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Projection of Groundwater Pumping Sustainability in Volta Wildlife Refuge, Merced County, CA

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Projection of groundwater pumping sustainability in Volta Wildlife Refuge, Merced County, CA

By:
Helen Siegel

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Submitted in partial fulfillment of the requirements

of Senior Independent Study at

The College of Wooster

Abstract

In 2014, California passed the Sustainable Groundwater Management Act (SGMA) the state's first groundwater management legislation. Under SGMA, local agencies have the ability to form their own groundwater basins and establish plans for the sustainable use of groundwater. It is vital to have a thorough understanding of aquifer conditions and processes when drafting management practices for sustainable groundwater use. Thus, to aid in the creation of groundwater management plans for agencies within California's Central Valley, we developed a preliminary groundwater model of Volta Wildlife Refuge using a finite element flow and transport model known as FEFLOW. Volta Wildlife Refuge (VWR) is well studied and outfitted with multiple monitoring stations, making it a good choice for preliminary model generation. In addition, it is one of few remaining seasonal wetlands in California, habitats which are increasingly important and reliant on supplementary groundwater supplies for annual flooding. The model was created using a collection of data from the USGS Central Valley Hydrologic Model (CVHM), California's Fish and Wildlife Service, and the Grassland Water District (GWD). Once set up, eight separate climate change projection scenarios (CCSM, PCM, GFDL, CNVP) were modeled to predict future changes in aquifer stability that would require the re-evaluation of current groundwater management practices.

Acknowledgments

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program. This work was made possible by the generosity of the Danish Hydrological Institute (DHI) and their members at DHI-WASY. Particular thanks are due to Alexia Carpentier, Colin Roberts, Volkner Clausnitzer, and Nikolas Bokisch. Additional support was provided from members of the GWD, California Fish and Wildlife Service, and Bureau of Reclamation, as well as Claudia Faunt, Jonathan Traum, and members of the CVHM team at the USGS.

Personally, I would like to thank my mentor at Lawrence Berkeley National Labs, Dr. Nigel W.T. Quinn, for his guidance throughout the project and the other members of the HydroEcological Advanced Decision Support (HEADS) division for their support and insight. Thanks also to the Geology Department at the College of Wooster for the opportunity to do this work and their amazing support over the past four years. I couldn't have asked for a better department or more inspiring professors. Particular thanks are due to my I.S. advisor Dr. Shelley Judge who has put up with my crazy ideas and has always encouraged me to shoot for the stars. She truly represents the best that Wooster has to offer.

Finally, I could not have gotten where I am today without the support of my family and friends. Thanks for sharing in this crazy journey with me!

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Introduction

During the past century, California has seen a decline in 95% of its wetland environments due to the diversion and impoundment of surface water for agricultural use (Igler, 2005). Preservation of California's remaining wetlands is increasingly important, as they provide not only critical habitat for migrating waterfowl and federally threatened species, such as the giant garter snake, but also vital groundwater recharge areas (Bureau of Reclamation, 2010). In order to maintain California's remaining wetlands, intensive management strategies are implemented to provide optimal conditions for wildlife and habitat development.

Naturally, the wetland areas would flood in the fall and drain through the spring and summer months. Under management, the Grassland Water District (GWD) is responsible for the delivery of 180,000 acre-feet (AF) of water to federal, state, and private wetland environments within the Central Valley (Bureau of Reclamation, 2013b). The GWD follows varying irrigation schedules of flood up, maintenance, and drainage to strike a delicate balance between maximum seed germination and canal carrying capacities.

With recent drought conditions, the GWD has had trouble meeting its irrigation supply needs. Between 2008 and 2009, the GWD received only 24% of its necessary Level 4 water supply (Bureau of Reclamation, 2010). Level 4 supplies are classified as additional supplies mandated by the Central Valley Project Improvement Act (CVPIA) of 1992 for maximum wetland area management (Central Valley Project Improvement Act, 1992). This includes maximum biomass production and seed germination. Seeds produced in the wetlands provide a major source of protein to migrating waterfowl and serve to increase their abundance (Naylor, 1999). Each year the GWD is contracted to deliver 55,000 AF of Level 4 water (Bureau of Reclamation, 2010).

As a result of this shortage, the Bureau of Reclamation developed a pilot program to diversify GWD surface water supplies. Under the program, two groundwater pumping wells were installed along the Volta Wasteway in the Volta Wildlife Refuge (VWR). The pump stations were designed to supply 5,000 AF of additional supply to the GWD wetland areas per year (Bureau of Reclamation, 2010).

Future climate predictions for California's Central Valley indicate increasing stress on surface water supplies due to increased average air temperature, higher evapotranspiration rates, and variable precipitation (Langridge et al., 2012). This will lead to an increased reliance on groundwater pumping as a major source of necessary water supply.

California's Sustainable Groundwater Management Act (SGMA) allows local agencies like the GWD to develop their own plans to sustainably manage local groundwater resources and meet their diverse needs (Sustainable Groundwater Management Act, 2014). In order to develop a sustainable groundwater management plan however, it is first necessary to have a reliable working groundwater model of the area and predictions of how aquifer resources may be expected to change with time. A projected model of groundwater pumping sustainability within the Volta Wildlife Refuge is an integral step towards long-term evaluation of future water supplies within the GWD and the development of a sustainable plan to manage these resources.

Hypothesis

The development of a realistic groundwater model of Volta Wildlife Refuge will provide an exemplar for the development of sustainable groundwater management plans for the San Joaquin Basin and allow other entities, such as the Grassland Water District evaluate long-term groundwater pumping strategies.

Background

Site Description

Volta Wildlife Refuge is a 3,800 acre wetland environment managed by the California Department of Fish and Wildlife (California Department of Fish and Wildlife, 2016). It is located in western Merced County, south of the Sacramento-San Joaquin Delta and six miles northwest of Los Banos, California (Figure 1).

Similar to other seasonal wetlands in California, Volta Wildlife Refuge is intensively managed, relying on seasonal water deliveries, which flood the refuge during the winter months and drain it through the spring and summer (Figure 2). The water conveyance system that runs through Volta Wildlife Refuge is owned by the Bureau of Reclamation and operated by the San Luis and Delta Mendota Water Authority (California Department of Fish and Wildlife, 2016). Inflow to the refuge is through the Volta Wasteway, and ultimately comes from the Delta-Mendota Canal and the San Luis Reservoir. Water then travels through the refuge to the Santa Fe

Cross Channel, Mosquito Ditch, and Malia Ditch where it is distributed to the northern Grassland Water District (Bureau of Reclamation, 2010b).

The refuge is home to native wildlife including coyotes, beavers, and the federally threatened giant garter snake (California Department of Fish and Wildlife, 2016; Bureau of Reclamation, 2010b). It also serves as a nesting location for over 150 species of migrating waterfowl that rely on seeds from the wetland as a major source of protein (Naylor, 1999). Reproduction of natural flooding cycles and the delivery of adequate water supplies is pivotal in the generation of sufficient biomass and germinating seeds to sustain the refuge's wildlife.

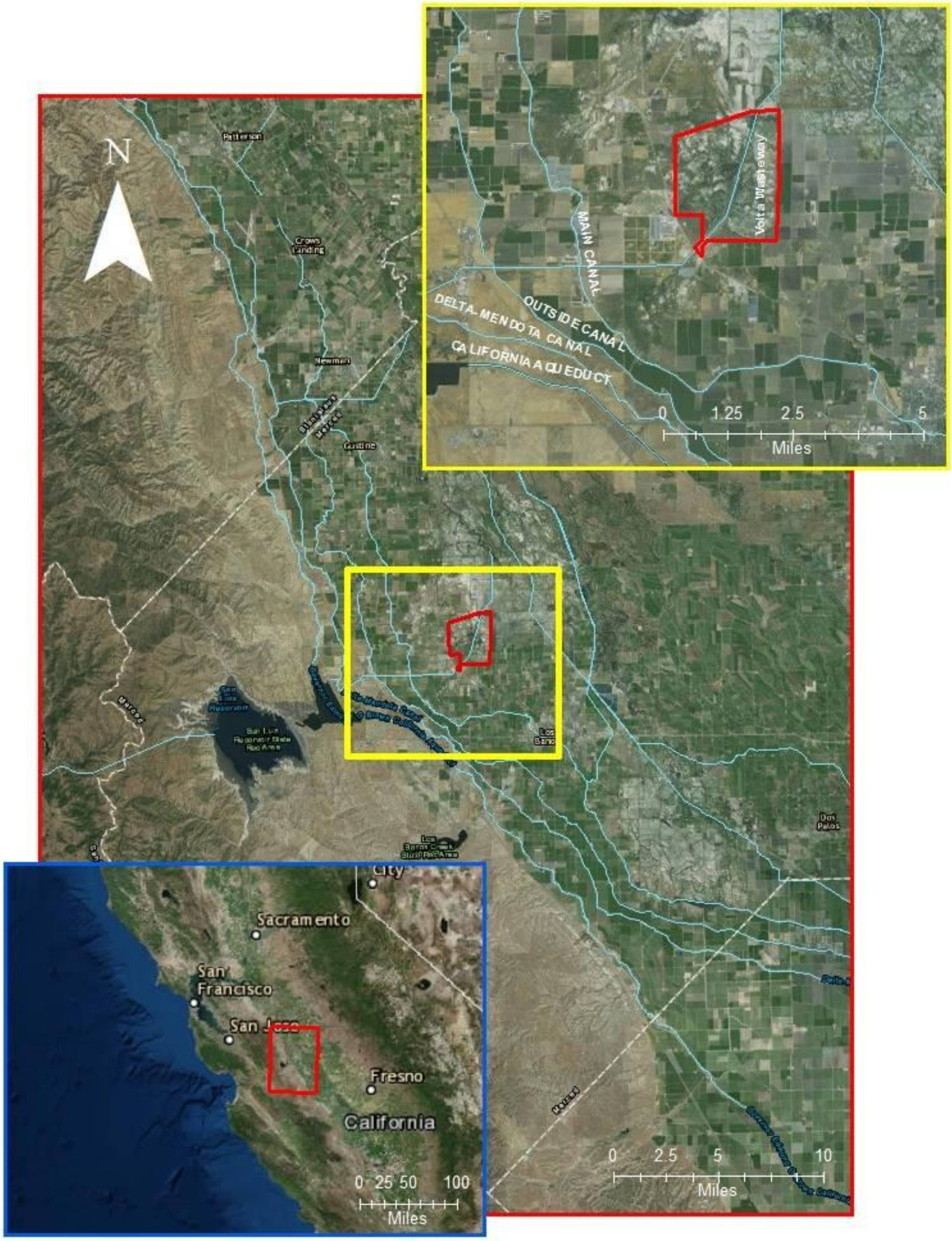


Figure 1: Location and bounds of Volta Wildlife Refuge within California (blue), Merced County (red box), and with respect to local conveyances (yellow). Water for the refuge comes from the Delta Mendota Canal and is pumped to Volta Wasteway. From here water moves through the refuge and onto fields managed by Grassland Water District.

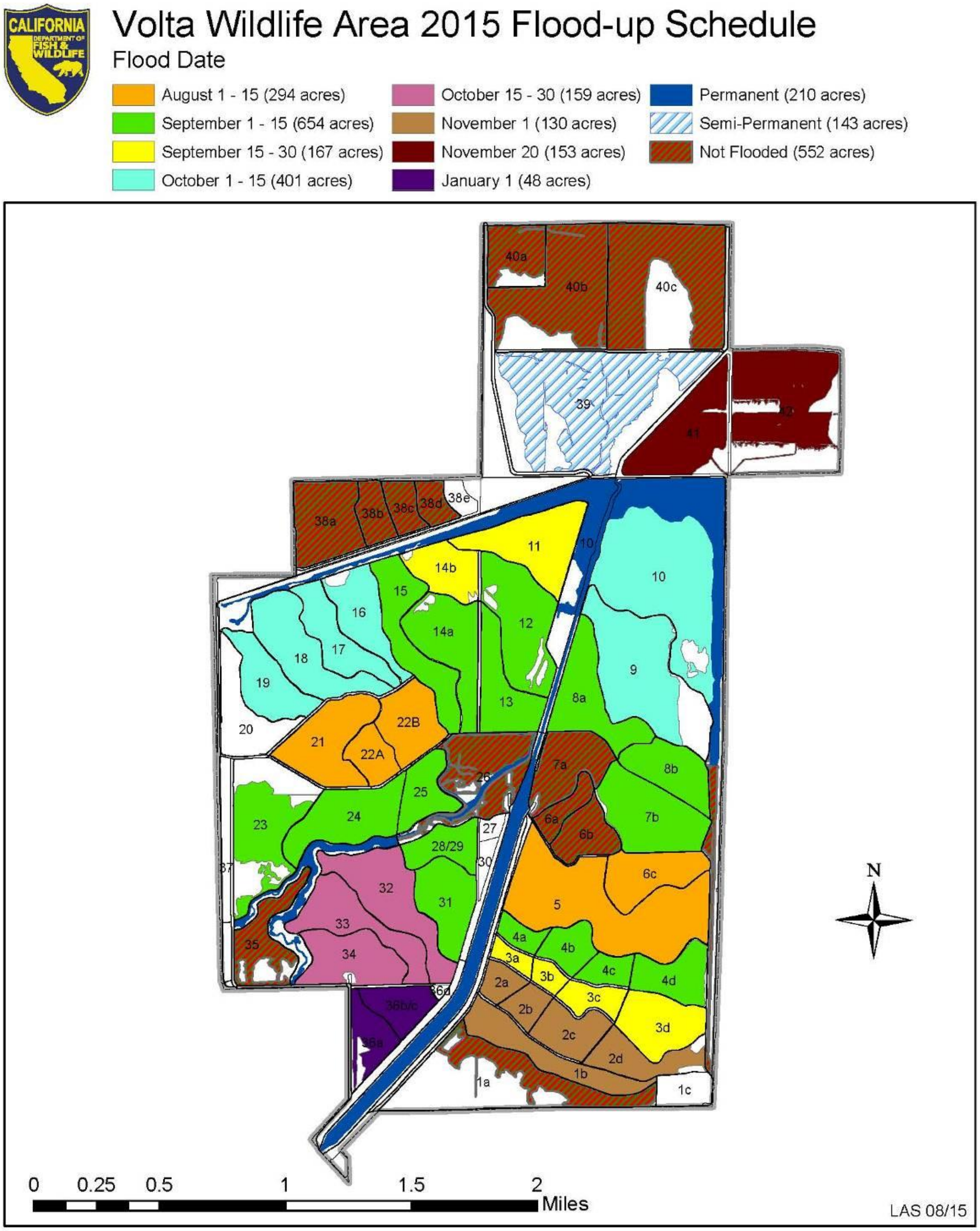


Figure 2: Schematic of flooding schedule for Volta Wildlife Fields. Flooding schedules are timed for optimum production of biomass and seeds for migrating waterfowl and local wildlife. Image from California Department of Fish and Wildlife, 2016.

Regional Hydrogeologic Framework

The Central Valley is underlain by the largest groundwater reservoir in the State of California and has a long history of groundwater use (Faunt et al., 2009). As such, its hydrogeologic characteristics have been well studied.

The valley itself is a northwest-trending, asymmetrical, structural trough, which has been filled with sediment that constitutes the aquifer system (Bureau of Reclamation, 2012). In its entirety the Central Valley aquifer system covers roughly 20,000 mi^2, running 400 mi from Redding, CA to the Tehachapi Mountains (Williamson et al., 1989). Bounded on the east by the Sierra Nevada and on the west by the Coastal Ranges, the Central Valley has been divided into several basins and sub-basins (Figure 3). Most notable are the Sacramento Valley in the north and the San Joaquin Basin in the south, with the Sacramento-San Joaquin Delta System dividing the two in the middle (Faunt et al., 2010).

Regional flow within the Central Valley aquifer is fairly isolated, as surrounding mountains and their related fault systems form boundaries to flow (Bertoldi et al., 1987; Faunt et al., 2009). As such, recharge to the aquifer for a large part comes off the Coastal Ranges and Sierra Nevada Mountains and flows east or west towards the valley axis, having limited interaction with outside waters, except at the Sacramento-San Joaquin Delta. Historically, flows from the Sacramento and San Joaquin Valley both moved towards the delta, flowing either south or north respectively, along the valley axis (Hotchkiss and Balding, 1971; Bertoldi et al., 1987).

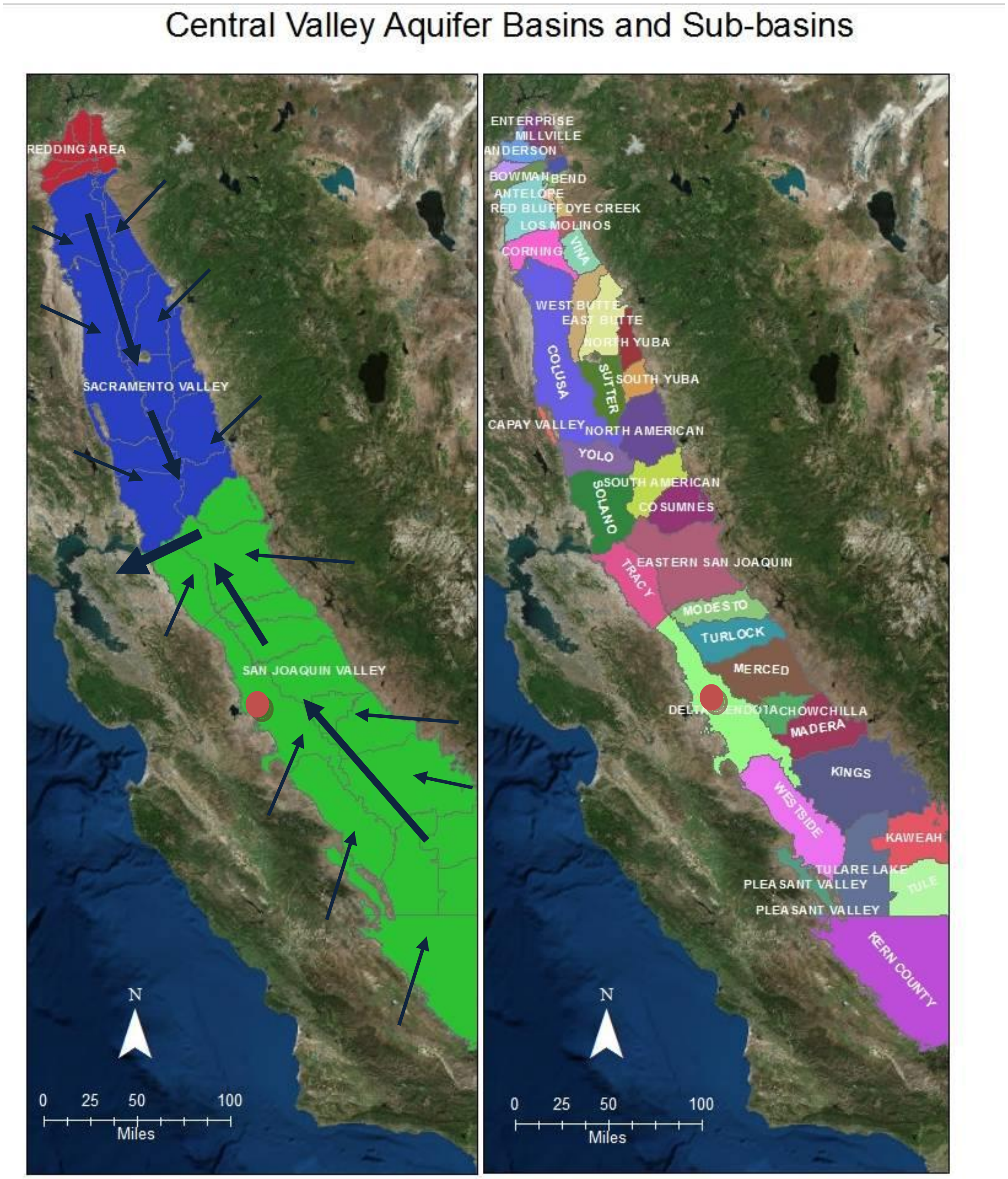


Figure 3: *Extent of the Central Valley Aquifer (left) and divisions into basins and sub-basins based on flow (right). The Sacramento Valley makes up almost a third of the aquifer area, while the San Joaquin Valley makes up the remaining two-thirds. General flow (blue arrows) within the Sacramento and San Joaquin Valleys is from the valley margins to the valley axis and south or north to the Sacramento-San Joaquin Delta respectively. The location of Volta Wildlife Refuge within the Delta-Mendota sub-basin of the San Joaquin Valley is noted (red dot).*

Development has somewhat altered this natural flow within the San Joaquin Valley. Beginning in 1849 with the wave of migration following the gold rush, the rate of groundwater pumping in the Central Valley for irrigation steadily increased as the demand for grain and textile crops climbed (Bertoldi et al., 1987; Bureau of Reclamation, 2013). Rates of groundwater extraction peaked in the 1970s with 11.5 million acre-feet/year (AF/yr) being removed annually from the valley; 20% of the total groundwater pumping in the entire United States at the time. The resulting artificial decrease in hydraulic head caused flow to move down from the mountainous valley sides to locations of high pumping instead of the San Joaquin River (Figure 4). With the loss in recharge from historical flows, irrigation has become the dominant means of recharge for the shallow aquifer and the San Joaquin (Bertoldi et al., 1987).

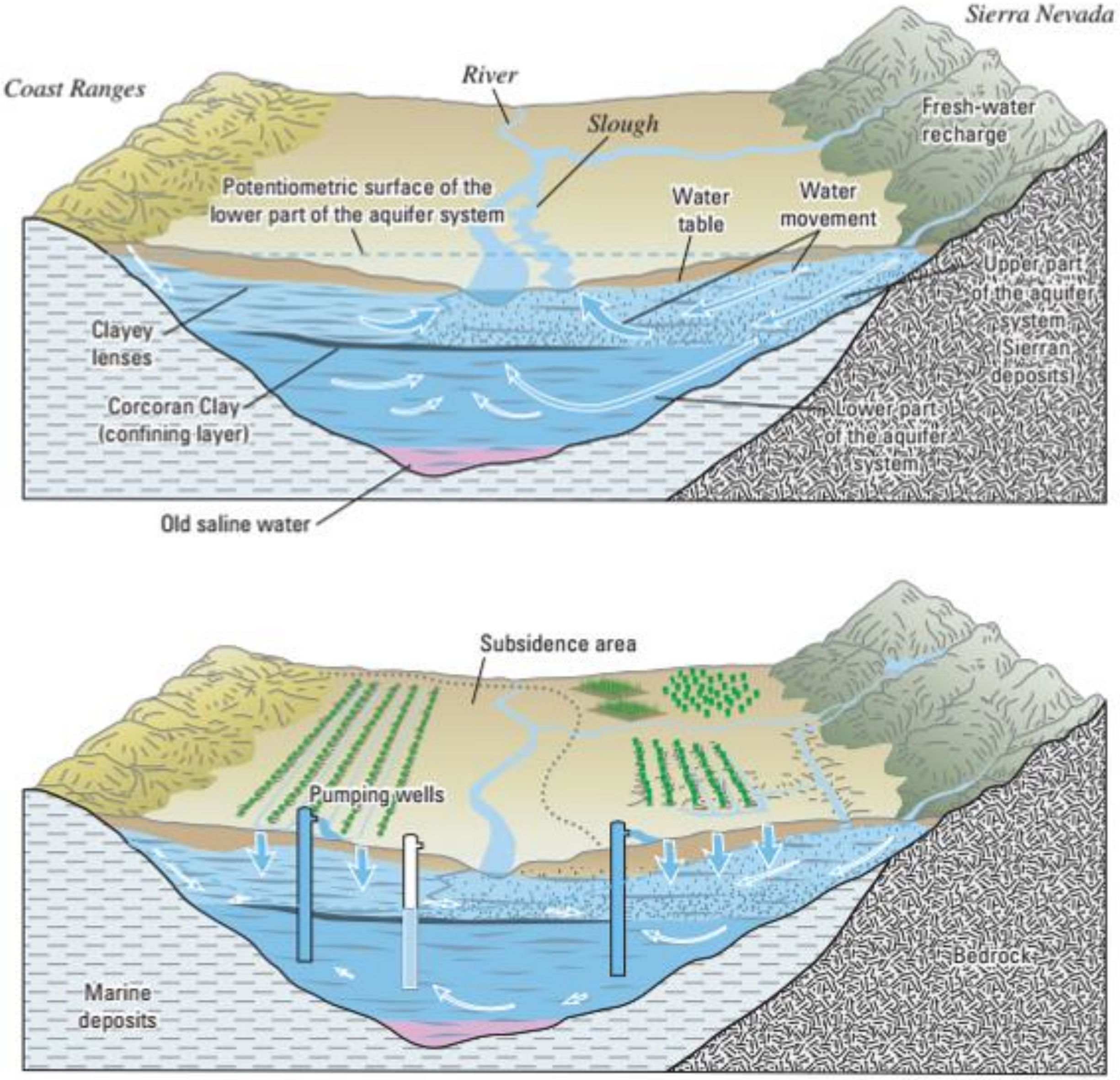


Figure 4: Cross-section of the San Joaquin Valley showing the change in regional flow before and after development. Prior to development flow in the San Joaquin Valley moved from the margins of the valley to the valley axis. Increased groundwater pumping to sustain agriculture within the valley has led to flow towards local areas of depressed hydraulic head. Diagram from Faunt, et al., 2009, Figure A9, B.

