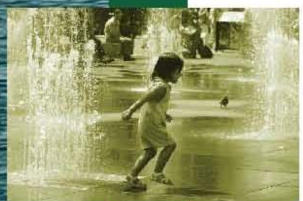

Hydrogeologic Conceptual Model Report

Prepared for

County of Glenn and County of Colusa

May 2018

277-16-17-07

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Prepared for

The County of Glenn and County of Colusa

Project No. 277-16-17-07

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List of Acronyms and Abbreviations

3D	Three-Dimensional
bgs	Below Ground Surface
BMP	Best Management Practice
C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CCR	California Code of Regulations
CDEC	California Data Exchange Center
cfs	Cubic-Feet per Second
Delta	San Joaquin-Sacramento River Delta
DTSC	Department of Toxic Substance Control
DWR	California Department of Water Resources
EC	Electrical Conductivity
ft/day	Feet per Day
GCID	Glenn-Colusa Irrigation District
gpm	Gallons per Minute
GSP	Groundwater Sustainability Plan
HCM	Hydrogeologic Conceptual Model
HUC	Hydrologic Unit Code
Ma	Million Years Ago
MCL	Maximum Contaminant Level
mg/L	Milligrams per Liter
MSL	Mean Sea Level
NAVD 88	North American Vertical Datum of 1988
NRCS	Natural Resources Conservation Service
PCE	Tetrachloroethylene
RD 108	Reclamation District No. 108
SAGBI	Soil Agricultural Groundwater Banking Index
SGMA	Sustainable Groundwater Management Act of 2014
SSURGO	Soil Survey Geographic Database
SVSim	Sacramento Valley Simulation Model
SWRCB	State Water Resources Control Board
TCCA	Tehama-Colusa Canal Authority
TDS	Total Dissolved Solids
µg/L	Micrograms per Liter
USBR	U.S. Bureau of Reclamation
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WBD	Water Boundary Datasets

ES.0 EXECUTIVE SUMMARY

This report provides a preliminary assessment of the hydrogeologic conceptual model (HCM) for the Counties of Glenn and Colusa to support development and implementation of one or more Groundwater Sustainability Plans (GSPs) for the groundwater subbasins underlying the two counties pursuant to the requirements of the Sustainable Groundwater Management Act of 2014 (SGMA). Title 23 Section §354.14(b) of the California Code of Regulations (23 CCR §354.14(b)) requires that the HCM shall include written descriptions for each of the following components:

- Regional geology and structure;
- Lateral basin boundaries;
- Definable bottom of the basin;
- Principal aquifers and aquitards including formation names, vertical and lateral extent, aquifer properties, restrictions to flow, water quality, and primary use; and
- Any data gaps and uncertainties identified in the previously listed topics.

Requirements listed in 23 CCR §354.14(c) through (d) state that the HCM shall include maps of each of the following physical components of the HCM. Additionally, all maps shall be informative, labeled, and clearly include the datum (23 CCR §352.4(d)).

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

This report addresses these requirements using currently available data and information in accordance with the Best Management Practices (BMPs) for the Sustainable Management of Groundwater: Hydrogeologic Conceptual Model BMP (DWR, 2016). The HCM will continue to be developed during preparation of one or more GSPs for the groundwater subbasins within the study area.

ES.1 Hydrogeologic Conceptual Model

The main components of the HCM include surficial features including 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. The following sections briefly summarize the components of the HCM.

ES.1.1 Geographic Setting and Land Use

The Counties of Glenn and Colusa encompass approximately 2,500 square miles in north central California; of which, 1,300 square miles are within the study area. The Glenn and Colusa County lines define the study area boundaries to the north, east, and south. The western boundary of the study area is defined by the western extent of the Colusa and Corning groundwater Subbasins. The study area is composed of high and medium priority groundwater basins as defined by the California Department of Water Resources (DWR) within Glenn and Colusa Counties, northern Sacramento Valley, California. The groundwater basins underlying the study area are shown on Figure ES-1 and include the entirety of the Colusa Subbasin (5-21.52), the southernmost portions of the Corning Subbasin (5-21.51) underlying Glenn County, and the southern part of the West Butte Subbasin (5-21.58) underlying Glenn and Colusa Counties (DWR, 2006).

Land within the study area is predominantly used for irrigated agriculture. Glenn and Colusa Counties house some of the richest rice-producing land in the country, as well as important waterfowl habitat along the Pacific Flyway (West Yost, 2014). Major commodities include rice, almonds, walnuts, prunes, tomatoes, seed crops, dairy products, and livestock. The land use pattern is typical of rural counties of the Sacramento Valley. Large acreage farms dominate the study area, with land ownership and road alignments often following square-mile section lines.

ES.1.2 Topography

The western side of the study area is elevated with low foothills transitioning to the more elevated Coast Range to the west, and low alluvial plains of coast range streams and flood basins of the Sacramento River to the east. The topography encourages drainage towards the Sacramento River and south. East of the Sacramento River, the topography within the West Butte Subbasin portion of the study area trends southward at a low gradient.

ES.1.3 Regional Hydrology

The study area is traversed by multiple natural streams and man-made water conveyance canals and drains. 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 streams, canals, and drains were analyzed and are discussed below.

Streams

The primary natural waterways of the study area include the Sacramento River, Stony Creek, and Butte Creek:

- The Sacramento River flows south along the eastern boundary of the Colusa and Corning Subbasins and the western boundary of the West Butte Subbasin. The Sacramento River is the water source for many of the irrigation and water districts within the study area.
- Stony Creek defines the boundary between the Colusa and Corning Subbasins, where it exists south of the Glenn-Tehama County line. Stony Creek drains the Coast Ranges of Glenn and Colusa Counties into Black Butte Lake before flowing across the Sacramento Valley and into the Sacramento River.

- Butte Creek drains the Sierra Nevada above Chico and flows into the Sacramento River east of Colusa, Colusa County. Butte Creek defines the eastern boundary of the West Butte Subbasin.

Most of the uplands within Glenn and Colusa Counties are drained via intermittent and ephemeral streams during the rainy season. Many of these streams flow into drainage canals within the study area.

Canals and Drains

Three major water conveyance systems exist within the basin:

- The Tehama-Colusa Canal provides irrigation water to farmers within Glenn, Colusa, Tehama, and Yolo Counties. The Tehama-Colusa Canal is the west-most major water conveyance canal, running parallel to the uplands of the Coast Ranges within the study area.
- The Glenn-Colusa Canal services approximately 1,200 acres of private habitat land and 20,000 acres of protected federal wildlife in addition to approximately 175,000 acres of agricultural lands within Glenn and Colusa Counties. 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.
- The Colusa Basin Drainage Canal system, otherwise known as the Colusa Basin Drain is a drainage system that transports agricultural runoff, return flows, and intermittent stream discharge away from the agricultural lands in Glenn and Colusa Counties to the Sacramento River. Some of the water within the Colusa Basin Drain is captured and reused prior to being discharged into the Sacramento River.

ES.1.4 Soils

Most soils in the study area contain either horizons (such as hardpan) or clays that restrict the vertical flow of water (DWR, 1978). This is typical of former flood basin soils of the Sacramento River Valley. Exceptions to this generalization include 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). Areas containing soils with few barriers to vertical flow are more likely to be recharge areas for underlying aquifers.

ES.1.5 Geologic Framework

The freshwater aquifers in the study area are comprised of two distinct semiconfined to confined aquifer systems and an overlying unconfined to semiconfined aquifer system. Underlying the geologic formations containing freshwater are older sedimentary marine geologic formations and crystalline plutonic and metasedimentary basement rocks. The Tehama and Tuscan Formations comprise the semiconfined to confined aquifer systems. The unconfined to semiconfined aquifer system is composed primarily of Holocene stream channel and basin deposits and the Riverbank and Modesto Formations. The freshwater geologic formations, faults, and folds are discussed in the following subsections.

Tuscan Formation

The Tuscan Formation comprises the oldest freshwater aquifer in the eastern half of the northern Sacramento Valley. Tuscan Formation deposits are characterized by their Cascade Range origin and volcanic signature and can be found primarily on the northeastern portion of the Sacramento Valley. The Tuscan Formation is exposed on the eastern side of the Sacramento Valley and occurs as interfingering layers at depth with the Tehama Formation 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.

The Tuscan Formation contains four map units, which are designated A through D, with A being the oldest (DWR, 2006). The low permeability deposits of Unit C are confining beds for the underlying Tuscan Units A and B. Unit D does not occur in 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.

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, 2006; Olmsted and Davis, 1961). The Tehama Formation is exposed at the land surface on the western side of the Sacramento Valley. It is buried beneath younger sediments to the east and interfingers with the Tuscan Formation in the central portion of the Sacramento Valley (DWR, 1978).

Riverbank and Modesto Formations

The Tuscan and Tehama Formations are unconformably overlain by the late Pleistocene age Riverbank and Modesto Formations. The thickness of the formation ranges from less than 10 feet to nearly 200 feet across the valley floor (DWR, 2006; 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, 2004; Lettis, 1988; Weissmann et. al., 2002). The formations are exposed at the land surface along creek channels as terrace deposits, and along the western margin of the study area, where they form a series of coalescing alluvial fans that emanate from the creek mouths.

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.

Faults and Folds

Significant structural features within the study area include the Willows Fault, Corning Fault, Paskenta Fault zone, Glenn Syncline, Greenwood Anticline, Zamora Syncline, Sutter Buttes, and Orland Buttes, in addition to other smaller, unnamed geologic structures. Some of these structural features affect younger Quaternary geologic units and may be geologically active at present (Harwood and Helley, 1987).

ES.1.6 Hydrogeologic Framework

Shallow groundwater in the study area occurs under unconfined to semiconfined conditions in the Holocene stream channel and basin deposits (DWR, 1978). At greater depths, groundwater occurs under semiconfined to confined conditions in a series of interconnected, heterogeneous aquifer systems. The aquifer properties, including hydraulic conductivity, vertical leakance, and degree of confinement are dependent on the properties of fine-grained sediment that surrounds the coarse-grained sediment within the aquifer material (Bertoldi et. al., 1991; Williamson et. al., 1989). Generally, groundwater flow is from the margins of the Sacramento Valley toward the Sacramento River and then southward towards the Sacramento-San Joaquin River Delta (Delta). The spatial, physical, chemical, and hydraulic hydrogeologic properties are discussed in the following subsections.

Basin Boundaries

Per the BMPs (DWR, 2016) and 23 CCR §354.14(b), the lateral basin boundaries are defined as geologic, hydrologic, or structural features that significantly affect groundwater flow. The lower boundary of the basin is defined based on either physical properties (top of marine rocks) or geochemical properties (base of fresh water).

Lateral Extents

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 groundwater basin boundary modifications made in 2016 redefined the northern and southern boundaries of the Colusa Subbasin to follow the jurisdictional boundaries of the Glenn-Tehama County line and the Colusa-Yolo County line along its northern and southern borders, respectively.

The study area also includes portions of Corning and West Butte Subbasins that underlie Glenn and Colusa Counties. The Corning Subbasin within the study area is hydrologically defined by Stony Creek, the Sacramento River, and the Coast Range uplands. The West Butte Subbasin within the study area is hydrologically defined by the Sacramento River and Butte Creek. The study area defined in this report includes only the portions of these subbasins within Glenn and Colusa Counties. Both Subbasins extend beyond the study area, but have quasi-jurisdictional boundaries defined at the county lines for the purposes of this report.

Vertical Extents

The approximate vertical extent of the fresh groundwater basin can be defined via chemical means. Previous studies have defined the base of fresh water to be where the specific conductance of the water exceeds 3,000 micromhos, or approximately 2,000 milligrams per liter (mg/L) total dissolved solids (TDS) (Olmsted and Davis, 1961). 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 approximate vertical extent of the fresh groundwater basin can also be defined via a physical interpretation. The physical base of the fresh water is preliminarily defined as the base of the Tehama and Tuscan Formations, the deepest fresh water-bearing geologic formations. This physical extent is similar to the chemical extent based on specific conductance, except near the western margins of the study area where brackish groundwater occurs above the Upper Princeton Valley Fill in the Tehama Formation.

Stratigraphic and Structural Features Potentially Affecting Flow

Stratigraphic and structural features that could potentially impact groundwater flow include topographic features, faults, folds, and stratigraphic or lithologic pinchouts. These features may impede or enable groundwater flow within and between each of the principal aquifers.

- Topography: The primary structures impacting flows within the shallow aquifer systems are most likely related to topography. The aquifer pinches out where topography is elevated and the older, less permeable units are exposed on the surface. An example of this is in the southwest corner of the Colusa Subbasin, where the shallow aquifer system pinches out on Tehama Formation outcrops.
- Faults: Faults may act as barriers to groundwater flow transverse to the fault, or, potentially, zones of preferential horizontal or vertical flow along the fault, if faulting has resulted in fractured zones.
- Folds: Synclines are folds in which sediments along the axis of the fold are displaced downward relative to sediments on the limbs. This results in a downward displacement of younger formations along the axis of the syncline and potential exposure of older formations along the margins. Synclines can be associated with 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, 2006). Anticlines are folds in which sediments along the axis of the fold are displaced upward relative to sediments on the limbs, potentially exposing older formations along the fold axis. In addition to thinning or thickening of stratigraphic units, the geologic forces responsible for folds can also cause reorientation of clays and other platy minerals causing decreased permeability.
- Stratigraphic Pinchouts: Pinchouts can occur where formations thin at their margins. Examples of this within the study area include the interfingering of the Tehama and Tuscan Formations throughout the Tehama-Tuscan Transition Zone or where the alluvial and basin deposits thin towards the uplands of the Coast Ranges. Pinchouts can also occur within the principal aquifer systems as the result of geologic

heterogeneity. The Tehama Formation is especially heterogeneous because of its alluvial and fluvial depositional history, which resulted in predominantly fine-grained sediments surrounding discontinuous lenses of sand and gravel. These sand and gravel lenses pinch out against the fine-grained sediments.

Principal Aquifers and Aquitards

Based on this preliminary HCM, there are three groupings of hydrostratigraphic units that define the principal aquifers within the study area:

1. Quaternary Alluvial Aquifer;
2. Tehama Formation Aquifer; and
3. Tuscan Formation Aquifer (consists of Unit A and Unit B).

Most of the fresh groundwater within the study area is contained within the Tehama Formation Aquifer. The principal aquitard within the study area is the Tuscan Unit C. Tuscan Unit C has low permeability that confines the lower aquifer units of the Tuscan Formation (Units A and B).

Physical and Aquifer Properties

The maximum thickness of the Quaternary Alluvial Aquifer is approximately 200 feet. The aquifer is unconfined to semiconfined depending on depth and location within the basin. The reported horizontal hydraulic conductivity of the Quaternary Alluvial Aquifer ranges from 10 to 229 feet per day (ft/day). Specific yield for the Quaternary Alluvial Aquifer is approximately 0.034 to 0.185 (3.4 percent to 18.5 percent) (Olmsted and Davis, 1961).

The Tehama Formation Aquifer is the primary aquifer within the study area. The thickness of the Tehama Formation Aquifer ranges up to approximately 2,000 feet (Olmsted and Davis, 1961). The Tehama Formation Aquifer pinches out at its contact with Coast Range rocks along the western margin of the basin and to the east where the Tehama Formation interfingers with the Tuscan Formation in the Tehama-Tuscan Transition Zone. The reported horizontal hydraulic conductivity of the Tehama Formation Aquifer is approximately 27 ft/day (West Yost, 2012). Storativity of the Tehama Formation is estimated to range from 0.0003 to 0.001 for the Tehama Formation Aquifer.

The Tuscan Formation Aquifer is composed of two confined units within the study area: Unit A and Unit B. Unit A is older than Unit B, but is composed of similar materials. The Tuscan Formation Aquifer can reach thicknesses of approximately 1,300 feet. The Tuscan Formation Aquifer within the study area exists primarily within the West Butte and Corning Subbasins, but extends into the Colusa Subbasin as lenses that interfinger with the Tehama Formation Aquifer system throughout the Tehama-Tuscan Transition Zone.

Reported horizontal hydraulic conductivity within the Tuscan Formation Aquifer (Units A and B) ranges from 11 to 88 ft/day. Vertical hydraulic conductivity for the confining unit (Tuscan Formation Unit C) is estimated to be 0.0036 ft/day (West Yost, 2012). Storativity of the Tuscan Formation is estimated to range from 0.003 to 0.00004 for the Tuscan Formation Aquifer.

Primary Use

The primary uses of the Quaternary Alluvial Aquifer are irrigation and domestic. The primary uses of the Tehama Formation Aquifer include irrigation, domestic, industrial, and municipal supply (DWR, 2006). The primary use of the Tuscan Formation Aquifer within the study area are irrigation, domestic, and municipal supply.

Water Quality

Groundwater quality concerns include locally elevated salinity, adjusted sodium absorption ratio, nitrate, manganese, and calcium. Salinity concentrations could potentially impact agricultural practices within both counties. These constituents probably impact all three of the principal aquifer systems.

Elevated boron within Colusa County has already impacted agricultural practices. Drinking water concerns within Glenn County include nitrate and hexavalent chromium. Drinking water concerns within Colusa County include salinity, iron, manganese, arsenic, and increasing concentrations of pesticides. An existing tetrachloroethylene (PCE) plume near Orland (referred to as the Orland Dry Cleaner site) extends approximately two miles from the source location in Glenn County. In 2007, PCE contamination was recorded at depths of 127 feet below ground surface (bgs) (DTSC, 2018), which is within the Quaternary Alluvial Aquifer.

