1 BACKGROUND ON FCGMA

The Fox Canyon Groundwater Management Agency (FCGMA) is an independent Special Act District established by the California Legislature, separate from the County of Ventura or any city government. The FCGMA enabling legislation known as the FCGMA Act, Assembly Bill (AB) No. 2995, was passed on September 13, 1982, and became effective January 1, 1983. The FCGMA was created in response to declining groundwater levels and increasingly poor water quality from wells in the southern part of the Oxnard Plain, conditions that were first recognized in the 1950s. Prior to the creation of the FCGMA, the SWRCB issued a Seawater Intrusion Abatement Project grant to the County of Ventura and the United Water Conservation District (UWCD) to develop a Groundwater Management Plan. The initial Groundwater Management Plan was developed in 1985 to balance water supply and demand in both the Upper Aquifer System (UAS) and the Lower Aquifer System (LAS). The most recent FCGMA Groundwater Management Plan Update is dated May 2007 and is currently available on the FCGMA website.

The boundary of the FCGMA (Figure 1) was established by Resolution of the Ventura County Board of Supervisors on December 21, 1982. The boundary was defined to include all area overlying the Fox Canyon Aquifer and was revised in 1991 to reflect updated knowledge of the extent of the aquifer. Groundwater pumped from aquifers within the FCGMA jurisdictional boundaries accounts for more than half of the water demand of the 700,000 residents in the cities of Ventura, Oxnard, Port Hueneme, Camarillo and Moorpark, and the unincorporated communities of Saticoy, El Rio, Somis, Moorpark Home Acres, Nyeland Acres, Point Mugu and Montalvo; and the majority of the water needs for the 58,649 acres of productive agriculture.

The California Department of Water Resources (DWR) maintains a catalog of groundwater basins known as Bulletin 118 that includes the status and boundaries of each groundwater basin in California. There are four groundwater basins or subbasins within the FCGMA service area: Las Posas, Oxnard, Pleasant Valley, and Arroyo Santa Rosa.

1.1 FCGMA Decision Making Process

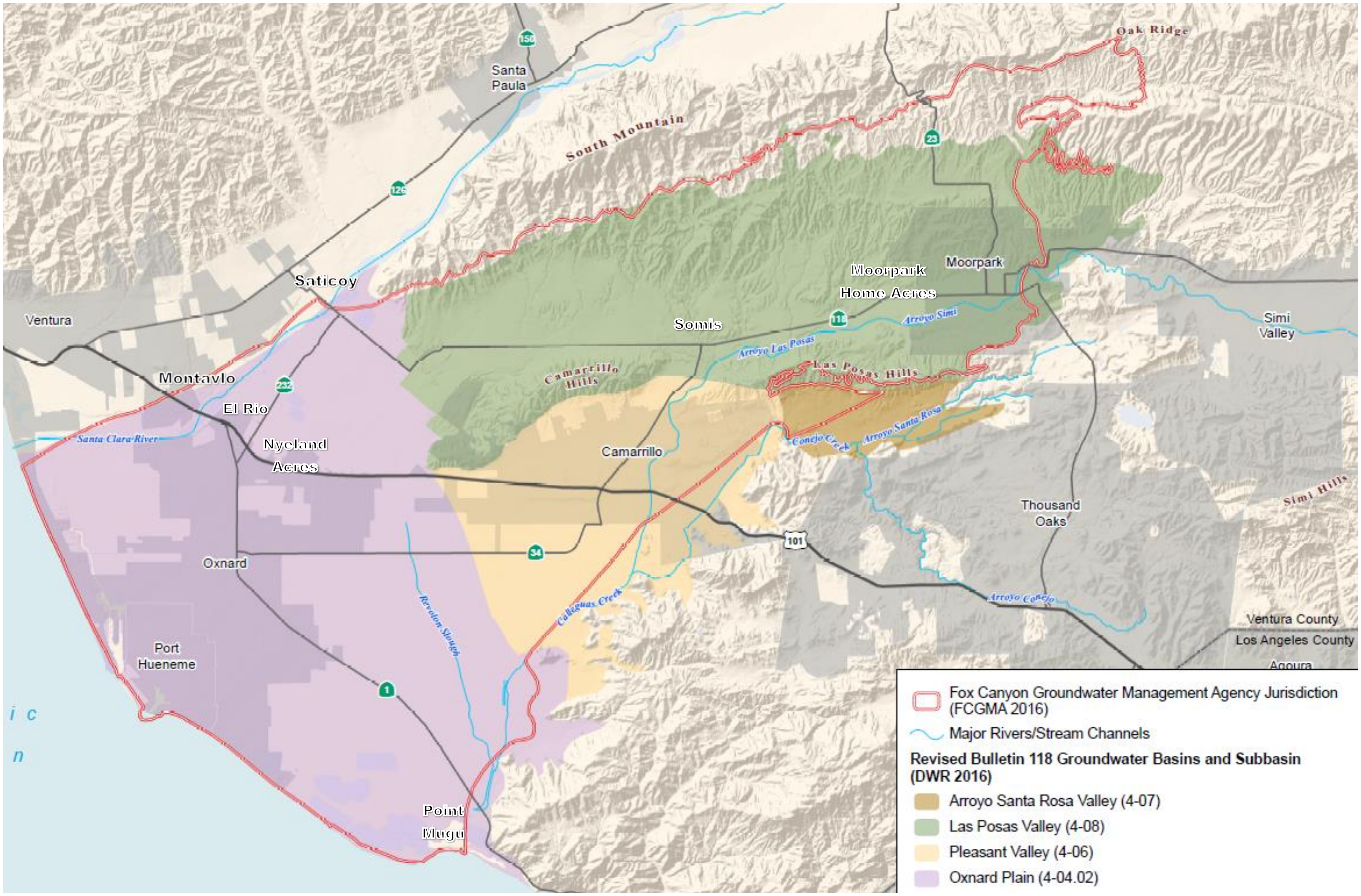
The FCGMA Board is defined by its enabling legislation and is comprised of five members representing the following interests:

1. County of Ventura,
2. United Water Conservation District,
3. the seven small water districts existing within the FCGMA at the time of its formation (Alta Mutual Water Company, Pleasant Valley County Water District, Berylwood Mutual Water Company, Calleguas Municipal Water District, Camrosa Water District, Zone Mutual Water Company, and Del Norte Mutual Water Company),

4. the five incorporated cities whose territory at least in part overlies the territory of the FCGMA (Ventura, Oxnard, Camarillo, Port Hueneme, and Moorpark), and
5. agriculture.

Each Board member has an alternate and all members serve a two-year term. All Board Members are appointed by their respective organizations or groups, except for the agricultural representative. The agricultural representative is appointed by the other four seated members from a list of at least five candidates jointly supplied by the Ventura County Farm Bureau (VCFB) and the Ventura County Agricultural Association (VCAA). Board Members are not paid by the FCGMA. Each member has one equal vote on the Board. The Board adopts ordinances for the purpose of regulating, conserving, managing, and controlling the use and extraction of groundwater within the territory of the agency. Ordinances are adopted, after noticed public hearings, by a majority vote of the board.

Figure 1. FCGMA Jurisdiction and Basin Boundaries



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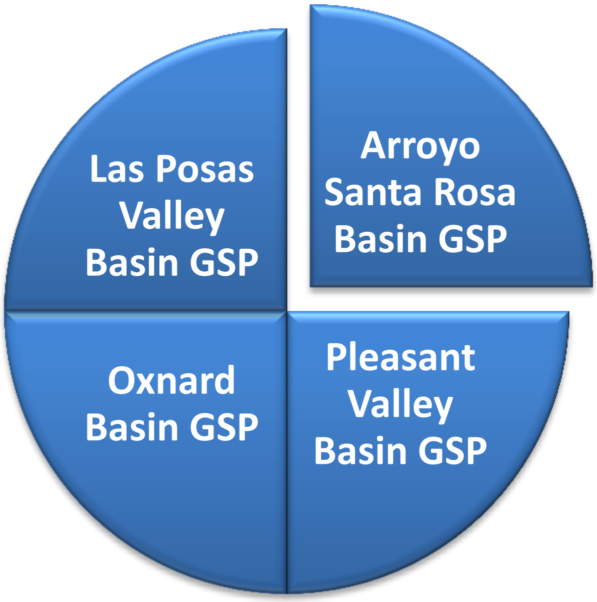
2 BACKGROUND ON GROUNDWATER SUSTAINABILITY PLANS

The SGMA of 2014 requires the creation of GSAs and provides that they develop, adopt and implement GSPs by 2022 for basins that the DWR has designated as either high or medium priority and by 2020 for critically overdrafted basins. All four of the groundwater basins within the FCGMA have been designated high or medium priority by DWR. The Oxnard and Pleasant Valley Basins have additionally been designated by DWR as critically overdrafted.

SGMA requires local public agencies to define a course of action to achieve sustainable groundwater management within 20 years of plan adoption. GSPs must identify local undesirable results and identify management actions to minimize undesirable results as well as milestones to track progress. A groundwater monitoring program must be developed and used to demonstrate improved conditions within the basins leading to sustainable management.

On January 26, 2015, the FCGMA provided DWR with notification of its intent to become a GSA for four groundwater basins: Las Posas, Oxnard, Pleasant Valley, and Arroyo Santa Rosa. Preliminary work began to develop a specific GSP for each of the four basins within the purview of the FCGMA in late 2015. In early 2017, it was determined that the Santa Rosa Basin GSP will move forward separately from the other three GSPs due to the need for additional coordination with the newly formed Arroyo Santa Rosa Basin Groundwater Sustainability Agency, which has jurisdiction over the eastern two-thirds of that groundwater basin.



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3 PURPOSE OF THE DOCUMENT

The purpose of this document is to outline the procedures used to create a common understanding and transparency throughout the groundwater sustainability planning process. The FCGMA encourages active involvement of diverse social, cultural, and economic elements of the population to ensure that all relevant and interested stakeholders and the public are involved throughout the GSP development.

3.1 The Importance of Public or Stakeholder Engagement

The FCGMA recognizes that stakeholder engagement can improve management of shared resources and has a track-record of successful stakeholder participation in FCGMA decision making.

3.1.1 Why Public Engagement is Important

The basins within the FCGMA jurisdiction underlie a variety of land uses and communities with varying needs and interests relating to sustainable management of groundwater resources. Participation from a diverse group of stakeholders will allow the FCGMA to make management decisions that take into account the varying needs and interests in the Basin.

3.1.2 SGMA Requirements

This document is designed to assist the public and FCGMA in developing a mutual understanding of how FCGMA will fulfill the requirements of SGMA as they relate to public engagement. Specifically, this plan addresses the following requirements of SGMA Section 354.10 (d).

> Section 354.10(d) A communication section of the Plan that includes the following:
>
> 1. An explanation of the Agency's decision-making process.
> 2. Identification of opportunities for public engagement and a discussion of how public input and response will be used.
> 3. A description of how the Agency encourages the active involvement of diverse social, cultural, and economic elements of the population within the basin.
> 4. The method the Agency shall follow to inform the public about progress implementing the Plan, including the status of projects and actions.

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4 OPPORTUNITIES FOR PUBLIC INVOLVEMENT AND ENGAGEMENT

The FCGMA Board has a longstanding commitment to public involvement and engagement in decision-making. FCGMA encourages members of the public to communicate directly with staff during regular business hours, and provide public comments at meetings. FCGMA provides ample time for public consideration of policy decisions through advanced noticing of public meetings. The FCGMA is committed to continuing to provide opportunities for public involvement and engagement throughout the GSP development and implementation processes. FCGMA recognizes that adapting involvement strategies to the needs of the public throughout the process is critical to effective engagement. This plan serves to update to the FCGMA Communications Guide (May 24, 2016) with ongoing, current, and future planned opportunities for engagement.

4.1 Meeting Opportunities

Opportunities for public comment are provided at all FCGMA Board meetings, Technical Advisory Group (TAG) meetings, Board appointed Committee meetings, and workshops.

4.1.1 Public Notices

All FCGMA Board, TAG meetings, Board appointed Committee meetings, and Board special workshops are noticed in accordance with the Brown Act. FCGMA Board meeting agendas are generally posted on the FCGMA website 5-7 days prior to each meeting to allow for additional time for public review. TAG meeting agendas are also posted as soon as they are completed. All public meeting agendas and minutes are posted on the FCGMA website, and sent directly via email to individuals that have requested meeting notices.

4.1.2 Board Meetings and Hearings

FCGMA Board meetings are typically held from 1:30pm to 4:00pm on the fourth Wednesday of each month. There typically is not an August meeting, and the November and December meetings are typically combined into an early December meeting. A calendar of meeting dates is published each year at www.FCGMA.org. Special Board meetings are scheduled by the Board as needed and generally fall on the second Wednesday or Friday of the month.

4.1.3 Workshops

The FCGMA held two GSP focused public workshops in November 2016 and September 2017. The workshops were well attended with over eighty-five participants representing individuals, municipalities, elected officials, water agencies, disadvantaged communities, mutual water companies, businesses, agriculture and environmental organizations.

4.2 Collaborative Opportunities

Many people including farmers, businesspersons, attorneys, water company employees, and elected officials volunteer their time and energy to work with FCGMA staff to resolve the critical issues and policies that affect beneficial users within the FCGMA.

Well owners and operators play a key role in that they are responsible for "self-reporting" groundwater extractions to the FCGMA accurately and in a timely manner (e.g., twice per year, once in January and once in August).

Several agencies also have a critical partnering role including UWCD, Camrosa Water District and the County of Ventura. All three agencies exercise shared responsibility with the FCGMA for the stewardship of the groundwater basins within the FCGMA territory. The Calleguas Municipal Water District (CMWD) is also an important partner agency.

4.2.1 Stakeholder Groups

The importance of groundwater to local stakeholders, as well as the FCGMA's commitment to work collaboratively with stakeholders, has catalyzed the establishment of several stakeholder groups that have come together to coordinate and articulate their positions on various issues to the FCGMA Board. Stakeholder groups in the Las Posas, Oxnard, and Pleasant Valley basins have organized themselves to form and make recommendations to the FCGMA Board regarding groundwater pumping in the basins. FCGMA staff is dedicated to working with organized groups of stakeholders and providing opportunities for their voices to be heard in open public forums before the FCGMA Board.

4.2.2 Technical Advisory and Charter Groups

The Technical Advisory Group (TAG) was developed by FCGMA to provide technical guidance for development of basin sustainable yield estimates and review for the four GSPs. Each Board Member selected a TAG member and two additional TAG members were selected by the full Board to represent the public and nongovernmental/environmental interests. All TAG meetings are conducted in accordance with the Brown Act and agendas are posted on the FCGMA website and emailed to members of the public who have requested to receive notifications.

The FCGMA has also established formal roles for some groups participating in the GSP process through Charters. More information about each of the Charter groups is available on the GSP page of the FCGMA website including the point of contact for each group and a copy of the signed Charter.

One long-established stakeholder group, the Las Posas Basin User Group (LPUG), has been meeting to discuss localized groundwater issues specific to the Las Posas Valley Basin since before SGMA. The LPUG requested their advisory role to the FCGMA be formally recognized through a Charter, effective as of April 2016. The LPUG continues to meet regularly to discuss aspects of the GSP including recommended groundwater allocations.

Another stakeholder group that was established and operates within an FCGMA Charter is the Water Market Group. The Water Market Group is a diverse group of stakeholders that came together to explore the feasibility of water markets as a tool for improving groundwater management. The FCGMA has initiated a pilot study that combines the findings of this chartered group with the Advanced Metering Infrastructure pilot study to further explore the potential benefits and drawbacks of a water market.

4.2.3 Regional Water Management Groups

FCGMA staff has actively engaged with broader regional water management groups since the initiation of the GSP process. Staff has given multiple presentations to the Santa Clara River Watershed Committee (Committee), a diverse group of stakeholders that collaborates on Integrated Regional Water Management (IRWM) through the countywide umbrella organization of Watersheds Coalition of Ventura County (WCVC). FCGMA staff regularly communicates with WCVC staff regarding the GSP progress and outreach opportunities. Public workshop notices are distributed to the stakeholder lists for both WCVC and the Committee.

FCGMA staff has also given targeted presentations to other regional groups and individual water-management agency boards. FCGMA staff continues to be available to give presentations to regional water-management groups as requested.

4.3 Communication with the Fox Canyon GMA

FCGMA is committed to an open and transparent process for GSP development including multiple mechanisms for ongoing broad communication as well as targeted outreach for feedback on specific GSP components. The FCGMA Board recognizes that the GSPs are highly technical documents moving forward on an ambitious schedule. The FCGMA Board is committed to moving the GSP process forward as quickly as reasonable in recognition that the completed GSPs will inform key groundwater management decisions that are time sensitive and important to stakeholders.

FCGMA Staff are available during regular business hours through email, phone, and in person communication. The FCGMA office is centrally located within the Ventura County Watershed Protection District office in the Ventura County Government Center Hall of Administration located at 800, South Victoria Ave, in Ventura California. The meetings of the FCGMA Board and TAG include opportunities for public comment on every agenda.

The FCGMA has set up a dedicated GSP development page on the website and has established a GSP dedicated email address to increase response time for GSP specific questions and comments.

4.4 Opportunities for Tribal Communities

According to the US Bureau of Indian Affairs California Tribal Homelands and Trust Land Map, updated in 2011, and available from the Department of Water Resources website, the entire FCGMA boundary is within the Chumash Tribal/Cultural area. There are not currently any federally recognized tribes, Indian land currently or historically held in Trust by the United States Government or smaller Reservation or Rancheria areas.

FCGMA recognizes that the Chumash culture and associated cultural resources are important in Ventura County. Several active local groups and individuals representing the interests of tribal communities in Ventura County have been added to the list of interested parties including representatives from the Barbareno/Ventureno Band of Mission Indians (Chumash) and the Wishtoyo Chumash Foundation.

FCGMA has reached out to the Department of Water Resources Southern Region Office Tribal Liason, Jennifer Wong, and added her to the list of interested parties. The San Gabriel Band of Mission Indians has also shown an interest in the groundwater sustainability planning process and has been added to the list of interested parties.

4.5 Opportunities for DAC Communities

The majority of the Disadvantaged Communities (DACs) within the FCGMA jurisdictional boundary receive water from cities, special districts, or mutual water companies. The FCGMA works closely with these water agencies and mutual that represent the interests of the DACs. The Watersheds Coalition of Ventura County (WCVC) has established a DAC Involvement Committee to discuss DAC Community needs and project opportunities related to Integrated Regional Water Management (IRWM). FCGMA staff participates in the DAC Committee. The DAC Committee will oversee work conducted through a Proposition 1 IRWM grant to involve DAC members in water resources decision making and identify water resource needs in DAC communities. There are several DACs within the FCGMA jurisdiction, and representatives of those communities will have the opportunity to participate in this process. As part of the grant-funded DAC involvement, process participants will identify their needs and potential projects to improve water resource management in these areas. Some of those projects could be incorporated into the GSPs. Proposition 1 includes grant funding for projects that benefit DACs and these funds may be a resource in implementing key projects identified in the GSPs. FCGMA staff will continue to participate in the WCVC DAC Committee throughout the GSP process.

Other members of the WCVC DAC Committee participated in the first FCGMA public stakeholder workshops and subscribe to the stakeholder list.

4.6 Stakeholder Email List

The FCGMA maintains a list of stakeholders interested in the GSP process, known as the *List of Interested Parties (List).* A monthly newsletter, meeting notices, and notices of GSP documents available for review are sent electronically to the List. There are currently over 400 individuals subscribed to the List representing a wide range of interests including agriculture, fisheries, municipalities, water agencies, tribal interest, and individual property owners. The List is continuously updated with individuals that request in writing to be placed on the list of interested parties. Written requests and questions can be sent via email to fcgma-gsp@ventura.org. Subscribers to the List can choose to unsubscribe at any time.

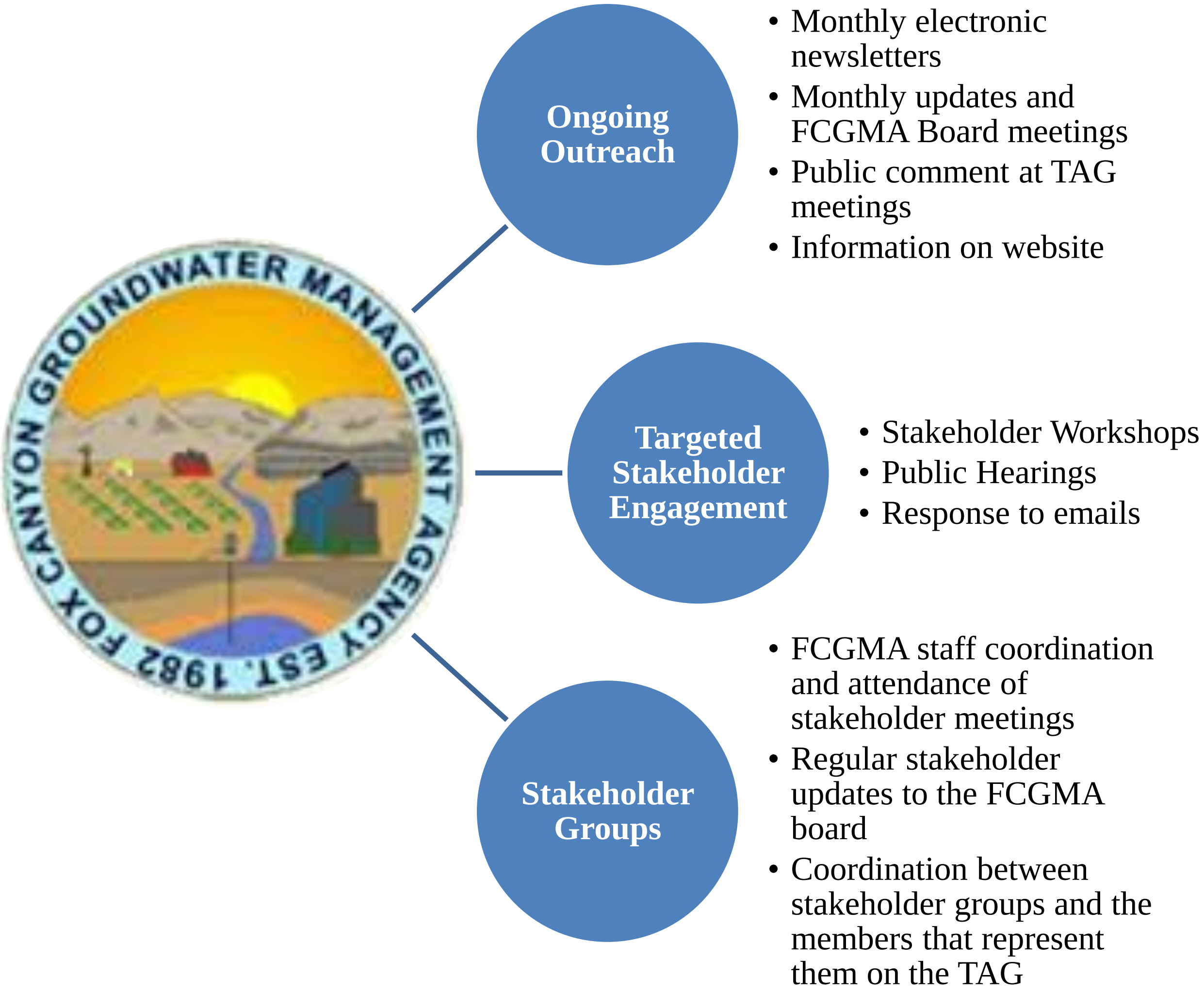
4.7 Online Resources

The FCGMA has a longstanding commitment to transparency of information and decision-making. All FCGMA Board meetings are broadcasted live online and available for later viewing at www.FCGMA.org. Meeting schedules, agendas, and minutes are posted on the website as soon as they are available for all FCGMA Board meetings, TAG meetings, and Board appointed Committee meetings. As draft documents are created for each of the GSPs, they are posted on the FCGMA website. A monthly newsletter, meeting notices, and notices of GSP documents available for review are sent electronically to the List.

4.8 Characterization of Current Communication

The FCGMA currently communicates with the public and interested stakeholders through ongoing outreach, targeted stakeholder engagement, and stakeholder group meetings (Figure 2). Ongoing outreach is used to continually update stakeholders regarding the progress of GSP development and is carried out through monthly electronic newsletters, monthly updates at FCGMA Board meetings, public comment opportunities at TAG meetings, and information made available on the FCGMA website. Targeted stakeholder engagement is when the FCGMA solicits feedback from the public or responds to specific comments or concerns that are raised through public workshops, public hearings and emails. Stakeholder group meetings are meetings that are initiated by interested parties outside of the FCGMA process; however, FCGMA staff is available to coordinate as appropriate with these groups to help them understand the GSP development process.

Figure 2. Diagram of Communication Structure



Ongoing Outreach

- Monthly electronic newsletters
- Monthly updates and FCGMA Board meetings
- Public comment at TAG meetings
- Information on website

Targeted Stakeholder Engagement

- Stakeholder Workshops
- Public Hearings
- Response to emails

Stakeholder Groups

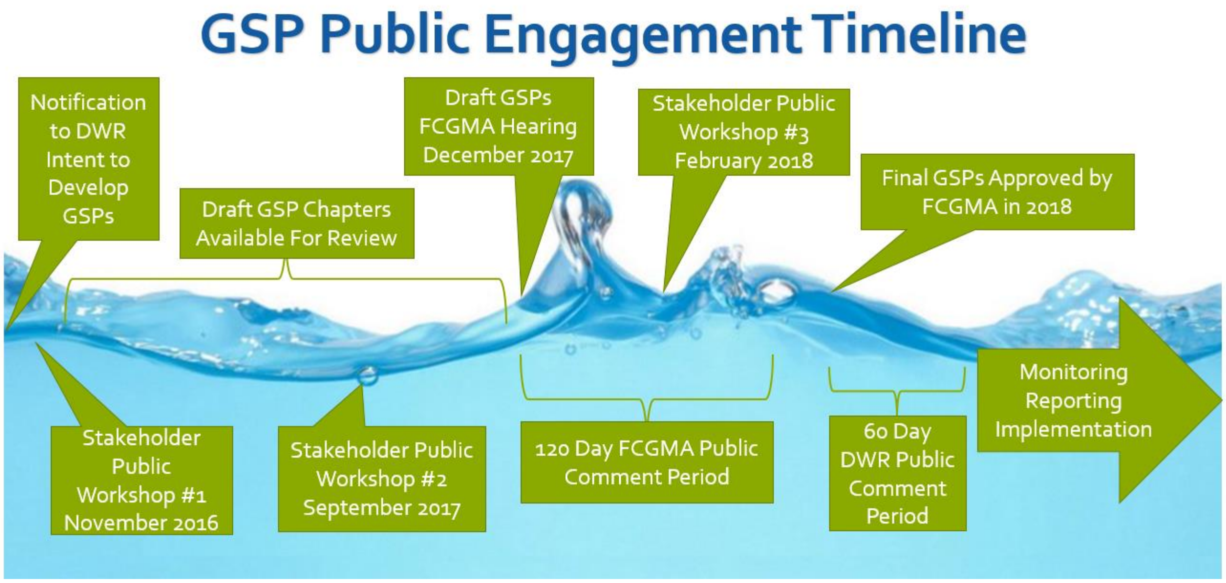
- FCGMA staff coordination and attendance of stakeholder meetings
- Regular stakeholder updates to the FCGMA board
- Coordination between stakeholder groups and the members that represent them on the TAG

5 STAKEHOLDER AND PUBLIC ENGAGEMENT TIMELINE

The initial Stakeholder Workshop #1 was held in November 2016 to give an introduction to the FCGMA, an overview of the SGMA, the GSPs and process. The primary objective of this meeting was to introduce the process and solicit public comments. A second set of Stakeholder Workshops were held to present preliminary results and provide an opportunity for members of the public to ask questions and provide comments. The workshops were held in September 2017 and focused on the identification of undesirable results, including discussions of what is significant and unreasonable, measureable objectives and sustainable yield. Ongoing stakeholder engagement has continued through regular FCGMA Board meeting updates, newsletters, TAG meetings, and draft documents made available on the FCGMA website.

The draft GSPs will be brought before the FCGMA Board in December 2017. The Board will consider opening a 120-day public comment period. The draft GSPs will be updated based on comments with subsequent adoption of the final GSPs by the FCGMA Board. After the final GSPs are adopted by the FCGMA Board, DWR will accept public comments in another 60-day public comment period. After the final GSPs are adopted by the FCGMA Board, regular monitoring and reporting will be conducted as required by DWR and outlined in the GSPs. A detailed schedule of the GSP process including stakeholder review opportunities can be found on the FCGMA website and is updated as needed. Below is a summary table of key GSP engagement opportunities for the public (Figure 3).

Figure 3. GSP Public Engagement Timeline



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6 CONCLUSION

This document serves as a tool for facilitating public engagement in the GSP development process. It is designed to be a living document that is updated as needed to reflect current mechanism of engagement. The GSP Implementation notification and communication phase will begin once the FCGMA submits the final GSP to DWR. This phase will include engagement with the public and beneficial users regarding the progress of monitoring and report, establishment of fees, and the development and implementation of management strategies including projects and actions as needed. FCGMA will continue to use the communication tools outlined in this document as necessary through the implementation phase of the GSP.

For additional information regarding the FCGMA and the GSP, Please Contact:

Jeff Pratt, P.E., Executive Officer of the FCGMA.
Phone: 805.654.2073
Email: Jeff.Pratt@ventura.org

Or

Keely Royas, Clerk of the FCGMA Board
Phone: 805.654.2014
Email: keely.royas@ventura.org

Mailing Address:
Fox Canyon Groundwater Management Agency
800 South Victoria Avenue
Ventura, California 93009-1610

Website: www.FCGMA.org

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APPENDIX C

Water Elevation Hydrographs

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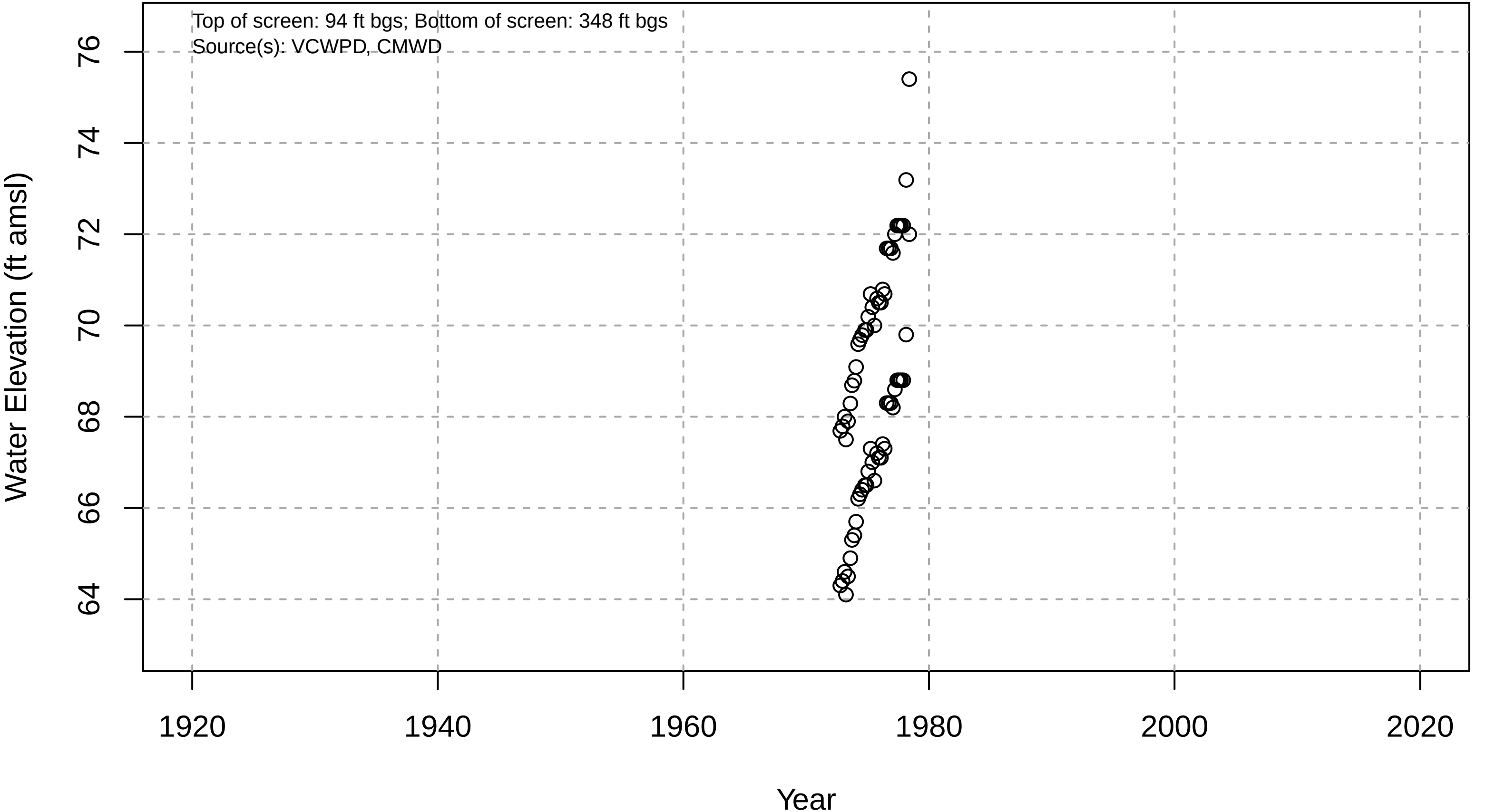

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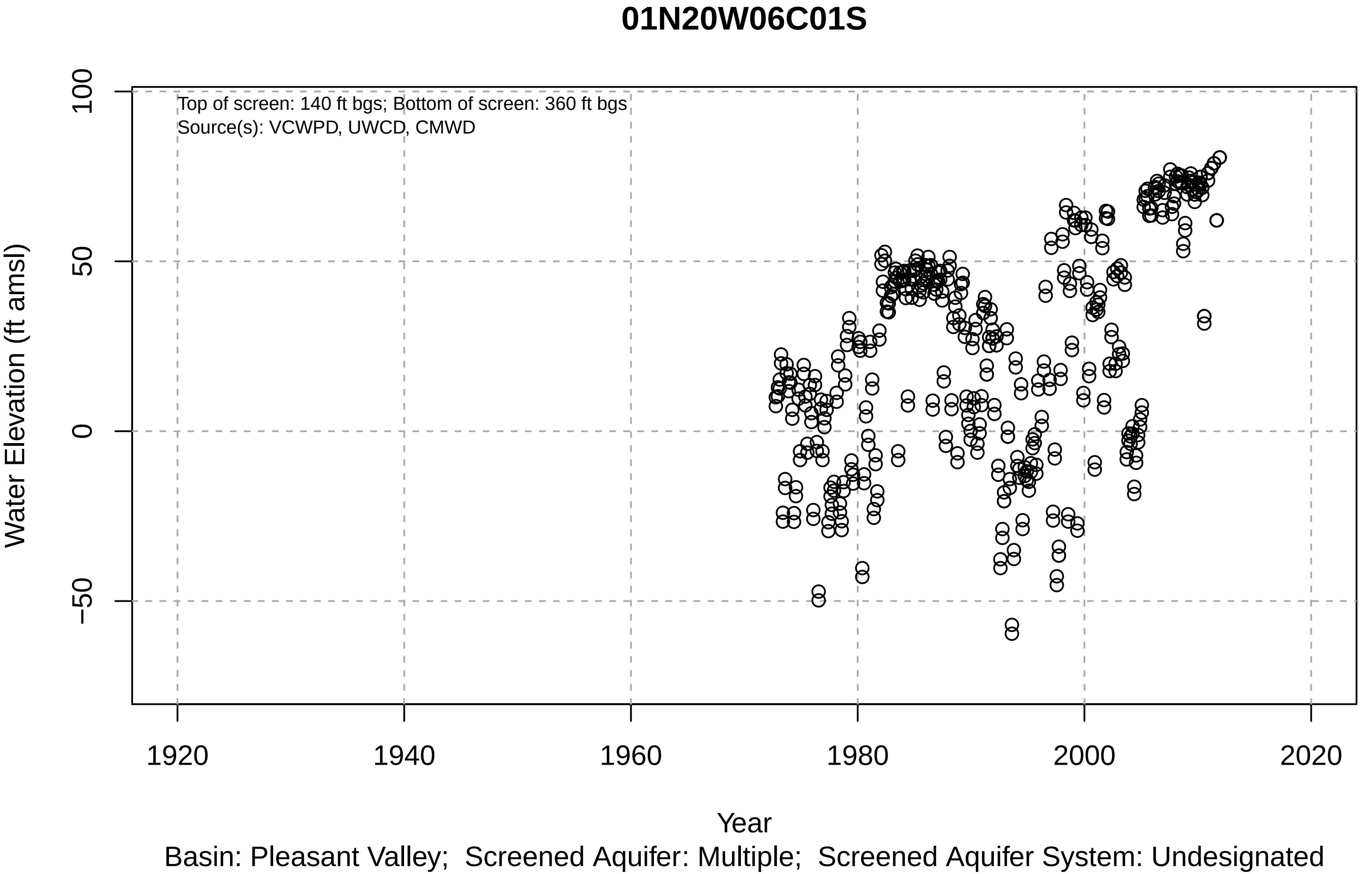
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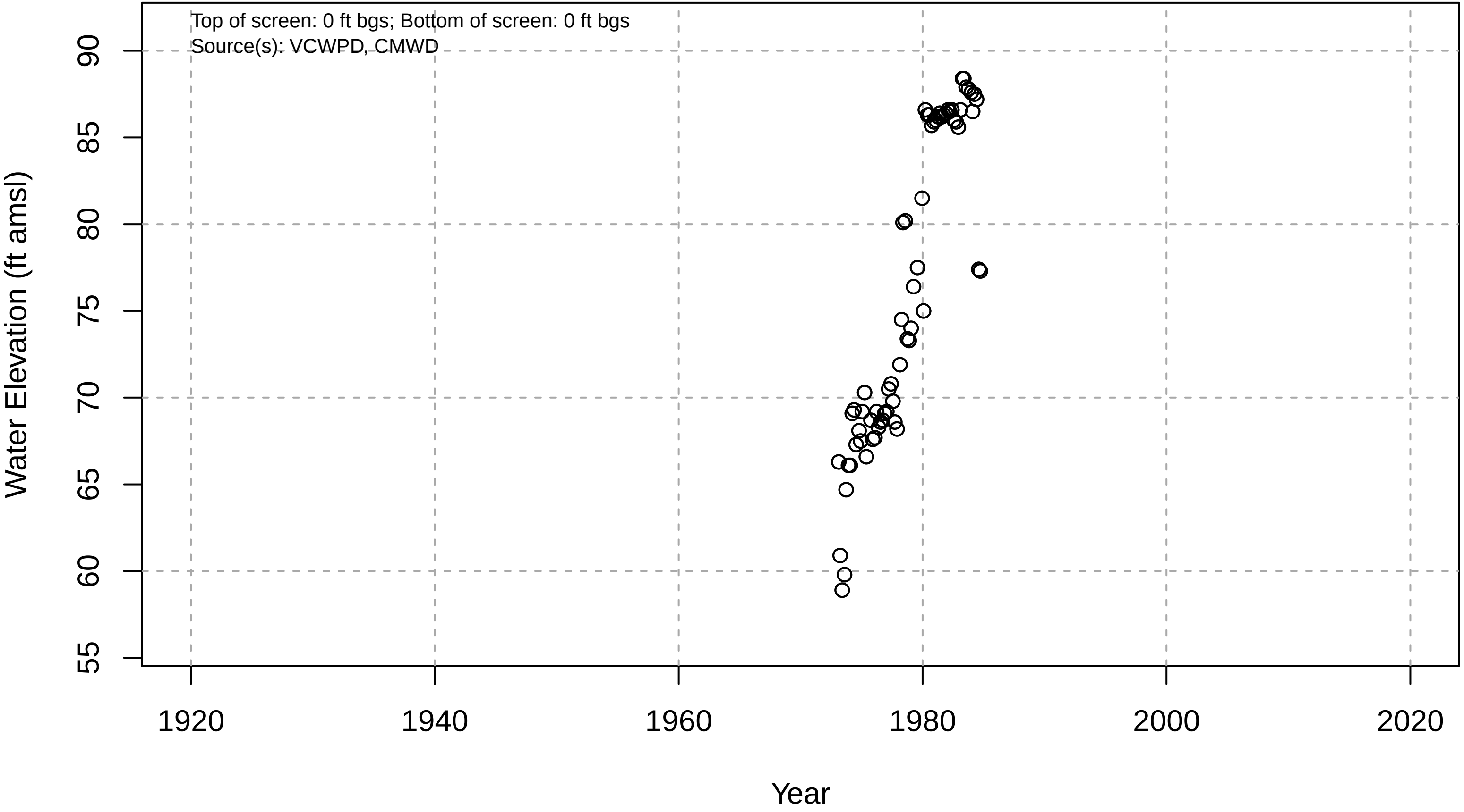

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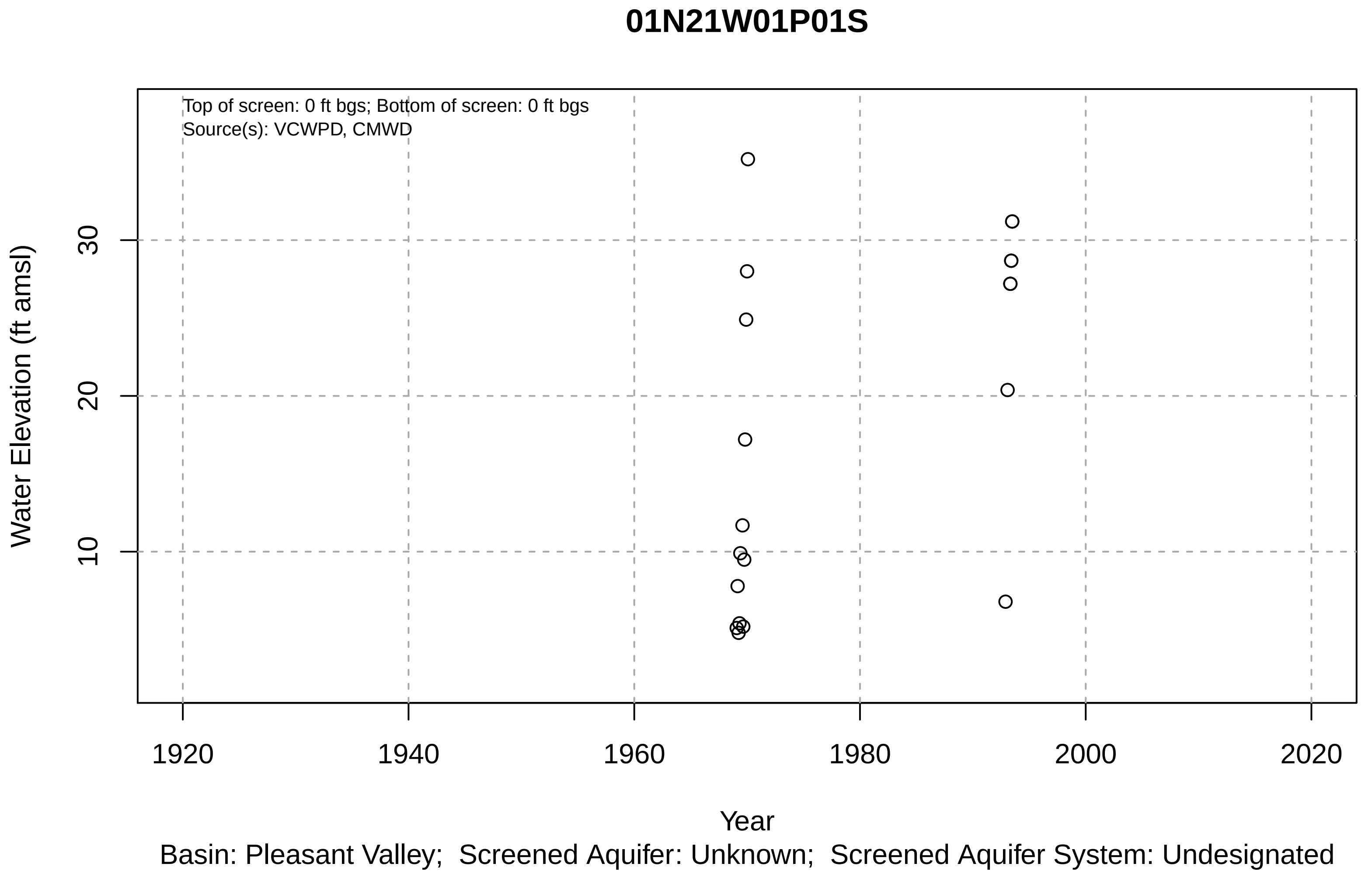
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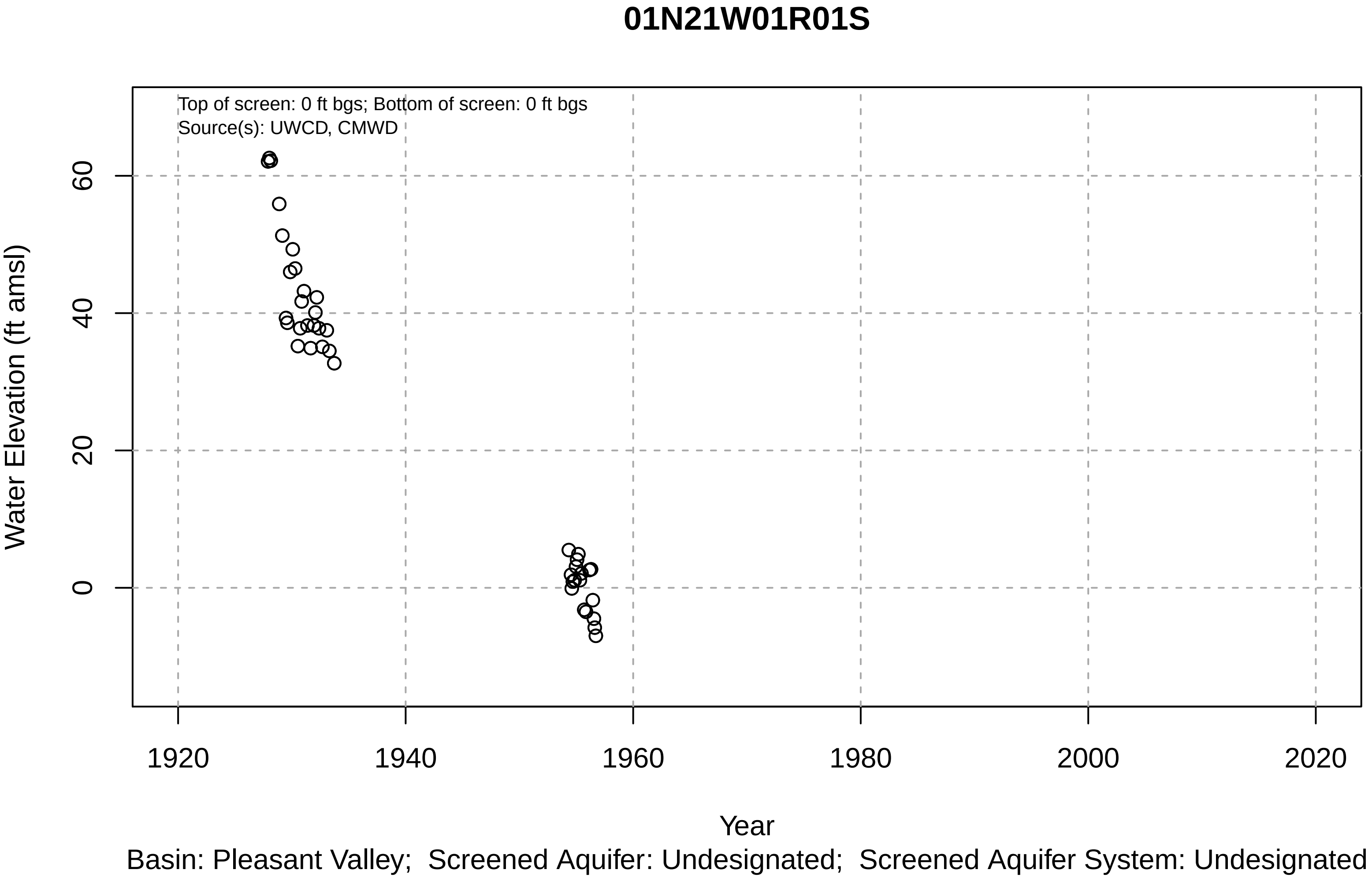

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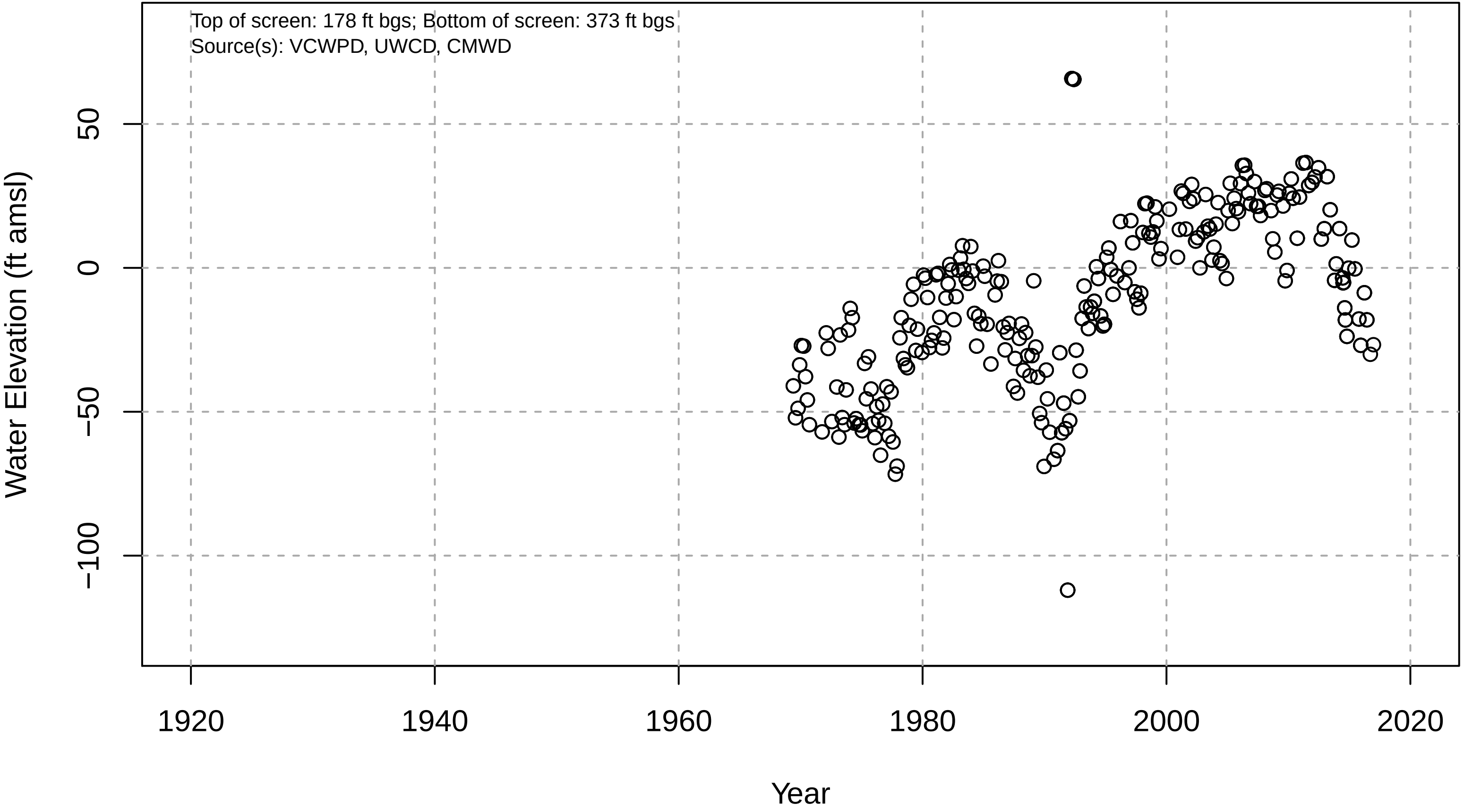

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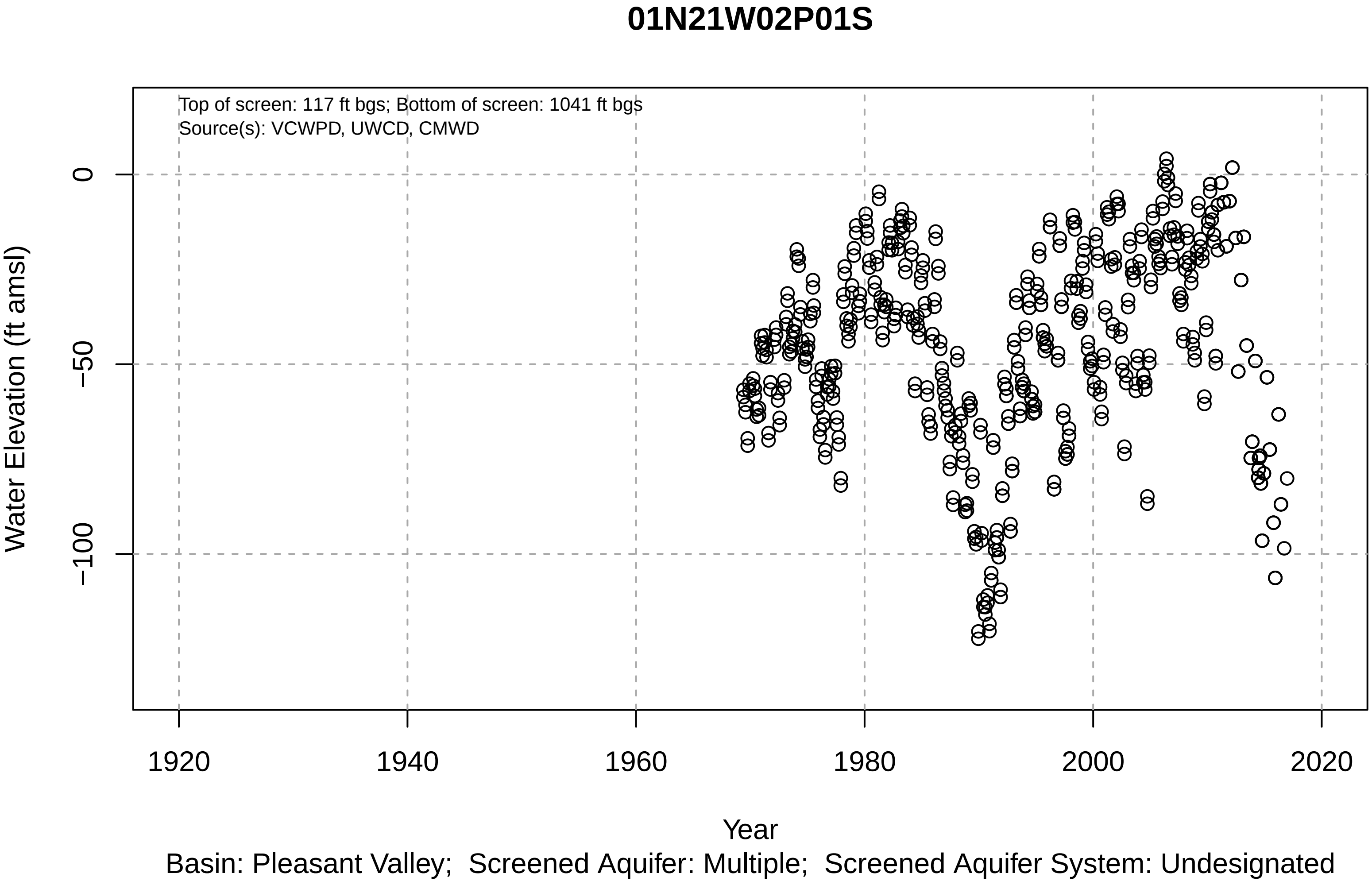
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Year
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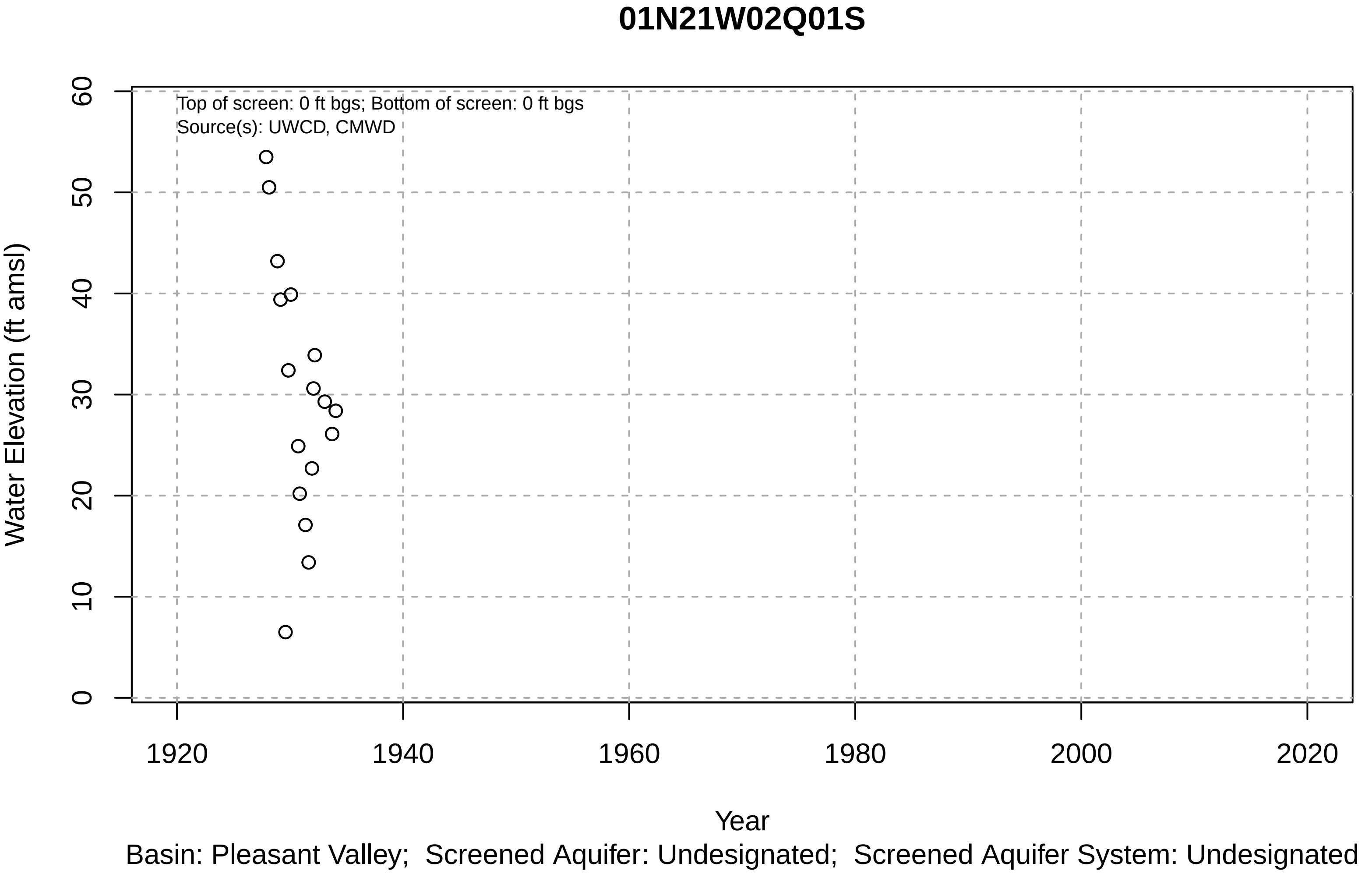
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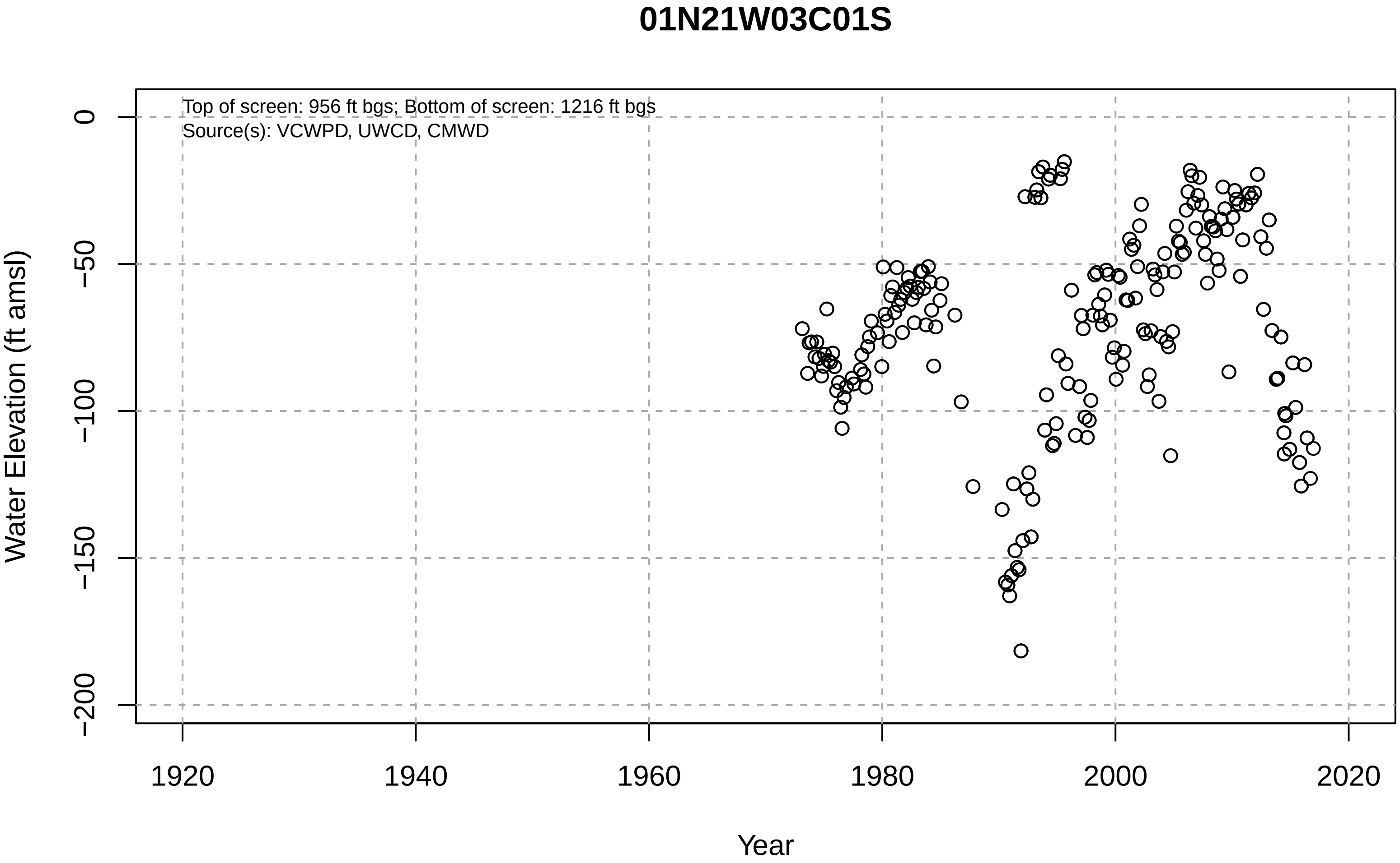