Additionally, inelastic aquifer compaction from pumping has further altered historic flow patterns within the San Joaquin by decreasing the storage of aquifer sediments (Page, 1983). The compaction of aquifer sediments can occur either elastically or inelastically. Inelastic compaction and the resulting land subsidence occur when the pre-consolidation stress level of the sediments is exceeded due to a drop in supporting hydraulic head or water pressure. Once the decline in hydraulic head reaches a critical level, known as a critical head, the effective stress increases past the stress level of aquifer sediments, causing a compaction of pore space and available water storage (Bertoldi et al., 1987) (Figure 5).

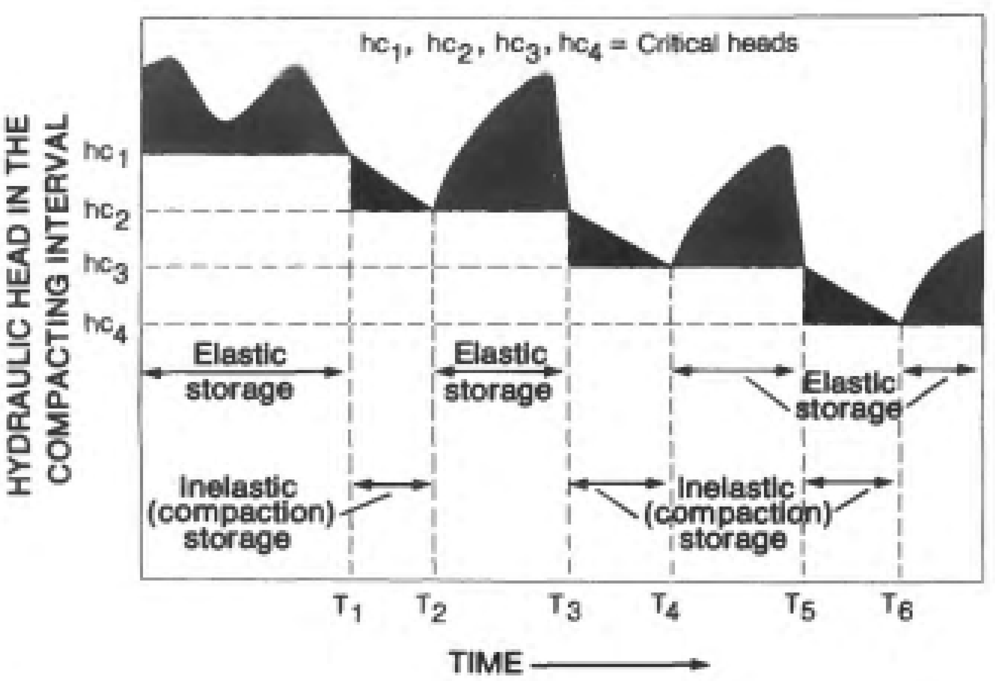


Figure 5: Graph of elastic and inelastic changes in storage in relation to critical head levels. Spans of inelastic storage represent a loss in aquifer volume due to an exceedance of pre-consolidation stress-levels upon reaching some critical head. Figure from Bertoldi et al., 1987, Figure 20.

By the mid-1950s, researchers were becoming aware of a large degree of land subsidence in the valley due to the removal of groundwater, oil and gas, and the compaction of peat soils in drained wetlands. Over the span of 20 years from 1950-1970 the Central Valley quickly experienced the largest volume of land subsidence to date in the world, with some locations subsiding 20 feet or more in elevation and the total aquifer storage decreasing by 60 million AF (Figure 6). Overall the total loss in storage resulting from subsidence is only a small part of the 800 million AF of freshwater within the Central Valley aquifer. However, locally it had a profound affect on groundwater flow, storage, and overlying infrastructure (Bertoldi et al., 1987; Faunt et al., 2009).

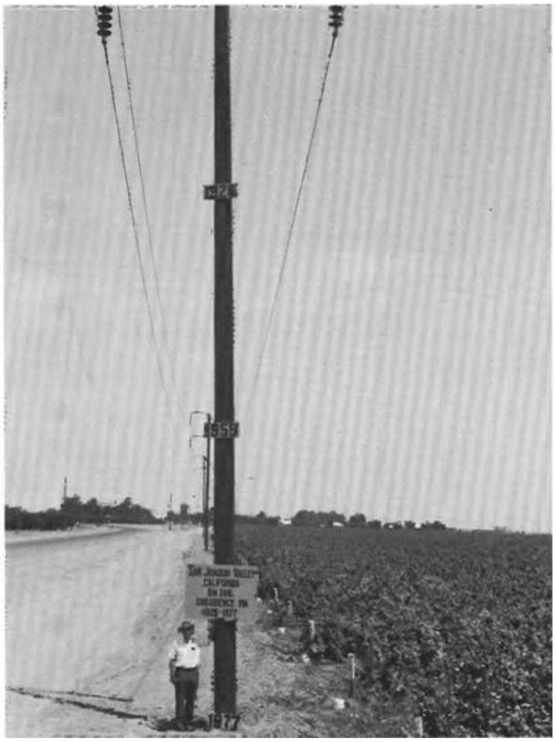


Figure 6: Poignant image depicting USGS researcher Joseph F. Poland by a telephone pole 10 miles outside of Mendota in the San Joaquin Valley illustrating the 25 ft of land subsidence that occurred in the Central Valley due to groundwater pumping between 1926 and 1977. Image from United States Geologic Survey, 2015.

Local Hydrogeologic Framework

Volta Wildlife Refuge and the Grassland Water District are both located in the Delta-Mendota sub-basin on the western side of the San Joaquin basin (Faunt et al.,). Sediments in the San Joaquin basin are a mixture of marine and continental deposits formed by fluctuating sea-levels and erosion off the Sierra Nevada Mountains and Coastal Ranges (Davis et al., 2006).

Sea-levels fluctuated in the valley throughout the Paleogene and Neogene forming marine deposits of varying thicknesses and extent (Figure 7). In many locations marine and continental deposits interfinger and overlap each other as environments shifted (Page, 1983; Bertoldi et al., 1987).

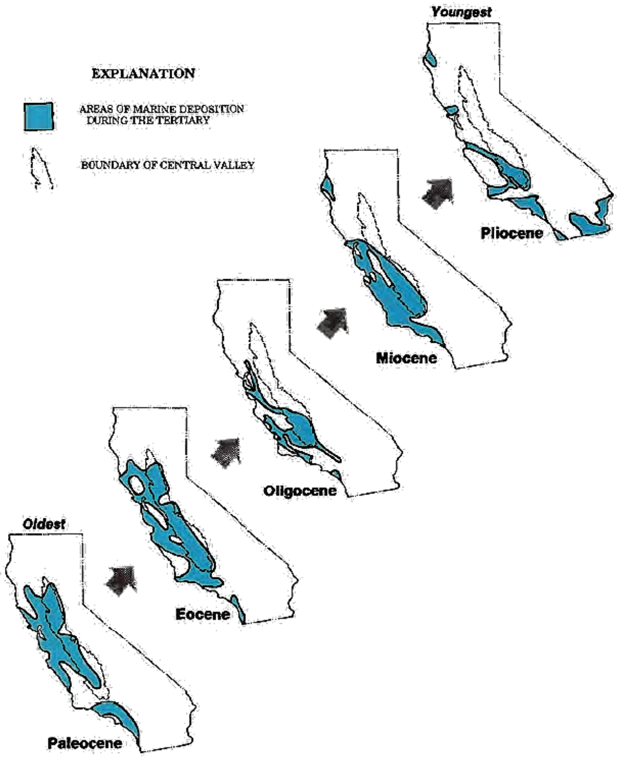
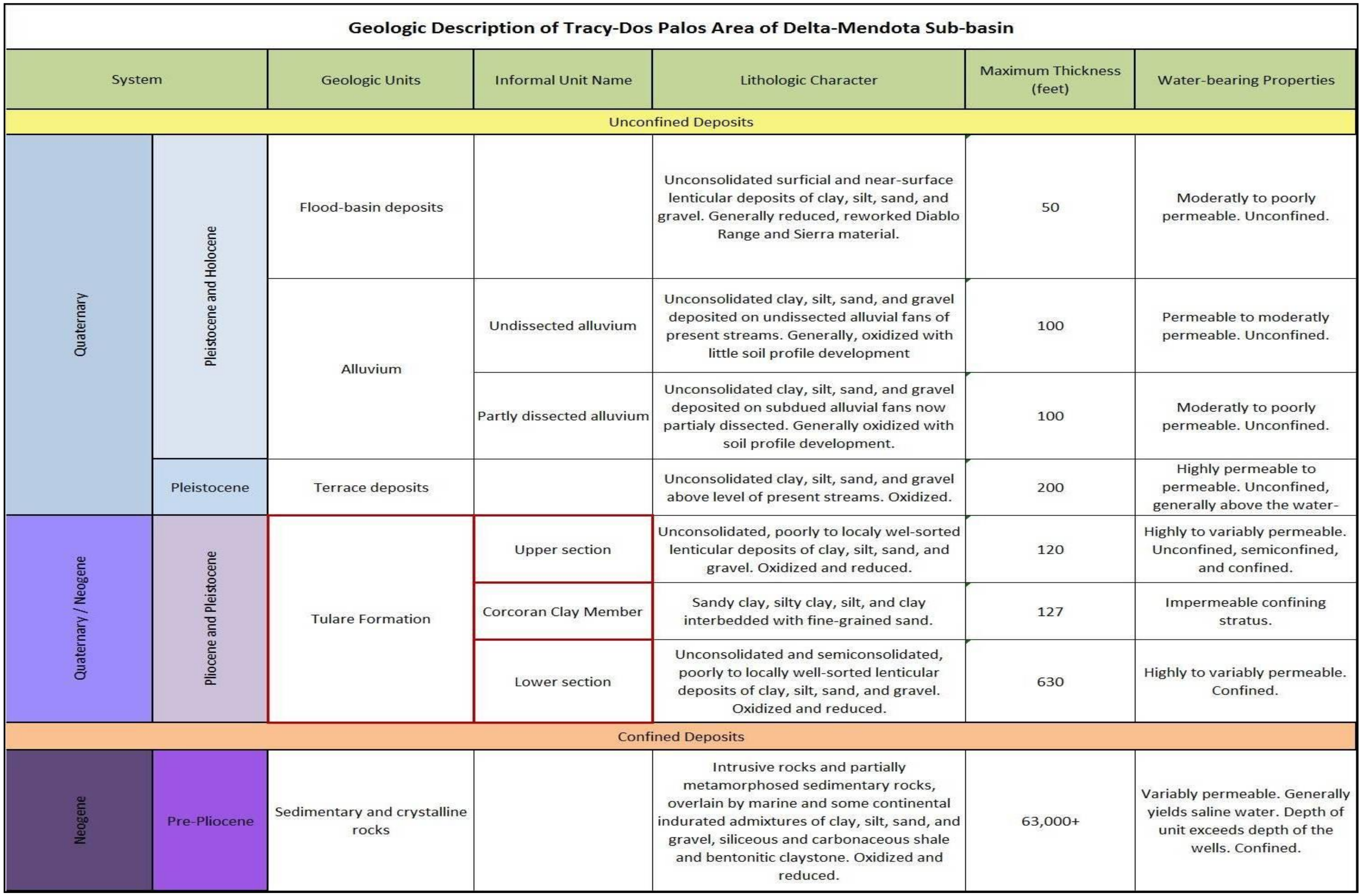


Figure 7: Extent of fluctuating sea-levels in the Central Valley from the Paleocene to the Pliocene. Following the Pliocene. Sea-levels retreated, and continental deposits were dominant in the valley. Image from Bertoldi et al., 1991, Figure 7.

Marine deposits within the basin provide very little freshwater as they contain a high degree of salts (Page 1983; Bertoldi et al., 1987; Faunt et al., 2009). Thus, the majority of freshwater is extracted from unconsolidated continental deposits post-Eocene in age. The dominant freshwater-yielding formation of the Delta-Mendota sub-basin is the Tulare Formation. Deposition of the Tulare Formation ranges from the Pliocene to the Holocene and across various fluvial environments, with sources from both the Coastal Ranges and Sierra Nevada Mountains (Page, 1983). Thus, it is a texturally and compositionally variable formation that changes drastically with both location and depth.

On the western side of the San Joaquin Valley within in the Delta Mendota sub-basin, the primary source material for the Tulare Formation is derived from the Coastal Ranges. Depositional environments range from alluvial-fan deposits to deltaic, flood-plain, lake, and marsh deposits. Over time these environments shifted, forming beds, lenses, and tongues of alternating clay, sand and gravel. Most prominent is the Corcoran Clay Member, which forms an extensive clay layer and semi-confining boundary to lower deposits (Page, 1983). Depths of the Corcoran Clay range from 100 to 500 ft below ground surface within the Delta-Mendota sub-basin (Page, 1983; Williamson et al., 1989; Faunt et al., 2010) (Figure 8).



Geologic Description of Tracy-Dos Palos Area of Delta-Mendota Sub-basin

System		Geologic Units	Informal Unit Name	Lithologic Character	Maximum Thickness (feet)	Water-bearing Properties
Unconfined Deposits						
Quaternary	Pleistocene and Holocene	Flood-basin deposits		Unconsolidated surficial and near-surface lenticular deposits of clay, silt, sand, and gravel. Generally reduced, reworked Diablo Range and Sierra material.	50	Moderatly to poorly permeable. Unconfined.
		Alluvium	Undissected alluvium	Unconsolidated clay, silt, sand, and gravel deposited on undissected alluvial fans of present streams. Generally, oxidized with little soil profile development	100	Permeable to moderatly permeable. Unconfined.
			Partly dissected alluvium	Unconsolidated clay, silt, sand, and gravel deposited on subdued alluvial fans now partialy dissected. Generally oxidized with soil profile development.	100	Moderatly to poorly permeable. Unconfined.
	Pleistocene	Terrace deposits		Unconsolidated clay, silt, sand, and gravel above level of present streams. Oxidized.	200	Highly permeable to permeable. Unconfined, generally above the water-
Quaternary / Neogene	Pliocene and Pleistocene	Tulare Formation	Upper section	Unconsolidated, poorly to localy wel-sorted lenticular deposits of clay, silt, sand, and gravel. Oxidized and reduced.	120	Highly to variably permeable. Unconfined, semiconfined, and confined.
			Corcoran Clay Member	Sandy clay, silty clay, silt, and clay interbedded with fine-grained sand.	127	Impermeable confining stratus.
			Lower section	Unconsolidated and semiconsolidated, poorly to locally well-sorted lenticular deposits of clay, silt, sand, and gravel. Oxidized and reduced.	630	Highly to variably permeable. Confined.
Confined Deposits						
Neogene	Pre-Pliocene	Sedimentary and crystalline rocks		Intrusive rocks and partially metamorphosed sedimentary rocks, overlain by marine and some continental indurated admixtures of clay, silt, sand, and gravel, siliceous and carbonaceous shale and bentonitic claystone. Oxidized and reduced.	63,000+	Variably permeable. Generally yields saline water. Depth of unit exceeds depth of the wells. Confined.

Figure 8: Stratigraphy of Delta-Mendota sub-basin through the Tracy-Dos Palos area. Dominant formation present below Volta Wildlife Refuge, the Tulare Formation, is outlined (red). Modified from Hotchkiss and Balding, 1971, Table 1.

In its simplest form the groundwater system in this section of the Central Valley is divided into an upper unconfined aquifer and a lower semi-confined aquifer, bounded above by the Corcoran Clay (Bertoldi et al., 1987; Faunt et al., 2009)(Figure 9).

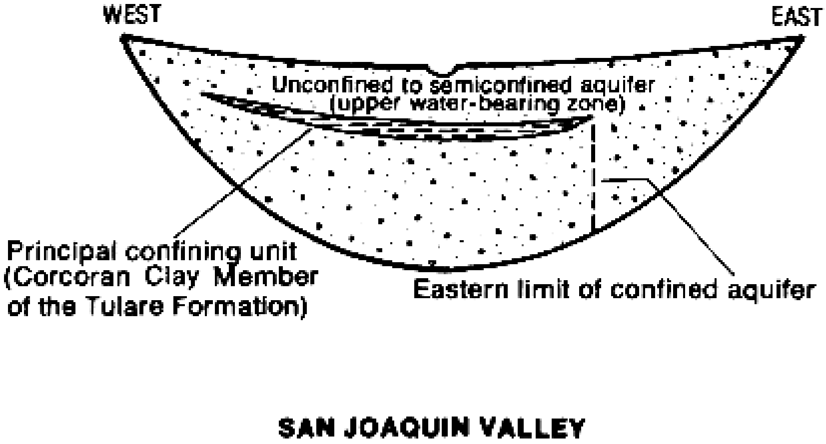


Figure 9: Profile of a simplified San Joaquin aquifer, with the Corcoran Clay member forming a semi-confining layer dividing the unconsolidated alluvium deposits into an upper unconfined and lower semi-confined zone. Image modified from Bertoldi et al., 1987, Figure 10.

However, many geologists like Page (1983) and Williamson et al. (1989) have emphasized the over simplicity of this view. In reality, the Central Valley aquifer system is better described as a single complex heterogeneous aquifer with varying confinement and vertical conductivity due to several overlapping discontinuous clay lenses and gravel deposits (Williamson et al., 1989) (Figure 10, 11). Page (1983) found that the isolated confining layers are numerous within the aquifer and make up to 50% of the aquifer volume, though they are not laterally extensive, further complicating predictions of flow within the basin. The importance of texture maps created by Page (1983) and Williamson et al. (1989) in quantifying and describing the heterogeneous nature of the Tulare cannot be overstated.

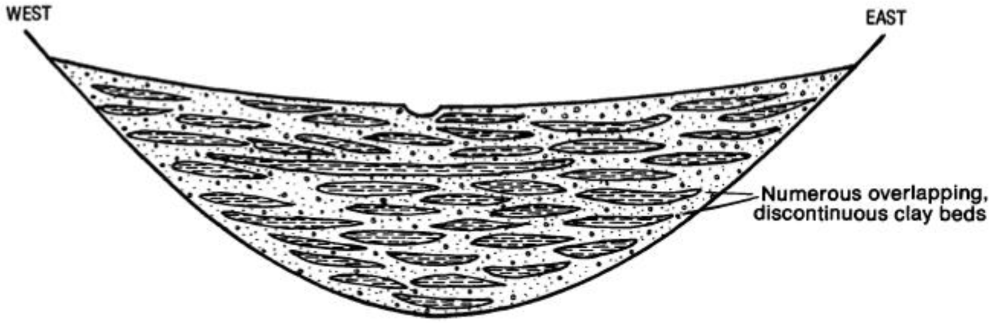


Figure 10: Representative profile of discontinuous confining layers that make up the San Joaquin Valley aquifer system. Image modified from Bertoldi et al., 1991, Figure 10.

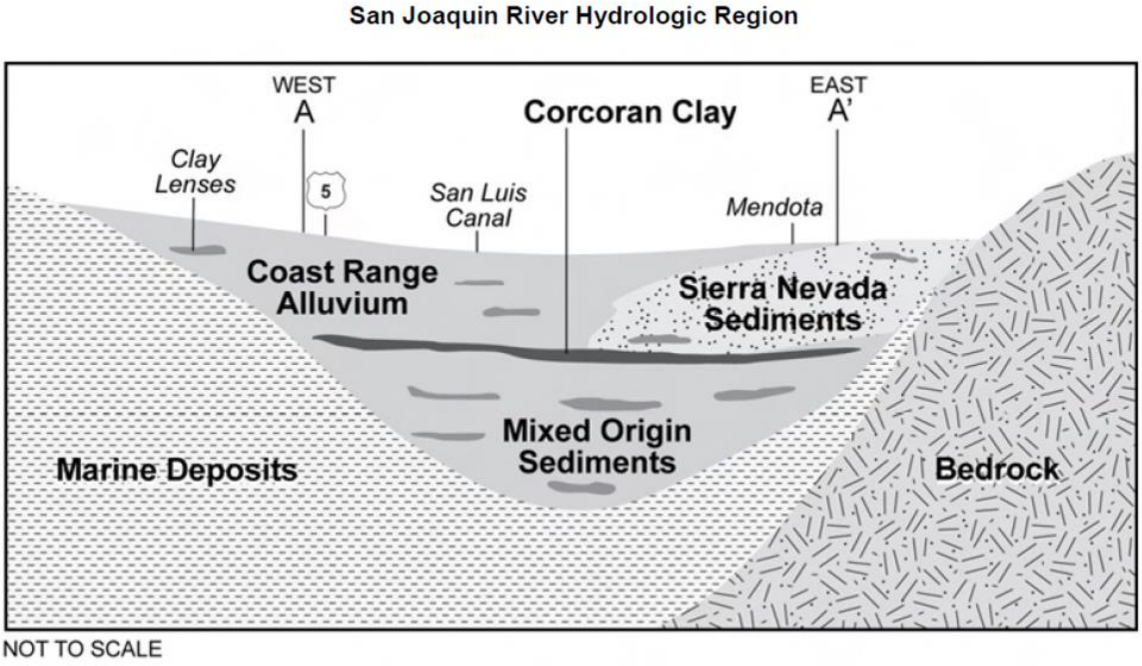
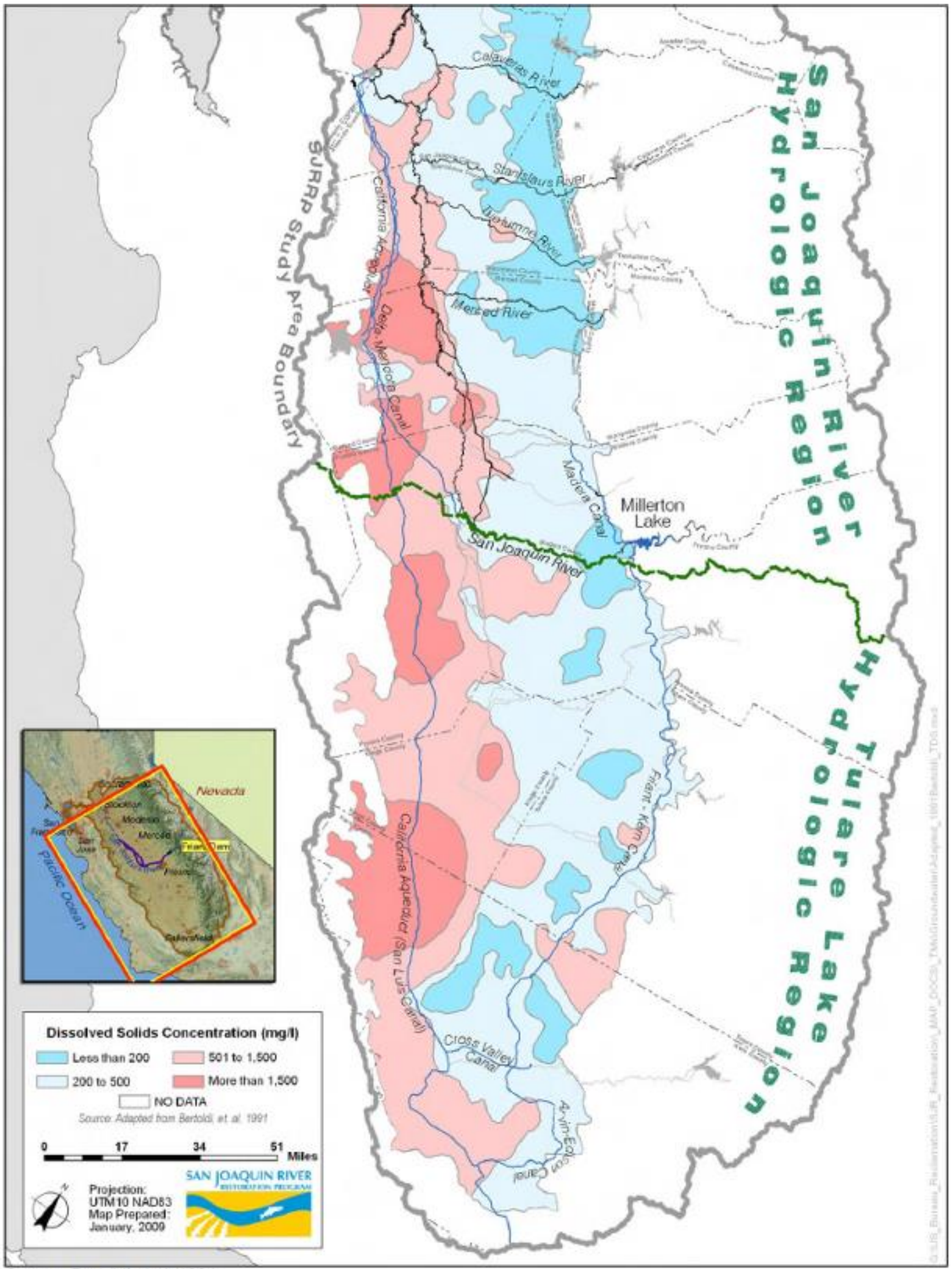


Figure 11: General stratigraphic profile of the San Joaquin aquifer system showing presence of Corcoran Clay layer as well as numerous clay lenses. The difference in sediment composition between western and eastern sections of the valley is illustrated as well. The predominant source material on the western side is the sedimentary Coastal Ranges and the eastern side is the igneous Sierra Nevada. Figure from Faunt, et al., 2009, Figure 12-2 A.