Groundwater Inflow and Outflow

Groundwater underflows between the study area groundwater subbasins and neighboring groundwater subbasins depend on fixed aquifer hydraulic properties and prevailing groundwater gradients, which are influenced by time-dependent natural recharge and discharge patterns, aquifer interactions with streams, pumping effects, and effects from both managed and unmanaged recharge. These groundwater inflows and outflows impact each of the three principal aquifers. The magnitude of these underflows is not currently quantified.

The primary sources of groundwater recharge in the study area are deep percolation of precipitation and applied water. Recharge occurs throughout the study area, but at variable rates depending on topography, soil properties, and the underlying geology. Potential recharge areas were identified based on the Soil Agricultural Groundwater Banking Index (SAGBI) (O'Geen et. al., 2015) which ranges from very poor to excellent over the study area. Moderately good to excellent soils correspond to areas overlying younger alluvial fan and stream channel deposits. These include soils associated with Stony Creek and other streams draining the Coast Ranges, and younger stream channel deposits located along the Sacramento River.

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.

Shallow depths to water can facilitate groundwater discharge via riparian or phreatophytic vegetation evapotranspiration or evaporation directly from the water table. When comparing depth to groundwater contours to land use, many areas with shallow depths to groundwater correspond to the areas of rice cultivation and wildlife refuges.

Groundwater pumping within the basin serves municipal, domestic, irrigation, and environmental needs. While municipalities rely on groundwater to serve their residents, many 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. The primary groundwater pumping areas for irrigation correspond to the farmlands that do not receive surface water supplies.

ES.2 Data Gaps and Uncertainties

Data gaps were identified within the hydrogeologic extent, aquifer parameter, water quality, and groundwater inflows and outflows categories. These topics are discussed in more detail below.

Hydrogeologic Extent

Additional subsurface data should be collected to help delineate the base of the Tehama and Tuscan Formations and characterize the Tehama-Tuscan Transition Zone. The hydrogeologic extents of the principal aquifers should 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, and in-depth evaluation of well completion reports (most of which are not deep enough to characterize the base of the Tehama and Tuscan Formations, but may be sufficient to better define the Tehama-Tuscan Transition Zone).

Aquifer Parameters

Aquifer parameter estimates should 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 should use pumping wells and dedicated monitoring wells discretely screened in the principal aquifers. The hydraulic properties of Tuscan Formation Unit C should be further investigated to verify the high hydraulic conductivities reported for Unit C and their applicability in the Colusa Subbasin.

Aquifer Water Quality

Future groundwater quality characterization efforts should utilize wells with known construction, each of which should screened within a single principal aquifer. The water quality data discussed in this report is based on wells that have not been specifically linked to the individual principal aquifers. 23 CCR §354.14(b)(4)(D) states that “general water quality of the principal aquifers” shall be included in the HCM.

Groundwater Inflows and Outflows

An appropriate integrated hydrologic model should be selected and developed to help quantify water budget components, including groundwater inflow and outflows. Sources and points of delivery for small riparian diverters from the Sacramento River have not been comprehensively evaluated. Imported water delivery volumes and points of delivery for these smaller diverters should be evaluated.

ES.3 Summary and Conclusions

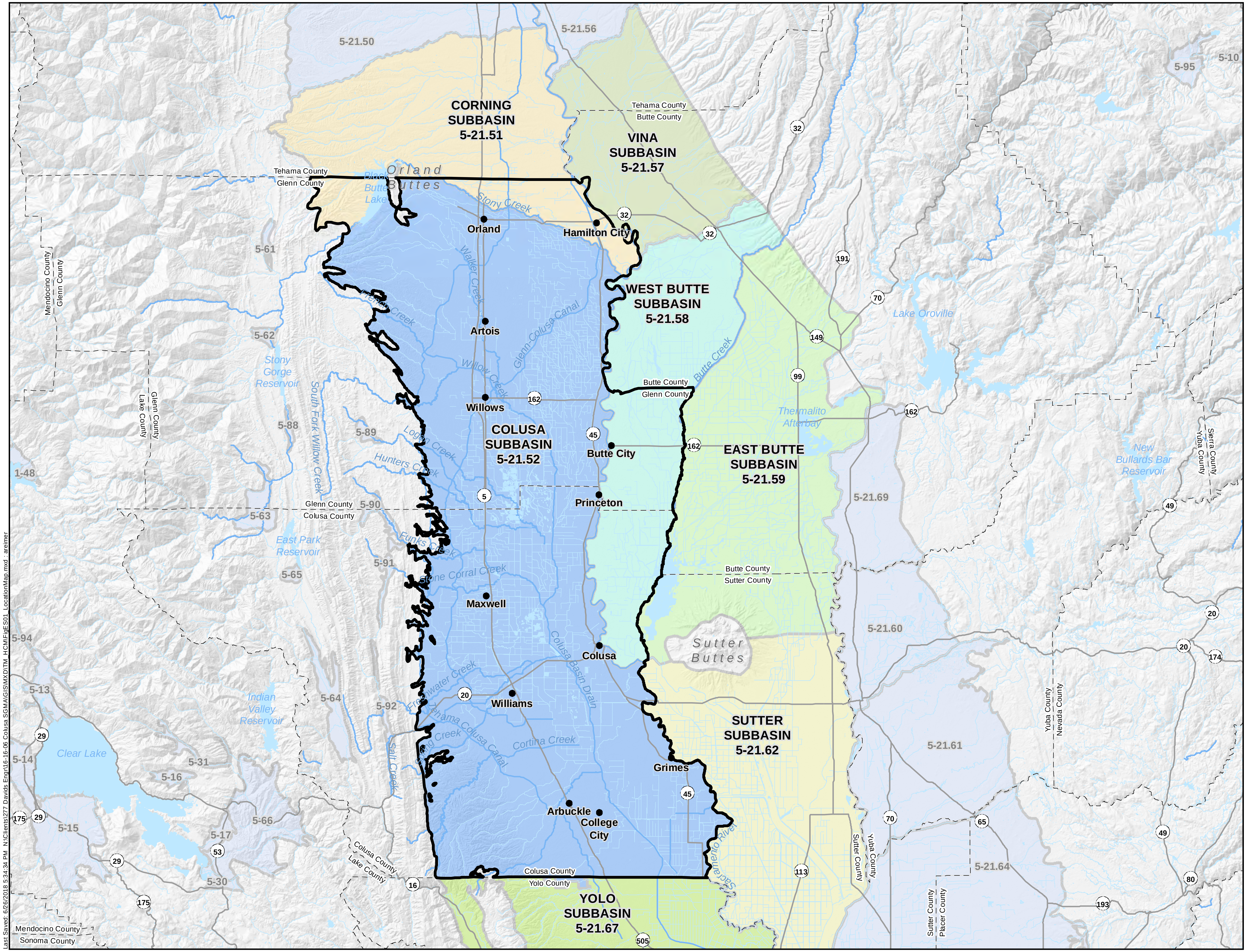
This report provides a preliminary assessment of the HCM for Glenn County and Colusa County and their collaborators to support development and implementation of one or more GSPs for the groundwater subbasins underlying Glenn and Colusa Counties. The report provides an assessment of the different components of the HCM including geographic setting, land use, topography, hydrology, soils, and regional geology and structure. Additionally, this report provides a preliminary description of the local groundwater subbasins, including the Colusa Subbasin and the portions of the Corning and West Butte Subbasins that are located within Glenn and Colusa Counties. The lateral and vertical boundaries, structures potentially affecting groundwater flow, and the hydrogeology of the principal aquifers are discussed.

The extents, physical and hydraulic properties, primary uses, and water quality characteristics of each of the principal aquifers are discussed in this report. The principal confining unit within the study area is Tuscan Formation Unit C. The principal aquifers are:

1. Quaternary Alluvial Aquifer;
2. Tehama Formation Aquifer; and
3. Tuscan Formation Aquifer (consists of Unit A and Unit B).

Data gaps identified within the preliminary HCM were related to the hydrogeologic extent of the principal aquifers, aquifer properties, groundwater quality for the principal aquifers, and groundwater inflows and outflows; specifically, diversions from small surface waters and inter-basin underflow volumes.

This report addresses the HCM requirements for GSPs on a preliminary basis using currently available data and information. The HCM will continue to be developed during preparation of one or more GSPs for the groundwater subbasins within the study area.



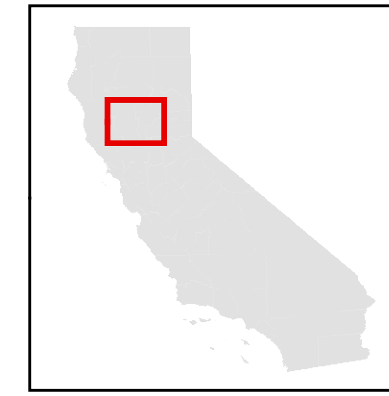


Figure ES-1

Location Map

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

1.0 INTRODUCTION

This report provides a preliminary assessment of the hydrogeologic conceptual model (HCM) for the Counties of Glenn and Colusa to support development and implementation of one or more Groundwater Sustainability Plans (GSPs) for the groundwater subbasins underlying the two counties pursuant to the requirements of the Sustainable Groundwater Management Act of 2014 (SGMA). This report was prepared through coordination of work conducted as part of Proposition 1 Counties with Stressed Basins Grants awarded to each county and administered by the California Department of Water Resources (DWR). The preliminary HCM described in this report therefore includes the Sacramento Valley groundwater subbasins within both counties. Costs associated with the work benefitting both counties were divided between the individual grants, while costs directly attributable to a specific county were allocated to the county receiving the benefit of the work.

This HCM report provides the general understanding of the physical setting, characteristics, and processes that occur within the study area groundwater subbasins. The HCM provides the foundation upon which analytical models and components of the water budget will be based. Title 23 Section §354.14(a) of the California Code of Regulations (23 CCR §354.14(a)) 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". Development of the HCM is the first step in understanding and conveying the GSP Basin Setting, and impacts decisions made regarding the evaluation of the basin's water budget, evaluation of sustainability indicators and undesirable results, modeling, monitoring, and stakeholder outreach.

23 CCR §354.14(b) requires that the HCM shall include written descriptions for each of the following components:

- Regional geology and structure (Section 2.5);
- Lateral basin boundaries (Section 2.6.1);
- Definable bottom of the basin (Section 2.6.1);
- Principal aquifers and aquitards, including formation names, vertical and lateral extent, aquifer properties, restrictions to flow, water quality, and primary uses (Section 2.6); and
- Any data gaps and uncertainties identified in the previously listed topics (Section 3.0).

Requirements listed in 23 CCR §354.14(c) through (d) state that the HCM shall include maps of each of the following physical components of the HCM. Additionally, all maps shall be informative, labeled, and include the datum (23 CCR §352.4(d)).

- Topography (Figure 2-3);
- Surface geology and a minimum of two cross sections (Figures 2-6 through 2-12);
- Soil properties (Figure 2-5);
- Recharge and discharge areas (Figures 2-14 through 2-16);

- Surface water features (Figure 2-4); and
- Sources and points of delivery of imported water (Figure 2-4).

This report addresses these requirements using currently available data and information in accordance with the Best Management Practices (BMPs) for the Sustainable Management of Groundwater: Hydrogeologic Conceptual Model BMP (DWR, 2016). The HCM will continue to be developed during preparation of one or more GSPs for the groundwater subbasins within the study area.

1.1 Scope

The scope of work for this preliminary HCM included:

- Compilation of data required for completing a preliminary HCM for the study area;
- Development of a preliminary HCM consistent with GSP regulations (23 CCR §354.14);
- Discussion regarding the components of the HCM; and
- Identification of data gaps.

1.2 Definition of Study Area

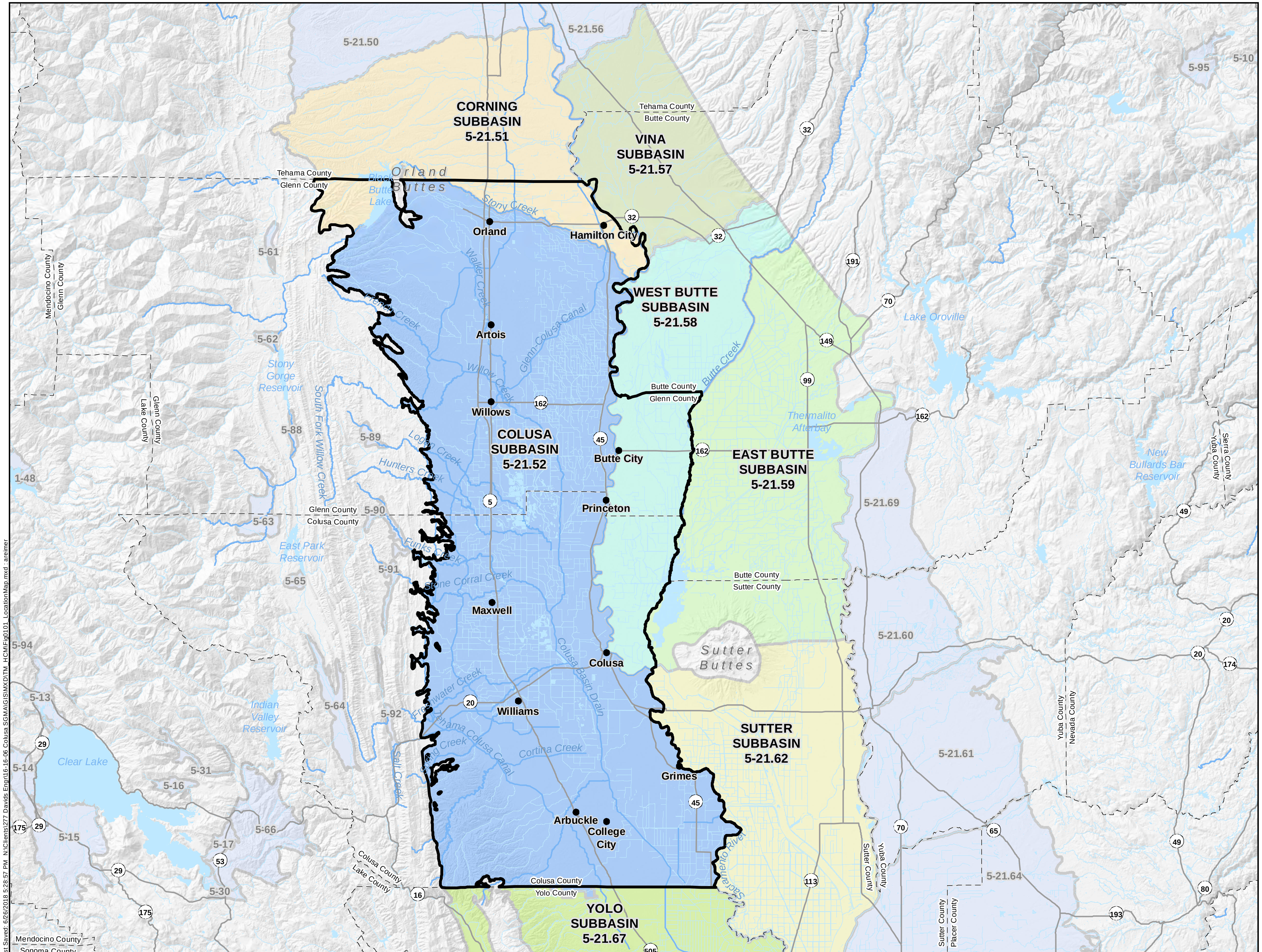
Figure 1-1 shows the study area, which is composed of the high and medium priority groundwater basins, as defined by DWR, within Glenn and Colusa Counties, northern Sacramento Valley, California. The groundwater basins underlying the study area include the entirety of the Colusa Subbasin (5-21.52), the southernmost portions of the Corning Subbasin (5-21.51) underlying Glenn County, and the southern part of the West Butte Subbasin (5-21.58) underlying Glenn and Colusa Counties (DWR, 2006). Groundwater subbasins adjacent to, but not included in, the study area (and therefore not included in this report) include the Vina Subbasin (5-21.57), East Butte Subbasin (5-21.59), Sutter Subbasin (5-21.62), and the Yolo Subbasin (5-21.67). These subbasins are all part of the Sacramento Valley Groundwater Basin (DWR, 2006).

1.3 Report Organization

The report is organized into the following sections:

- Section 1.0: Introduction
- Section 2.0: Hydrogeologic Conceptual Model
- Section 3.0: Data Gaps and Uncertainty Within the Hydrogeologic Conceptual Model
- Section 4.0: Summary and Conclusions
- Section 5.0: References

Appendix A contains a list of data sources for each of the HCM components discussed in this report.