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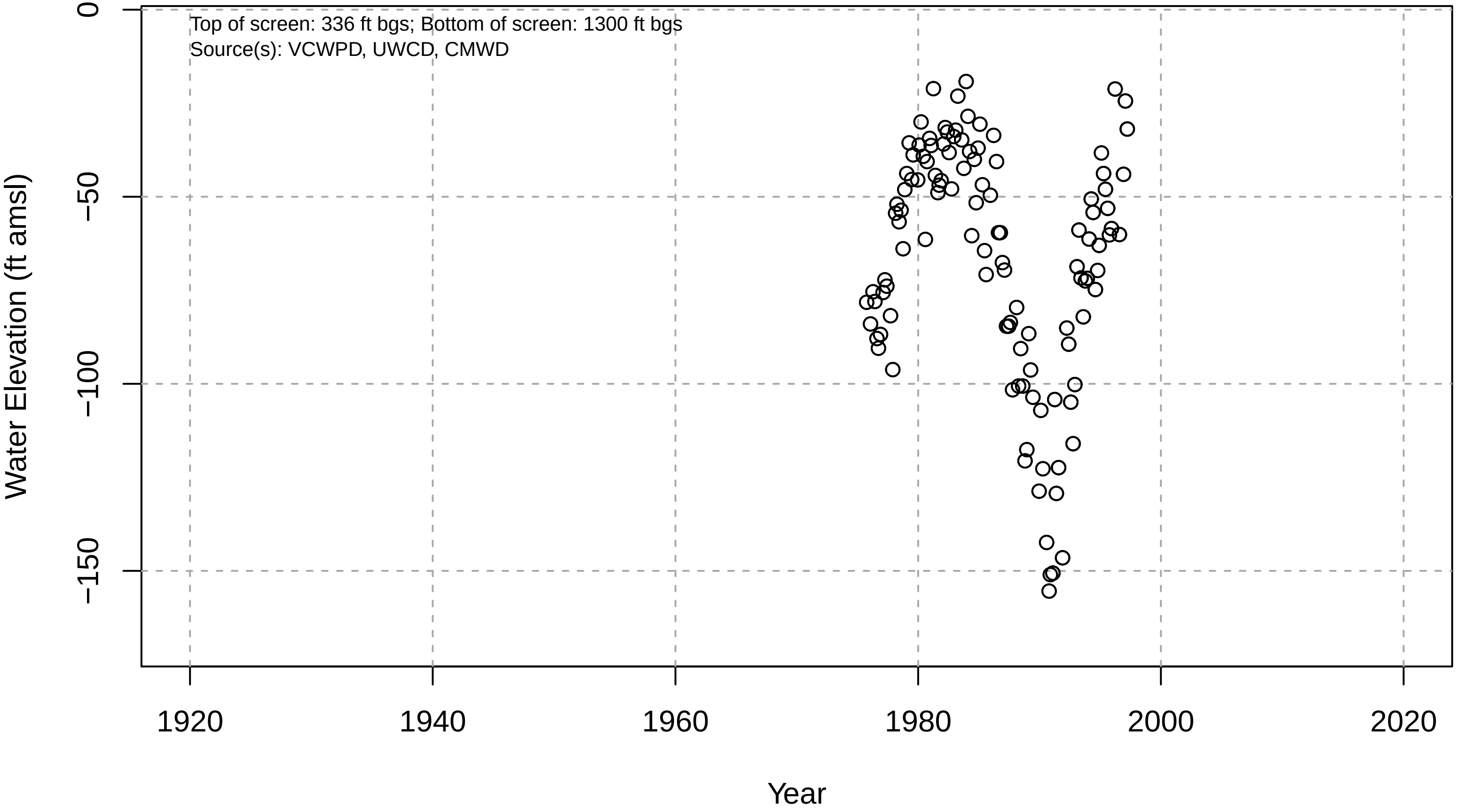

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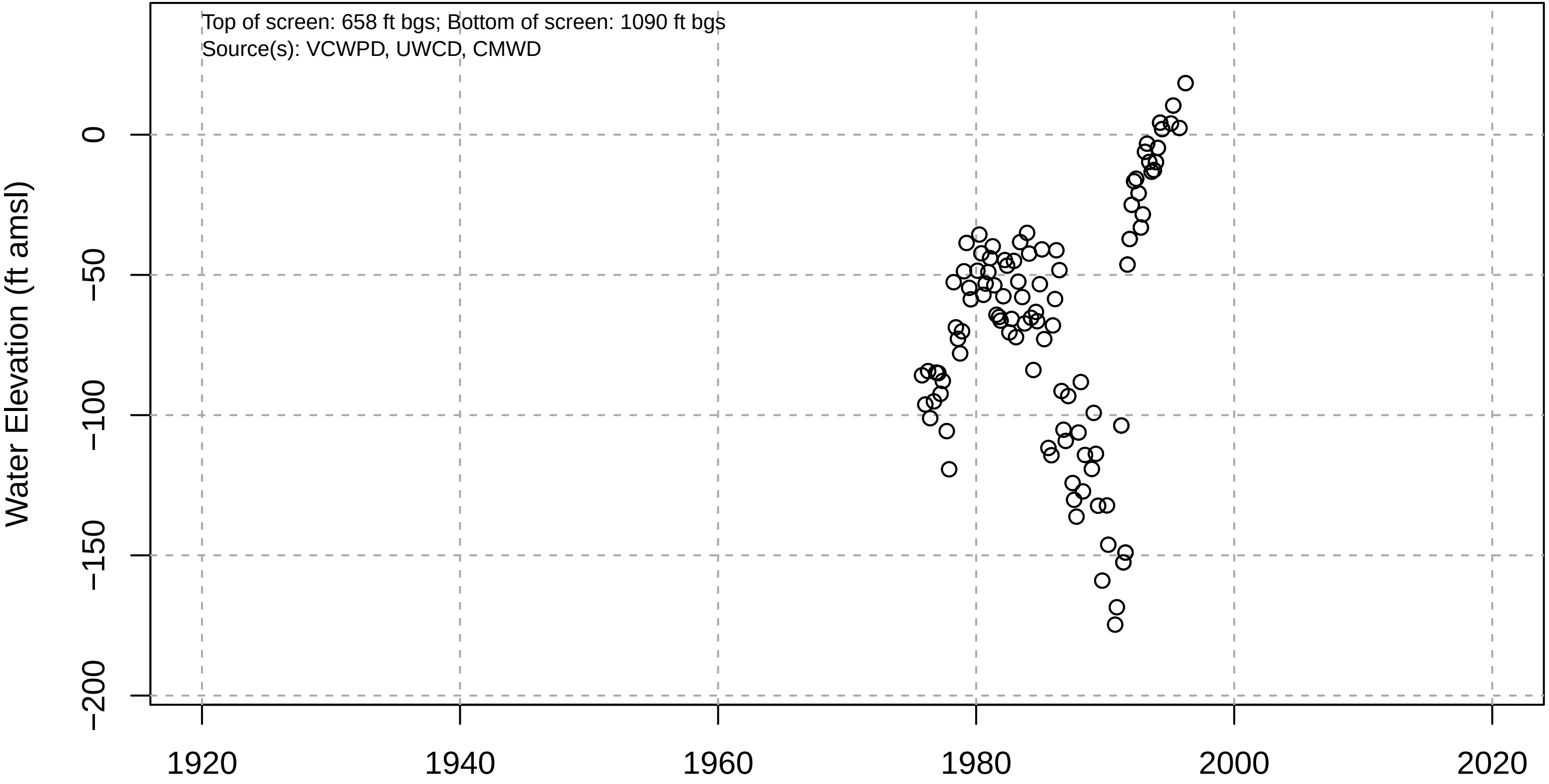

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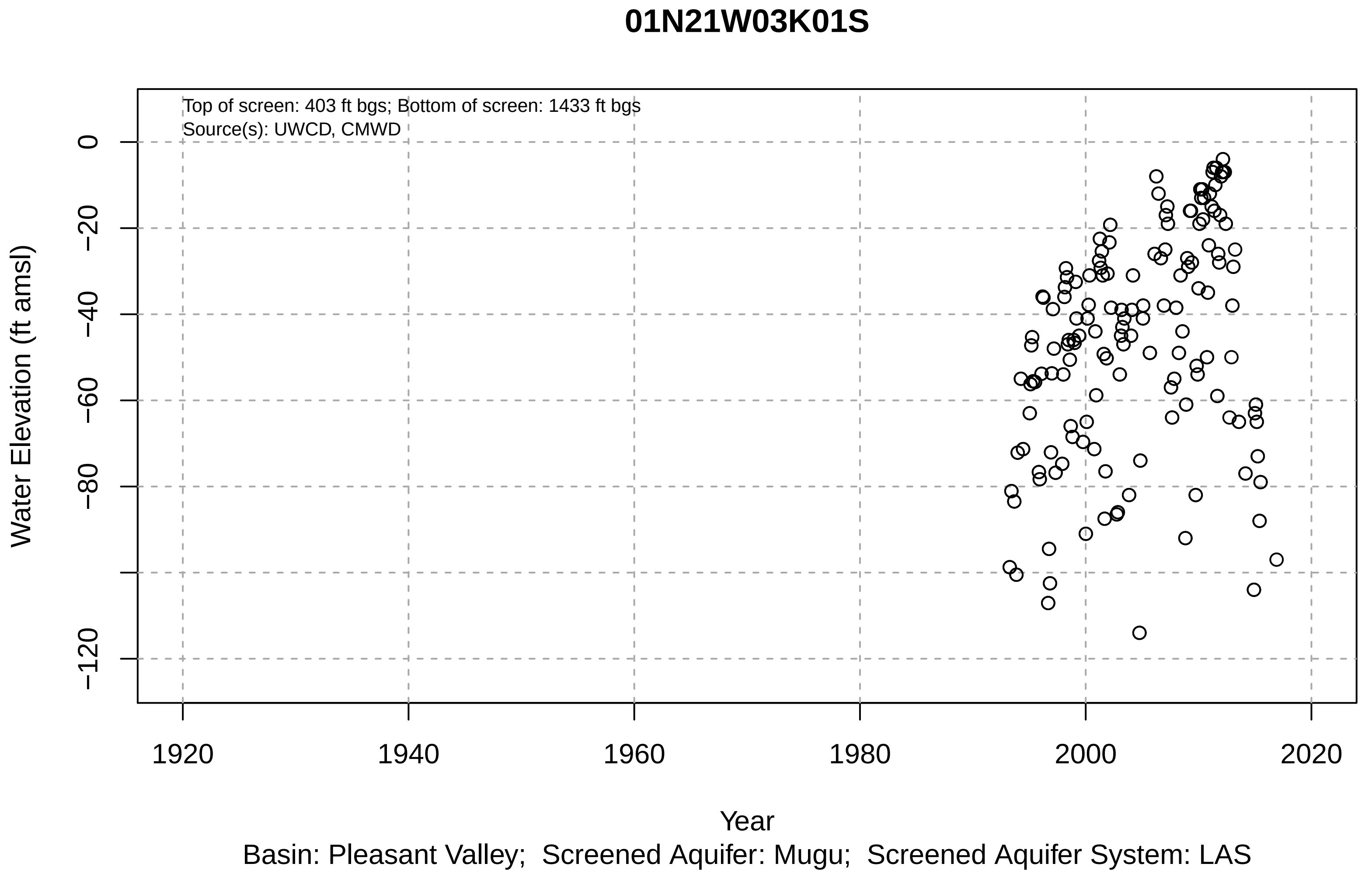01N21W03K01S
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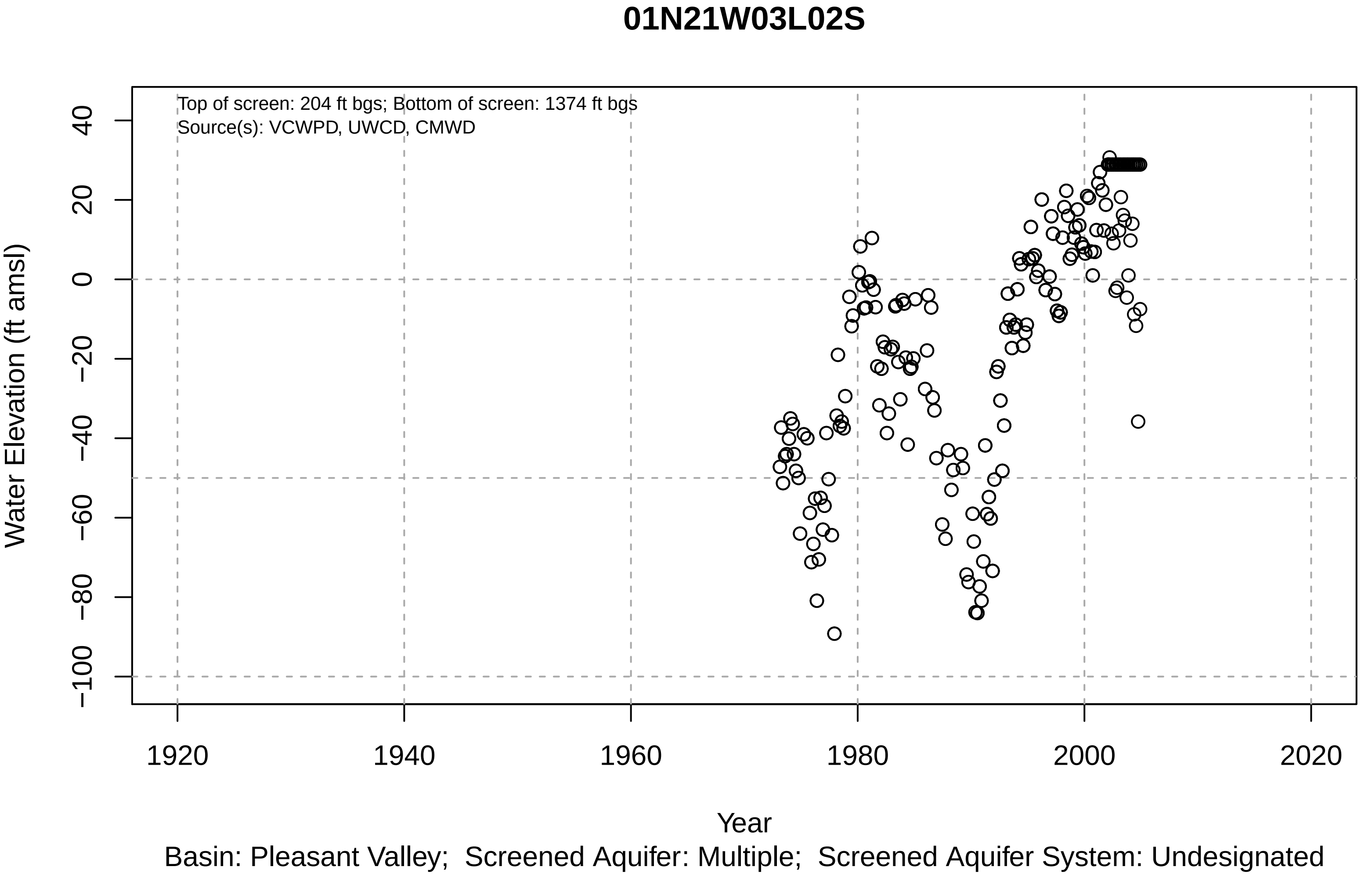
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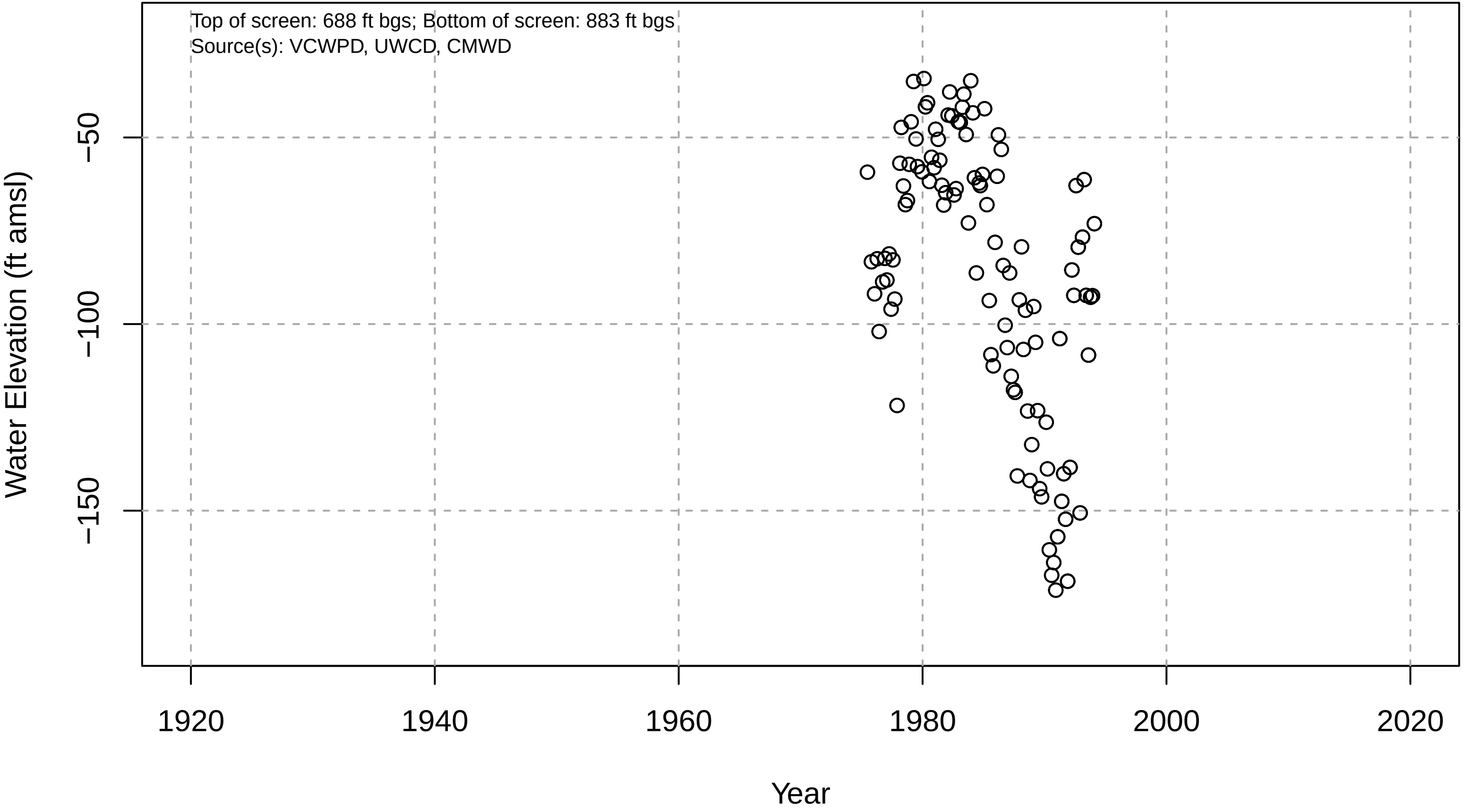

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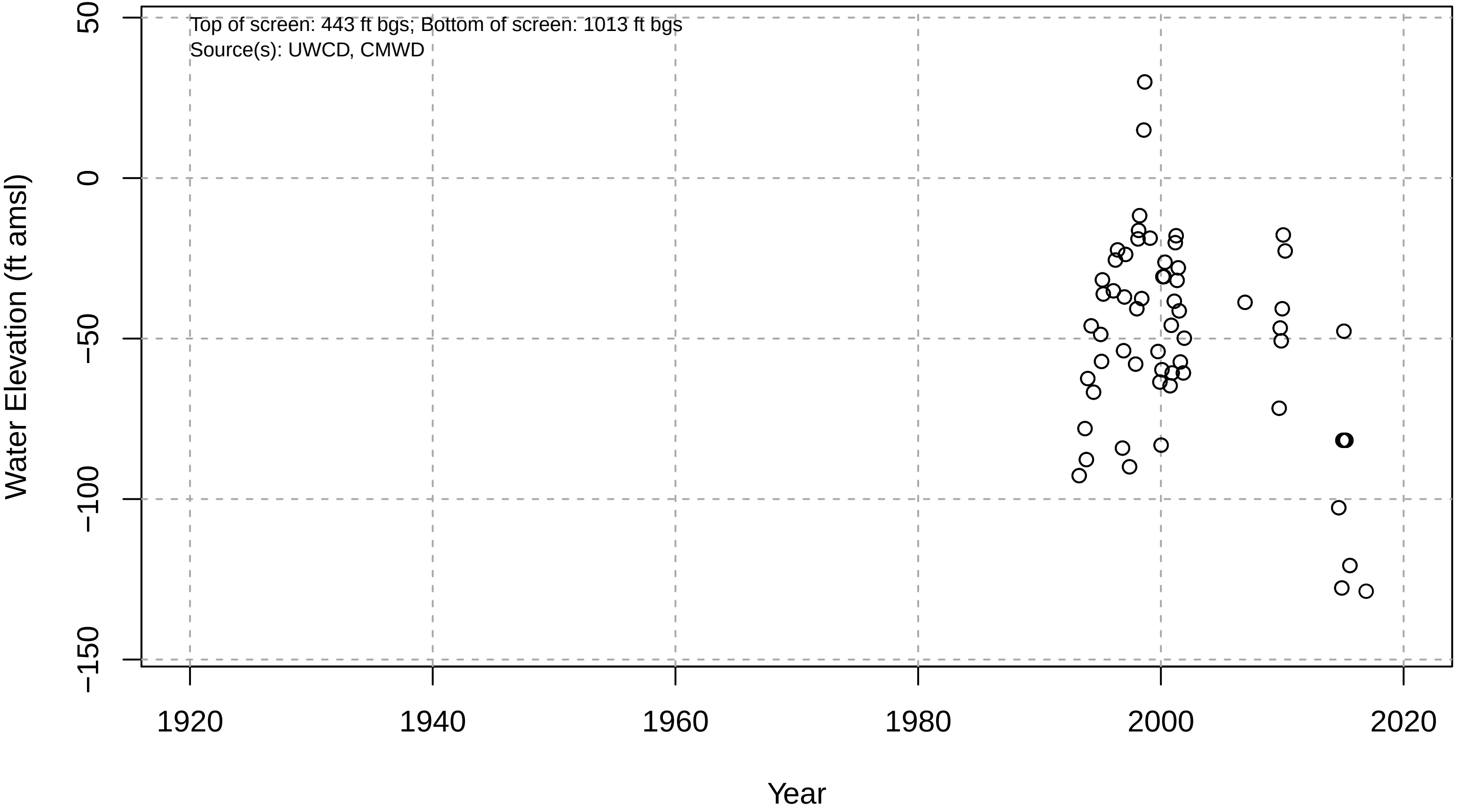
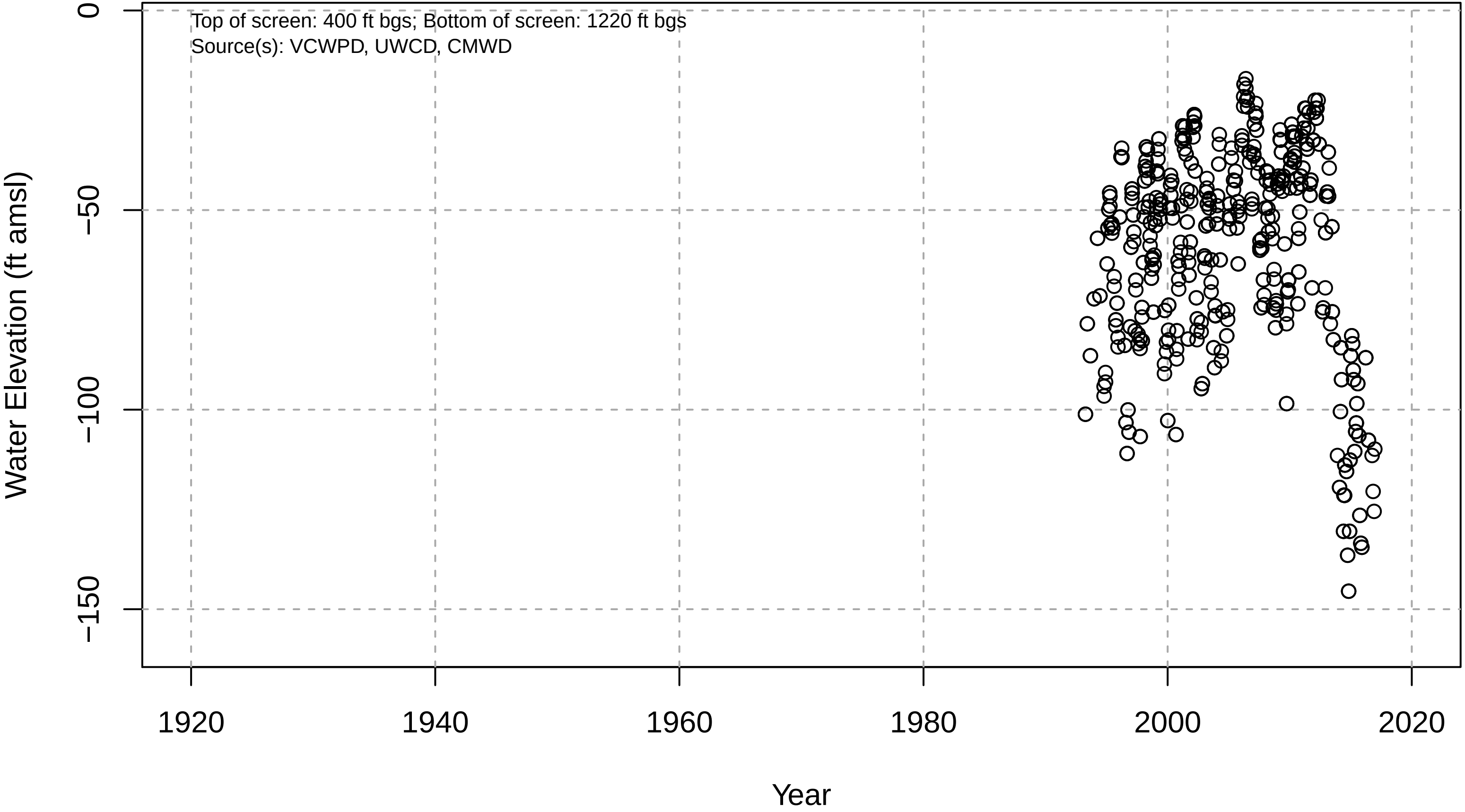


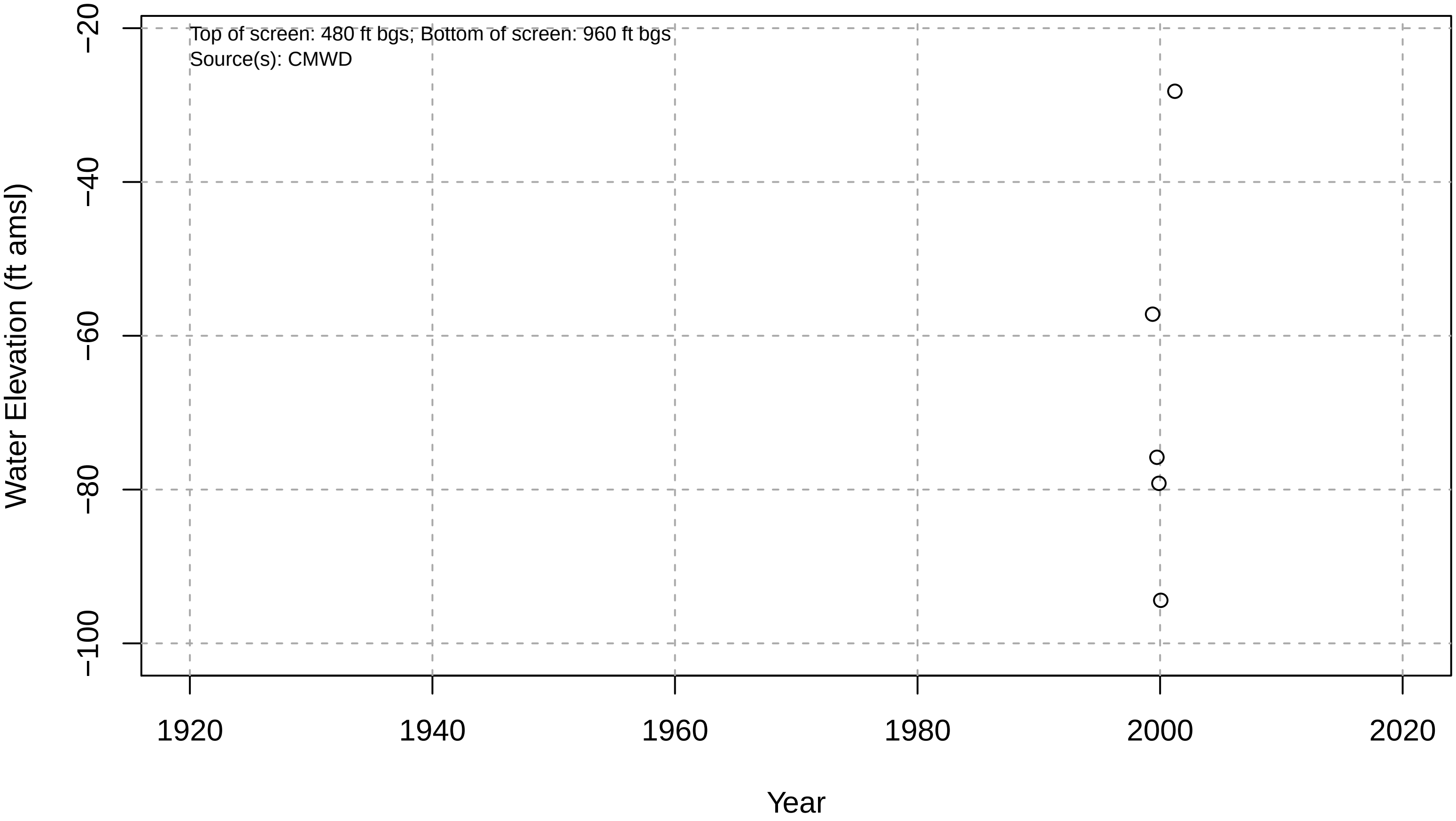
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS

01N21W04K01S



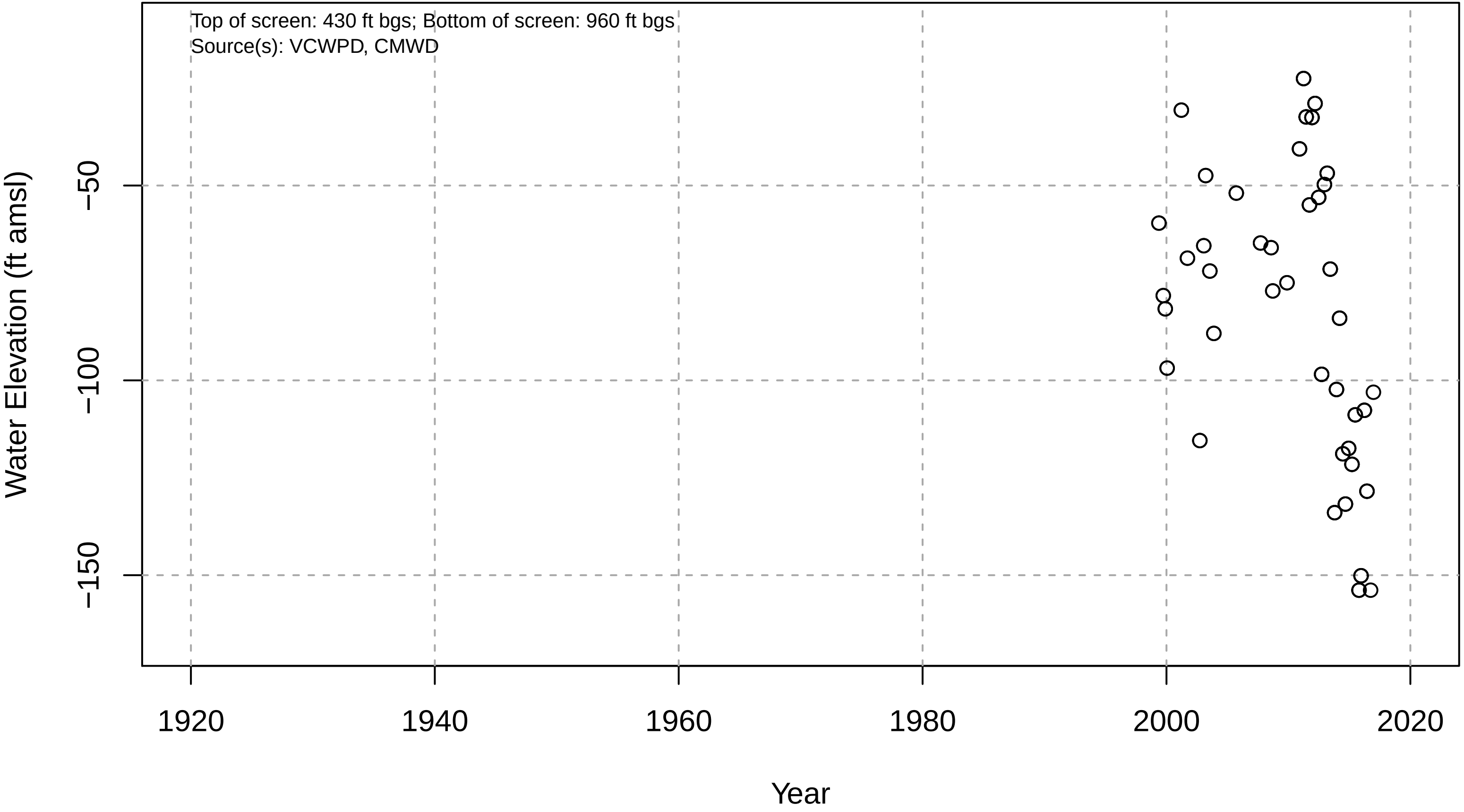
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS

01N21W09J02S

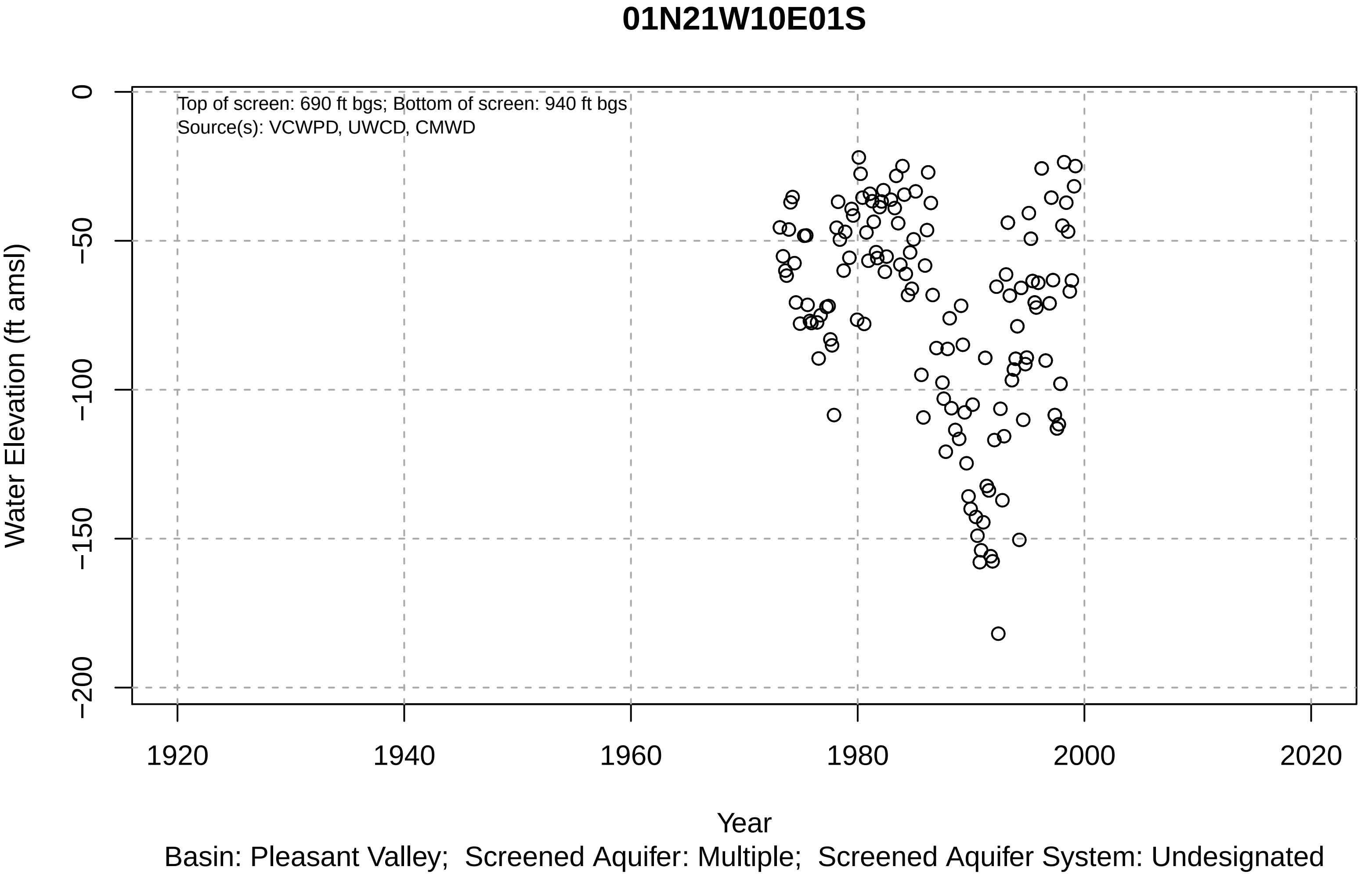


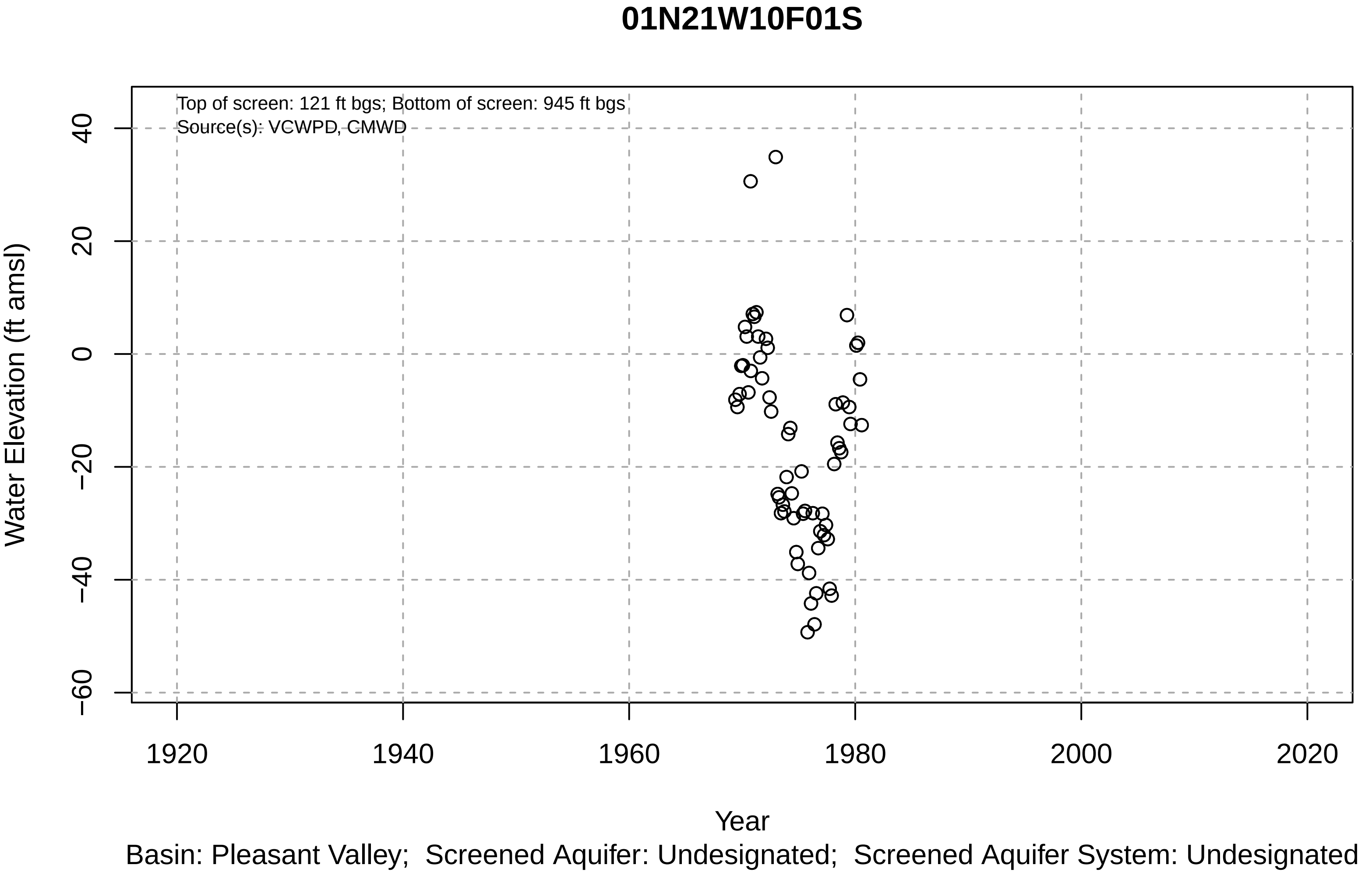
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

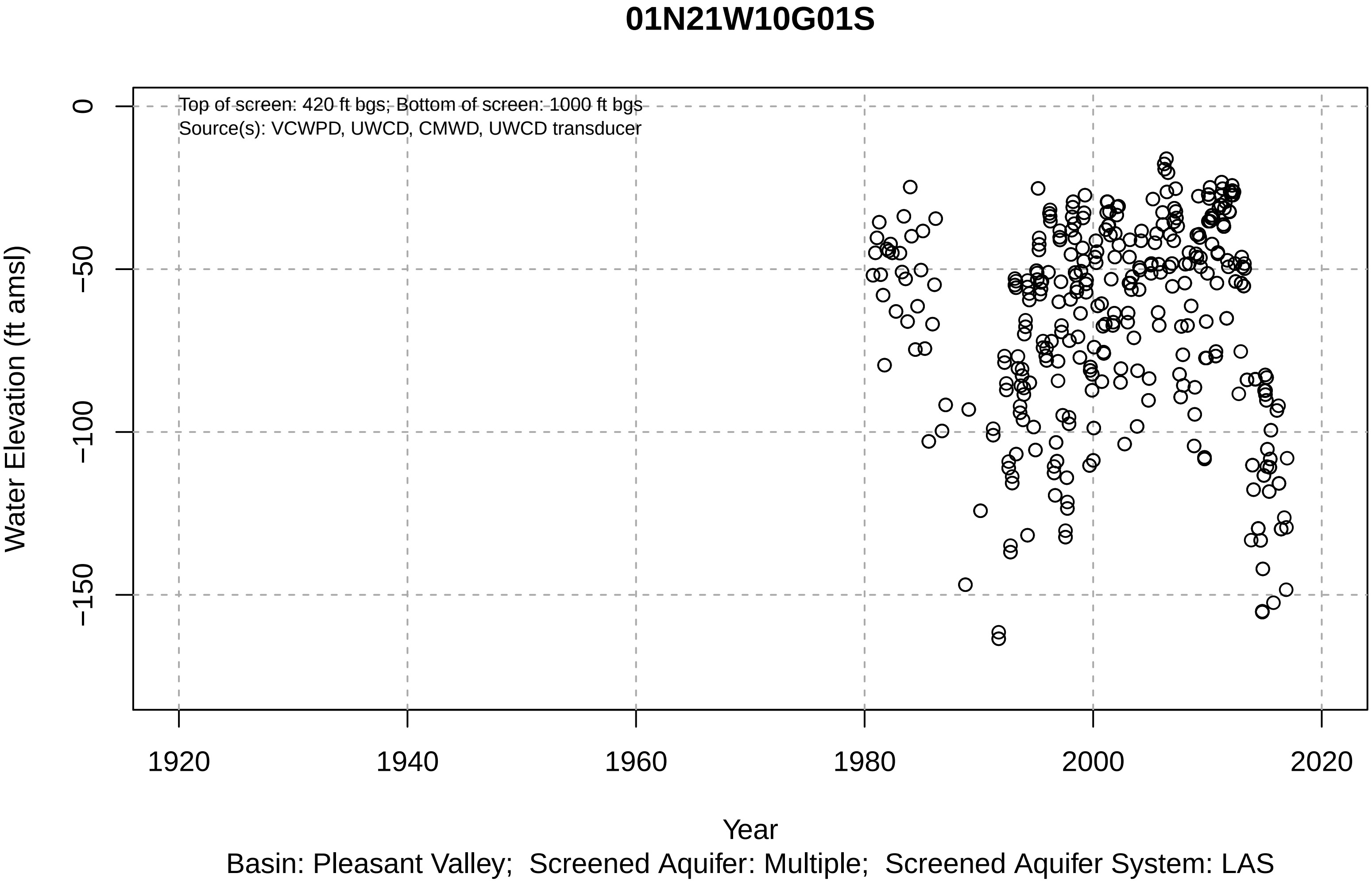
01N21W09J03S

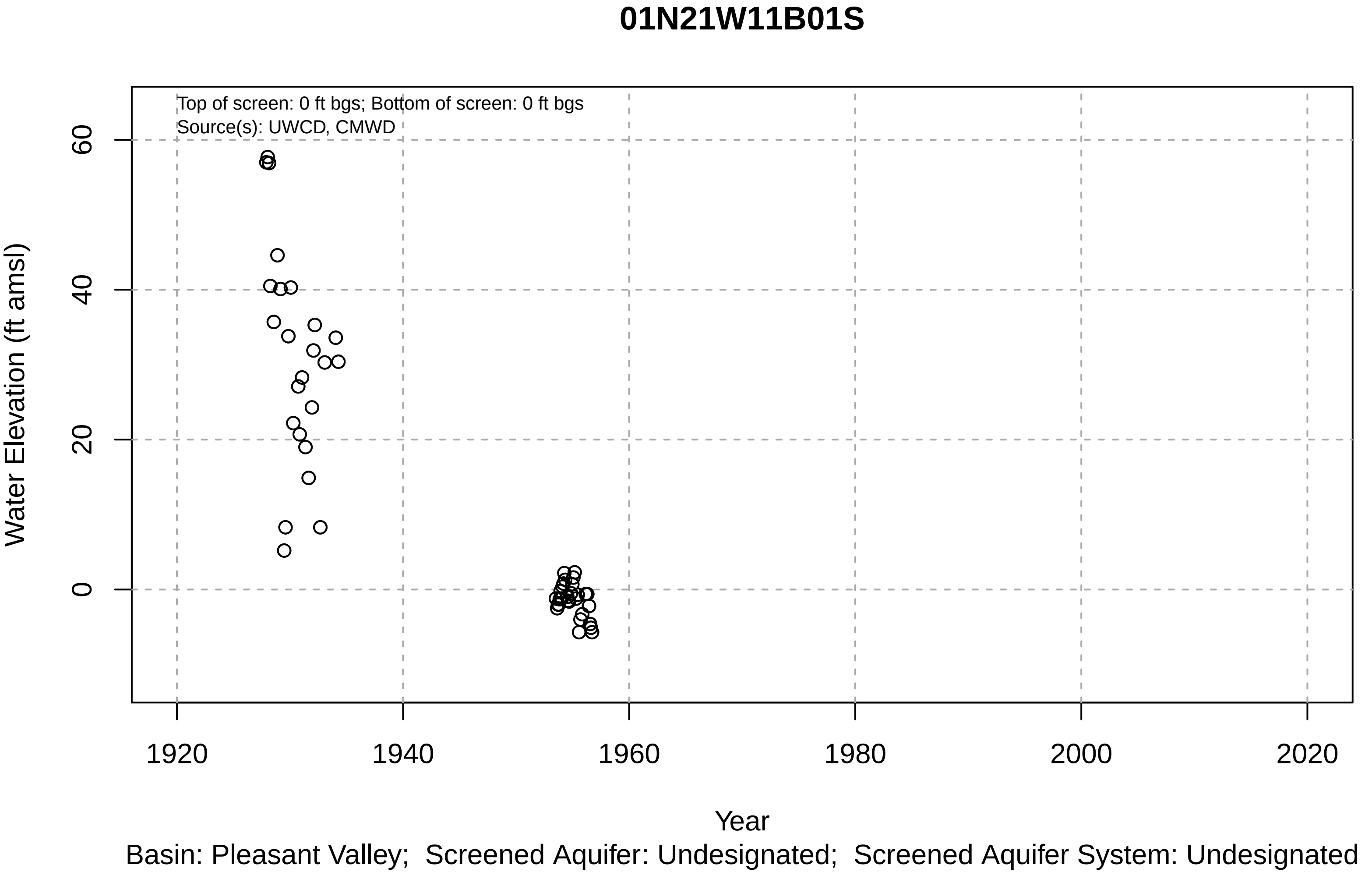


Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS

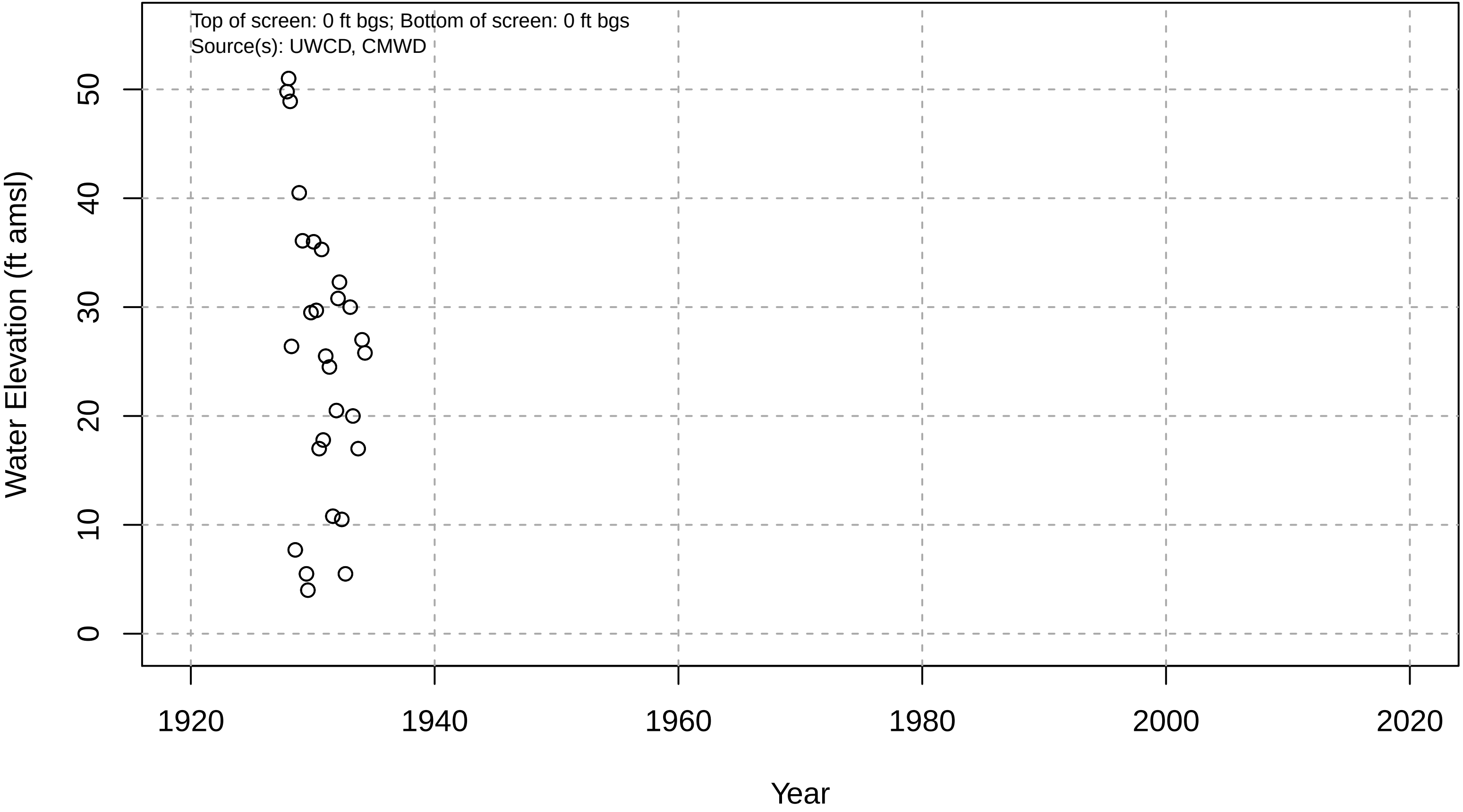

01N21W10E01S
Top of screen: 690 ft bgs; Bottom of screen: 940 ft bgs
Source(s): VCWPD, UWCD, CMWD
Water Elevation (ft amsl)
0
−50
−100
−150
−200
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated


01N21W10F01S
Top of screen: 121 ft bgs; Bottom of screen: 945 ft bgs
Source(s): VCWPD, CMWD
Water Elevation (ft amsl)
40
20
0
−20
−40
−60
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

01N21W10G01S
Top of screen: 420 ft bgs; Bottom of screen: 1000 ft bgs
Source(s): VCWPD, UWCD, CMWD, UWCD transducer
Water Elevation (ft amsl)
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS

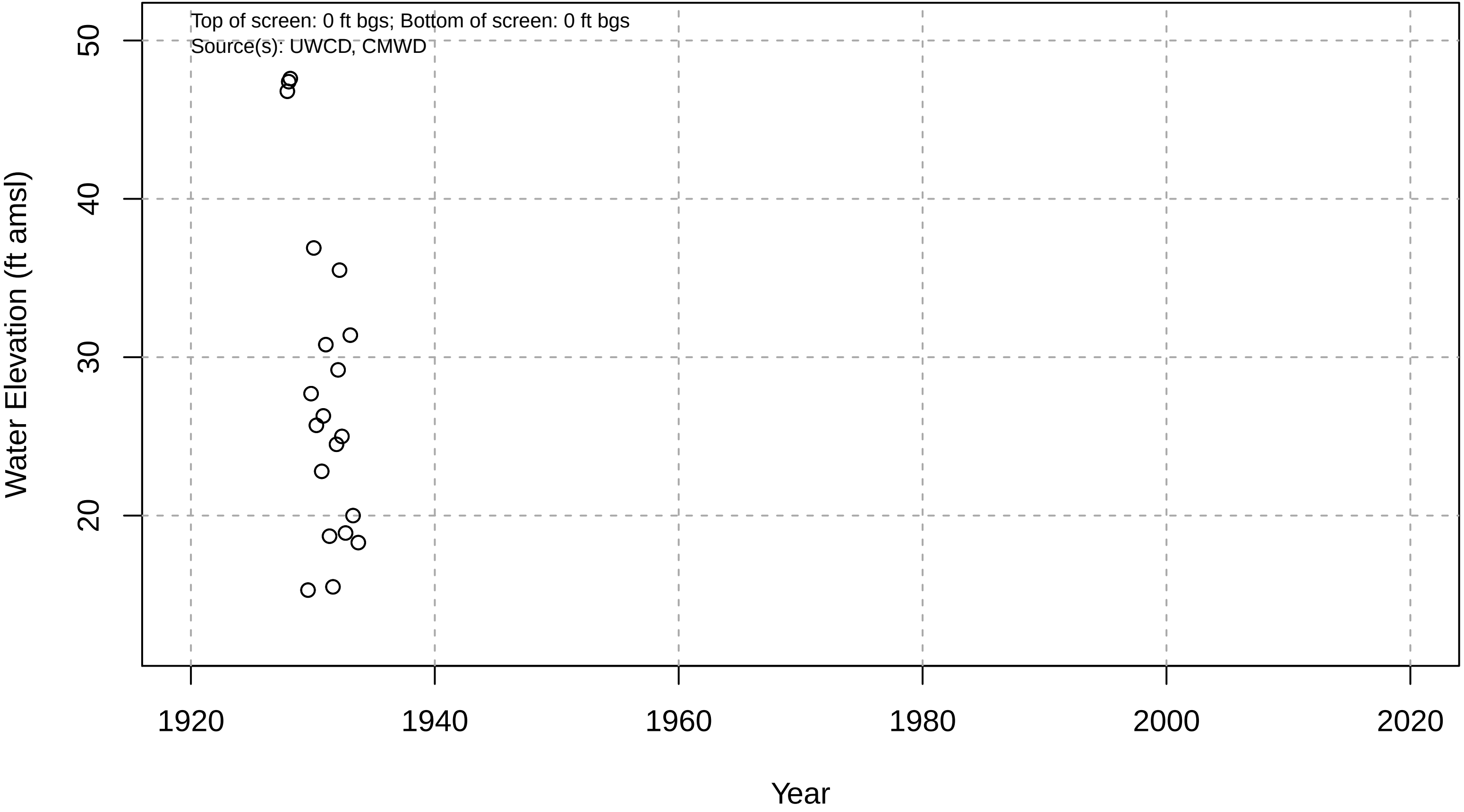

01N21W11B01S
Top of screen: 0 ft bgs; Bottom of screen: 0 ft bgs
Source(s): UWCD, CMWD
Water Elevation (ft amsl)
60
40
20
0
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

01N21W11G02S



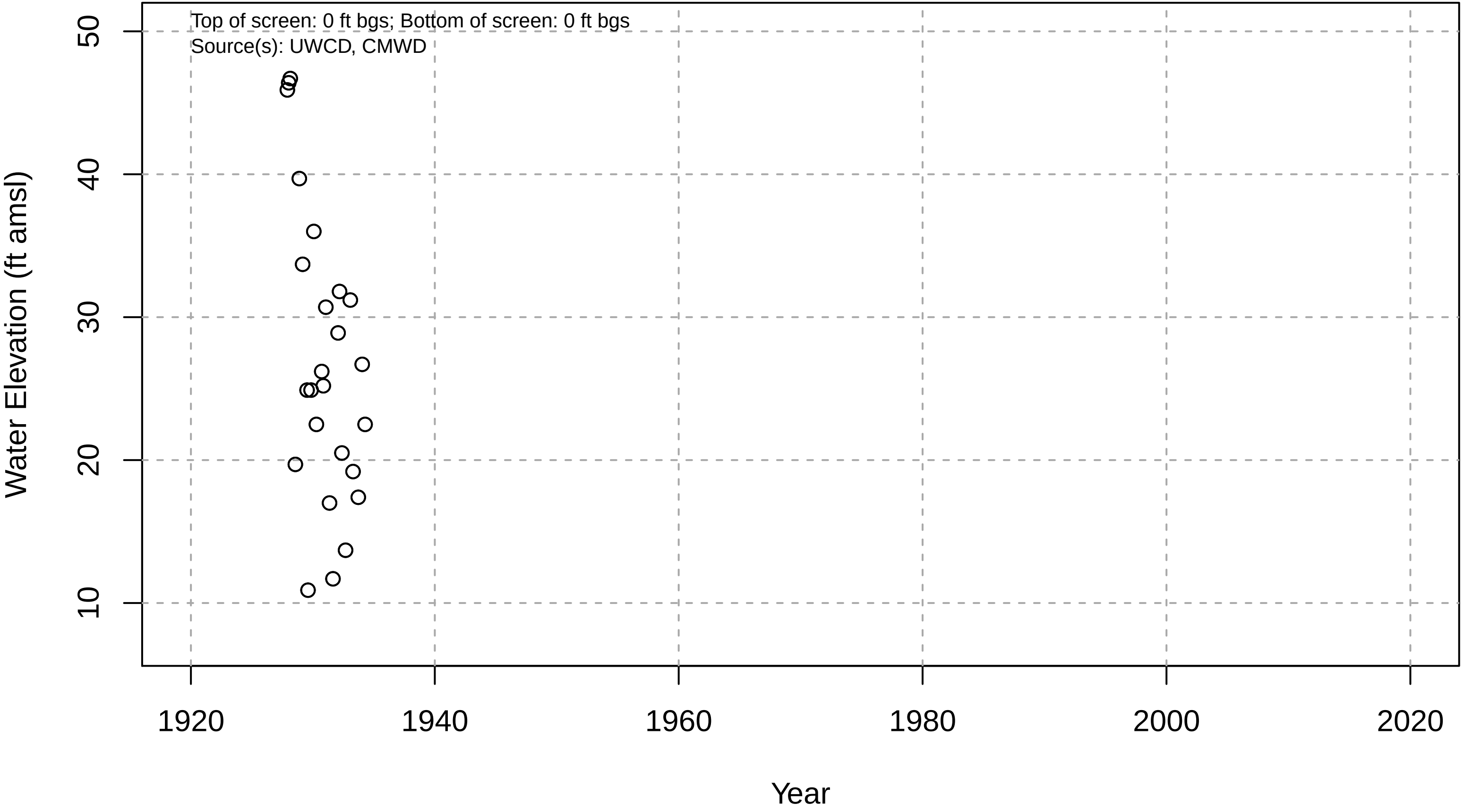
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