Water Quality

Another consequence of the heterogeneous nature of the Delta-Mendota sub-basin, and the Tulare Formation as a whole, is its impact on groundwater quality and yield. Some parts of the sub-basin have been recorded as yielding only 20 gal/min, while others have produced up to 5,000 gal/min depending upon underlying beds (Davis et al., 2006). This presents a challenge for attempts at accurate small-scale groundwater modeling within the basin, which is only overcome by the use of assemblages of local groundwater and stratigraphy studies such as the texture models collected by Page (1983) and Williamson et al. (1989).

The marine origin of much of the Coastal Ranges also means that natural salts and elements are abundant within basin sediments and have been known to form isolated regions of increased salinity and famously selenium (Se) (Davis et al., 2006; Faunt et al., 2009, 2010). Documented Total Dissolved Solids (TDS) values range from 100 to 6,000 mg/L within the sub-basin (Davis et al., 2006) (Figure 12). For reference, the upper limit of the Secondary Maximum Contaminant Levels (SCML) set by the California State Water Resources Control Board Division of Drinking Water (DDW) is 1,000 mg/L with warnings about the effects of long-term use of high TDS groundwater on crop yield after 1,500 mg/L (Groundwater Ambient Monitoring and Assessment, 2016).



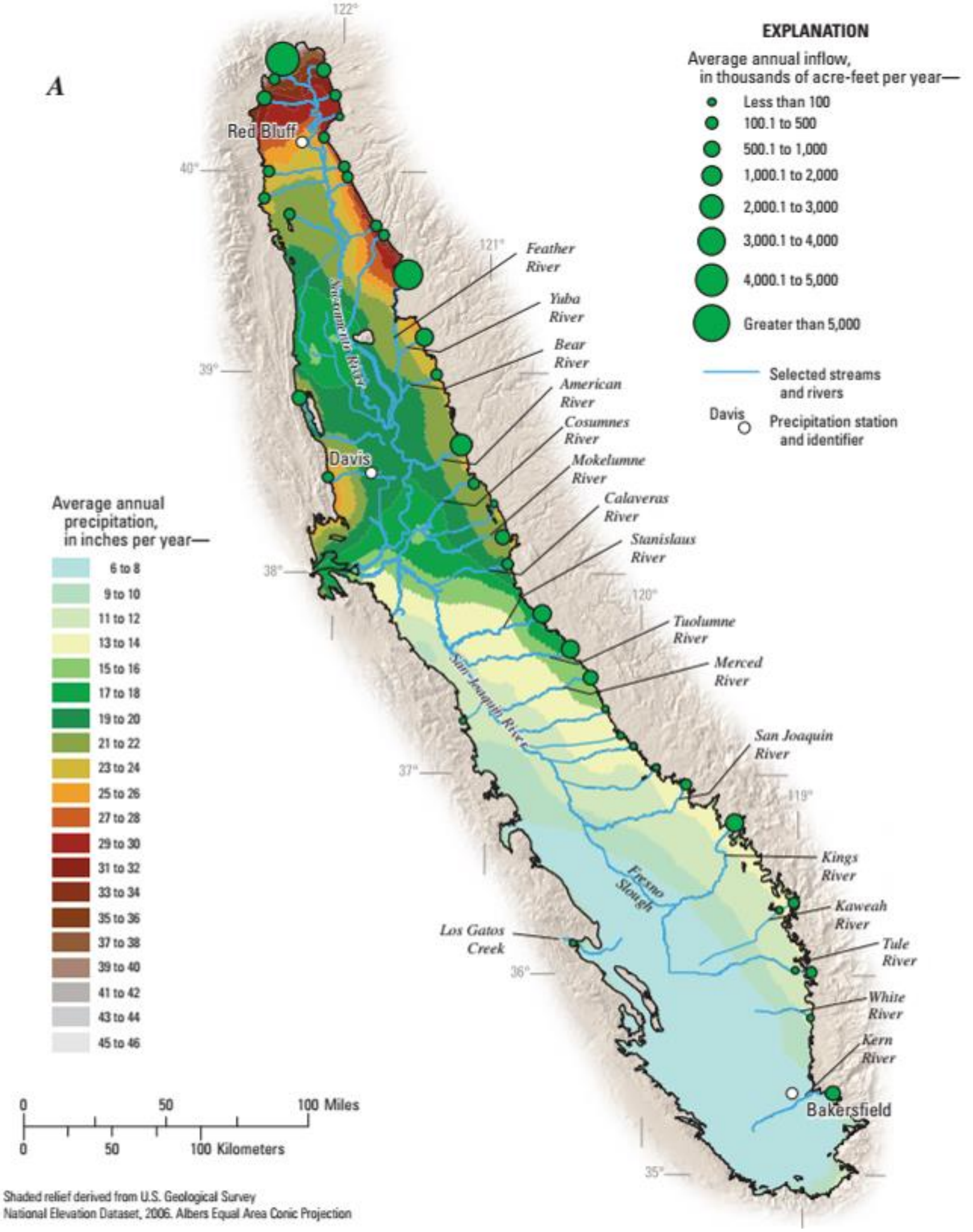
Source: Bertoldi et al. 1991

Figure 12: Map of Total Dissolved Solids (TDS) in the San Joaquin Valley as one indicator of water quality heterogeneity. Note that the highest concentration of TDS (dark pink) is on the western side of the valley where deposits are derived from marine sediments off the Coastal Ranges. Image from Bertoldi et al., 1991, Figure 24, and modified by United States Bureau of Reclamation (personal memo).

Climate and Recharge

The Central Valley has a Mediterranean climate, dominated by seasonal floods and droughts, with most precipitation occurring during the winter and spring months (Bureau of Reclamation, 2012) (Figure 13). Over three-fourths of all precipitation within the Central Valley falls between the months of December and April. Annually, precipitation within the valley ranges from more than 30 inches in the northern end to 5 inches in the south (Bureau of Reclamation, 2013a). Thus, the majority of precipitation in the San Joaquin Basin is seasonal and falls in the winter months.

Naturally, wetlands such as those in the Grassland Water District and Volta Wildlife Refuge would flood during this time and drain steadily through the spring and summer, though increased surface water controls have diminished this natural cycle. Presently, management practices imitate natural flooding cycles using canals and diversions to seasonally flood the wetlands and drain them in the spring. Therefore, recharge to the shallow aquifer occurs through these canals and flooded fields largely at a seasonal rate as well (Bureau of Reclamation, 2010).



Shaded relief derived from U.S. Geological Survey National Elevation Dataset, 2006. Albers Equal Area Conic Projection

Figure 13: Map of annual precipitation and major inflows into the Central Valley. Note that the San Joaquin Valley is significantly drier than the northern Sacramento Valley and that the majority of inflows are from the Sierra Nevadas to the east. Map from Faunt et al., 2009, Figure A5.

Recharge into the semi-confined aquifer along the western side of the Central Valley occurs mainly from the Coastal Ranges as well as some vertical flow through the Corcoran Clay (Hotchkiss and Balding, 1971; Bertoldi et al., 1987; Williamson et al., 1989). However, development and the construction of groundwater pumping wells within the Central Valley has again altered historic flow patterns to some extent. The construction of wells screened within both the unconfined and semi-confined aquifers, before strict regulation, has reduced the confining abilities of the Corcoran Clay and increased vertical conductivity between the aquifers by providing a high conductivity pathway (Page, 1983; Williamson et al., 1989; Davis et al., 2006; Faunt et al., 2009). Meaning that for modeling purposes an effective (average) vertical conductivity value needs to be constructed to account for increases in vertical flow, as well as decreases in conductivity due to compaction(Faunt et al., 2009).

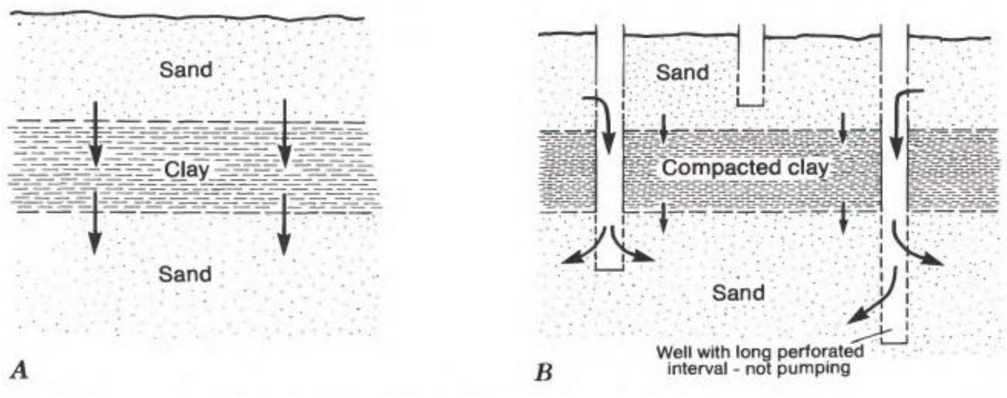


Figure 14: Illustration of the changes in the effective vertical conductivity of the aquifer following the construction of wells screened both above and below the Corcoran Clay confining layer and the compaction of clay layers due to subsidence. Figure from Bertoldi et al., 1991, Figure 17.

Central Valley Project (CVP)

With the development of agriculture in California in the late 1800s, competition for water during the summer months caused farmers to turn to groundwater as a source of water for irrigation. Resulting decreases in groundwater levels led not only to flow and elevation changes as previously discussed, but also to salt intrusion from San Francisco Bay into the San Joaquin-Sacramento River Delta (Bureau of Reclamation, 2013a). In 1924, a combination of drought conditions and the redirecting of groundwater recharge away from the San Joaquin River allowed salt water from the bay to intrude into Suisun Bay. The brackish water ruined fields and agriculture, and allowed the growth of a salinity-loving wood-boring bivalve known as *Teredo navalis.* Within months, the spread of *T. navalis* had destroyed $25 million worth of docks and infrastructure within Antioch and Pittsburg, California (Bertoldi et al., 1987). Another series of droughts and floods wrought havoc in the Central Valley over the next six years drawing attention to the need for a comprehensive statewide water project (Bureau of Reclamation, 2013). Thus the Central Valley Project (CVP) was born.

The CVP serves as a means of flood control for the Central Valley as well as a system of reservoirs and dams to provide water for local agricultural and domestic use (Figure 15). It consists of 500 mi of canals, 20 dams, and 11 power plants, which stretch the full 400 mi of the Central Valley from Redding to Tehachapi, California. Overall, the CVP provides 7 million AF of water per year for industrial, agricultural, and municipal use (Bureau of Reclamation, 2013a).

The project has the unforeseen consequence, however, of diverting and retaining the water that seasonally flooded California's many wetlands. After the construction of Friant Dam and diversion of San Joaquin River flow to irrigable areas in the Tulare and Kern Basins, a drastic decrease in seasonal wetland area within the Central Valley followed.

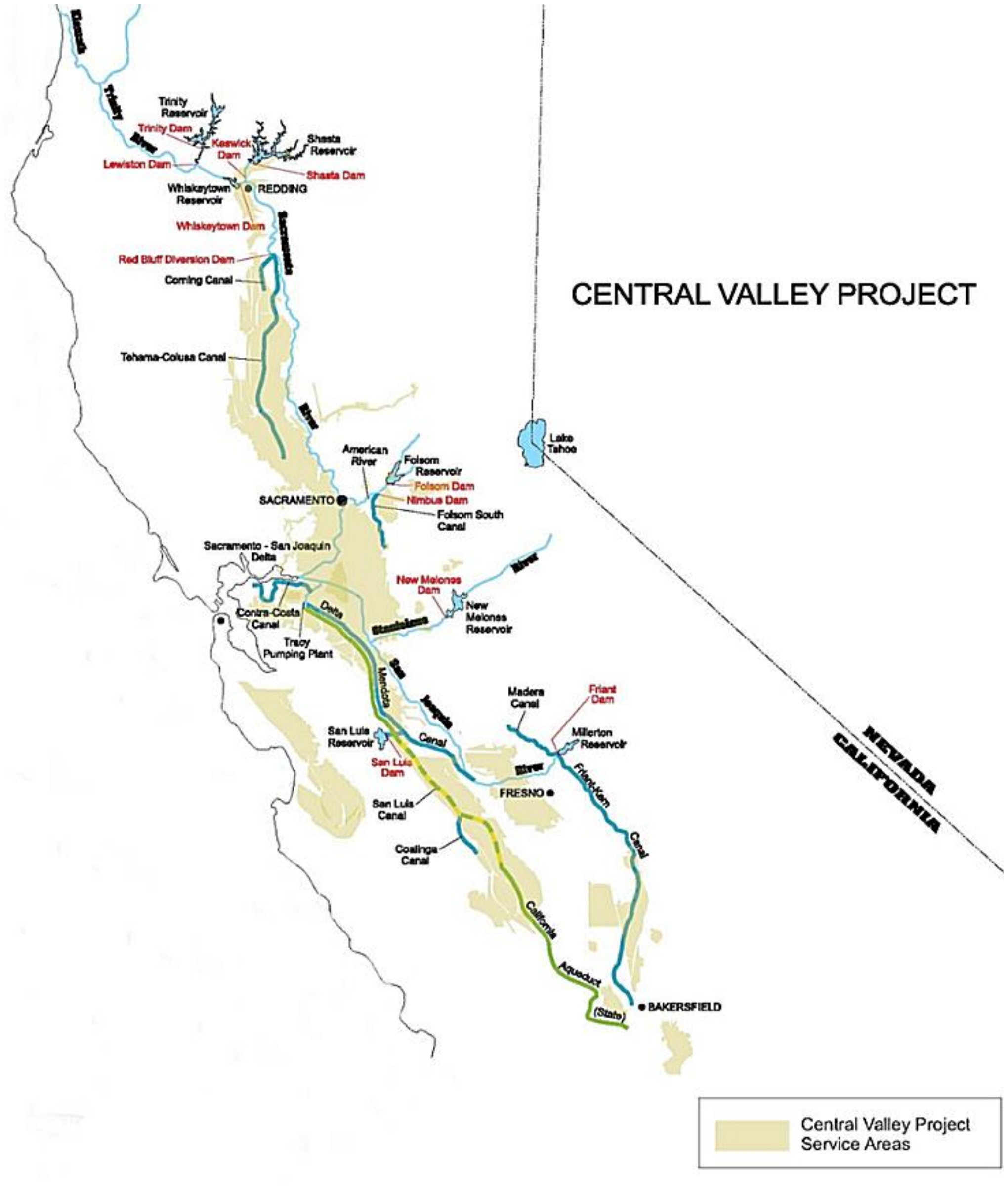


Figure 15: Generalized diagram of all Central Valley Project (CVP) canals and reservoirs as well as benefiting areas served by the CVP. Image from United States Bureau of Reclamation, 2013a.

Central Valley Project Improvement Act (CVPIA)

As a reaction to declining wetland environments, the Central Valley Project Improvement Act (CVPIA) was instituted in 1992 as part of the larger Reclamation Projects Authorization and Adjustment Act signed by President George H. W. Bush. The act makes the restoration and protection of fish and wildlife in the Central Valley a goal of the CVP equal to that of irrigation and domestic use (Central Valley Project Improvement Act, 1994). In total, the CVPIA reallocated 800,000 AF of CVP water to the restoration of valley fisheries and wildlife areas (Bureau of Reclamation, 2013a).

The CVPIA distinguishes between two classifications of water designated for wildlife restoration and improvement. Level 2 water is defined as water historically used in wetland management prior to the implementation of the CVPIA, from 1977 to 1984. Additional supplies deemed necessary for the optimization of habitat and local wildlife, are referred to as Level 4 supplies (Central Valley Project Improvement Act, 1994).

Grassland Water District (GWD)

The Grassland Water District (GWD) is a recognized public entity responsible for the delivery of 180,000 AF of water each year to 51,537 acres of public and private wetlands within its borders (Bureau of Reclamation, 2010) (Figure 16). Private wetlands within its borders include duck hunting clubs such as Ducks Unlimited (Ducks Unlimited, 2016). Public wetlands include state refuges, like Volta Wildlife Refuge (VWR), and several national preserves. Together the boundary of GWD makes up the largest freshwater wetland environment on the Pacific Flyway, a major bird migration pathway along the west coast of North and South America, making the habitat vital to the continued survival of many migratory waterfowl species (Naylor, 1999).

Of its total required delivery amounts, 125,000 AF is designated as Level 2 and 55,000 AF as Level 4. Through surface water supplies alone, the GWD was unable to provide more than 24% of its required CVPIA Level 4 supplies between 2008 and 2009 (Bureau of Reclamation, 2010).

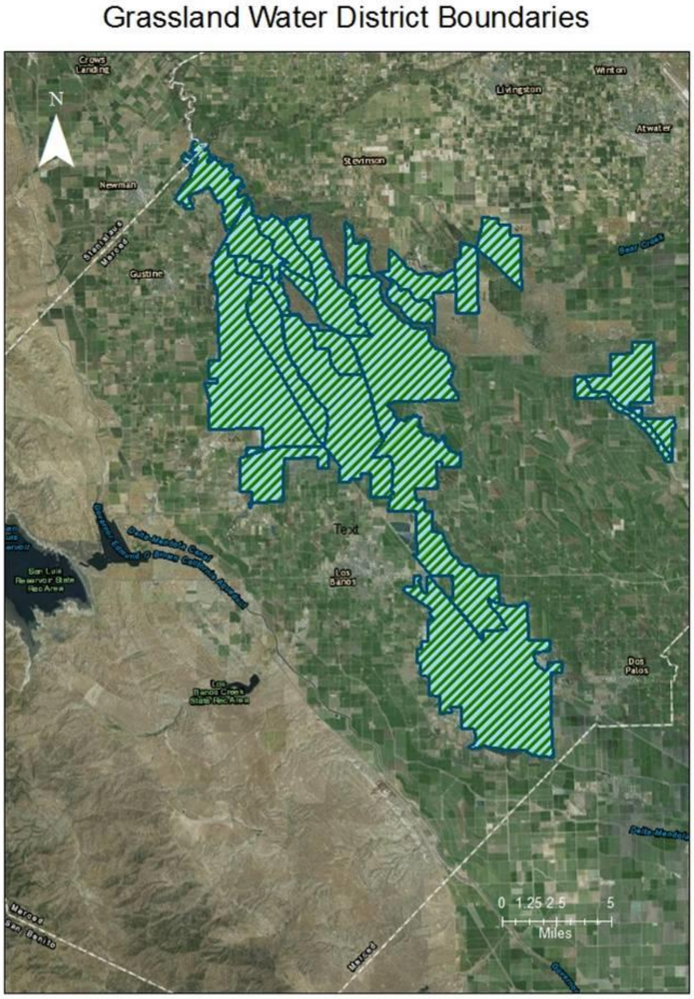


Figure 16: Boundary of Grassland Water District delivery areas. Outline shows a combination of both the northern and southern fields.

Volta Wildlife Area Incremental Level 4 Development Project

In order to obtain the necessary water supplies to fully comply with the CVPIA Level 4 requirements for wildlife area development, the Bureau of Reclamation developed a plan to install two sub-Corcoran pumping wells and five observation wells along the Volta Wasteway in the Volta Wildlife Refuge (Figure 17). Water produced by the pumps was to be used to diversify existing Level 2 supplies in case of drought conditions and attempt to reach full Level 4 supply amounts (Bureau of Reclamation, 2010). The wells were installed at depths of 770 ft and 780 ft below ground surface and 1,500 ft apart on opposite sides of the wasteway (Figure 18). Both were constructed using 18 in diameter steel casings and were screened below the Corcoran Clay (Strandberg and Heppner, 2013).

Figure 17: Locations of the two supplementary groundwater pumps and associated monitoring wells along the Volta Wasteway.