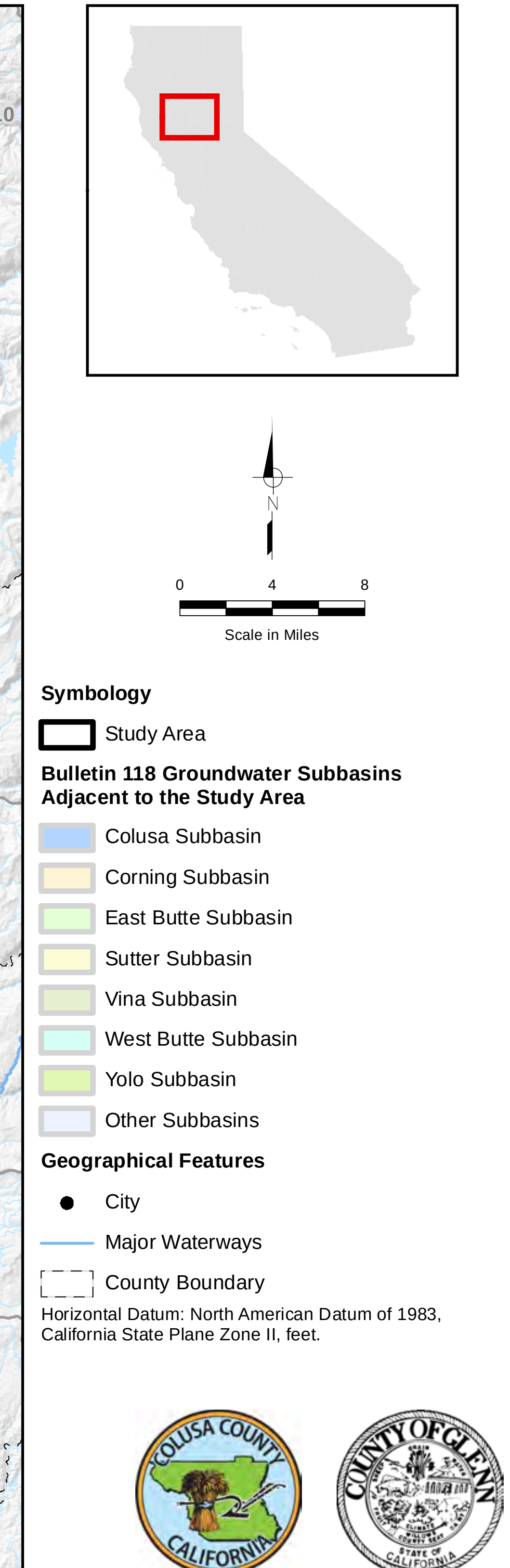


Figure 1-1

Location Map

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

2.0 HYDROGEOLOGIC CONCEPTUAL MODEL

Figure 2-1 depicts a generalized HCM (DWR, 2016). The main components of the HCM include surficial features, including topography, hydrology, and 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 are discussed in the following subsections.

2.1 Geographic Setting and Land Use

The Counties of Colusa and Glenn encompass approximately 2,500 square miles in north central California, of which, 1,300 square miles are within the study area (Figure 1-1). The Sacramento River bounds the eastern edge of the Colusa Subbasin, and Butte Creek bounds the eastern edge of the West Butte Subbasin. The northern boundary of the West Butte Subbasin within the study area is defined by the Glenn-Butte County line. The western extent of the study area is bounded by the Coast Ranges, where additional small, low or very low priority groundwater basins are located. The Colusa-Corning Subbasin boundary follows the channel of Stony Creek. The study area includes most of Black Butte Lake. The northern extent of the study area cuts through the Corning Subbasin and is defined by the Glenn-Tehama County line. The southern boundary of the study area is defined by the Colusa-Yolo County line, which is also the boundary between the Colusa and Yolo Subbasins.

Figure 2-2 shows the 2014 Provisional DWR Land Use Survey designations for the Counties of Glenn and Colusa. Land in the study area is predominantly used for irrigated agriculture. Glenn and Colusa Counties house some of the richest rice-producing land in the country, as well as important waterfowl habitat along the Pacific Flyway (West Yost, 2014). Major commodities include rice, almonds, walnuts, prunes, tomatoes and seed crops, dairy products, and livestock. The land use pattern is typical of rural counties of the Sacramento Valley. Large acreage farms dominate the study area, with land ownership and road alignments often following square-mile section lines. The land is generally flat and is covered by fields of rice, orchards, and row crops, but rises to the west towards the Coast Ranges, with orchards and cultivated fields giving way to rangelands on rolling hills and upland valleys.

2.2 Topography

Figure 2-3 shows the topography of the study area. The western side of the study area is elevated with low foothills transitioning to the higher elevation Coast Range to the west, and low alluvial plains of coast range streams and flood basins of the Sacramento River to the east. The topography encourages drainage towards the Sacramento River and south towards the San Joaquin-Sacramento River Delta (Delta). East of the Sacramento River, the topography within the West Butte Subbasin portion of the study area trends southward at a low gradient.

Elevations greater than 1,000 feet North American Vertical Datum of 1988 (NAVD 88) occur within the northwestern portion of the study area (Corning Subbasin) and the southwestern portion of the study area (Colusa Subbasin). Minimum land surface elevations of approximately 20 feet NAVD 88 occur along the southern boundary of the study area in the Colusa Subbasin west of the Sacramento River. Land surface elevations along the Sacramento River range from about 150 feet NAVD 88 at the northeast boundary of the study area to about 40 feet NAVD 88 near the southeast boundary of the study area.

2.3 Regional Hydrology

The regional hydrology and watershed delineations are shown on Figure 2-4. The Sacramento River is the principal stream in the study area and region, 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 (Figure 2-4):

- Big Chico Creek-Sacramento River watershed (hydrologic unit code 08 [HUC08] 18020157), which drains into the Corning Subbasin;
- Butte Creek watershed (HUC08 18020158), which drains into the West Butte Subbasin; and
- Sacramento-Stone Corral and Upper Stony Creek watersheds (HUC08 18020104 and 18020104, respectively), which drain into the Colusa and Corning Subbasins.

Figure 2-4 shows the inflow portions of these watersheds relative to the study area boundary. These watersheds define the drainage system of natural surface waters.

2.3.1 Streams

The primary natural waterways flowing into, through, or along the boundary of the study area include the Sacramento River, Stony Creek, and Butte Creek. Many smaller tributary streams drain the Coast Ranges west of the Colusa Subbasin. These streams are shown on Figure 2-4 and discussed in the following subsections.

Sacramento River

The Sacramento River flows north to south along the eastern boundary of the Colusa and Corning Subbasins and the western boundary of the West Butte 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 (West Yost, 2014). In addition to providing flows to the Delta, the Sacramento River is the water source for many irrigation districts within the study area. According to data reported for a U.S. Geological Survey (USGS) stream gauge located near Grimes, Colusa County, mean monthly discharge ranged from approximately 6,000 to 16,000 cubic-feet per second (cfs) from 1946 through 2017. The minimum discharge was recorded at less than 1,000 cfs in August 1939, and the maximum discharge was recorded at greater than 32,000 cfs in February 1986.

Stony Creek

The Upper Stony Creek watershed drains approximately 770 square miles. About 720 square miles are outside of the study area, including the north Coast Range foothills and uplands within the Counties of Glenn, Colusa, and Tehama. Stony Creek south of the Glenn-Tehama County line defines the boundary between the Colusa and Corning Subbasins (Figures 1-1 and 2-4). The Stony Creek headwaters are in the hills of western Colusa County. Stony Creek flows north toward Stony Gorge Reservoir. Water is discharged from Stony Gorge Reservoir and continues north to Black

Butte Lake. Most of the drainage within the Stony Creek watershed is eventually captured by Black Butte Lake. According to data listed in the California Data Exchange Center (CDEC) for a stream gage located below Black Butte Lake, Glenn County, stream stage between 2010 and 2018 fluctuated between approximately 0.7 and 9 feet. Discharges are not recorded at this stream gage in the CDEC database, however, total scheduled discharges from Black Butte Lake, monitored by the U.S. Bureau of Reclamation (USBR) and available in CDEC, for the same period fluctuated between 0 and 9,500 cfs (CDEC, 2018). Scheduled discharges from Black Butte Lake include discharges to canals and Stony Creek.

Butte Creek

The Butte Creek watershed drains approximately 810 total square miles. Approximately 690 square miles are outside of the study area. Butte Creek drains the Sierra Nevada above Chico and flows into the Sacramento River east of Colusa, Colusa County. Butte Creek defines the eastern boundary of the West Butte Subbasin. According to data reported for a USGS stream gage located on Butte Creek near Chico, mean monthly discharge ranged between approximately 100 and 800 cfs from 1931 through 2017. The minimum discharge was recorded at less than 50 cfs in August 1931, and the maximum discharge was recorded at greater than 35,000 cfs in January 1997.

Other Streams

Walker Creek (near Artois) and Willow Creek (near Willows) are north-south trending streams largely contained within the study area (Figure 2-4). Other ephemeral and intermittent streams within the study area were delineated based on the small inflow watersheds defined in the DWR California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). The following streams comprise the Sacramento-Stone Corral watershed, which bounds most of the study area on its western side (Figure 2-4):

- 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 originates in Yolo County)

Runoff in these ephemeral streams begins in late fall when the rainy season starts and may continue until late spring. Many of these streams flow into drainage canals within the study area. 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 its lower reaches (Figure 2-4).

2.3.2 Canals and Drains

Three major water conveyance systems 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. These canals, and their interconnected smaller canal systems, are shown on Figure 2-4 and described below.

Tehama-Colusa Canal

The Tehama-Colusa Canal originates north of the study area at the Red Bluff Diversion Dam in Tehama County, runs along the west side of the study area, and terminates south of the study area 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.

Glenn-Colusa Canal

The Glenn-Colusa Canal system is situated east of the Tehama-Colusa Canal and west of the Sacramento River in Glenn and Colusa Counties. The Glenn-Colusa Canal originates on the Sacramento River north of Hamilton City, Glenn County and extends south of Williams, Colusa County. 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.

Colusa Basin Drain

The Colusa Basin Drain is a drainage system that transports 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.

2.4 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 where the Tehama Formation is exposed; 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 2-5 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).

2.5 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.

2.5.1 Regional Geology

Table 2-1 lists the geologic units within the study area and characterizes their age, lithologic character, thickness, and water bearing character (WRIME, 2003). Figure 2-6 shows detailed surface geologic mapping for the study area and surrounding region, and the locations of five geologic cross sections through the study area. Figure 2-7 includes elevation contours for the top of the Cretaceous rocks, which are older than the freshwater-bearing formations (Harwood and Helley, 1987). Cross sections are provided on Figures 2-8 through 2-10, and a three-dimensional (3D) representation of the preliminary HCM is provided on Figure 2-11. Figure 2-12 shows the Tehama and Tuscan Formation surficial outcrops and subsurface extents, including an approximation of the subsurface Tehama-Tuscan Transition Zone, in which both Tehama and Tuscan Formation deposits occur (DWR, 2009).

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 2-6). 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 Appendix A. The cross sections were used to generate a 3D model of the post-Cretaceous water bearing formations, discussed below, for this report and for assessment of the current groundwater monitoring network associated with this project (West Yost, 2018).

Table 2-1. Description of Geologic Units in Study Area

System	Series	Geologic Unit	Lithologic Character	Maximum 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.

Notes:

(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.

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 2-6). 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 study area groundwater basins. The Great Valley Sequence is included in the pre-Paleogene and Cretaceous rocks referenced in the maps and within the report text. Figure 2-7 shows contours of the elevation of the top of the Cretaceous rocks in the study area.

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 Figures 2-8 and 2-9. Cross Section F-F’, on Figure 2-10, 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 (Figures 2-8 and 2-9). 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 from the margins of 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 (Figure 2-12). 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 2-12). The interlayering of the Tehama and Tuscan Formations can be seen in Cross Sections B-B', C-C', D-D', and F-F' (Figures 2-8 through 2-10). 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 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 (Figure 2-6). 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 Nilson, 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 Figures 2-8 through 2-10 because of their limited thicknesses relative to the older formations (Table 2-1).

The Red Bluff Formation is thin sand and gravel deposit resting on a pediment or erosional surface on the Tehama Formation (Figure 2-6). 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.

2.5.2 Freshwater-Bearing Formations in the Study Area

The geologic formations forming the freshwater aquifer in the study area are composed of two distinct semiconfined to confined aquifer systems overlain by an unconfined aquifer system. The Tuscan and Tehama Formations comprise the primary semiconfined to confined aquifers. The unconfined aquifer is composed primarily of Holocene deposits and the Riverbank and Modesto Formations. These formations are discussed below.

2.5.2.1 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. Figures 2-6 and 2-12 show the approximate surface and subsurface extents of the Tuscan Formation in the vicinity of the study area. 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 2-12). 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, 2006). 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, 2006).

2.5.2.2 Tehama Formation

Figures 2-6 and 2-12 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, 2006; 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 Formation is exposed at the land surface on the western side of the Sacramento Valley, beginning approximately three miles west of Orland and continuing into the Orland Buttes. 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 central portion of the Sacramento Valley (DWR, 1978).

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, 2006), but is typically less than that exhibited by the Tuscan Formation.

2.5.2.3 Riverbank and Modesto Formations

The Tuscan and Tehama Formations are unconformably overlain by the late Pleistocene age Riverbank and Modesto Formations. The thickness of the formation ranges from less than 10 feet to nearly 200 feet across the valley floor (DWR, 2006; 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, 2004; 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 2-6 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, 2006; 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, 2006). Wells screened in the Riverbank and Modesto Formations are generally domestic and shallow irrigation wells (DWR, 2006).

2.5.2.4 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, 2006). Because of their low permeability, limited extent, and generally poor water quality, flood basin deposits are typically not used for groundwater production (DWR, 2006).

2.5.3 Geologic Structure

Figure 2-7, from Harwood and Helley (1987), shows the structural contour lines in meters delineating the top of the Cretaceous marine sedimentary rocks in the vicinity of the study area. The shaded color intervals on Figure 2-7 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 2-6 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).

2.5.3.1 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 2-6 and discussed in the following subsections.

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’ (Figures 2-8 through 2-10). 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).

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 2-8). 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.

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 2-6 depicts the Black Butte Fault as a northward offshoot of the Willows Fault, much like the Corning Fault.

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 2-6 (DWR, 2014).

2.5.3.2 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 2-6 and discussed in the following subsections.

Zamora Syncline

The Zamora Syncline is located in the subsurface east of Arbuckle, Colusa County and extends into Yolo County (Figure 2-6). 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 2-7, where the elevation of the top of the Cretaceous formations is depressed west and south of College City, Colusa County.

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. 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 2-7, 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 2-8). 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.

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 Figures 2-6 and 2-7, highs in the top of the Cretaceous formations are associated with the locations of the anticlines. Examples of these features include the Greenwood Anticline near Orland and Artois and the unnamed anticline southwest of the Sutter Buttes.

2.5.3.3 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.

2.5.3.4 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).

2.6 Hydrogeologic Framework

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 groundwater basins and principal aquifer systems are discussed in the following subsections.

2.6.1 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).

2.6.1.1 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 revised Bulletin 118 groundwater basin delineations of 2016 have redefined the southern boundary of the Colusa Subbasin to be the Colusa-Yolo County line, a jurisdictional boundary (DWR, 2016). Additionally, the portion of the Colusa Subbasin originally within Tehama County has been redefined as the Corning Subbasin, making the Glenn-Tehama County line the northernmost extent of the Colusa Subbasin (Figure 1-1).

The study area includes the portions of Corning and West Butte Subbasins that underlie Glenn and Colusa Counties (Figure 1-1). The Corning Subbasin is located north of Stony Creek, where the creek exists south of the Glenn-Tehama County line, and the Colusa Subbasin, which form its southern boundary. The Corning Subbasin is bounded on the east by the Sacramento River and the Vina Subbasin, on the north by Thomes Creek and the Red Bluff Subbasin, and on the west by the foothills and uplands of the Coast Ranges.

The West Butte Subbasin is located east of the Sacramento River and the Colusa Subbasin, which form its western boundary. The West Butte Subbasin is bounded on the east by Butte Creek and the East Butte Subbasin, and on the north by Big Chico Creek and the Vina Subbasin (DWR, 2004). The southern extent of the West Butte Subbasin is defined by the confluence of Butte Creek and the Sacramento River (Figure 1-1).

2.6.1.2 Vertical Boundaries

Figure 2-7 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 Corning and Colusa Subbasins, excluding the portion of the study area within the West Butte Subbasin, where the top of Cretaceous-age rocks was not contoured (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 2-7 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 2-7.

The base of the groundwater subbasins can also be defined chemically as the base of fresh water. Figure 2-13 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 State Water Resources Control Board (SWRCB) upper maximum contamination level (MCL) for TDS (DWR, 2016).

The cross sections shown on Figures 2-8 through 2-10 contain an approximate delineation of the base of the study area subbasins as preliminarily defined for this HCM report. The physical base of the subbasins was defined as the base of the Tuscan or Tehama Formations. This preliminary definition excludes Cretaceous-age formations, post-Cretaceous age sediments of marine origin (Lower Princeton Valley Fill and the Ione Formation) and the post-Cretaceous, non-marine Upper Princeton Valley Fill 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.

2.6.2 Stratigraphic and Structural Features Potentially Affecting Flow

Stratigraphic and structural features that could potentially impact groundwater flow were introduced in Section 2.5.2 of this report. The structures discussed below are not necessarily basin boundaries, but may impede or enable groundwater flow within each of the principal aquifers.

2.6.2.1 Topography

The primary structures impacting flows within the shallow aquifer systems are most likely related to topography. The aquifer pinches out where topography is elevated and the older, less permeable units are exposed on the surface.

2.6.2.2 Faults

Geologic investigations have shown displacement of the hydrogeologic formations along the Willows and Corning Faults. This is evident in the cross sections of Figures 2-8 through 2-10. The movement along 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.

2.6.2.3 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, 2006). Folds can also cause reorientation of naturally anisotropic units causing decreased permeability within the aquifer, however this has not yet been quantified or proven within the study area.

2.6.2.4 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 2-12) or where the alluvial and basin deposits truncate against the uplands of the Coast Ranges (Figure 2-6). These can also be seen in the cross sections on Figures 2-8 through 2-10.

Pinchouts can also occur at a larger scale within each of the confined principal aquifer systems. 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.

2.6.3 Principal Aquifers and Aquitards

Based on this preliminary HCM, there are three groupings of hydrostratigraphic units that define the principal aquifers within the study area:

1. Quaternary Alluvial Aquifer;
2. Tehama Formation Aquifer; and
3. Tuscan Formation Aquifer (consists of Unit A and Unit B).