01N21W11J01S

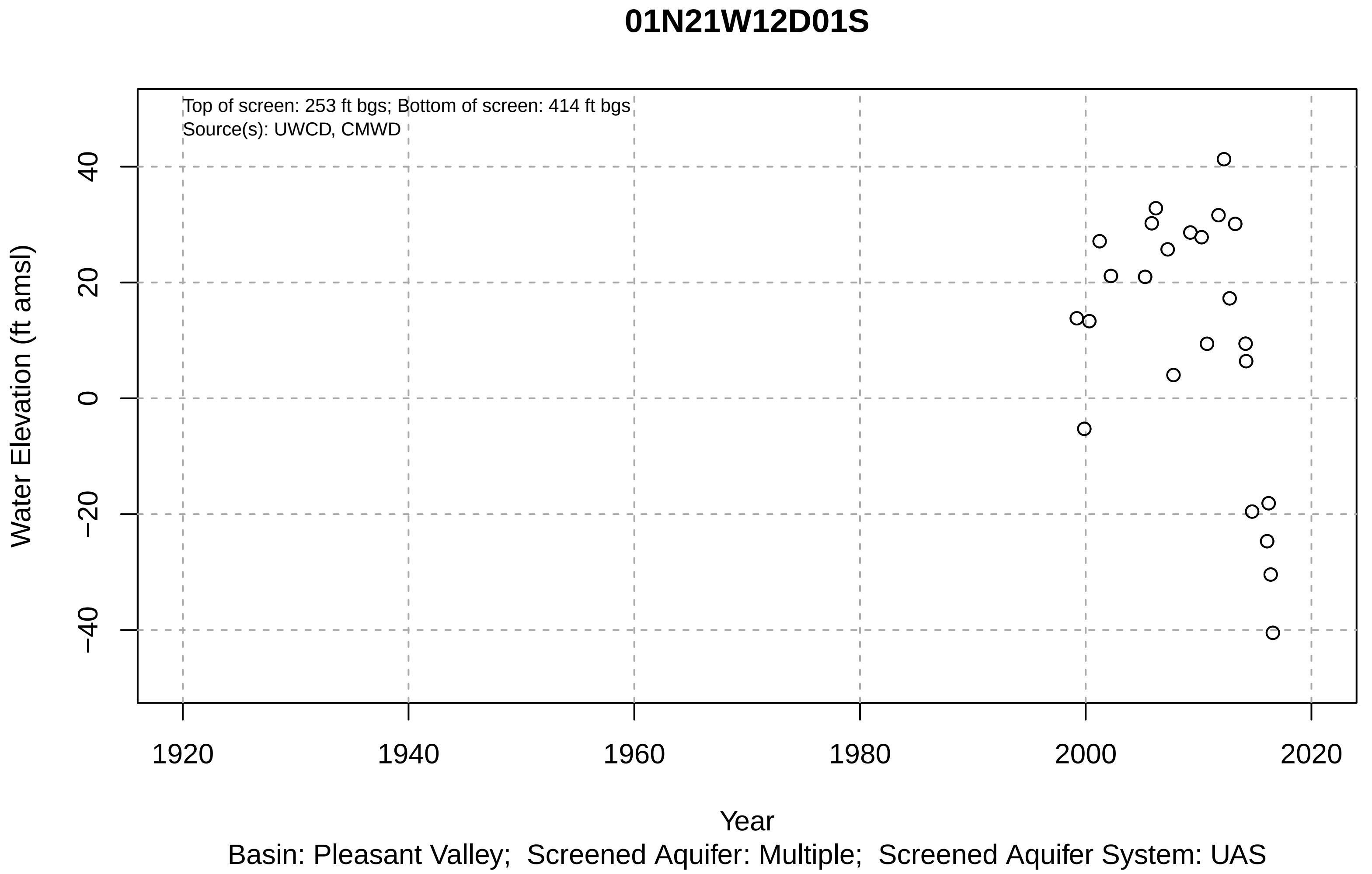


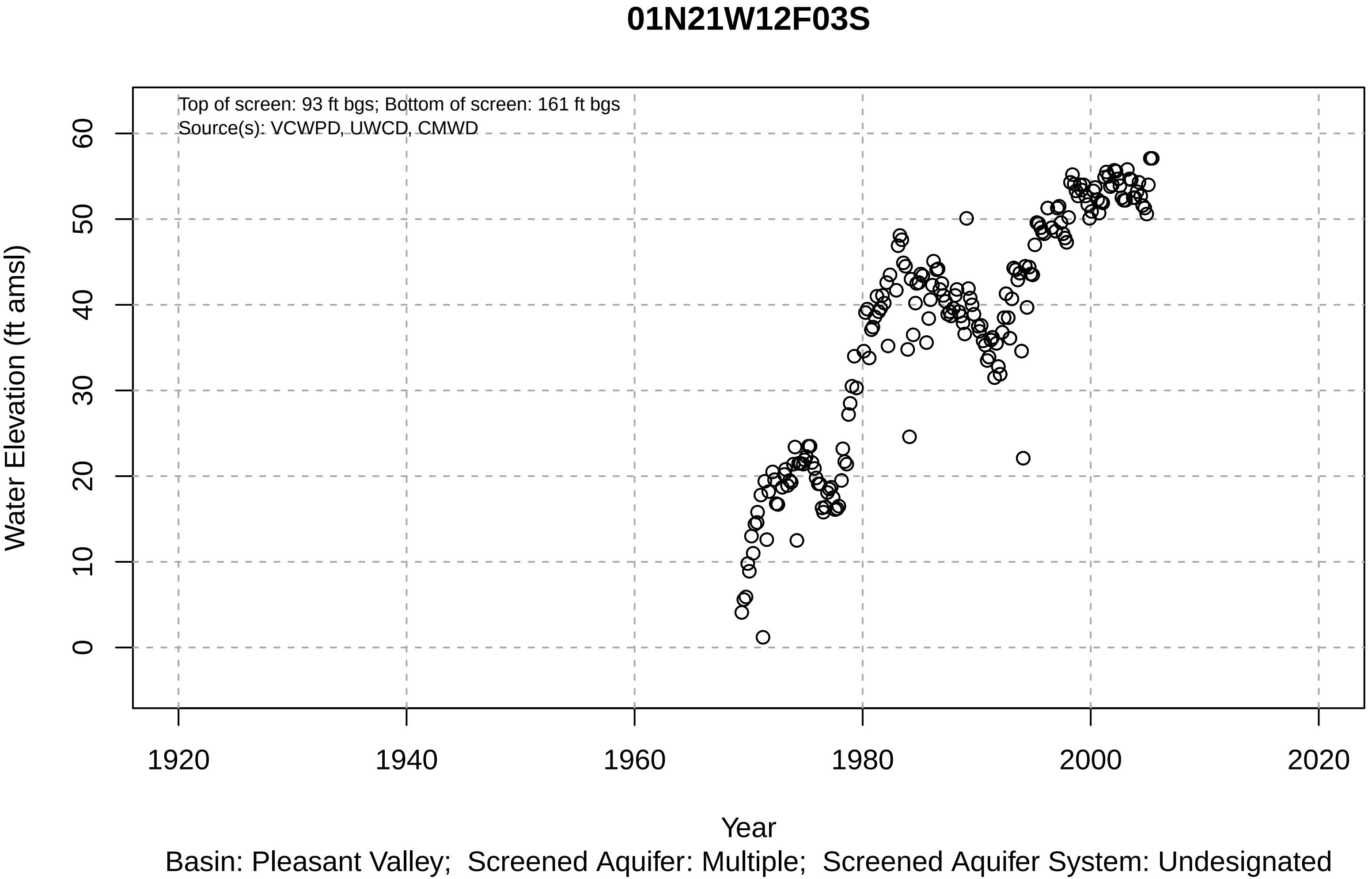
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

01N21W11R01S

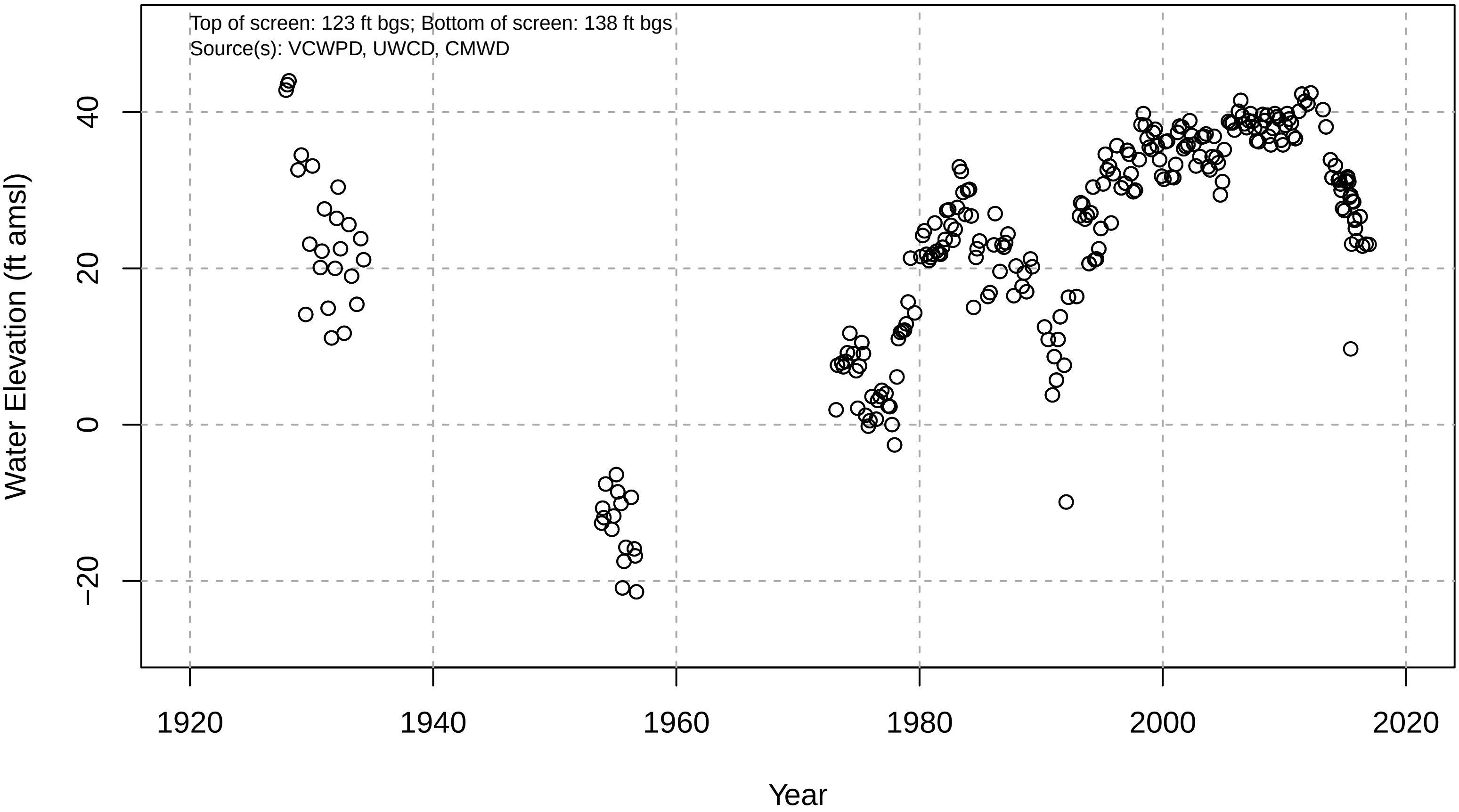


Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

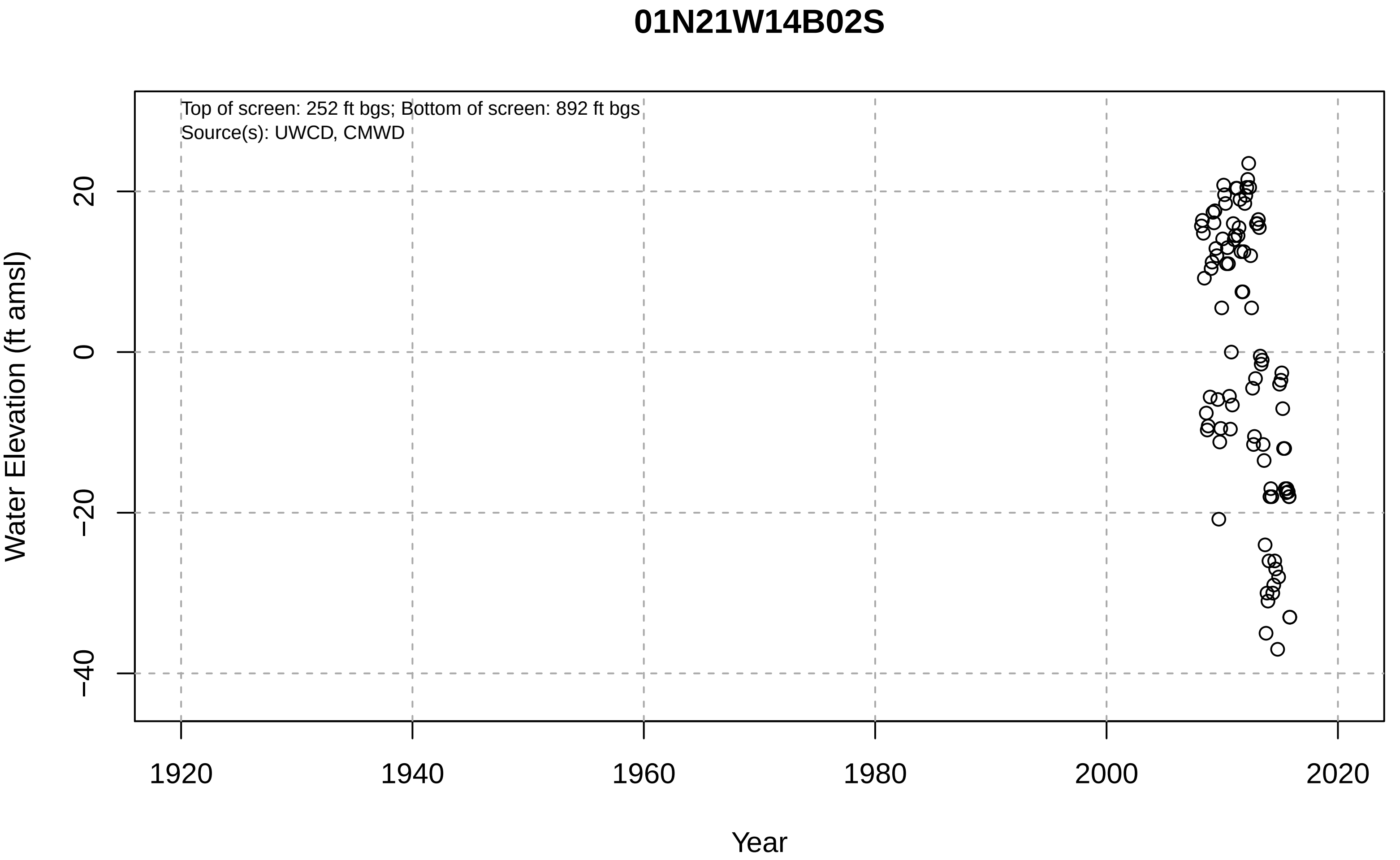

01N21W12D01S
Top of screen: 253 ft bgs; Bottom of screen: 414 ft bgs
Source(s): UWCD, CMWD
Water Elevation (ft amsl)
40
20
0
−20
−40
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: UAS


01N21W12F03S
Top of screen: 93 ft bgs; Bottom of screen: 161 ft bgs
Source(s): VCWPD, UWCD, CMWD
Water Elevation (ft amsl)
0
10
20
30
40
50
60
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

01N21W14A01S

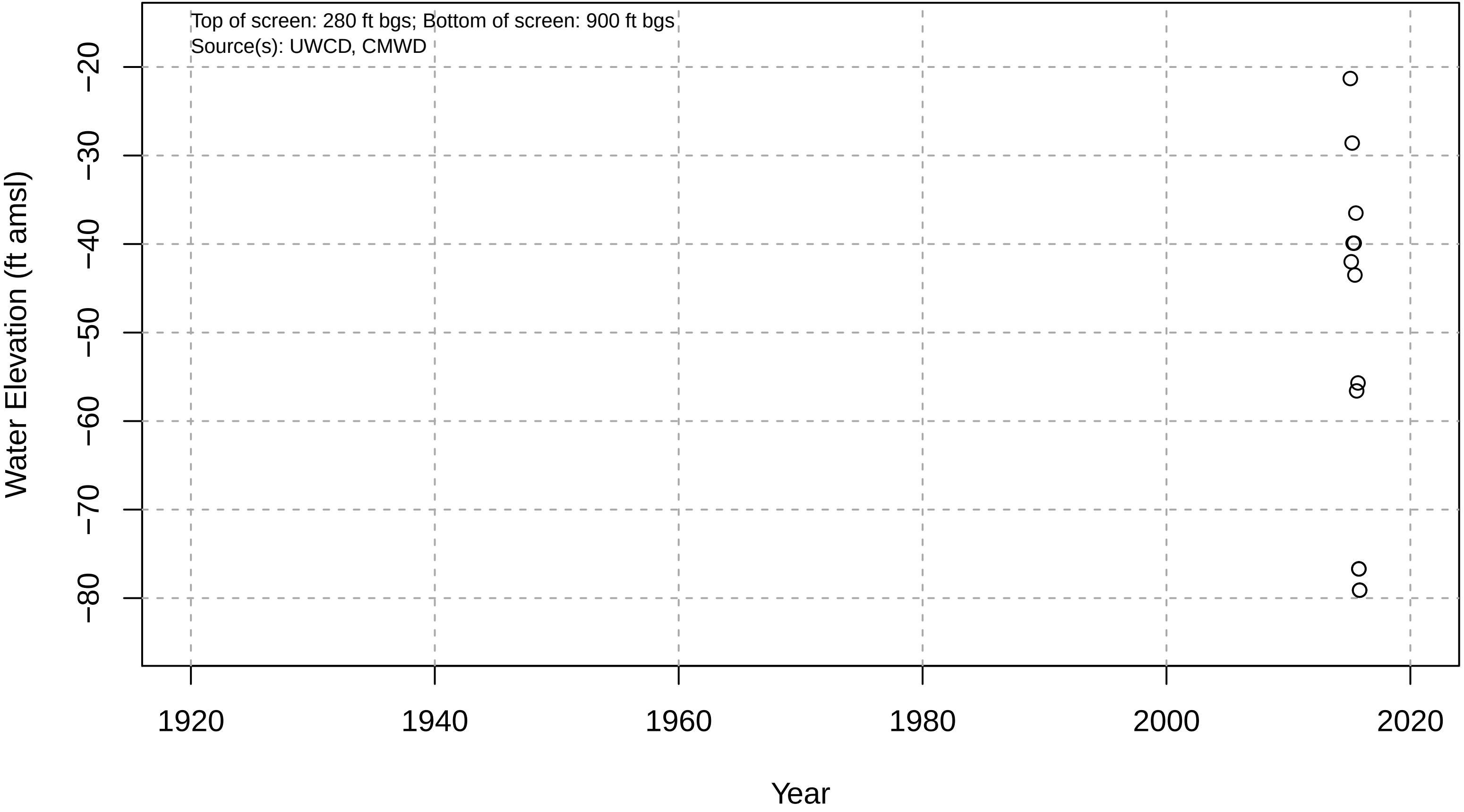


Basin: Pleasant Valley; Screened Aquifer: Unknown; Screened Aquifer System: Undesignated

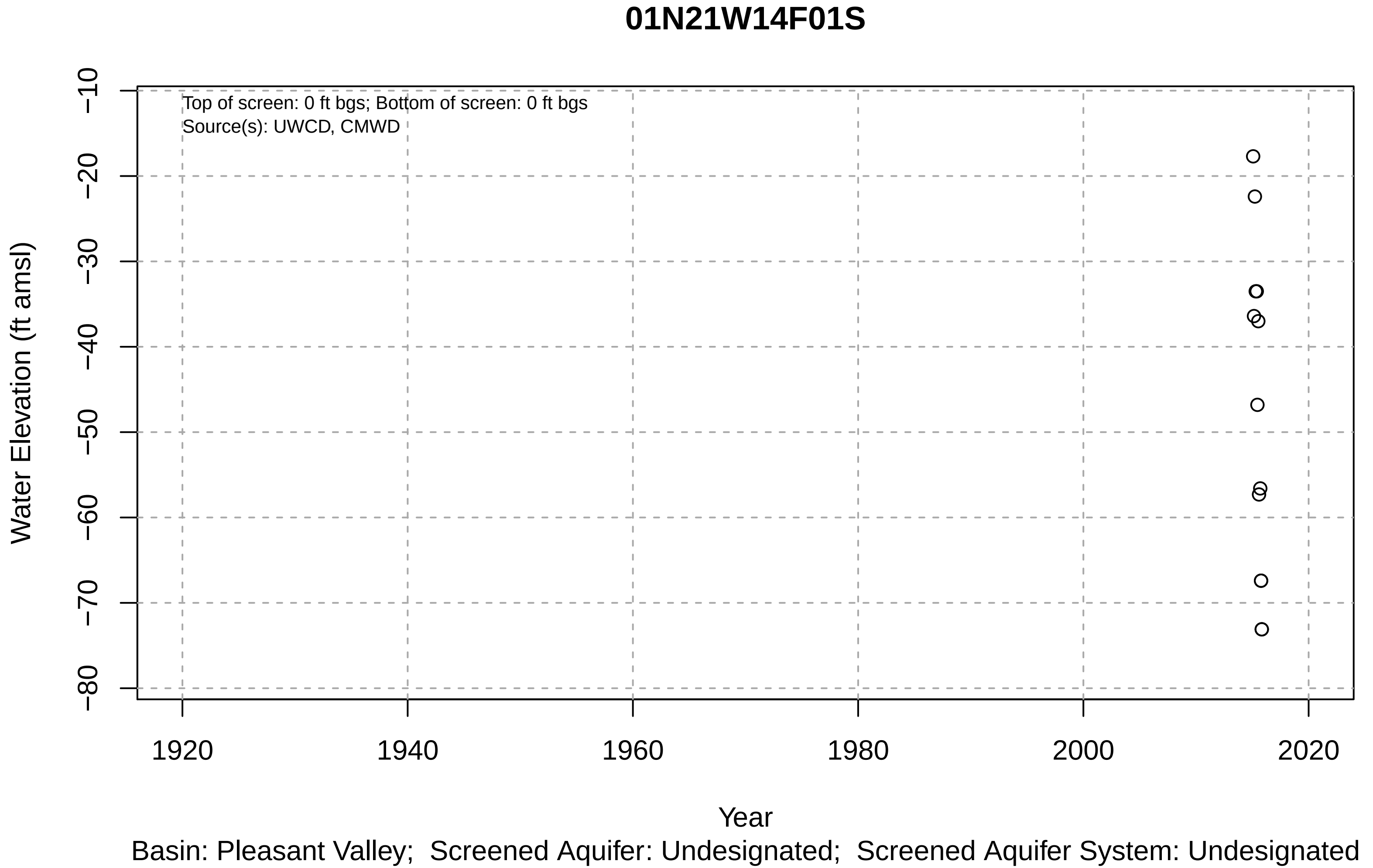


Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

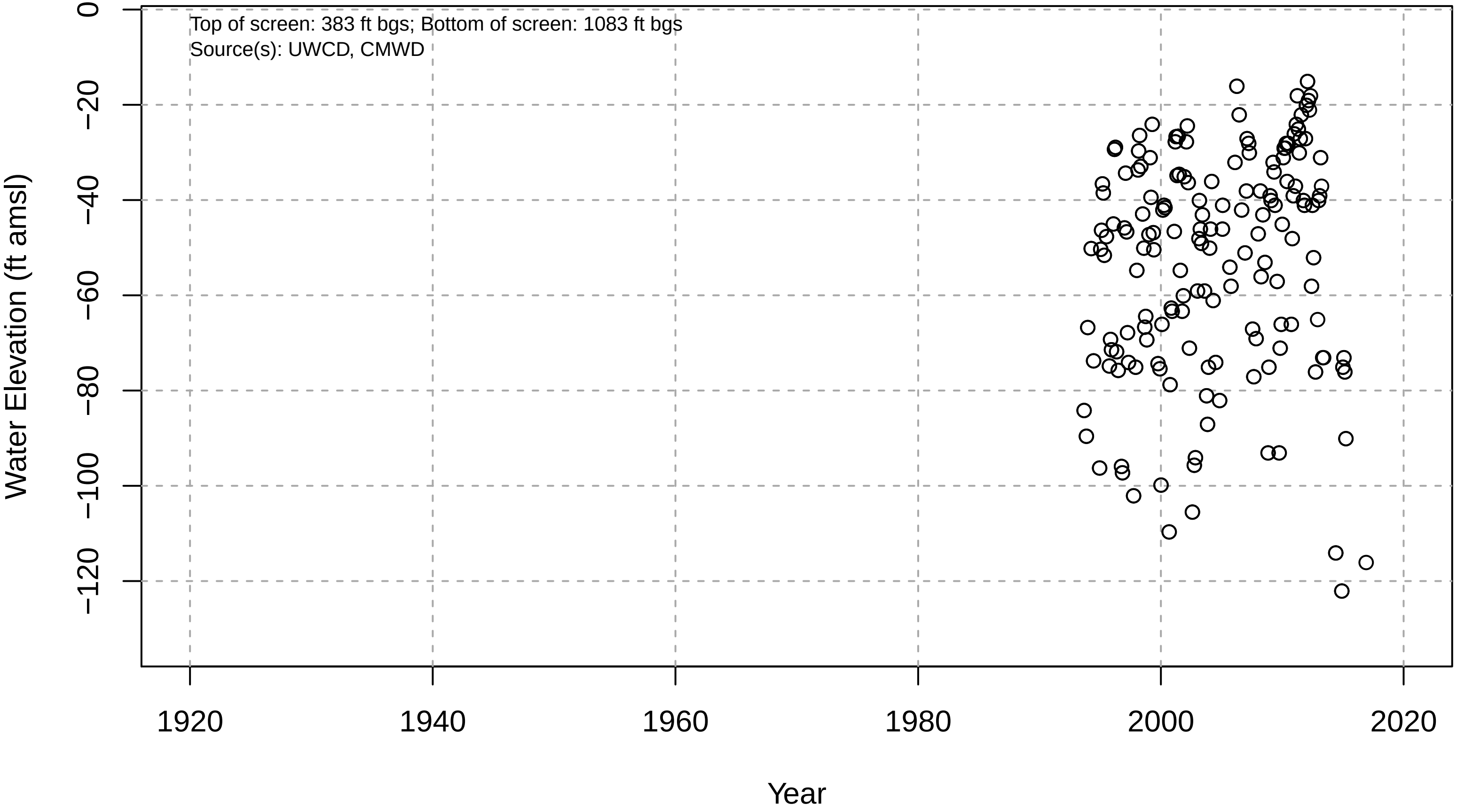
01N21W14B03S



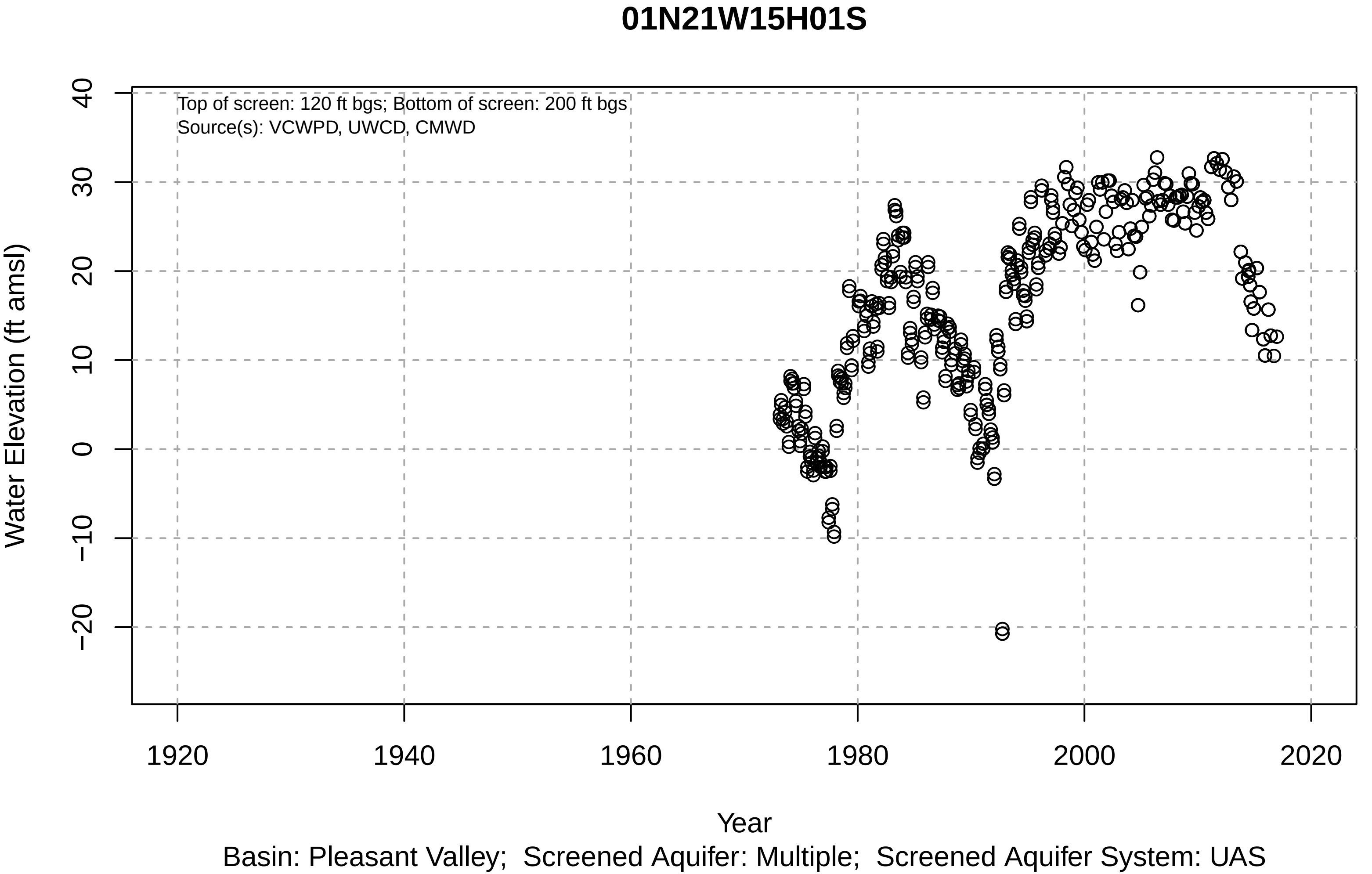
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated


01N21W14F01S
Top of screen: 0 ft bgs; Bottom of screen: 0 ft bgs
Source(s): UWCD, CMWD
Water Elevation (ft amsl)
−10
−20
−30
−40
−50
−60
−70
−80
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

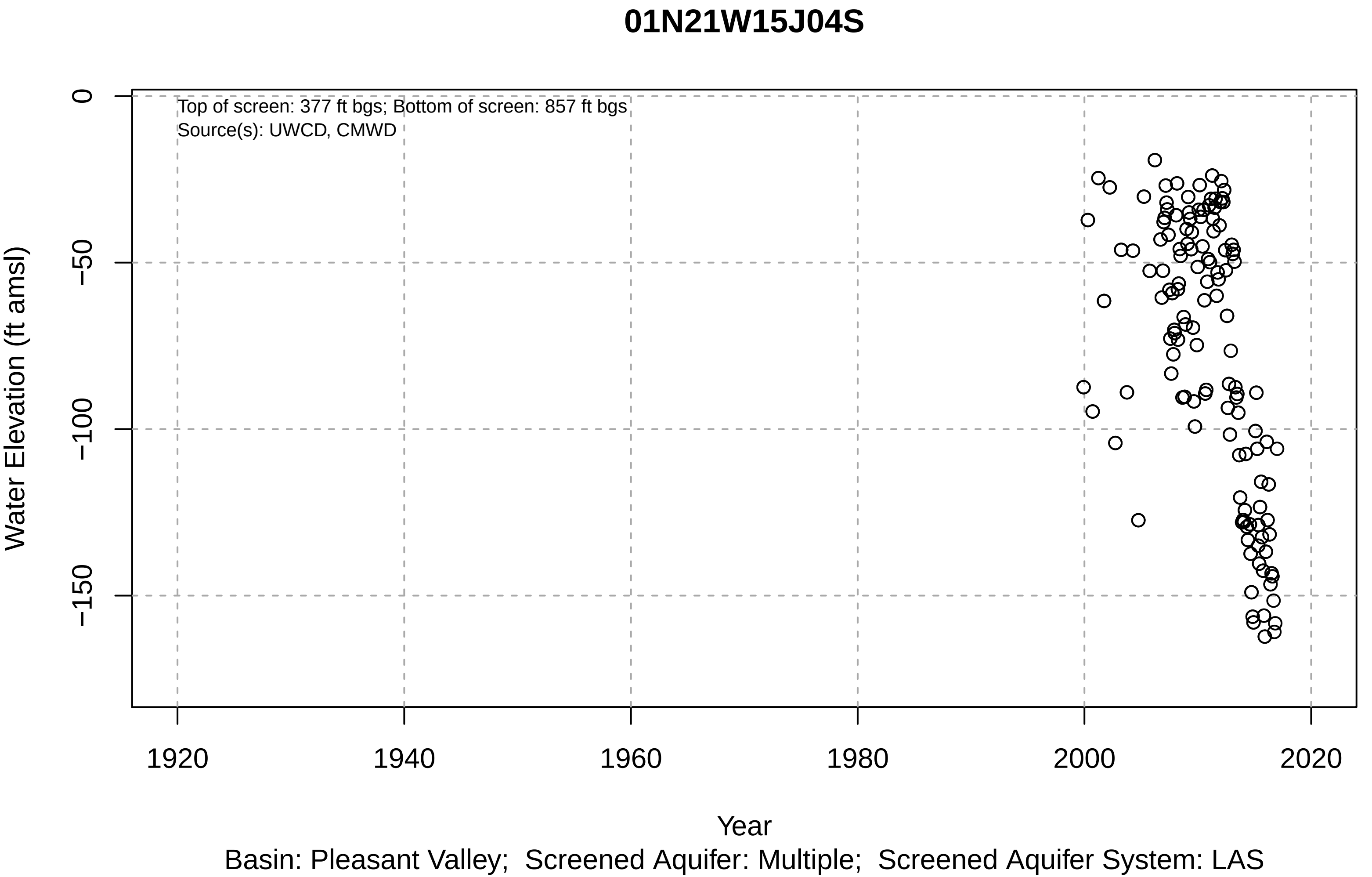
01N21W15D02S

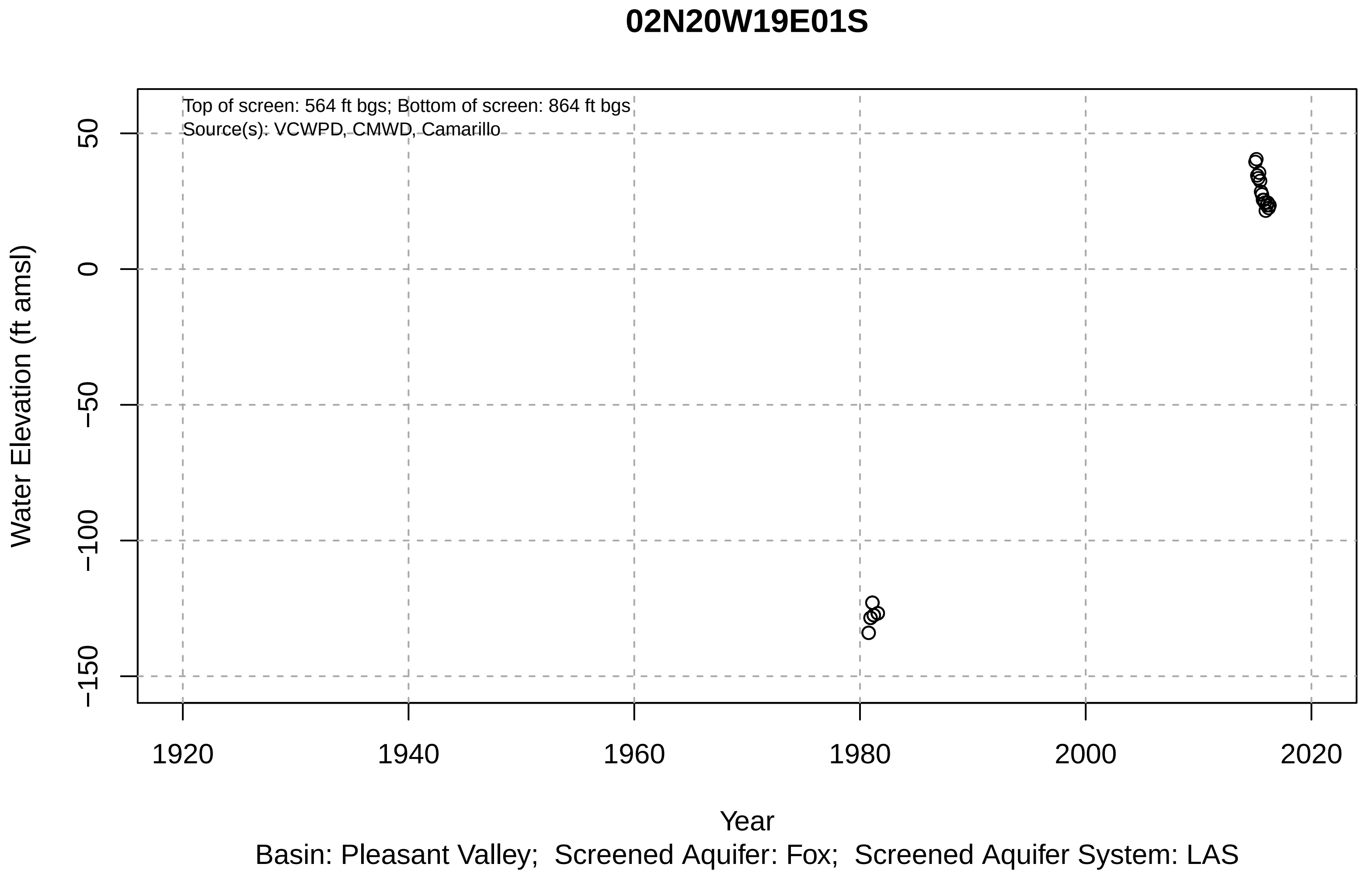


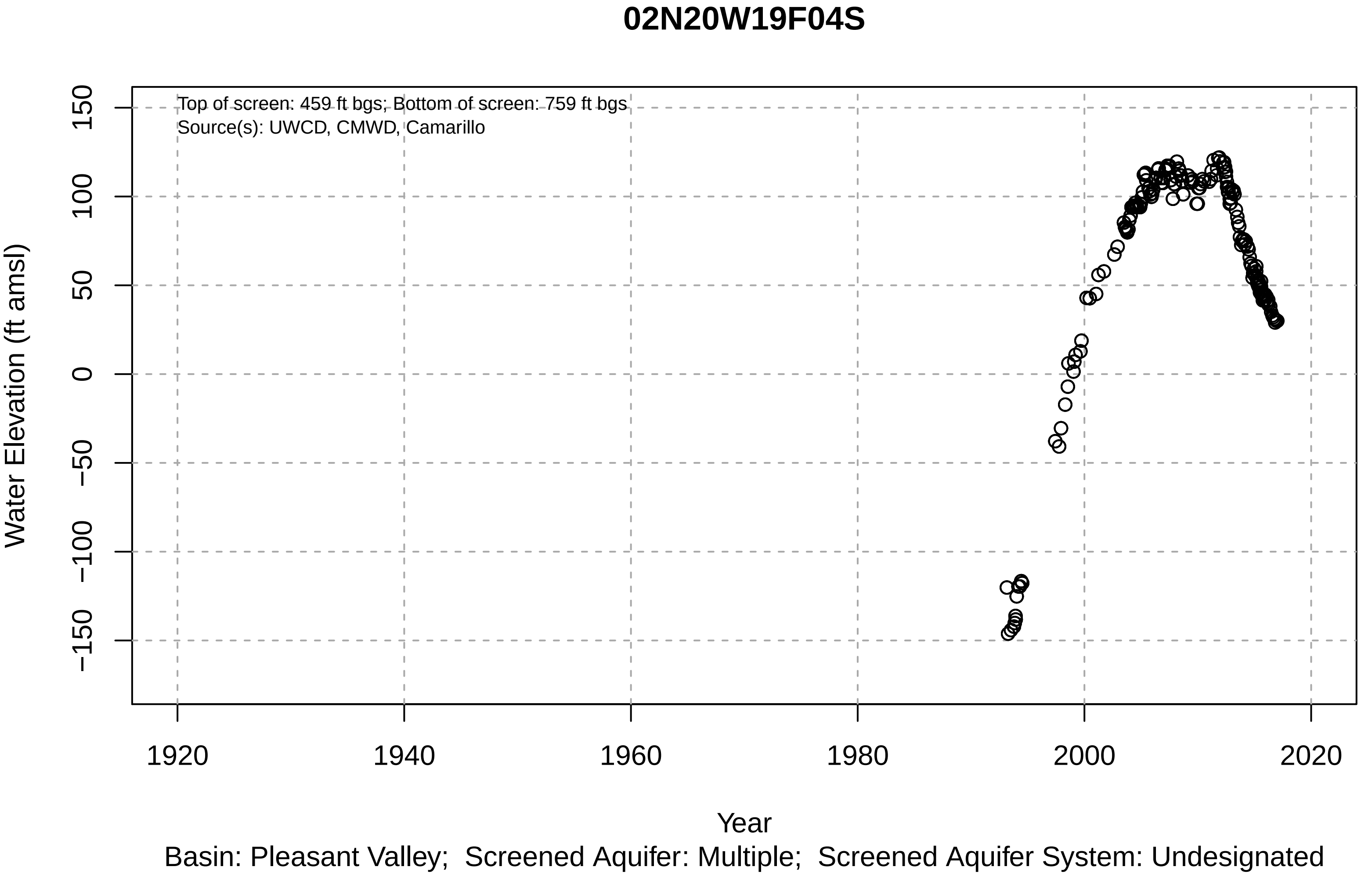
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS



01N21W15H01S
Top of screen: 120 ft bgs; Bottom of screen: 200 ft bgs
Source(s): VCWPD, UWCD, CMWD
Water Elevation (ft amsl)
40
30
20
10
0
−10
−20
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: UAS

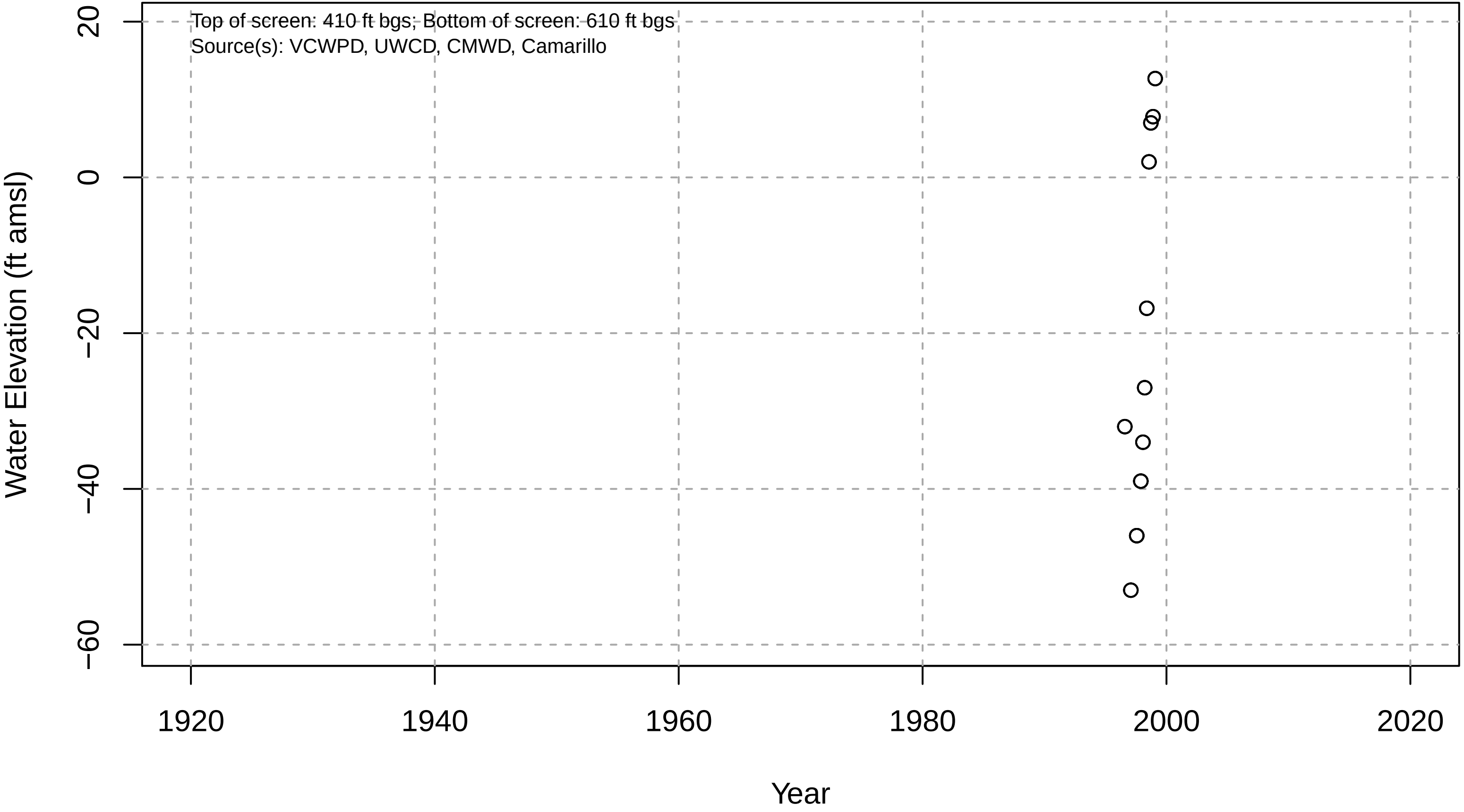
01N21W15J04S
Top of screen: 377 ft bgs; Bottom of screen: 857 ft bgs
Source(s): UWCD, CMWD
Water Elevation (ft amsl)
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS


02N20W19E01S
Top of screen: 564 ft bgs; Bottom of screen: 864 ft bgs
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
50
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS

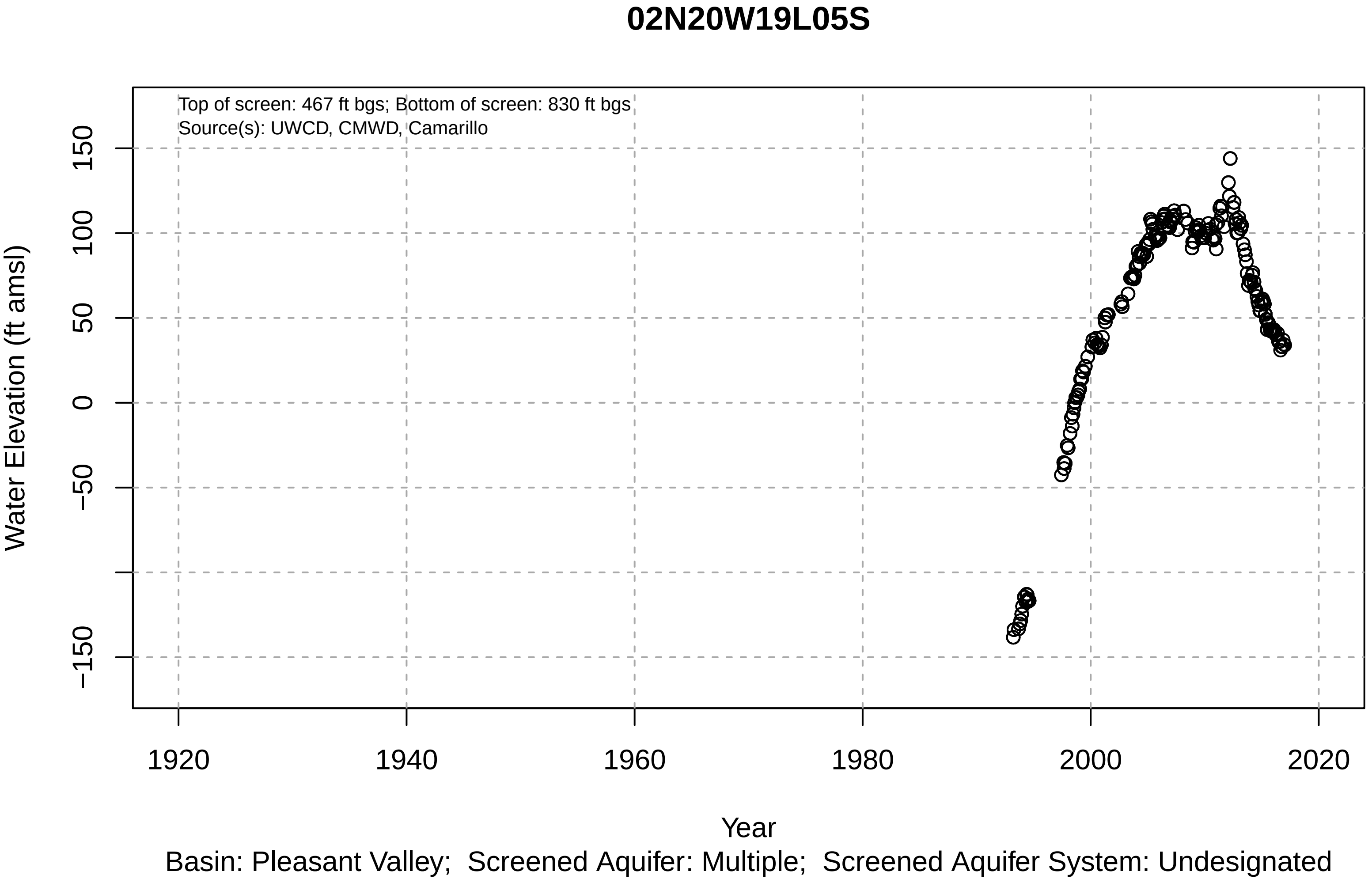


02N20W19F04S
Top of screen: 459 ft bgs; Bottom of screen: 759 ft bgs
Source(s): UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
150
100
50
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

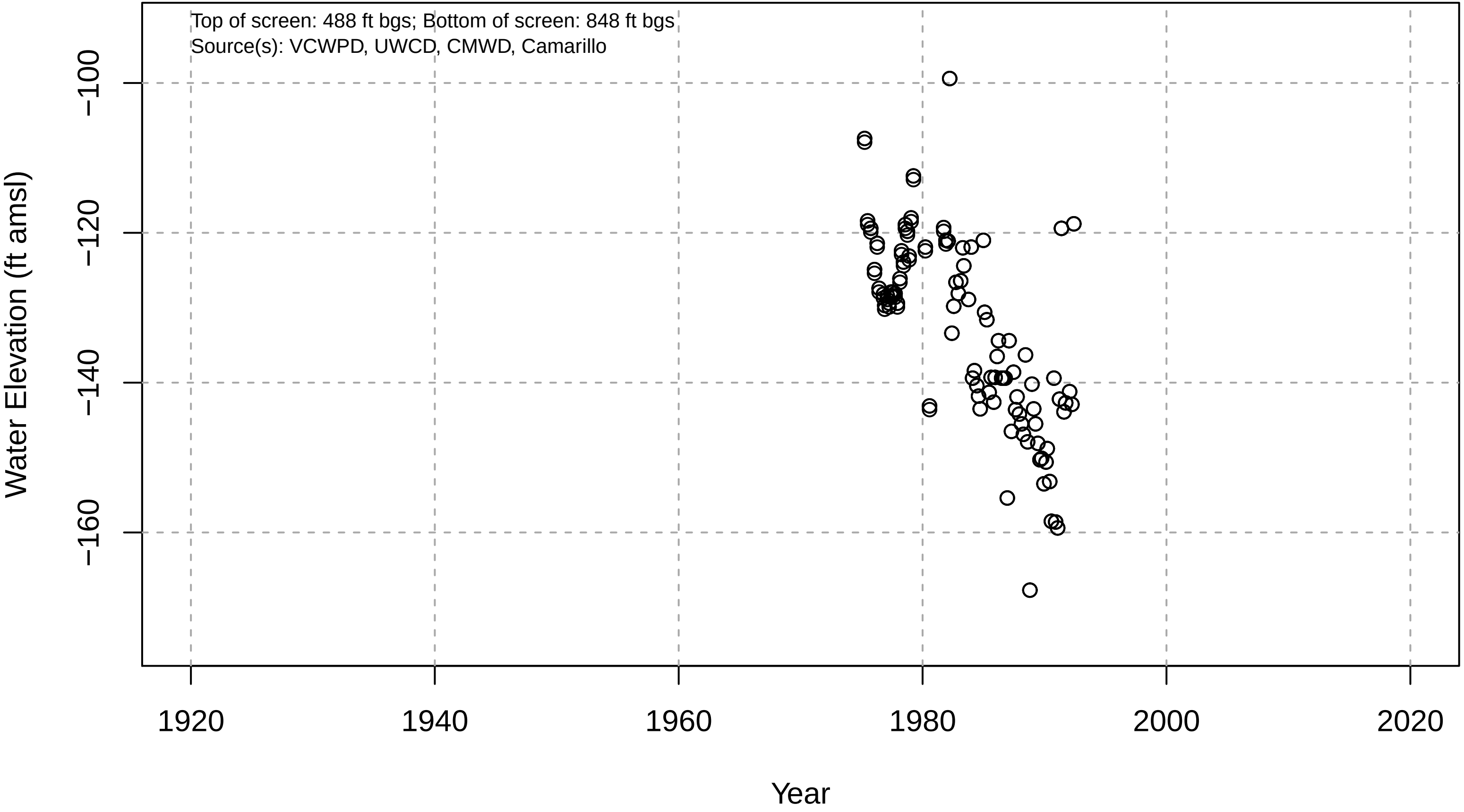
02N20W19J02S



Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS

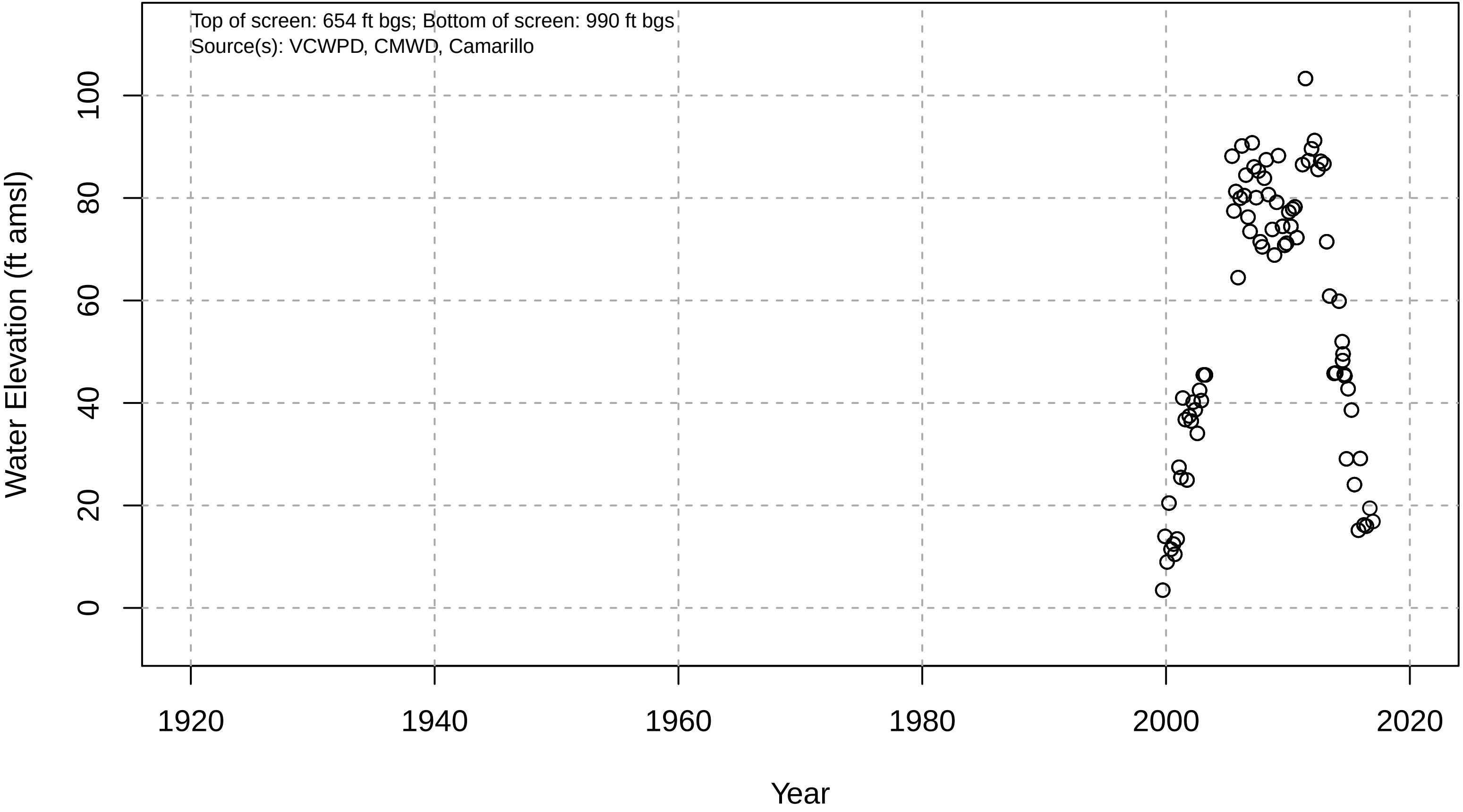

02N20W19L05S
Top of screen: 467 ft bgs; Bottom of screen: 830 ft bgs
Source(s): UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
150
100
50
0
−50
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N20W19M04S

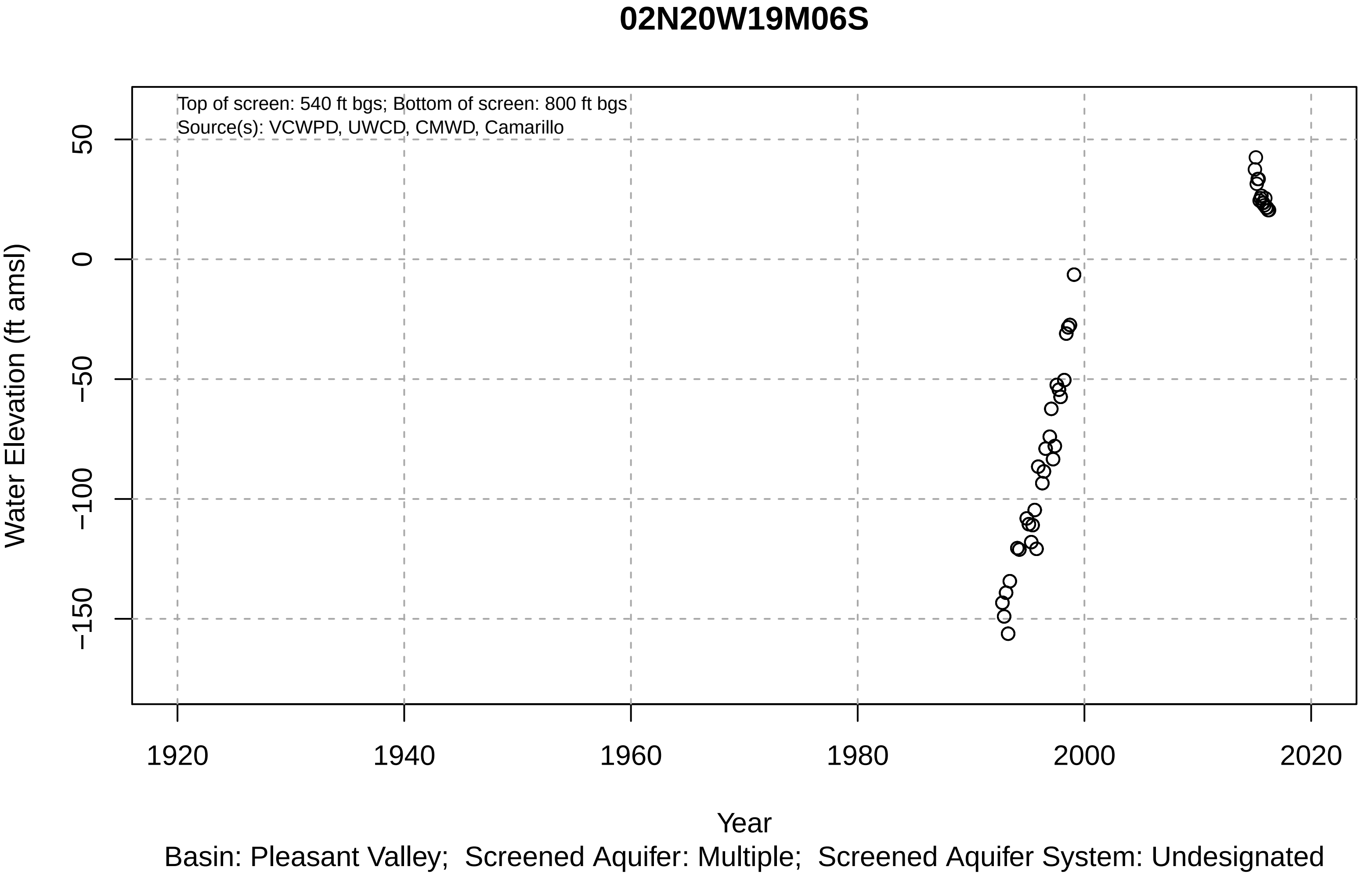


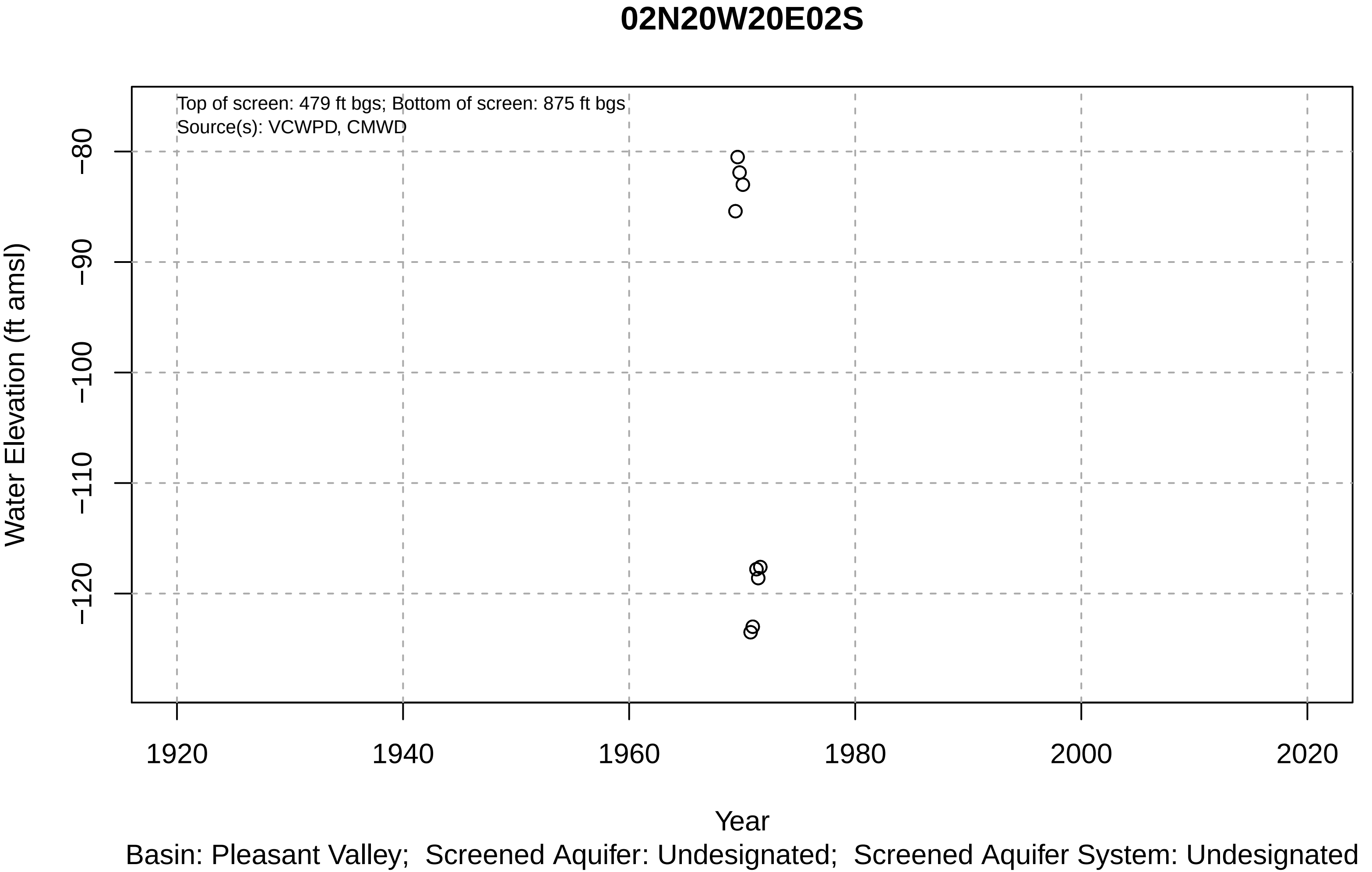
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N20W19M05S