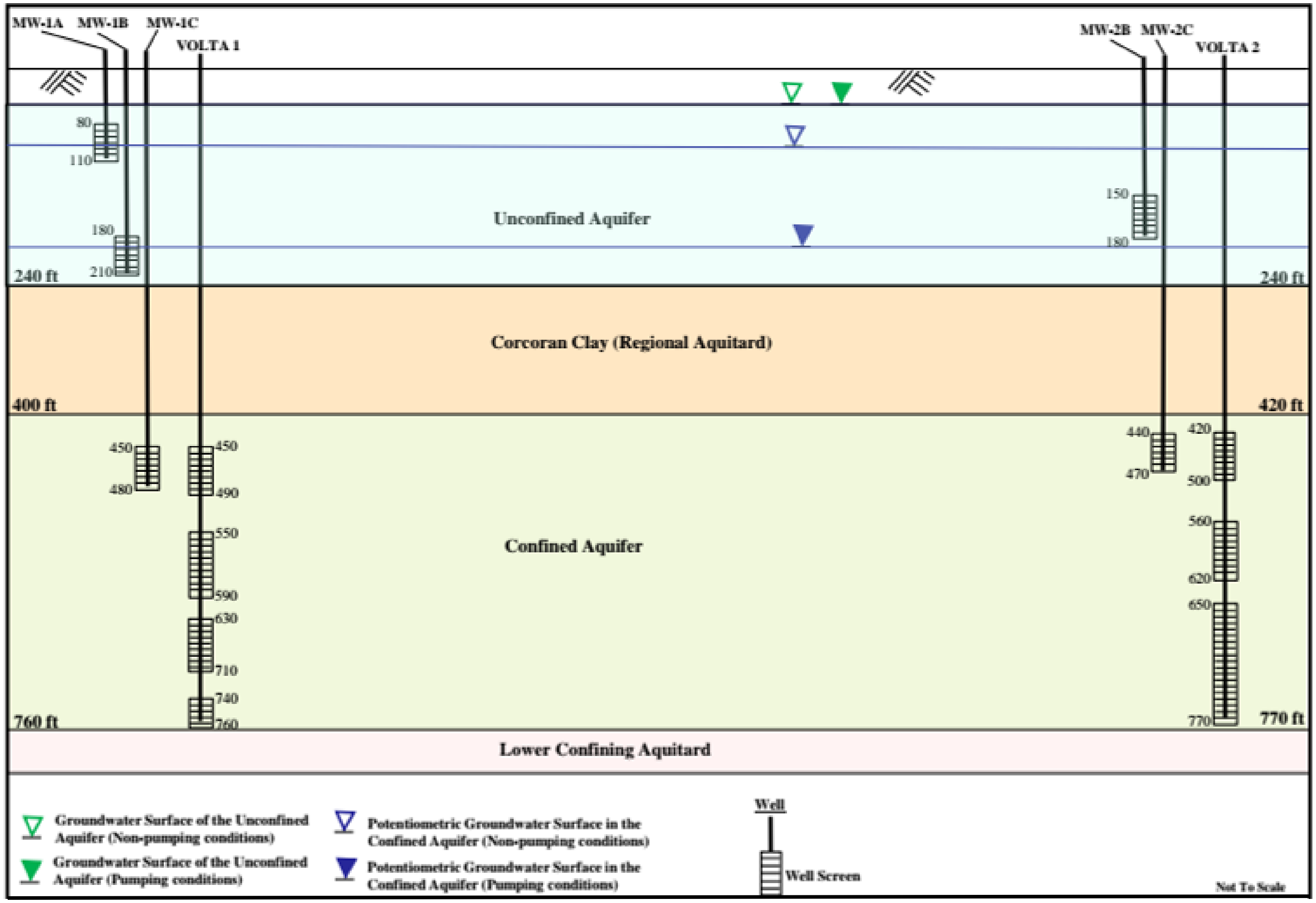


Figure 18: Generalized cross-section of the two groundwater pumps and associated monitoring wells in the Volta Wildlife Refuge showing depth and screened intervals of each well. Image from EKI (personal memo), Figure 5.

A three-year pilot program was initiated in 2010 to examine the feasibility and impact of the program on the wildlife refuge. Over the three years the rate of pumping was to be increased from 2,000 AF the first year to 5,000 AF per year the following two years. The pumps were slated to pump at a maximum pumping rate of 2,500 gpm and 1,500 gpm respectively (Bureau of Reclamation, 2010). In reality, the pumps achieved rates of 2,700 gpm and 1,800 gpm on average according to a study conducted by EKI after the first year of pumping (Strandberg and Heppner, 2013). Though, several mechanical failures prohibited continuous pumping for the first year.

During the duration of the pilot program, four parameters were closely observed; groundwater quality, aquifer hydrogeology, subsidence rates, and biologic activity. Water quality, including electrical conductivity, flow, and various constituents, were monitored to prevent any degradation of surface water. Pumping was only allowed to occur at times when groundwater was of a higher quality than that of surface water entering the refuge through the wasteway so as to provide a dilution to incoming surface water. Well efficiency and the sphere of influence were recorded to learn more about the hydrogeologic conditions present in the semi-confined aquifer. Relatedly, the rate of subsidence within the refuge and surrounding areas was observed to prevent compaction due to over-pumping from the aquifer. Finally, biological signatures in the refuge, such as the population size of the giant garter snake, were taken into account to evaluate the impact of the wells on local wildlife (Bureau of Reclamation, 2010).

Currently, the two Volta pumping wells are providing an additional supply of 5,000 to 6,000 AF/year of water for use in the development of Level 4 supplies in the Wildlife Refuge and the Grass Land Water District (Bureau of Reclamation, 2013b). To evaluate their long-term viability and impact a reliable groundwater model of the region is needed.

Sustainable Groundwater Management Act (SGMA)

California's Department of Water Resources (DWR) established the new Sustainable Groundwater Management Program (SGM) in accordance with the Sustainable Groundwater Management Act (SGMA) of 2014. SGMA details the new regulations concerning the development of groundwater basin boundaries and the creation of sustainability programs for these basins in California.

Under the new regulations, local agencies and stakeholders have the ability to establish groundwater sustainability agencies that are able to adapt sustainability plans that are specific to their own water needs. The act is the first of its kind in California and allows local agencies to continue to use groundwater supplies in the ways that most benefit them, while establishing management standards to increase resiliency against drought and climate change (Sustainable Groundwater Management Act, 2014). SGMA allow agencies such as the Grassland Water District to determine their own needs and develop strategies to best maintain their groundwater sources. However, this new ability to dictate sustainable practices also requires a more thorough understanding of present hydrogeologic conditions and impacts of groundwater pumping on aquifer integrity.

To create a groundwater basin, agencies must generate a report of historical, present, and future flow projections for the basin, including both surface and groundwater resources. They must use this data to create a sustainability plan that will be implemented and evaluated consistently over the next 20 years. Any groundwater models used in the development of the plan must meet the guidelines established under SGMA, including the use of 50 years of historical data as a baseline for future predictions of flow (Sustainable Groundwater Management Act, 2014).

Materials and Methods

A number of different databases and software programs were utilized in the creation of the groundwater model. Below is a list of the different programs and data sources used.

FEFLOW – A preliminary groundwater simulation model of Volta Wildlife Refuge was created in FEFLOW, a finite element flow and transport model building application (MIKE Software, 2014a; MIKE Software, 2014b; DHI-WASY Software 2016). FEFLOW provides the means to simulate groundwater flow, as well as heat and mass transport, in both saturated and unsaturated conditions. It was developed by Dr. Hans-Jorg G. Diersch in 1990 for WASY, the German Institute for Water Resources Planning and Systems Research, but was purchased in 2007 by the Danish Hydrological Institute (DHI). DHI is a not-for-profit international organization, which specializes in hydrological modeling software and engineering solutions. A student license to use the program was obtained in collaboration with DHI.

GIS Coverages and Shapefiles – Supermesh features for the FEFLOW model of the Volta Wildlife Refuge were imported using existing GIS coverages of the Grassland Water District and Volta Wildlife Refuge. These coverages were created by a combination of HEADS (HydroEcological Advanced Decision Support) interns from Lawrence Berkeley National Lab, California Fish and Wildlife Service, and the Grassland Water District.

WGEO – Maps and coverages used in the model were geo-referenced using the supplementary geo-referencing software supported in FEFLOW. WGEO allows for the geo-referencing of layers and maps using known coordinates or comparison with a referenced basemap (DHI-WASY Software, 2016; WASY Software, 2005).

ArcMap – Existing GIS coverages were edited to fit modeled area and known point data was added to create a comprehensive representation of relevant features (ESRI, 2016).

Central Valley Hydrological Model – Model input parameters and initial assumptions were based upon those used in the Central Valley Hydrological Model (CVHM) developed by the U.S. Geological Survey (USGS) (Faunt et al., 2016). The CVHM is a comprehensive USGS MODFLOW model for the entire central valley; a total of 20,000 mi^2. It simulates not only groundwater and surface water processes but also irrigation systems and land subsidence rates by implementing several additional packages compatible with MODFLOW such as the Farm Process (FMP) (USGS, 2015; USGS, 2016). The CVHM is divided up into a square mile mesh that is accurate enough to be used for water district management but at a scale that is useful for obtaining a valley wide perspective of the regional flow system. Data for the model was collected from a variety of sources including federal, state, and local scale studies. The combination of this rich collection of data makes the CVHM one of the most detailed models of the Central Valley to date.

Hydrogeologic parameters for the CVHM were extracted using a texture model describing the relevant soil properties. These properties were collected from 8,500 drill logs from throughout the entire valley and analyzed for percent coarseness and relative sorting at 15 meter intervals. Using the percentage of coarse material from the drill logs, a geostatistical model was applied to relate them to usable hydrologic characteristics representing heterogeneity within the valley. Soil properties within the valley were also used to divide the model into 17 zones of similar properties and into 13 vertical layers (Faunt et al., 2010).

Mesh Generation and Model Set Up

A supermesh is a preliminary map of all applicable boundaries and features used to create the model mesh. Coverages of the Grassland Water District drainage boundaries and conveyances, obtained from the GWD and previous HEADS interns, were used to create the supermesh. The coverages were geo-referenced with UTM coordinates extracted from GIS data using the supplementary geo-referencing software WGEO. Once the coverages were referenced, they were imported into FEFLOW and converted into supermesh features. A GIS shapefile of pumping and observation well locations was created in ArcMap from GPS coordinates and imported in the same manner.

An additional buffer was added around the fields to reduce error at the points of interest. The eastern side of this buffer follows the Delta-Mendota Canal as a constant head boundary. In its entirety the model covers 411,325 acres, 4,000 of those containing the Volta Wildlife Refuge and 75,000 the GWD fields. The model was made intentionally large to include the entirety of the GWD for future studies and comparisons. However, the portion of interest for this study included only the Volta Wildlife Refuge and surrounding buffer zones; 51,000 acres in size (Figure 19).

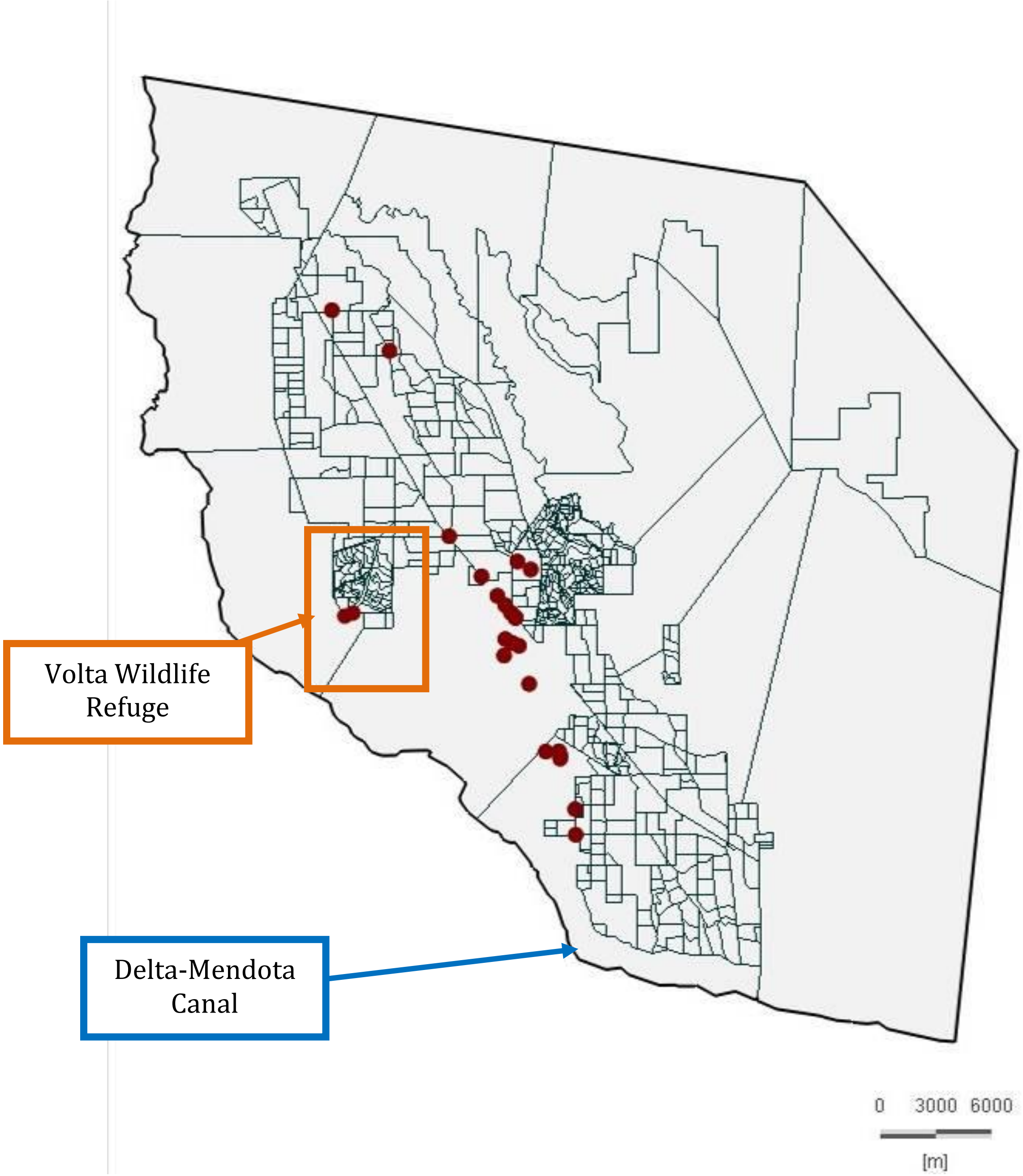


Figure 19: Supermesh design for the model including Volta wildlife Refuge and Grassland Water District fields and conveyances (black) and supplementary pumping well locations (red). Location of interest is outlined (orange). The western boundary follows the Delta-Mendota canal as a constant head boundary (blue).

One of the benefits of FEFLOW is that it allows the refinement of a mesh around selected supermesh features, increasing the precision of calculations in these locations. Supermesh features may also be used later on as boundary conditions, zones of heterogeneity, or as sources and sinks. Thus, it was important to include all relevant features and points of interest in the supermesh before mesh generation, whether or not they were to be refined in the final mesh.

The resultant supermesh includes an outer boundary, boundaries for flood-up and drainage fields within GWD and Volta Wildlife Refuge, local conveyances and canals, pumping well locations, and observation points. For the final mesh only the pumping well locations and the boundaries of flood-up and drainage fields were used in refinement of the mesh. Other features were included for later use in assigning parameter conditions and observing model results.

Around the pumping wells the mesh was refined the most, to 0.2 meters with a gradation of eight (Figure 20). The mesh around flood-up and drainage fields was refined to 1000 meters and canals were refined to 100 meters, both with a gradation of two (Figure 21). Mesh development was conducted using the triangle method in FEFLOW because it allowed the most flexibility for refinement and extrapolating into 3D (Figure 22). Statistics, including the condition number and maximum interior angle of the triangles, were gathered for the resulting mesh to ensure its efficiency.

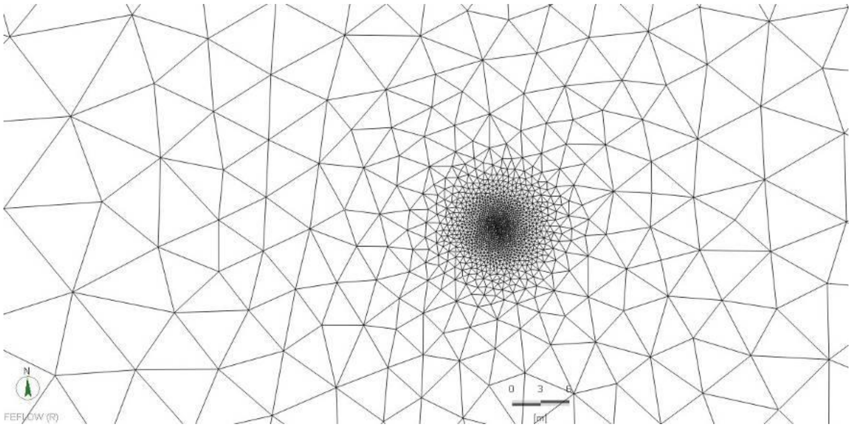


Figure 20: Close-up view of mesh refinement around pumping wells illustrating the enhanced resolution of model results at these locations due to the increase in the concentration of nodes.

Mesh Generation			
Meshing Style		Triangle	
Polygon Gradation	2	Polygon Target Size (m)	1000
Line Gradation	2	Line Target Size (m)	100
Point Gradation	8	Point Target Size (m)	0.2

Figure 21: Table of mesh generation parameters used. Points were refined the most, while polygons were refined the least.

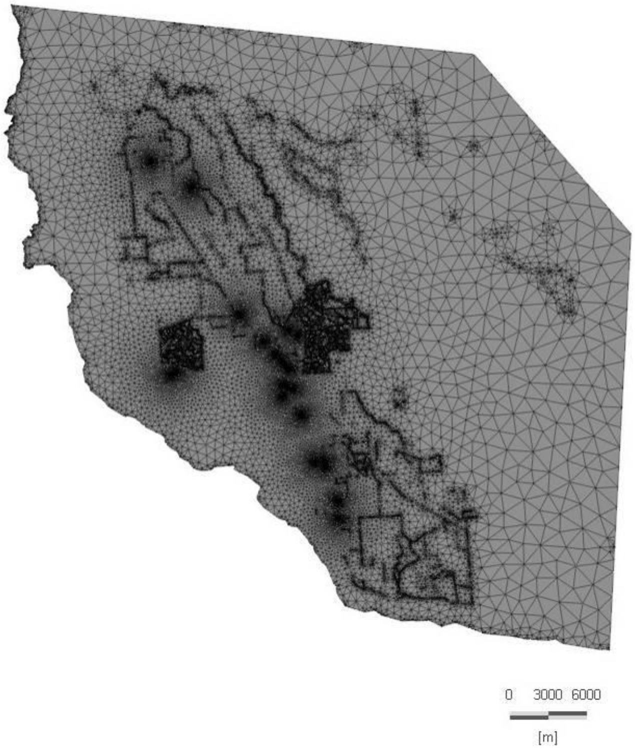


Figure 22: Overview of finished mesh.

When finished, the 2D mesh was extended into 10 vertical layers that were assigned elevations from the USGS Central Valley Hydrologic Model (CVHM) database available online (Figure 23). The CVHM data is based on a mile mesh with central nodes, which covers the entirety of the central valley. An Akima linear interpolation was used to smooth the data over the model and increase the resolution.

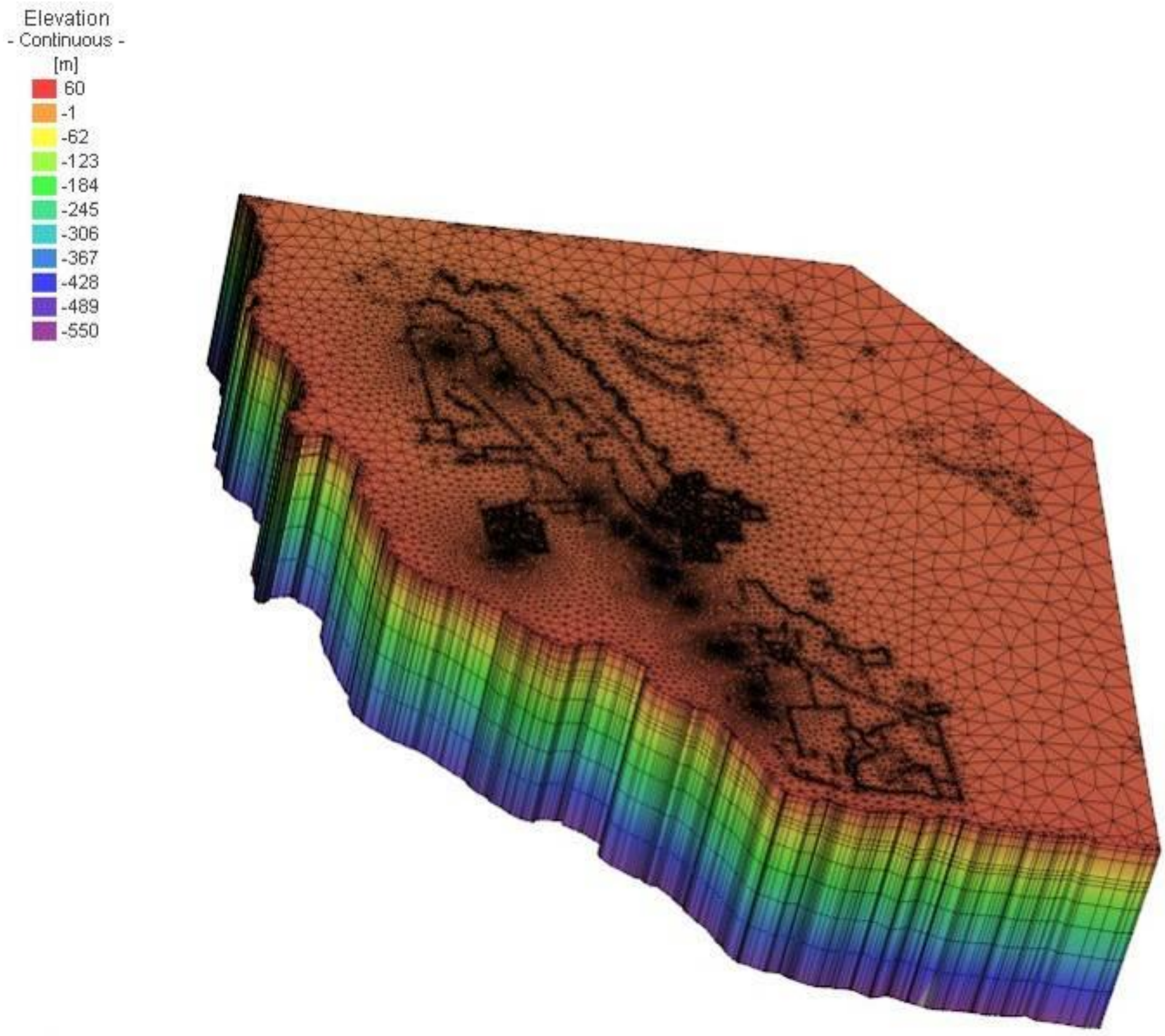


Figure 23: Snapshot of expansion of 2D mesh to 3D and elevation assignment.

Though Page et al. (1983) and Williamson et al. (1989) have shown that the aquifer is in actuality a single heterogeneous aquifer of varying confinement, to reduce computational effort the aquifer was divided into unconfined and semi-confined zones. This is a sufficient simplification when one takes into account the scale of the model and average conductivities within the aquifer. Therefore, layers 1 through 3 represent the upper unconfined aquifer, while layers 4 and 5 represent the semi-confining Cocoran Clay and layers 6 through 10 the semi-confined aquifer (Figure 24). This division is the same as in the CVHM, excluding the extraneous layers used in the CVHM that are necessary for MODFLOW to simulate the confining layer (Faunt et al., 2010).