Most of the fresh groundwater within the study area is contained within the Tehama Formation Aquifer. The fraction of fresh groundwater contained within the Tehama Formation Aquifer decreases in the northeastern portion of the study area, where the Tuscan Formation Aquifer is more prevalent (Figure 2-12). 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, 2009). These mixed sediment zones grade into the Tehama and Tuscan Formations and probably result in continuity of flow between the Tehama Formation Aquifer and the Tuscan Formation Aquifer.

The Quaternary Alluvial Aquifer thinly overlies the Tehama and Tuscan Formation Aquifers and consists of the Holocene basin and stream channel deposits, the Modesto Formation, and the Riverbank Formation.

The principal aquitard within the study area is the Tuscan Unit C. Tuscan Unit C consists of massive mudflow deposits, or lahars, with low permeability that confine the lower aquifer units of the Tuscan Formation (Units A and B).

2.6.3.1 Physical Properties

The Quaternary Alluvial Aquifer consists of the Riverbank and Modesto Formations, as well as the overlying Holocene stream channel and basin deposits. The base of the Quaternary Alluvial Aquifer is defined as the base of the Riverbank Formation. Thickness of the Quaternary Alluvial Aquifer can reach approximately 200 feet. Being the shallowest aquifer system in the study area, the Quaternary Alluvial Aquifer can be found at depths that equal its thickness (approximately 200 feet below ground surface [bgs]). The Quaternary Alluvial Aquifer pinches out near the western margin of the basin where the foothills and uplands of the Coast Ranges commence and the Tehama Formation outcrops. The aquifer is unconfined to semiconfined depending on depth and location within the basin.

The Tehama Formation Aquifer is the primary aquifer within the study area. The aquifer is heterogeneous with discontinuous sand and gravel lenses. Thicknesses of the Tehama Formation Aquifer can be as much as approximately 2,000 feet (Olmsted and Davis, 1961) and can reach depths of approximately 2,000 feet bgs, even where it is overlain by the Quaternary Alluvial Aquifer. The Tehama Formation Aquifer pinches out along the western margin of the basin with the Coast Ranges and to the east where the Tehama Formation interfingers with the Tuscan Formation in the Tehama-Tuscan Transition Zone (Figure 2-12).

The Tuscan Formation Aquifer is composed of two confined units within the study area: Unit A and Unit B. Unit A is older than Unit B, but is composed of similar materials: interbedded lahars, conglomerate, volcanic sandstone, and volcanic ash layers. The Tuscan Formation Aquifer can reach thicknesses of approximately 1,300 feet and is found at depths of approximately 1,500 feet bgs. The Tuscan Formation Aquifer within the study area exists primarily within the West Butte and Corning Subbasins, but extends into the Colusa Subbasin via lenses that interfinger with the Tehama Formation Aquifer system throughout the Tehama-Tuscan Transition Zone (Figure 2-12). The Tuscan Formation Aquifer system pinches out along its western extent where it transitions with the Tehama Formation Aquifer system. The eastern extent of the Tuscan Formation Aquifer system follows the Sacramento River and Butte Creek, the hydrologic rationale being that these surface water features are, or may be, coincident with groundwater divides. The geologic Tuscan Formation, however, can be found as far east as the foothills of the Sierra Nevada Mountain Range.

2.6.3.2 Aquifer Properties

Table 2-2 contains the ranges of vertical and horizontal hydraulic conductivity, transmissivity, storativity, and specific yield values for the three principal 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. Because of this relationship between the aquifer materials and the confining units, vertical hydraulic conductivity is only reported in Table 2-2 for the Tuscan Formation Unit C (the confining unit of the aquifer system).

Horizontal hydraulic conductivity of the Quaternary Alluvial Aquifer ranges from 10 to 229 feet per day (ft/day).

Horizontal hydraulic conductivity of the Tehama Formation Aquifer is approximately 27 ft/day.

Within the permeable units of the Tuscan Formation Aquifer (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 Aquifer (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 3.0 of this report.

Vertical hydraulic conductivity for the confining unit in the Tehama-Tuscan Transition Zone (assumed equivalent to Tuscan Formation Unit C) 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 Aquifer and 0.003 to 0.00004 for the Tuscan Formation Aquifer. Storativity of Unit A of the Tuscan Formation Aquifer (the deepest unit) is generally higher than that of Unit B (Brown and Caldwell, 2013), but still lower than that of the Tehama Formation Aquifer. The Quaternary Alluvial Aquifer is a mostly unconfined system so storativity values are not reported.

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 Quaternary Alluvial Aquifer. Specific yield for the Quaternary Alluvial Aquifer is approximately 0.034 to 0.185 (3.4% to 18.5%) (Olmsted and Davis, 1961).

Table 2-2. Hydraulic Properties of Principal Hydrogeologic Units

Hydraulic Property per Source	Quaternary Alluvial Aquifer	Tehama Formation Aquifer	Tuscan Formation Aquifer		
			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					
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					
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

2.6.3.3 Primary Uses

The primary uses of the Quaternary Alluvial Aquifer are irrigation and domestic supply. The primary uses of the Tehama Formation Aquifer include irrigation, domestic, industrial, and municipal supply (DWR, 2006). Primary uses of the Tuscan Formation Aquifer within the study area are domestic, irrigation, and municipal supply.

2.6.3.4 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, 2006; Wood Rodgers, 2008). These constituents most likely impact all three of the principal aquifer systems. 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 the Quaternary Alluvial Aquifer and the deeper Tehama and Tuscan Formation Aquifers, or report water quality results from their wells collectively, without specifying if the well was constructed in the Quaternary Alluvial Aquifer, Tehama Formation Aquifer or Tuscan Formation Aquifer. This data gap is discussed in more detail in Section 3.0 of this report.

Recent groundwater quality concerns within the Colusa Subbasin include salinity, boron, nitrate, arsenic, heavy metals, 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 Quaternary Alluvial Aquifer, but there is a risk that the contamination could migrate into the deeper Tehama Formation Aquifer and Tuscan Formation Aquifer. The largest contamination site is the Orland Dry Cleaner site, a tetrachloroethylene (PCE) plume within the Colusa Subbasin that extends approximately two miles southeast of the source location in Orland, Glenn County (Department of Toxic Substances Control [DTSC], 2018; SWRCB, 2018). In 2007, PCE contamination was recorded at depths of 127 feet bgs (DTSC, 2018), which is within the Quaternary Alluvial Aquifer.

2.6.3.5 Groundwater Inflow and Outflow

Groundwater underflows between the study area groundwater subbasins 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.

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 1-1). Groundwater underflow may occur as either outflow or inflow across the northern and eastern hydrologic borders of the study area, where the study area groundwater subbasins abut 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.

Groundwater Recharge Areas

The primary sources of groundwater recharge in the study area 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.

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 2-4). Water applied to agricultural lands has a significant contribution to groundwater recharge.

Recharge occurs throughout the study area, but at variable rates depending on topography, soil properties and the underlying geology, as introduced in Sections 2.2, 2.4 and 2.5, respectively. Figure 2-14 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 2-14, 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.

Soils with indices in the moderately good to excellent range correspond to hydrologic soil groups A through C, as discussed in Section 2.4, 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 (Figures 2-5 and 2-6).

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.

Figures 2-15 and 2-16 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 2-15). 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 (Figure 2-16).

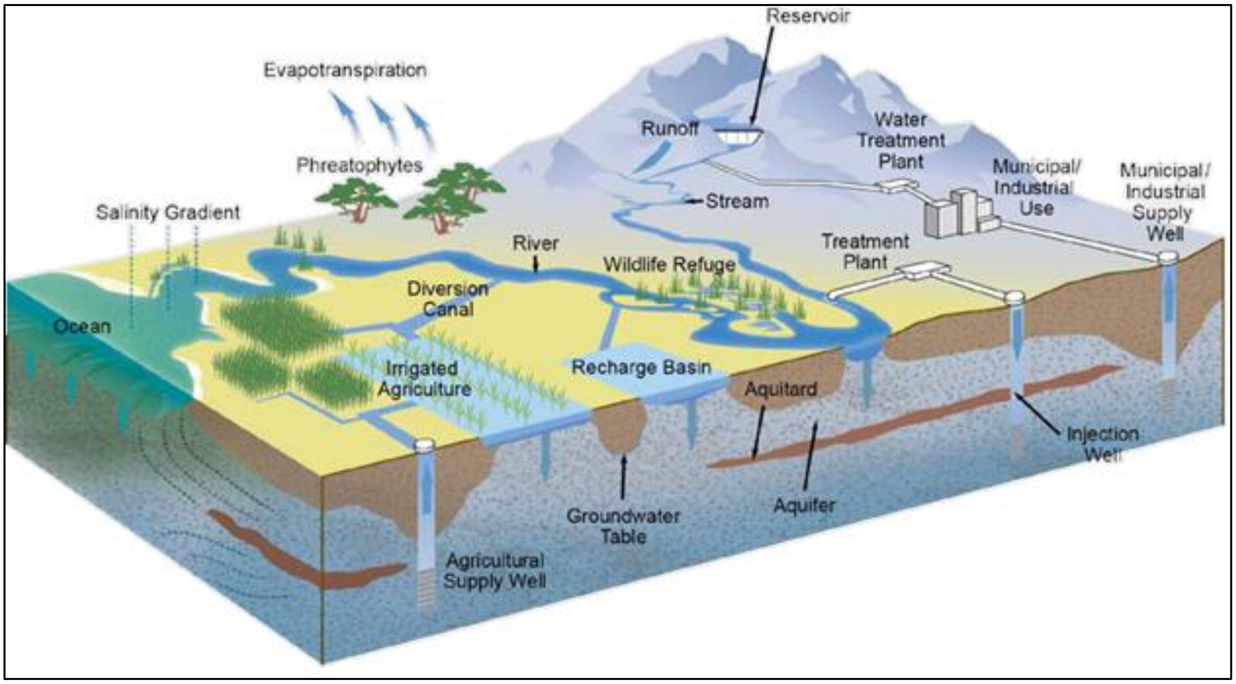
Comparison of the depth to groundwater contours to land use (Figure 2-2), shows that many areas with shallow depths to groundwater correspond to the areas of rice cultivation and wildlife refuges. Ponded agricultural fields tend to be in areas that contain a high percentage of silts and clays, which 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.

The potential for flowing artesian conditions is evident in the historical groundwater level measurements for some monitoring wells in the Colusa Subbasin. Figure 2-17 contains a hydrograph for a multiple completion well located north of the Sacramento National Wildlife Refuge, west of Princeton. As seen on Figure 2-17, 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 to the end of the record, however, the depth to groundwater within the deepest completion has increased 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.

Groundwater pumping within the basin serves municipal, domestic, irrigation, and environmental needs. Figures 2-15 and 2-16 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 acre-feet for agricultural applications, 14,000 acre-feet for municipal and industrial consumption, and 22,000 acre-feet for environmental wetland use (DWR, 2006). There are also many unmetered domestic wells located throughout the study area. Colusa County estimates approximately 1,200 acre-feet of groundwater extraction from domestic wells (Wood Rodgers, 2008) within County lines.

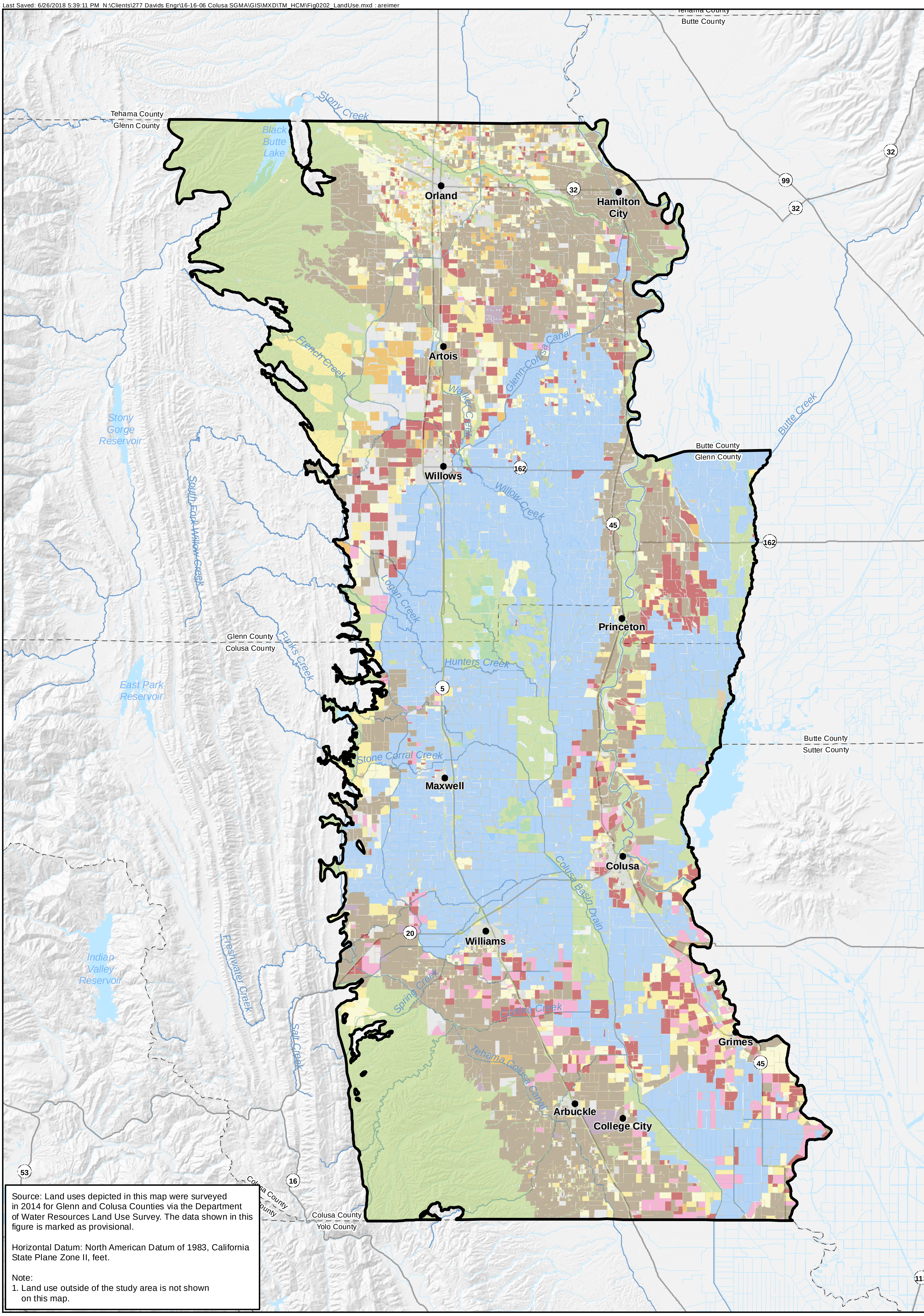
While the municipalities rely on groundwater to serve their residents, much of the agricultural lands within the study area divert surface water supplies for irrigation. Some of the farmlands use a mix of surface water supplies and groundwater (Figures 2-15 and 2-16). The primary groundwater pumping areas for irrigation correspond to farmlands that do not receive surface water supplies. An example of this includes farm lands that are not part of an existing irrigation district.

Figure 2-1. Hydrogeologic Conceptual Model Representation



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.

Last Saved: 6/26/2018 5:39:11 PM N:\Clients\277 Davids Engr\16-16-06 Colusa SGMA\GIS\MXD\TM_HCM\Fig0202_LandUse.mxd : areimer



Source: Land uses depicted in this map were surveyed in 2014 for Glenn and Colusa Counties via the Department of Water Resources Land Use Survey. The data shown in this figure is marked as provisional.

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

Note:
1. Land use outside of the study area is not shown on this map.