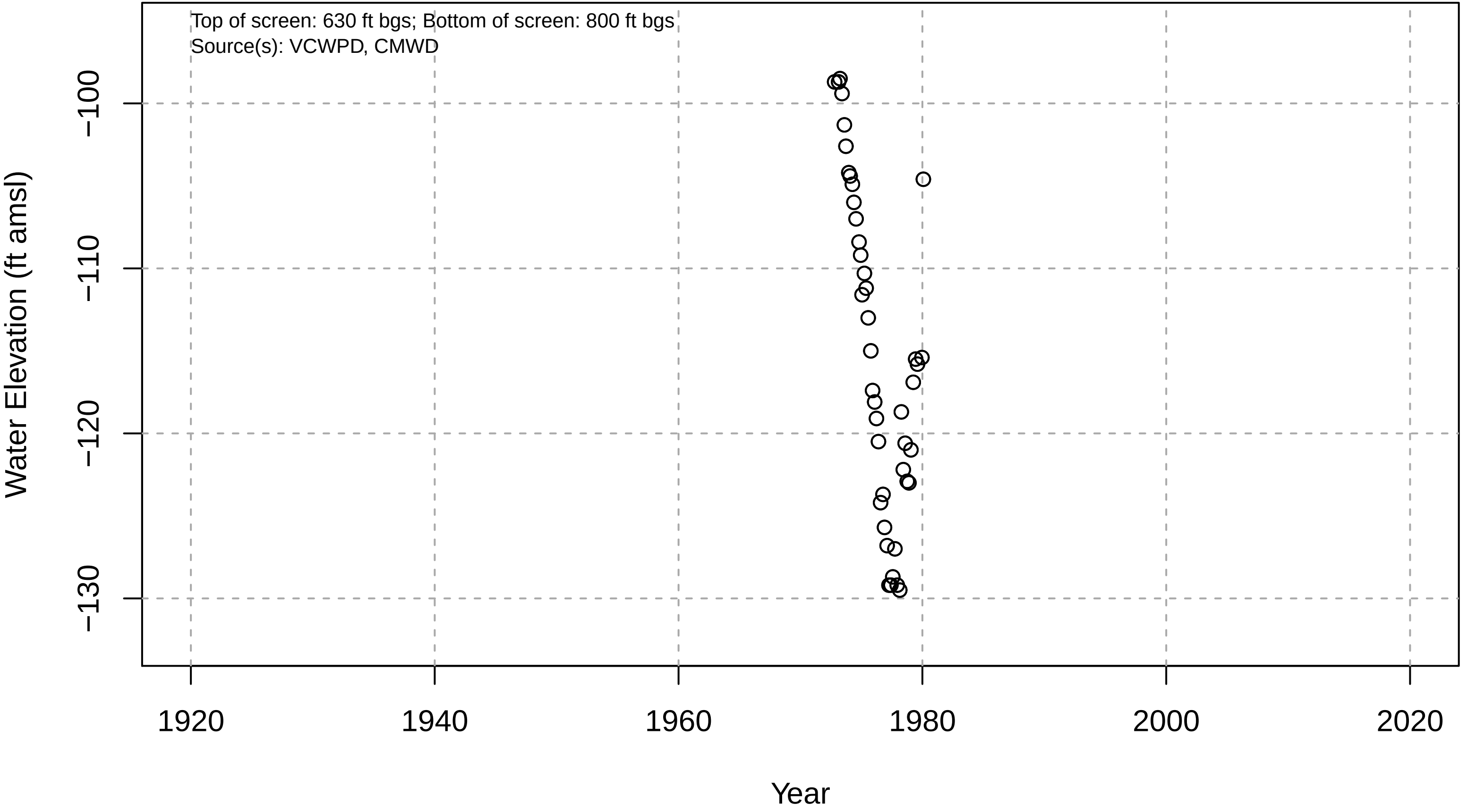


Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

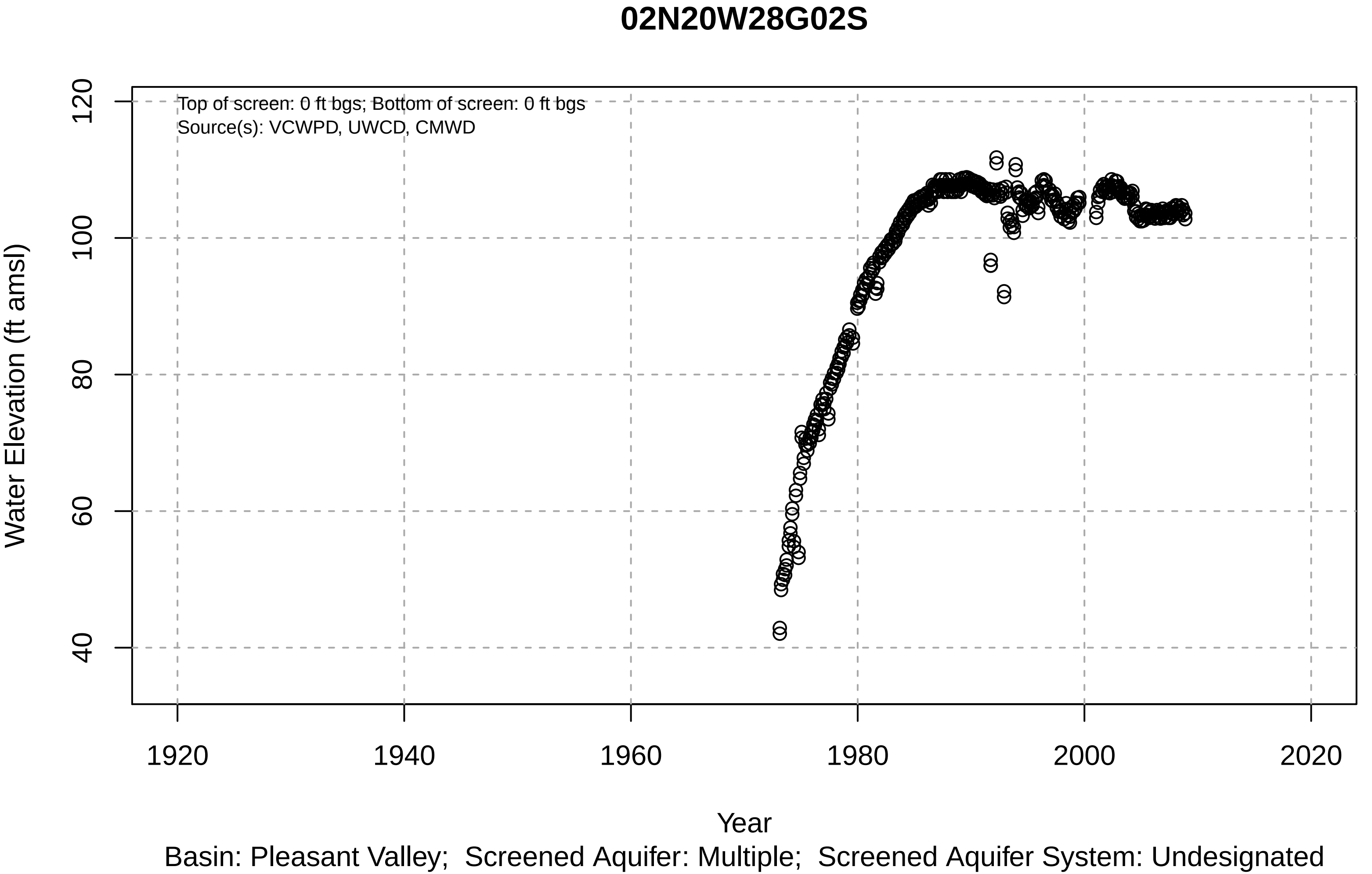
02N20W19M06S
Top of screen: 540 ft bgs; Bottom of screen: 800 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
50
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated


02N20W20E02S
Top of screen: 479 ft bgs; Bottom of screen: 875 ft bgs
Source(s): VCWPD, CMWD
Water Elevation (ft amsl)
−80
−90
−100
−110
−120
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

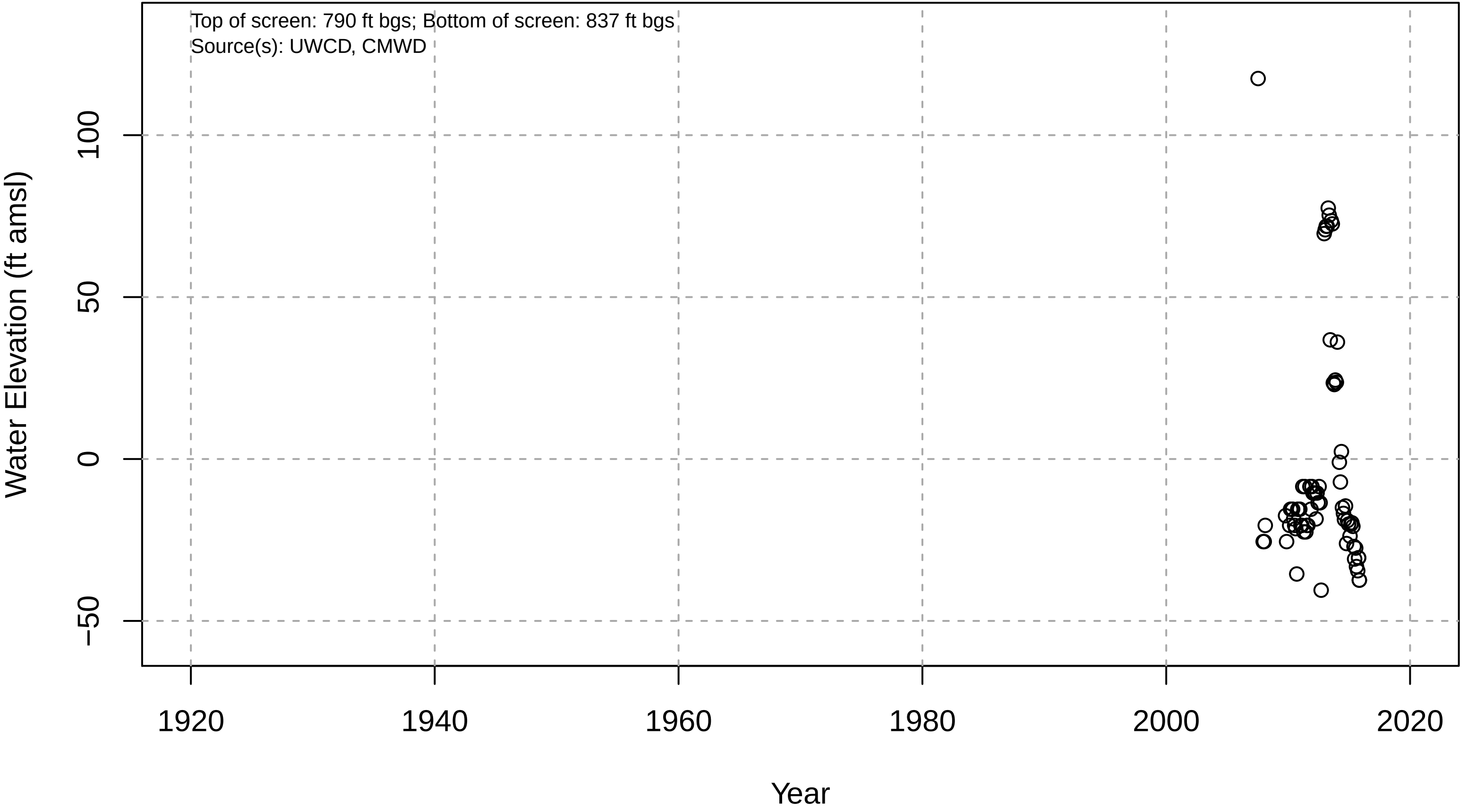
02N20W20M03S



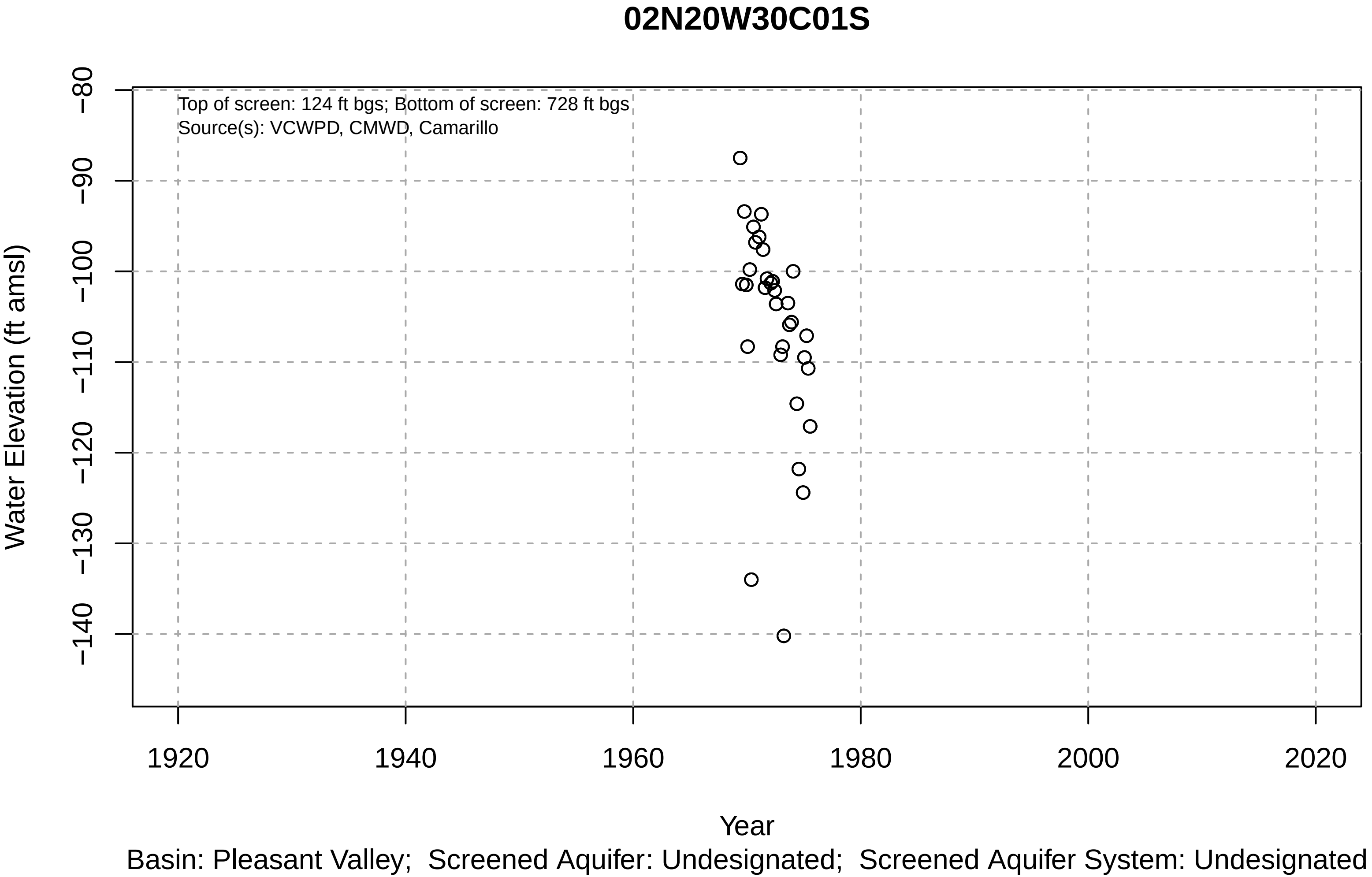
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated


02N20W28G02S
Top of screen: 0 ft bgs; Bottom of screen: 0 ft bgs
Source(s): VCWPD, UWCD, CMWD
Water Elevation (ft amsl)
40
60
80
100
120
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N20W29B02S



Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

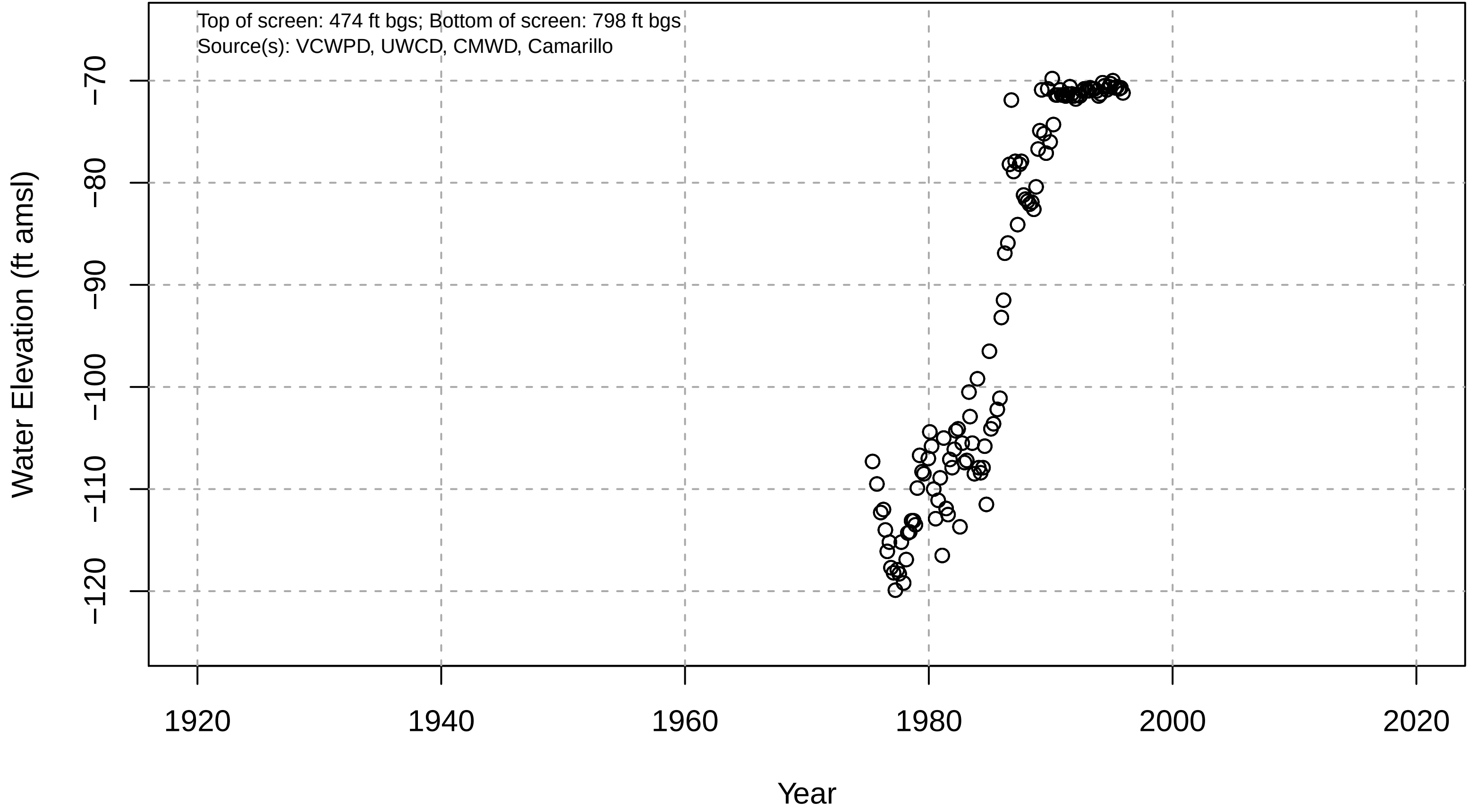


02N20W30C01S

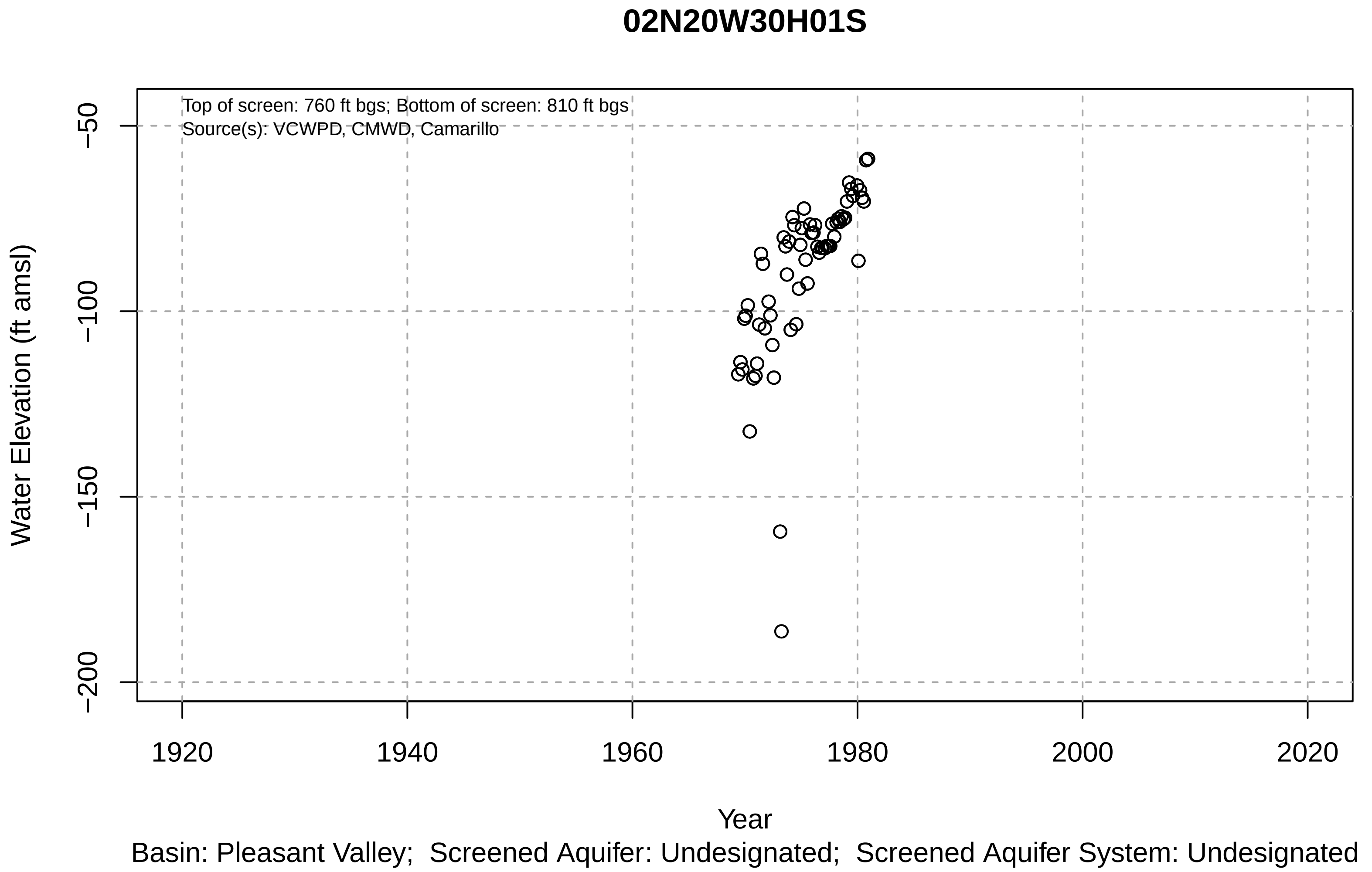
Top of screen: 124 ft bgs; Bottom of screen: 728 ft bgs
Source(s): VCWPD, CMWD, Camarillo

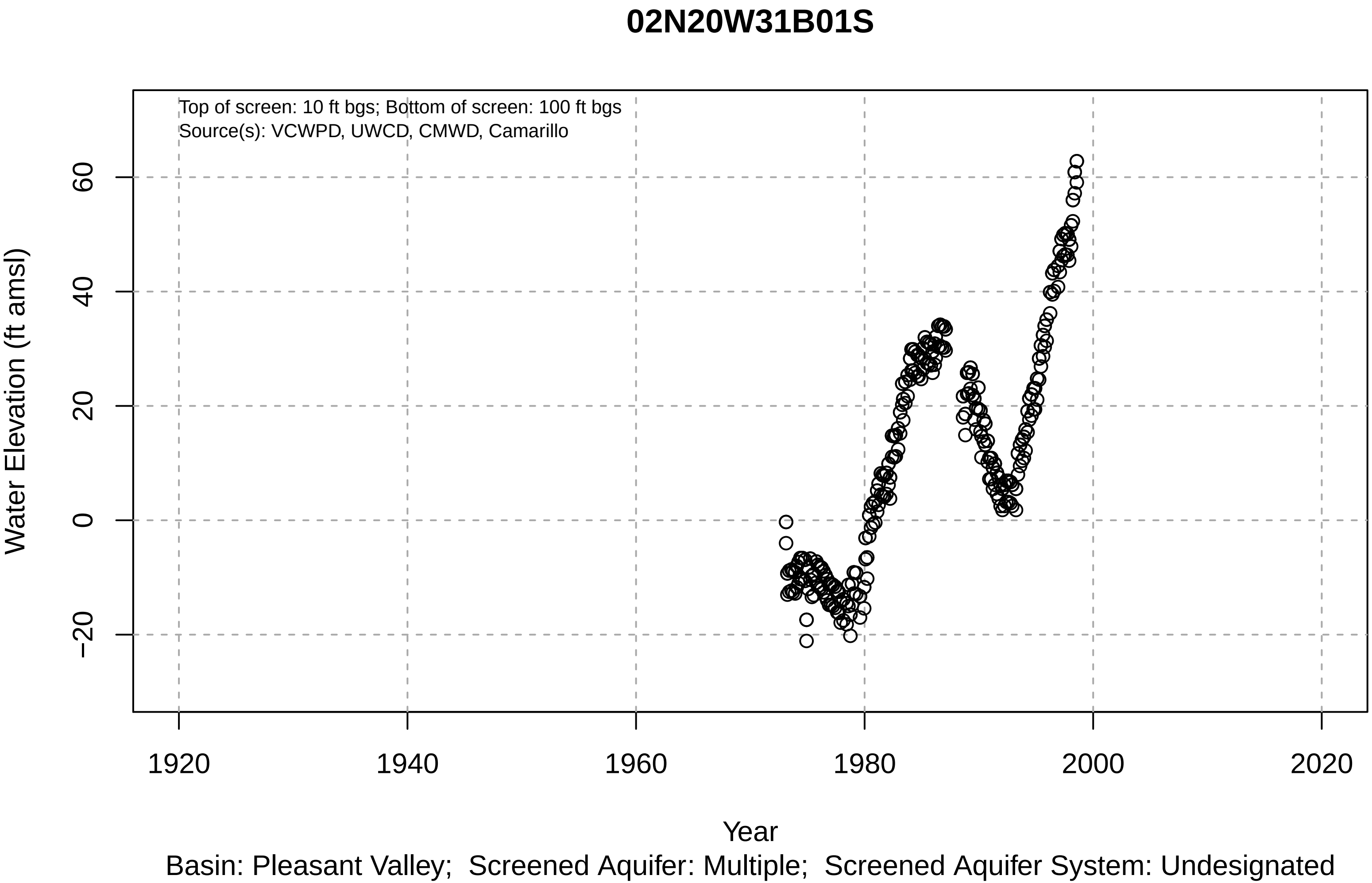
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

02N20W30F01S

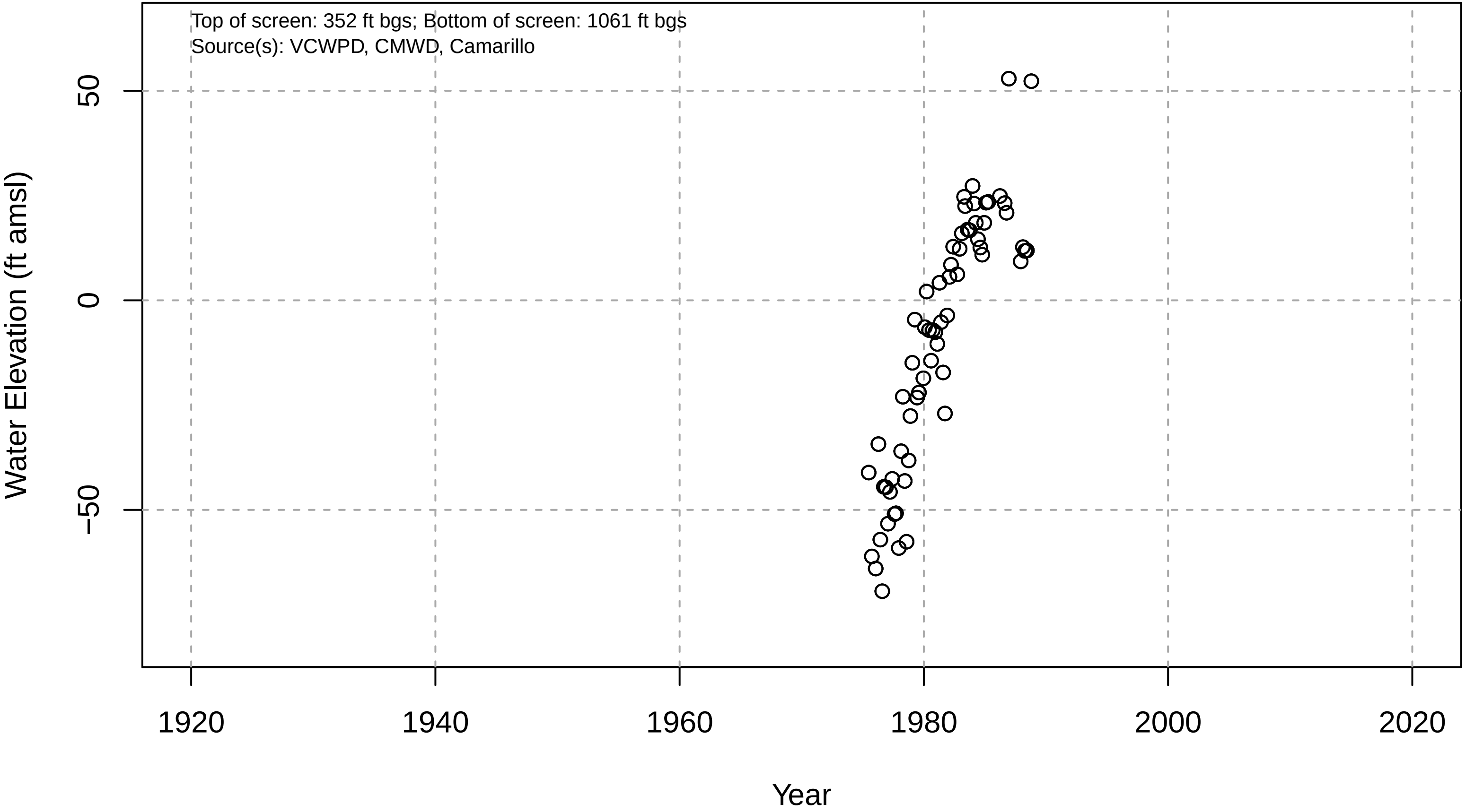


Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated


02N20W30H01S
Top of screen: 760 ft bgs; Bottom of screen: 810 ft bgs
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
−50
−100
−150
−200
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

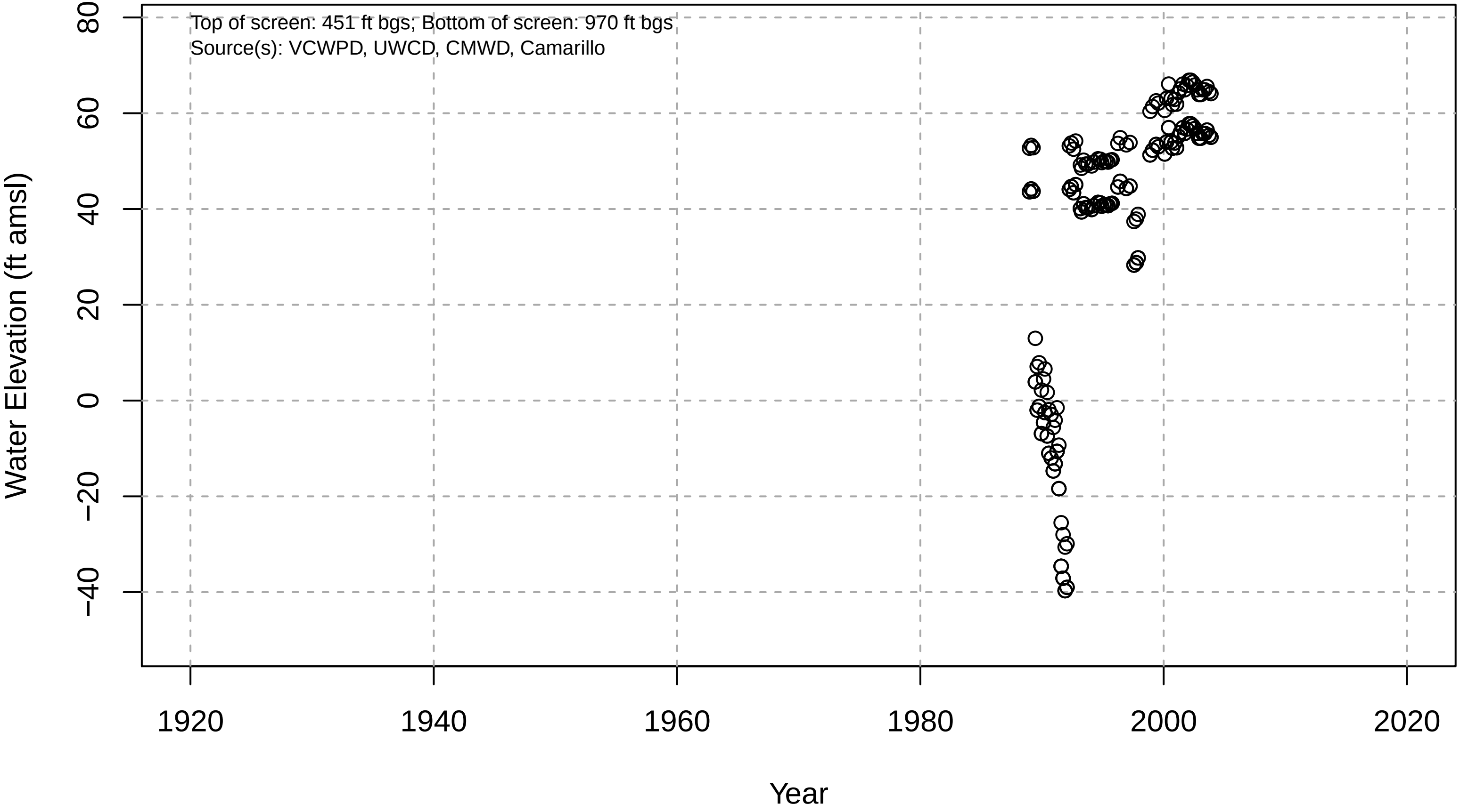

02N20W31B01S
Top of screen: 10 ft bgs; Bottom of screen: 100 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
60
40
20
0
−20
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N20W31F02S

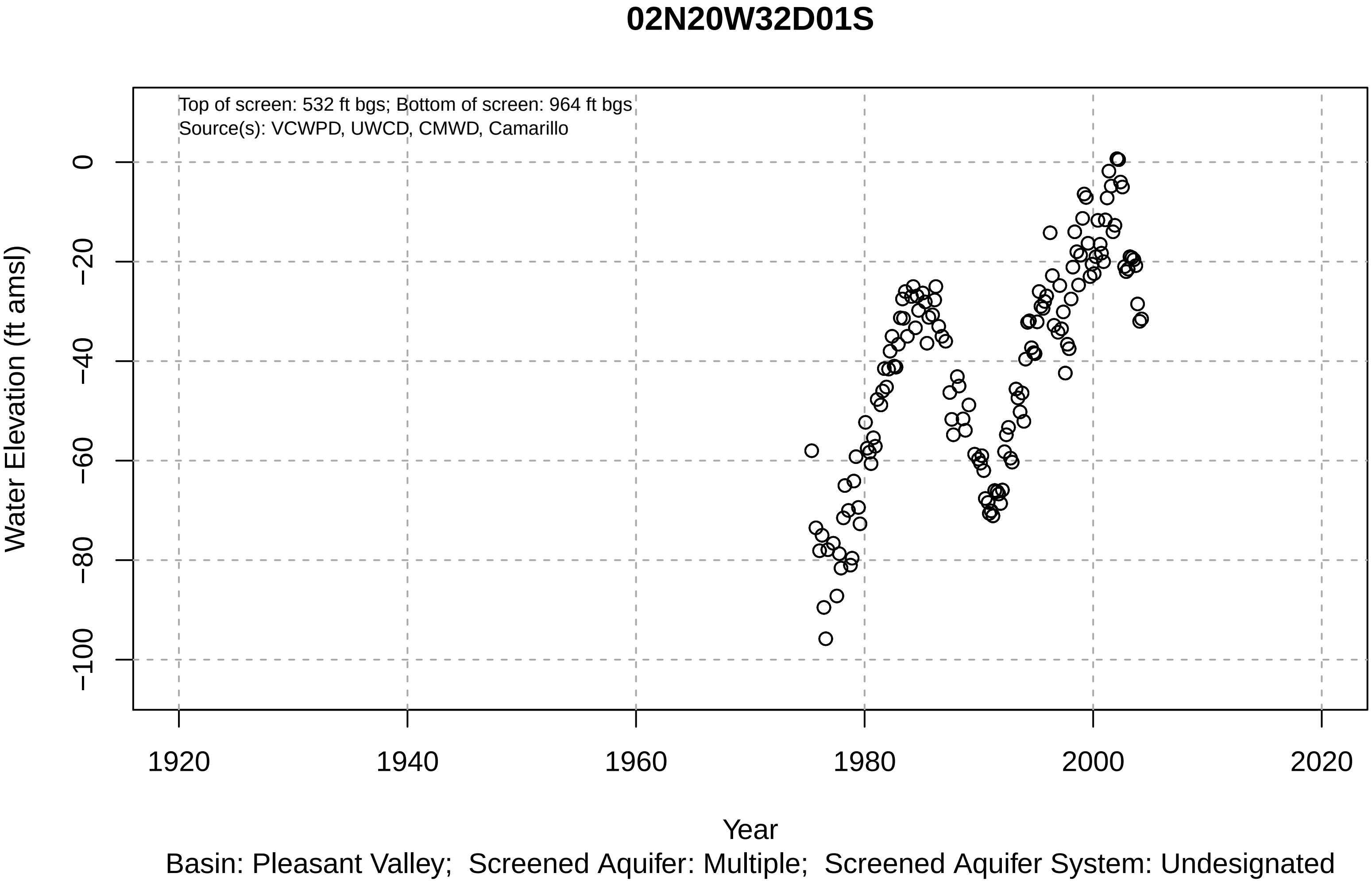


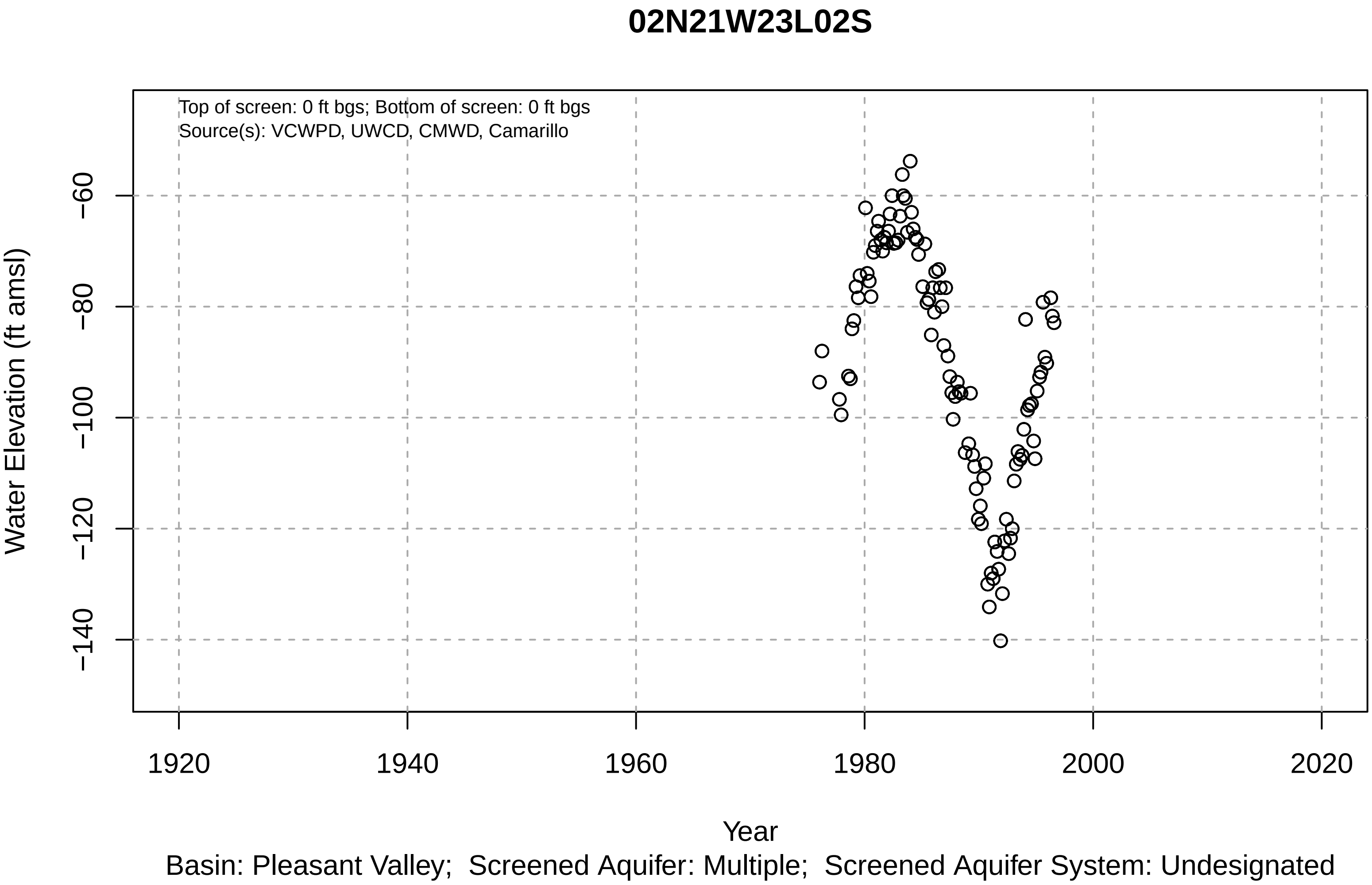
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N20W31F03S

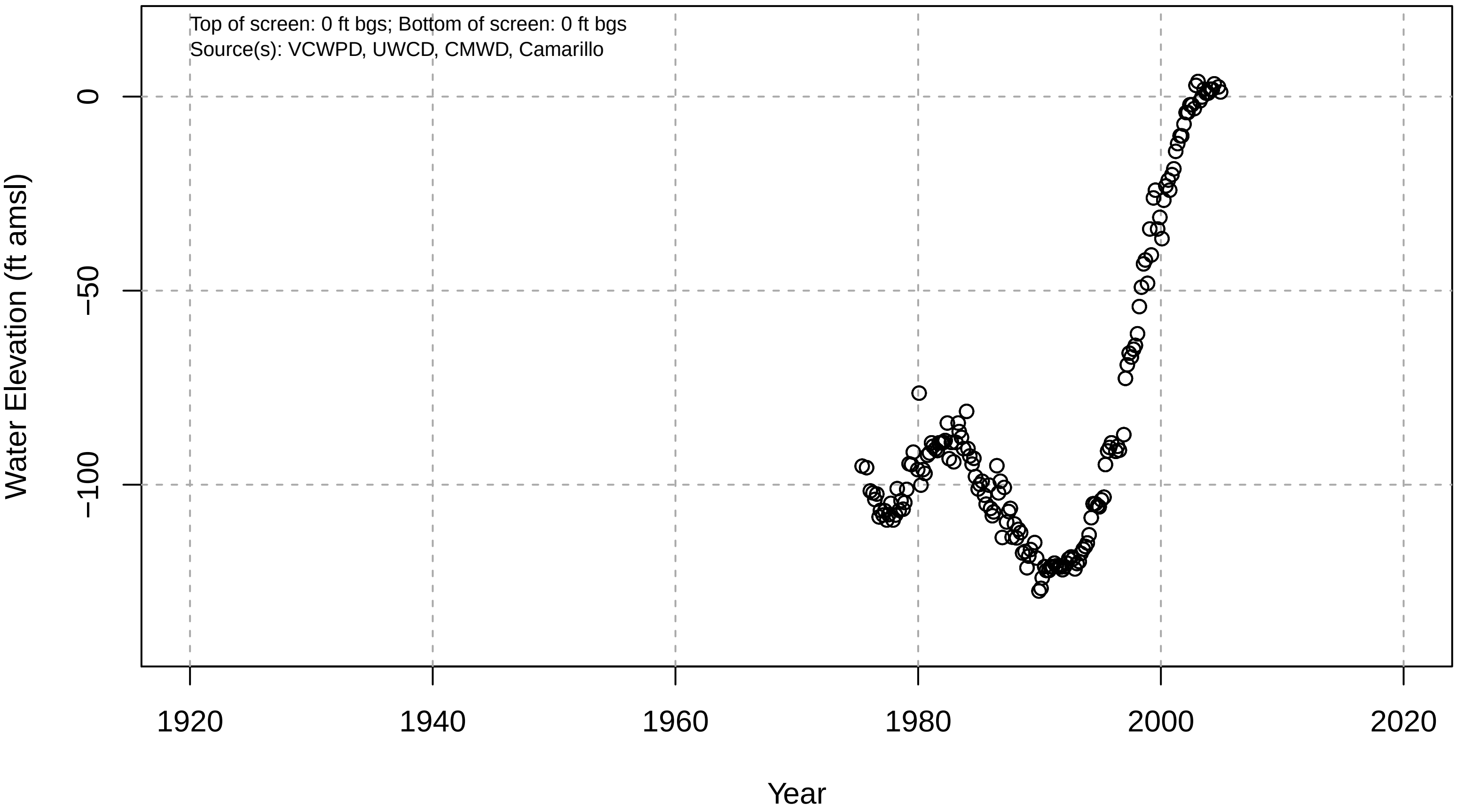


Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

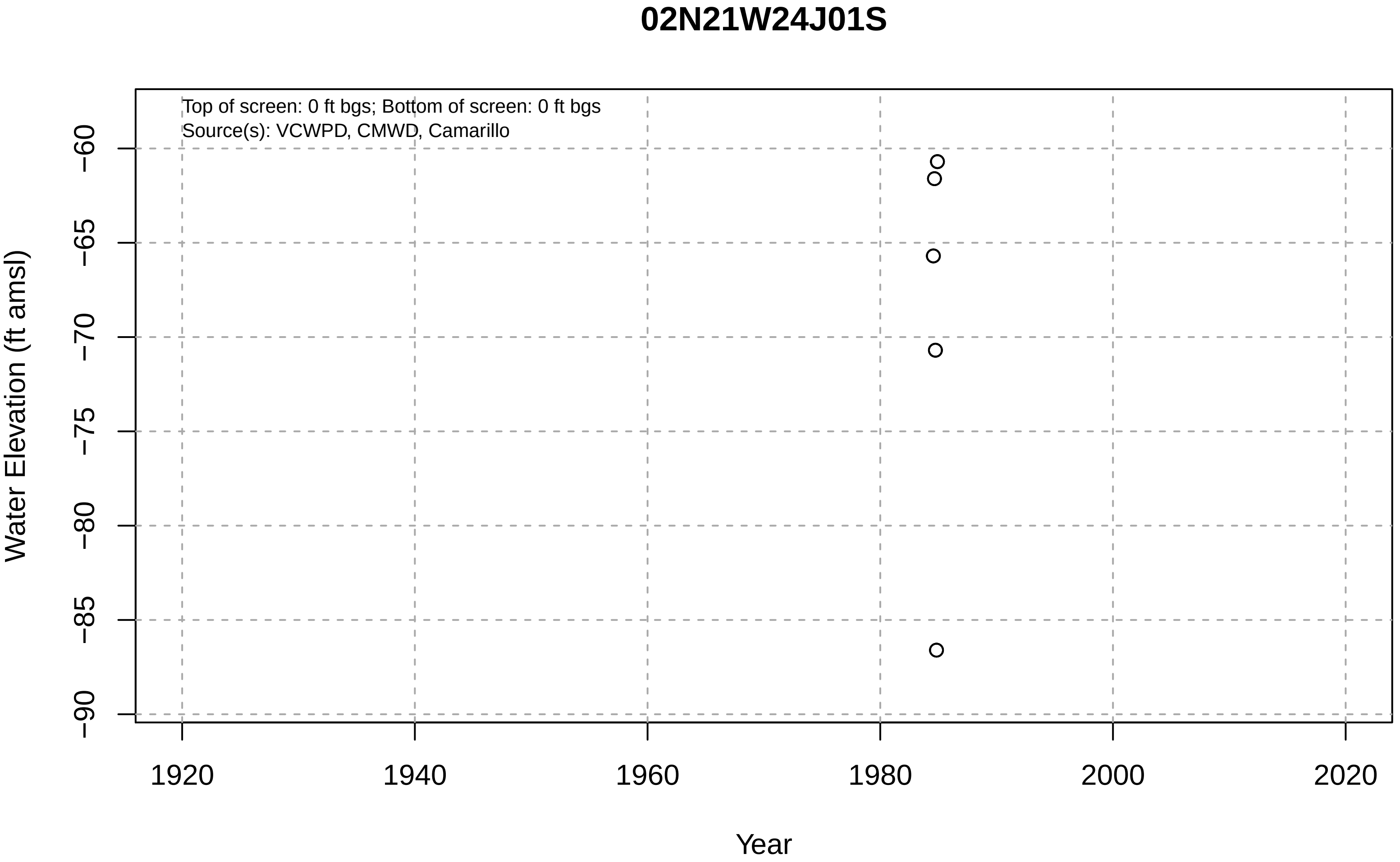

02N20W32D01S
Top of screen: 532 ft bgs; Bottom of screen: 964 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
0
−20
−40
−60
−80
−100
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated


02N21W23L02S
Top of screen: 0 ft bgs; Bottom of screen: 0 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
−60
−80
−100
−120
−140
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

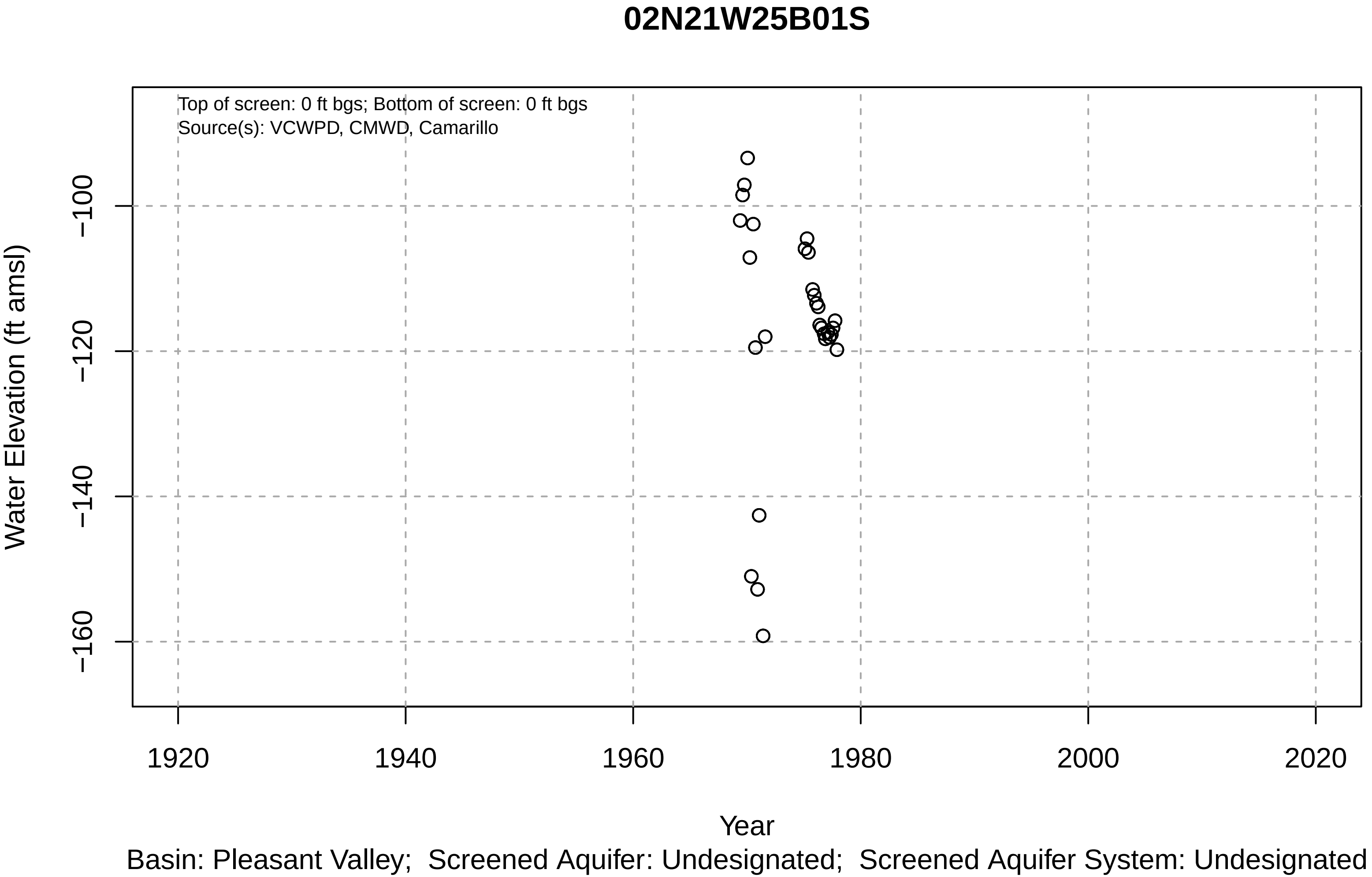
02N21W24F01S



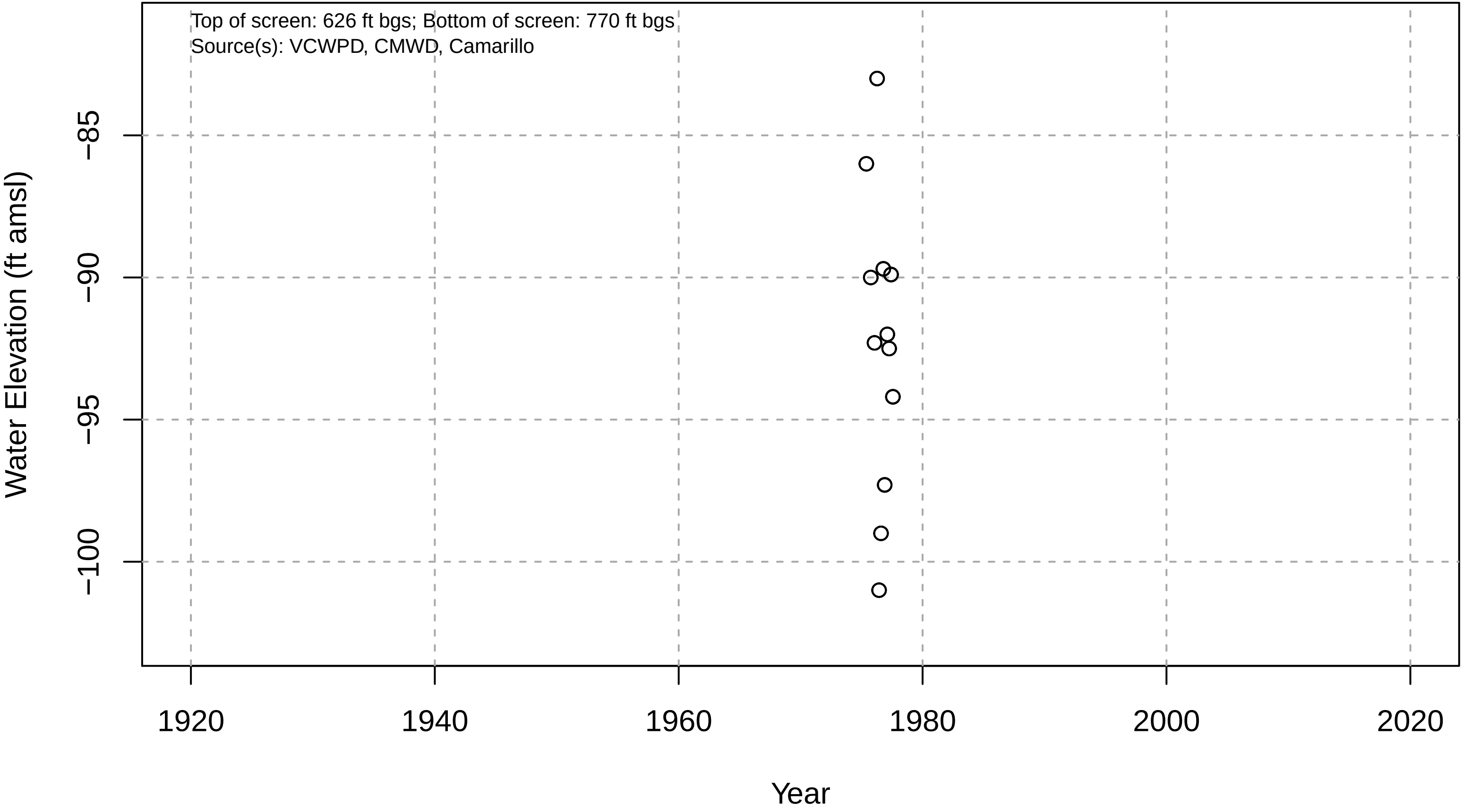
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated