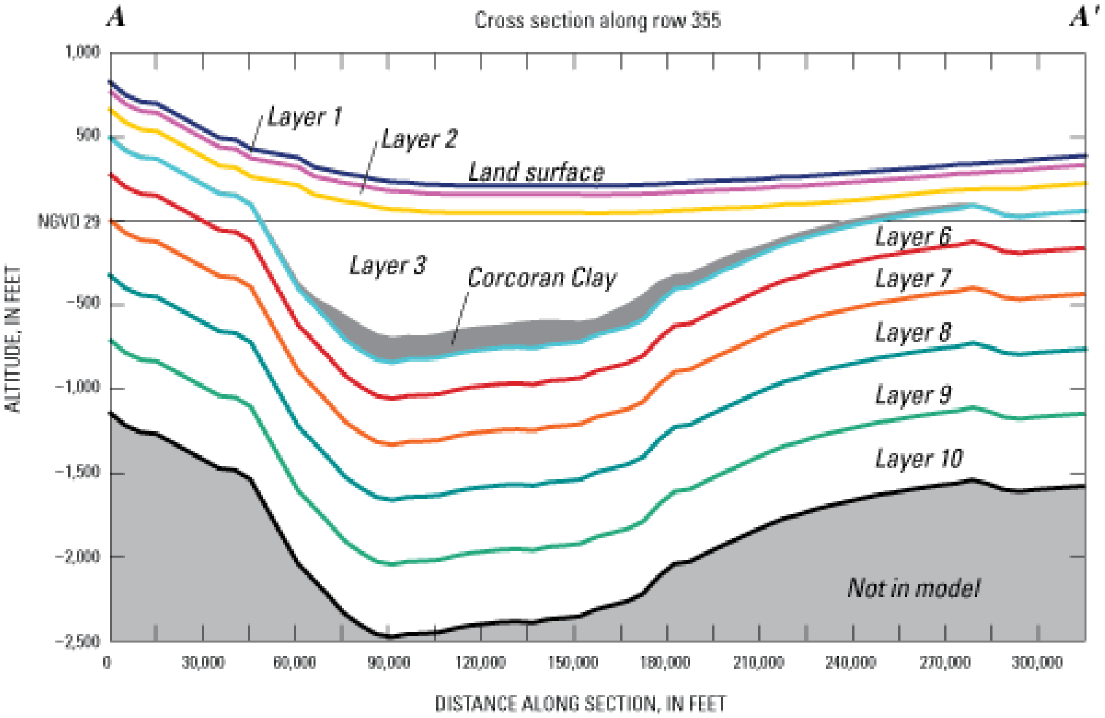


Figure 24: General cross-section of model layers and corresponding depths. Layers 1 through 3 represent the upper unconfined aquifer, while layers 4 and 5 represent the semi-confining Cocoran Clay and layers 6 through 10 the semi-confined aquifer. Image from Faunt, et al., 2009, A11.

Material properties associated with these layers were also assigned using values based off those used in the CVHM. These properties included horizontal conductivity (Kx), vertical conductivity (Kz), specific yield (Sy), and specific storage (Ss). All of these properties varied by layer, as well as by node, so as to most accurately represent the inherent heterogeneities. An Akima interpolation was used to assign data in the same manner as elevation values.

Initial Conditions Setup

Initial equilibrium conditions were established by conducting a 50-year historical flow simulation upon the model, according to SGMA guidelines (Sustainable Groundwater Management Act, 2014). To do this, boundary conditions and forcing mechanisms had to be assigned for the model.

For the layers above the confined aquifer (layers 1 through 3) each side was assigned a fluid transfer boundary to simulate a Darcy flux across the boundary. This boundary condition is based off the equations for 3rd kind/Cauchy boundary conditions, where inflow/outflow is related to a reference hydraulic head (DHI-WASY Software, 2016). The equation for this is:

$$Q = A*\Phi*(h_{ref}-h)$$

Where Q is equal to the rate inflow or outflow to or from the model, A is the selected surface area, Φ is a rate of fluid transfer, h_{ref} is a specified reference water level, and h is the current hydraulic head in groundwater. For our uses, Φ was set equal to conductivity to convert the equation into one of Darcy flux in and out of the model. The h_{ref} was set to that of ground surface elevation along the western border, coinciding with the Delta-Mendota canal, and half the ground surface elevation along the remaining borders based on average head values for these areas.

Final assignments included a method of forcing for the model. The uppermost slice of the model was converted into a source of precipitation using 50 years of evapotranspiration and rainfall data for Merced County, obtained through the USGS PRISM database (Northwest Alliance of Science and Engineering, 2016). This initial simulation was used as the basis for all future simulations and was compared to initial conditions established by the CVHM and observed hydraulic heads prior to the initiation of groundwater pumping.

Pumping Test

Once the 50-year set-up simulation was run and assessed for feasibility, the resulting conditions were used as equilibrium conditions for three constant pump test simulations. The goal of these tests was to verify the accuracy of calculated drawdown in relation to observed well test results prior to future attempts at simulation.

To begin, multi-layer wells were inserted into the model at two point locations included in the supermesh. The simulated wells had diameters of 18 inches and screened intervals of 450-770 ft below ground surface and 420-780 ft below ground surface, just like their real life counterparts (Bureau of Reclamation, 2010). However, unlike the existing pumps, the simulated water is not directed into the refuge conveyance network upon being brought to the surface. Instead, after being extracted from the semi-confined aquifer (layers 6 and 7) the pumped water simply spills out onto the top of the model and is treated the same as other surface water applications, such as precipitation. It is important to note that this does not accurately represent actual surface water use or conditions, but is simpler computationally and does not directly affect the results of the investigation.

To observe the results of the pump tests, multiple observation points were inserted at even intervals around the wells. A total radius of 500 m around the wells was included for each layer, with a greater number of points between the wells and within the first 50 m to increase resolution of results.

Time series data detailing the pump tests were compiled from actual pump tests completed by EKI consultants and assigned to the two Volta Wildlife Refuge multi-layer wells. For the first test, VWR well 2 was offline and well 1 was pumping at 15,879 m^3/d (2,913 gpm). During the second test well 1 was offline and well 2 was operating at 10,548 m^3/d (1,935 gpm). Both tests lasted thirty-eight days total (Strandberg and Heppner, 2013). Following the simulated tests, simulated drawdown values were compared with observed values for accuracy in model representation.

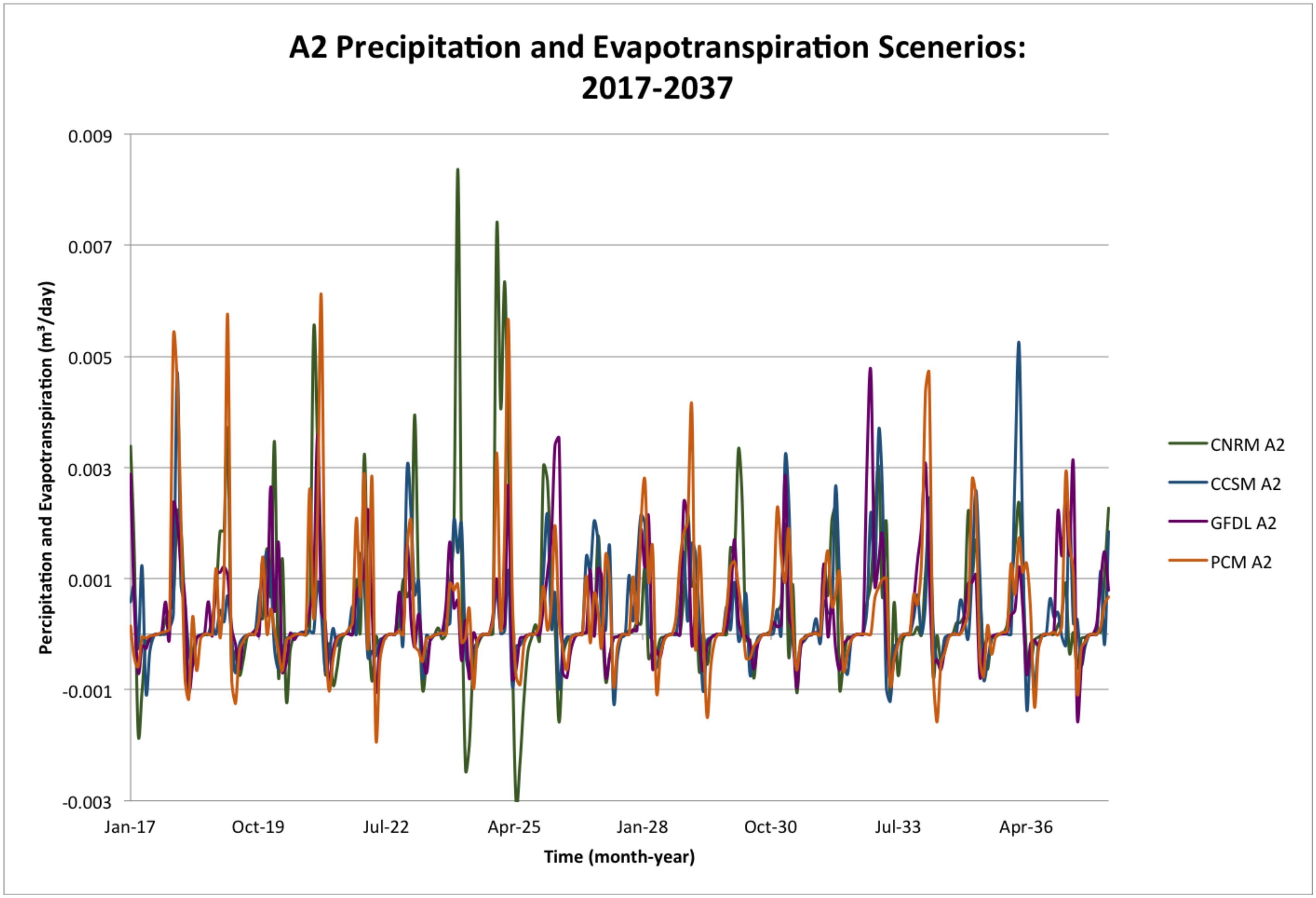
Test number three did not have a correlating observed pump test, but was conducted to visually observe the shape of the overlapping cones of depression produced with both wells pumping together. This test occurred over two days or 2,900 minutes total.

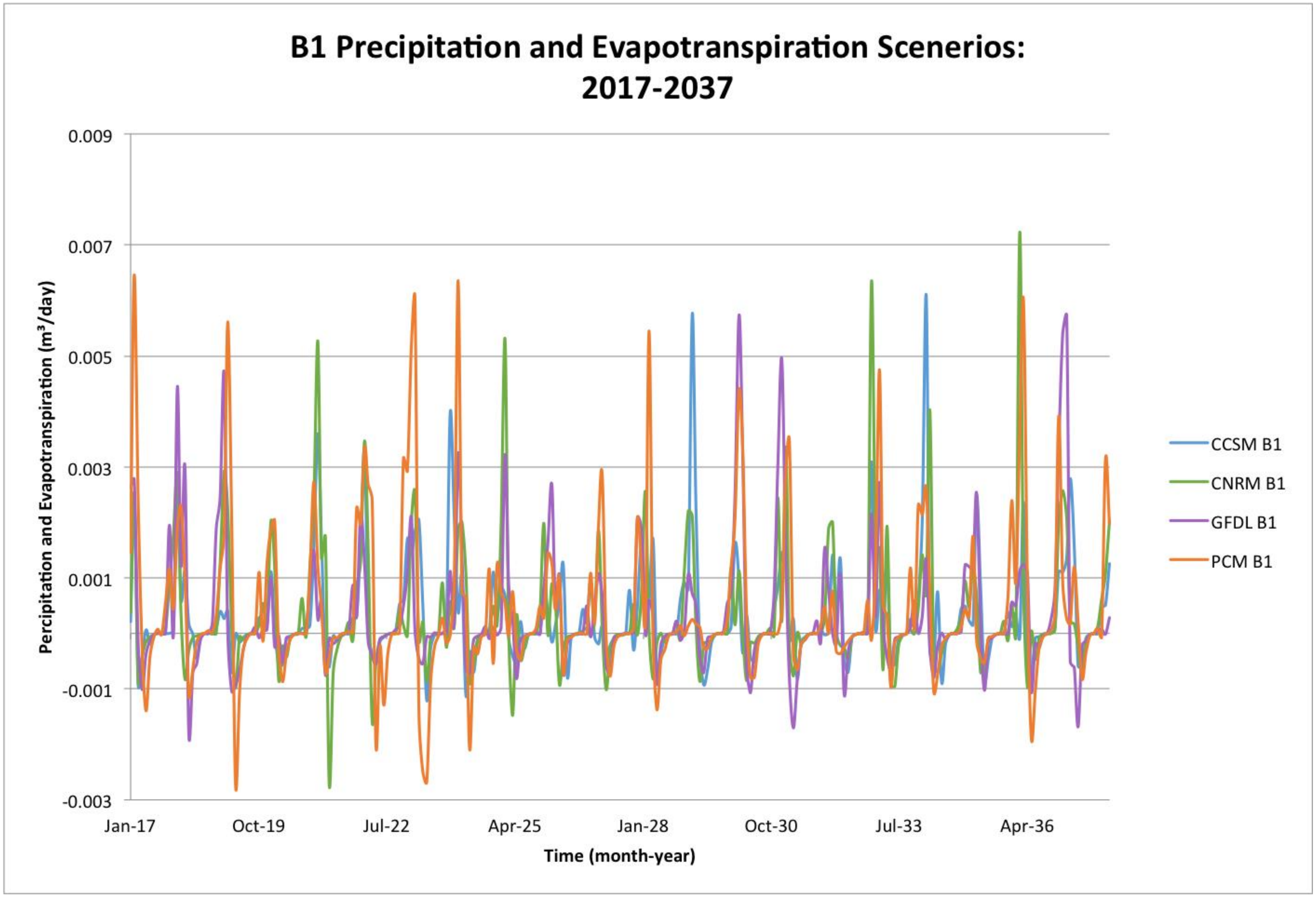
Climate Change Simulations

After the validity of model simulation was confirmed, eight 20 year projected simulations were run to evaluate the sustainability of pumping within the refuge under the continuation of current management practices. The simulations were based off the high (A2) and low (B1) carbon emission scenarios modeled by four different general circulation models: the Parallel Climate Model (PCM), the Community Climate System Model (CCSM3), the Geophysical Fluid Dynamics Laboratory (GFDL), and the National de Recherches Meteorolgiques (CNRM) obtained for the area through California's Cal Adapt database (California Energy Commission, 2016) (Figure 25 and 26) (See Appendix A).

Figure 25: Graph of the four A2 precipitation and evapotranspiration scenarios, CNRM, CCSM, GFDL, and PCM that were used as forcing in the model.

Figure 26: Graph of the four B1 precipitation and evapotranspiration scenarios, CNRM, CCSM, GFDL, and PCM that were used as forcing in the model.


A2 Precipitation and Evapotranspiration Scenerios: 2017-2037
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Percipitation and Evapotranspiration (m³/day)
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CNRM A2
CCSM A2
GFDL A2
PCM A2


B1 Precipitation and Evapotranspiration Scenerios:
2017-2037
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Percipitation and Evapotranspiration (m³/day)
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CCSM B1
CNRM B1
GFDL B1
PCM B1

High emissions scenarios (A2) were calculated based on continuous population growth with little development of lower carbon emissions technologies. Under these scenarios the amount of CO_2 in the atmosphere triples from pre-development levels by the year 2100. Low emissions scenarios (B1), on the other hand, predict a mid-century peak in population and emissions due to the implementation of alternative energy technologies resulting in only double the amount of CO_2 in the atmosphere by 2100. Thus, A2 and B1 emission scenarios represent upper and lower estimates of future climate conditions (California Energy Commission, 2016).

A time period of 20 years was chosen for the simulations, in agreement with the minimum time period for evaluation of a groundwater sustainability plan detailed in SGMA (Sustainable Groundwater Management Act, 2014). The eight different climate model precipitation and evapotranspiration predictions were converted into time series tables and assigned to the surface of the model as the inflow/outflow forcing mechanism. Pumping rates for the two Volta Wildlife Refuge wells were held constant at the current real life pumping rates of 13,608 m^3/day (2,500 gpm) and 9,798 m^3/day (1,800 gpm) respectively to replicate the continuation of current management practices (Strandberg and Heppner, 2013). Changes in hydraulic head of the confined aquifer were recorded for the duration of the simulation to evaluate the effect of pumping on long-term aquifer stability.

Results and Discussion

Initial Conditions Setup

Following the initial 50 year historical simulation, the model achieved initial conditions comparable to those use in the CVHM. Most notably, calculated equilibrium hydraulic head values were well within the range of those utilized by the CVHM. The CVHM is one of the most accurate representations of Central Valley aquifer conditions to date, combining data from a wide variety of sources. The initial conditions used in the CVHM were generated using parameter optimization techniques (PEST) and are the best reference for saturation within the Central Valley. Agreement between CVHM initial head values and those produced during the preliminary run supports the assumption that the model has achieved equilibrium and represents realistic conditions.

Within the confined aquifer, total saturation was achieved with pressure heads of averaging around 24.9 m above sea-level, about half a meter less than those modeled in the CVHM. However, this is still well within acceptable results.

In the unconfined zone the calculations resulted in more variability, with complete saturation of layer 3 and variable saturation across layers 1 and 2. Hydraulic head values averaged to 26.2 m above sea-level but exhibited a much larger standard deviation between results than in the confined aquifer, reaching 4 m of deviation in layers 3 and 4 (Figure 27). This is to be expected in an unconfined aquifer of varying conductivity.

Layer	CVHM Model Initial Head (m)	Standard Deviation	FEFLOW Model Initial Head (m)	Standard Deviation
1	27.2633	2.248	26.2387	2.785
2	27.2633	2.248	26.1908	3.644
3	27.2633	2.248	26.1885	4.394
4	27.2633	2.248	26.1749	4.089
5	27.2633	2.248	25.8556	3.658
6	25.3879	5.010	25.1758	3.054
7	25.3879	5.010	25.1320	2.868
8	25.3879	5.010	24.9588	2.828
9	25.3879	5.010	24.9352	2.805
10	25.3879	5.010	24.9057	2.786

Figure 27: Chart of average CVHM initial hydraulic head conditions and modeled head conditions within the extent of Volta Wildlife Refuge with standard deviation among values. All modeled results are comparable to those used in the CVHM and fit expected saturation conditions within the refuge. Thus, it can be assumed that the model has reached sufficient equilibrium conditions to conduct a transient simulation.

The model accurately represented this heterogeneity, even predicting surface water at un-modeled streams and rivers such as Mosquito Ditch and the San Joaquin River basin. It's also for this reason that the average of about 26.2 m above sea-level for the unconfined aquifer is almost a meter less than the 27.26 m above sea-level found by the parameter estimation techniques for the CVHM model (United States Geological Survey, 2015). Overall, the baseline model results are within range of the ideal conditions predicted by the CVHM but seem to represent the existing aquifer heterogeneities to a greater extent due to its smaller scale.

As a secondary check of representative baseline conditions, the calculated head values were also compared to observed head levels in nearby observation wells. These were also comparable to each other in magnitude with the average observed head value, 28 m, higher than those modeled, but still confirming that reasonable baseline conditions had been set.

Pumping Test

The pump-tests used to evaluate the accuracy of pumping well simulation resulted in varied ranges of drawdown depending upon the point of observation, as expected. Within the unconfined aquifer no decreases in hydraulic head were observed, showing that the simulated confining layer was acting as barrier to vertical flow and maintaining a pressure differential. As a result all drawdown was constrained to the confined aquifer (Figure 28). Greater drawdown occurred in close proximity to the pumping wells, decreasing exponentially farther from the wells. When contoured the hydraulic head values around the pumping wells demonstrated two cones of depression that overlapped in the center during the third pump test, as described by field tests (Figure 29, 30, 31).

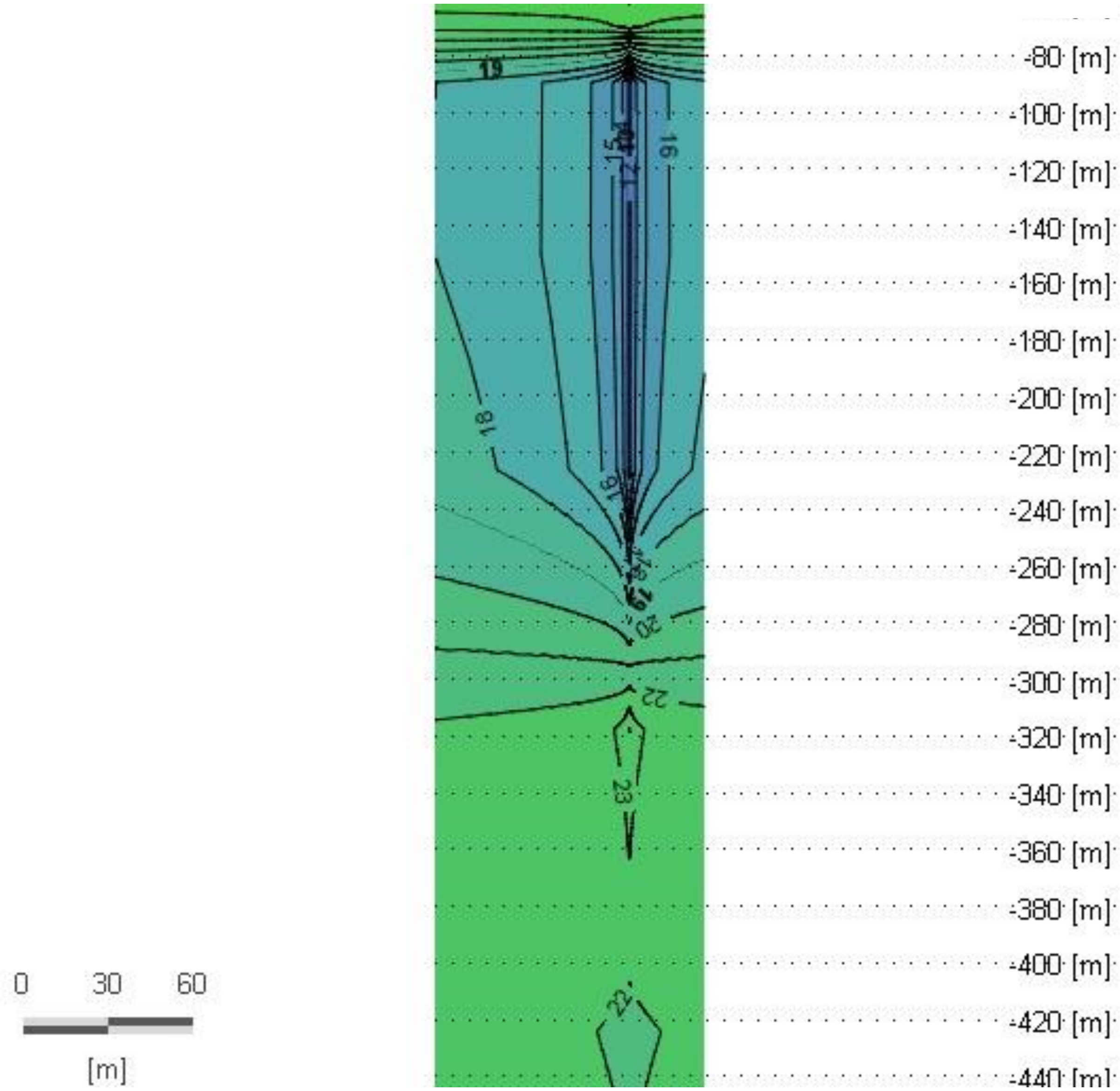


Figure 28: Cross-sectional view of Volta Wildlife Refuge Well 1 while in operation illustrating the resulting cone of depression. Hydraulic head values are centered along the length of the pumping well, where pressure differentials are the greatest, and increase with distance from the well. No drawdown is shown in the upper 4 layers representing the unconfined aquifer confirming that the simulated Corcoran clay layers is acting as a barrier to flow.