Symbology

Study Area

Land Use Classification

- Subtropical Crops
- Fruit and Nut Crops
- Field Crops
- Grain and Hay Crops
- Pasture
- Rice Crops
- Nursery and Berry Crops
- Vineyards
- Semiagricultural
- Native Lands
- Urban
- Idle

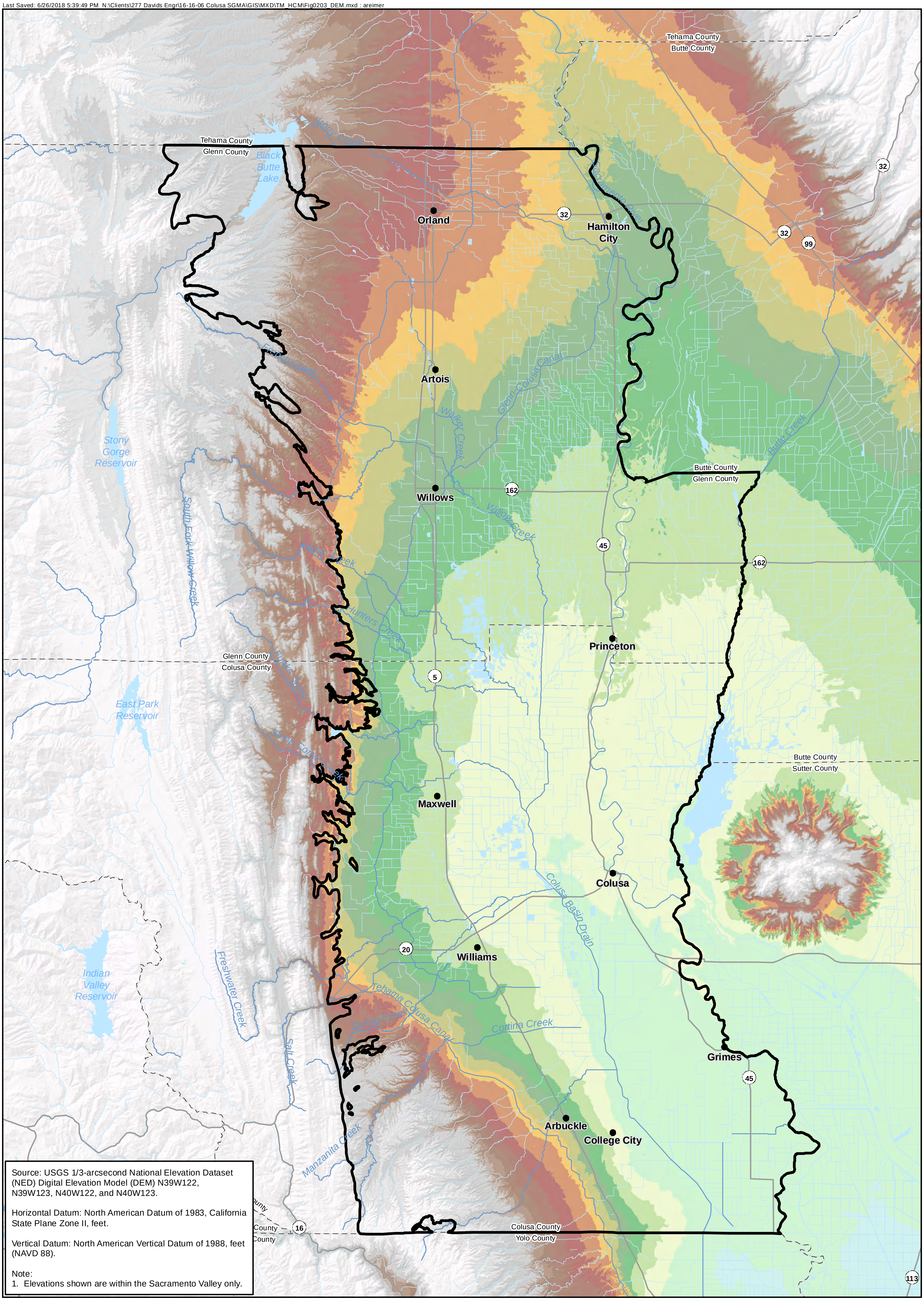
N

0 2.5 5
Scale in Miles

Figure 2-2

Land Use

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Symbology

Study Area

Land Surface Elevation (NAVD 88, feet)

< 25	100 - 125	200 - 250	400 - 450
25 - 50	125 - 150	250 - 300	450 - 500
50 - 75	150 - 175	300 - 350	500 - 750
75 - 100	175 - 200	350 - 400	750 - 1000
			> 1000

N

0 2.5 5

Scale in Miles

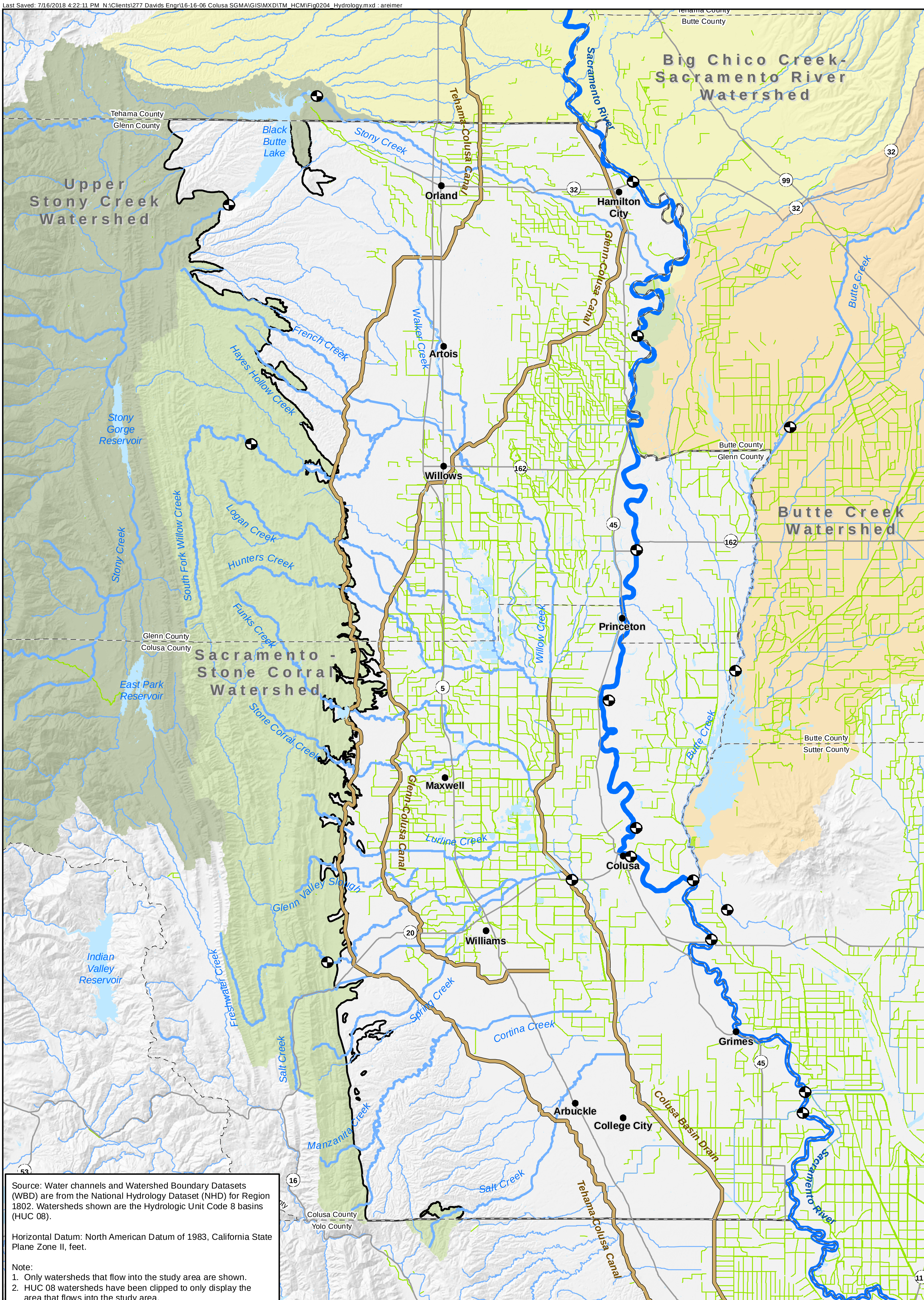
COLUSA COUNTY CALIFORNIA

COUNTY OF GLENN STATE OF CALIFORNIA

Figure 2-3

Topography

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Source: Water channels and Watershed Boundary Datasets (WBD) are from the National Hydrology Dataset (NHD) for Region 1802. Watersheds shown are the Hydrologic Unit Code 8 basins (HUC 08).

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

Note:
1. Only watersheds that flow into the study area are shown.
2. HUC 08 watersheds have been clipped to only display the area that flows into the study area.

Symbology

- Stream Gage
- Sacramento River
- Major Water Conveyance Infrastructure
- Major Streams and Creeks
- Other Streams and Creeks
- Other Water Conveyance Infrastructure

HUC 08 Inflow Watersheds

- Big Chico Creek-Sacramento River
- Butte Creek
- Sacramento-Stone Corral
- Upper Stony Creek

N

0 2.5 5
Scale in Miles

Figure 2-4

Watersheds, Streams and Surface Water Conveyance Facilities

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

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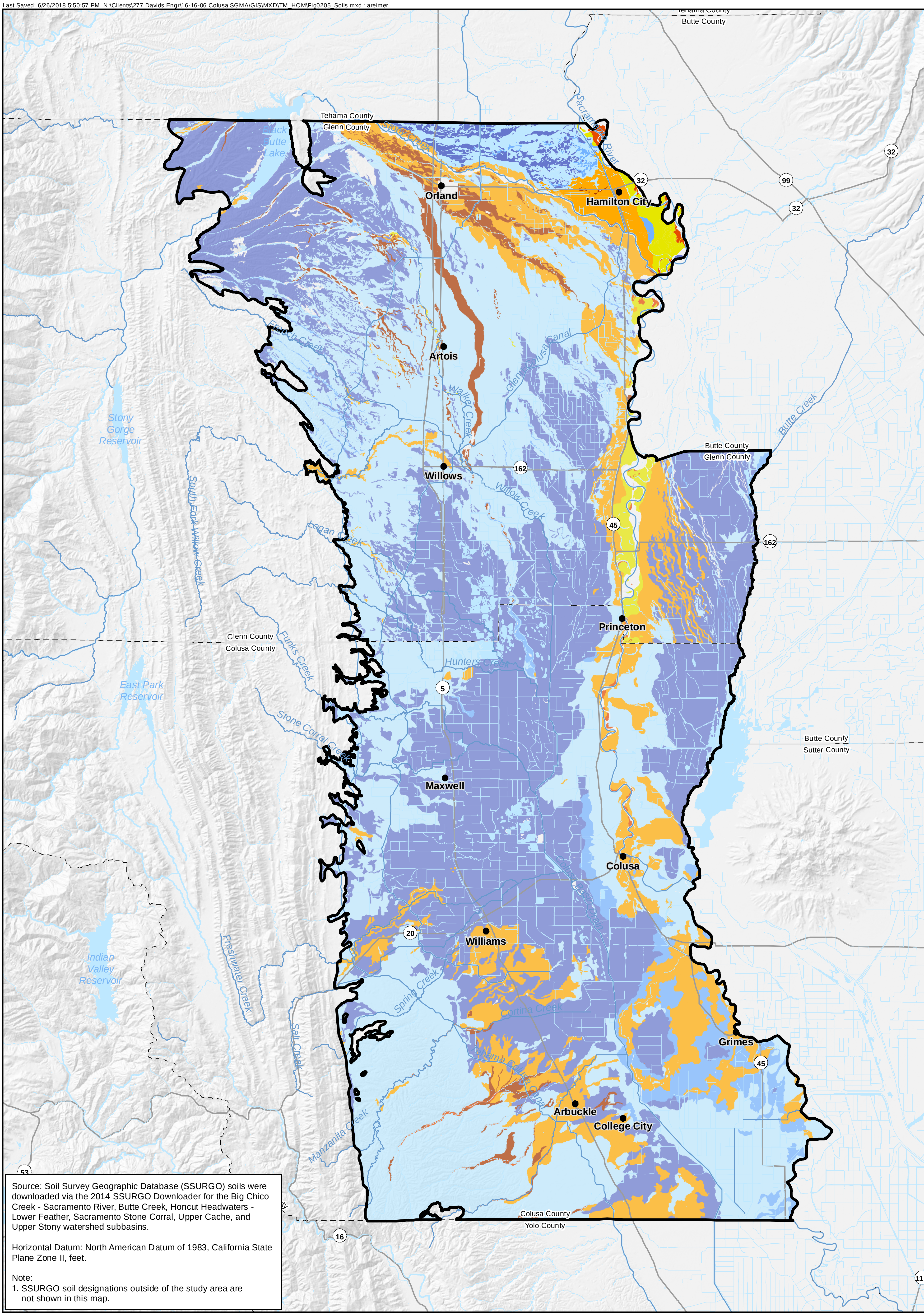


Source: Soil Survey Geographic Database (SSURGO) soils were downloaded via the 2014 SSURGO Downloader for the Big Chico Creek - Sacramento River, Butte Creek, Honcut Headwaters - Lower Feather, Sacramento Stone Corral, Upper Cache, and Upper Stony watershed subbasins.

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.

Symbology

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

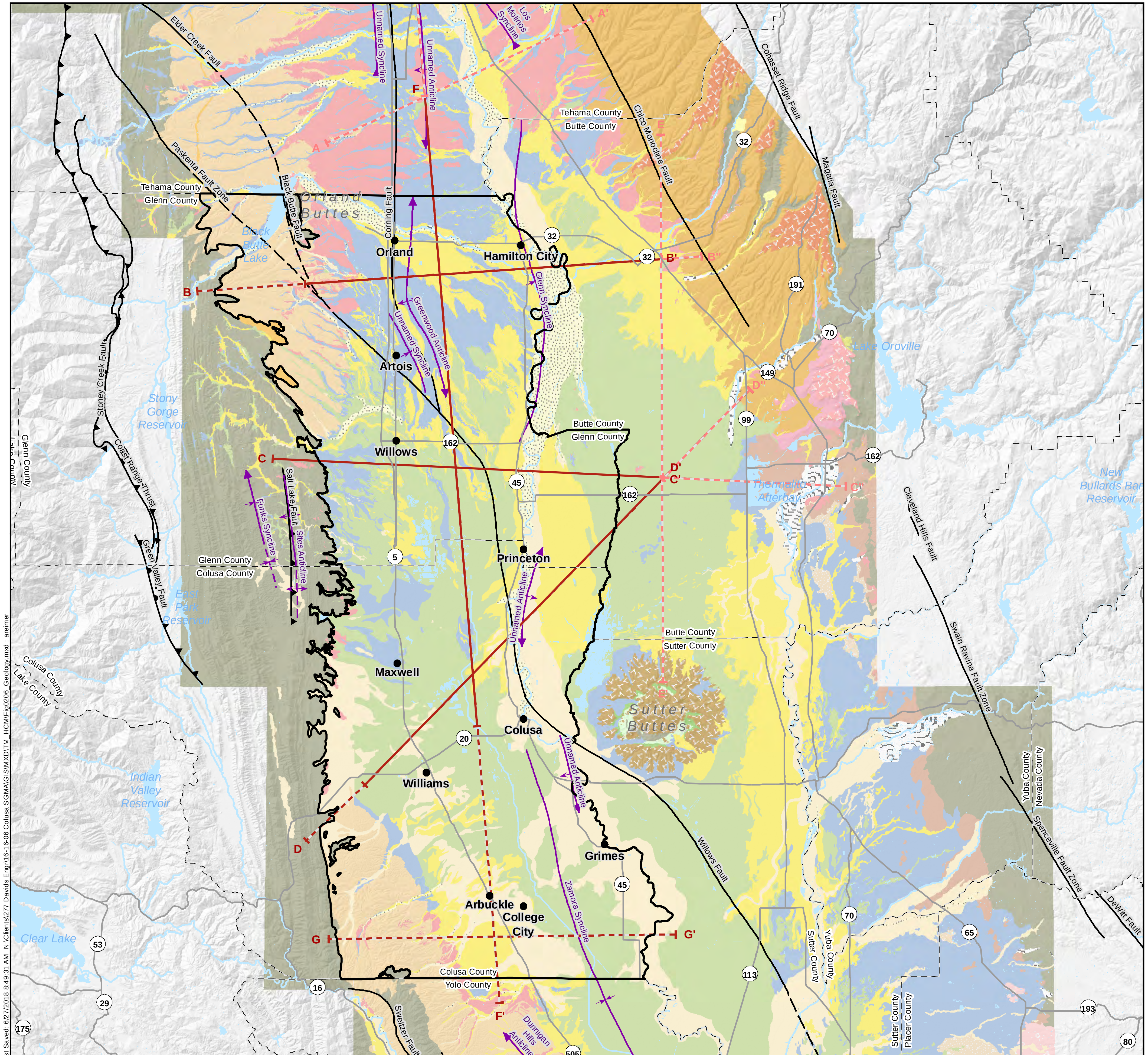
N

0 2.5 5
Scale in Miles

Figure 2-5

Hydrologic Soil Groups

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Symbology

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

0 4 8
Scale in Miles

N

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)
- Older Gravel Deposits (Pleistocene - Pliocene)
- Rockland Ash Bed (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.

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 with geologic mapping from the California Department of Natural Resources Division of Mines and Geology sheets to cover the entire study.
2. Geologic structures are dashed where approximated.

Figure 2-6

Geologic Map

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

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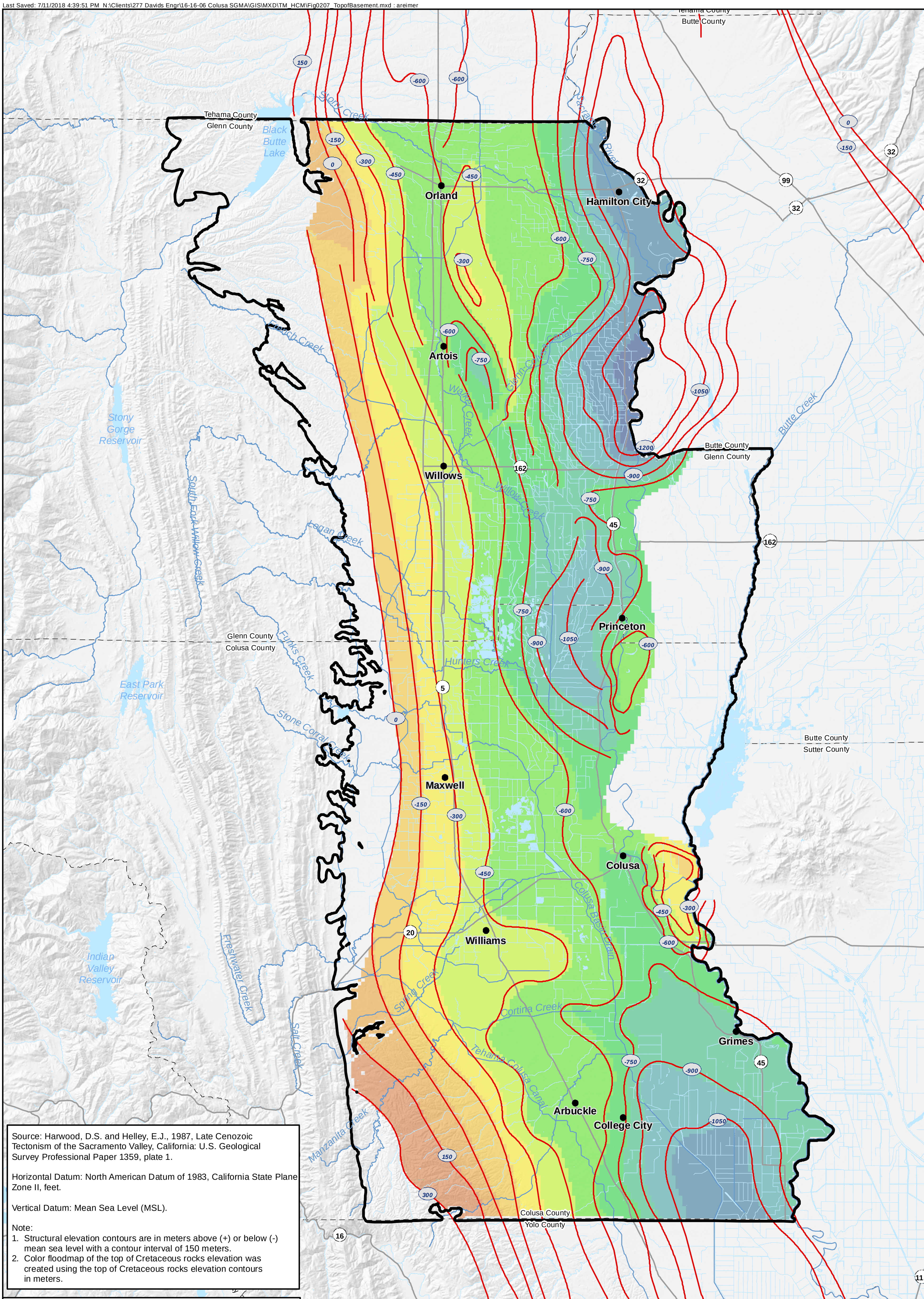


Source: Harwood, D.S. and Helley, E.J., 1987, Late Cenozoic Tectonism of the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1359, plate 1.