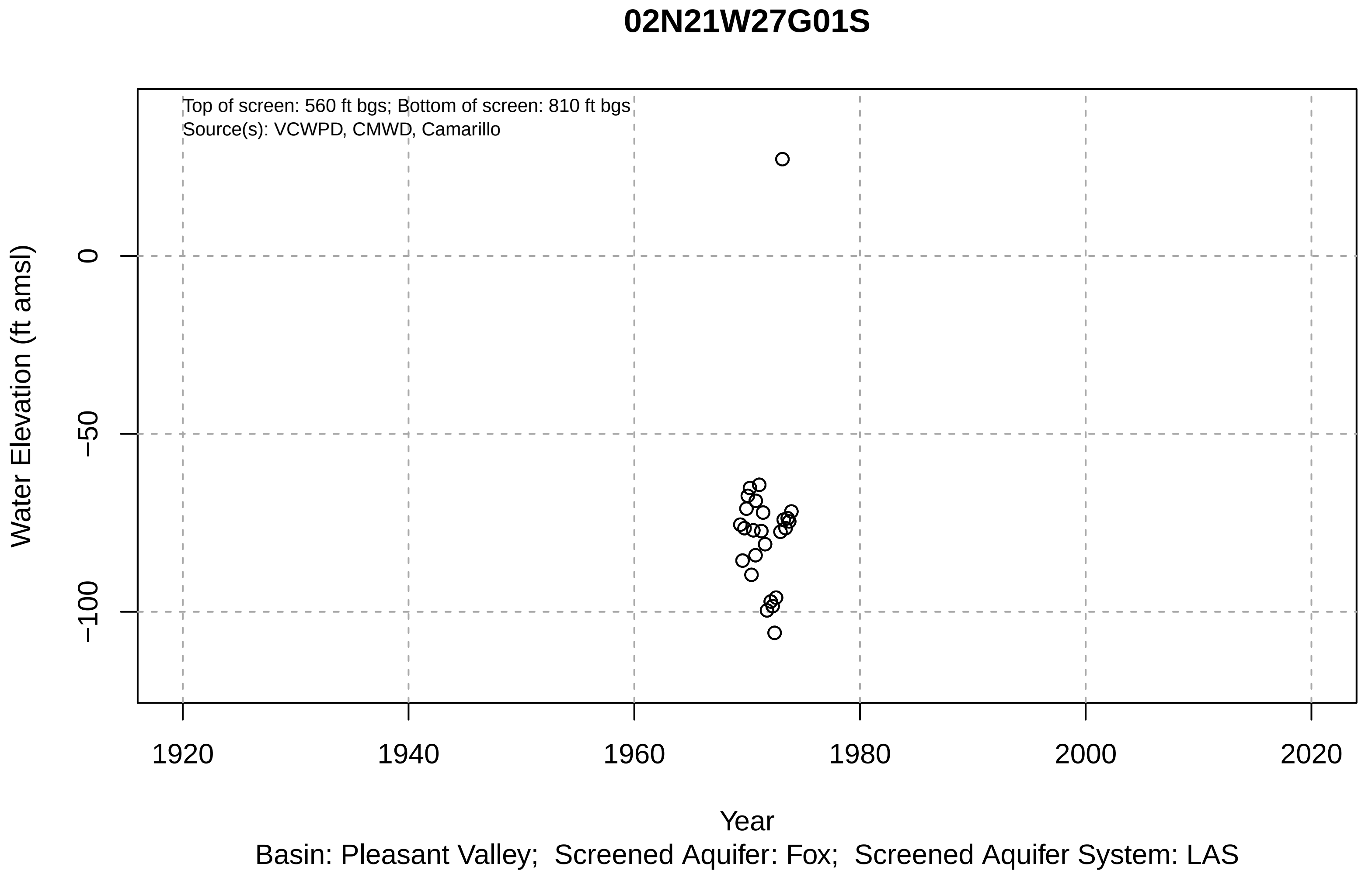
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

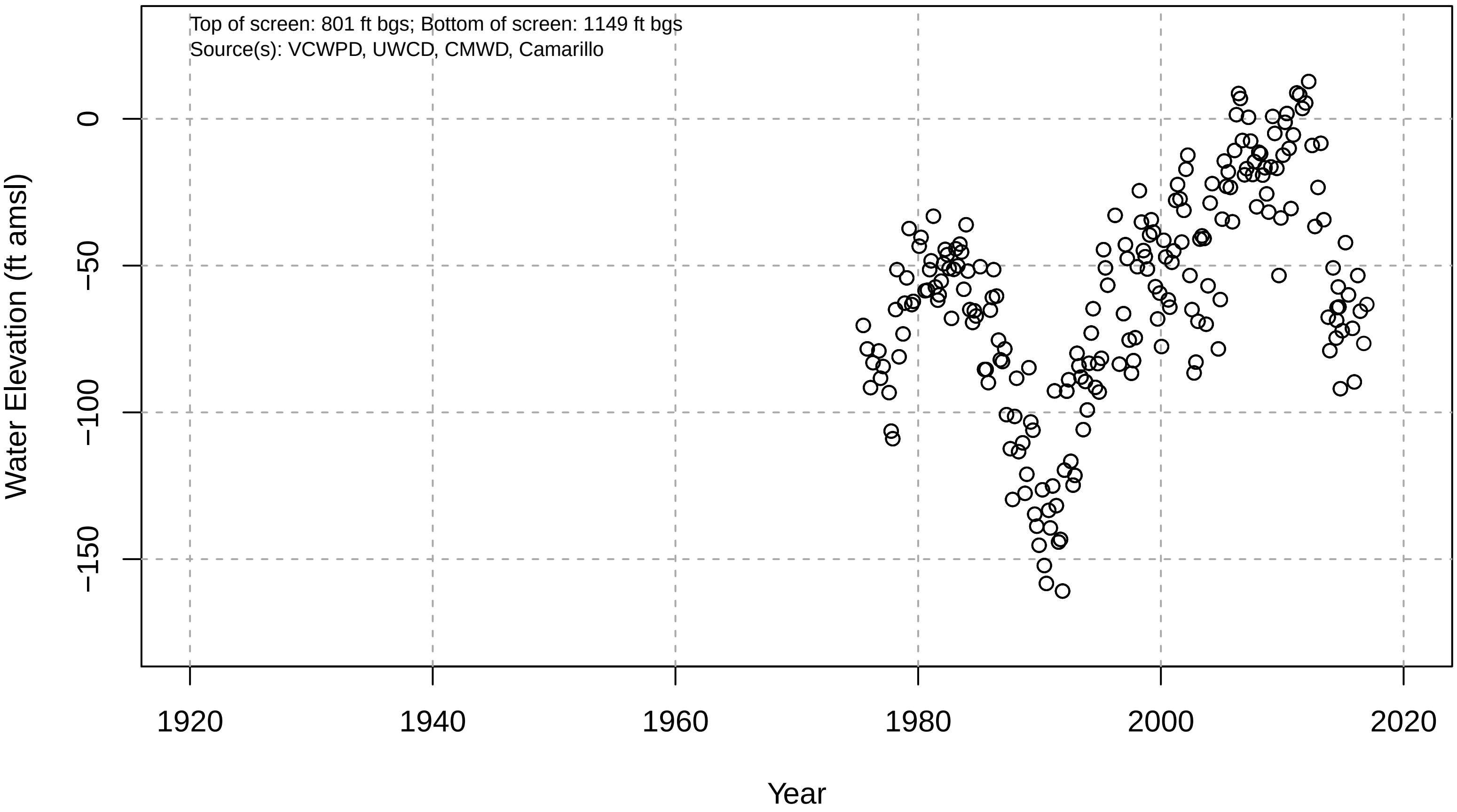

02N21W25B01S
Top of screen: 0 ft bgs; Bottom of screen: 0 ft bgs
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
−100
−120
−140
−160
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

02N21W26D06S



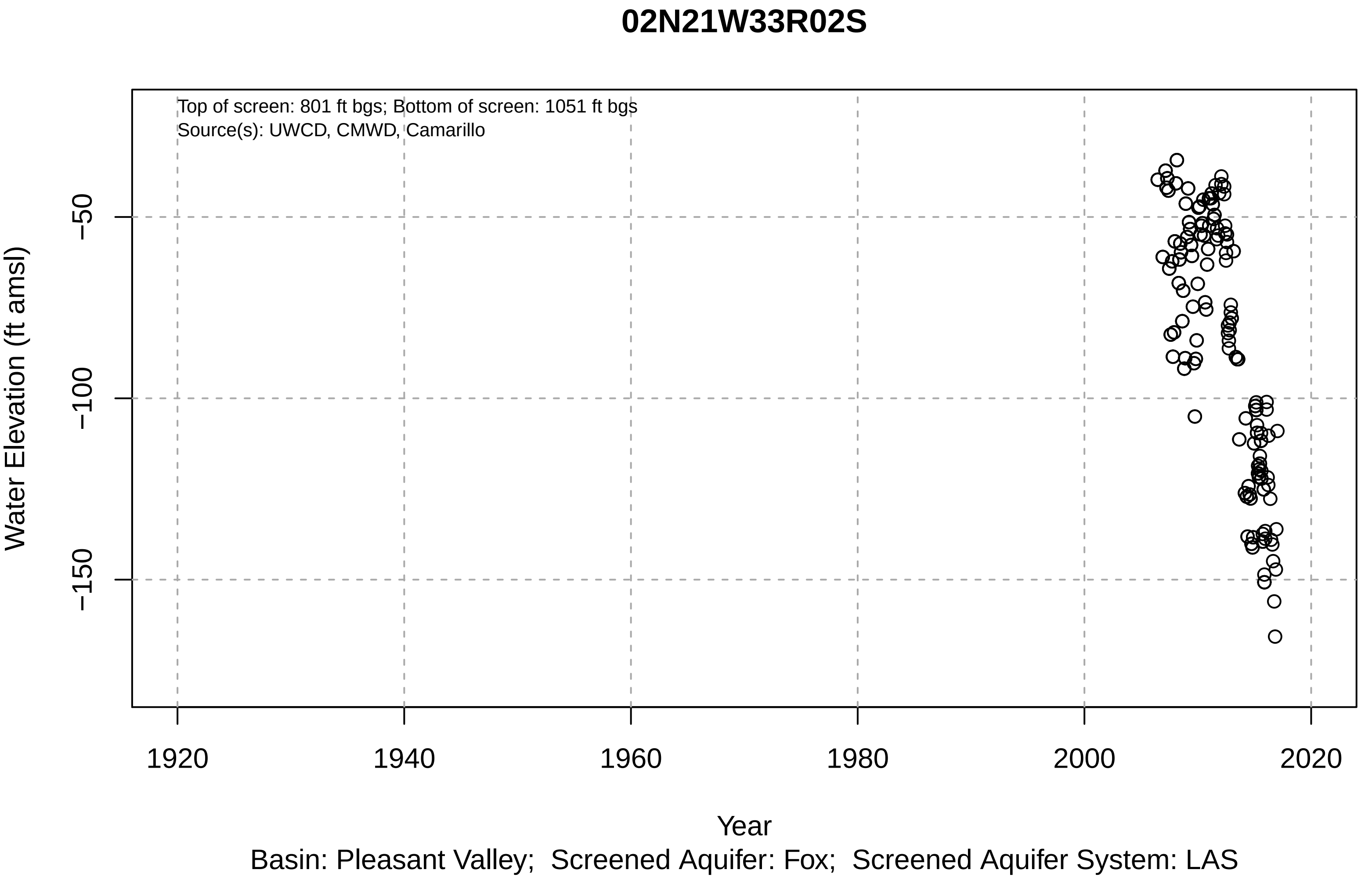
Basin: Pleasant Valley; Screened Aquifer: Below Grimes; Screened Aquifer System: Undesignated


02N21W27G01S
Top of screen: 560 ft bgs; Bottom of screen: 810 ft bgs
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
0
−50
−100
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS

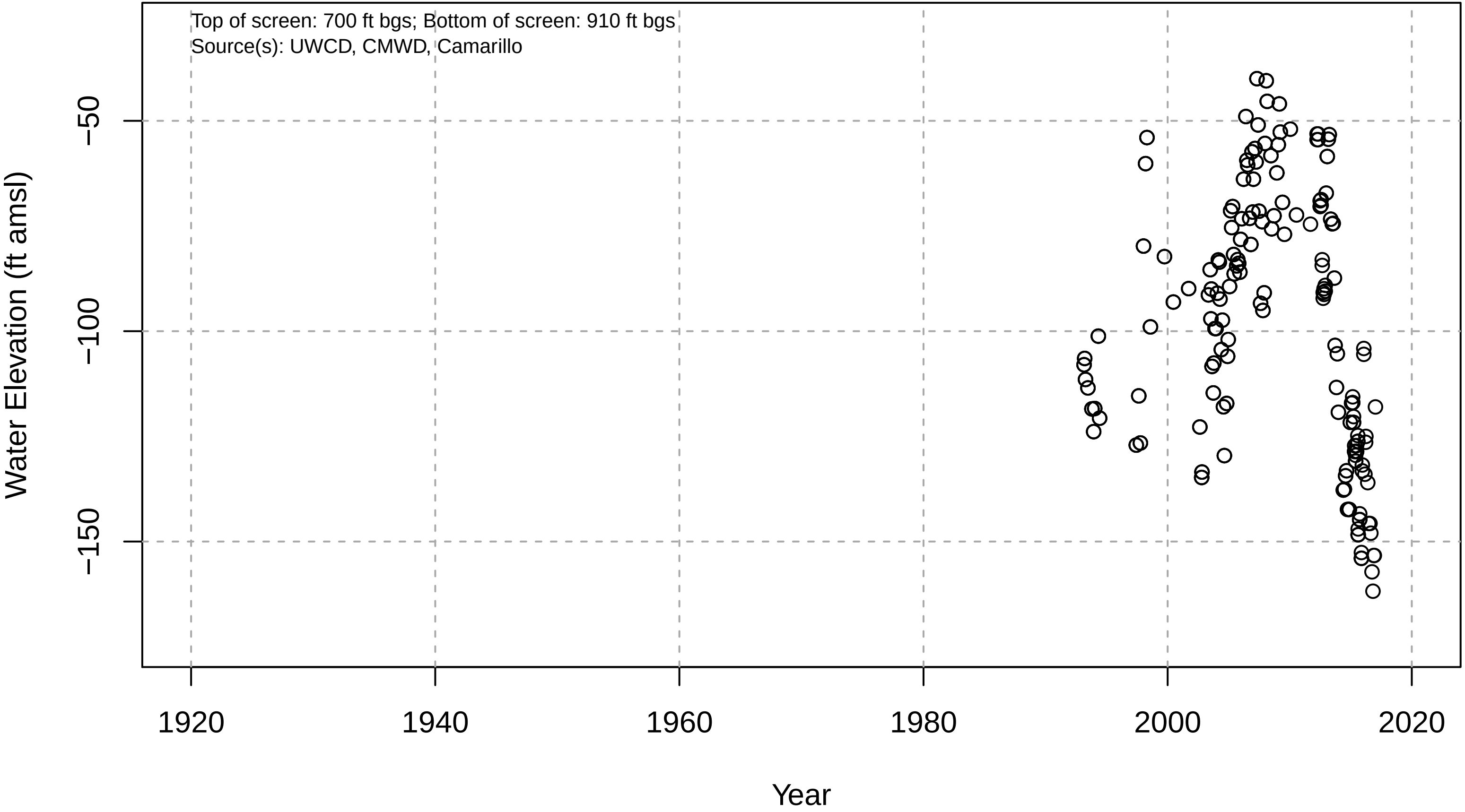


02N21W33P02S

Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS


02N21W33R02S
Top of screen: 801 ft bgs; Bottom of screen: 1051 ft bgs
Source(s): UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS

02N21W34C01S



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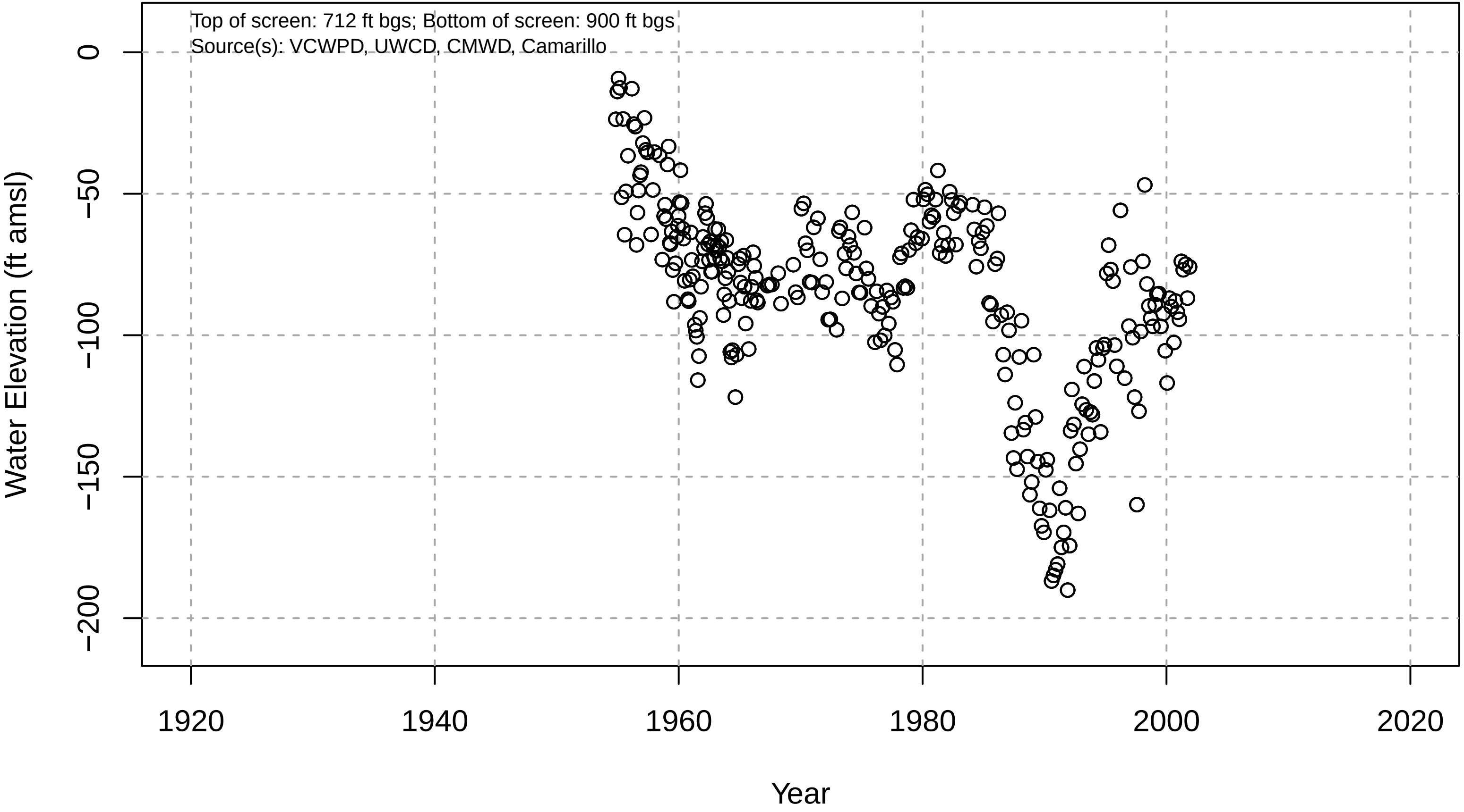
02N21W34D01S

Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated

02N21W34D02S



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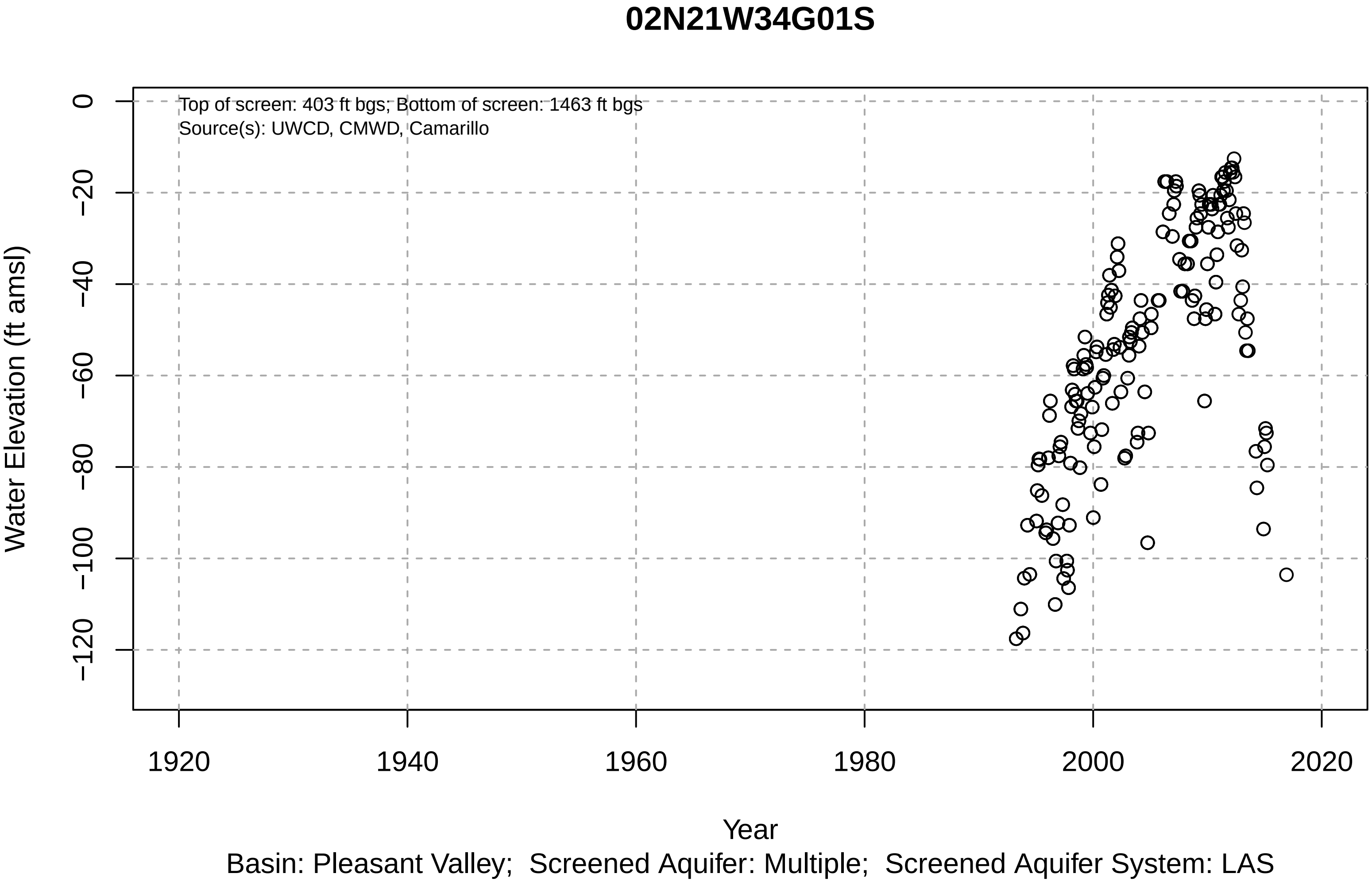
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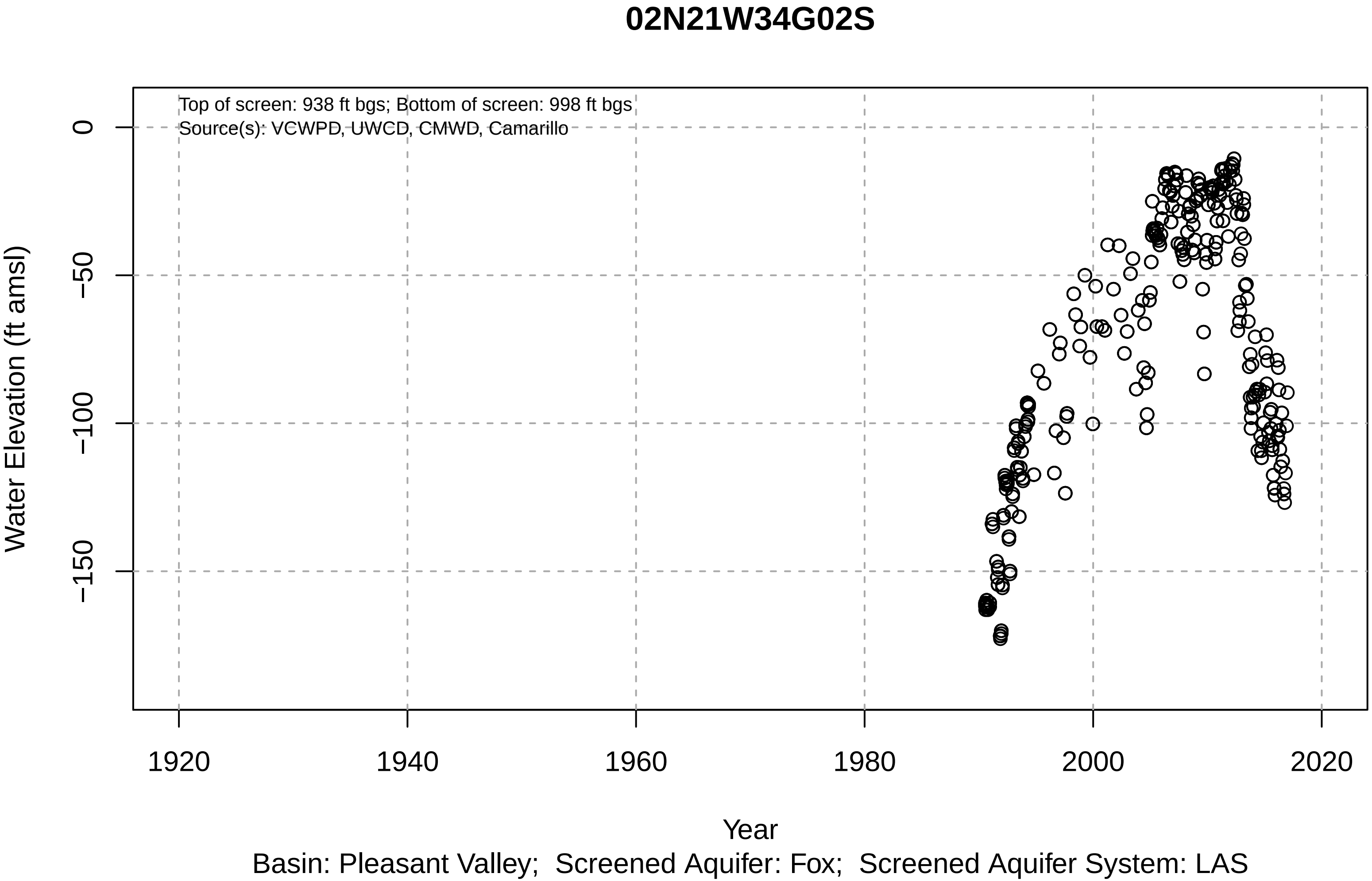
Source(s): UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
0
−20
−40
−60
−80
−100
−120
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS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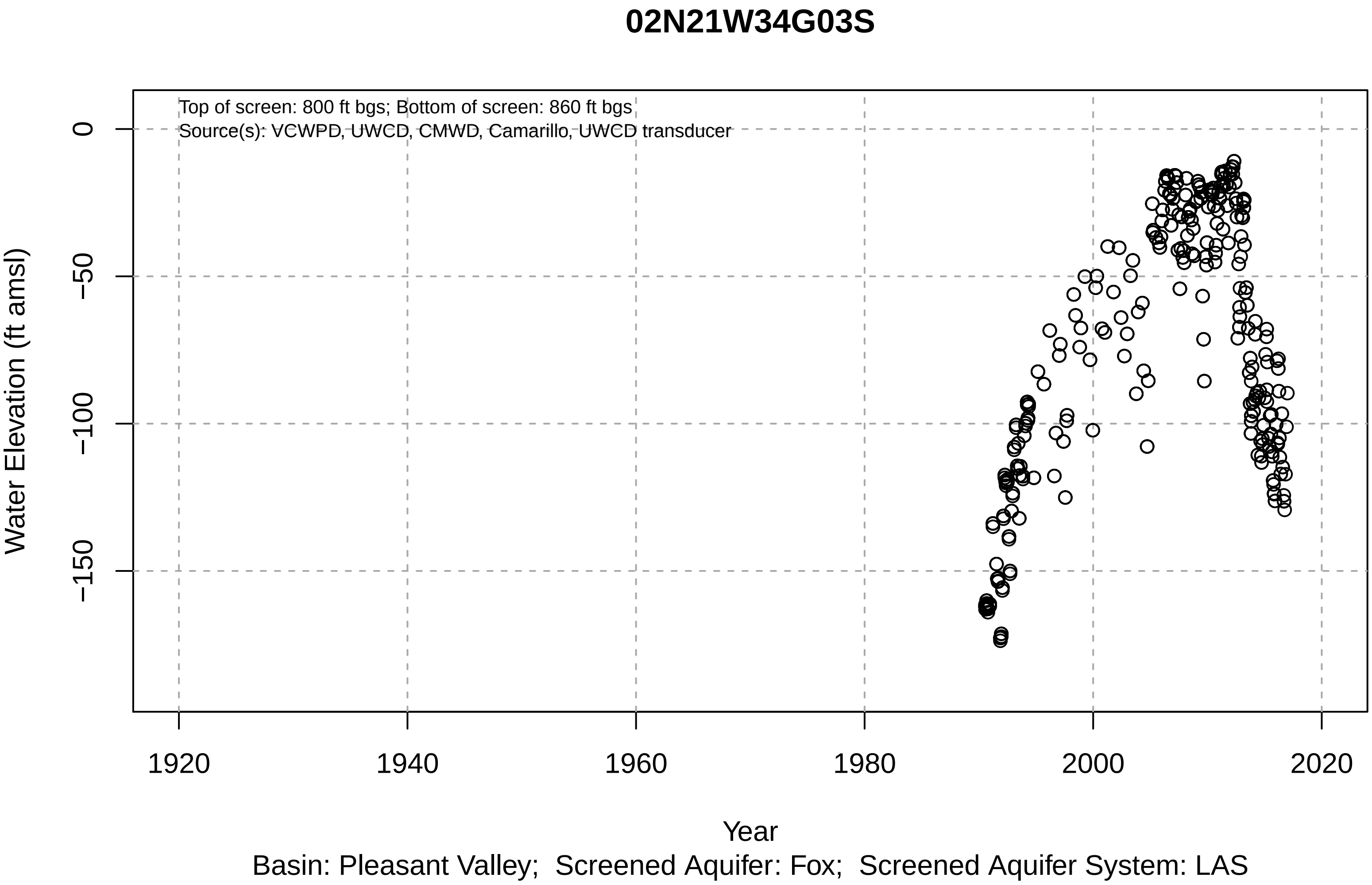
Top of screen: 938 ft bgs; Bottom of screen: 998 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS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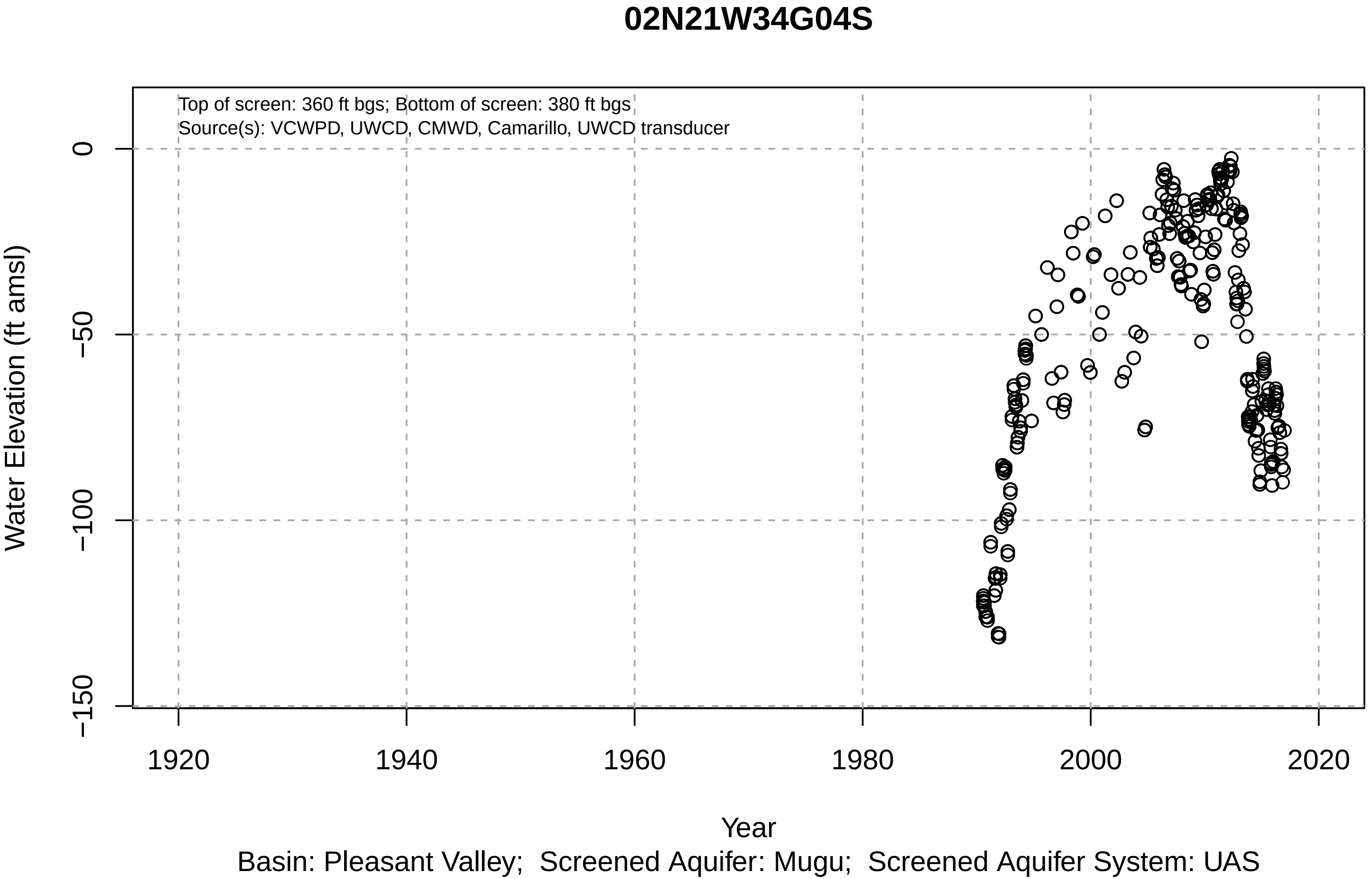
Top of screen: 800 ft bgs; Bottom of screen: 860 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo, UWCD transducer
Water Elevation (ft amsl)
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Fox; Screened Aquifer System: LAS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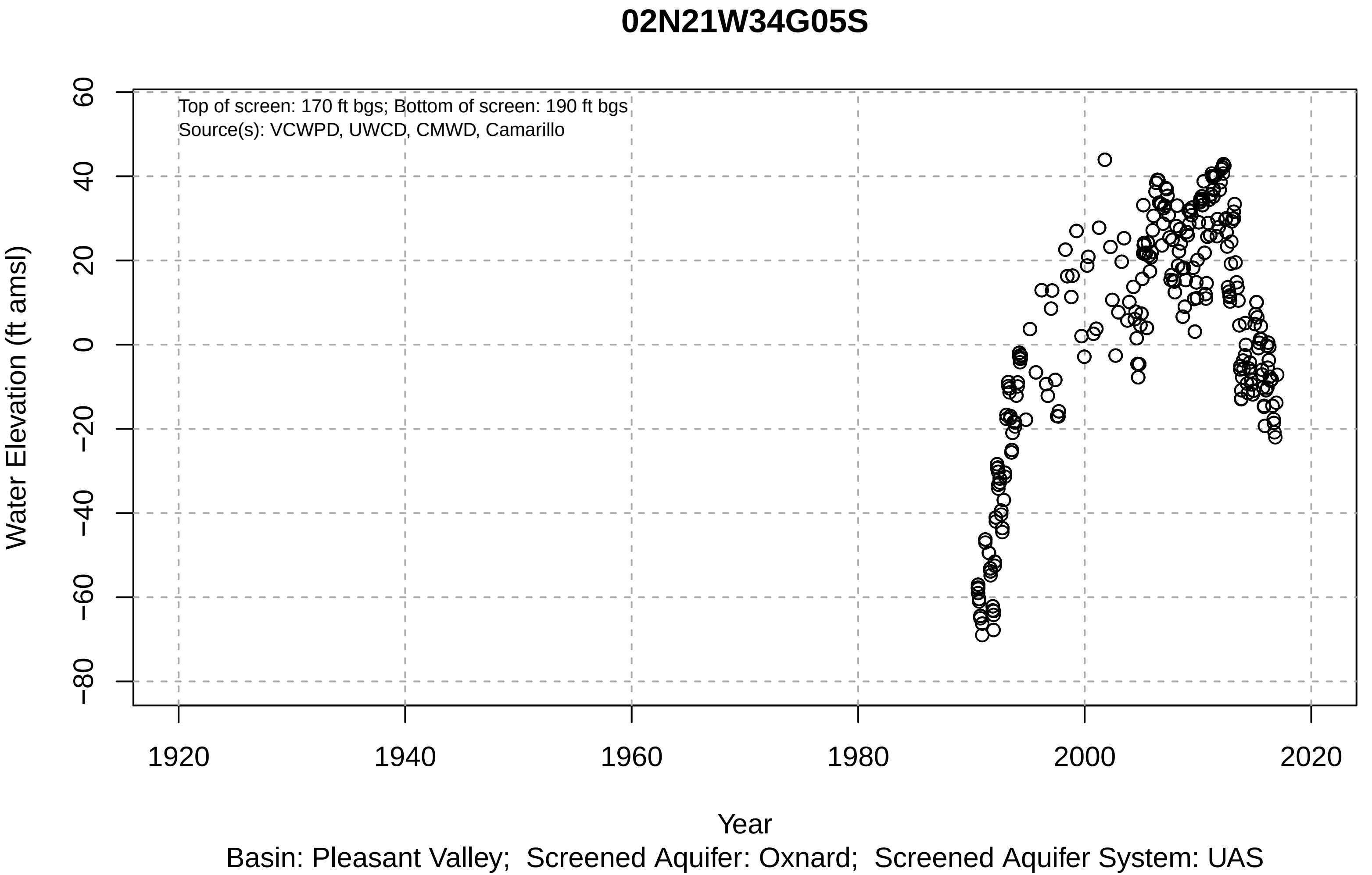
Source(s): VCWPD, UWCD, CMWD, Camarillo, UWCD transducer
Water Elevation (ft amsl)
0
−50
−100
−150
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Mugu; Screened Aquifer System: UAS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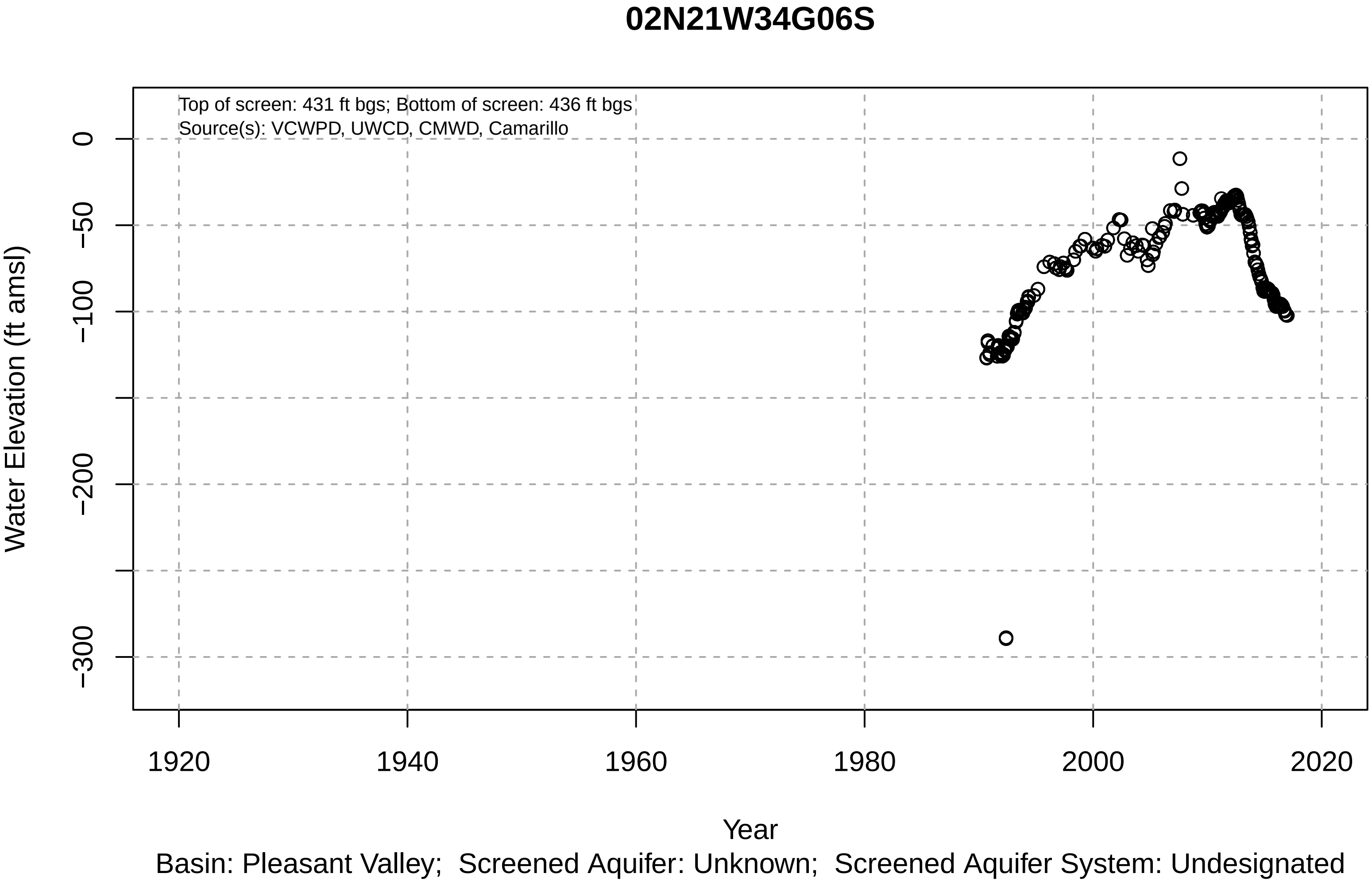
Water Elevation (ft amsl)
60
40
20
0
−20
−40
−60
−80
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Oxnard; Screened Aquifer System: UAS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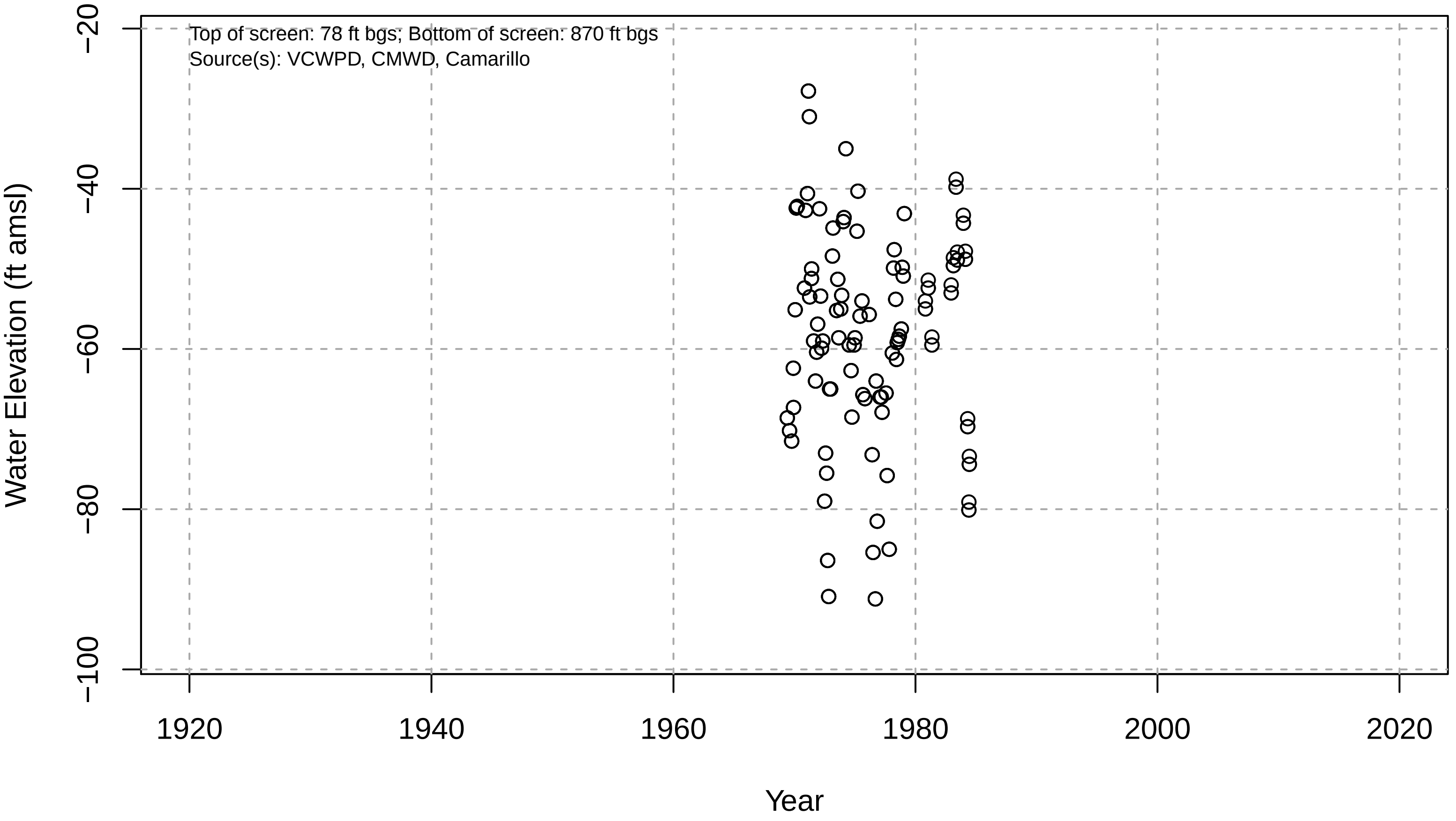
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
0
−50
−100
−200
−300
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Unknown; Screened Aquifer System: Undesignated

02N21W34J01S



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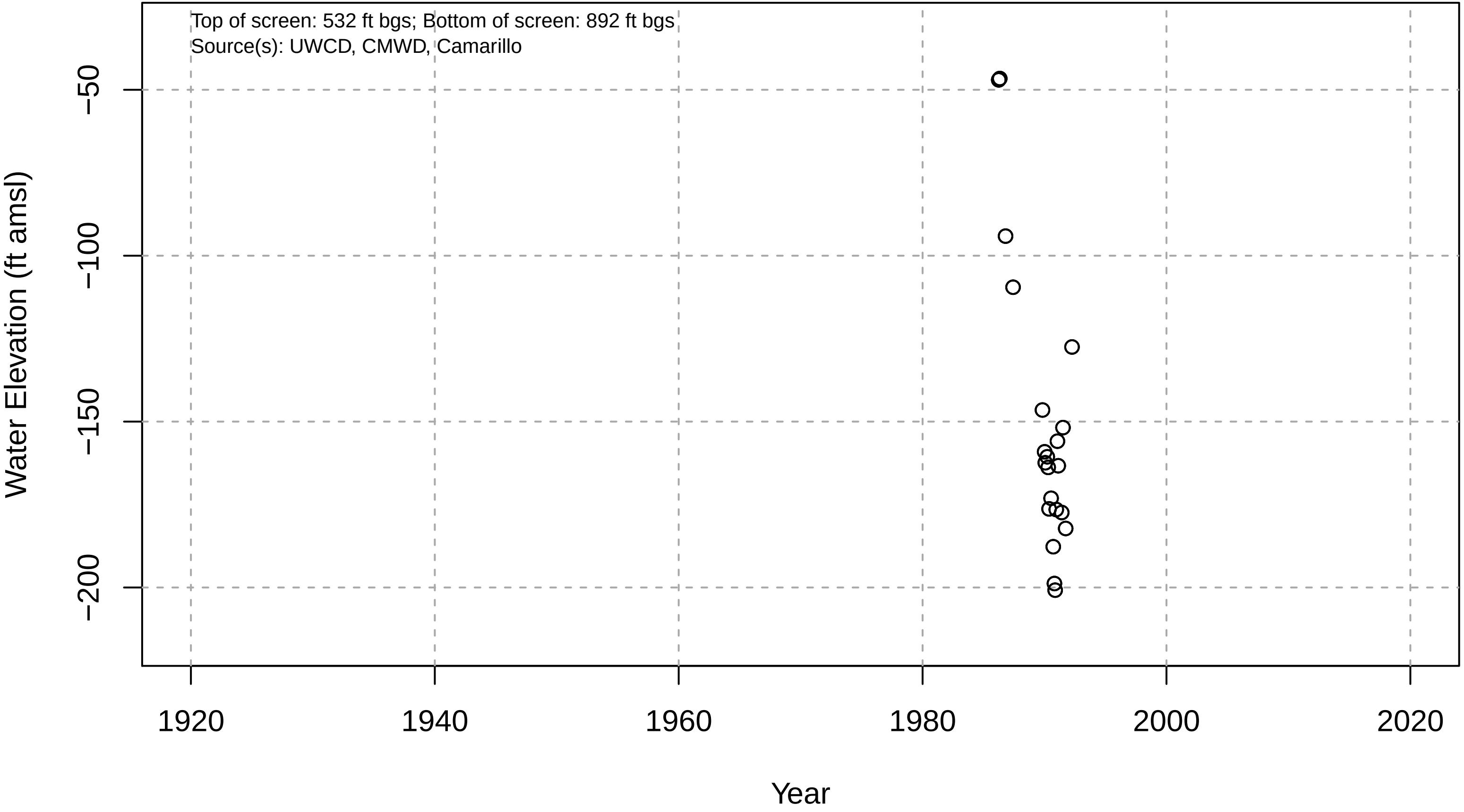

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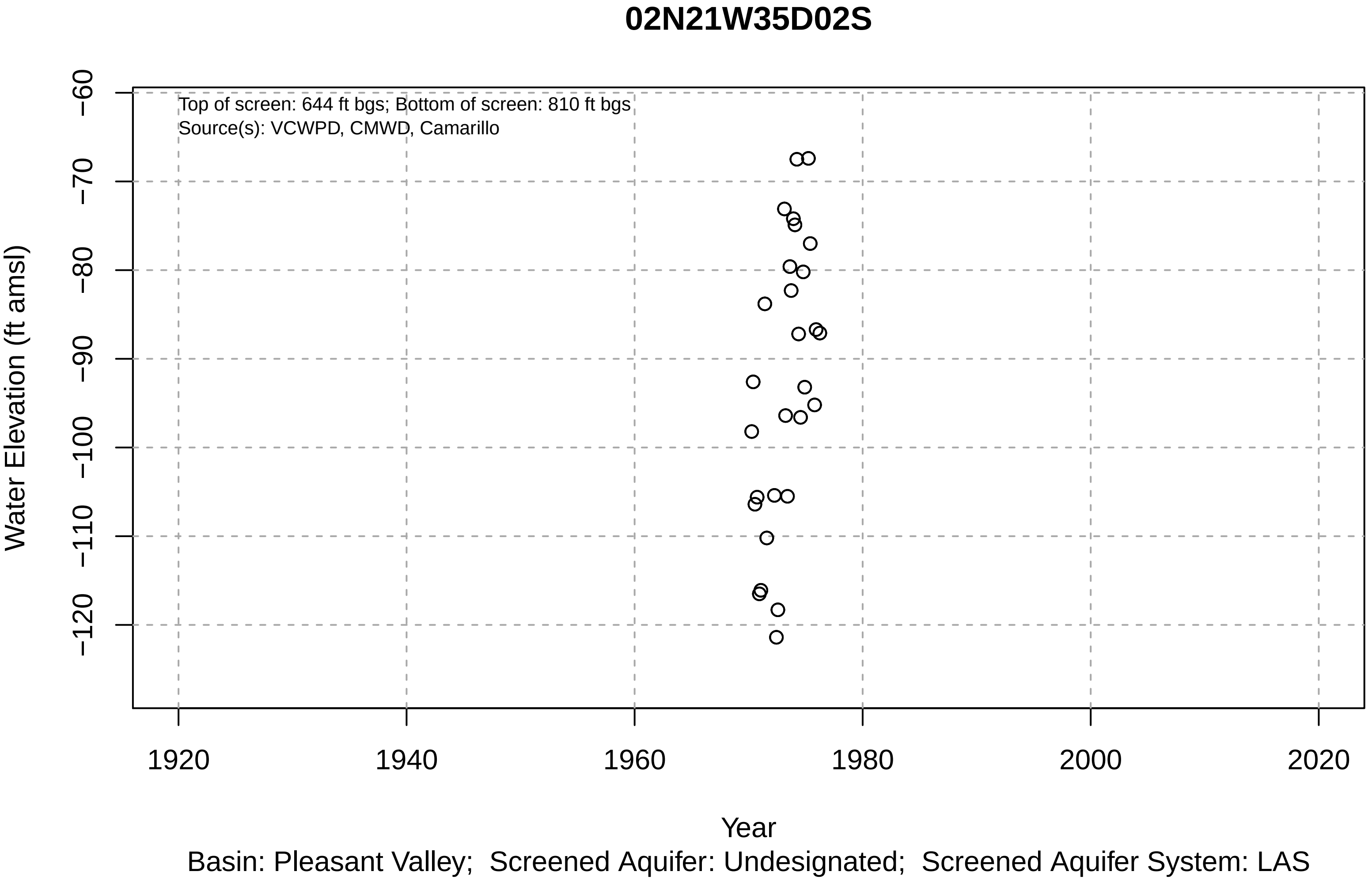
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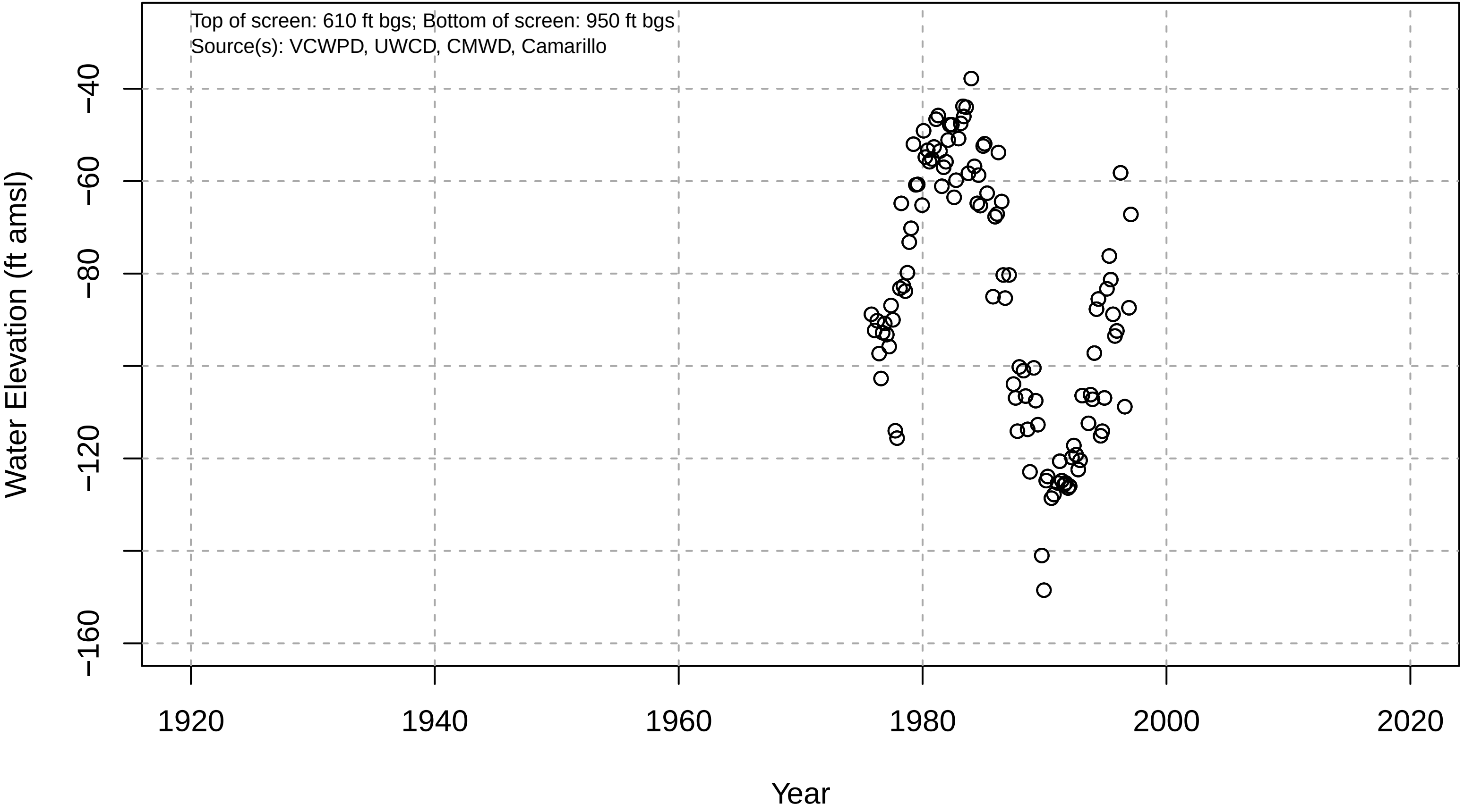
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
−60
−70
−80
−90
−100
−110
−120
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: LAS

02N21W35K01S



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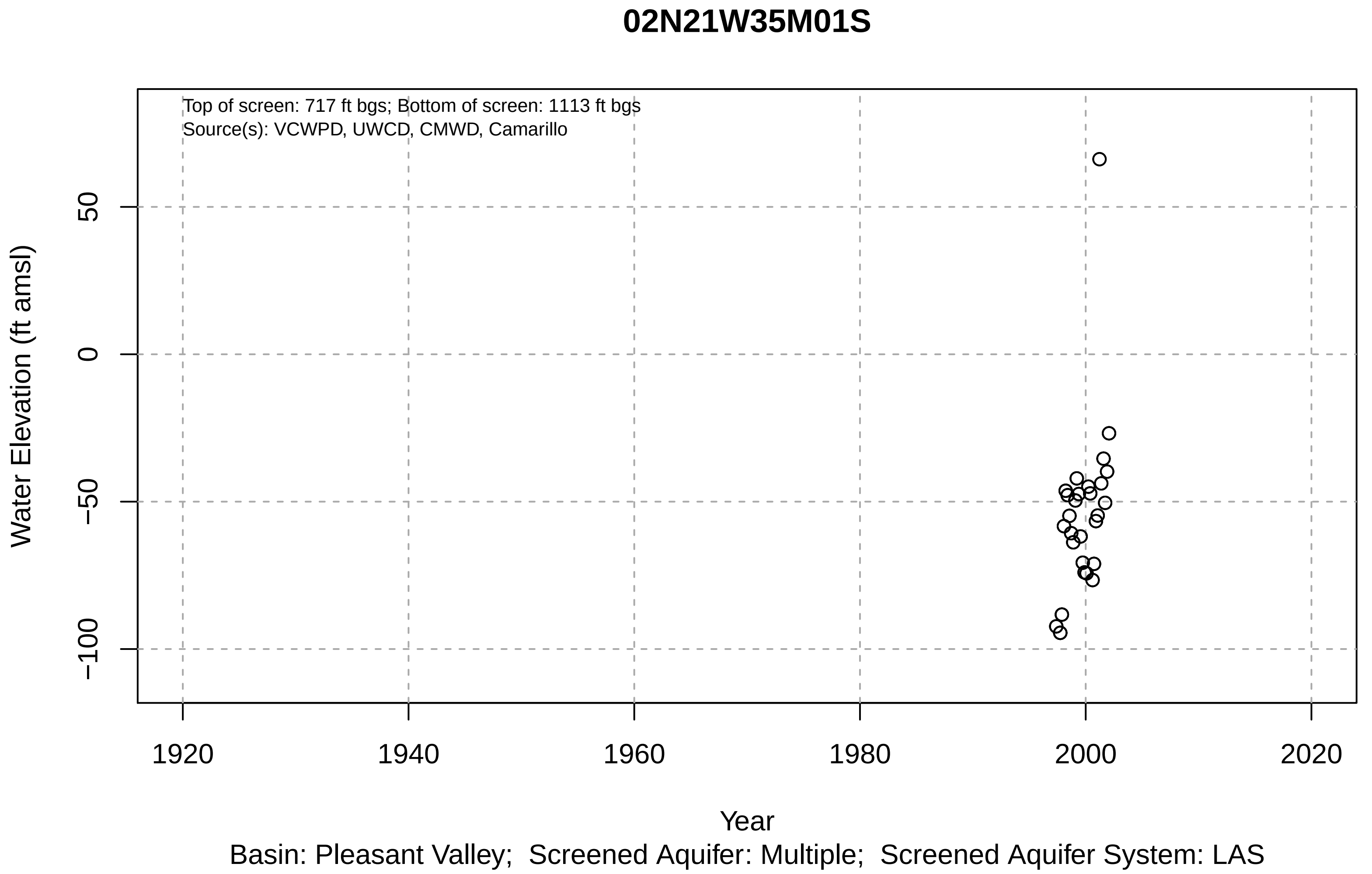
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Top of screen: 717 ft bgs; Bottom of screen: 1113 ft bgs
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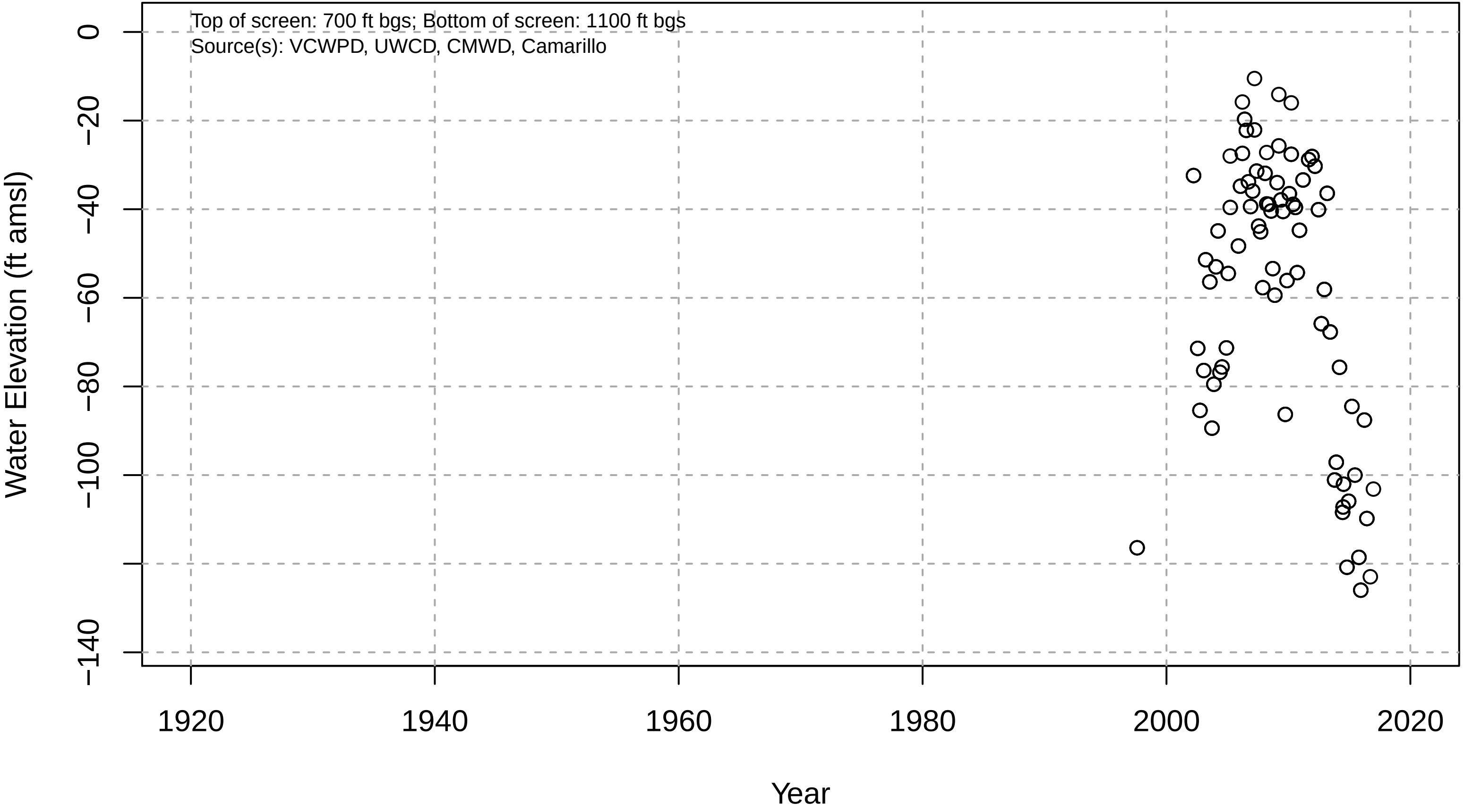
Water Elevation (ft amsl)
50
0
−50
−100
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: LAS

