo subbasins (147 taf/yr).

There is a very small (-7.3 taf/yr) change in groundwater storage under the Future Condition, 2070 Climate Change water budget.

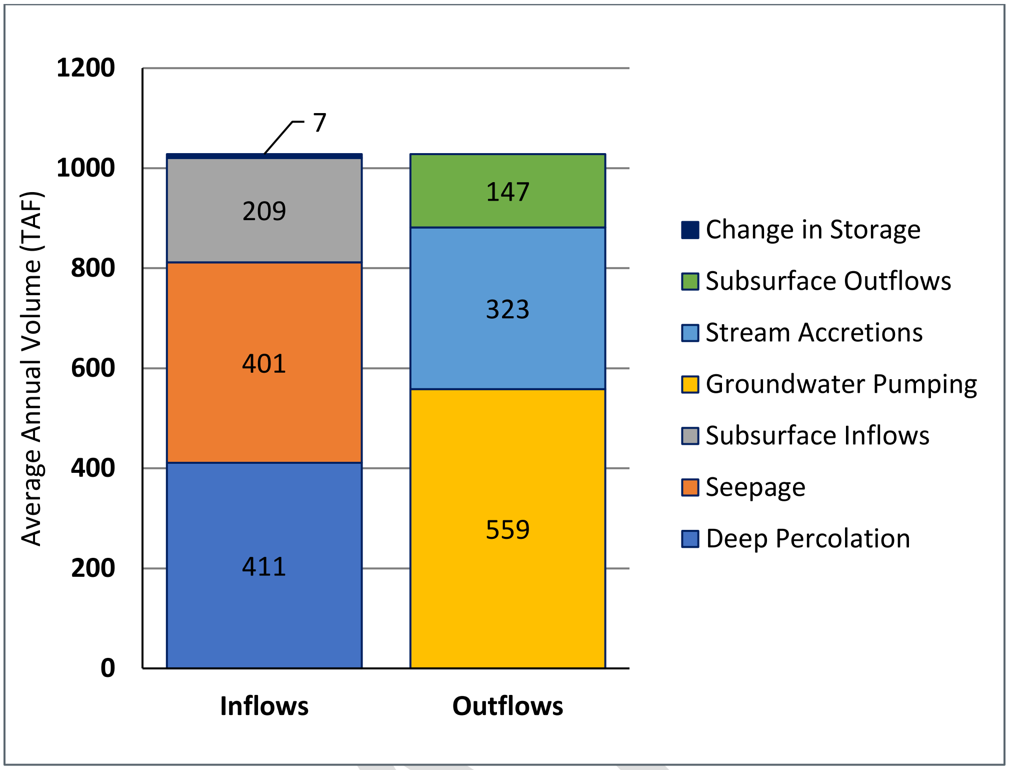

Figure 3-47. Average Annual Future Conditions, 2070 Climate Change Baseline Groundwater System Water Budget Summary

3.3.4.3.4 Comparison of Water Budget Scenarios

A figure depicting cumulative change in storage for the current conditions and three future conditions baseline scenarios is provided on the following page (Figure 3-48). In the figure, the cumulative change in groundwater storage is shown for the 50-year hydrologic period. The x-axis (horizontal axis) is labeled with the historical reference year along with the corresponding water year type based on the Sacramento Valley Water Year Index. Years are identified as wet (W), above normal (AN), below normal (BN), dry (D), or critical (C).

Estimated changes in storage are practically zero for the current conditions and future conditions without climate change scenarios. Current conditions and future conditions with no climate change are identical, except for minor urban growth represented in the future scenario without climate change. For the two future with climate change scenarios, there are small decreases in groundwater storage over the 50-year period, due primarily to increased groundwater pumping needed to meet increasing agricultural water demands resulting from climate change. For all scenarios, the changes in groundwater storage are substantial across wet and dry cycles, with the total range in storage change for all scenarios exceeding 800 TAF over the 50-year period.