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

Vertical Datum: Mean Sea Level (MSL).

Note:
1. Structural elevation contours are in meters above (+) or below (-) mean sea level with a contour interval of 150 meters.
2. Color floodmap of the top of Cretaceous rocks elevation was created using the top of Cretaceous rocks elevation contours in meters.

Symbology

Study Area

Top of Cretaceous Rocks Elevation Contours (MSL, meters)

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

N

0 2.5 5

Scale in Miles

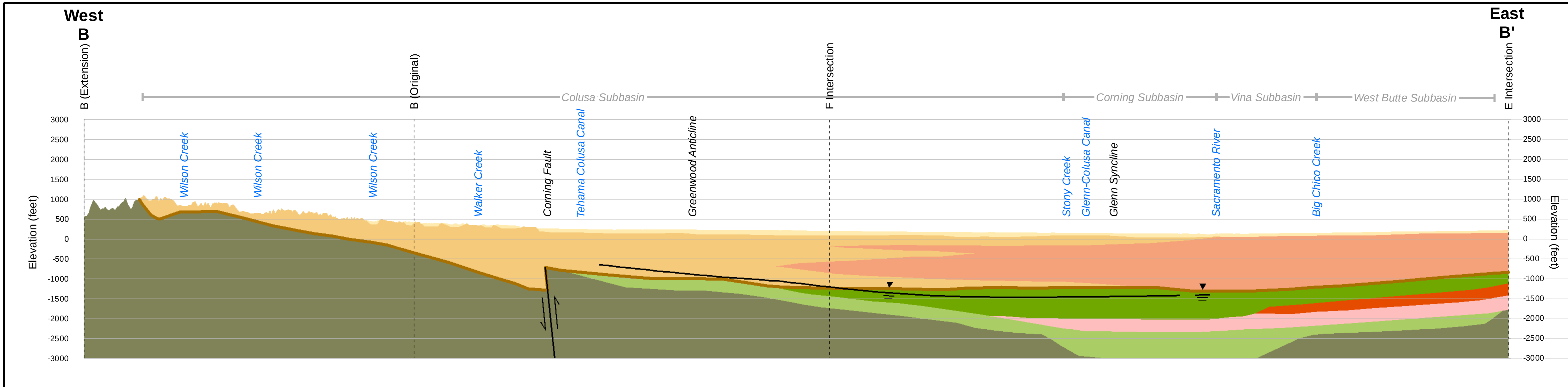
COLUSA COUNTY CALIFORNIA

COUNTY OF GLENN STATE OF CALIFORNIA

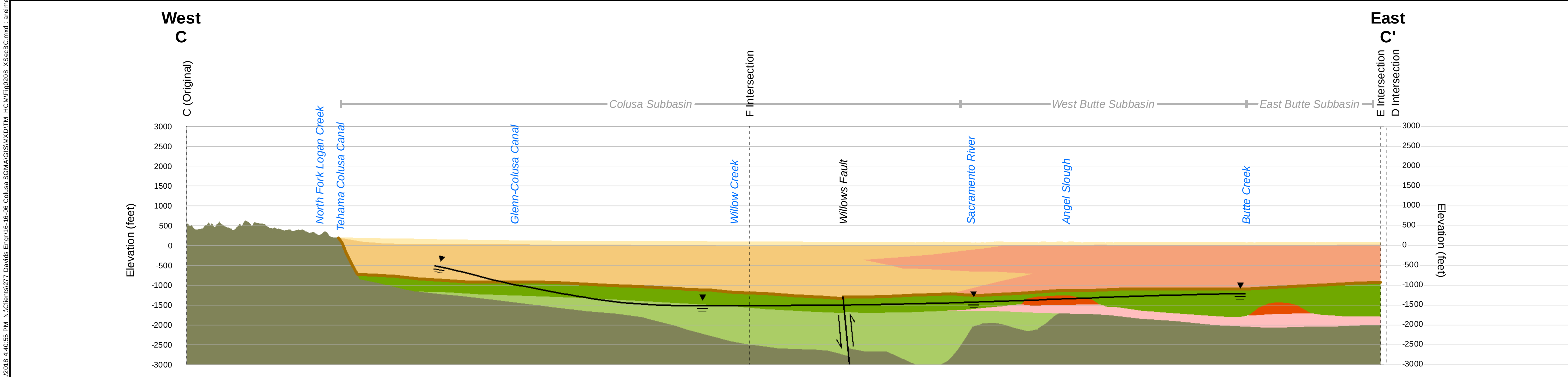
Figure 2-7

Top of Cretaceous Rocks Structural Contour Map

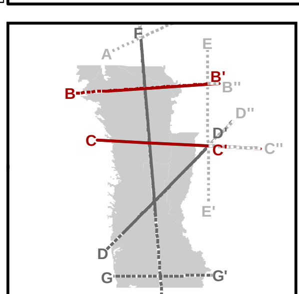
Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Cross Section B-B'



Cross Section C-C'



Symbology

- Fault
- Approximate Base of Groundwater Subbasin
- Base of Fresh Water (~2,000 mg/L TDS)

Geologic Units

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

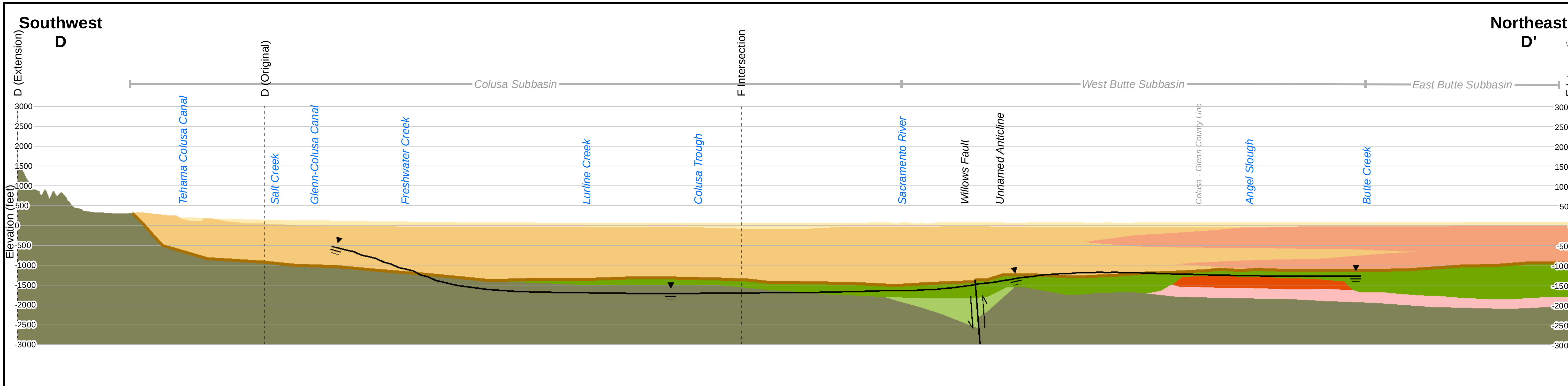
Notes:
1. Elevations are in North American Vertical Datum of 1988, feet (NAVD 88).
2. Cross sections shown are digitized versions of the cross sections included in the Department of Water Resources (DWR) Geology of the Northern Sacramento Valley, California report (DWR, 2014). Existing cross sections 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.

0 1.25 2.5
Scale in Miles
Vertical Exaggeration: 5.28

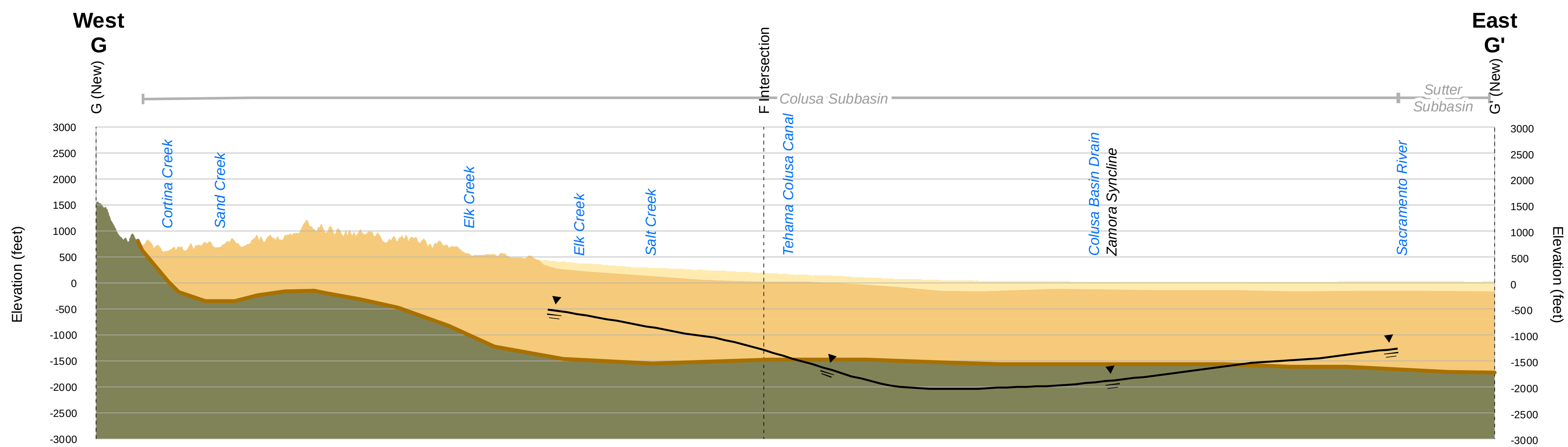
Figure 2-8

Cross Sections B-B' and C-C'

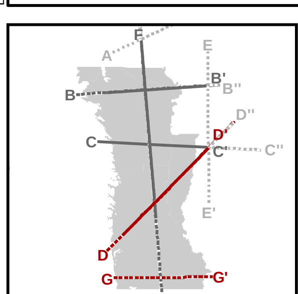
Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Cross Section D-D'



Cross Section G-G'



Symbology

- Fault
- Approximate Base of Groundwater Subbasin
- Base of Fresh Water (~2,000 mg/L TDS)

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.

0 1.25 2.5

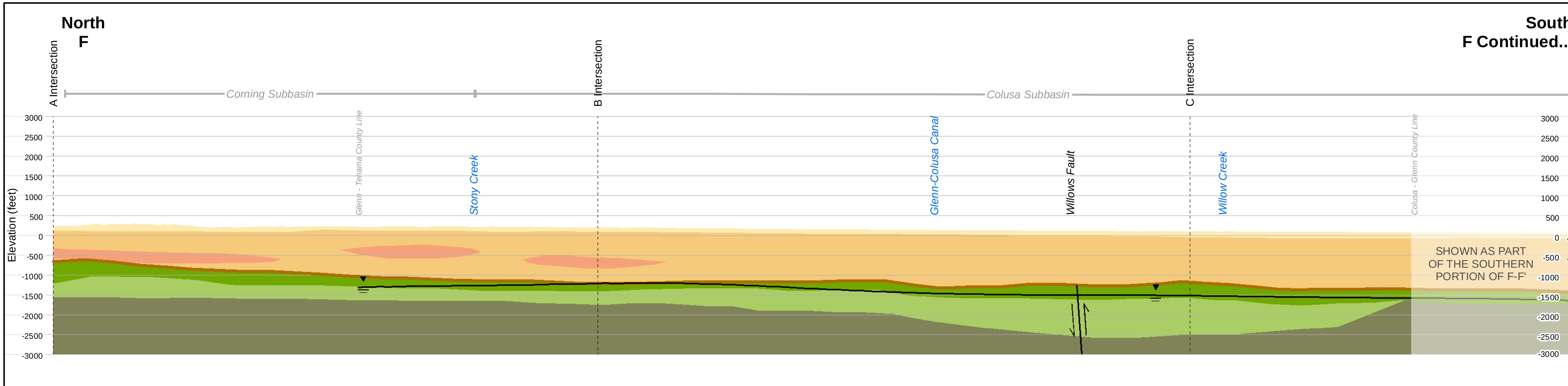
Scale in Miles

Vertical Exaggeration: 5.28

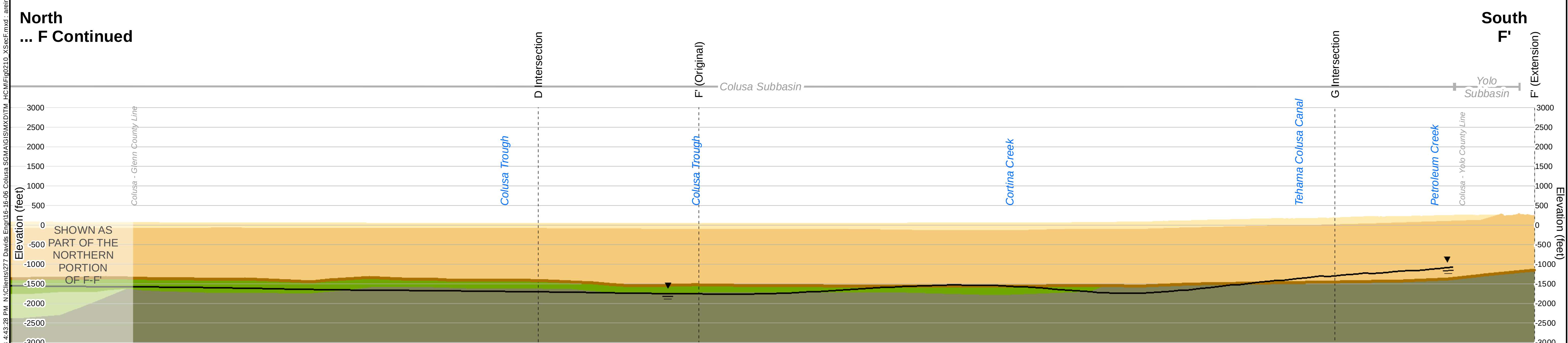
Figure 2-9

Cross Sections D-D' and G-G'

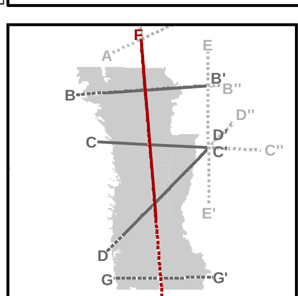
Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



Cross Section F-F' Northern Portion



Cross Section F-F' Southern Portion



Symbology

- Fault
- Approximate Base of Groundwater Subbasin
- Base of Fresh Water (~2,000 mg/L TDS)

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.