02N21W35M02S



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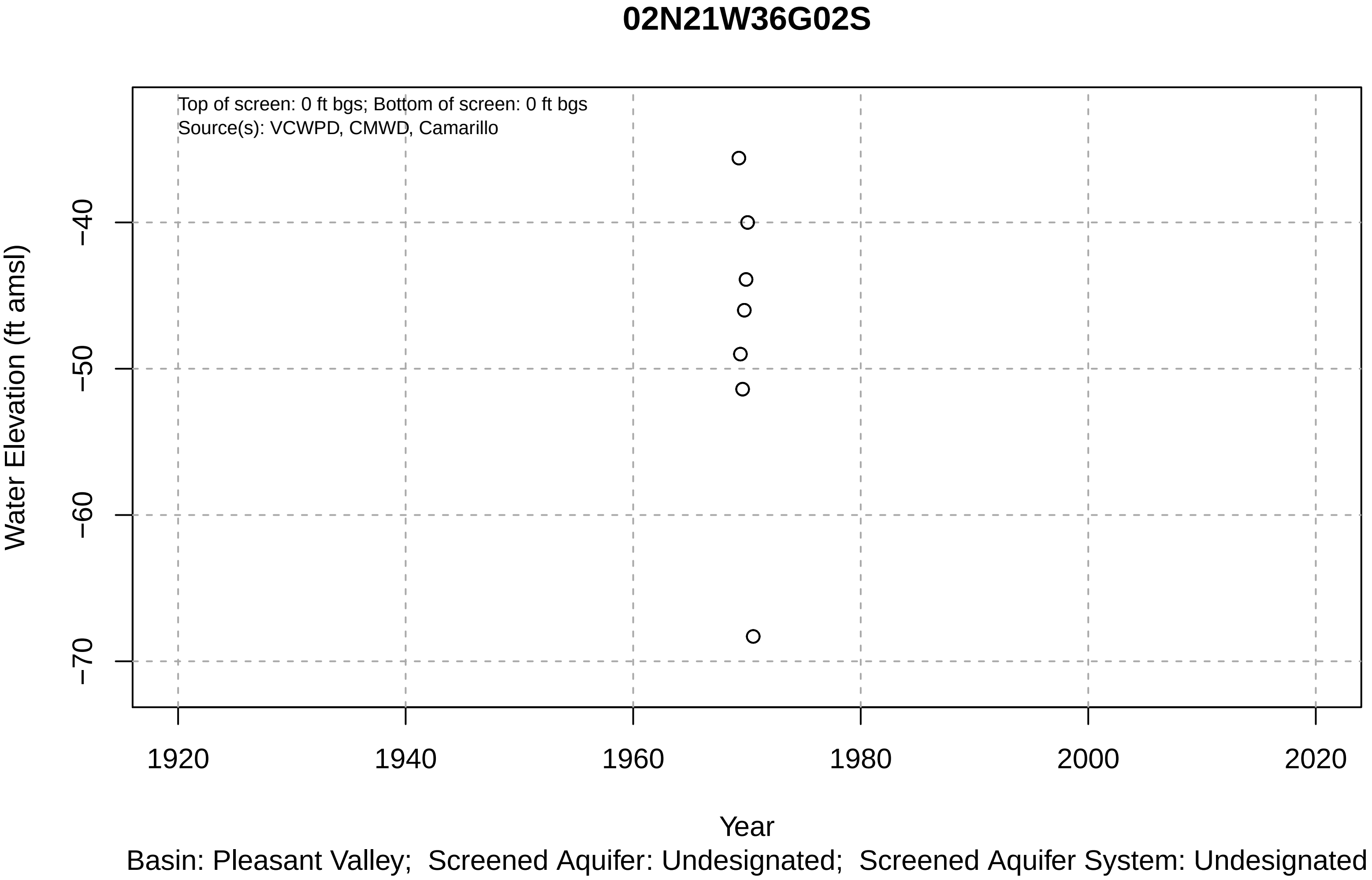
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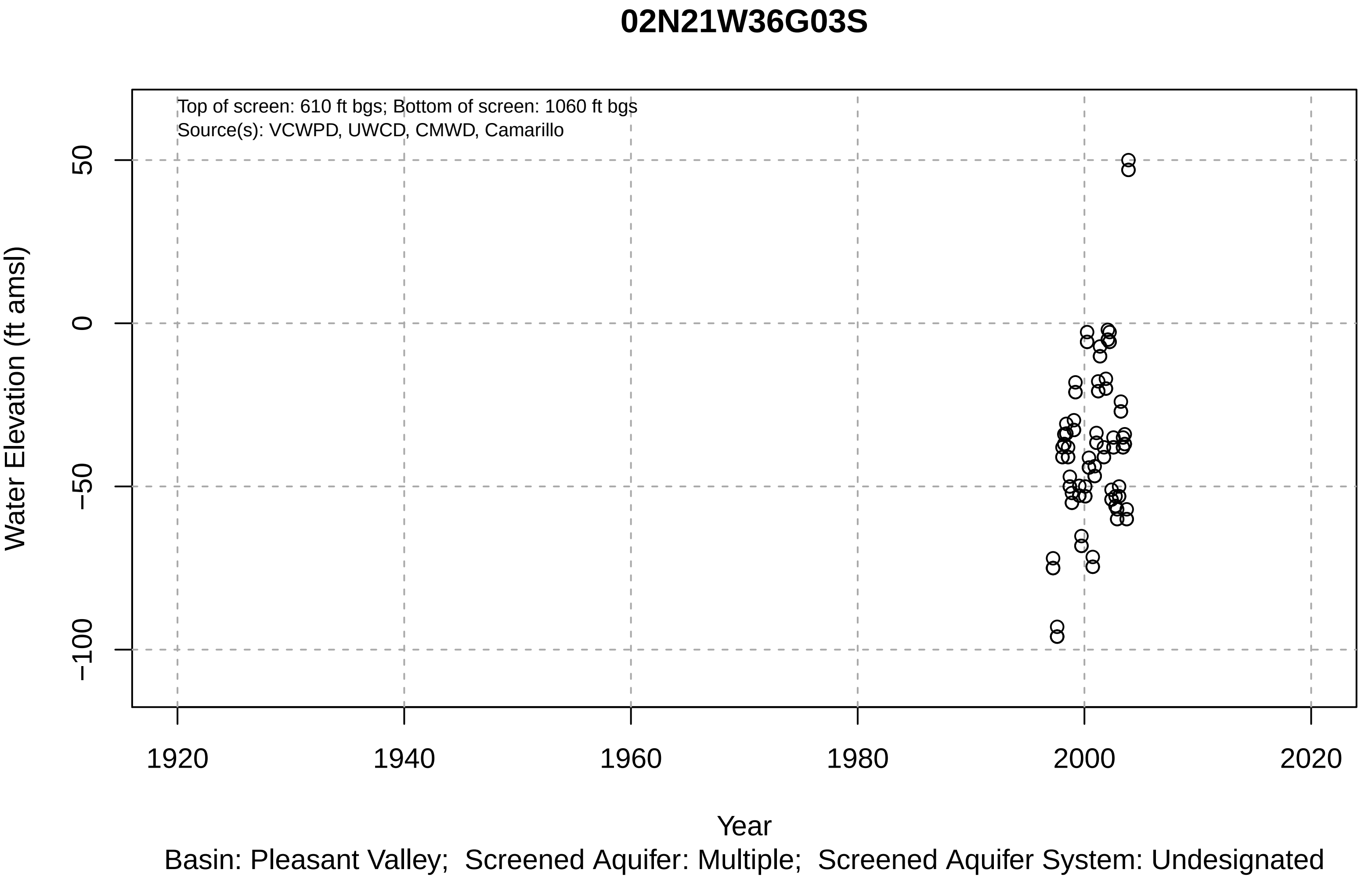
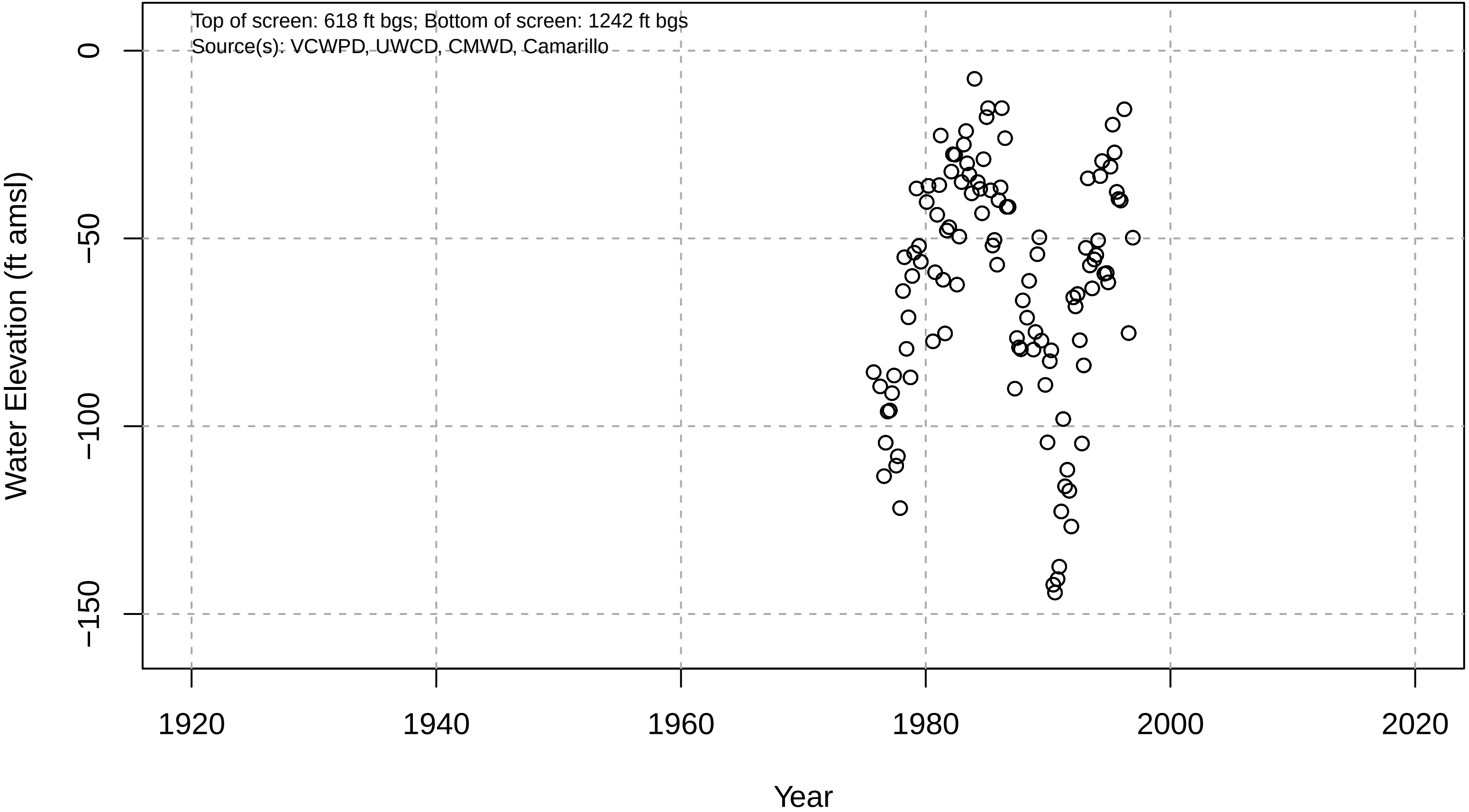
Source(s): VCWPD, CMWD, Camarillo
Water Elevation (ft amsl)
−40
−50
−60
−70
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Undesignated; Screened Aquifer System: Undesignated


02N21W36G03S
Top of screen: 610 ft bgs; Bottom of screen: 1060 ft bgs
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
50
0
−50
−100
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: Undesignated

02N21W36L02S



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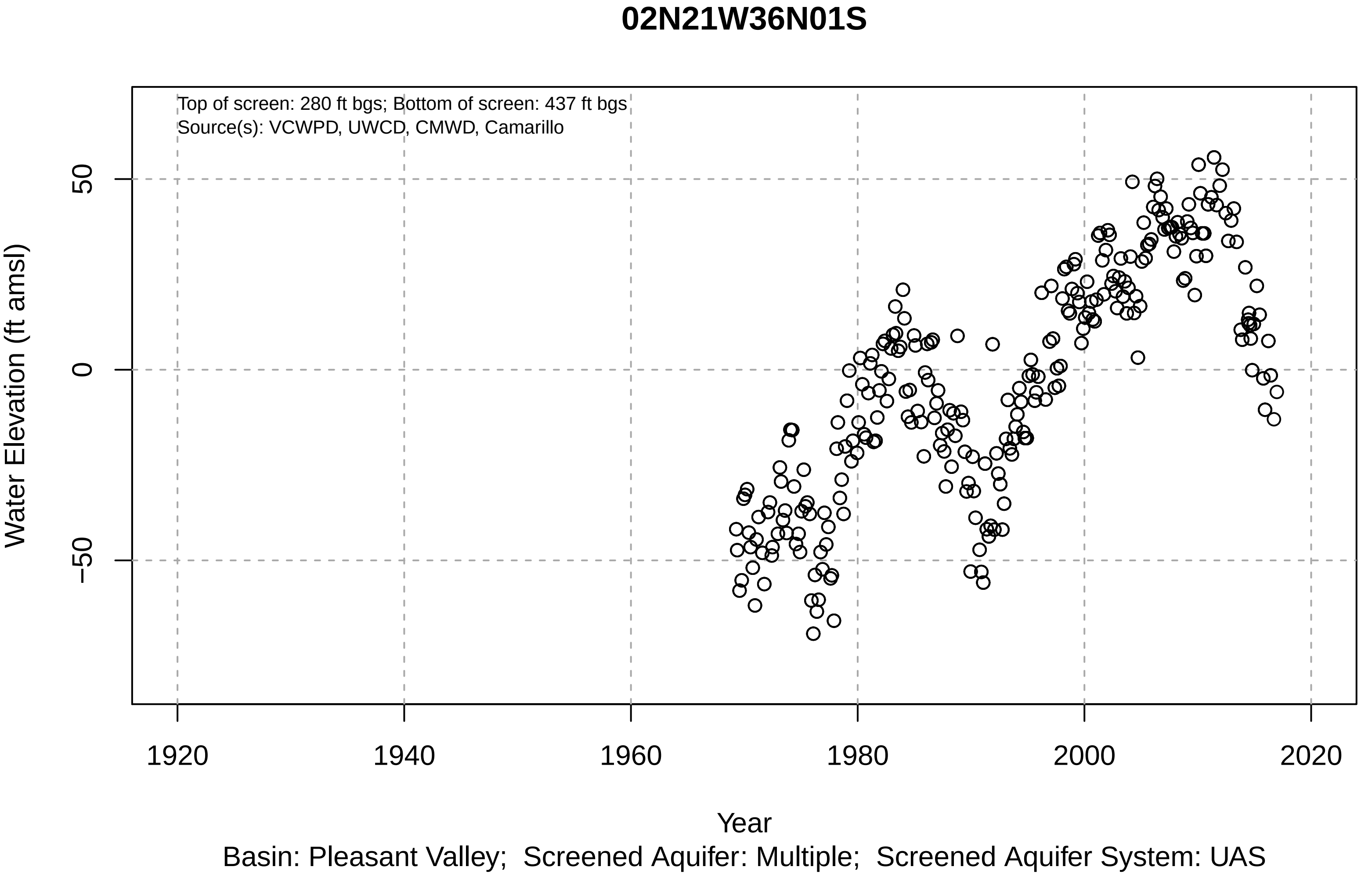
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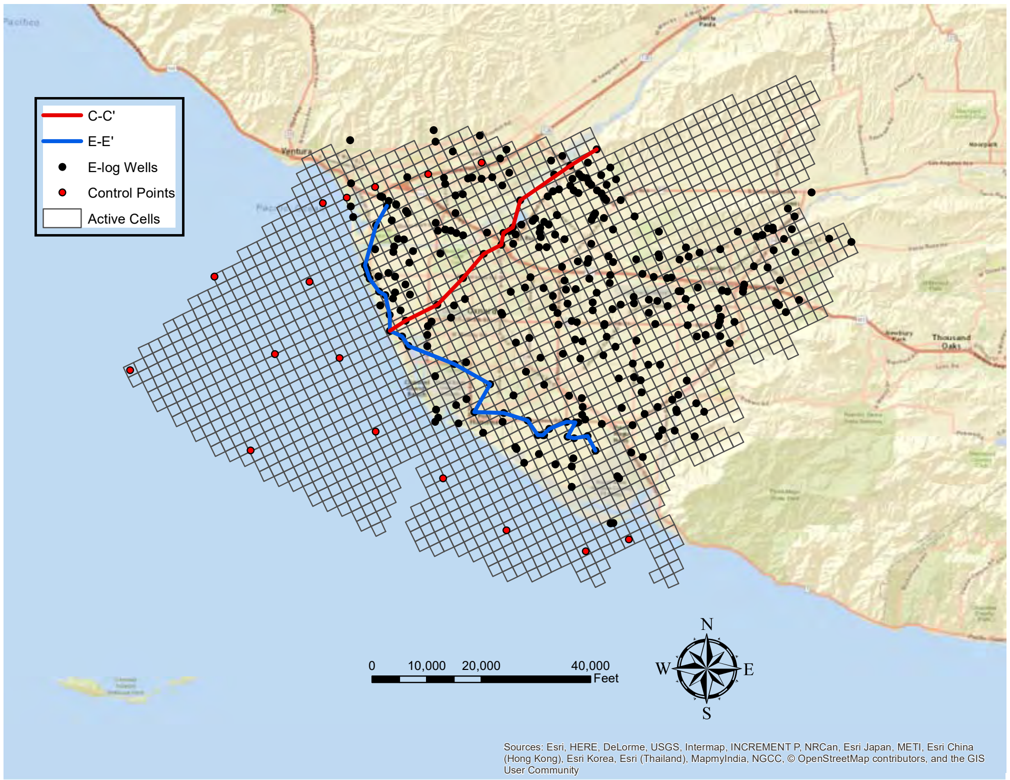
Source(s): VCWPD, UWCD, CMWD, Camarillo
Water Elevation (ft amsl)
50
0
−50
1920
1940
1960
1980
2000
2020
Year
Basin: Pleasant Valley; Screened Aquifer: Multiple; Screened Aquifer System: UAS

APPENDIX D

UWCD Model Report

VENTURA REGIONAL GROUNDWATER FLOW MODEL AND UPDATED HYDROGEOLOGIC CONCEPTUAL MODEL: OXNARD PLAIN, OXNARD FOREBAY, PLEASANT VALLEY, WEST LAS POSAS, AND MOUND GROUNDWATER BASINS

Open-File Report 2018-02
July 2018



Sources: Esri, HERE, DeLorme, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community

PREPARED BY
GROUNDWATER
RESOURCES
DEPARTMENT

UNITED WATER
CONSERVATION
DISTRICT

Cover Image: Model grid superimposed on map of the study area for this investigation.

Preferred Citation: United Water Conservation District, 2018, Ventura Regional Groundwater Flow Model and Updated Hydrogeologic Conceptual Model: Oxnard Plain, Oxnard Forebay, Pleasant Valley, West Las Posas, and Mound Basins, United Water Conservation District Open-File Report 2018-02, July.

VENTURA REGIONAL GROUNDWATER FLOW MODEL AND UPDATED HYDROGEOLOGIC CONCEPTUAL MODEL: OXNARD PLAIN, OXNARD FOREBAY, PLEASANT VALLEY, WEST LAS POSAS, AND MOUND GROUNDWATER BASINS

Open-File Report 2018-02
July 2018

Prepared by:

Dr. Jason Sun
P.E. #78655
Senior Hydrogeologist/Modeler

John Lindquist
P.G. #7076, C.Hg. #756
Senior Hydrogeologist

Dan Detmer
P.G. #7440, C.Hg. #806
Supervising Hydrogeologist

Tim Moore

Timothy Moore
P.G. #9268, C.Hg. #1027
Assistant Hydrogeologist

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FOREWORD

United Water Conservation District's (United) effort of the past six years to develop a significantly improved groundwater flow model for the Oxnard Plain and adjacent basins, as described in this report, is part of a broader effort by United and other agencies in the region to better understand the key factors that affect availability and usability of our area's groundwater resources. Use of these resources, which have been supplemented for the past 90 years by spreading (artificial recharge) of surface water diverted from the Santa Clara River, has been key to the past growth and the future sustainability of cities and agriculture on the Oxnard coastal plain. Groundwater of suitable quality for a wide range of beneficial uses can be withdrawn from wells and delivered to cities or farms on the Oxnard coastal plain and in the Santa Clara River valley without construction of extensive, costly infrastructure projects (such as the aqueducts and surface reservoirs of the State Water Project), and provides a reliable water supply and resilience against potential major disruptions such as earthquakes and droughts. Although imported surface water from northern California began contributing significantly to the region's municipal water-supply portfolio over the past half century, and desalination of brackish water or seawater may play an important water-supply role for the region in the future, neither of these alternative sources of water-supply can match the low cost and small environmental footprint of the existing groundwater resources, as enhanced by United's recharge operations.

Unfortunately, the relative accessibility, reliability, and low cost of groundwater for water supply has resulted in it being extracted from the aquifers underlying the Oxnard coastal plain at a faster rate than it has been replenished over the long term. This "overdraft" has resulted in corresponding groundwater-level declines in regional aquifers that have only been partly reversed during wet climatic cycles. In turn, these groundwater-level declines have resulted in seawater intrusion into the regional aquifers near the coast (since the 1930s), and could potentially exacerbate other water-quality problems or cause subsidence of land surface if allowed to continue. United coordinated with other regional water-supply stakeholders to plan and implement major projects in the 1950s, 1980s, and 1990s to mitigate the effects of overdraft, and these efforts have been partially successful. However, under California's Sustainable Groundwater Management Act (SGMA) of 2015, groundwater sustainability plans (GSPs) must be developed and implemented by 2020 to provide long-term solutions that will prevent further negative impacts in "critically overdrafted basins," including the Oxnard Plain and Pleasant Valley basins, and by 2022 for other groundwater basins in United's service area.

The geometry and physical characteristics of the aquifers, combined with the interactions of the stresses acting on those aquifers, within the regional groundwater basins are complex. The complexity is compounded by spatial and temporal variability of groundwater recharge and discharge. In order to forecast the effects of potential future water-supply alternatives with a sufficient level of certainty to evaluate and design new projects, it became evident to United in 2011 that the region needed a numerical groundwater-flow model that could discretely simulate each of the seven individual aquifer systems and six intervening aquitards that comprise the multi-layered regional aquifer system beneath the Oxnard and Pleasant Valley groundwater basins. The California Department of Water Resources notes that "while models are, by definition, a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process. Models can be useful tools for estimating the potential hydrologic effects of proposed water management activities" (Joseph and others, 2016).

Numerical models of local groundwater basins developed by California Department of Water Resources in the 1970s, and by the U.S. Geological Survey in the 1990s, were useful for answering the questions about groundwater being asked at those times. However, these models assumed a greatly simplified hydrologic system, consisting of one, two, or three "lumped" aquifers, rather than explicitly modeling the seven aquifers (and six aquitards) that actually exist in the region. This over-simplification was necessary at the time due to limitations in available data, as well as limitations in computer processing power. Consequently, these models produced simulated groundwater elevations that did not always match measured groundwater elevations very well in some key areas, including near the coast and in recharge zones, reducing the reliability and increasing the uncertainty of forecasts for future conditions. Therefore, in 2012 United initiated, with financial and technical support from regional stakeholders, development of the numerical model described in this report ("Ventura Regional Groundwater Flow Model," or VRGWFM), which discretely simulates each aquifer and aquitard underlying the Oxnard coastal plain as a distinct "layer" (in modeling terminology). The goal of this effort is to achieve significant improvement in calibration compared to previous models, allowing simulation of a greater range of natural and man-made hydrogeologic processes that have occurred in the past, and thereby increase the reliability of model predictions for the future. That said, the California Department of Water Resources warns, "there should be no expectation that a single 'true' model exists. All models and model results will have some level of uncertainty" (Joseph and others, 2016). For this reason, United is committed to continuous improvement of the VRGWFM as new data and improved methods become available, to minimize potential uncertainty.

United would like to acknowledge the financial support provided by the Fox Canyon Groundwater Management Agency (FCGMA) and the Santa Clara River Watershed Committee, as well as the technical input and assistance provided by the FCGMA Technical Advisory Group (TAG), the Calleguas Municipal Water District's technical staff and consultants, and the participants of the Expert Panel convened by United to review and provide guidance for improving the model (Dr. Sorab Panday, James Rumbaugh, and John Porcello). United would also like to acknowledge the various water and sanitation districts (including Ventura County Watershed Protection District), municipalities, and individuals that provided data to support development of the VRGWFM. We especially want to acknowledge the importance of the U.S. Geological Survey effort in the 1990s and 2000s to establish a regional groundwater monitoring-well network and construct the first MODFLOW model for the basins underlying the entire Santa Clara River and Calleguas Creek watersheds; their model was a critical "jumping-off point" for the VRGWFM. Finally, United's Groundwater Department staff would like to recognize the foresight and patience of United's Board of Directors, previous and present

General Managers, and—most notably—former Groundwater Department Manager Tony Morgan, for their efforts in kicking off this modeling effort six years ago and guiding/pushing staff to completion of “Version 1.0” today.

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VENTURA REGIONAL GROUNDWATER FLOW MODEL AND UPDATED HYDROGEOLOGIC CONCEPTUAL MODEL: OXNARD PLAIN, OXNARD FOREBAY, PLEASANT VALLEY, WEST LAS POSAS, AND MOUND GROUNDWATER BASINS

EXECUTIVE SUMMARY

This report documents the purpose, background, conceptualization, construction, and calibration of United's Ventura regional groundwater flow model (VRGWFM), which currently includes the Oxnard Plain (including the Forebay), Pleasant Valley, West Las Posas, and Mound groundwater basins (study area) of southern Ventura County. The VRGWFM incorporates a significant update of the hydrostratigraphic conceptual model for the study area and simulates individual aquifers and aquitards, thus representing a major upgrade from the previously available tools and information for understanding hydrogeologic conditions and forecasting effects of future aquifer stresses. Over the coming months, United intends to expand the model area to include the Santa Paula, Fillmore, and Piru basins, incorporate relevant new data received, and apply new modeling software (modules or packages) as they become available and are deemed helpful in answering regional groundwater and water-supply questions. Additional technical memoranda or reports will be prepared as needed in the future to document anticipated expansion of the model domain, modification of input parameters as a result of collection of new data, and selection of new or different modeling packages that improve simulation of hydrogeologic conditions within the study area.

BACKGROUND AND PURPOSE

In 2003, the U.S. Geological Survey (USGS) released documentation of their groundwater flow model for the lower portions of the Santa Clara River and Calleguas Creek watersheds (referred to herein as "the USGS model"), including the Piru, Fillmore, Santa Paula, Mound, Oxnard Plain (including the Forebay), Pleasant Valley, Santa Rosa, and Las Posas Valley (West, East, and South) basins. The USGS model included two layers, representing the Upper Aquifer System (UAS) and Lower Aquifer System (LAS). Although the USGS model was an effective starting point for developing an understanding of hydrogeologic conditions in the area, its relatively coarse discretization limited the level of detail at which it could be calibrated and prevented its use for evaluating impacts of future pumping/recharge scenarios on specific aquifers, particularly those impacted by seawater intrusion. Furthermore, the USGS model did not explicitly simulate the shallow Semi-perched Aquifer, including recharge and discharge processes occurring in that aquifer that are significant components of the groundwater budget in the Oxnard and Pleasant Valley basins. Therefore, in 2011 United and

FCGMA determined that an updated and more detailed conceptual model of hydrostratigraphy should be developed, followed by construction and calibration of a higher-resolution numerical groundwater-flow model that (unlike earlier models) would provide discrete simulation capabilities for each individual aquifer and aquitard. The purpose of the current modeling effort described in this report has been to construct the VRGWFM envisioned by United and FCGMA in 2011, and verify (via historical calibration, sensitivity analysis, and review) that it would serve as an improved tool for simulating the future occurrence and movement of groundwater within the study area.

The VRGWFM is anticipated to be used in support of United's and FCGMA's groundwater planning and management activities, which will require predictive simulations of potential future pumping, recharge, and land- and water-use scenarios in the study area. United intends to use the model as a planning tool to maximize the regional benefits of its conjunctive use operations and to forecast effects of water-supply projects operated by United and other local agencies. The FCGMA may elect to use the model to evaluate the effectiveness of potential groundwater management strategies and regulatory policies on eliminating overdraft and saline-intrusion in the coastal areas of the Oxnard Plain.

HYDROGEOLOGIC CONCEPTUAL MODEL

In order to construct an improved numerical groundwater flow model that explicitly and accurately represents all of the major hydrostratigraphic units (HSUs) in the study area, United staff collected and reviewed more than 900 borehole resistivity logs (electric logs or "e-logs") from oil/gas and water wells within the model domain and nearby areas, with the goal of updating and refining the hydrostratigraphic conceptual model. This updated hydrostratigraphic model forms the basic "framework" required to define the geometry and layering of the numerical flow model, as described in Section 3 of this report.

The conceptual model for groundwater flow in the study area can be distilled down to the following key points or elements:

- Most groundwater in the study area is stored in, and flows through, two aquifers comprising the UAS and four aquifers comprising the LAS. A relatively small quantity of groundwater also occurs in the uppermost (shallow) aquifer system, referred to as the Semi-perched Aquifer in the Oxnard coastal plain area (where a thick clay unit is present between this shallow aquifer and the underlying UAS). Due to the limited quantity and poor quality of groundwater typically found in the shallow aquifer system, it is largely unused by agriculture, municipalities, or industry.
- Most of the adjacent groundwater basins within the study area are in hydraulic connection with each other, and groundwater within each aquifer can flow from one basin to an adjacent basin with moderate to no impediment (depending on hydraulic conductivity and gradients) in most instances.
- Groundwater generally flows from areas of recharge to areas of discharge. The largest single source of groundwater recharge to the UAS and LAS in the study area is the artificial recharge introduced to the Forebay by United. In the Forebay, the sediments comprising the shallow aquifer system have been uplifted and eroded away, exposing the highly permeable aquifers

of the UAS at land surface, providing an ideal situation for recharge via spreading basins. Some of this artificial recharge percolates downward to the aquifers of the LAS in the Forebay and adjacent basins in response to vertical hydraulic gradients between the UAS and LAS. Smaller quantities of groundwater recharge the UAS and LAS as a result of:

  - groundwater underflow from upgradient basins,
  - mountain-front and stream-channel recharge,
  - seawater intrusion near the coast,
  - downward flux from the shallow aquifer system, and
  - deep percolation of precipitation, agricultural return flows, municipal/industrial return flows, and treated wastewater in the few areas where the UAS and LAS are exposed at land surface.

- Most groundwater discharge from the UAS and LAS in the study area occurs via pumping from hundreds of water-supply wells located in the Oxnard Plain (including the Forebay) and Pleasant Valley basins, and a smaller number of wells in the Mound, West Las Posas, and Santa Paula basins.
- Because the preponderance of recharge in the study area occurs in the Forebay, while most discharge consists of pumping in surrounding basins, groundwater in the UAS and LAS typically flows radially outward from the Forebay to the adjacent basins. However, two notable disruptions to this pattern can occur, as follows:
  - When United's recharge operations are limited due to drought conditions, groundwater elevations in the UAS have periodically dropped below sea level as far north as the northern part of the Forebay area, and the typical pattern of radial groundwater flow outward from the Forebay becomes replaced by landward gradients at the coastline across the Oxnard Plain basin. This results in seawater intrusion from the adjacent Pacific Ocean to the aquifers underlying the Oxnard coastal plain.
  - A large groundwater "cone of depression" has persisted for decades in the LAS in the agricultural area east of Oxnard and south of Camarillo as a result of the concentration of pumping from water-supply wells in this area and the substantial distance from the Forebay (where most recharge occurs). Groundwater elevations in this cone of depression have long been tens to over 100 feet below sea level, producing landward hydraulic gradients and strong vertical gradients from the UAS to the LAS that contribute to seawater intrusion in the LAS.
- In the shallow aquifer system, recharge occurs throughout the study area (mostly via deep percolation of precipitation, agricultural and municipal/industrial return flows, and treated wastewater), as does groundwater discharge (mostly via evapotranspiration and tile drains, with relatively small amounts of groundwater discharging to the lower Santa Clara River and the Pacific Ocean). Because most land in the study area is used for municipal, industrial, or agricultural purposes, and agricultural irrigation occurs year-round, groundwater elevations in the shallow aquifer system typically remain stable at elevations within approximately 5 to 8 feet of land surface (where most evapotranspiration occurs and tile drains are installed, respectively).

A summary of estimates for inflow and outflow components to the groundwater system in the study area is provided in Table ES-1, below. Approximately half of the total inflow consists of artificial recharge, which is metered by United and, therefore, volumes are known with a high level of certainty. Over the past 50 years, United's recharge operations in the Forebay are estimated to have contributed a greater volume of recharge to the aquifers of the UAS and LAS in the study area than all other sources of recharge combined (the Semi-perched Aquifer is not present in the Forebay, so does not receive artificial recharge from United's spreading basins). Therefore, artificial recharge can be considered the most important long-term groundwater influx term to the study area. Similarly, groundwater pumping from water-supply wells is, by far, the largest component of estimated groundwater discharges (or outflows) from the overall groundwater system in the study area, and comprises 100 percent of the net discharge from the UAS and LAS in the study area (some discharge from the UAS and LAS to the Pacific Ocean occurs, but this is countered over the long-term by seawater intrusion; therefore, net inflow of seawater is occurring rather than net discharge).

The small magnitude of the other inflows and outflows relative to artificial recharge and groundwater pumping—the major inflow and outflow components—means that even if there is relatively large percentage uncertainty (e.g. +/-25%) in deep infiltration of precipitation, for example, which could result in a hypothetical "error" of +/-4,500 AF/yr, the magnitude of this uncertainty is less than 10% of the average artificial recharge rate of 48,000 AF/yr (which is known to a high level of certainty since it is carefully monitored by United). Therefore, despite some uncertainties, the water budget in the study area is better suited to construction of a groundwater flow model than are water budgets for many other basins. Furthermore, much of the recharge in the study area derived from sources other than artificial recharge enters the groundwater system in the Semi-perched Aquifer, which is not used for water supply. This recharge is removed from the groundwater system via the extensive drainage systems in the Semi-perched Aquifer (and ET) within hours, days, or a few weeks, at most, and has little influence on groundwater conditions in the aquifers of the UAS and LAS.

Many, but not all, of the inflow and outflow components listed in Table ES-1 are required groundwater flow-model input parameters (shown in bold in Table ES-1). There are varying degrees of uncertainty associated with some of the smaller inflow and outflow components (i.e. stream-channel recharge, deep infiltration of precipitation, agricultural and M&I return flows, mountain-front recharge, percolation of treated wastewater, drainage, ET, underflow to/from adjacent basins, and seawater intrusion), as is common in regional-scale flow models. Therefore, consistent with standard modeling practice, the values for these uncertain inflow components were adjusted during model calibration to improve the overall model calibration. The inflow and outflow components not required as input to the model (shown in italics in Table ES-1) are calculated by the model based on simulated boundary conditions, aquifer stresses, and aquifer parameters.

NUMERICAL MODEL CONSTRUCTION

The first step in construction of the VRGWFM was selection of a suitable modeling "platform" (software) and determination of appropriate spatial and temporal limits or boundaries for the model (the domain). The next step was to decide how to subdivide (discretize) both space and time in the model such that the simulation results were produced at an appropriate scale to meet the modeling objectives, while keeping computing and post-processing requirements reasonable. Next, estimates of aquifer hydraulic parameters were entered into digital input files ("packages"), completing

Table ES-1. Comparison of Previous Estimates of Groundwater Inflow and Outflow Components in Study Area to VRGWFM Recharge and Discharge Rates for Historic Calibration Period

Groundwater Inflow or Outflow Component	Estimates from Available Data or Previous Investigations (AF/yr)[a]	VRGWFM Recharge and Discharge Rates (AF/yr)
Inflows: (**bold** font used for components that are required as input to the VRGWFM, *italic* font used for flows that are calculated by the VRGWFM [provided solely for comparative purposes])		
Artificial Recharge (at Saticoy and El Rio Spreading Grounds)	**48,000**	**48,000**
Areal Recharge (combined deep infiltration of precipitation and return flows [Ag + M&I])	**38,000 to 43,000**	**48,000[b]**
Mountain-Front Recharge (sum of ungauged streamflow and bedrock recharge)	**3,000**	**7,900[b]**
Percolation of Treated Wastewater at WWTPs	**280**	**280**
Stream-Channel Recharge in Santa Clara River	*8,400*	*9,600*
Stream-Channel Recharge in Arroyo Las Posas	*4,000*	*4,300*
Groundwater Underflow from Santa Paula Basin	*1,800 to 7,400*	*3,800*
Groundwater Underflow from East Las Posas Basin	*700 to 1,900*	*1,600*
Net Seawater Intrusion into UAS and LAS	*12,000*	*9,400*
Outflows: (**bold** font used for components that are required as input to the VRGWFM, *italic* font for flows that are calculated by the VRGWFM [provided solely for comparative purposes])		
Pumping from Water-Supply Wells	**130,000[c]**	**130,000[b]**
Shallow groundwater drainage (to tile and other manmade drain systems)	*8,000 to 12,000*	*12,000*
ET	*15,000*	*9,900*
Discharge of Shallow Groundwater in Semi-perched Aquifer to Santa Clara River	*1,500*	*1,200*
Semi-perched Aquifer Discharge to Pacific Ocean	*No previous estimates*	*1,100*

Notes:

All numbers rounded to two significant digits.

[a] Details regarding sources and calculation methods for averages calculated from existing data or estimated by previous investigators are provided in Section 2.7 and Table 2-2. Most of the averages summarized in this column are for the combined area of the Oxnard Plain, Forebay, Pleasant Valley, Mound, and West Las Posas basins. The relatively small inflow and outflow quantities occurring in the minor area of the active domain of the VRGWFM located outside of those basins (e.g., western margin of Santa Paula basin) are generally not included in the averages presented in this column.

[b] The VRGWFM-input or -calculated quantities listed in this table for these inflows and outflows include the entire active model domain, including small areas outside of the Oxnard Plain, Forebay, Pleasant Valley, Mound, and West Las Posas basins. Therefore, these quantities can be somewhat higher than those listed in the first column of this table, which generally focus specifically on these basins.

[c] Unlike most quantities listed in this column, the estimated total pumping from water-supply wells was calculated for the entire active model domain. Therefore, it is identical to the VRGWFM-input average pumping rate.

construction of the basic model framework. Next, known and estimated aquifer stresses over the calibration period (CY 1985 through 2015) were entered into input files. With this information, together with instructions regarding how the model should process input and output, the modeling software computes heads and flows throughout the model domain based on a numerical solution of the partial-differential equation that defines groundwater flow (the continuity equation). Comparison of model-simulated groundwater elevations to measured historical groundwater elevations, typically accompanied by adjustment of modeled aquifer parameters as needed to reduce any differences (residuals), is referred to as calibration, and was conducted iteratively with refinement of the model. Finally, sensitivity of the model to variability and uncertainty in its input parameters was analyzed.

The USGS software package MODFLOW-NWT was selected by United to be the modeling platform for initial development of the VRGWFM. The groundwater system in the study area is influenced by cycles of extended drought and wet periods that cause groundwater levels to fluctuate over 100 feet, requiring a numerical model capable of simulating the desaturation and resaturation (drying and wetting) of portions of the aquifers. MODFLOW-NWT was developed in large part to simulate this type of condition.

The current active domain of the VRGWFM includes the Forebay, Mound, Oxnard Plain, Pleasant Valley, and West Las Posas basins, part of the Santa Paula basin, and the submarine (offshore) outcrop areas of the principal aquifers that underlie the Oxnard Plain and Mound basins. The active model domain spans approximately 176,000 acres (275 square miles). The domain of the VRGWFM was discretized (subdivided) into finite-difference grid cells and layers such that basin-scale hydrogeologic features, boundaries, and flow patterns could be simulated at an acceptable level of resolution, while keeping model run-times to a reasonable length during calibration and sensitivity analysis. At present, the VRGWFM model-grid spacing is a uniform 2,000 feet (in both the north-south and east-west directions), divided into 13 layers of variable thickness.

Initial values were input to the VRGWFM for horizontal hydraulic conductivity, vertical conductance between layers, specific yield, storage coefficient, and conductance across horizontal flow barriers (faults). Conductance values and other input parameters applied to local-scale features and stresses were also input. Previous investigators have typically estimated aquifer hydraulic parameters for the UAS and LAS rather than for individual aquifers within those systems. Best-management practices for modeling suggest modifying input values for aquifer parameters during model calibration. This was United's approach to assigning aquifer hydraulic parameters in the VRGWFM; start with values based on available data (or typical values reported in the literature for the soil and rock types present), then adjust the values as appropriate (within reasonable ranges) during model calibration.

Table ES-1 summarizes the stresses (recharge and discharge rates) input to the model, and compares them to the long-term average inflow and outflow components in the study area that were estimated by previous investigators (as discussed above). Some of inflow and outflow components to the study area are known with a reasonable level of confidence and can be directly translated to the model as recharge and discharge components, on a one-to-one basis (e.g., pumping and artificial recharge rates). However, some of the inflow and outflow components estimated by previous investigators were subject to substantial uncertainty due to limited data availability, or were estimated for limited time periods in the past that may not be representative for current hydrologic conditions in the region, and thus do not necessarily match model recharge and discharge quantities (e.g., irrigation return flows and ET rates) very closely. In such cases, reasonable application rates were estimated from the previous investigations or from other methods, and applied to current land uses to calculate total recharge or discharge volumes in the model to be used for a starting point. These volumes (or rates) were then adjusted in the calibration process (the final calibrated average flow rates are what is shown in Table ES-1).

Several of the groundwater flow components within the study area are calculated by the model as the product of hydraulic gradients and conductivities, rather than being input directly (e.g., groundwater underflows and seawater intrusion rates). These inflows and outflows are typically among the most difficult to measure or estimate in the field, and are subject to large uncertainty; therefore, groundwater modeling is commonly considered to provide the best estimates. Inflows and outflows calculated by the model, rather than input directly, are shown in Table ES-1 in italics, and are provided solely for comparison purposes.

RESULTS OF MODEL CALIBRATION AND SENSITIVITY ANALYSIS

By comparing simulated groundwater levels with measured groundwater levels, and adjusting model input parameters to minimize differences between the two, a set of calibrated input parameters was determined to yield an optimal fit based on thousands of manual and automated calibration simulations. Input parameters that were adjusted during calibration of the VRGWFM included:

- hydraulic conductivity
- specific yield and storage coefficient
- stream-channel conductance
- general-head boundary conductance
- horizontal flow barrier conductance
- areal recharge rates
- multi-node wells

To better define the effects of parameter uncertainty on calibration results, a sensitivity analysis was conducted on the VRGWFM. The sensitivity analysis was conducted by adjusting key model input parameters and quantitatively evaluating the impact of each adjustment on the resulting simulated groundwater elevations and flow budget. Results of sensitivity analysis indicate that the VRGWFM is most sensitive to changes in the following input parameters:

- hydraulic conductivity in Layer 6 (the aquitard between the UAS and LAS)
- agricultural return flows (affecting chiefly the Semi-perched Aquifer)
- streambed conductance of the Santa Clara River, Conejo Creek, Arroyo Las Posas, and Calleguas Creek

- conductance of the general-head boundary representing interaction between the Pacific Ocean and the aquifers of the UAS and LAS

REVIEW

The process of internal review and refinement of both the conceptual and numerical models for the VRGWFM was iterative and occurred frequently from 2013 through 2018. This internal review included comparison of model input files to available data in the study area. The goal of the internal review was to ensure that reasonable values were input to the model and that model output (primarily groundwater levels) throughout the calibration period were consistent with measured values. United hydrogeologists also reviewed calibration results to evaluate potential causes for substantial deviations between measured and simulated groundwater elevations—in some cases, reported groundwater elevation measurements were rejected as likely being erroneous or the result of damage to the well in which the measurement was obtained, and in other cases changes were required in either the hydrostratigraphic model or as input to the numerical model.

Since 2015, United has led and participated in several workshops, presentations, and meetings designed to provide information and solicit input from the FCGMA and other stakeholders in the study area regarding development of the VRGWFM. United held an all-day “TAG-review workshop” in coordination with the FCGMA during March 2017. At the conclusion of discussion of model calibration, no “fatal flaws” in the VRGWFM were noted by the TAG. TAG members concurred that the calibration of the VRGWFM generally was a significant improvement compared to the USGS model, and that including 13 model layers in the VRGWFM should prove valuable for simulating potential future water-supply projects. A follow-up workshop was held in April 2017 to focus on key issues in Pleasant Valley basin.

Following the TAG-review and Pleasant Valley workshops described above, United regularly updated the TAG on modeling progress during monthly TAG meetings, and met separately with individual members of the TAG and other stakeholder representatives on several occasions to further discuss various aspects of the VRGWFM and its potential future uses. In addition, United staff gave several presentations to stakeholder groups in Ventura County regarding VRGWFM construction, calibration, and how it could potentially be applied to future evaluation of sustainable yield and water-supply projects in the study area. Feedback from those meetings was noted and given consideration as model development progressed.

The Expert Panel reviews were conducted by three groundwater modeling experts focused on appropriateness of model construction, as well as the procedures used by United to convert raw data to model-input files, conduct calibration, and evaluate model sensitivity to the different input parameters. Key components of the Expert Panel’s review included, but were not limited to, qualitative and quantitative evaluation of model calibration, and consideration of whether the VRGWFM was suitable for its intended uses. The Expert Panel concluded:

- “In summary, the expert panel finds the model to be a well-designed and well-calibrated tool, and a tool that is a substantial enhancement and upgrade over previously available tools. Version 1.0

of the VRGWFM provides a newly robust and detailed method of evaluating how the multiple aquifers in the region behave and how they might respond to the design and implementation of specific regional management programs and specific projects in the five groundwater basins that the model currently simulates in southern Ventura County."

- "Version 1.0 of the VRGWFM is viewed by the expert panel as being ready for use in regional and local planning efforts, and is of sufficient quality to support development of GSPs under SGMA, including conducting water budget analyses, estimating the sustainable yield of the regional aquifers under various long-term management alternatives, and evaluating the ability of specific projects and management actions to meet minimum threshold levels that will be established in basin-specific GSPs."

LIMITATIONS

USGS guidance notes that non-unique configurations of model parameters can produce reasonably good calibration statistics, but not necessarily yield a good model. This issue is of particular concern in models where calibration data are limited over space or time. However, the abundant pumping, groundwater-level, and aquifer-parameter data that have been collected over the past several decades in the VRGWFM study area result in a detailed conceptualization of the groundwater systems in the study area, while also providing a spatially and temporally extensive calibration dataset. This combination greatly reduces both the potential for conceptual model error and the number of possible alternative configurations of model input parameters that could produce a similar result.

Similar to the USGS model of the Santa Clara-Calleguas watersheds, the VRGWFM is a regional-scale model, and should not be applied to questions about well performance at individual farms or contaminant-transport at corner gas station sites, for example, unless finer discretization is applied to the model and site-specific data are reviewed (and incorporated into the model, as appropriate). However, as noted previously, the VRGWFM incorporates a significant update of hydrostratigraphic conceptual model for the study area and discretely simulates individual aquifers and aquitards, and thus represents a major upgrade from the previously available tools and information available for understanding hydrogeologic conditions and forecasting effects of future aquifer stresses. As needed for future simulations, the VRGWFM can be further discretized or otherwise modified to more precisely or elegantly simulate actual groundwater flow processes that occur in specific areas of interest.

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VENTURA REGIONAL GROUNDWATER FLOW MODEL AND UPDATED HYDROGEOLOGIC CONCEPTUAL MODEL: OXNARD PLAIN, OXNARD FOREBAY, PLEASANT VALLEY, WEST LAS POSAS, AND MOUND GROUNDWATER BASINS

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VENTURA REGIONAL GROUNDWATER FLOW MODEL AND UPDATED HYDROGEOLOGIC CONCEPTUAL MODEL: OXNARD PLAIN, OXNARD FOREBAY, PLEASANT VALLEY, WEST LAS POSAS, AND MOUND GROUNDWATER BASINS

1 INTRODUCTION

United Water Conservation District (United) is a public agency (i.e., a California special district) with a service area of approximately 335 square miles (214,000 acres) of southern Ventura County. United's service area includes the Ventura County portion of the Santa Clara River Valley and much of the Oxnard coastal plain, including the lower part of the Calleguas Creek watershed, as shown on Figure 1-1. United serves as a steward for managing the surface water and groundwater resources within all or part of eight groundwater basins and subbasins. It is governed by a seven-person board of directors elected by region, and receives revenue from property taxes, pump charges, recreation fees, and water delivery charges. United is authorized under the California Water Code to conduct water resource investigations, acquire water rights, build facilities to store and recharge water, construct wells and pipelines for water deliveries, commence actions involving water rights and water use, prevent interference with or diminution of stream/river flows and their associated natural subterranean supply of water, and to acquire and operate recreational facilities (California Water Code, section 74500 et al).

The developed areas of the District include agricultural, municipal, and industrial land, with prime farmland supporting high-value crops such as strawberries, avocados, row crops, lemons, and flowers. Approximately 400,000 people live within United's service area, including residents of the Cities of Oxnard, Port Hueneme, Santa Paula, Fillmore, the east part of San Buenaventura (Ventura), and unincorporated areas of Ventura County. The City of Camarillo borders United's service area to the east, and some of the suburban and industrial/commercial areas surrounding Camarillo have grown into United's service area.

Groundwater has been an important component of the water supply in the watersheds of the Santa Clara River and Calleguas Creek since the early 1900s (Hanson and others, 2003). Since the 1920s water users in the area have been concerned that increasing agricultural and municipal demand for groundwater could exceed replenishment (recharge), resulting in wells going dry. In 1927, the Santa Clara Water Conservation District (United's predecessor agency) was established, and the practice of "conjunctive use" (artificial recharge of surface water during wet periods to increase the volume of groundwater available for withdrawal during dry periods) commenced on the Oxnard coastal plain, although recharge quantities were small during those early years. In the 1930s, potential displacement of fresh water under the Oxnard coastal plain resulting from seawater intrusion was recognized as a potential future concern, and in the 1940s it became reality, with declining groundwater levels measured throughout the area and seawater intrusion occurring near the coastline (Edmonston, 1956). These problems motivated the reorganization of the Santa Clara Water Conservation District into United Water Conservation District in 1950. A new partnership with the cities within United's boundaries provided a much greater bonding capacity, allowing the construction of Santa Felicia Dam on Piru Creek, new spreading grounds at El Rio and a potable water system to deliver water to coastal areas threatened by seawater intrusion. United's records indicate that artificial recharge rates on the Oxnard coastal plain have increased from an average of 23,000 acre-feet per year (AF/yr) during the 1950s to over 50,000 AF/yr in the 2000s, with an additional 16,000 AF/yr delivered as surface water in lieu of pumping since the 1990s. This combination of increased recharge and delivery of surface water in lieu of pumping has raised groundwater levels and mitigated seawater intrusion in some areas and aquifers (United, 2017b). However, between wet and dry periods, large variations in groundwater levels (more than 100 feet in some areas) and flow directions (seaward versus landward) still occur in some of the aquifers underlying the Oxnard coastal plain, creating complex groundwater flow patterns that cannot be completely understood or predicted by the simplified analytical solutions used by early researchers. For this reason, it was recognized that a quantitative tool, specifically a well-calibrated numerical groundwater flow model that explicitly simulates conditions in each aquifer, would be needed to better understand the groundwater flow dynamics in southern Ventura County and to aid in planning for groundwater resources management.

This report documents the purpose, background, conceptualization, construction, and calibration of United's Ventura regional groundwater flow model (VRGWFM), which currently includes the Mound, Oxnard Plain (including Oxnard Forebay), Pleasant Valley, and West Las Posas groundwater basins (study area) of southern Ventura County. The VRGWFM incorporates a significant update of the hydrostratigraphic conceptual model for the study area and simulates individual aquifers and aquitards, thus representing a major upgrade from the previously available tools and information available for understanding hydrogeologic conditions and forecasting effects of future aquifer stresses. Over the coming months to years, United intends to expand the model area, incorporate relevant new data received, and apply new modeling software (modules or packages) as they become available and are deemed helpful to United's efforts to answer regional groundwater and water-supply questions. Additional technical memoranda or reports will be prepared as needed in the future to document anticipated expansion of the model domain, modification of input parameters as a result of collection of new data, and selection of new or different modeling packages that improve simulation of hydrogeologic conditions within the study area.

1.1 LOCATION

The domain (active and inactive area) of the VRGWFM extends from near Lake Piru in eastern Ventura County to several miles offshore of the Pacific Ocean coastline in the southwest, as shown on Figure 1-2. This domain includes all of the area of interconnected groundwater basins and subbasins along the Santa Clara River watershed within Ventura County and part of the Calleguas Creek watershed. Currently, the active portion of the model domain includes the Mound, Oxnard Plain, Oxnard Forebay (Forebay), Pleasant Valley, and West Las Posas groundwater basins and subbasins (the study area) as defined by John F. Mann Jr. & Associates (Mann) in 1959 (for the sake of brevity, groundwater subbasins are commonly referred to as "basins" in this report). The study area coincides with the following groundwater basins and subbasins as described in California Department of Water Resources (DWR) Bulletin 118 (DWR, 2003):

- Oxnard (4-004.02) and Mound (4-004.03) subbasins of the Santa Clara River Valley basin (4-004)
- Pleasant Valley basin (4-006)
- western part of Las Posas Valley basin (4-008)

A small (approximately 5-square-mile) portion of the Santa Paula basin along its southwest boundary with the Mound and Forebay basins is also included in the active model domain, to allow groundwater flow in this area to be simulated with a general-head boundary (GHB) condition (discussed further in Section 3 of this report). Outside of the active portions of the VRGWFM, the model domain is inactive (groundwater levels and movement are neither input nor simulated in these portions of the model), at present. However, in the next 6 to 18 months United plans to add the area representing the remainder of the Santa Paula basin, together with the Fillmore and Piru basins (Figure 1-2), to the active domain of the VRGWFM, and calibrate the model in these areas. Calleguas Municipal Water District (Calleguas or CMWD) has developed a numerical groundwater flow model for the eastern and southern parts of the Las Posas Valley basin (Intera, 2018), which is also within the Calleguas Creek watershed. The eastern boundary of the active model domain of the VRGWFM in Las Posas Valley approximately aligns with the western boundary of the Calleguas model.

1.2 PREVIOUS INVESTIGATIONS

In the 1920s, State officials found it necessary to study the water resources of Ventura County before ruling on the various applications for water rights. The initial progress reports for a *Ventura County Investigation* were published by the California Division of Water Rights in 1928 and the California Division of Water Resources in 1929. The final report was printed in 1933, as Bulletin No. 46 – Ventura County Investigation (California Division of Water Resources, 1933). This report included consideration of groundwater resources, percolation of streamflow, and relationships between surface water and groundwater resources. A significant advancement of Bulletin No. 46 was the concept of the regional resources of the Santa Clara watershed operating as part of a single large system: "the Coastal Plain (Oxnard Plain and Pleasant Valley basins) derives its natural supply from overflow of water which has percolated into the Santa Clara River Valley and also from percolation of floods crossing Montalvo (Forebay) Basin."

In the late 1940s, the region experienced several years of below-average precipitation. Seawater intrusion was recognized as a threat to the groundwater resources underlying the Oxnard coastal plain at this time, and population was increasing in this period of post-war American prosperity. The California State Water Resources Board (Edmonston, 1956) published Bulletin 12, an update to the earlier *Ventura County Investigation*, including details from subsequent investigations of the groundwater resources of the region. Bulletin 12 introduced the seven groundwater basins of the Santa Clara River Hydrologic Unit as the most important in Ventura County. Consistent with earlier investigations, groundwater occurring in the Piru, Fillmore, Santa Paula, and Forebay basins was classified as unconfined, while the aquifers of the Mound, Oxnard Plain, and Pleasant Valley basins were identified as being confined by clay beds of low permeability. Recharge mechanisms for the unconfined basins were identified: "The unconfined ground water basins are replenished by percolation of flow in the Santa Clara River and its tributaries, percolation of direct precipitation, artificial spreading and percolation of surface waters, and by percolation of the unconsumed residuum of water applied for irrigation and other uses" and "recharge to the confined aquifers of the Mound, Oxnard Plain, and Pleasant Valley Basins" was noted to be "largely supplied by subsurface flow from areas of free (unconfined) ground water." The major mechanisms for groundwater losses from the basins were also identified: "Ground water in the seven major basins of the Santa Clara River Hydrologic Unit is disposed of by effluent discharge to lower basins, by pumped extractions to meet beneficial consumptive uses, by consumptive use of phreatophytes in areas of high ground water, and by subsurface flow to lower basins and to the ocean."

In the late 1950s, Mann was contracted by United to synthesize available information from previous investigations and data collected by United staff, with the following objectives:

1. "A refinement of the ground water geology of the District (United), in order to analyze the influence of the geologic complexities on ground water management;
2. A recalculation of the District's ground water inventories on the basis of the refined geologic framework;
3. A detailed study of ground water quality to spell out the influence of poor quality waters on continued ground water development;
4. A description of the current status of sea-water intrusion, and the development of a general plan for combating it."

Mann's (1959) final report estimated potential groundwater yields from the various basins, delineated hydrostratigraphic units (HSUs), and reported on water quality problems specific to certain aquifers and locations. This report also detailed the occurrence of groundwater underflow between the various groundwater basins within the district. Earlier reports had commonly focused on rising water and gains in surface water flow around basin boundaries, and less on the subsurface flow at these constrictions in the groundwater flow system.

The earliest numerical groundwater flow model of the aquifers underlying the Santa Clara River Valley and Oxnard coastal plain was developed by DWR in the early 1970s (Hasan and others, 1974); this flow model was coupled with a solute-transport model for the purpose of forecasting total-dissolved-solids (TDS) concentrations under alternative groundwater management plans under consideration at that time. The modeling software used by Hasan and others reportedly was an adaptation of DWR software (reference not available), which relied on the principle of superposition and used numerical methods to frame and solve the continuity equation for groundwater flow across a polygonal model grid. A total of 162 grid nodes, ranging in area from 100 to 1,000 acres each, were used to represent the study area, with the Piru, Fillmore, Santa Paula, Mound, Las Posas, Pleasant Valley, and Arroyo Santa Rosa Valley (Santa Rosa) basins simulated using a single layer, and the Oxnard Plain and Forebay basins simulated using two layers of model grid nodes (the upper layer represented the Semi-perched Aquifer). The model was calibrated using groundwater-level measurements from 1957 through 1967; during the calibration process, recharge, transmissivity, and storage coefficients were adjusted in the model to obtain a better match between measured and simulated groundwater levels. In some areas, simulation of historical groundwater levels was unachievable; review of measured groundwater levels in these areas indicated that they could be "reasonably modified to be consistent with the computed water levels from the model" (Hasan and others, 1974). Ultimately, simulated groundwater levels at a few model nodes remained "anomalous and were finally ignored."