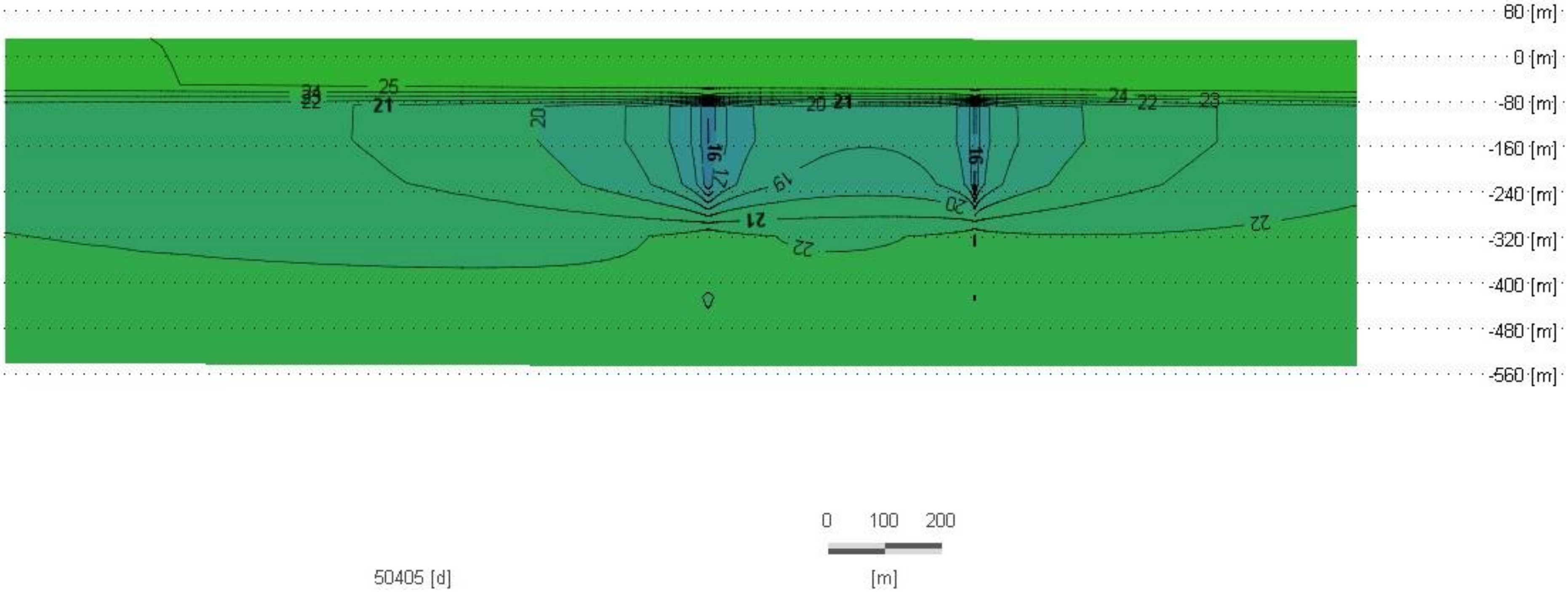


Figure 29: Contoured cross-section through both Volta Wildlife Refuge wells, while both are in operation. Drawdown is isolated to the lower confined aquifer layers and shows a decreasing trend with distance from the wells. Between the two wells, the contoured gradient illustrates the interference of the two cones of depression

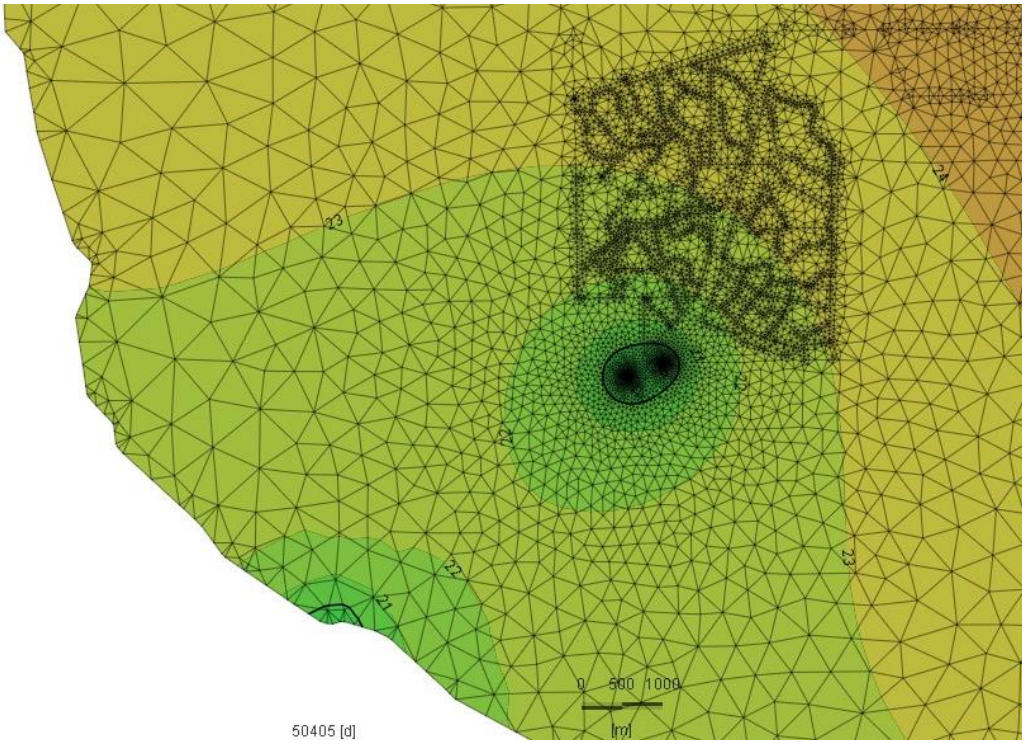


Figure 30: Aerial view of the two Volta Wildlife Refuge wells, while both are in operation. Notice the elongated combined cone of depression and the area of depressed hydraulic head to the SW of the two wells. This is caused by the generally SW directed groundwater flow at this location being caught by the wells and pumped up to the surface creating a shadow of decreased head values.

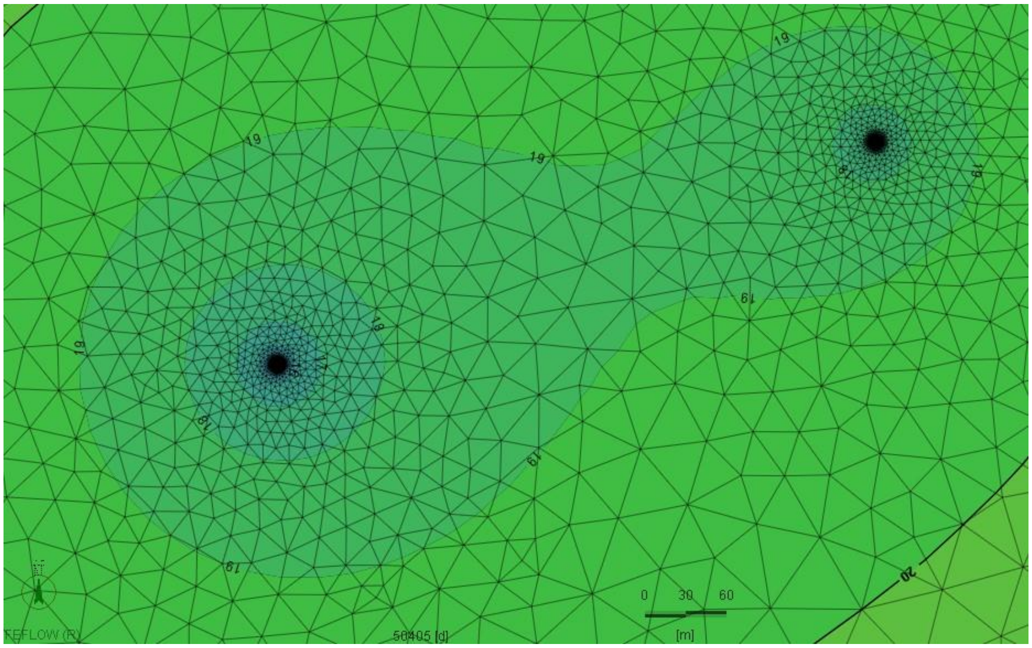


Figure 31: A close up aerial view of the two wells in operation showing the shape of the overlapping cones of depression. The left well (well 1) is rated at a higher pumping capacity and so creates a larger cone of depression.

The largest simulated drawdown values, 26.8 m and 26.2 m respectively, occurred at the center of the pumping wells. These both fall short of the target range of observed values of 33.8 m to 36.6 m (Strandberg and Heppner, 2013). However, during the simulated tests hydraulic head values showed a continuing downward trend through the end of the simulation instead of reaching a new equilibrium as expected. When the pumping tests were extended an extra 10 days the model eventually flat lined and reached a new equilibrium at 33.9 and 33.7 m of drawdown, at the low end of the range of observed drawdown values.

This indicates there is a short lag in the simulated system response not represented in real life. This implies that the model is not able to accurately represent short-term changes in aquifer response. However, this is not much of a concern because the length of future climate simulations is great enough to make this lag negligible.

Climate Change Simulations

After the model was verified, realistic simulations of transient conditions could be run to predict future conditions. The eight climate change simulations of the A2 and B1 projections for the PCM, CCSM3, GFDL, and CNRM global circulation models produced almost identical results, only varying at the small scale due to differences in predicted drought and flood years. The PCM B1 scenario, being the wettest overall projection (Figure 32), found a range of head values in the confined aquifer from 6.24 to 9.05 m. CCSM A2 was the driest overall simulation and found ranges in head from 6.38 to 8.73 m.

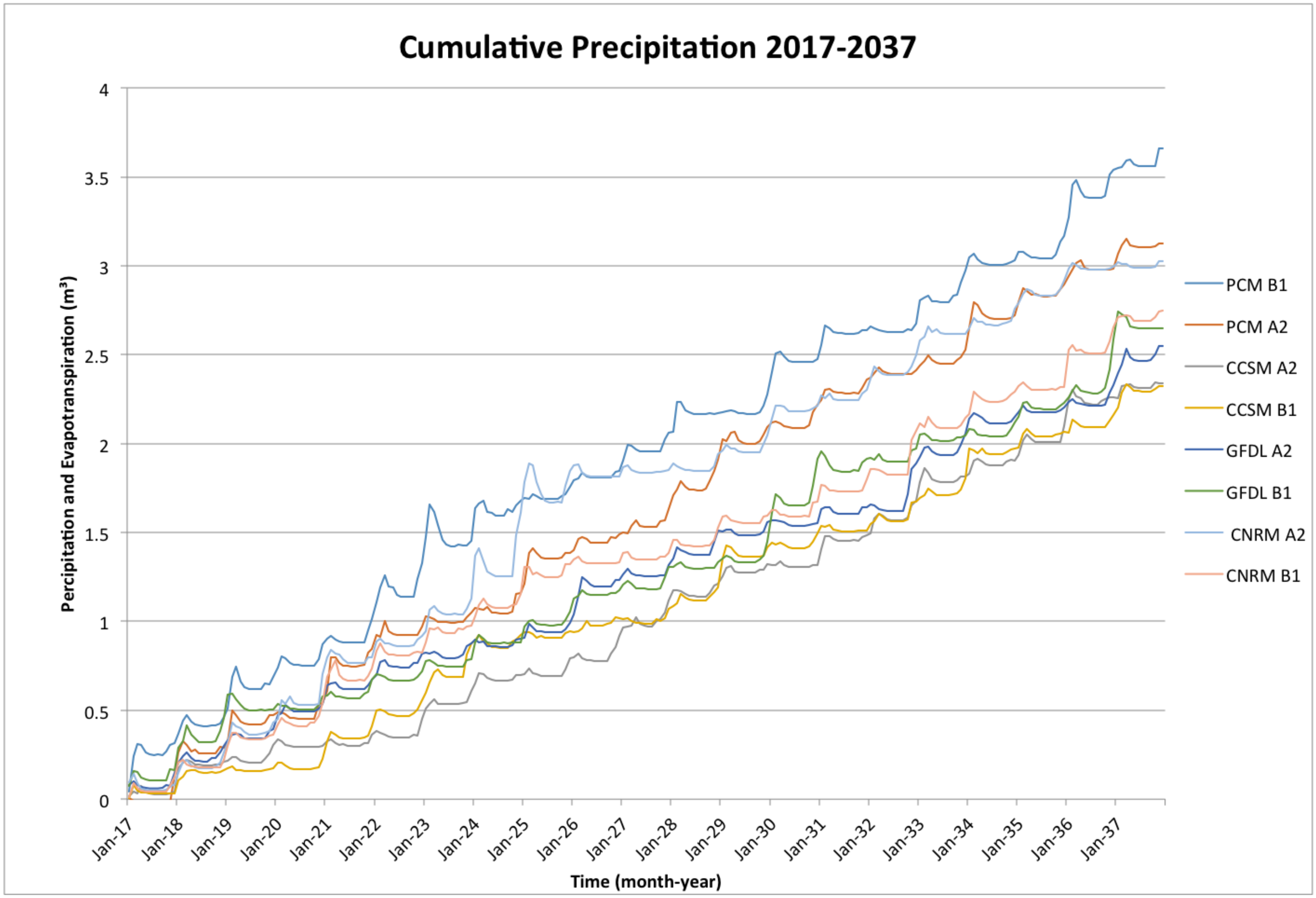


Figure 32: Graph of the cumulative precipitation amounts for each model, PCM, CCSM, GFDL, and CNRM and each emission scenario, A2 and B1. CCSM A2 was the driest overall simulation closely followed by CCSM B1. PCM B1 was the wettest simulation predicted out of the eight.

However, as for long-term changes in the groundwater system due to continued pumping of the Volta Wildlife Refuge wells, the model predicted consistent drawdown levels around 17.9 – 18.6 m over the entire 20-year period for all eight climate projections (Appendix B). Showing that the well drawdown had reached a balance with the surrounding aquifer conditions and was not influenced to a large degree by external changes in climate.

If the drawdown was influenced by changes in climate, one would observe a period of long-term decreasing in hydraulic head towards a new equilibrium level, even with consistent pumping rates. This would indicate that current-pumping rates could become unsustainable in the near future depending upon the new equilibrium head level reached and would need to be reevaluated. The consistent drawdown produced by the 20-year simulation instead indicates that at current pumping rates the VWR wells do not pose a large threat to aquifer conditions or land stability with changes in climate, at least for the next twenty years. Additionally, because the Volta Wildlife Refuge supplementary wells are currently pumping at their maximum rated capacity they are already producing the maximum amount of supplementary water possible. Thus, they are already working at maximum efficiency to meet level 4 Central Valley Project Improvement Act (CVPIA) requirements.

Remaining concerns over long term pumping sustainability, however, relate to variables not considered in the scope of this project due to constraints in data availability and presently unpredictable changes in the groundwater system. For example, numerous privately owned large capacity industrial and agricultural sub-Corcoran wells play a much larger role in the local and regional groundwater system. Do to the lack of publically available information on these wells it was not feasible to include them in the model simulations. Though it is known that they pump at a much greater capacity than either of the Volta Wildlife Refuge wells and that their cones of depression can be observed in some monitoring wells within the refuge. Future changes in the rate of groundwater extraction of these nearby wells, will play an important role in the long-term sustainability of the underlying VWR aquifer system.

In addition, the already increasing scarcity of surface water deliveries has led Grassland Water District to look into the construction or leasing of additional sub-Corcoran pumping wells to further supplement their supplies. If this trend continues, depending upon the number of additional wells and their pumping capacity, the current management practices for Volta Wildlife Refuge may become unsustainable in a similar way to an increase in industrial and agricultural wells.

Conclusions and Future Work

In order to develop management plans for Central Valley groundwater basins, it is necessary to have an understanding of existing aquifer conditions and responses. The development of an accurate groundwater model of Volta Wildlife Refuge and the Grassland Water District will aid in this understanding, as well as the drafting of groundwater management plans that are able to balance the conservation of seasonal wetlands with sustainable groundwater pumping practices. Therefore, the purpose of this project was to create an accurate groundwater model of VWR, which could simulate the drawdown of two existing deep groundwater wells, in order to evaluate their long-term sustainability in compliance with the new Sustainable Groundwater Management Act (SGMA) specifications, while optimizing their production to fulfill level 4 delivery requirements set forth by the Central Valley Project Improvement Act (CVPIA).

Our completed groundwater model of Volta Wildlife Refuge was brought to verifiable equilibrium conditions and was precise enough to predict existing surface flow conditions. The simulation of two sub-Corcoran groundwater pumping wells within the refuge was tested and was able to replicate observed pump test data with a small, 10 day, delay in response. Four global circulation climate models (CCSM, CNRM, GFDL, PCM) with two carbon emission scenarios (A2, B1) were used to make predictions about future sustainability of existing management practices within the refuge over the next 20 years. These simulations showed that current pumping rates will remain sustainable with predicted changes in precipitation and evapotranspiration.

However, the presence of many large sub-Corcoran industrial and agricultural pumping wells in the vicinity, also impact the future sustainability of VWR management practices. Due to the lack of available data on these well systems it is impossible to accurately model their influence. This, together with the unpredictable but highly likely increase in groundwater reliance over time due to decreases in available surface water, makes it impossible to conclude definitively whether or not current predictions will remain true over the next 20 years.

So while the present study reaches sufficient conclusions based on available data, the undertaking of a larger scale project, which is able to integrate information about nearby industrial and agricultural wells and future predicted increases in groundwater extraction, is recommended to determine the larger impact of groundwater pumping on the stability of the aquifer system. Additionally, there are many other possible applications of such a model, such as modeling changes in groundwater quality or the flow of incoming salts to the aquifer. In many ways this project is just the one step in the much larger goal of optimizing California's seasonal wetland habitats.