0 1.25 2.5

Scale in Miles

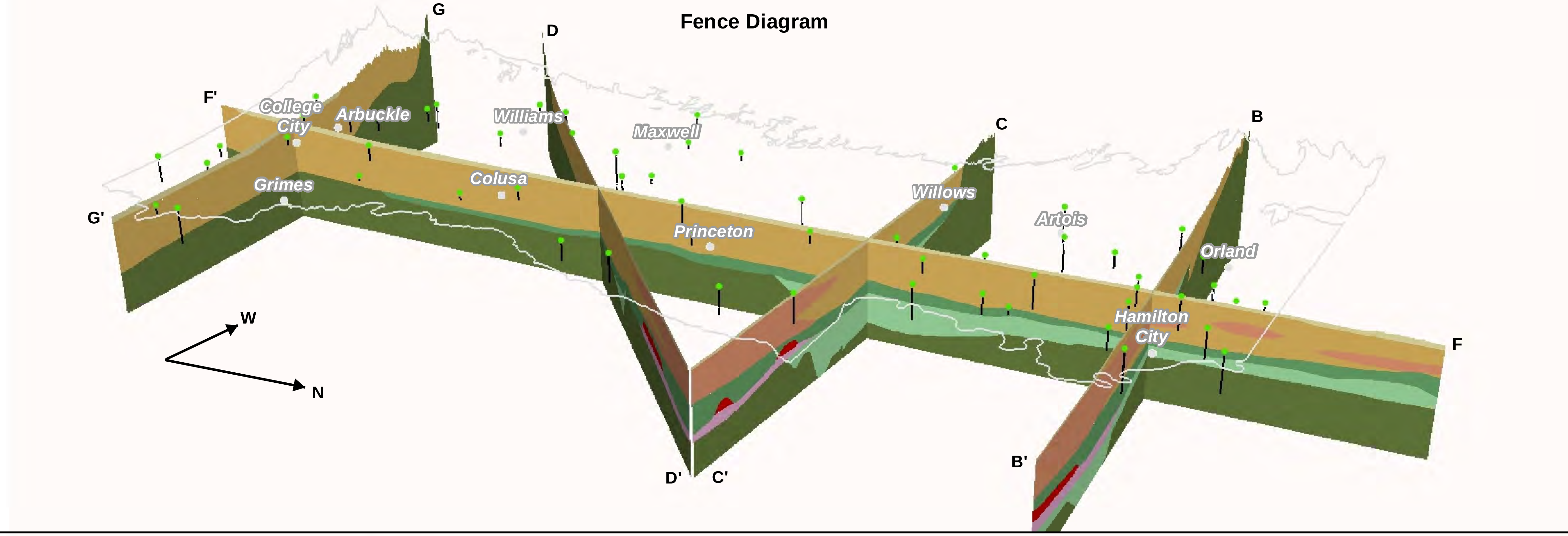
Vertical Exaggeration: 5.28

Figure 2-10

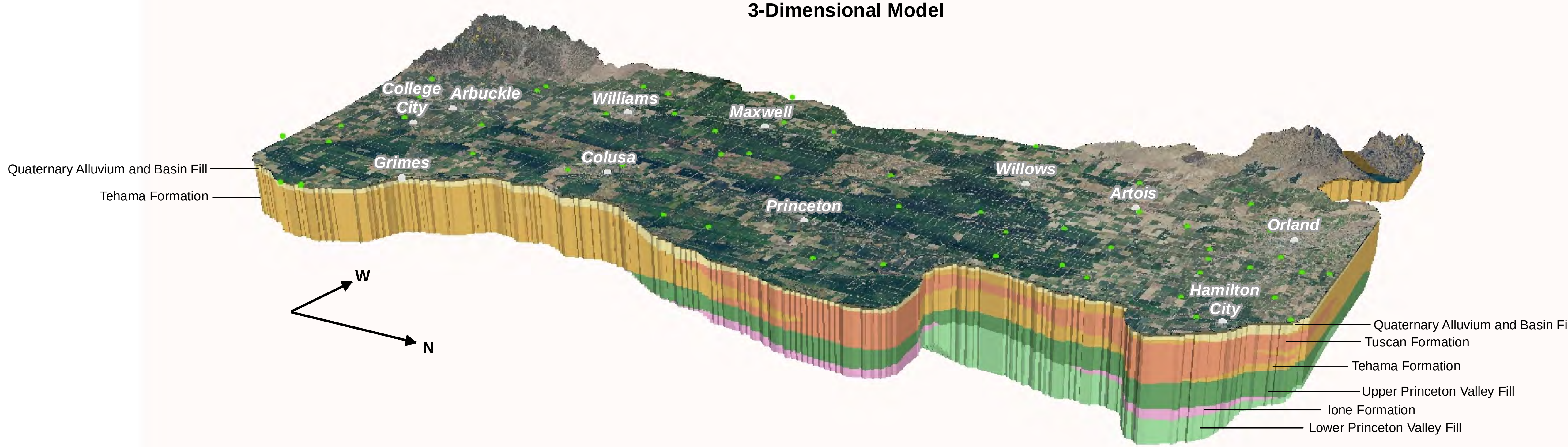
Cross Section F-F'

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

Fence Diagram



3-Dimensional Model



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)

Groundwater Monitoring Network

- Groundwater Monitoring Network Well
- Groundwater Monitoring Network Borehole

Horizontal Datum: North American Datum of 1983, California State Plane Zone II, 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.
5. The groundwater monitoring network wells include the Glenn County Dedicated Groundwater Monitoring Network wells and the Colusa County Groundwater Monitoring Network wells.

Figure 2-11

3D Hydrogeologic Conceptual Model

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

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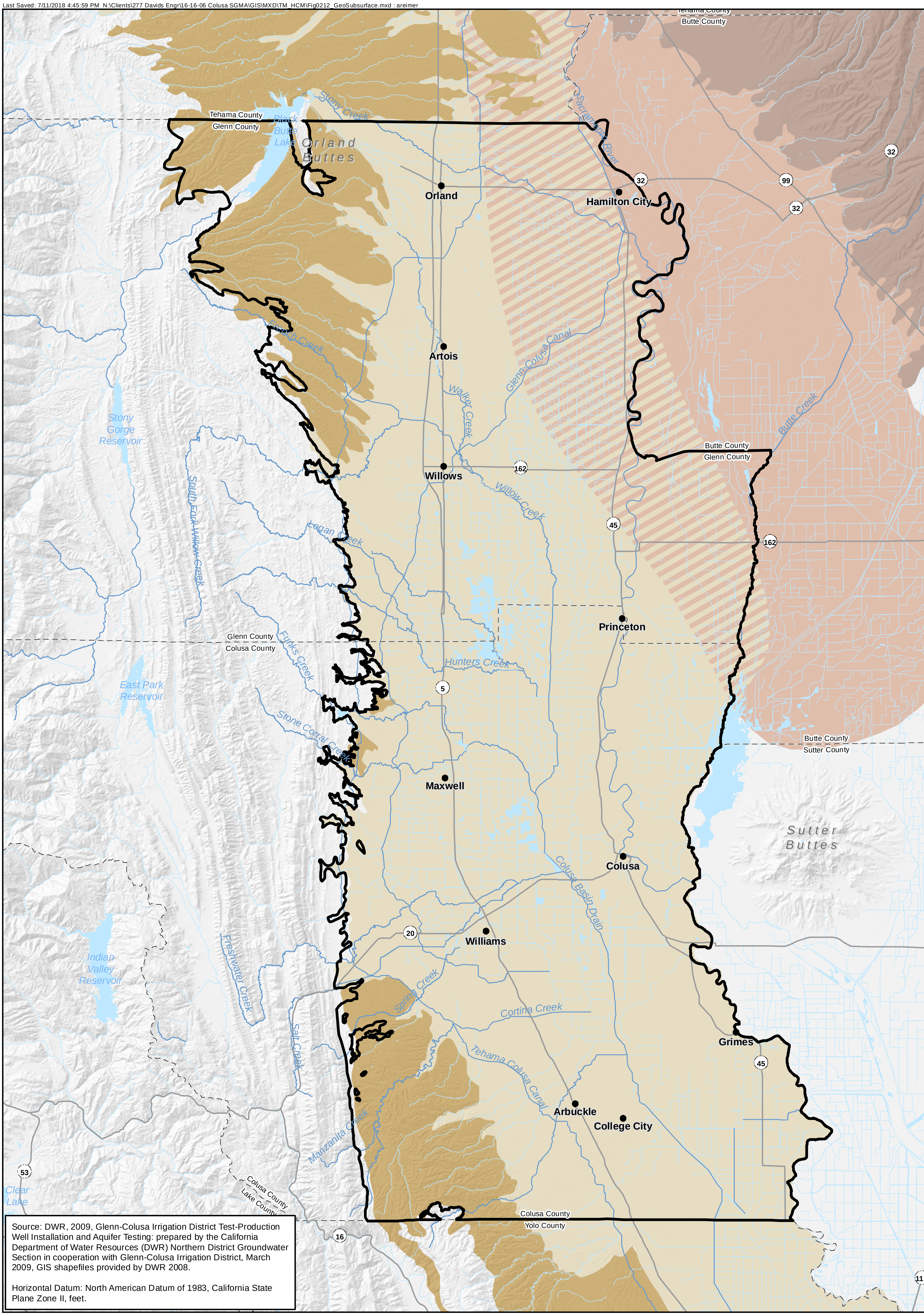

Symbology

Study Area

Geologic Unit

- Tehama Subsurface
- Tehama-Tuscan Subsurface Transition Zone
- Tuscan Subsurface
- Tehama Outcrop
- Tuscan Outcrop

N

0 2.5 5

Scale in Miles

COLUSA COUNTY CALIFORNIA

COUNTY OF GLENN STATE OF CALIFORNIA

Figure 2-12

Tuscan and Tehama Formation Subsurface Extents Map

Counties of Colusa and Glenn Hydrogeologic Conceptual Model

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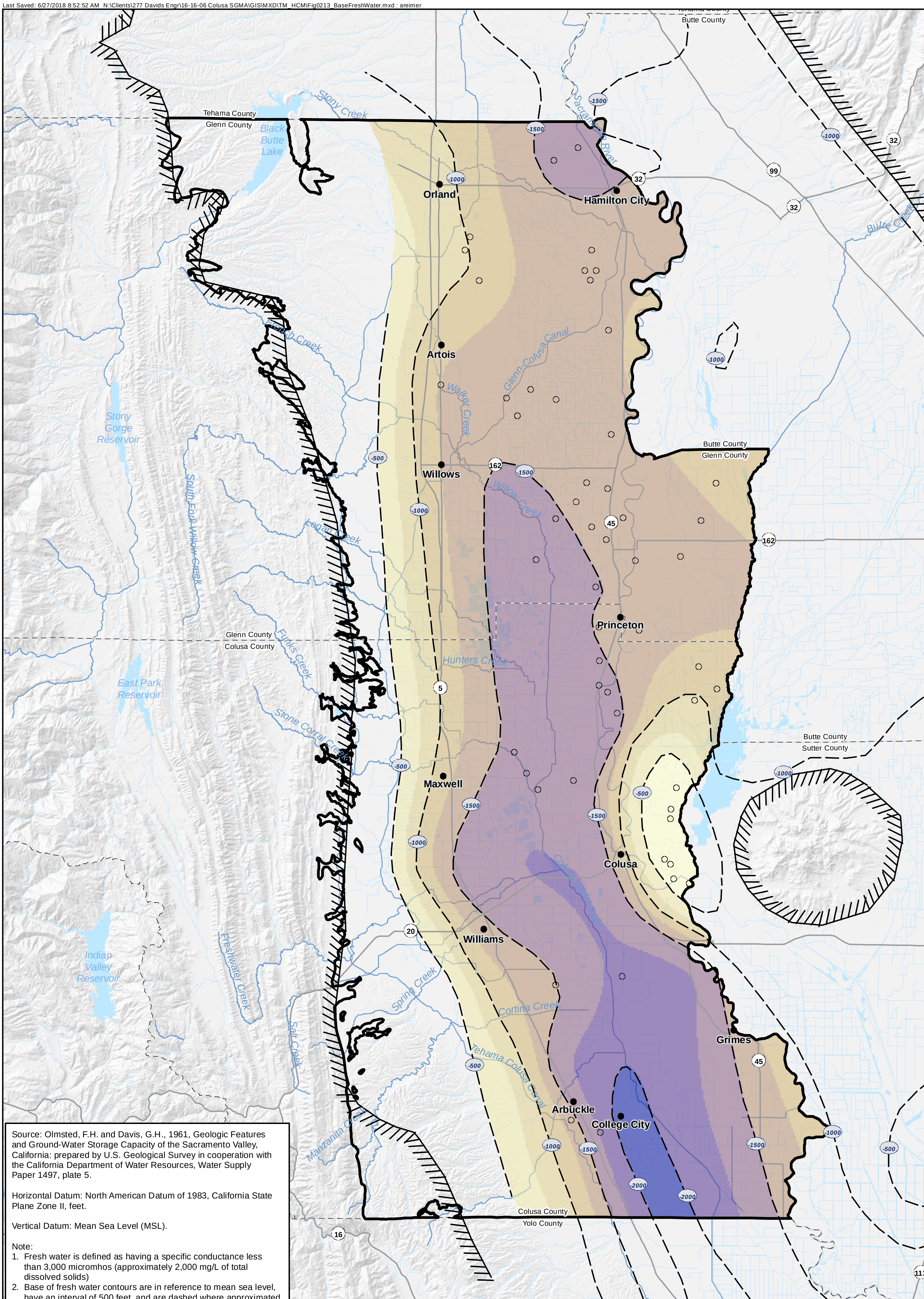

Source: Olmsted, F.H. and Davis, G.H., 1961, Geologic Features and Ground-Water Storage Capacity of the Sacramento Valley, California: prepared by U.S. Geological Survey in cooperation with the California Department of Water Resources, Water Supply Paper 1497, plate 5.

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)
2. Base of fresh water contours are in reference to mean sea level, have an interval of 500 feet, and are dashed where approximated.

Symbology

- Well Used for Contouring
- Study Area
- Base of Fresh Water Elevation Contour (Feet)
- 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
- <-2000

N

0 2.5 5
Scale in Miles

COLUSA COUNTY CALIFORNIA

COUNTY OF GLENN STATE OF CALIFORNIA

Figure 2-13

Base of Fresh Water

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

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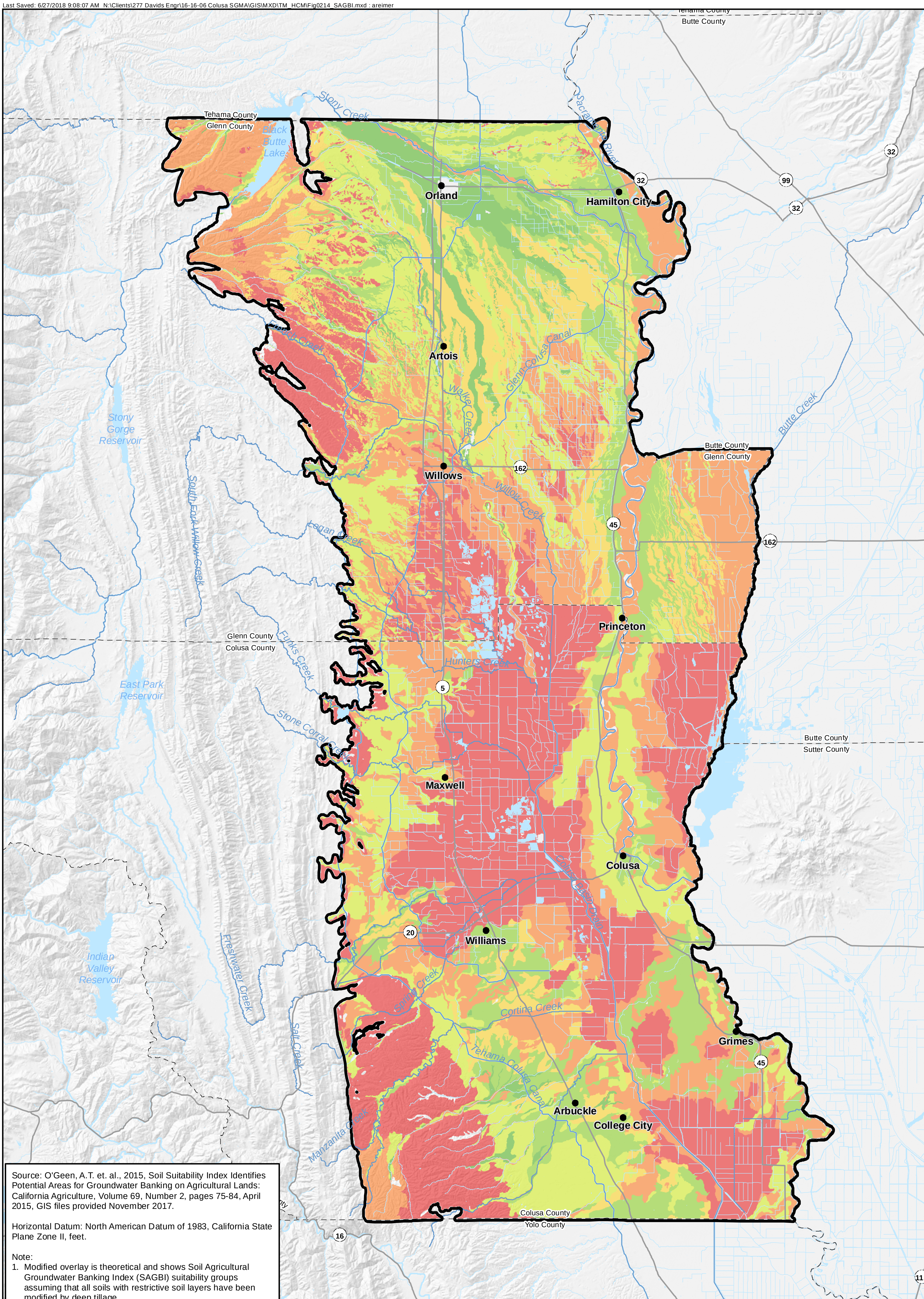


Source: O'Geen, A.T. et. al., 2015, Soil Suitability Index Identifies Potential Areas for Groundwater Banking on Agricultural Lands: California Agriculture, Volume 69, Number 2, pages 75-84, April 2015, GIS files provided November 2017.

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

Note:
1. Modified overlay is theoretical and shows Soil Agricultural Groundwater Banking Index (SAGBI) suitability groups assuming that all soils with restrictive soil layers have been modified by deep tillage.