The hydrogeologic information input to Hasan's model was subsequently released in two volumes by the Ventura County Department of Public Works, Flood Control District (Mukae and Turner, 1975). Mukae and Turner reviewed previous reports, water-well logs, and oil- and gas-well logs to update geologic maps and cross-sections presented in Bulletin 12, Ventura County Investigations (Edmonston, 1956), and refined delineation of the aquifers and base of fresh water in "the Oxnard-Calleguas Area" of Ventura County (including the Oxnard Plain, Forebay, Pleasant Valley, East, West, and South Las Posas, and Santa Rosa basins). Volume 2 of the Mukae and Turner (1975) report included new and reinterpreted evaluations of groundwater and surface-water parameters for much of the study area.

Following an extended period of population growth and several dry years in the mid-1970s, DWR published Bulletin 118-80, "Ground Water Basins in California" (DWR, 1980). This publication introduced the "Ventura Central Basin" and reasoned "the four valleys identified in Bulletin 118 (1975a) as the Santa Clara River Valley, Pleasant Valley, Arroyo Santa Rosa Valley and Las Posas Valley are contiguous and hydrologically continuous" and stated "ground water moves into the Santa Clara River Valley from the other three valleys, particularly into the Oxnard Plain." This change in naming convention was based on recognition that the local groundwater basins are more appropriately considered subbasins of a larger regional groundwater flow system.

In 1979, the State Water Resources Control Board (SWRCB) released a document simply titled "Staff Report—Oxnard Plain Groundwater Study," focusing on overdraft of groundwater in the Oxnard Plain, Forebay, and Pleasant Valley basins, and resultant seawater intrusion. The SWRCB (1979) report summarized hydrogeologic conditions in the area as understood at the time, recognized the mergence of UAS and LAS aquifers in certain areas vulnerable to seawater intrusion, and described potential actions that could be taken to prevent further seawater intrusion and permanent damage to the aquifer system, in particular the Fox Canyon Aquifer. The SWRCB threatened adjudication under Water Code Section 2100 if actions were not taken to correct overdraft and seawater intrusion on the Oxnard coastal plain. In response, the Fox Canyon Groundwater Management Agency (FCGMA) was created in 1982 to fill an oversight role in preventing further deterioration of the groundwater conditions causing seawater intrusion in the area. The FCGMA prepared a groundwater management plan in 1985 (Ventura County Public Works Agency, 1985) for the Oxnard Plain, Forebay, Pleasant Valley, East Las Posas, and West Las Posas basins, together with parts of Santa Rosa and South Las Posas basins. The FCGMA's 1985 groundwater management plan was updated in 2007 (FCGMA and others, 2007). The 2007 update included new interpretations of hydrogeologic conditions in the FCGMA's area of responsibility, including the Oxnard Plain and Pleasant Valley basins, based on extensive data collected by the U.S. Geological Survey (USGS) and others since 1985.

In the late 1980s, with financial support from United, Calleguas, and the FCGMA, the USGS began a major investigation of the regional alluvial-aquifer systems of the Santa Clara River and Calleguas Creek watersheds, including the basins of the current (VRGWFM) study area. This study of the hydrogeology of the Santa Clara-Calleguas watersheds was completed as part of the Southern California Regional Aquifer-System Analysis (RASA) program (Sun and Johnston, 1994). The regional groundwater system in southern Ventura County was selected as a representative southern California basin for study, with cultural practices and hydrogeologic processes common to other basins or groups of basins. The nested monitoring wells installed in Ventura County as part of the RASA program provided aquifer-specific groundwater-elevation and water-quality data that were key to improved understanding of groundwater conditions in the study area.

United also contracted the USGS to further study the basins and subbasins of the Santa Clara River Valley, this time focusing on the interaction between surface water and groundwater. The USGS report summarized "…the groundwater system and stream-aquifer interactions along the Santa Clara River," and included additional technical discussions of the hydrologic conditions (e.g., rising groundwater at subbasin boundaries, correlations of water quality with surface water flow magnitudes, interaction between various aquifers) in the Santa Clara River Valley (Reichard and others, 1998).

The USGS followed up with development of a numerical groundwater flow model (Hanson and others, 2003) for the Santa Clara River and Calleguas Creek watersheds, as shown on Figure 1-3 (referred to herein as "the USGS model"). The USGS model was constructed using their MODFLOW software (McDonald and Harbaugh, 1988) together with the subsequently developed streamflow-routing (Prudic, 1989), subsidence (Leake and Prudic, 1991), and horizontal-flow-barrier (Hsieh and Freckleton, 1993) packages. The USGS model included two layers, representing the Upper Aquifer System (UAS) and Lower Aquifer System (LAS), which are described in Section 2.5 of this report. The model domain included the Piru, Fillmore, Santa Paula, Mound, Oxnard Plain (including the Forebay), Pleasant Valley, Santa Rosa, East Las Posas, West Las Posas, and South Las Posas basins. The USGS model was calibrated to estimated historical surface-water flows and measured groundwater levels during the period from calendar year (CY) 1891 through CY 1993, and was an effective starting point for developing an understanding of aquifer boundary conditions and basin-scale hydraulic effects of complex stratigraphic and structural relationships between the UAS and LAS. However, its relatively coarse discretization (uniform 1/2-mile grid spacing and representation of six distinct aquifers, several of which are separated by thick aquitards, using only two model layers) limited the level of detail at which it could be calibrated and prevented it from being able to evaluate impacts of future pumping/recharge scenarios on specific aquifers, particularly those impacted by seawater intrusion. Furthermore, the USGS model did not explicitly simulate the shallow Semi-perched Aquifer, including recharge and discharge processes occurring in that aquifer that are significant components of the groundwater budget in the Oxnard and Pleasant Valley basins. Although calibration statistics for the USGS model indicated that simulated heads were commonly within 20 feet of measured heads in model layer 1 (UAS) near the coast, model residuals exceeding 50 feet were common in layer 2 (LAS) throughout the model domain. And calibration of the Semi-perched Aquifer was impossible, since it was not simulated in that model. A subsequent adaptation of the USGS model by United in the mid-2000s, adding a third model layer to represent a shallow Semi-perched Aquifer system overlying the UAS and LAS in the study area, allowed simulation of groundwater conditions at the near-surface, but did not significantly improve calibration in the deeper aquifers, where most groundwater extractions occur.

1.3 PURPOSE AND SCOPE

United, FCGMA, and other stakeholders tasked with management of groundwater resources in the study area have been working toward quantifying sustainable yields and mitigating impacts of groundwater overdraft. In 2011, United and FCGMA realized that to effectively interpret historic groundwater-level trends and, more importantly, forecast impacts of potential future groundwater extraction, recharge, and management scenarios under consideration within the study area, an updated and more detailed conceptual model of hydrostratigraphy would be required, followed by construction and calibration of a higher-resolution numerical groundwater-flow model that (unlike earlier models) provides discrete simulation capabilities for each individual aquifer and aquitard. The purpose of the current modeling effort to date has been to construct the VRGWFM envisioned by United and others in 2011, and verify (via historical calibration, review, and sensitivity analysis) that it can adequately simulate the future occurrence and movement of groundwater within the study area.

Development of the current VRGWFM consisted of four primary tasks, including:

- **Update of Hydrostratigraphic Conceptual Model**: An updated hydrostratigraphic conceptual model for the Mound, Oxnard Plain, Forebay, Pleasant Valley, and West Las Posas basins was developed from review of geophysical and lithologic logs from hundreds of gas, petroleum, and water wells in the area, followed by preparation of detailed hydrostratigraphic cross sections, resulting in significant adjustment to the top and bottom elevations of aquifers and aquitards in key areas. Information used to support development of the hydrostratigraphic conceptual model, together with other hydrogeological data and information relevant to this modeling effort, is described in Section 2 of this report.

- **Numerical Model Construction**: Available data for aquifer geometry, hydraulic parameters, stresses (recharge and discharge), and boundary conditions were compiled, reviewed, and entered into the “packages” (model input files with specific functions) required for the numerical modeling software, MODFLOW-NWT (Niswonger and others, 2011), which is an updated version of McDonald and Harbaugh’s (1988) MODFLOW software package. Details of how the information from the hydrostratigraphic conceptual model and other required hydrogeologic data were input to the numerical model are described in Section 3 of this report.

- **Calibration and Sensitivity Analysis**: Following initial numerical model development, the transient calibration of the VRGWFM was conducted for the period from January 1985 through December 2012, and later extended to December 2015. United selected 1985 as the starting point for historical calibration of the VRGWFM chiefly because that is when pumping rates for individual wells in the FCGMA became consistently available; in addition, the quality and quantity of other groundwater data used for model input and calibration markedly increased in the 1980s compared to previous decades. Calibration of the VRGWFM was conducted iteratively during conceptual and numerical model development. This process continued until: a) calibration targets were achieved at key locations, or b) a point of diminishing returns was reached, where further improvement in calibration was negligible. After internal and external model review efforts had begun and no major concerns were raised regarding development and calibration of the VRGWFM, a sensitivity analysis was conducted for the purpose of determining the degree to which model output was influenced by adjustment of model input parameters (within a reasonable range).

- **Review**: After the differences between the numerical model and the conceptual model were resolved and progress made on initial model calibration, internal and external reviews of the model began. Review continued throughout model calibration, and model input revised as necessary in response to reviewer comments.

The VRGWFM is anticipated to be used in support of United's and FCGMA's groundwater planning and management activities, which will require predictive simulations of potential future pumping, recharge, and land- and water-use scenarios in the study area. United intends to use the model as a planning tool to maximize the regional benefits of its conjunctive use operationsand to forecast effects of water-supply projects operated by other local agencies. The FCGMA may elect to use the model to evaluate the effectiveness of potential groundwater management strategies and regulatory policies on eliminating overdraft and saline-intrusion in the coastal areas of the Oxnard Plain.

The content and structure of this report conforms to USGS guidance for documenting groundwater flow models, and includes the following "specific topics that should be addressed in reports that describe studies in which simulation is used" (Alley, 1996):

1. "Describe the purpose of the study and the role that simulation plays in addressing that purpose" (Section 1).
2. "Describe the hydrologic system under investigation" (Section 2).
3. "Describe the mathematical methods used and their appropriateness to the problem being solved" (Section 3).
4. "Describe the hydrogeologic character of the boundary conditions used in the simulation of the system" (Sections 2 and 3).
5. "If the method of simulation involves discretizing the system (finite-difference and finite-element methods for example), describe and justify the discretized network used" (Section 3).
6. "Describe the aquifer system properties that are modeled" (Sections 2 and 3).
7. "Describe all the stresses modeled such as pumpage, evapotranspiration from ground water, recharge from infiltration, river stage changes, leakage from other aquifers, and source concentrations in transport models" (Sections 2 and 3).
8. "For transient models, describe the initial conditions that are used in the simulations" (Section 3).

9. “If a model is calibrated, present the calibration criteria, procedure, and results” (Section 4).
10. “Discuss the limitations of the model’s representation of the actual system…” (Sections 4 and 5).

This report documents construction, historical calibration, and sensitivity analysis of United’s current version of the VRGWFM, as of June 2018. Moving forward, as United applies the VRGWFM to estimate the effects of past or future conditions or stresses on groundwater conditions in the study area, separate memoranda or reports will be prepared by United describing the goals and outcomes of those modeling efforts. Any significant updates or modifications made to the VRGWFM as required to conduct such investigations will also be described in these memoranda or reports.

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2 HYDROGEOLOGIC CONCEPTUAL MODEL

This section provides a summary of the hydrogeologic conceptual model for the study area, focusing on those aspects of basin geology and hydrology that are relevant to development of the VRGWFM. As recommended in DWR modeling guidance (Joseph and others, 2016), "The development of a mathematical model starts with assembling applicable information relevant to the basin or site-specific characteristics. A detailed HCM (hydrogeologic conceptual model) forms the basis of the model by providing relevant physical information of the aquifer and surface systems, as well as applicable boundary conditions of the basin and stressors (such as pumping and artificial recharge)." More detail regarding historical groundwater conditions in the study area can be found in:

- Mann, 1959 ("A Plan for Groundwater Management—United Water Conservation District")
- Mukae and Turner, 1975 ("Ventura County Water Resources Management Study-Geologic Formations, Structures and History in the Santa Clara Calleguas Area")
- Hanson and others, 2003 ("Simulation of ground-water/surface water flow in the Santa Clara-Calleguas ground-water basin, Ventura County, California, U.S. Geological Survey Water-Resources Investigations Report 02-4136")

In addition, the FCGMA released preliminary draft Groundwater Sustainability Plans (GSPs) that provide comprehensive descriptions of groundwater occurrence and movement in the Oxnard Plain (including Forebay), Pleasant Valley, and Las Posas basins from 1985 through 2015 (Dudek, 2017a, 2017b, and 2017c). These plans are currently available on the FCGMA's website (http://fcgma.org/component/ content/article/8-main/115-groundwater-sustainability-plans).

This section also presents new data and revisions to the hydrostratigraphic conceptual model resulting from United's ongoing update effort. As noted previously in this report, past groundwater flow models represented the hydrogeologic system in the study area using just two or three layers to represent the seven aquifers and six aquitards present in the study area. In order to construct the VRGWFM in a manner that explicitly and accurately represents all 13 of these hydrostratigraphic units, including some important lateral variations occurring within and between groundwater basins, United staff made a significant effort to review available lithologic data and revise the hydrostratigraphic conceptual model for the study area. Section 2.6 of this report provides documentation of this updated conceptual model, which incorporates some important changes in the understanding of the characteristics of aquifers and aquitards in the study area based on United's review of the data.

The descriptions provided in this section of the various geographic, climatic, geologic, hydrologic, and cultural conditions occurring in the study area that influence groundwater flow and were incorporated into the VRGWFM during its construction and calibration are extensive. To help the reader keep track of which parameters and stresses play significant roles in regional flow and model development, the conceptual model can be distilled down to the following key points or elements:

1. Most groundwater in the study area is stored in, and flows through, two aquifers comprising the UAS and four aquifers comprising the LAS. A relatively small quantity of groundwater also occurs in the uppermost (shallow) aquifer system, referred to as the Semi-perched Aquifer in the Oxnard coastal plain area (where a thick clay unit is present between this shallow aquifer and the underlying UAS). Due to the limited quantity and poor quality of groundwater typically found in the shallow aquifer system, it is largely undeveloped.
2. Most of the adjacent groundwater basins within the study area are in hydraulic connection with each other, and groundwater within each aquifer can flow from one basin to an adjacent basin with moderate to no impediment (depending on hydraulic conductivity and gradients) in most instances.
3. Groundwater generally flows from areas of recharge to areas of discharge. The largest single source of groundwater recharge to the UAS and LAS in the study area is, by far, the artificial recharge introduced to the Forebay by United. In the Forebay, the sediments comprising the shallow aquifer system have been tectonically uplifted and eroded away, exposing the highly permeable aquifers of the UAS at land surface, providing an ideal situation for recharge in spreading basins. Some of this artificial recharge percolates downward to the aquifers of the LAS in the Forebay and adjacent basins in response to vertical hydraulic gradients between the UAS and LAS. Smaller quantities of groundwater recharge the UAS and LAS as a result of:
    a. groundwater underflow from upgradient basins,
    b. mountain-front and stream-channel recharge,
    c. seawater intrusion near the coast,
    d. downward flux from the shallow aquifer system, and
    e. deep percolation of precipitation, agricultural return flows, municipal/industrial return flows, and treated wastewater in the few areas where the UAS and LAS are exposed at land surface.
4. Most groundwater discharge from the UAS and LAS in the study area occurs via pumping from hundreds of water-supply wells located in the Oxnard Plain and Pleasant Valley basins, and a smaller number of wells in the Mound, West Las Posas, and Santa Paula basins.
5. Because the preponderance of recharge in the study area occurs in the Forebay, while most discharge occurs as a result of pumping in surrounding basins, groundwater in the UAS and LAS typically flows radially outward from the Forebay to the adjacent basins. However, two notable disruptions to this pattern can occur, as follows:
    a. When United's recharge operations are limited due to drought conditions, groundwater elevations in the UAS have periodically dropped below sea level as far north as the northern part of the Forebay area, and the typical pattern of radial groundwater flow outward from the Forebay becomes replaced by landward gradients at the coastline areas across the Oxnard Plain basin, resulting in groundwater flux and seawater intrusion from the adjacent Pacific Ocean.
    b. A large groundwater-elevation "cone of depression" has persisted for decades in the LAS in the agricultural area east of Oxnard and south of Camarillo, as a result of the concentration of water-supply wells in this area and distance from the Forebay (where most recharge occurs). Groundwater elevations in this cone of depression have long been tens to over 100 feet below sea level, producing landward hydraulic gradients and strong vertical gradients from the UAS to the LAS that contribute to seawater intrusion in the LAS.

6. In the shallow aquifer system, recharge occurs throughout the study area (mostly via deep percolation of precipitation, agricultural and municipal/industrial return flows, and treated wastewater), as does groundwater discharge (mostly via evapotranspiration and tile drains, with relatively small amounts discharging to the lower Santa Clara River and the Pacific Ocean). Because most land in the study area is used for municipal, industrial, or agricultural purposes, and agricultural irrigation occurs year-round, groundwater elevations in the shallow aquifer system typically remain stable at elevations within approximately 5 to 8 feet of land surface (where most evapotranspiration occurs and tile drains are installed, respectively).

Details and supporting references for hydrogeologic conditions in the study area are provided in the following sub-sections.

2.1 PHYSIOGRAPHY AND LAND USE

The major physiographic features within the study area include the Oxnard coastal plain, the Camarillo Hills, the western portion of the Las Posas Valley, and a portion of the Pacific Ocean that overlies the regional aquifers, as shown on Figure 2-1. This area comprises approximately 176,000 acres (108,000 acres on land, 68,000 acres under the Pacific Ocean), bounded by:

- the Sulfur Mountain foothills, mouth of the Santa Clara River Valley, and South Mountain to the north
- the eastern Las Posas Valley, Santa Rosa Hills, Santa Rosa Valley, and Santa Monica Mountains to the east
- the southern margin of the Ventura Shelf and Hueneme-Mugu Shelf on the floor of the Pacific Ocean (3 to 10 miles offshore from the coastline to the south and west)

The dominant physiographic feature of the onshore portion of the study area is the relatively flat-lying Oxnard coastal plain, which slopes gently southwestward from elevations of approximately 150 feet at the base of South Mountain and the Camarillo Hills, to sea level at the coastline (Figure 2-1). The City of Oxnard (the most populous in Ventura County) and much of the farmland within the study area occupy the Oxnard coastal plain. North and east from the Oxnard coastal plain, land surface rises more steeply to the hills and valleys at the margins of the study area, with elevations typically ranging from 300 to 600 ft msl. The dominant physiographic features of the offshore portion of the study area are the gently sloping Ventura and Hueneme-Mugu Shelves, with elevations ranging from 0 ft bls at the coast to approximately -400 ft msl at their southwest margin, and the Hueneme and Mugu submarine canyons (Figure 2-1).

While the modern extent of the lower portion of the Santa Clara River watershed occupies a limited portion of the model domain, the hydrology of the Santa Clara River is of primary significance across the Oxnard coastal plain. The total area of the Santa Clara River watershed is 1,634 square miles, most of which is outside of the study area. Land surface elevations in the watershed range from sea level at the coast to 8,847 ft msl at Mount Pinos. The Santa Clara River watershed encompasses three significant tributary watersheds—those of Santa Paula, Sespe, and Piru Creeks (Figure 1-1). Much of the discharge in the Santa Clara River is derived from streamflow originating in the mountain regions drained by these tributaries. More than half of the study area (including the West Las Posas, Pleasant Valley, and east part of the Oxnard Plain basins) is within the Calleguas Creek watershed, which has an area of 343 square miles (most of which also lies outside of the study area), with elevations ranging from sea level at Mugu Lagoon to approximately 3,600 ft msl in the Santa Susana Mountains northeast of Simi Valley. Rainfall and runoff volumes from the valley and foothill areas of the Calleguas Creek watershed are smaller than those from the Santa Clara River watershed.

Figure 2-2 shows the extent of farmland and "urban/built-up" (municipal and industrial) land in southern Ventura County as of 2016, based on data available online from the California Department of Conservation's Farmland Mapping and Monitoring Program (http://www.conservation.ca.gov/dlrp/fmmp). Approximately 14,000 acres of land along the coastline and in the floodplain of the Santa Clara River within the study area is neither farmland nor urban/built-up land, instead consisting of State and County park land, privately-held wetlands and nature preserves, and open space within Navy Base Ventura County (primarily the Point Mugu facility) and the Channel Islands Air National Guard Station. Figure 2-2 also shows the expansion of urban and built-up land since 1984, immediately prior to the beginning of the historical model calibration period, in 6- to 8-year increments. Inspection of Figure 2-2 indicates that the largest expansion of urban/built-up land within the study area during this period occurred by 1990, chiefly in northwest and northeast Oxnard. Total urban and built-up land in the study area as of 2016 was approximately 44,000 acres. The vast majority of farmland in the study area is used for growing fruits and vegetables, dominated by avocadoes, lemons, strawberries, and celery (Ventura County Office of the Agricultural Commissioner, 2016). Total farmland in the study area as of 2016 was approximately 50,000 acres. The estimated gross value of Ventura County agriculture in 2015 was $2.2 billion (Ventura County Office of the Agricultural Commissioner, 2016), with approximately half of that value coming from the study area (Highland Economics, LLC, 2017).

Historical census data (available at http://docs.vcrma.org/images/pdf/planning/demographics/Census_Pop_Ventura_Co_1850-2000.pdf) indicate that the population of the four incorporated cities within or adjacent to the study area has increased from 8,573 as of the 1920 census (Port Hueneme did not exist and Camarillo was not incorporated at that time), to 243,910 in 1980, to 400,897 in 2015 (estimated by the U.S. Census Bureau, "American Community Survey 5-Year Estimates" at https://www.census.gov/programs-surveys/acs/). Population growth in each city is summarized as follows:

City	1920 Census	1980 Census	2015 Estimate
Oxnard	4,417	108,195	203,495
Port Hueneme	*did not exist*	17,803	22,058
Camarillo	*not incorporated*	44,138	66,445
Ventura	4,156	73,774	108,899
Sum:	*8,573*	*243,910*	*400,897*

The greatest population growth in or adjacent to the study area since 1980 has occurred in Oxnard, consistent with the land-use mapping (Figure 2-2), which indicates most of the growth in urban and built-up land from 1984 to 2016 has occurred in Oxnard.

2.2 CLIMATE

According to the Köppen-Geiger climate classification system (Peel and others, 2007), the climate type for most of the study area is classified as warm-summer Mediterranean (Csb), grading to a hot-summer Mediterranean (Csa) climate type along the inland margins of the study area (see Oregon State University's "Parameter-elevation Regressions on Independent Slopes Model" [PRISM] website at http://prism.oregonstate.edu for data and additional information). The average annual maximum temperature at Oxnard Airport, near the center of the study area, is 74 degrees Fahrenheit (occurring in August), and the average annual minimum temperature is 47 degrees (in December). Mediterranean climates are characterized by warm, dry summers and cool winters with variable precipitation. They typically occur along the mid-latitude western edges of continents, which are subject to polar fronts in winter but are dominated by subtropical high-pressure systems during summer and fall, blocking most storms. Cold ocean currents along the coast allow a cool marine layer to intrude into coastal valleys in these zones during early summer, moderating temperatures and often producing fog. As a result of the Mediterranean climate of coastal California, very little rain falls in the study area during the peak growing season, when warm temperatures increase both evaporation rates and agricultural productivity. Therefore, application of groundwater pumped from wells has been used by farmers in the study area for over a century to supplement rainfall as a source of irrigation water.

The annual precipitation in the study area tends to cycle between periods of above-average and below-average rainfall, as shown on Figure 2-3, which illustrates annual water-year (WY) precipitation and cumulative departure from average precipitation at Oxnard Airport (VCWPD Station 168), together with pan evaporation at United's El Rio spreading grounds (VCWPD Station 239). These stations were selected as examples for the study area based on their central locations and long period of record. During development of the VRGWFM, precipitation data from 70 rain gauges in the region (many of which are shown on Figure 2-1) were used to interpolate monthly precipitation across the study area; analysis of these data indicate that average annual precipitation in the study area from 1985 through 2015 was 13.4 inches, with more than half of precipitation occurring in winter and much of the remainder occurring in spring and fall. Average annual precipitation rates in the study area are lowest near the coast and increase inland (north and east), coincident with increasing land-surface elevation. A strong orographic effect on rainfall occurs in central and northern Ventura County, where land surface elevation ranges from 2,500 to 8,800 ft msl; annual rainfall exceeds 30 inches per year on the higher mountains of the Santa Clara River watershed in Ventura County (outside of the study area). Virtually all of the precipitation in the study area consists of rain; however, 2 to 4 feet of snow falls annually, on average, on the highest peaks in the watershed, occurring north of the study area.

In addition to the wet-winter/dry-summer pattern of a Mediterranean climate, rainfall in coastal California, including Ventura County, is also influenced by multi-year, cyclical climate phenomena, most importantly the El Niño-Southern Oscillation and the Pacific Decadal Oscillation. Most of the recorded extreme rainfall and flooding events in the southwestern U.S., including Ventura County, have occurred during "El Niño" years (e.g. 1992, 1995, 1998, 2005), characterized by warmer-than-normal sea-surface temperatures in the central and eastern Pacific Ocean (see the U.S. National Oceanic and Atmospheric Administration's website at https://www.ncdc.noaa.gov/teleconnections/enso/ for data and information). However, not all El Nino years produce abundant precipitation in the region.

Average annual pan evaporation recorded by United at its El Rio spreading grounds (approximately 4.5 miles north of the Oxnard Airport) for the period of record (1974-2013) was 63.2 inches, approximately four times the annual average precipitation. Pan evaporation is measured as a proxy for the evaporation and transpiration (evapotranspiration [ET]) processes that remove water from the surface and subsurface of soil following a rainfall event. Despite this annual-average excess of potential ET relative to precipitation in the study area, during the wet season the rate of precipitation occasionally exceeds ET, resulting in rainfall percolating through the soil to become groundwater recharge, especially during years with average to above-average rainfall amounts. Recharge is discussed further in Section 2.7 of this report.

2.3 SURFACE-WATER HYDROLOGY

Within the study area, there are several surface-water bodies that interact with groundwater to a significant degree, as shown on Figure 2-4. In the Oxnard Plain basin, fresh surface-water bodies that are in hydraulic communication with groundwater include parts of the Santa Clara River (including its estuary), Revolon Slough/Beardsley Wash, McGrath Lake, Ormond Beach wetlands, and Mugu Lagoon wetlands (Figure 2-4). In the Pleasant Valley basin, fresh surface-water bodies that are hydraulically connected to groundwater in some reaches include Conejo Creek and Arroyo Las Posas, which converge and become Calleguas Creek (which overlies both the Oxnard Plain and Pleasant Valley basins). In addition, a significant quantity of imported surface water is used in the study area, then discharged to streams as treated wastewater. Each of the above surface-water bodies, as well as imported water, is discussed in more detail below.

The interaction of surface water with groundwater near these surface-water bodies can affect the occurrence, movement, and quality of groundwater in the shallow groundwater system, and thus is relevant to development of the VRGWFM. Furthermore, areas of interaction between surface water and shallow groundwater commonly are of ecological importance, and are a focus of evaluations of groundwater sustainability. This section focuses on those inland bodies of water, including freshwater streams and brackish-water lagoons and wetlands along the coast that interact with shallow groundwater. The interaction of groundwater (both shallow and deep) with seawater in the Pacific Ocean is also important, but has distinct effects on groundwater elevations and quality; therefore, groundwater-seawater interaction is discussed separately in Section 2.7.

The primary sources for fresh surface water in the study area include:

- Overland flow of stormwater runoff (much of which eventually collects in stream channels and storm drains),

- Continuation of surface-water flows from upstream watersheds into the study area (generally in defined stream channels, as opposed to overland flow)
- Collection and diversion of treated wastewater or collected stormwater runoff into streams, wetlands, and natural or artificial ponds, lakes, or basins,
- Discharge of shallow groundwater to stream channels, lakes, and wetlands.

Direct interaction between surface-water and groundwater occurs where there is exchange of water between a surface-water body and the water table (i.e., where the saturated zone of an aquifer intersects land surface, without an intervening unsaturated, or vadose, zone). In areas where an unsaturated zone of significant thickness occurs between a surface-water body and the water table, the interaction is indirect and effectively one-way—surface water can percolate downward to become groundwater recharge, but groundwater cannot discharge to land surface or have an effect on surface-water flows. Accordingly, direct hydraulic interaction usually occurs in surface water bodies that are predominantly perennial in nature, whereas ephemeral streams are predominantly decoupled from underlying aquifers because of the presence of an unsaturated zone between the stream channel and the water table, thus flow only in response to storm flows and/or artificial influx from sources such as drainage systems and wastewater discharges. The occurrence of coupled versus decoupled stream/aquifer systems fundamentally defines where the potential for impacts to streamflow can arise from upward or downward movement of the water table; perennial reaches are the only stream reaches that receive sustained groundwater discharge over long time periods. Furthermore, if a surface-water body is separated from an aquifer by one or more confining units, then groundwater pumping from the aquifer will have a limited (potentially negligible) effect on the surface-water body.

2.3.1 SANTA CLARA RIVER

The Santa Clara River is the largest fresh surface-water body (in terms of both areal extent and discharge) in the study area (Figure 2-4). Its watershed extends well beyond the domain of the VRGWFM, with a total area of 1,634 square miles (Figure 2-1). The average discharge of the Santa Clara River at Freeman Diversion, which is located immediately upstream from the northern boundary of the Forebay (11 miles inland from the Pacific Ocean), was 287 cubic feet per second (208,000 AF/yr) during the period of record (WY 1956 through 2016). However, annual discharge of the Santa Clara River, like most largely ephemeral streams in southern California, is highly variable, ranging from 8 cubic feet per second (5,800 AF/yr) in WY 2016 to 1,590 cubic feet per second (1,150,000 AF/yr) in WY 2005, as shown on Figure 2-5. The primary sources of surface-water flow in the Santa Clara River within the study area are surface runoff originating as precipitation in the watershed and groundwater discharge to the river (in a few locations). The majority of the flow occurring in the Santa Clara River in the study area discharges to the Pacific Ocean or infiltrates in the dry, sandy, ephemeral reach of the river in the Forebay area. Prior to 1985, a minor quantity of surface water may have been diverted from the river within the study area for agricultural use, but this has not been the case in recent decades.

Within the study area, the Santa Clara River is perennial only within the 5-mile reach that is closest to the Pacific Ocean, from approximately ¼-mile upstream of U.S. Highway 101 to the mouth of the river (Figure 2-4). Baseflow in this reach (consisting of discharge of shallow groundwater to the stream channel) has been estimated to be approximately 2 cfs (1,500 AF/yr; Stillwater Sciences, 2017). Phreatophytic plants are abundant in the river channel throughout this reach, likely taking up shallow groundwater that would otherwise contribute to baseflow. Therefore, the estimated baseflow likely does not represent all of the rising groundwater in this reach. Historical observations from the 1800s indicate that the 6-mile reach of the river from just north of U.S. Highway 101 to the Santa Paula basin has typically been ephemeral (Beller and others, 2011), except for extended periods of flow during portions of extremely high rainfall years. The locations of the typically perennial and ephemeral reaches correspond to the presence and absence, respectively, of the Semi-perched Aquifer (which is not used for significant groundwater production) and the underlying confining unit (the Clay Cap), which separates the Semi-perched Aquifer from the Oxnard Aquifer (the uppermost of the aquifers used for groundwater production in the region, as discussed further in Section 2.5). Where the Semi-perched Aquifer is present (from approximately ¼-mile upstream of the U.S. Highway 101 bridge to the coastline), groundwater typically discharges to the Santa Clara River. Such a condition is often referred to as “rising groundwater” in a “gaining reach” of stream channel. The ultimate source of the rising groundwater in this gaining reach is a mixture of applied irrigation water (agricultural and municipal) and rainfall that has percolated through the farmland north and south of the river to recharge the Semi-perched Aquifer.

Annual discharge totals recorded at stream gauges on the Santa Clara River (since 1950) are shown on Figure 2-5. The upper chart shows records for a gauge at Freeman Diversion, which is located in the Santa Paula basin 0.6 miles upstream (east) from the margin of the Forebay and just outside of the study area for this investigation. The lower chart on Figure 2-5 shows records for a series of three gauges located downstream from Freeman Diversion (Figure 2-4). Note that discharge was not recorded from 2005 through 2007 downstream from Freeman Diversion due to gauging station 708a being destroyed during record-high flows in 2005. United diverts some of the surface water flows in the Santa Clara River at Freeman Diversion to its recharge facilities (spreading basins) and two of its pipelines (Pleasant Valley Pipeline [PVP] and Pumping Trough Pipeline [PTP]), as discussed further in Sections 2.7 and 2.8. Due to the presence of bedrock immediately underlying the river bed near Freeman Diversion, the Santa Clara River flows perennially at the Freeman Diversion, except in periods of extended drought. Downstream of the Freeman Diversion, in the Forebay, the presence of highly permeable stream-channel deposits and the Oxnard Aquifer immediately underlying these deposits allows this surface water to readily percolate back into the ground. For these reasons, even in drier years some discharge (typically less than 20,000 AF) may be recorded at the Freeman Diversion gauge, while no discharge is recorded at the downstream gauges in the Forebay (upstream of the perennial reach near the ocean). Following major rainfall events, however, the volume of flow in the river can temporarily exceed infiltration capacity of the river bed, allowing the river to flow all the way through the Forebay to the Pacific Ocean for periods lasting from several hours to several days. Such flows do not occur every year.

In addition to runoff of precipitation and rising groundwater, treated wastewater has been (and, in some cases, still is) discharged to the Santa Clara River in the study area. Small wastewater treatment plants (WWTPs) in Saticoy and southeast Ventura (the Montalvo neighborhood) formerly discharged an estimated 300 AF/yr or less to the river (Figure 2-4), but now discharge their treated wastewater to percolation ponds, to recharge groundwater. Recharge of wastewater in the study area is discussed further in Section 2.7. In addition, Ventura operates a WWTP near the coast, which discharges approximately 9,000 AF/yr into the estuary at the mouth of the Santa Clara River. Because this discharge occurs so close (within ½ mile) to the Pacific Ocean in a coastal lagoon, its expected hydraulic effect on the underlying (semi-perched) aquifer is of minor significance compared to tidal influences on groundwater levels and gradients in this area.

2.3.2 REVOLON SLOUGH AND BEARDSLEY WASH

Revolon Slough and Beardsley Wash are the names applied to two reaches of a single continuous channel that conveys storm water and agricultural return flows from the western Las Posas Valley and central Oxnard coastal plain to Mugu Lagoon (Figure 2-4). North of U.S. 101, the channel is referred to as Beardsley Wash, and it is in a largely natural state (few manmade levees) in the western Las Posas Valley. On the Oxnard coastal plain, the channel is constrained by manmade earthen or concrete levees along most of its course to Mugu Lagoon (it is referred to as Revolon Slough south of U.S. 101), and most of its flow consists of irrigation return flows discharged from tile drains beneath agricultural fields. Revolon Slough/Beardsley Wash may, in places, receive a small influx of groundwater from the Semi-perched Aquifer, especially in the four miles of channel upstream of Mugu Lagoon where the channel is unlined. Flow in Revolon Slough is perennial; annual discharge rates are shown on Figure 2-6. Revolon Slough/Beardsley Wash is not in direct hydraulic communication with the deeper aquifers that are used for groundwater production in the region.

2.3.3 MCGRATH LAKE, ORMOND BEACH WETLANDS, AND MUGU LAGOON WETLANDS

McGrath Lake, the Ormond Beach wetlands, and the Mugu Lagoon wetlands (Figure 2-4) are hydraulically connected to, and exchange fresh- to brackish-water with, the Semi-perched Aquifer near the coast on the Oxnard coastal plain. These lakes and wetlands occur in shallow depressions where the southwesterly flow of surface water and shallow groundwater slows as hydraulic gradients flatten near the constant-head boundary represented by the Pacific Ocean, or is reversed due to higher groundwater elevations present below coastal dunes, which have 6 to 15 feet of topographic relief above the surrounding landscape. McGrath Lake is approximately 1 mile south from the mouth of the Santa Clara River; the Ormond Beach wetlands lie between Mugu Lagoon and Port Hueneme; and the Mugu Lagoon wetlands surround the tidally-influenced Mugu Lagoon. These surface-water bodies and wetlands are much too shallow to be in direct hydraulic communication with the Oxnard Aquifer or any of the deeper aquifers used for groundwater production in the region. These water bodies and wetlands act as groundwater "sinks" (areas where groundwater is discharged from the Semi-perched Aquifer) during much of the year, as a result of evaporation from surface water exposed directly to the atmosphere. In addition, transpiration from phreatophytes in and around these features likely contributes further to groundwater discharge rates. During the wet season, these lakes and wetlands may temporarily act as "sources" of groundwater (recharge areas) for the Semi-perched Aquifer, when rainfall exceeds ET rates.

2.3.4 CONEJO CREEK

Conejo Creek, a tributary of Calleguas Creek, flows along the eastern margin of the Pleasant Valley basin for nearly five miles upstream from its confluence with Calleguas Creek (Figure 2-4). Conejo Creek is formed by the confluence of Arroyo Conejo and Arroyo Santa Rosa, which drain the Conejo Valley and the Santa Rosa Valley, respectively. The Arroyo Conejo watershed includes much of the City of Thousand Oaks as well as the City's Hill Canyon WWTP. Streamflow occurs through the dry months of the year, primarily due to the discharge of reclaimed water from the Hill Canyon WWTP. This plant serves a population of more than 120,000 in the City of Thousand Oaks. The contribution of reclaimed water (treated wastewater) to Conejo Creek had made it a reliable source for diversions for irrigation supply. Other creeks with watersheds of this size in Ventura County, when left in their natural state, are typically dry or have very little flow throughout the summer and fall months.

In summer 2002, the Camrosa Water District completed construction of the Conejo Creek Diversion project and began diverting surface water from Conejo Creek near Highway 101 in Pleasant Valley basin for agricultural use. This diverted water is conveyed to Pleasant Valley County Water District for irrigation deliveries. A minimum of 6 cfs of flow must remain in the creek below this diversion for habitat maintenance purposes (SWRCB, 2012). A variable portion of this 6 cfs left in Conejo Creek reaches Calleguas Creek, approximately 1.5 miles downstream (Figure 2-4).

Annual flows in Conejo Creek at gauges 800 and 800A (above Highway 101 and at Ridge View Street in Camarillo, respectively) are shown on Figure 2-7. The Semi-perched Aquifer and an underlying fine-grained aquitard are thought to be present beneath Conejo Creek in Pleasant Valley basin. Shallow groundwater is thought to be a minor contributor to perennial flow in Conejo Creek in Pleasant Valley basin, and the creek is separated from the deeper aquifers used for water supply in the basin by the presence of underlying fine-grained deposits.

2.3.5 ARROYO LAS POSAS

Arroyo Las Posas flows into the northern Pleasant Valley basin from the adjoining East Las Posas basin through a gap between the Camarillo Hills and the Santa Rosa Hills (Figure 2-4), often referred to as the "Somis Gap." Arroyo Las Posas is usually perennial in its most-downstream reach within the East Las Posas basin, but all of its baseflow infiltrates through the stream channel shortly after entering the Pleasant Valley basin. Annual flows in Arroyo Las Posas at Highway 101 are shown on Figure 2-8. As described by Bachman (2016), baseflow in Arroyo Las Posas is a mixture of natural dry-weather flows, discharges from upstream WWTPs, discharge from dewatering wells in western Simi Valley, and agricultural tail waters. The terminus of the baseflow historically occurred in the East Las Posas basin, but in the early 1990s began to move downstream as the East Las Posas basin began to fill with groundwater as a result of higher baseflow contributions from Simi Valley. During the drought that began in 2012, the terminus of the baseflow began to retreat back upstream into the East Las Posas basin. In the future, baseflow in Arroyo Las Posas may decrease as a result of increased use of recycled water (i.e., the existing discharges from upstream WWTPs) in the South Las Posas basin.

Bachman (2016) reports that Arroyo Las Posas baseflow entering the Pleasant Valley basin has typically infiltrated along a 1,400-foot long reach of the creek at the northern margin of the Pleasant Valley basin. Bachman (2016) also estimated that the next 5,500 ft of stream channel can infiltrate some or all of the storm flows in Arroyo Las Posas that reach the Pleasant Valley basin during an individual storm event. In this area of the northern Pleasant Valley basin, the Semi-perched Aquifer is absent and surface water in Arroyo Las Posas readily percolates into the underlying regional aquifer system (Hopkins Groundwater Consultants, Inc., 2008). In summary, this creek's chief hydrogeologic role in the study area is as a source of recharge to the underlying regional aquifer system. Arroyo Las Posas is not perennial in the Pleasant Valley basin and lies above (is not hydraulically connected to) the water table.

2.3.6 CALLEGUAS CREEK

Calleguas Creek extends from the confluence of Arroyo Las Posas and Conejo Creek downstream (southward) to Mugu Lagoon and the Pacific Ocean (Figure 2-4). The sources of water to Calleguas Creek are a minimum flow of 6 cfs by Camrosa Water District below its diversion structure on Conejo Creek, discharges from the Camarillo Sanitary District WWTP next to Conejo Creek, and inflows from agricultural tile drains. Annual flows in Calleguas Creek at California State University Channel Islands are shown on Figure 2-9. The Semi-perched Aquifer is present throughout this area, but insufficient information is available to identify whether (and how much) shallow groundwater discharge from the Semi-perched Aquifer might also be providing a portion of the perennial flow in Calleguas Creek. Shallow groundwater is thought to be a minor contributor to perennial flow in the creek, which is separated from the pumped aquifers in the region by an aquitard below the Semi-perched Aquifer. However, within most its reach in the Oxnard Plain basin, the channel elevation of Calleguas Creek within its levees is higher than the surrounding land elevation. Under such conditions, discharge of groundwater to the creek would be highly unlikely.

2.3.7 IMPORTED SURFACE WATER

Imported surface water, primarily from northern California (via California State Water Project [SWP] aqueducts and pipelines), indirectly contributes to surface-water flows and groundwater recharge in the study area. As described above, most of the baseflow in Conejo Creek consists of reclaimed water from Thousand Oaks, which imports the vast majority of its municipal and industrial water supply via the SWP. Data provided by Calleguas MWD indicates that they, Camrosa Water District, and the Cities of Camarillo, Oxnard, and Port Hueneme, import an average of 22,000 AF/yr from the SWP, primarily for municipal and industrial use. Other water districts import smaller quantities of surface water from the SWP or groundwater from adjacent basins into the study area as needed to supplement their local groundwater supply. Approximately half of the SWP water imported by cities in the study area is used indoors and enters sewer systems, where a small percentage may leak out of sewer pipes and into underlying aquifers such as the Semi-perched Aquifer (where present). Camarillo's treated wastewater is discharged to Conejo Creek, while Oxnard and Port Hueneme have historically discharged their treated wastewater to the Pacific Ocean by means of an ocean-outfall pipe. Oxnard recently began treating a portion of their wastewater via an advanced water purification (AWPF) process, and is developing plans to store it in underlying aquifers for future use. The remaining half (approximately) of SWP water imported to cities in the study area is likely used for outdoor irrigation (landscaping), and some fraction of that water can percolate beyond the root zone to recharge underlying aquifers, most commonly the Semi-perched Aquifer. Recharge of wastewater and irrigation return flows are discussed further in Section 2.7 of this report. In addition, United imports up to 5,000 AF/yr of water from the SWP to Lake Piru or Castaic Lake, where it is released at optimal times for recharging groundwater in the Piru basin, upstream from the study area on the Santa Clara River. A fraction of these releases may ultimately reach the Mound, Oxnard Plain, and other basins in the study area as groundwater underflow from the Santa Paula basin.

2.4 GEOLOGY

Southern Ventura County is in the Transverse Ranges geomorphic province of California. Within this province, the axes of mountain ranges and valleys are oriented east-west rather than northwest-southeast as is typical in the adjacent Peninsular and Coastal Ranges geomorphic provinces. Most of the study area overlies an elongate, structurally complex syncline that trends east to west (Yeats and others, 1981), referred to as the Ventura structural basin. Active thrust faults border the Ventura structural basin, causing uplift of the adjacent mountains while the basin continues to deepen. The total stratigraphic thickness of upper Cretaceous, Tertiary, and Quaternary marine and terrestrial deposits in the Ventura structural basin reportedly exceeds 55,000 feet (Sylvester and Brown, 1988). Surface exposures of the major rock units and faults in the region are shown on Figure 2-10; hydrogeologically significant features are described below.

2.4.1 GEOLOGIC UNITS PRESENT IN STUDY AREA

Geologic units (strata) exposed at land surface within the study area are commonly classified as follows, from youngest (top) to oldest (bottom):

- Recent (active) stream-channel deposits along the present course of the Santa Clara River and its tributaries;
- undifferentiated younger alluvium of Holocene age, covering most of the Oxnard coastal plain;
- Holocene- to Pleistocene-age alluvial-fan and stream-terrace deposits adjacent to surrounding mountains and the Santa Clara River, respectively;

- undifferentiated older alluvium of Holocene to late Pleistocene age, underlying the undifferentiated younger alluvium of Holocene age across most of the Oxnard coastal plain;
- semi-consolidated sand, gravel, and clay deposits of the San Pedro Formation (also referred to as the Saugus Formation by some researchers), of late Pleistocene age; and,
- sandstone, siltstone, and shale of the Santa Barbara Formation, of early Pleistocene age.

These exposed strata in the study area were classified based largely on their hydrogeologic characteristics, as these are the units that typically bear freshwater in usable quantities and are of primary interest for groundwater supply. Other researchers have divided these deposits in other, equally valid ways, based on their geomorphological or other characteristics (e.g., Mukae and Turner, 1975; Hanson and others, 2003).

Older (lower) strata, which are regarded as hydrologic bedrock in the region, typically are poorly permeable or contain water that is too brackish or saline for municipal or agricultural uses. These strata include (following the descriptions of Burton and others, 2011):

- marine siltstones, sandstones, and conglomerates of the Pico Formation, of Pliocene or early-Pleistocene age;
- terrestrial sandstones and shales of the Repetto Formation, of Pliocene age;
- shale of the Monterey Formation, of late Miocene age;
- basalt and other extrusive (mostly) volcanic rocks of the Conejo Volcanics, of mid-Miocene age;
- marine siltstones and sandstones of the Topanga and Vaqueros Sandstones, of early Miocene age; and,
- terrestrial sandstones and claystones of the Sespe Formation, of Oligocene age.

2.4.2 FAULTS

In some cases, geologic faults can be pathways or barriers for groundwater movement. In crystalline or cemented rocks, faults can create fractures that act as conduits to groundwater flow. However, the aquifers within the study area consist of semi-consolidated sedimentary formations, which tend to create fine-grained, low-permeability “smear zones” when faulted, effectively producing weak to strong barriers to groundwater flow, particularly in the deeper aquifers. Within the study area, the trend of many, but not all, of the faults is west-southwest to east-northeast, consistent with regional structural trends (Figure 2-10). The Ventura, Country Club, Oak Ridge, McGrath (sometimes referred to as Montalvo), and Bailey faults have previously been identified as significantly limiting or diverting groundwater flow (Mann, 1959; Mukae and Turner 1975; Weber and others, 1976). Additional faults in the study area identified by United and the USGS (Hanson and others, 2003) as limiting or diverting groundwater flow include the Springville, Camarillo, Simi-Santa Rosa, Long Canyon, Hueneme Canyon, Sycamore Canyon, and Somis faults, and an unnamed fault just southwest from Mugu

Lagoon (Figure 2-10). In general, the older (deeper) geologic units (e.g., LAS) show greater displacement across these faults than the younger (shallower) units (e.g., UAS); therefore, groundwater flow in the LAS can typically be expected to be more disrupted across faults than flow in the UAS. More details regarding effects of faults on groundwater flow in the study area can be found in the above-referenced works.

2.4.3 FOLDS

Similar to faults in the study area, the axes of major anticlines and synclines in the sedimentary strata tend to be oriented approximately west-southwest to east-northeast (Figure 2-10). Similar to the discussion of faulting, above, the works of Mann (1959), Hanson and others (2003), and other previous investigators provide more details on the potential effects of folds on groundwater flow within the study area. The folding is ongoing, with older strata (including the LAS) being more deformed than younger strata (UAS). The limbs of the folds are gently dipping within most of the freshwater-bearing strata in the study area; therefore, it is unlikely that the folds themselves commonly have a notable direct impact on groundwater flow. However, it is recognized that changes in thickness (which affects transmissivity), outcrop area (which affects where recharge occurs), and other hydrogeologic properties of strata can be indirectly influenced by fold geometry. The most important hydrogeologic effect of folding in the study area has been to uplift the strata in the Forebay area, such that the regional aquifers are exposed at land surface and can be readily recharged, both naturally and artificially.

2.5 HYDROSTRATIGRAPHIC UNITS

Strata with distinct hydrogeologic characteristics are commonly referred to as HSUs. Within the study area, 13 HSUs (7 aquifers and 6 aquitards) are currently recognized by United, and are generally grouped into three major “aquifer systems” by most investigators: Shallow, Upper, and Lower. This section provides a general description of these HSUs, based largely on reporting by previous investigators (Mann, 1959; Mukae and Turner, 1975; Hanson and others, 2003). Since 2012, United has been evaluating downhole geophysical and lithologic log for numerous water, oil, and gas wells in the region to develop an updated conceptual hydrostratigraphic model; results of that effort are discussed in Section 2.6.

2.5.1 GENERAL CHARACTERISTICS

As noted above, the HSUs within the study area are typically grouped into three “systems” with distinct hydrogeologic characteristics, summarized in Table 2-1. The discussion presented in this section is intended to provide only a broad overview of the major HSUs present and their general characteristics; more information regarding the extents and hydraulic properties of each HSU is provided in Sections 2.6 and 3.4 of this report.

Table 2-1. Hydrostratigraphic Units in Study Area

System	Aquifer or Aquitard	General Characteristics
Shallow	Semi-perched Aquifer	Stream- and coastal-deposited sands and gravels with minor silt and clay interbeds, Holocene to recent age. Ranges from 0 to 200 feet thick (average thickness approximately 75 feet). Does not exist in the Forebay. Becomes hard to distinguish from underlying HSU in some parts of Pleasant Valley basin. Due to poor water quality and low yields, rarely used for water supply.
Upper Aquifer System (UAS)	Clay Cap	Silt and clay layers with interbedded sands, Holocene to recent age. Ranges from 0 to 160 feet thick (average thickness approximately 50 feet). Does not exist in the Forebay and northern Pleasant Valley basins. Becomes hard to distinguish from overlying and underlying units in some parts of Pleasant Valley basin. Limits downward migration of poor-quality groundwater from Semi-perched Aquifer to Oxnard Aquifer (and confines the Oxnard Aquifer).
	Oxnard Aquifer	Marine and non-marine sands, gravels, and cobbles, with clay and silt interbeds, of late-Pleistocene to Holocene age. Ranges from 0 to 265 feet thick (average thickness approximately 120 feet). Historically one of the most important and widely used aquifers in the Oxnard Plain basin.
	Oxnard-Mugu aquitard	Interbedded clay, sand, and gravel, of late Pleistocene age. Ranges from 0 to 240 feet thick (average thickness approximately 40 feet).
	Mugu Aquifer	Marine and non-marine sand and gravel with silt and clay interbeds, late-Pleistocene age. Ranges from 0 to 340 feet thick (average thickness approximately 160 feet).
Lower Aquifer System (LAS)	Mugu-Hueneme aquitard	Interbedded clay, silt, sand, and gravel of the upper San Pedro Formation, of late-Pleistocene age. Ranges from 0 to 70 feet thick in most areas, but increases to 590 feet thick in the area east of Port Hueneme. This aquitard thins in the Forebay area, and merges with the Hueneme-Fox Cyn. aquitard to become an aquitard between the Oxnard Aquifer and the Fox Cyn. Aquifer in the southeast Oxnard Plain basin, where the Hueneme Aquifer is absent.
	Hueneme Aquifer	Marine and non-marine interbedded sand, silt and clay, and minor gravel of the upper strata of the San Pedro Formation. Ranges from 0 to 1,500 feet thick (average thickness approximately 430 feet); absent from the southeast Oxnard Plain basin.
	Hueneme-Fox Cyn. aquitard	Marine and non-marine silt and clay, with interbedded sand and gravel, of the San Pedro Formation. Ranges from 0 to 200 feet thick (average thickness approximately 50 feet).
	Fox Cyn. Aquifer-upper	Marine interbedded fine to medium sand with stringers of gravel (80%), and silt, clay, and sandy clay (20%) of the San Pedro Formation. Ranges from 0 to 620 feet thick (average thickness approximately 270 feet).
	Mid-Fox Cyn. aquitard	Marine and non-marine silt and clay, with interbedded sand and gravel, of the basal San Pedro Formation. Ranges from 0 to 180 feet thick (average thickness approximately 50 feet).
	Fox Cyn.-Aquifer basal	Similar composition and age as Fox Canyon Aquifer-upper. Comprises the basal member of the San Pedro Formation. Ranges from 0 to 300 feet thick (average thickness approximately 125 feet).

Table 2-1. Hydrostratigraphic Units in Study Area

System	Aquifer or Aquitard	General Characteristics
	Fox Cyn.-Grimes Cyn. aquitard	Primarily silt and clay, with interbedded sand and gravel, of the basal San Pedro Formation or the upper Santa Barbara Formation, of early-Pleistocene age. Ranges from 0 to 500 feet thick (average thickness approximately 70 feet).
	Grimes Canyon Aquifer	Local sands and gravels in the upper Santa Barbara Formation. Ranges from 0 to 520 feet thick (average thickness approximately 200 feet). Present in parts of Oxnard Plain, West Las Posas, and Pleasant Valley basins; not present in Forebay or Mound basins.
Hydrologic bedrock		Older sedimentary and igneous rocks of low permeability and/or containing saline groundwater.
Information in this table is primarily from Mukae and Turner (1975), Mann (1959), and Hanson and others (2003), or new information from United's conceptual model update (Section 2.6 of this report).		

Schematic hydrogeologic cross sections A-A' and B-B' that conceptually illustrate the vertical (depth) relationships between the major aquifers are provided on Figure 2-11. The correlation of HSUs to geologic units is shown on Figure 2-12. The Semi-perched Aquifer is the sole HSU of the shallow aquifer system. The Semi-perched Aquifer is assumed to extend from land surface to the top of the underlying aquitard (the Clay Cap) in the area where the Clay Cap exists, which includes the Oxnard Plain basin (excluding the Forebay) and part of the Pleasant Valley basin. The Semi-perched Aquifer is unconfined and varies in composition from sand and gravel along the Santa Clara River to silty or clayey sand in other areas. The Semi-Perched Aquifer is believed to be continuous across most of the Oxnard Plain basin (excluding the Forebay). In the Forebay, folding has resulted in uplift of the underlying aquifer systems, and the Semi-perched Aquifer (and Clay Cap) have been eroded away, exposing the Oxnard Aquifer at land surface. The depositional history in the Pleasant Valley basin, which is in the Calleguas Creek watershed, is different from the Oxnard Plain and Forebay basin. In the Pleasant Valley basin, the shallow and the Oxnard Aquifer have increasing clay content from west to east, becoming less and less distinguishable from each other or the Clay Cap.

The UAS consists of two important confined, regional aquifers—the Oxnard and Mugu Aquifers; and two aquitards—the Clay Cap and the Oxnard-Mugu aquitard. These four HSUs consist of alluvial and near-shore marine deposits of Holocene to late Pleistocene age. The Oxnard and Mugu Aquifers are present throughout the Forebay and Oxnard Plain basins, transitioning into finer-grained, stratigraphically equivalent units with different hydrogeologic characteristics in the Mound and Pleasant Valley basins. The Oxnard Aquifer consists of a highly-permeable assemblage of marine- and non-marine sands, gravels, and cobbles, with clay and silt interbeds. The Mugu Aquifer consists of slightly older marine and non-marine sands and gravels, with interbedded silt and clay.

The LAS is more folded, tilted, and faulted than the UAS, and has been eroded along an unconformity that separates the UAS from the LAS (Turner, 1975). The Hueneme, Fox Canyon (main and basal members), and Grimes Canyon Aquifers comprise the LAS. Where they occur in the Forebay and Oxnard Plain basins, these aquifers correlate with the San Pedro and Santa Barbara formations of early- to late-Pleistocene age (Hanson and others, 2003). The aquifers of the LAS are isolated from each other vertically by relatively low-permeability silt and clay layers. The base of the LAS is considered to be the base of fresh water (Mukae and Turner, 1975). Beneath the LAS lies older sedimentary and volcanic rocks that are generally considered to contain brackish to saline water or to be poorly transmissive (Mukae and Turner, 1975), and are rarely used for water supply.

2.5.2 HYDRAULIC PARAMETERS

Although many specific capacity measurements (and some aquifer tests or slug tests) have been conducted at water-supply and monitoring wells in the study area, estimates of hydraulic conductivity and storage coefficient (the key hydraulic parameters for groundwater modeling) for individual HSUs are generally lacking, for the following main reasons:

- Water-supply wells in the study area commonly are screened across multiple aquifers (and often across aquitards, as well), or the screened intervals only partially penetrate the aquifers that are intersected by the well;
- Most aquifer tests and specific capacity measurements have a duration of 2 to 24 hours, which is insufficient to evaluate the effects of other factors—such as delayed yield, leaky aquitards, or boundary effects—that can influence estimates of aquifer parameters;
- Most aquifer tests are for the pumped well only (no observation wells) or are affected by interference effects from nearby production wells turning on and off during aquifer tests;
- Very few wells (typically only monitoring wells) are screened solely in poorly producing zones, thus few data are available to estimate hydraulic parameters of the aquitards;

In addition to the above issues, it must be noted that even a properly conducted aquifer test is representative of a limited area around the pumped well and any observation wells measured during the test. Slug tests and specific capacity measurements are applicable to an even smaller area than aquifer tests, and are considered to provide only rough estimates of aquifer parameters. For these reasons, previous investigators have typically estimated aquifer parameters for the UAS and LAS (wells are commonly screened across multiple HSUs in each of these aquifer systems), rather than for individual aquifers within those aquifer systems.

2.5.2.1 TRANSMISSIVITIES AND HYDRAULIC CONDUCTIVITIES

Mukae and Turner (1975) used specific capacity data to estimate transmissivities in the study area, which ranged from approximately 7,000 to 50,000 feet squared per day (ft^2/day) in the UAS, and 3,000 to 40,000 ft^2/day in the LAS. The USGS used the Mukae and Turner (1975) specific-capacity data, their own slug test data, and results of modeling to estimate transmissivities of <1,000 to 74,000 ft^2/day in the UAS and <1,000 to 27,000 ft^2/day in the LAS within the study area, as shown on Figures 2-13 and 2-14 (Hanson and others, 2003). The USGS divided these transmissivities by aquifer thickness to estimate horizontal hydraulic conductivities for input to their model, ultimately arriving at values ranging from <1 to 300 ft/day in the UAS, and <1 to 110 ft/day in the LAS. The USGS (Hanson and others, 2003) and Mukae and Turner (1975) recognized that hydraulic conductivity of the Oxnard Aquifer was higher than that of the Mugu Aquifer; therefore, the USGS's aggregate estimate of horizontal hydraulic conductivity for the UAS may underestimate the actual hydraulic conductivity of the Oxnard Aquifer, and overestimates the hydraulic conductivity of the Mugu Aquifer. Hydraulic conductivities of the aquitards in the study area have rarely been studied. Hydraulic conductivities for silt (which is the major component of the aquitards) are typically in the range from 0.001 to 10 ft/day (Heath, 1983). Neuman and Witherspoon (1972) conducted an aquifer test at a site in the southern Oxnard Plain using a single pumping well and multiple observation wells (piezometers), and estimated the vertical hydraulic conductivities of the Clay Cap and the Oxnard-Mugu aquitard at the test site to be 0.0078 ft/day and 0.0056 ft/day, respectively. Li and Neuman (2007) reevaluated the same data using a different approach and estimated the vertical hydraulic conductivities of the Clay Cap and the Oxnard-Mugu aquitard at the test site to be somewhat smaller, at 0.0060 ft/day and 0.0037 ft/day, respectively. It should be noted that these vertical hydraulic conductivity estimates represent only one aquifer test (the data were analyzed using two different methods by different researchers) at a single location in the Oxnard Plain basin; therefore, these estimates should not be assumed to be representative of vertical hydraulic conductivities across the entire domain of the VRGWFM.

2.5.2.2 STORAGE COEFFICIENTS

Field-testing for specific yield (for unconfined aquifers) and storage coefficient (for confined aquifers) generally requires observation-well data, which have been infrequently collected in the study area. Furthermore, such estimates of storage values from aquifer tests are even more sensitive than transmissivity to influence by the factors noted above that limit the usefulness of pumping test results for hydraulic conductivity and transmissivity. Therefore, Mukae and Turner (1975) relied primarily on reported typical literature values of specific yield, and the USGS (Hanson and others, 2003) relied on previous models in the region combined with theoretical values of storage coefficients computed from typical porosities, compressibility of water, and estimated thickness of HSUs. In addition, specific storage estimates were used in these calculations, using values derived from a few local aquifer tests and reported typical values for alluvial sediments. Considering the limited availability and reliability of aquifer-test-based estimates of specific yield and storage coefficients, the values used by the USGS were considered a reasonable starting point for this investigation, and were refined during model calibration (Section 4) in accordance with common model-construction practice. The USGS estimated specific yield to range from 10 to 19 percent and storage coefficients to range from 5×10^{-6} to 7×10^{-2} (unitless) in their model of the region (Hanson and others, 2003). As a point of comparison, Li and Neuman (2007) estimated that the storage coefficients for the Oxnard and Mugu Aquifers were 2.1×10^{-4} and 1.4×10^{-4} at their test site in the southern Oxnard Plain basin near Port Hueneme.

2.6 UPDATE OF HYDROSTRATIGRAPHIC CONCEPTUAL MODEL

In order to construct an improved numerical groundwater flow model that explicitly and accurately represented all of the major HSUs in the study area, United staff collected and reviewed more than 900 borehole resistivity logs (electric logs or "e-logs") from oil/gas and water wells within the model domain and nearby areas, with the goal of updating and refining the hydrostratigraphic conceptual model. This updated hydrostratigraphic model forms the basic "framework" required to define the geometry and layering of the numerical flow model, as described in Section 3.