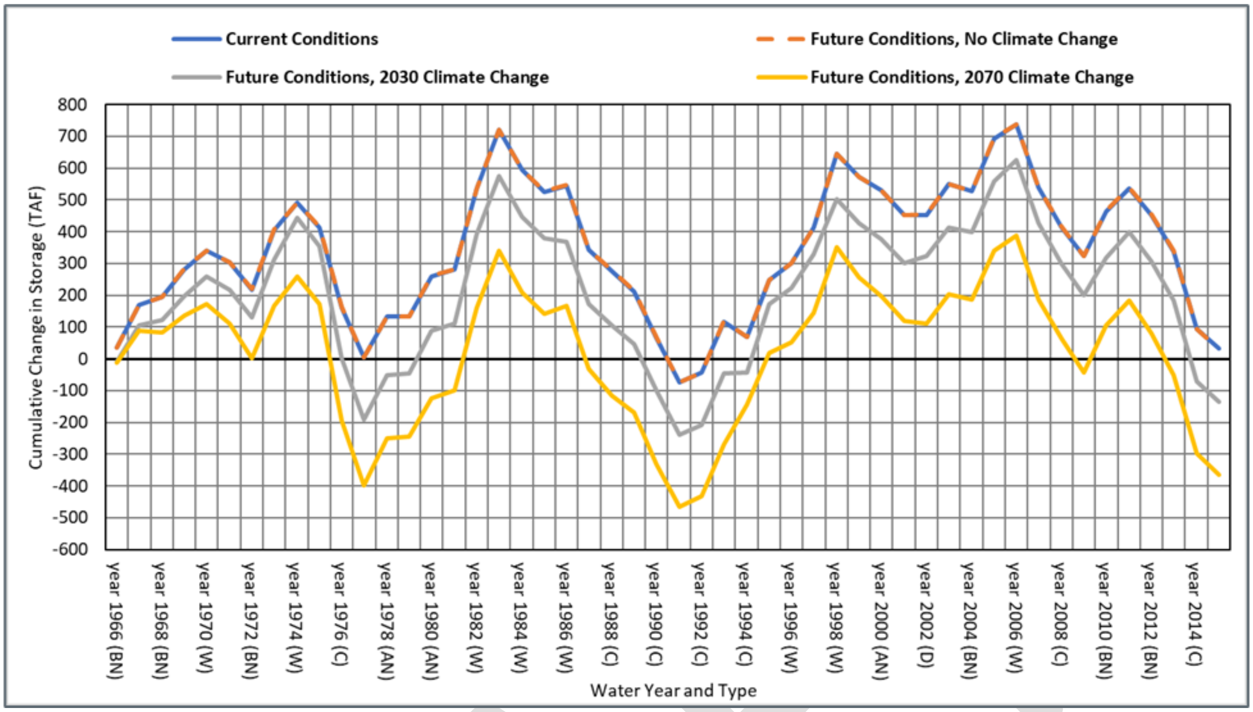

Figure 3-48. Cumulative Change in Groundwater Storage for Current and Future Conditions Baseline Scenarios

3.3.5 Water Budget Uncertainty

Uncertainty refers to a lack of understanding of the basin setting that significantly affects an Agency's ability to develop sustainable management criteria and appropriate projects and management actions in a GSP, or to evaluate the efficacy of plan implementation, and therefore may limit the ability to assess whether a basin is being sustainably managed. Substantial uncertainty exists in all components of each water budget component. Substantial uncertainty also exits in the assumptions used to project potential future conditions related to planned development and associated urban demands, as well as, projections of climate change. Consequently, the estimated negligible or very small changes in groundwater storage for current and future water budgets, calculated as total subbasin inflows minus outflows, are highly uncertain. It is anticipated that confidence in model results will be increased over time through additional monitoring and data collection, refinements to C2VSimFG-Colusa input, and coordination with neighboring subbasins.

However, the uncertainties that currently exist do not substantially limit the ability to develop and implement a GSP for the basin including the ability to develop sustainable management criteria and appropriate projects and management actions, including improved monitoring, nor the ability to assess whether the basin is being sustainably managed over time. GSPs are by nature iterative, and each opportunity will allow for improvements that will (1) lower uncertainty and (2) facilitate more refined analyses of sustainable management criteria and projects and management actions, and (3) refine the GSP implementation.

3.3.6 Overdraft Conditions

Overdraft refers to a negative average annual change in storage for the groundwater system over time. Based on the current conditions and future conditions with no climate change scenarios, which represent long-term average conditions in the subbasin, overdraft conditions are not expected to occur in the Colusa Subbasin. An average annual change in storage of approximately 0.6 taf/yr is expected, as presented in Table 3-10 previously and Table 3-13 in the following section. However, based on the future conditions scenarios with climate change, modest overdraft is expected to occur. Average annual overdraft is approximately 2.7 taf/yr in the 2030 scenario to 7.3 taf/yr in the 2070 scenario.

3.3.7 Sustainable Yield Estimate

As described previously, sustainable yield refers to the maximum quantity of water, calculated over a base period representative of long-term conditions in the basin, and including any temporary surplus that can be withdrawn annually from a groundwater supply without causing an undesirable result. Provisional estimates of sustainable yield have been calculated from water budget parameters for each scenario as the long-term annual average groundwater pumping, minus the average annual decrease in groundwater storage, as summarized in Table 3-13**.** Sustainable basin operation is expected to be achievable in current and future conditions scenarios, but modest overdraft is expected in future conditions with 2030 climate change and future conditions with 2070 climate change. Ultimately, it is anticipated that other factors will be considered in refining these sustainable yield estimates as part of development of sustainable management criteria for the basin, and as monitoring is improved and operational experience is gained during GSP implementation.

Table 3-13. Estimated Groundwater Pumping, Change in Groundwater Storage, and Sustainable Yield by Baseline Scenario, taf/yr

Baseline Scenario	Groundwater Pumping	Change in Groundwater Storage	Sustainable Yield
Current	499.4	0.6	500.1
Future, No Climate Change	498.8	0.6	499.4
Future, 2030 Climate Change	525.4	-2.7	522.7
Future, 2070 Climate Change	558.6	-7.3	551.2

3.4 MANAGEMENT AREAS (AS APPLICABLE) *(REG. § 354.20)*

Note to Readers: At the time of this writing, formation of Management Areas within the Colusa subbasin is being discussed among the CGA and GGA member agencies. If the decision is made to form Management Areas, this section will be completed according to the requirements of the GSP Emergency Regulations.

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