Symbology

Study Area

Soil Agricultural Groundwater Banking Index Modified for Assumed Deep Tillage

- Excellent
- Good
- Moderately Good
- Moderately Poor
- Poor
- Very Poor

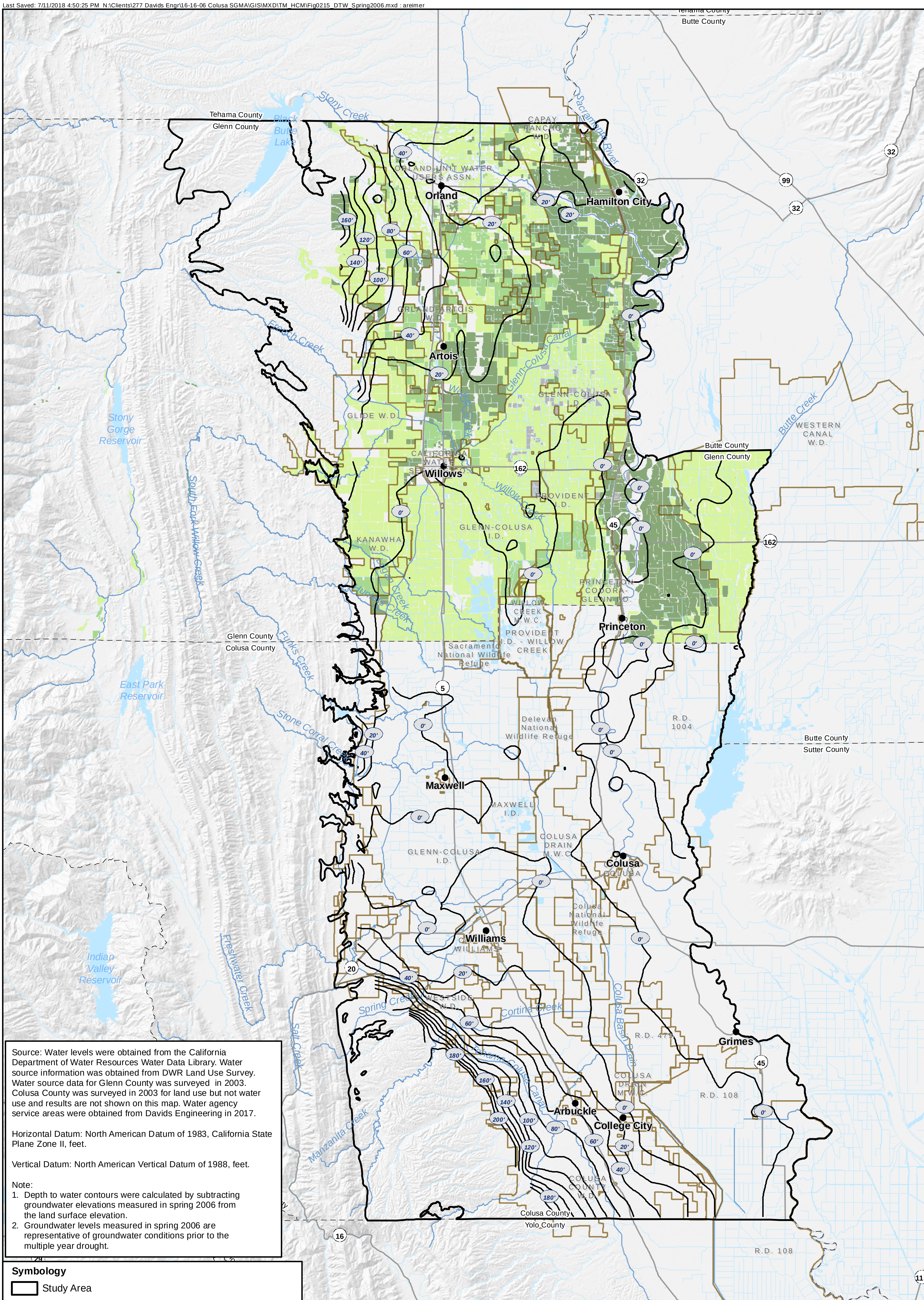
N

0 2.5 5
Scale in Miles

Figure 2-14

Soil Agricultural Groundwater Banking Index Modified for Deep Tillage

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model



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 and results are not shown on this map. Water agency service areas were obtained from Davids Engineering in 2017.

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

Vertical Datum: North American Vertical Datum of 1988, feet.

Note:
1. Depth to water contours were calculated by subtracting groundwater elevations measured in spring 2006 from the land surface elevation.
2. Groundwater levels measured in spring 2006 are representative of groundwater conditions prior to the multiple year drought.

Symbology

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

Water Source 2003

- Surface Water
- Mixed Surface and Groundwater
- Groundwater
- Unknown
- Reclaimed or Recycled Water

N

0 2.5 5

Scale in Miles

Figure 2-15

Depth to Groundwater Contours Spring 2006

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

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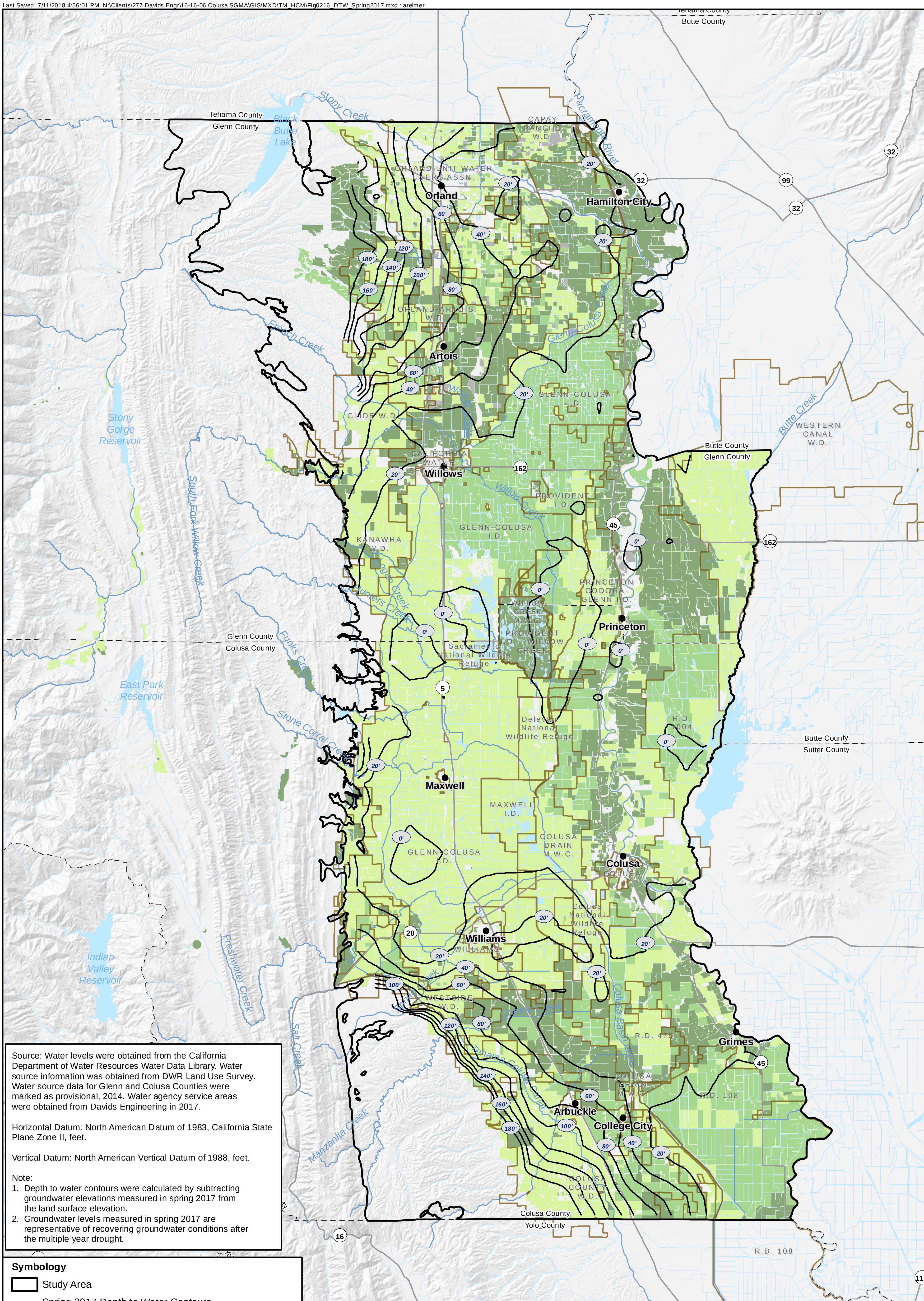

Source: Water levels were obtained from the California Department of Water Resources Water Data Library. Water source information was obtained from DWR Land Use Survey. Water source data for Glenn and Colusa Counties were marked as provisional, 2014. Water agency service areas were obtained from Davids Engineering in 2017.

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

Vertical Datum: North American Vertical Datum of 1988, feet.

Note:
1. Depth to water contours were calculated by subtracting groundwater elevations measured in spring 2017 from the land surface elevation.
2. Groundwater levels measured in spring 2017 are representative of recovering groundwater conditions after the multiple year drought.

Symbology

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

Water Source 2014

- Surface Water
- Mixed Surface and Groundwater
- Groundwater
- Unknown
- Reclaimed or Recycled Water

0 2.5 5
Scale in Miles

Figure 2-16

Depth to Groundwater Contours Spring 2017

Counties of Colusa and Glenn
Hydrogeologic Conceptual Model

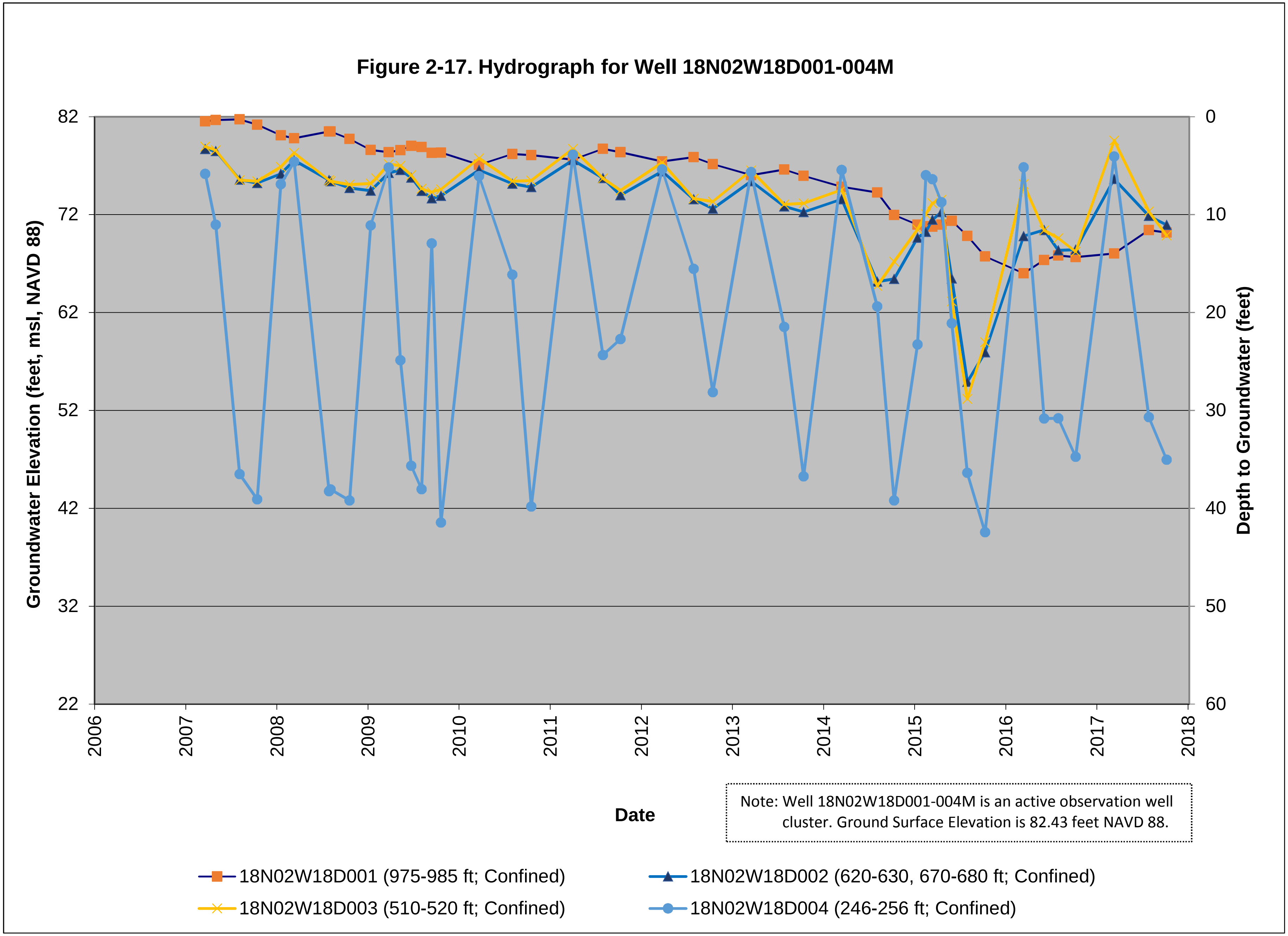

Figure 2-17. Hydrograph for Well 18N02W18D001-004M
Groundwater Elevation (feet, msl, NAVD 88)
Depth to Groundwater (feet)
82
72
62
52
42
32
22
0
10
20
30
40
50
60
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Date
Note: Well 18N02W18D001-004M is an active observation well cluster. Ground Surface Elevation is 82.43 feet NAVD 88.
18N02W18D001 (975-985 ft; Confined)
18N02W18D002 (620-630, 670-680 ft; Confined)
18N02W18D003 (510-520 ft; Confined)
18N02W18D004 (246-256 ft; Confined)

3.0 DATA GAPS AND UNCERTAINTY WITHIN THE HYDROGEOLOGIC CONCEPTUAL MODEL

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”. Data gaps were identified within the hydrogeologic extent, aquifer parameter, water quality, and groundwater inflows and outflows categories. These topics are discussed in more detail in the following subsections.

Hydrogeologic Extent

Additional subsurface data should be collected to help delineate the base of the Tehama and Tuscan Formations and characterize the Tehama-Tuscan Transition Zone. The hydrogeologic extents of the principal aquifers should 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, and in-depth evaluation of well completion reports (most of which are not deep enough to characterize the base of the Tehama and Tuscan Formations, but may be sufficient to better define the Tehama-Tuscan Transition Zone).

Aquifer Parameters

Aquifer parameter estimates should 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 should use pumping wells and dedicated monitoring wells discretely screened in the principal aquifers. The hydraulic properties of Tuscan Formation Unit C should be further investigated to verify the high hydraulic conductivities reported for Unit C and their applicability in the Colusa Subbasin.

Aquifer Water Quality

Future groundwater quality characterization efforts should utilize wells with known construction, each of which should screened within a single principal aquifer. The water quality data discussed in this report is based on wells that have not been specifically linked to the individual principal aquifers. 23 CCR §354.14(b)(4)(D) states that “general water quality of the principal aquifers” shall be included in the HCM.

Groundwater Inflows and Outflows

An appropriate integrated hydrologic model should be selected and developed to help quantify water budget components, including groundwater inflow and outflows. Sources and points of delivery for small riparian diverters from the Sacramento River have not been comprehensively evaluated. Imported water delivery volumes and points of delivery for these smaller diverters should be evaluated.

4.0 SUMMARY AND CONCLUSIONS

This report provides a preliminary assessment of the HCM for Glenn and Colusa Counties, and their collaborators to support development and implementation of one or more GSPs for the groundwater subbasins underlying the counties. The report provides an assessment of the components of the HCM, including geographic setting, land use, topography, hydrology, soils, and regional geology and structure. Additionally, this report provides a preliminary description of the local groundwater subbasins, including the Colusa Subbasin and the portions of the Corning and West Butte Subbasins that are located within Glenn and Colusa Counties. The lateral and vertical boundaries, potential geologic controls on groundwater flow, and principal aquifer systems and confining units of the local groundwater subbasins are discussed.

The extents, hydraulic properties, primary uses, and water quality characteristics of each of the principal aquifers are discussed in this report. There is one principal confining unit within the study area: Tuscan Formation Unit C. The principal aquifers are:

1. Quaternary Alluvial Aquifer;
2. Tehama Formation Aquifer; and
3. Tuscan Formation Aquifer (consists of Unit A and Unit B).

Data gaps identified within the preliminary HCM were related to the hydrogeologic extent of the principal aquifers, aquifer properties, groundwater quality of each principal aquifer, and groundwater inflows and outflows.

This report addresses the HCM requirements for GSPs on a preliminary basis using currently available data and information. The HCM will continue to be developed during preparation of one or more GSPs for the groundwater subbasins within the study area.

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APPENDIX A

Data Sources

Table A-1. 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, 2016, Bulletin 118 Interim Update 2016 Data: California Department of Water Resources (DWR).	http://wdl.water.ca.gov/groundwater/bulletin118/b118_2016_data.cfm
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	TNC	The Nature Conservancy (TNC), TBD, Mapping Potential Groundwater Dependent Ecosystems in California: The Nature Conservancy in cooperation with the California Department of Water Resources.	Not Available[(b)]
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/
Land Use	GIS Shapefile	DWR	DWR, 2003, Land Use Survey, Glenn County: California Department of Water Resources	https://www.water.ca.gov/Programs/Water-Use-And-Efficiency/Land-And-Water-Use/Land-Use-Surveys
Land Use	GIS Shapefile	DWR	DWR, 2003, Land Use Survey, Colusa County: California Department of Water Resources.	https://www.water.ca.gov/Programs/Water-Use-And-Efficiency/Land-And-Water-Use/Land-Use-Surveys
Natural Communities Commonly Associated with Groundwater	GIS Shapefile	DWR	DWR, 2018, 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.
(b) The report and corresponding groundwater dependent ecosystem GIS files from The Nature Conservancy are draft and confidential as of the writing of this report. Availability information, publication dates, and the files themselves are therefore not included in this report. An alternative data source is the Natural Communities Commonly Associated with Groundwater dataset which is a cooperative dataset between California Department of Water Resources, California Department of Fish and Wildlife, and The Nature Conservancy.