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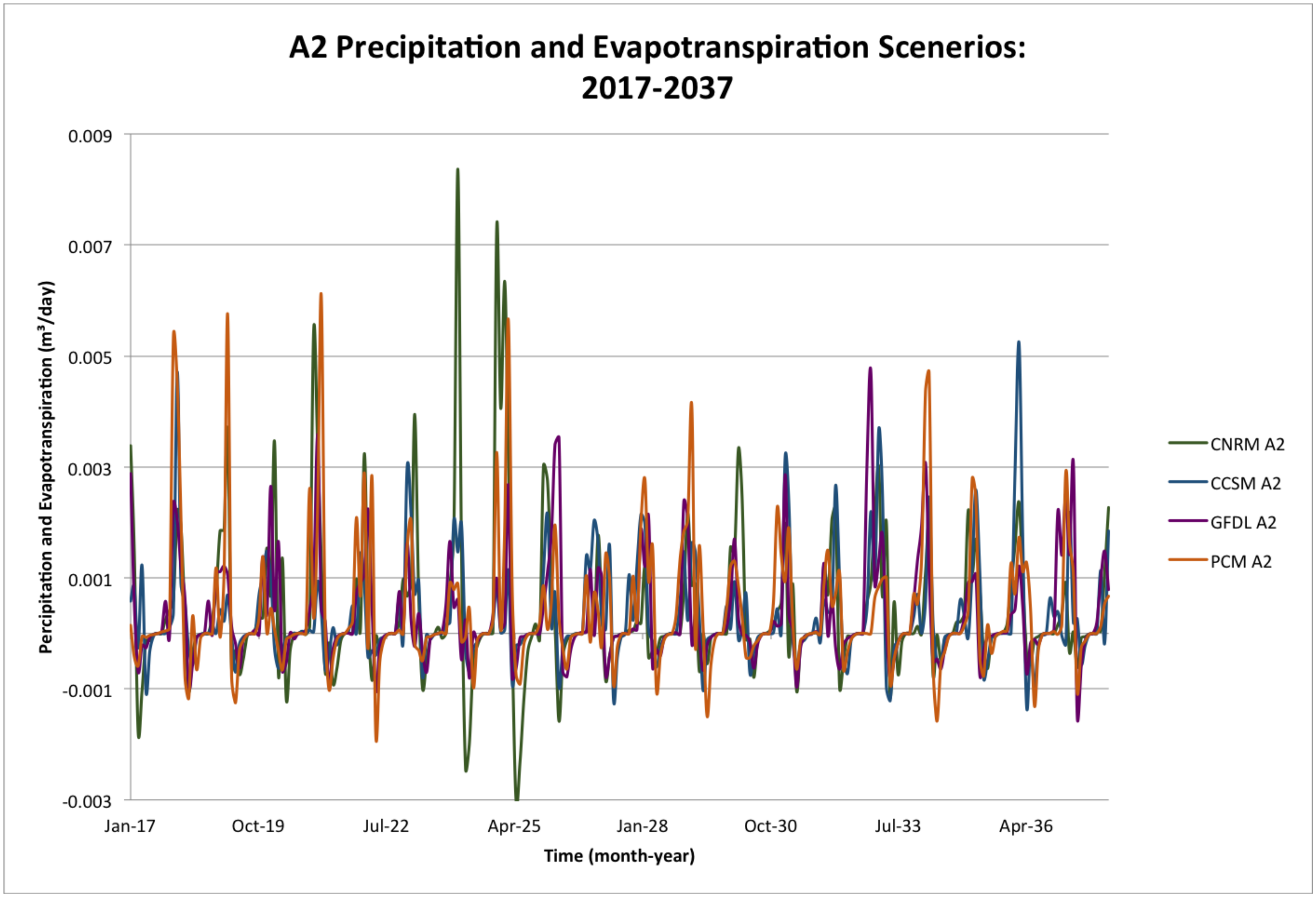
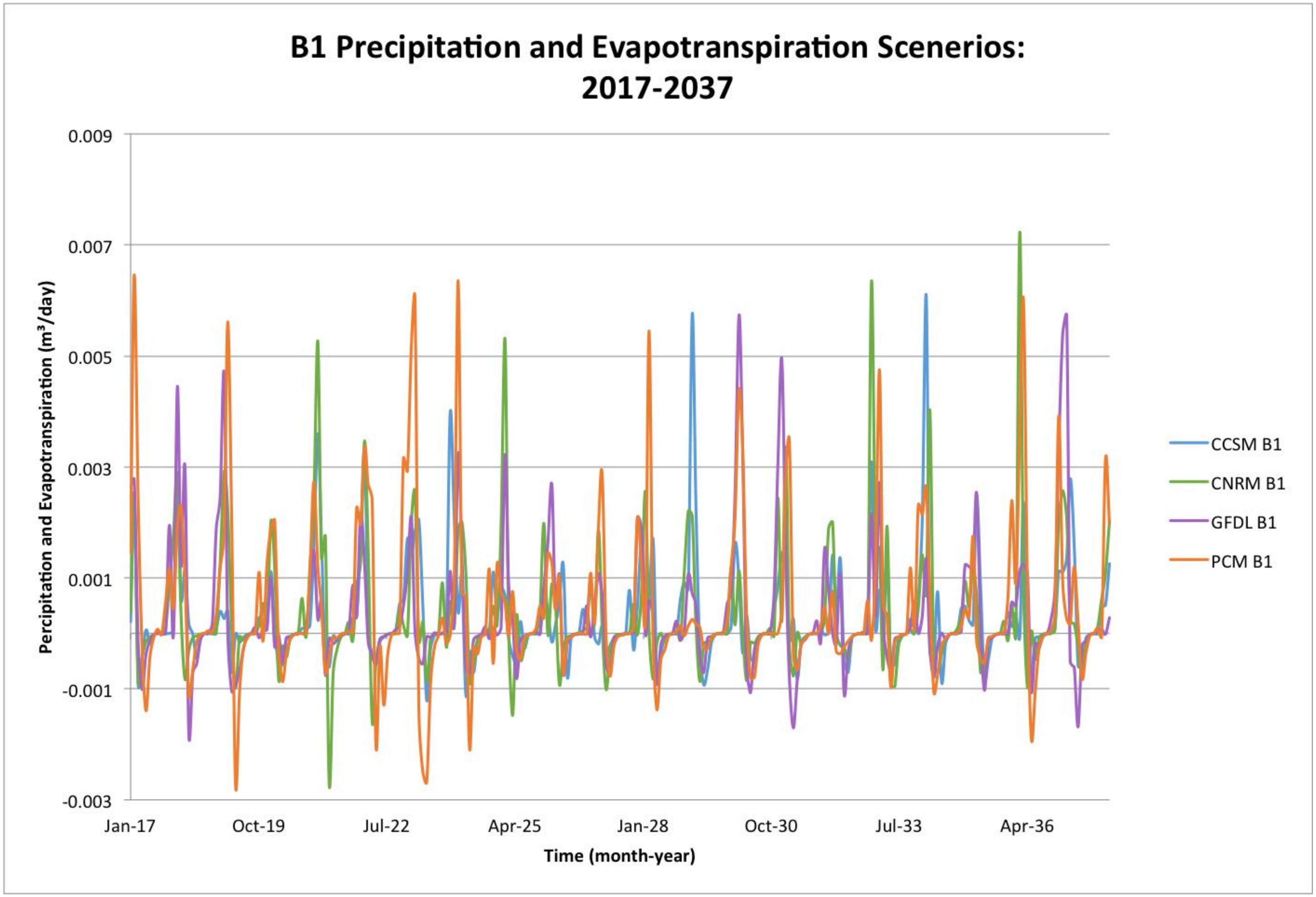
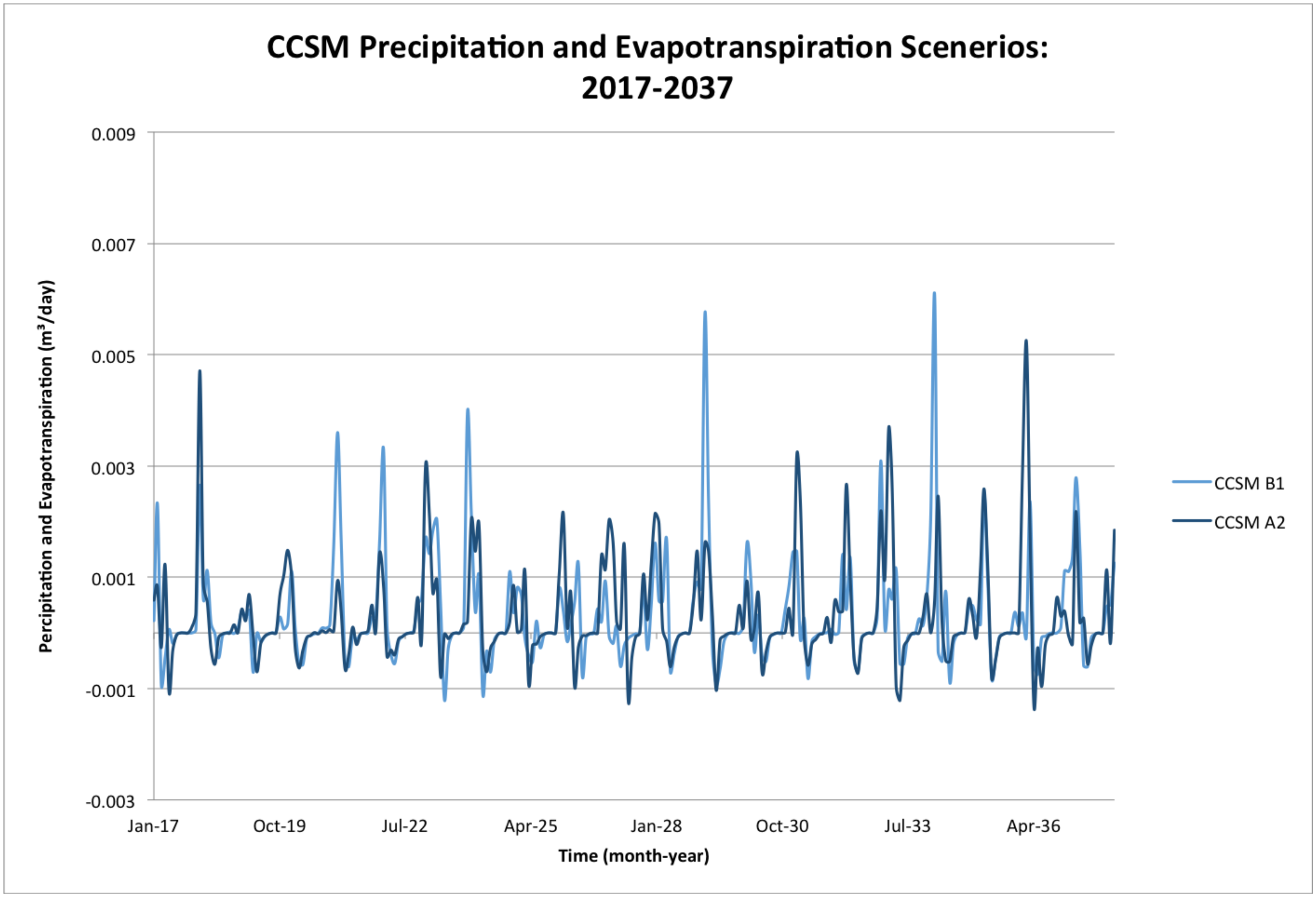
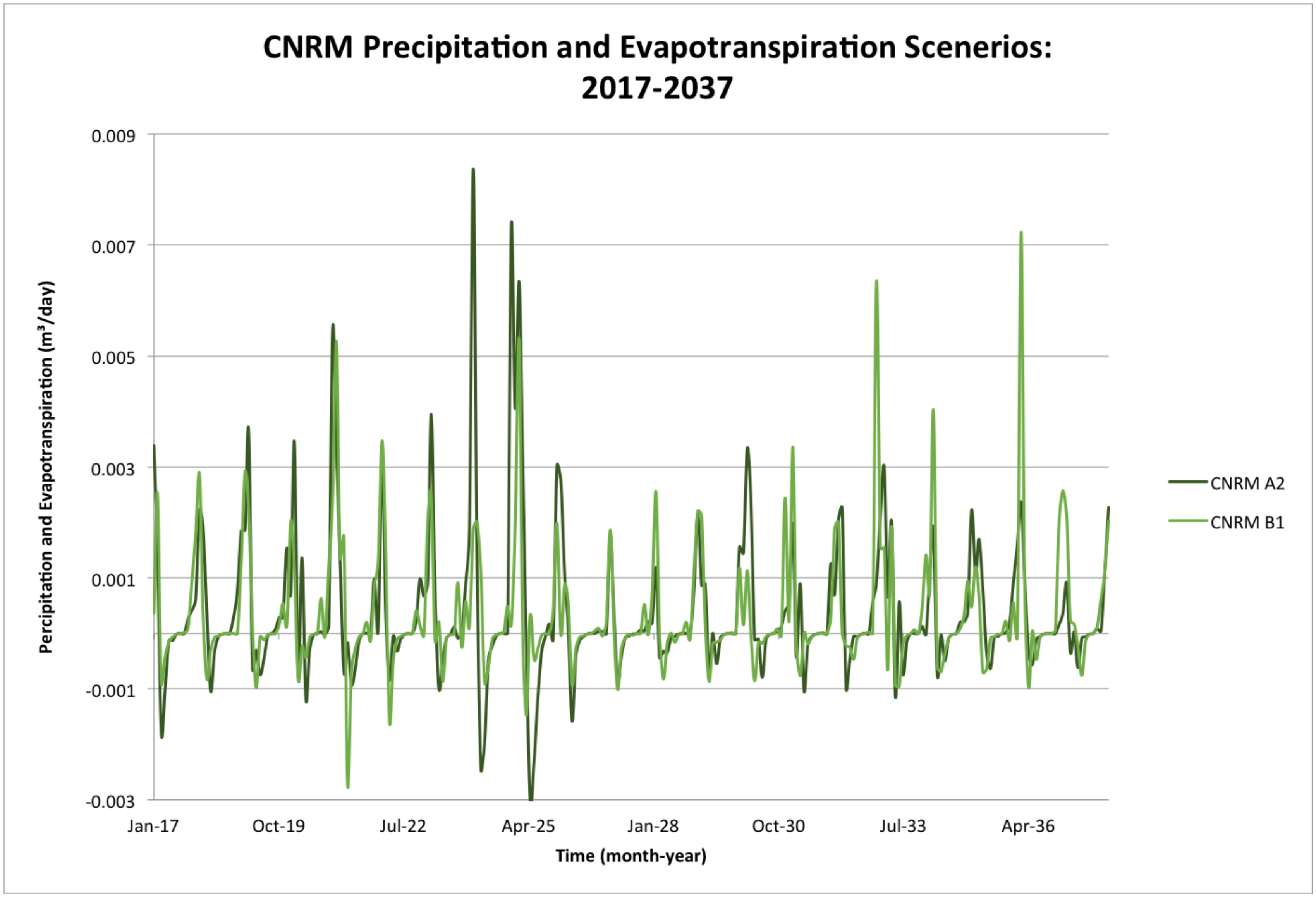
Appendix A


A2 Precipitation and Evapotranspiration Scenerios: 2017-2037
Percipitation and Evapotranspiration (m³/day)
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CNRM A2
CCSM A2
GFDL A2
PCM A2


B1 Precipitation and Evapotranspiration Scenerios:
2017-2037
Percipitation and Evapotranspiration (m³/day)
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CCSM B1
CNRM B1
GFDL B1
PCM B1


CCSM Precipitation and Evapotranspiration Scenerios: 2017-2037
Percipitation and Evapotranspiration (m³/day)
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CCSM B1
CCSM A2


CNRM Precipitation and Evapotranspiration Scenerios: 2017-2037
Percipitation and Evapotranspiration (m³/day)
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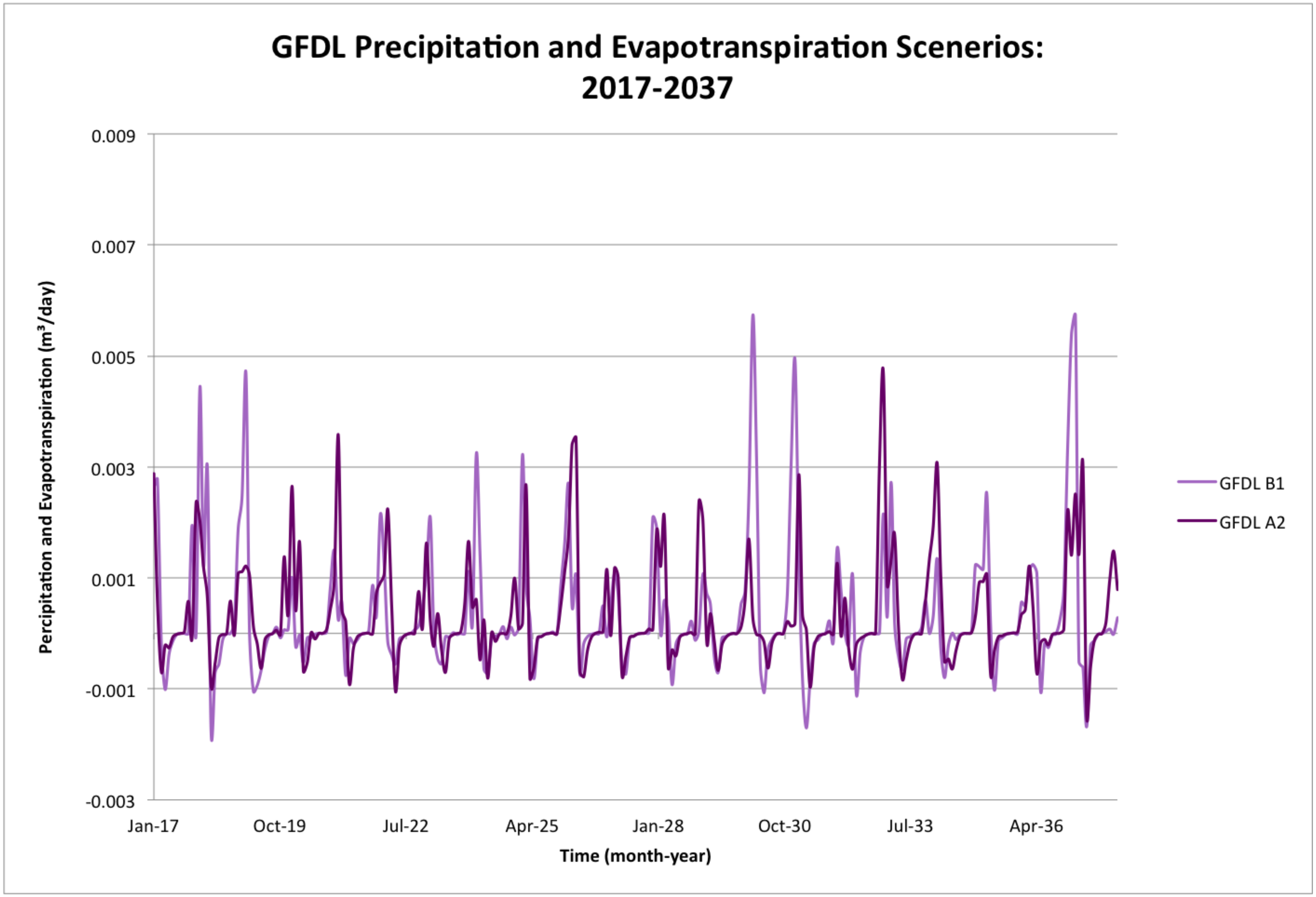
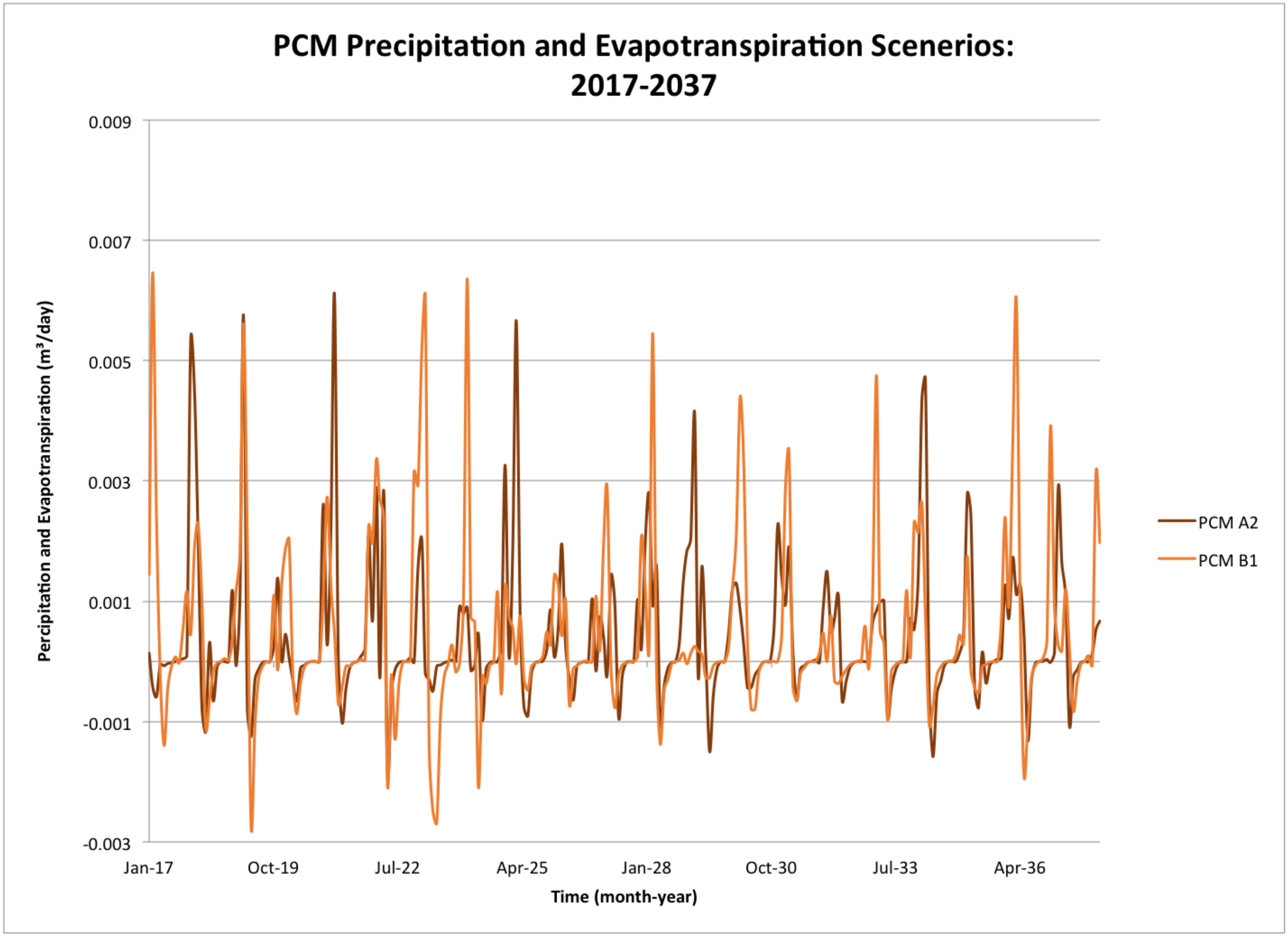
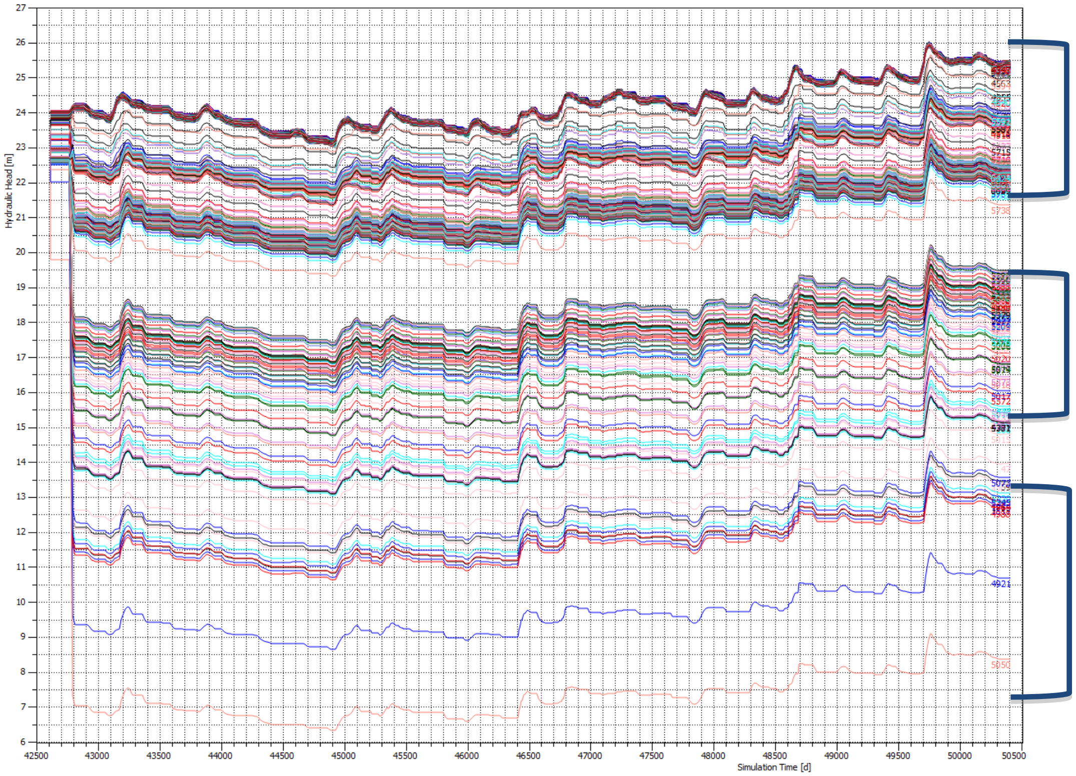
0.007
0.005
0.003
0.001
-0.001
-0.003
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
CNRM A2
CNRM B1


GFDL Precipitation and Evapotranspiration Scenerios: 2017-2037
Percipitation and Evapotranspiration (m³/day)
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
GFDL B1
GFDL A2


PCM Precipitation and Evapotranspiration Scenerios: 2017-2037
0.009
0.007
0.005
0.003
0.001
-0.001
-0.003
Percipitation and Evapotranspiration (m³/day)
Jan-17
Oct-19
Jul-22
Apr-25
Jan-28
Oct-30
Jul-33
Apr-36
Time (month-year)
PCM A2
PCM B1

Appendix B

Simulated hydraulic head values for the 8 climate change scenarios for a 20-year interval from 2017-2037 at observation points. Observation wells were installed at a radius of 200 meters around each well in every layer. The graphs show three groups of drawdown. The top group is all observation wells within the top unconfined aquifer that show no drawdown. The second group represents the cone of depression surrounding the two wells at distances of 5-200 meters within the confined aquifer. The lowest group is more dispersed and represents the most drawdown; within the screened interval of the wells. The most drawdown occurred within well 1 in layer 8.



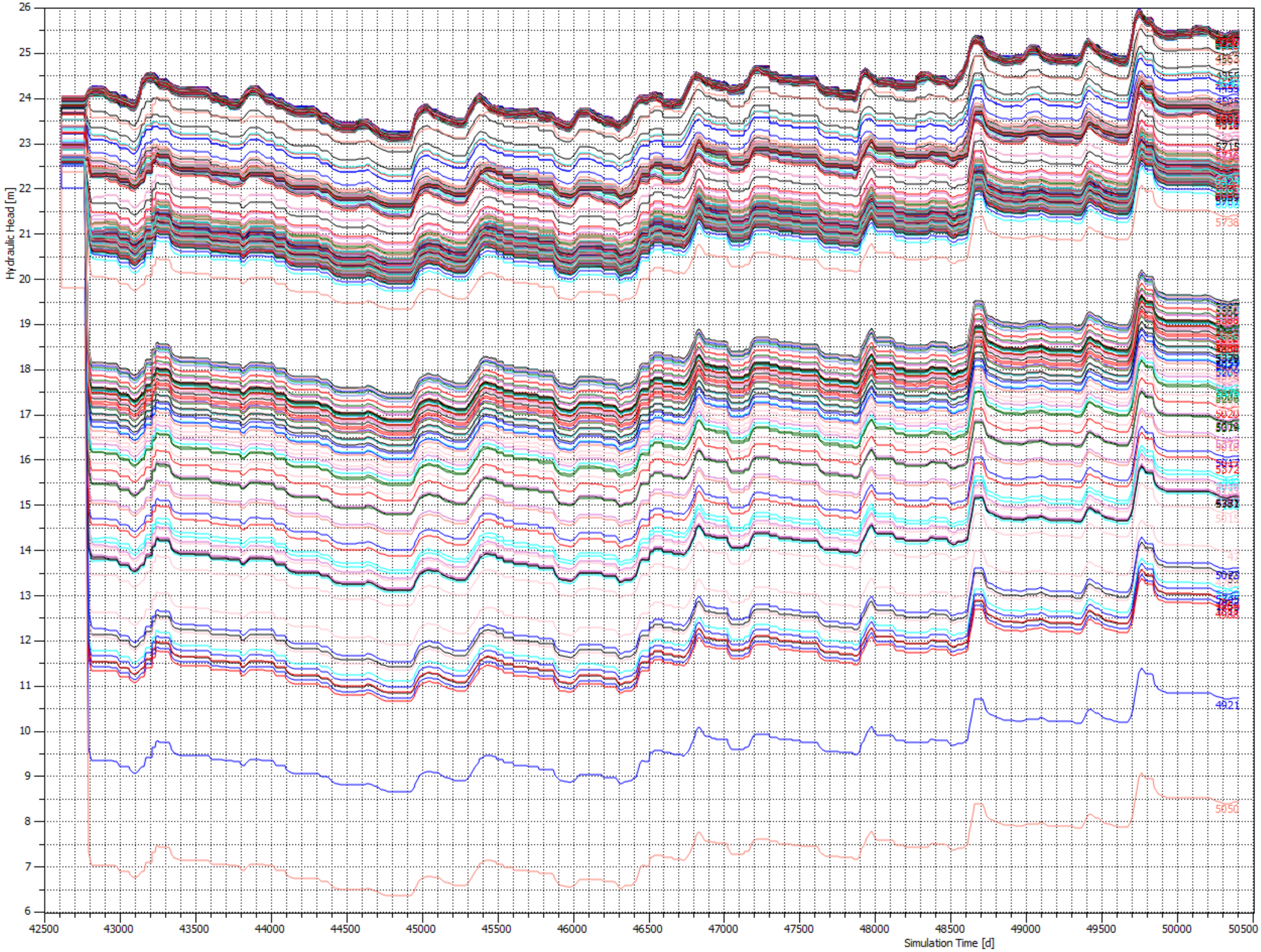
Observation wells in the unconfined aquifer (layers 1-5)

Observation wells in the confined aquifer (layers 6-11) at a distance from the wells (5-200 meters)

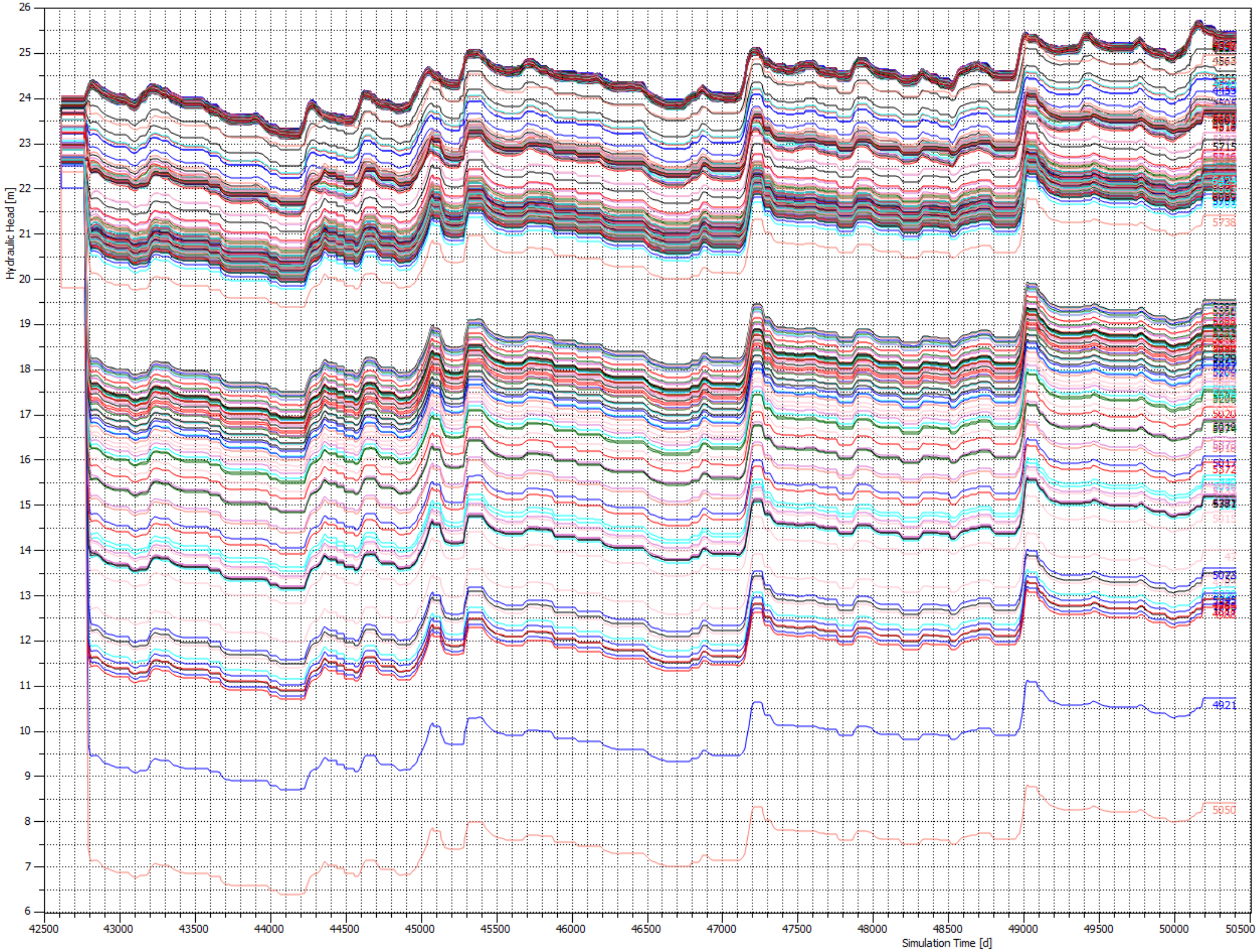
Observation wells within the confined aquifer within the screened interval (layers 6-8) at well locations (0 meters)

Individually the hydraulic head shows varying trends in response to seasonal and year-to-year changes in precipitation and evaporation. Overall however the consistency of drawdown illustrates that pumping is sustainable for the next 20 years and doesn't represent a threat to aquifer sustainability on its own.

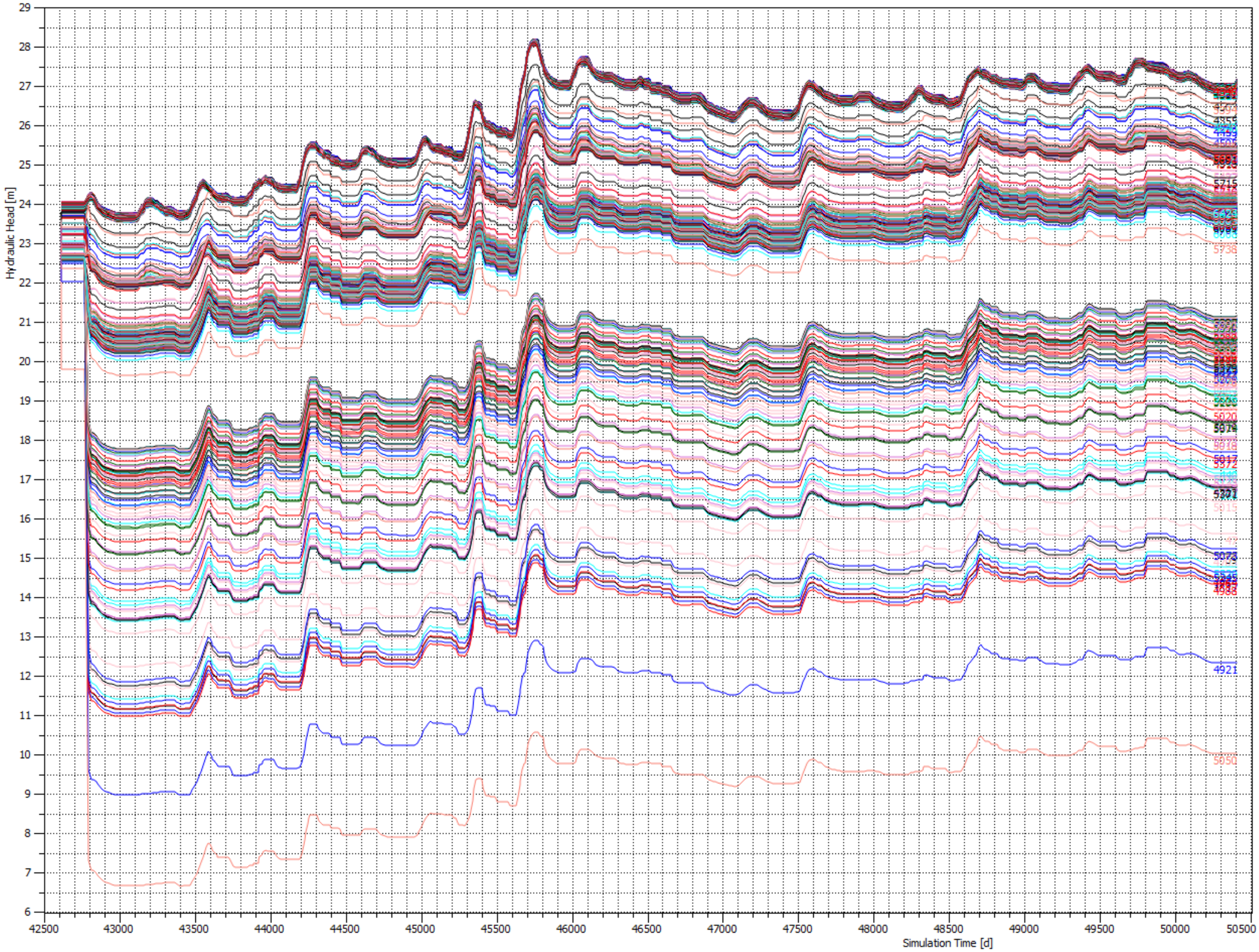
Simulated Hydraulic Head in Volta Wildlife Refuge CCSM A2 Projection: 2017-2037



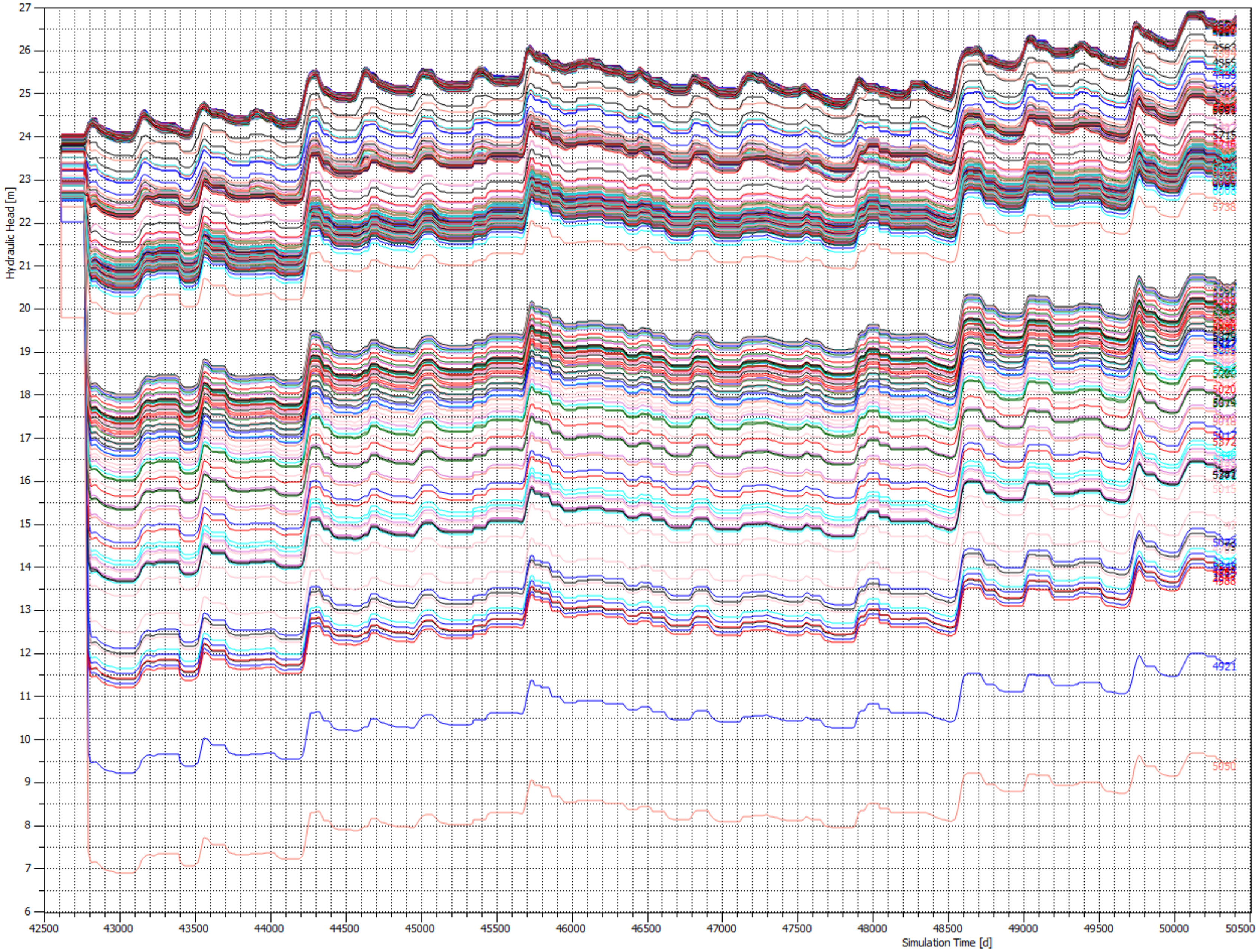
Simulated Hydraulic Head in Volta Wildlife Refuge CCSM B1 Projection: 2017-2037



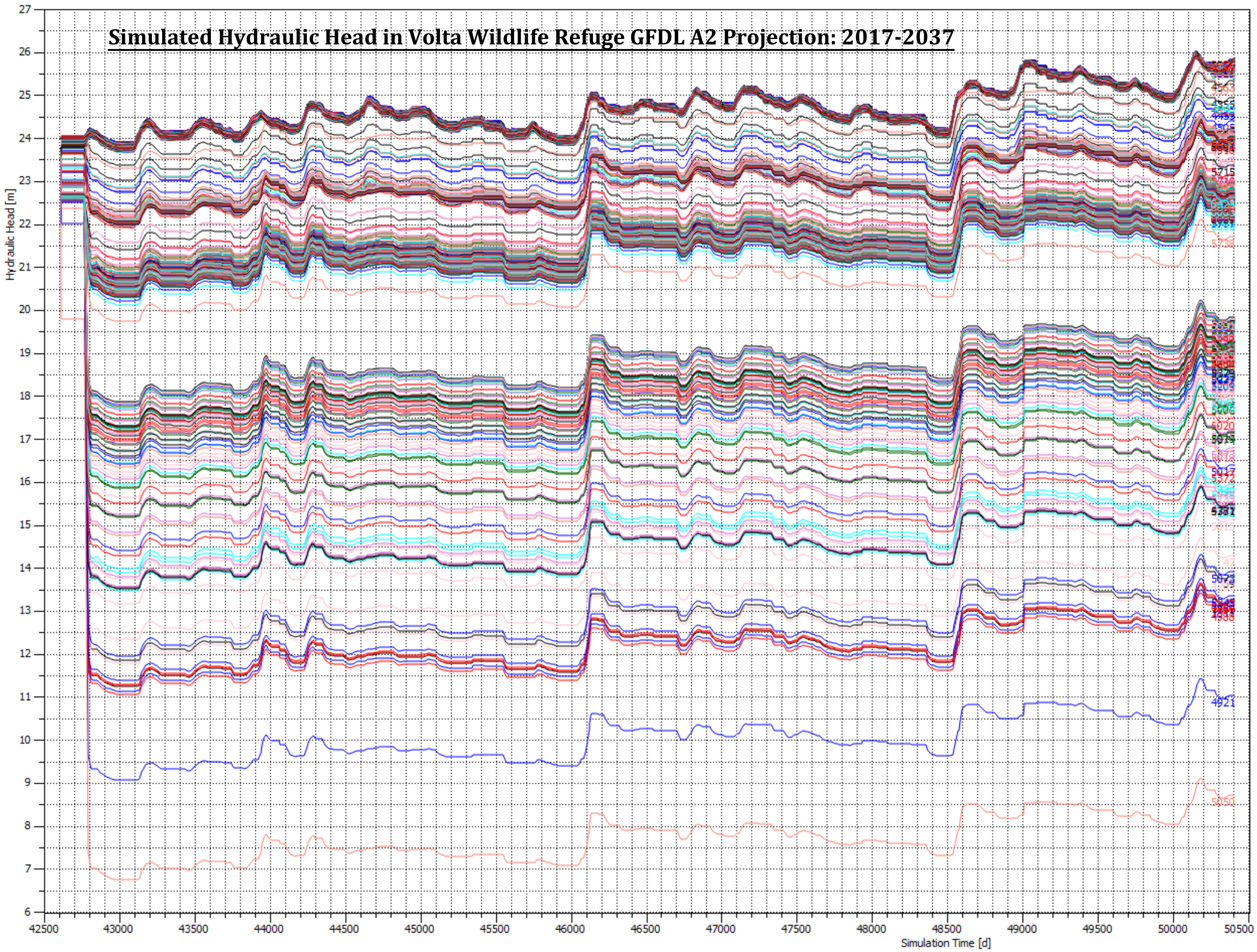
Simulated Hydraulic Head in Volta Wildlife Refuge CNRM A2 Projection: 2017-2037



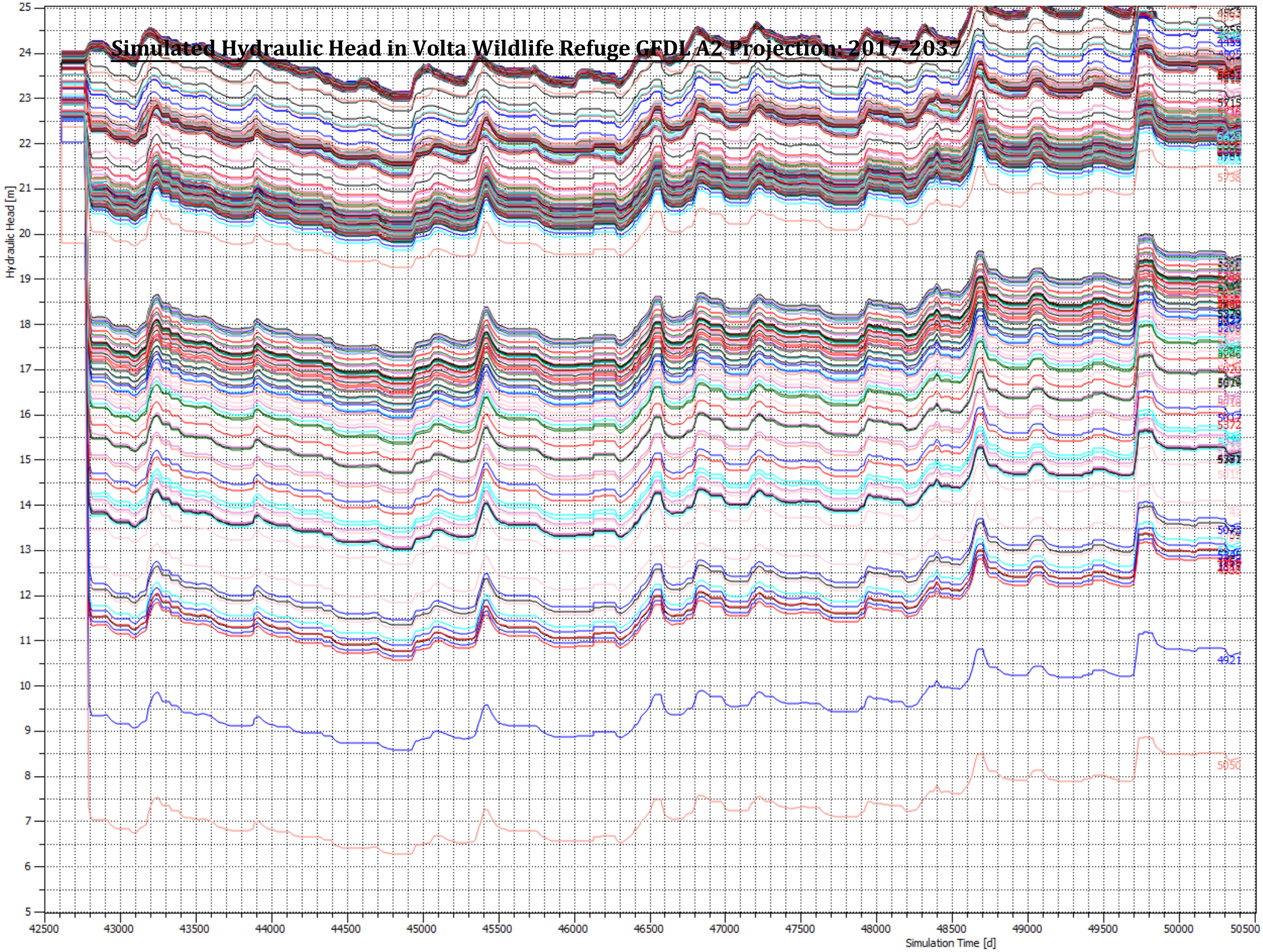
Simulated Hydraulic Head in Volta Wildlife Refuge CNRM B1 Projection: 2017-2037



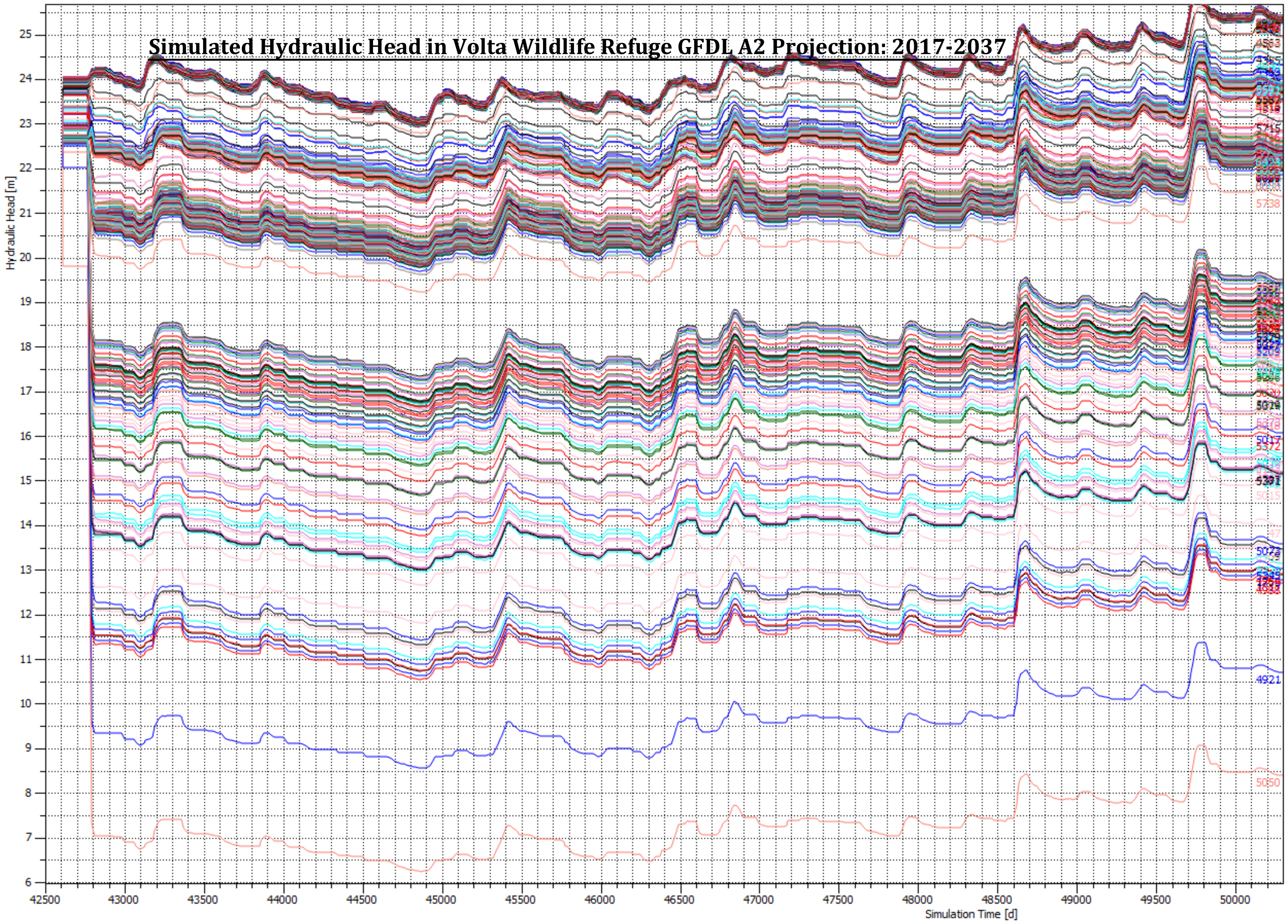
Simulated Hydraulic Head in Volta Wildlife Refuge GFDL A2 Projection: 2017-2037



Simulated Hydraulic Head in Volta Wildlife Refuge GFDL B1 Projection: 2017-2037



Simulated Hydraulic Head in Volta Wildlife Refuge PCM A2 Projection: 2017-2037


Simulated Hydraulic Head in Volta Wildlife Refuge GFDL A2 Projection: 2017-2037

Simulated Hydraulic Head in Volta Wildlife Refuge PCM B1 Projection: 2017-2037