The available borehole e-logs were reviewed to determine the depth and quality of the logs, and that locations of the wells were plotted appropriately. A subset of available e-logs (~575) was selected based on quality, depth and location, and sent to a private contractor to be digitized. The digitized logs were received in "log ASCII standard" (*.las) format, allowing import to RockWorks® (ver. 15), the software used to record aquifer picks and construct cross-sections. Lines for cross-sections were identified in GIS, where shapefiles of oil well and water well locations, faults, basin boundaries, surface geology and other pertinent features were available to aid in selection of optimal section lines. Alignments were selected to intersect locations of known structural and stratigraphic change in the subsurface while utilizing as many e-logs as practical. Land surface elevations for the well heads with e-logs were determined based on the USGS National Elevation Data Set digital elevation model of land surface within the model domain. E-logs from selected wells along the various sections were printed on plotter paper for identification of HSUs ("aquifer picks") and correlation of those units. Vertical exaggeration of the various plotted sections was determined by the depths of the well logs and the length of the section. Lithologic descriptions from wells along and near the lines of section were commonly noted on the working sections to help identify aquitards and aquifer units. Upon finalization of picks for a given section, depths of the various HSUs were entered into a RockWorks® database, along with notes supporting the aquifer picks as necessary.

As mentioned in Section 2.5 and shown in Table 2-1, thirteen HSUs consisting of seven aquifers and six aquitards were identified and picked on e-logs. The water-bearing HSUs identified by United generally conform to the traditional published aquifer delineations for southern Ventura County. With the location of e-logs and the picked HSU depth, thirteen surfaces (bottom elevation of the thirteen HSUs) were digitally interpolated using Kriging methods. The top elevation and thickness of each HSU are shown in Appendix A.

An early version of the hydrostratigraphic conceptual model (referred to herein as "basin conceptual model" [BCM] 11) relied on 159 e-logs to construct cross-sections covering the Oxnard Plain and the Mound basin, and included preliminary picks along a single section in the Pleasant Valley basin. Cross-section lines roughly following the alignment of those published by Mukae and Turner (1975) were included, so as to facilitate conformity with traditional published interpretations of aquifer units on the Oxnard coastal plain. Initially, the numerical model was constructed and calibration was started based on HSUs identified in BCM 11. As numerical model construction progressed, it was recognized that additional cross-sections were needed to provide sufficient data for HSU top and bottom elevations for critical areas such as the Oxnard Forebay and the onshore areas adjacent to the Hueneme and Mugu Submarine Canyons that are subject to saline intrusion. The additional cross sections resulted in adjustment of HSU picks in some areas. Additional cross-sections were also constructed for the Pleasant Valley basin, including the northernmost portion of the basin near Somis, where significant recharge associated with flow in Arroyo Las Posas is known to occur at times. Lastly, eight cross-section lines were added in the West Las Posas basin and HSUs were picked within that basin. The current version of the hydrostratigraphic model, BCM 13, relies on 414 e-logs, some of which are located just outside of the model domain, allowing extension of the cross-section lines to, and slightly beyond, basin boundaries. BCM 13 includes 13 layers (from top to bottom, Layers 1 through 13) representing each of the major hydrostratigraphic units in the study area. Most of the e-logs fall on one or more of the 43 cross-section lines, but a number of off-section wells were picked in areas where well density was poor or interpolated surfaces (representing tops and bottoms of HSUs in three dimensions) were considered to inadequately define HSU geometry. Figure 2-15 shows the location of the wells with e-logs used to develop BCM13, and the cross-section lines. A three-dimensional representation of the final hydrostratigraphic conceptual model is shown on Figure 2-16. The onshore portion of the model domain covers an area of approximately 169 square miles; 411 e-logs were picked within this area, resulting in a density of about 2.4 e-logs per square mile.

An additional 23 control points were added manually in specific areas to better define the geometry of known geologic structures. In the offshore portion of the model domain, few e-logs were available and some 12 additional offshore control points were added to represent the layering and thickness of HSUs as they exist near the coastline. In the Mound basin, control points were added to improve the interpolated surfaces defining the Ventura-Santa Clara River syncline (the wide spacing between wells with e-logs, combined with the tendency of the Kriging algorithm used for interpolation to excessively flatten structural folds if their axes were not sufficiently delineated, would have yielded an inaccurate representation of this syncline without addition of control points along the axis). Control points were also manually added along the northern portion of the West Las Posas basin at the base of the mapped outcrop of the San Pedro Formation, allowing the bottom of this unit to be more accurately represented in cross-sections and interpolated surfaces. Control points were also added near faults with significant vertical offset in order to more accurately represent these features. Several points were used along the Oakridge Fault which forms the basin boundary along the northern portion of the Oxnard Plain basin.

The following subsections describe key areas and issues in the hydrostratigraphic conceptual model of the study area that were better understood as a result of United's effort to develop BCM 13.

2.6.1 AREAS OF AQUIFER MERGENCE

Throughout much of the model domain, aquitards of various thickness are known to exist between aquifers. However, in some areas, such as the Forebay and the northernmost portion of the Pleasant Valley basin, aquitards (most notably the Clay Cap) are absent or discontinuous. In these areas unconfined conditions exist in the underlying aquifers, allowing water to move downward from recharge sources, such as stream channels and recharge basins, to the water table with minimal impediment or lateral flow. In areas where BCM 13 Layers 1 and 2 (typically representing the Semi-perched Aquifer and the Clay Cap) were not identified in the e-logs, Layer 3 (typically representing the Oxnard Aquifer) was commonly mapped to land surface (as shown in Sections K, G, S; all cross-sections referred to in Section 2.6 are provided in Appendix A). These unconfined areas of the Oxnard Aquifer or other regionally important aquifers are relatively limited in extent and are limited to up-gradient areas of the Oxnard coastal plain. Regional aquitards exist between the major aquifers across much of the remainder of the coastal plain.

In the confined portions of the Oxnard Plain and Pleasant Valley basins, Layer 2 of BCM 13 (the Clay Cap) was mapped as continuous, but with variable thickness beneath Layer 1. In many areas, Layer 2 varied in thickness from 20 to more than 100 feet, but some water is thought to move through this layer (i.e., between Layer 1 and Layer 3). This flow between aquifers likely occurs in areas where the aquitard is thin, and where silts and fine sands rather than clays dominate the composition of Layer 2. Wells without deep surface seals also likely facilitate the movement of water between Layers 1 and 3.

The Layer 2 aquitard is mapped as being continuous outside of the Oxnard Forebay and northern Pleasant Valley, but areas of aquifer mergence were mapped among the deeper confined aquifers of the Oxnard Plain basin in the central and coastal portions of the basin. Layer 4, which commonly lies between the Oxnard aquifer and the underlying Mugu aquifer of the UAS, generally ranges from 40 to more than 100 feet thick in the Pleasant Valley basin. On the Oxnard Plain, Layer 4 is thickest in the areas adjacent to the West Las Posas and Pleasant Valley basins, with mapped thicknesses greater than 40 feet common in these eastern portions of the basin. Across the remainder of the Oxnard Plain basin, Layer 4 thickness is rarely greater than 20 feet. Mergence of the Oxnard and Mugu Aquifers is apparent in e-logs from wells in the area inland of McGrath Lake (Section H of Appendix A) and an area south of Hueneme Road (Section M of Appendix A). Previous studies have identified areas of Oxnard-Mugu aquifer mergence in the northwestern portion of the Oxnard Plain (SWRCB, 1979). Layer 4 is mapped as being absent throughout most of the Oxnard Forebay. These areas of aquifer mergence facilitate the vertical flow of water between aquifers when vertical gradients are present.

Layer 6 represents a layer of low permeability between the Mugu Aquifer of the UAS and the Hueneme Aquifer of the LAS. Layer 6 is generally thickest in the eastern portions of the model domain, but a thick deposit of clay located just east of Port Hueneme is included in this layer. Farther east, centered at the intersection of Hueneme Road and Rice Avenue, Layer 6 is absent, resulting in the base of the Mugu aquifer being in direct hydraulic connection with LAS aquifers. Layer 6 is also thin or absent in the vicinity of McGrath Lake, and near the intersection of Third Street and Oxnard Blvd. in the central portion of the Oxnard Plain basin. Layer 6 is observed to be thin or absent in certain wells in the central and northern portions of the Oxnard Forebay, but within a smaller area than the large, elongate area of Mugu-Hueneme aquifer mergence mapped by the SWRCB (1979) in the central Oxnard Plain basin.

2.6.2 LOWER AQUIFER SYSTEM UPLIFT IN FOREBAY

The Forebay is west of, and in alignment with, the tectonically uplifted terrain of South Mountain. Deposits of the San Pedro Formation are exposed in places on South Mountain, then plunge westward from South Mountain, extending under the Oxnard coastal plain. The youngest San Pedro Formation deposits have been removed by erosion in the northeast part of the Forebay, where tectonic uplift has been greatest—in places the aquifers of the UAS directly and unconformably overlie some of the deeper LAS aquifers (Section K). In these areas of the Forebay, surface water infiltration in the channel of the Santa Clara River and artificial recharge at United's Saticoy spreading basins can effectively recharge aquifers of both the UAS and the LAS.

2.6.3 AREAS OF STRATIGRAPHIC CHANGE IN THE NORTHEAST OXNARD PLAIN

The thickest portion of the Hueneme Aquifer is mapped in the southern Forebay along the axis of the Oxnard-Las Posas syncline, where the aquifer reaches a thickness of 1,100 feet. The aquifer thins to the east, and wells in the northeastern Oxnard Plain basin near the boundary with West Las Posas basin show the Hueneme Aquifer to be some 350 to 550 feet thick in this vicinity. In this area the character of the Hueneme Aquifer is distinct from other areas on the Oxnard Plain basin, being finer-grained and having thinner bedding (Section U). While the resistivity log signatures are not vastly different in this vicinity, driller's logs in the area commonly describe the Hueneme Aquifer as having abundant clay, along with sand. The more fine-grained nature of the Hueneme Aquifer in this area slows the flow of groundwater moving south from the Forebay. In the past there has been speculation that a "flow barrier" exists in this vicinity, given the change in LAS water levels between the northern Forebay and the area near the western terminus of the Camarillo Hills. United's hydrostratigraphic conceptual model includes a change in Hueneme Aquifer properties in this area, but evidence suggestive of significant faulting or other structural barrier was not recognized in the analysis of well logs in this area.

2.6.4 UPPER SAN PEDRO FORMATION IN THE WEST LAS POSAS BASIN

The aquifers of the UAS only extend about ½-mile east of the Wright Road fault in the westernmost part of the West Las Posas basin. A shallow alluvial aquifer (BCM 13 Layer 1) is mapped across the floor of Las Posas Valley, overlying an aquitard (Layer 6) that varies from less than 50 to more than 300 feet thick; this aquitard serves to confine the deeper aquifers in the basin. Layer 7 is therefore the shallowest confined aquifer mapped across the West Last Posas basin. While Layer 7 is associated with the Hueneme Aquifer in the Oxnard Plain and Pleasant Valley basins, the common terminology for age-equivalent deposits in the West Las Posas basin is "upper San Pedro Formation." The thick sequence of sedimentary deposits in the upper San Pedro Formation is dominated by fine-grained materials. Some sand layers (indicated by higher resistivity in the e-logs) are present, but are generally less than 50 feet thick (Section Y, Section Z). Groundwater-level data are limited in the upper San Pedro Formation, but available data suggest that significant vertical gradients exist within this HSU.

2.6.5 CLAY DEPOSITS NEAR HUENEME CANYON

As mentioned above, a thick clay deposit exists in BCM13 Layer 6 just east of the Port Hueneme harbor complex. The deposit is penetrated by well 01N22W28G01S (USGS monitoring well CM4) and two exploratory oil wells located north of Hueneme Road. The USGS logs hundreds of feet of "sandy mud," and the e-logs of all three wells show a thick interval of low resistivity without significant bedding. This feature may represent a former onshore extension of the nearby Hueneme submarine canyon that was subsequently filled with fine-grained material. This deposit was mapped as part of Layer 6 in BCM 13 (see Section H).

2.6.6 UPPER AQUIFER SYSTEM IN THE PLEASANT VALLEY BASIN

The productive and typically well-defined aquifers of the UAS in the Oxnard Plain basin have a different character in the Pleasant Valley basin, becoming finer grained and less reliable as sources of groundwater. The sediments forming the UAS in the Pleasant Valley basin were deposited by streams draining the Calleguas Creek watershed, which is considerably smaller and less mountainous than the watershed of the Santa Clara River (which is the source of most UAS sediments occurring in the Oxnard Plain basin). Nevertheless, logs from wells in the Pleasant Valley basin do indicate some assemblages of aquifer material above the LAS. These "upper" aquifers are more interbedded than the UAS on the Oxnard Plain, and have lower hydraulic conductivities. United's BCM13 shows continuity within the Oxnard and Mugu Aquifers across much of the Pleasant Valley basin, but the character of the UAS deposits are different than they are within the Oxnard Plain basin. The degree of connectivity among the sandy lenses and interbeds of the UAS in the Pleasant Valley basin is not well known.

2.6.7 EXTENT OF THE GRIMES CANYON AQUIFER

The Grimes Canyon Aquifer is the deepest freshwater aquifer included in United's hydrostratigraphic conceptual model for the study area. This aquifer generally dips to the northwest in the groundwater basins underlying the Oxnard coastal plain, from the Santa Monica Mountains in the southeast to a line that extends from the Camarillo Hills to Port Hueneme. The Grimes Canyon Aquifer is mapped to depths as great as 2,400 feet below sea level in the area south of Hwy 101 and west of Del Norte Blvd. This is also the area of the Oxnard oil field, where the Vaca Tar Sands are mapped within hundreds of feet of the deepest mapped extent of the Grimes Canyon Aquifer.

2.6.8 LOWER AQUIFER SYSTEM UPLIFT NEAR MUGU LAGOON

Although the Oxnard and Mugu Aquifers are fairly flat-lying in the southernmost portions of the Oxnard Plain basin, the aquifers of the LAS dip northward (Sections M and N). The aquifers of the LAS appear to have been uplifted in the southern Oxnard Plain basin, possibly related to movement on the Sycamore Canyon fault, which is present a short distance offshore. Erosion of the Hueneme

Aquifer as far north as Hueneme Road near Nauman Road has resulted in the Mugu Aquifer directly overlying the Fox Canyon Aquifer in the area north of Mugu Lagoon.

2.6.9 RECENT DEPOSITS IN MOUND BASIN

Some of the signatures of the Mugu, Hueneme, and Fox Canyon Aquifers (and the aquitards between these aquifers) observed in e-logs for wells in the Oxnard Plain basin can be traced northward across the Oak Ridge Fault and into the Mound basin (the Grimes Canyon Aquifer is absent this far north). However, late Pleistocene deposits that overlie the Mugu Aquifer appear to differ substantially across the basin boundary. United's BCM13 includes a surficial Layer 1 in Mound basin, commonly ranging from 30 to more than 100 feet in thickness, below which lies a thick sequence of clays and silts. These sediments are logged to depths of some 350 to 450 feet in a number of wells in Mound basin (Section A, Section D). In well 02N22W07M01S, located near the axis of the Ventura-Santa Clara River syncline, these fine-grained Pleistocene sediments are mapped to a depth of 585 feet. Along the Oxnard Plain basin boundary these deposits abut or interfinger with the Oxnard aquifer.

2.7 GROUNDWATER INFLOW AND OUTFLOW COMPONENTS

A summary of estimates for inflow and outflow components to the groundwater system in the study area is provided in Table 2-2, below. Approximately half of the total inflow consists of artificial recharge, which is metered by United and, therefore, volumes are known with a high level of certainty. Similarly, more than 80 percent of the total outflow consists of groundwater pumping from wells, which is also metered. The small magnitude of the other inflows and outflows relative to artificial recharge and groundwater pumping—the major inflow and outflow components—means that even if there is relatively large uncertainty (e.g. +/-25%) in deep infiltration of precipitation, for example, which could result in a hypothetical "error" of +/-4,500 AF/yr in the water balance, the magnitude of this uncertainty is less than 10% of the average artificial recharge rate of 48,000 AF/yr, which is known to a high level of certainty since it is carefully monitored by United. Furthermore, much of the recharge in the study area derived from sources other than artificial recharge enters the groundwater system in the Semi-perched Aquifer, which is not used for water supply. This recharge is removed from the groundwater system via the extensive drainage systems in the Semi-perched Aquifer (and ET) within hours, days, or a few weeks, at most, and has little influence on groundwater conditions in the aquifers of the UAS and LAS.

Table 2-2. Estimates of Groundwater Inflow and Outflow Components to Study Area

Groundwater Inflow or Outflow Component	Estimated Long-Term Averages from Previous Investigations (AF/yr)
Inflows: (**bold** font used for components that are required as input to the VRGWFM, *italic* font for flows that are calculated by the VRGWFM [provided solely for comparative purposes])	
Artificial Recharge (at Saticoy and El Rio Spreading Grounds)	**48,000[a]**

Table 2-2. Estimates of Groundwater Inflow and Outflow Components to Study Area

Groundwater Inflow or Outflow Component	**Estimated Long-Term Averages from Previous Investigations (AF/yr)**
Stream-Channel Recharge in Santa Clara River	*8,400*[b]
Stream-Channel Recharge in Arroyo Las Posas	*4,000*[b]
Deep Infiltration of Precipitation	**11,000**[c] **to 15,000**[d]
Return Flows (Ag + M&I)	**27,000**[e] **to 28,000**[f]
Mountain-Front Recharge (sum of ungauged streamflow and bedrock recharge)[g]	**3,000**[h]
Percolation of Treated Wastewater at WWTPs	**280**[i]
Groundwater Underflow from Santa Paula Basin	*1,800*[j] *to 7,400*[k]
Groundwater Underflow from East Las Posas Basin	*700 to 1,900*[l]
Net Seawater Intrusion into UAS and LAS	*12,000*[m]
Outflows: (**bold** font used for components that are required as input to the VRGWFM, *italic* font for flows that are calculated by the VRGWFM [provided solely for comparative purposes])	
Pumping from Water-Supply Wells	**130,000**[a]
Shallow groundwater drainage (to tile and other manmade drain systems)	*8,000 to 12,000*[n]
ET	*15,000*[o]
Discharge of Shallow Groundwater in Semi-perched Aquifer to Santa Clara River	*1,500*[p]
Semi-perched Aquifer Discharge to Pacific Ocean	*No previous estimates found*

Notes:

Most of the averages summarized in this table are those reported or estimated for the combined area of the Oxnard Plain, Forebay, Pleasant Valley, Mound, and West Las Posas basins. The relatively small inflow and outflow quantities occurring in the minor area of the active domain of the VRGWFM located outside of those basins (e.g., western margin of Santa Paula basin) are generally not included in the averages presented in this table.

[a] Calculated from United's records.

[b] Calculated from United's streamflow measurements and extrapolated over time using VCWPD stream gauge records.

[c] Deep infiltration of precipitation in the Pleasant Valley, Oxnard Plain, Forebay, and West Las Posas basin was estimated by Daniel B. Stephens & Associates, Inc. (DBSA; 2017a). United used DBSA's average infiltration rate to develop an estimate for the Mound basin, and 3,000 AF/yr was subtracted from the total to account for the fact that DBSA's estimate of deep infiltration of precipitation seems to include mountain-front recharge . More details are provided in Section 2.7.

Table 2-2. Estimates of Groundwater Inflow and Outflow Components to Study Area

Groundwater Inflow or Outflow Component	Estimated Long-Term Averages from Previous Investigations (AF/yr)

[d] Estimated by United using the Grunsky approach (see Section 2.7.3), solely for comparison. A more complex approach was used to apply deep infiltration of precipitation to the VRGWFM, as described in Section 3.5

[e] Adapted from DBSA (2017a) estimates of "irrigation infiltration" (including both agricultural and M&I return flows) as described later in Section 2.7.

[f] Estimated by United using ITRC leaching rates (United, 2013) and total volume of applied water for agricultural use as described later in Section 2.7.

[g] Sum of "bedrock recharge" and "ungauged streamflow" within study area.

[h] Based on graphs and text presented by the USGS (Hanson and others, 2003) describing their mountain-front recharge estimates.

[i] Sum reported discharges to percolation ponds of the Montalvo and Saticoy WWTPs (described later in Section 2.7).

[j] Mann's (1959) estimate of underflow from the Santa Paula basin to the Forebay during the period from WY 1937 through 1957 (Mann assumed underflow from the Santa Paula basin to the Mound basin was negligible).

[k] DBSA's (2017b) estimate of groundwater underflow from Santa Paula basin to the Mound basin and Forebay during the period from WY 1999 through 2012.

[l] Range of estimates by Intera Geoscience and Engineering Solutions (2018) based on their model of the Las Posas Valley basin.

[m] Mann's (1959) estimate of seawater intrusion into the UAS and LAS in the Oxnard Plain basin during the period from WY 1946 through 1957.

[n] Calculated by United based on Isherwood and Pillsbury (1958) estimated tile-drain discharges, modified by United to incorporate current land uses and irrigation practices (see Section 2.7 for details).

[o] Calculated by United based on mapped area of wetlands (from the National Fish and Wildlife Service) in the study area that are believed to be fed by groundwater, and the average of USGS-estimated ET rates for wetlands (Hanson and others, 2003).

[p] Estimated baseflow in Santa Clara River below Victoria Avenue (Stillwater Sciences, 2017).

Many, but not all, of the inflow and outflow components listed in Table 2-2 are required groundwater flow-model input parameters (shown in bold in Table 2-2). There are varying degrees of uncertainty associated with some of the smaller inflow and outflow components (i.e. stream-channel recharge, deep infiltration of precipitation, agricultural and M&I return flows, mountain-front recharge, percolation of treated wastewater, drainage, ET, underflow to/from adjacent basins, and seawater intrusion), as is common in regional-scale flow models. Therefore, consistent with standard modeling practice, the values for these uncertain inflow components were adjusted during model calibration, as described in Section 4, to improve the overall model calibration. The inflow and outflow components not required as input to the model (shown in italics in Table 2-2) are calculated by the model based on simulated boundary conditions, aquifer stresses, and aquifer parameters, as described in Section 3. It should be noted that change in groundwater storage is often included in a water balance; however Table 2-2 is not intended as a water balance, and change in groundwater storage is an output from the VRGWFM, not an input parameter. Therefore, change in storage is not included in Table 2-2.

Each groundwater inflow and outflow component is described further in the following subsections.

2.7.1 GROUNDWATER INFLOWS

Multiple sources of groundwater recharge (water that enters an underlying groundwater system from land surface) occur in the study area, including:

- “Artificial” recharge (“spreading”)
- Stream-channel recharge
- Deep infiltration of precipitation
- Agricultural return flows
- Municipal and industrial return flows
- Mountain-front recharge
- Percolation of treated wastewater

In addition to the types of recharge (from land surface) listed above, subsurface inflow of groundwater also occurs in the study area as a result of:

- Groundwater underflow from adjacent basins
- Seawater intrusion
- Subsidence

Locations where each type of groundwater recharge are understood to occur in the study area are shown on Figure 2-17. Each of these recharge sources is discussed in further detail below. Groundwater underflow to/from other basins is discussed in Section 2.8.

2.7.1.1 ARTIFICIAL RECHARGE

Artificial recharge consists of diverting surface water to “spreading” or infiltration basins for the express purpose of enhancing replenishment of groundwater supplies. The average rate of artificial recharge in the Forebay by United from 1985 through 2015 was approximately 48,000 AF/yr, which constitutes approximately half of the previously estimated total influx to groundwater in the study area (as a long-term average), and is nearly twice the magnitude of the next largest recharge component (sum of agricultural and M&I return flows). Over the past 50 years, United’s recharge operations in the Forebay are estimated to have contributed a greater volume of recharge to the aquifers of the UAS and LAS in the study area than all other sources of recharge combined (the Semi-perched Aquifer is not present in the Forebay, so does not receive artificial recharge from United’s spreading basins). Therefore, artificial recharge can be considered the most important long-term groundwater influx term to the study area. Fortunately for development of the VRGWFM, volumes of water recharged in each of United’s facilities have been accurately recorded throughout the period of interest (1985 through 2015). Recharge quantities vary from year to year, with the highest volumes occurring in years of high rainfall (usually, but not always, associated with “El Nino” years, including 1992, 1995, 1998, and 2005), and the lowest volumes are associated with periods of drought. Annual recharge volumes at United’s Forebay spreading facilities from 1985 through 2015 are shown graphically on Figure 2-18. Artificial recharge rates in the study area also vary by season, with the highest rates occurring during spring and the lowest during summer. Some recharge also occurs in fall, largely as a result of releases of water stored by United in Lake Piru (Figure 1-1).

United and its predecessor agency (the Santa Clara Water Conservation District) have been conducting artificial recharge in the Forebay since 1928, using surface water diverted from the Santa Clara River at the Saticoy Diversion, and later at the Freeman Diversion. Water releases from Lake Piru and a portion of the natural runoff from the Santa Clara River are diverted at that point. The Freeman Diversion is located on the Santa Clara River about 11 miles upstream from the Pacific Ocean. The concrete Freeman Diversion structure was completed in 1991, replacing the previous diversion method of building temporary sand and gravel diversion dikes, levees, and canals in the river channel using bulldozers and other heavy equipment. Most of the diverted surface water from the Santa Clara River is conveyed to United's Saticoy and El Rio recharge facilities (Figure 2-17). The remainder of the diverted water is delivered directly to agricultural users to satisfy irrigation demands "in lieu" of the users pumping groundwater. These surface-water deliveries are designed to reduce groundwater pumping in areas where overdraft is common and to mitigate groundwater conditions that contribute to saline intrusion.

2.7.1.2 STREAM-CHANNEL RECHARGE

Infiltration of surface-water flows in "losing" reaches of the Santa Clara River and Arroyo Las Posas (Figure 2-17) is the second largest source of recharge from land surface to the aquifers of the UAS and LAS in the study area. The average total stream-channel recharge rate in the study area from this source has been estimated by United to be approximately 12,000 AF/yr (details and references provided below). Most of this recharge occurs in the Forebay and northern Pleasant Valley basin, where the Semi-perched Aquifer and Clay Cap are absent. Therefore, the UAS and LAS directly receive the majority of this recharge, and only a small portion recharges the Semi-perched Aquifer (which is also the source of some groundwater ***discharges*** to stream channels).

The interaction of groundwater with surface water in streams can be complex; locations, extents, and rates of exchange between surface-water and groundwater vary from season to season and year to year. At times and places where the water table rises above the elevation of the water surface in the stream, discharge from the aquifer to the stream (rising groundwater) occurs instead of recharge. In areas where the Clay Cap is present, including all of the Oxnard Plain basin and the southern part of the Pleasant Valley basin, streams in the study area typically act as drains for (receive water from) the Semi-perched Aquifer, although small amounts of stream-channel recharge to the Semi-perched Aquifer are possible. Much of the Revolon Slough and many of the creeks and storm drains located in urban areas of the study area are lined with concrete, which is less permeable than soil and rapidly conveys surface flows to discharge outfalls, thereby reducing the opportunity for stream-channel recharge.

Surface-water flows in the Santa Clara River can infiltrate into the underlying UAS (Oxnard Aquifer, specifically) in the Forebay, where the Semi-perched Aquifer and Clay Cap are absent. On rare occasions, the reach of Santa Clara River overlying the northern portion of the Forebay is the site of groundwater discharge to the river (gaining stream) rather than recharge, as a result of the presence of exceptionally high groundwater levels in the alluvial deposits adjacent to the river channel. This condition occurred in 1999 and 2006, following periods of record-setting rainfall in 1998 and 2005, which allowed United to recharge exceptionally large volumes of groundwater in the adjacent Saticoy spreading grounds. Estimates by United's lead hydrologist of stream-channel recharge rates from CY 1985 through 2012 (the most recent year estimated) in the Forebay reach of the Santa Clara River range from -11,500 AF/yr (signifying a net ***outflow***, or discharge, of groundwater to the stream channel) in 2006 to 36,800 AF/yr (this is a positive value, signifying recharge) in 1993. The estimated average stream-channel recharge rate in the Santa Clara River during this period was 8,400 AF/yr. For comparison, Mann (1959) estimated stream-channel recharge in the Santa Clara River during the period from WY 1937 to 1957 to range from 1,000 to 39,300 AF/yr.

Surface water in Arroyo Las Posas infiltrates into aquifers of the LAS in the northern Pleasant Valley basin, where overlying fine-grained deposits have been eroded away resulting in more permeable layers coming into direct contact with coarse-grained stream-channel deposits. Estimates by United's lead hydrologist of stream-channel recharge rates from CY 1985 through 2011 (the most recent complete year estimated) for Arroyo Las Posas in northern Pleasant Valley basin range from 800 AF/yr in 1989 to 8,900 AF/yr in 2005. The estimated average stream-channel recharge rate in Arroyo Las Posas during this period was 4,000 AF/yr. For comparison, the USGS estimated stream-channel recharge in the Calleguas Creek watershed portion of their study area during the period from 1956 to 1993 to range from 0 to 6,100 AF/yr (Hanson and others, 2003). However, their estimate excluded treated wastewater flows in the watershed, which comprised a substantial fraction of flows in Arroyo Las Posas beginning in the early 1990s and continuing through the 2000s (subsequent to the timeframe for the USGS estimate).

2.7.1.3 DEEP INFILTRATION OF PRECIPITATION

Much of the rain that falls in the study area quickly returns to the atmosphere via evaporation, or runs off to creeks, storm drains, and ultimately the ocean; the remainder percolates into the soil beneath land surface where it is subject to absorption by the soil matrix, uptake by plant roots, or delayed evaporation back into the atmosphere during subsequent dry periods. However, a part of the rainfall that percolates into the soil continues downward past the root zone and reaches an underlying aquifer—this recharge process is referred to as deep infiltration (or percolation) of precipitation.

Deep infiltration of precipitation is highly variable over time and location, as it depends on multiple factors, including: precipitation rate and duration, evaporation rate, ambient temperature, texture and slope of land surface, soil type and texture, antecedent soil moisture, vegetation cover, seasonal plant activity, and others (Stonestrom and Harrill, 2007). For these reasons, estimates of deep infiltration of precipitation at a given location or time are typically subject to substantial uncertainty. However, there are methods for estimating long-term average deep infiltration of precipitation that are generally accepted as giving reasonable results on a basin-wide scale. Estimates using these methods for deep infiltration of precipitation in the study area have ranged from 11,000 to 15,000 AF/yr, as discussed further below.

On portions of the Oxnard coastal plain where the Clay Cap exists, much of the precipitation (and agricultural return flows, which are discussed in a subsequent subsection of this report) that infiltrates to the Semi-perched Aquifer is then removed by tile drains installed under agricultural fields, or flows laterally to storm drains, streams, and wetlands, where it is discharged as surface water or evaporated (drainage of shallow groundwater is discussed further in Section 2.7.2). Due to the presence of the Clay Cap and urban infrastructure (e.g. pavement) across much of the Oxnard coastal plain, deep infiltration of precipitation is not as important of a source of recharge to the UAS and LAS within the study area as are artificial recharge and stream-channel recharge. However, deep infiltration of precipitation is still an important source of recharge to the Semi-perched Aquifer, and also provides a limited quantity of recharge to the Oxnard Aquifer in the Forebay, and the Fox Canyon Aquifer along the margins of the Mound, West Las Posas, and northeastern Pleasant Valley basins. Typically, deep infiltration of precipitation in Ventura County has the best chance of occurring during winter and spring, particularly during years of above-average rainfall, when storms are more frequent and longer in duration, and temperatures and evaporation rates are relatively low (compared to summer and fall).

As noted above, due to the complex interplay of factors that influence deep infiltration of precipitation and the difficulty in measuring some key parameters, the quantities of this source of recharge are usually subject to substantial uncertainty in basinwide studies. The USGS noted in a report on groundwater recharge in the southwestern United States that two approaches were appropriate for estimating spatially distributed recharge at a regional scale for the purpose of groundwater flow modeling (Flint and Flint, 2007). These approaches are:

- Empirical transfer methods that relate precipitation to ground-water discharge, and
- Distributed-parameter water-balance models.

Watershed-scale empirical relationships that compare rainfall with runoff, ET, and natural recharge within southern California basins have been developed by Grunsky (1915) and Turner (1991). Recently, the Grunsky method has been demonstrated to be valid for estimating watershed yield in a variety of Meditteranean climates (Santos and Hawkins, 2011). Both the Grunsky and Turner methods calculate annual recharge as approximately equal to the annual precipitation rate multiplied by a dimensionless factor that is 1/100th of the precipitation rate. For example, across the study area, where average annual precipitation is approximately 15 inches, deep infiltration using the Grunsky method would be 0.15 x 15 inches, or 2.3 inches; this would equate to approximately 21,000 AF/yr of recharge on average over the entire inland portion of the study area, if accepted without modification. Turner's approach is an evolution of the Grunsky method, with a maximum recharge rate (the recharge rate might achieve a constant value for precipitation rates greater than 36 inches per year), an exponential rainfall-vs-recharge curve, and a lower limit for annual precipitation capable of producing recharge (e.g., recharge would be zero during years with less than 3 inches of precipitation). Both the Turner and Grunsky methods assume that the watersheds are largely undeveloped, although they still provide reasonable results for areas with agricultural land use. The quantity of deep infiltration of rainfall on agricultural lands of the Oxnard coastal plain may be influenced to some degree by anthropogenic changes to soil conditions (e.g. tilling or irrigation) and vegetation cover (e.g. crop type), while deep infiltration of rainfall in municipal and industrial areas is likely to be significantly decreased due to the widespread presence of man-made impermeable surfaces (pavement and rooftops) and storm drains. If it is assumed that only 5 percent of rainfall in municipal/industrial areas (44,000 acres) infiltrates deeply enough to become recharge, while deep infiltration of rainfall in the remainder of the study area (both agricultural and undeveloped areas; 64,000 acres) follows Grunsky's rule, then total deep infiltration of precipitation in the study area would be estimated to be approximately 15,000 AF/yr.

The previous basinwide hydrogeologic investigations conducted in the study area (Section 1.2) focused on the aquifers of the UAS and LAS, and generally did not make estimates of recharge (or most other groundwater inflow and outflow components) occurring in the Semi-perched Aquifer. For example, Mann (1959), included "rainfall penetration" in the Forebay as an inflow component to the water budget (at an average rate of 2,320 AF/yr), but did not include it in the remainder of Oxnard Plain basin or the Mound basin (the Mann study did not include the West Las Posas or Pleasant Valley basins). Mann calculated rainfall penetration as monthly rainfall minus the sum of crop demand and the volume of water required to restore the soil to field moisture capacity. The USGS (Hanson and others, 2003) estimated recharge resulting from deep infiltration of rainfall (which they referred to as direct infiltration) "as a percentage of precipitation" based on the modified rational method, "in which the amount of potential recharge is the fraction of runoff from the index subdrainage basin multiplied by the total volume of precipitation for each ground-water subbasin." Similar to Mann, the USGS assumed that deep infiltration of rainfall did not reach the aquifers of the UAS and LAS in the Mound basin and areas of the Oxnard Plain and Pleasant Valley basins where widespread, near-surface confining layers (such as the Clay Cap) are present.

The other approach to estimating deep infiltration of precipitation—distributed-parameter water-balance modeling—computes the theoretical deep percolation at a watershed or larger scale using an analytical or numerical solution for a water-balance equation. The water-balance equations represent the complex processes and parameters that are believed to control evaporation, transpiration, runoff, and infiltration (described earlier in this section) on a daily to monthly basis, using a mathematical expression and requiring simplifying assumptions for parameters that are uncertain or are rarely measured in the field. Basinwide distributed-parameter water-balance models can usually only be calibrated to runoff, and the calculated quantities of runoff versus recharge can be sensitive to several parameters. Flint and Flint (2007) reported that both the empirical-transfer and the water-balance modeling approaches produce results that should be considered to be "initial" recharge estimates. In a comparison study of 12 basins in eastern Nevada, the authors reported that the recharge rates estimated by the water-balance model were "somewhat higher, but relatively close to the estimates" obtained using an empirical transfer relationship. Distributed-parameter water-balance models can take into account the effects of agriculture and urban development on rates of deep infiltration of rainfall, but require input of several soil, climate, and other parameters, many of which have uncertain values over much of the area and timeframe of interest.

Daniel B. Stephens & Associates, Inc. (DBSA, 2017a), was contracted by the FCGMA to estimate water-balance components for the Oxnard Plain (including the Forebay), Pleasant Valley, West Las Posas, and East Las Posas basins, including estimation of recharge from deep infiltration of precipitation and irrigation water using their proprietary distributed-parameter watershed model. DBSA noted that their model was not calibrated, and, therefore, the "recharge estimates are subject to a greater amount of uncertainty as compared to a calibrated soil-moisture balance model." However, their recharge estimates are still useful for comparison to those of previous investigators. The DBSA estimates of average annual deep infiltration of precipitation in individual basins within the VRGWFM study area for the period from 1985 through 2015 were (rounded to the nearest 100 AF/yr):

- Oxnard Plain (including Forebay) basin: 7,000 AF/yr
- Pleasant Valley basin: 3,300 AF/yr
- West Las Posas subbasin: 1,700 AF/yr (includes recharge in "external alluvial channels")
- Mound basin: not included

The average combined deep infiltration of precipitation in the Oxnard Plain, Forebay, Pleasant Valley, and West Las Posas basins estimated using the DBSA approach is 12,000 AF/yr; however, the Mound basin was not included in DBSA's estimate. Applying DBSA's average rate of deep infiltration of precipitation for the Oxnard Plain, Forebay, and Pleasant Valley basins (0.129 feet per year) to the area of the Mound basin (14,800 acres) would increase the total rate of deep infiltration of precipitation by approximately 1,900 AF/yr. It is assumed that DBSA's deep infiltration of precipitation estimate incorporates mountain-front recharge, since that is not accounted for elsewhere in their water-balance tables. Therefore, the USGS-estimate (Hanson and others, 2003) of mountain-front recharge (3,000 AF/yr, as discussed subsequently in this section) should be subtracted from DBSA's estimate of deep infiltration of precipitation (because mountain-front recharge is accounted for separately in this report), bringing the adjusted total of DBSA's deep infiltration of precipitation to 11,000 AF/yr. This value is somewhat lower than the estimate developed using the Grunsky approach (15,000 AF/yr), highlighting uncertainty associated with estimating deep infiltration of precipitation.

2.7.1.4 AGRICULTURAL RETURN FLOWS

Agricultural return flows are defined as applied irrigation water (water applied in addition to rainfall) that infiltrates to a depth beyond which removal by ET can occur to a significant degree (referred to as "the ET extinction depth"). This applied irrigation water that infiltrates beyond the ET extinction depth eventually reaches the underlying water table to become recharge. The long-term average rate of recharge from this source has been estimated to be 25,000 to 27,000 AF/yr in the study area, as discussed further below. Estimated agricultural return flows of this magnitude might appear to be a potentially significant fraction of the water budget within the study area. However, as discussed further in Section 2.8, tile drains remove most of the agricultural return flows in the Oxnard Plain (excluding the Forebay) and Pleasant Valley basins almost immediately after infiltration (within the Semi-perched Aquifer), and rapidly convey it to the ocean via drainage ditches. Therefore, similar to deep infiltration of precipitation, agricultural return flows are not as important of a source of recharge to the UAS and LAS within the study area as are artificial recharge and stream-channel recharge in the Forebay, but are believed to provide much of the recharge to the Semi-perched Aquifer, and some recharge to the aquifers of the UAS and LAS in the Forebay and northeastern Pleasant Valley basins, where the Clay Cap does not exist.

The major sources of water applied for agricultural use in the study area include:

- Groundwater extracted from the UAS and LAS at wells located on or adjacent to the farms where the water is applied
- Groundwater extracted from the UAS and LAS at wells located within the study area (e.g. United's Saticoy wellfield in the Forebay), but at some distance from farms where the water is used, and delivered via pipeline
- Surface water diverted from the Santa Clara River at Freeman Diversion and conveyed to farms via pipeline
- Surface water diverted from Conejo Creek and conveyed to farms via pipeline
- Rainfall

In addition, relatively minor volumes (compared to total agricultural water use in the study area) of irrigation water used in the study area are obtained from imported SWP water and groundwater extractions located outside of the study area, conveyed to farms within the study area via pipeline. Within a few years, up to 7,000 AF/yr of municipal wastewater from the City of Oxnard that has undergone an advanced-treatment process may also become available in the study area for agricultural and other uses.

Isherwood and Pillsbury (1958) were probably the first investigators to attempt quantification of irrigation return flows in the study area, based on measurement of outflow from tile drains. They estimated irrigation return flows of 22 percent of applied water at a farm field near the intersection of Del Norte Boulevard and 5th Avenue, in the northern Oxnard coastal plain between Oxnard and Camarillo, during a single season in 1953. Their study was performed at a site representing a small portion of the study area, more than 60 years ago, and thus should not be assumed to be representative of modern irrigation practices across the Oxnard coastal plain.

More recently, the Irrigation Training and Research Center (ITRC) at California Polytechnic State University in San Luis Obispo, California, investigated efficiency of agricultural water use in Ventura County for the FCGMA in 2010 by analyzing the percentages of applied irrigation water that were lost to evaporation, taken up by plant roots for transpiration, and required in excess of ET demand to flush (or leach) out salts that would otherwise concentrate in the root zone to the point where crop productivity was reduced. This evaluation was conducted for a variety of crops and soil conditions. ITRC determined that the leaching requirement ranges from 5 percent for sod to 19 percent for avocados (Table A-3 in ITRC, 2010). Based on the ITRC analysis, United calculated an average leaching requirement of 14 percent for the Oxnard Plain basin based on crop types and crop area. This leaching requirement assumes perfect distribution of irrigation, which is seldom achievable in practice. When variations in distribution uniformity are considered, agricultural return flows are estimated to be in the range from 22 to 25 percent of applied water (United, 2013).

Annual volumes of water reportedly applied for agricultural use in the study area are shown on Figure 2-19; the average (1985 through 2015) is approximately 99,300 AF/yr. Therefore, an average of approximately 2 feet of irrigation water was applied to the 50,200 acres of farmland in the study area per year during that period (there is significant variability in irrigation application rates within the study area and over time, due to differences in crop types, local-scale climate zones, and efficiency measures implemented by farmers). Southern Ventura County has a year-round growing season, thus irrigation occurs during all months of the year. However, less irrigation water is typically required during the winter and spring months, when rainfall is greatest and ET is minimal, than in summer or fall months. Assuming 25 percent, or 0.5 feet, of irrigation water is applied in excess of ET requirements (for the purpose of leaching salt out of the root zone), then approximately 25,000 AF/yr of irrigation water can be assumed to become recharge as agricultural return flows on average. For comparison, the USGS assumed a 70 percent irrigation efficiency factor (30 percent irrigation return) in their modeling of the Santa Clara-Calleguas watershed areas, based on general U.S. Department of Agriculture guidance for irrigation requirements developed in the 1950s and 1960s (Hanson and others, 2003). However, the USGS did not include the Semi-perched Aquifer (and associated recharge) in their model. Therefore, the USGS estimates for irrigation return flows cannot be directly translated to this study.

As noted previously, DBSA (2017a), estimated recharge from “irrigation infiltration” using their distributed-parameter watershed model as part of a water-balance study they conducted on behalf of the FCGMA. The DBSA estimates of irrigation return flows include both agricultural and municipal (landscaping) return flows in a single, combined output value. The DBSA estimates of annual average irrigation return flows (both agricultural and municipal) in individual basins within the VRGWFM study area for the period from 1985 through 2015 include (rounded to the nearest 100 AF/yr):

- Oxnard Plain (including Forebay) basin: 21,000 AF/yr
- Pleasant Valley basin: 3,700 AF/yr
- West Las Posas subbasin: 1,300 AF/yr (includes recharge in “external alluvial channels”)
- Mound basin: not part of DBSA’s analysis

The sum of “irrigation infiltration” (combined return flows from agricultural and M&I uses) for the Oxnard Plain, Forebay, Pleasant Valley, and West Las Posas basins as estimated by DBSA (2017a) is 26,000 AF/yr. The Mound basin was not included in DBSA’s study area. If combined return flows in the Mound basin are added (assumed to be approximately 1,300 AF/yr, equal to DBSA’s estimate for the West Las Posas basin, which is similar in area), DBSA’s estimate for total (the sum of agricultural and M&I) return flows for the study area would be approximately 27,000 AF/yr. As noted previously in this report, the majority of recharge occurring in the Oxnard Plain basin can only briefly be considered to effectively recharge the Semi-perched Aquifer, which is not used for water supply, before exiting the groundwater system via tile drains. This recharge has a modest to negligible effect on the aquifers of the UAS and LAS. Therefore, any uncertainty in agricultural-return-flow rates is countered in large part by their minor impact on the water budget and hydraulic conditions in the primary water-supply aquifers of the study area.

2.7.1.5 MUNICIPAL AND INDUSTRIAL RETURN FLOWS

In urban, suburban, commercial, and industrial settings, groundwater recharge can result from deep infiltration of:

- Excess water applied for irrigation of landscaping (e.g. yards, parks, golf courses)
- Leaked water from water-supply pipes, sewer lines, and storm drains
- Storm-water collection/infiltration systems (e.g. detention basins with permeable bottoms, or dry wells)

Recharge from these and similar sources is termed "municipal and industrial (M&I) return flows" in this report. The estimated long-term average recharge rate from this source is approximately 3,000 AF/yr, although it should be noted that much of this recharge occurs in the Semi-perched Aquifer, and thus M&I return flows represent a minor source of recharge to the UAS and LAS compared to the sources noted previously in this report.

The major sources of water used for municipal and industrial purposes within the study area include:

- Groundwater extracted from the UAS and LAS at wells operated within each city
- Groundwater extracted from the UAS and LAS at wells located within the study area, but at some distance from cities (e.g. United's El Rio well field in the Forebay) and delivered via pipeline
- Imported water from the SWP

Annual volumes of water reportedly applied for M&I use in the study area are shown on Figure 2-20; the average (for 1985 through 2015) is approximately 63,500 AF/yr. Comparison of Figure 2-19 with Figure 2-20 indicates that M&I water use is less variable from year to year compared to agricultural water use. Agricultural water use fluctuates depending on whether annual rainfall is above or below average (i.e., during wet years less water must be applied for irrigation and during dry years more irrigation is required). In contrast, a significant fraction of M&I water is typically used indoors (e.g. to meet sanitation needs) and, therefore, is less influenced by outdoor conditions.

Estimates of M&I return flows are subject to substantial uncertainty; estimates of losses from water and sewer pipes in typical cities vary widely, and return flows from irrigation of landscaping are not well studied. Despite this uncertainty, much of the M&I return flows in the area's largest city by area and population, Oxnard, reach the Semi-perched Aquifer. Therefore, similar to deep infiltration of precipitation and agricultural return flows, M&I return flows are not as important of a source of recharge to the UAS and LAS within the study area as are artificial recharge and stream-channel recharge in the Forebay. However, M&I return flows are believed to provide some recharge to the Semi-perched Aquifer, and directly contribute to recharge of the UAS and LAS in urban and built-up areas in the Forebay and northeastern Pleasant Valley basins (Figure 2-2), where the Clay Cap does not exist. To provide a reasonable estimate as a starting point, M&I return flows were assumed to comprise 5 percent of ***total*** M&I water use (the values for recharge ultimately input to the model are presented in Section 3 of this report).

2.7.1.6 MOUNTAIN-FRONT RECHARGE

Two types of mountain-front recharge were identified by the USGS as occurring in the study area (Hanson and others, 2003); the combined long-term average recharge rate to the basin from these sources has been estimated to be approximately 3,000 AF/yr. One type is infiltration of surface water occurring in small stream channels along the margins of the groundwater basins; this surface water emanates from the mountains immediately east and north of the basin boundaries in the study area (Figures 1-1 and 2-1). Rainfall in the mountains is typically greater than in the basins due to the orographic effect, while the steeper stream gradients and relatively low-permeability of rocks in the mountains limit opportunity for deep infiltration until the streams reach the basins, where stream-channel gradients flatten, flow velocities decrease, and the substrate commonly consists of permeable alluvial sand and gravel. Consequently, surface-water runoff from small watersheds in the hills and mountains can be significant during rainfall events, and a portion of that runoff can infiltrate the groundwater basins near their margins. The USGS (Hanson and others, 2003) referred to this process as “ungauged streamflow” in their modeling report for the Santa Clara-Calleguas watersheds, and estimated a few hundred acre-feet per season (6 months) in the Oxnard Plain basin, which has mountainous areas along only a small fraction of its eastern boundary, to 8,000 acre-feet per season (during exceptionally wet years) in the Pleasant Valley basin, which borders the Santa Monica Mountains. The USGS estimated this ungauged streamflow as a percentage of the precipitation occurring in each mountain sub-watershed area that drains to the study area. The percentages they used were 4 percent and 7.5 percent of precipitation for the dry and wet seasons, respectively.

The other type of mountain-front recharge occurring in the study area is what the USGS referred to as “bedrock recharge” (Hanson and others, 2003), which consists of deep infiltration of precipitation into permeable (usually young and poorly consolidated) “bedrock” outside of the defined groundwater basins. This process can recharge aquifers within the study area. Specifically, the San Pedro Formation (described in Section 2.4) crops out in the foothills north of the Mound basin and dips southward below the unconsolidated alluvial deposits that define the limits of the Mound basin. The precipitation that infiltrates deeply enough in these outcrop areas to avoid evaporation and transpiration percolates down-dip and until it recharges the main and basal portions of the Fox Canyon Aquifer (Section 2.5). This is essentially the same process described above as “deep infiltration of precipitation,” but this bedrock recharge directly affects aquifers that lie deep below the surface, instead of just the uppermost aquifer (such as the Semi-perched Aquifer, in most of the study area). Because this form of mountain-front recharge “bypasses” the Semi-perched Aquifer, it can have a direct effect on groundwater conditions in the main and basal Fox Canyon Aquifers, which are important sources of groundwater supply throughout the study area. The USGS used a precipitation-recharge relationship developed by the Santa Barbara County Water Agency in 1977 to estimate bedrock recharge in the USGS Santa Clara-Calleguas model study area ranging from a few hundred to a few thousand acre-feet per year, depending on annual rainfall (Hanson and others, 2003).

2.7.1.7 PERCOLATION OF TREATED WASTEWATER

Percolation of treated wastewater contributes a relatively small portion of recharge to the study area, estimated to be approximately 1,200 AF/yr, on average. Two small community WWTPs adjacent to the Santa Clara River in the study area, one in Saticoy (just west of Highway 118) and one in Montalvo (just west of US 101), discharge treated effluent to percolation ponds (Figure 2-17). The average annual volumes of effluent discharged to the percolation ponds are approximately 80 and 200 AF, respectively, based on reports provided by California's State Water Resources Control Board online database, GeoTracker (http://geotracker.waterboards.ca.gov/). The Saticoy WWTP is within the Forebay basin, where percolating water can directly recharge the UAS. The Montalvo WWTP is in the Oxnard Plain basin, where percolating water recharges the Semi-perched Aquifer, which is not used for water supply (it should be noted that the Montalvo WWTP ceased operating in 2016, subsequent to the VRGWFM calibration period). Treated effluent from other WWTPs in the study area is discharged to surface water bodies where it may subsequently interact with groundwater, as described in Section 2.3.

Recharge resulting from the diminishing number of remaining domestic septic systems in the Oxnard Plain, Pleasant Valley, and West Las Posas basins, as of 2015, was estimated by DBSA (2017a) to be:

- 324 AF/yr in the Oxnard Plain basin (including the Forebay)
- 115 AF/yr in the Pleasant Valley basin
- 341 AF/yr in the West Las Posas basin

DBSA's (2017a) investigation area did not include the Mound basin. There are estimated to be approximately 2,000 domestic septic systems distributed throughout the agricultural, undeveloped, and portions of the suburban lands within the study area, and are each estimated to recharge approximately 0.16 AF/yr, on average, as of 2015 (DBSA, 2017a). These estimated quantities of recharge (less than 1,000 AF/yr total, distributed across the entire study area) represent less than 1 percent of the estimated total recharge in the study area, and can be most effectively incorporated into a groundwater flow model implicitly with agricultural or municipal/industrial return flows, rather than attempting to simulate each domestic septic system as a distinct source of recharge.

Within the next few years, both the City of Oxnard and the City of Ventura are planning to test, and will likely implement, aquifer storage and recovery (ASR) projects that involve injection and extraction of a portion (several thousand acre-feet per year) of their treated wastewater effluent ("recycled water"), following advanced water purification and filtration (AWPF) processes. The City of Oxnard is also considering future recharge of AWPF-treated effluent at United's Saticoy spreading grounds. Details regarding volume and timing of such recharge efforts are uncertain at this time, but could involve a few thousand acre-feet recharged each winter, when demand for irrigation water for agriculture and municipal landscaping is low.

2.7.1.8 GROUNDWATER UNDERFLOW FROM SANTA PAULA AND EAST LAS POSAS BASINS

Underflow from the Santa Paula and East Las Posas basins is described in more detail (including references) in Section 2.8. To summarize the inflow components, groundwater underflow into the study area from Santa Paula basin has been estimated by previous investigators to be 1,800 to 7,400 AF/yr; underflow into the study area from East Las Posas basins has been estimated to be 700 to 1,900 AF/yr. Underflow estimates are typically subject to significant uncertainty and long-term variability; therefore, groundwater flow models, such as the VRGWFM, are often used to improve estimates of underflow.

2.7.1.9 SEAWATER INTRUSION

Within the study area, both the Oxnard Plain and Mound basins are adjacent to the Pacific Ocean; therefore, groundwater in these basins can discharge to the ocean (see Section 2.7.2), or seawater can enter the aquifer, depending on hydraulic gradients, as described further below. Mann (1959) estimated the net rate of seawater intrusion into the Oxnard Plain and Mound basins to be 12,000 AF/yr from WY 1946 through 1957. Considering the seaward hydraulic gradient reported at that time in the Mound basin, most of the seawater intrusion would have occurred in the Oxnard Plain basin. The USGS (Hanson and others, 2003) used groundwater flow modeling to estimate time-averaged "mean coastal flows" into and out of the UAS and LAS in the Oxnard Plain and Mound basins during a "pre-development" period and a "reported pumpage period" (1984 through 1993), as follows:

- Pre-development: 16,000 AF/yr of seaward flow in the UAS, and 2,900 AF/yr of seaward flow in the LAS
- 1984 through 1993: 950 AF/yr of seaward flow in the UAS, and 6,400 AF/yr of landward flow in the LAS

These "mean coastal flow" values from the USGS are simulated fluxes toward land or toward the ocean in each of the two USGS model layers (simulating the UAS and the LAS) at the coastline, not where the aquifers are simulated to crop out under the seafloor. Furthermore, these values integrate simulated inflows and outflows along the entire coastline, over multi-year periods. Therefore, although the values may approximately represent average rates of seawater intrusion or discharge of groundwater to the ocean in the study area (for the specific periods evaluated), they should not be considered to be directly comparable to actual fluxes of seawater into the aquifers at Port Hueneme and Mugu Lagoon, where seawater intrusion is known to have occurred. Groundwater elevations in the Semi-perched Aquifer are nearly always above sea level; therefore, groundwater in the study area generally discharges from the Semi-perched Aquifer to the Pacific Ocean.

Much of the most recent information on seawater intrusion that is summarized below was obtained from United's recent detailed report on the presence of saline water in the Oxnard Plain and Pleasant

Valley basins (United, 2016); details and supporting documentation can be found in that document. Additional interpretation of the timing and expansion of seawater intrusion in the study area is provided in the 2007 FCGMA groundwater management plan update (FCGMA and others, 2007). The primary cause of seawater intrusion in coastal aquifers of the UAS and LAS is formation of landward hydraulic gradients in areas where groundwater withdrawals have caused inland groundwater elevations to decline below sea level. The Pacific Ocean is effectively a constant-head source of potential seawater influx to the basins when groundwater elevations inland of the coast fall below sea level. Groundwater quality may also be degraded by chloride in isolated areas not directly affected by lateral seawater intrusion, due to upwelling of connate saline water from deeper formations or the compaction of marine clays within aquifers, usually as a result of declining groundwater levels. The Pleasant Valley basin appears to have brines that originate at greater depths, and some of the deeper wells in the basin routinely produce water with moderately-elevated chloride concentrations, not related to seawater intrusion.

The aquifers of the UAS and the LAS in the southern Oxnard Plain basin are particularly vulnerable to lateral seawater intrusion where the aquifers crop out below sea level in the Hueneme and Mugu submarine canyons (Figure 2-10). Such a situation allows direct interchange of groundwater with seawater. When and where the potentiometric head of groundwater in the aquifer is greater than that of seawater at the submarine outcrop, groundwater flows seaward and discharges to the ocean; when and where the potentiometric head in the aquifer declines below that of seawater, the flow direction is landward and seawater intrusion can occur. The aquifers of the UAS and LAS also crop out along the more gently sloping Ventura and Hueneme-Mugu Shelves, farther offshore (Figure 2-10). However, as noted by the USGS (Hanson and others, 2003), “submarine leakage through the tops of the upper- and lower-aquifer systems that crop out along the submarine shelf probably is small.” This is partly because these outcrops occur 1 to 7 miles offshore--distant from the supply wells that draw down groundwater levels beneath farms and cities on the Oxnard coastal plain--and partly because younger, fine-grained marine sediments overlie the aquifers where they outcrop on the submarine shelf, potentially reducing transmissivity at the interface between groundwater and seawater. Therefore, most lateral seawater intrusion into the aquifers is believed to originate in the submarine canyons (which are located near the shore and have steeper slopes than the outer shelves).

Available data further suggests that lateral seawater is not intruding directly into the LAS in the vicinity of Mugu Lagoon. The USGS model (which was used as a starting point for the VRGWFM) included faults in the Mugu Lagoon area that limit the hydraulic connection of the LAS in the Oxnard Plain basin to the Pacific Ocean (Hanson and others, 2003). Calibration of the VRGWFM, discussed later in this report, supports the USGS conceptual model regarding fault-related horizontal flow barriers in the Mugu Lagoon area that limit connection of the LAS to the ocean. In addition, United’s recent saline intrusion update report (United, 2016) interpreted the dominant source of elevated chloride concentrations in the LAS near Mugu Lagoon to be saline water yielded from marine clays and/or from adjacent Tertiary-age sedimentary rocks as a result of large declines in potentiometric head in the LAS over the past several decades, rather than direct lateral seawater intrusion through the aquifer.

High chloride levels were first detected in groundwater inland from the Hueneme and Mugu submarine canyons in the early 1930s (DWR, 1971) and became a wider concern in the 1950s. Historically, groundwater quality problems resulting from saline intrusion under the Oxnard coastal plain were limited to the aquifers of the UAS, from which most groundwater production occurred. Over time, production increased from the aquifers of the LAS as drilling technology improved and groundwater users recognized the value of the lower total dissolved solids (TDS) concentrations in some of the deeper aquifers, and as degradation continued in the UAS. Seawater intrusion is not a problem in the Semi-perched Aquifer, as essentially no groundwater pumping occurs in this aquifer and groundwater levels are normally above sea level, resulting in groundwater discharging from the Semi-perched Aquifer to the Pacific Ocean.

In fall 1975, potentiometric heads in the UAS and LAS across much of the southeastern Oxnard Plain and southern Pleasant Valley basin were below sea level. These conditions led the State Water Resources Control Board (SWRCB) to consider adjudication of water rights in the basins (SWRCB, 1979). To improve groundwater conditions without resorting to adjudication, the FCGMA was formed in 1983, and its initial goals were to bring the aquifers of the UAS into balance by the year 2000, and of the LAS by the year 2010 (FCGMA and others, 2007). Since 1983, major investments have been made in infrastructure to enhance recharge and convey surface water to areas with the greatest pumping depressions, importation of water from the State Water Project was increased, and programs to reduce groundwater pumping were implemented by the FCGMA, United, and Calleguas MWD. These actions achieved some degree of success at limiting and even reversing the extent of seawater intrusion in the UAS. However, groundwater levels in much of the LAS in the southern Oxnard Plain and Pleasant Valley basins has remained below sea level during the intervening years. As a result of drought conditions since 2012, groundwater elevations in large areas of both the UAS and LAS in the coastal basins declined to record or near- record low levels (below sea level) in 2016, exacerbating the potential for seawater intrusion (United, 2016).

Despite the efforts to mitigate the conditions that cause saline intrusion in the UAS and LAS, such conditions persist in the coastal areas of the southern Oxnard Plain basin. In wet and normal years since the mid-1990s, existing groundwater recharge facilities and surface water delivery pipelines generally have distributed enough water to maintain groundwater levels above sea level in the UAS. However, much of the existing water infrastructure is reliant on flow in the Santa Clara River to be effective. During periods of drought the recharge facilities and surface water distribution pipelines are largely idle for lack of surface water, and groundwater extraction lowers groundwater elevations in the basins. Following the recent four years of drought conditions, water levels are below sea level in the UAS in all but the most northerly portions of the coastal basins, and a new episode of seawater intrusion is degrading water quality in the coastal areas of the southern Oxnard Plain (United, 2016). Recent samples from UAS wells near Hueneme Canyon show increasing chloride concentrations. The Oxnard aquifer monitoring well near Mugu Canyon consistently records chloride concentrations near that of seawater. When groundwater levels in the UAS are eventually restored, much of the seawater that entered the UAS aquifers via Hueneme Canyon will likely be swept down the coast to the southeast by the prevailing groundwater gradients, and not exit via the same submarine outcrops by which it entered the groundwater flow system.

In recent decades there has been increased groundwater production from the aquifers of the LAS, and, as a result of the drought beginning in 2012, water levels are now as much as 180 feet below sea level in these deeper aquifer units. Areas with significant groundwater extraction from the LAS do not record water levels above sea level, even in the wettest of years. Chloride concentrations are rising steadily in many of the LAS monitoring wells surrounding Mugu Lagoon. This is believed to largely be a result of upwelling of connate saline water from deeper formations and the compaction of marine clays within aquifers in response to declining groundwater levels, together with downward migration of seawater-impacted groundwater from the UAS in the area, and migration of seawater-impacted groundwater from the Port Hueneme area. The inland extent of saline intrusion near Hueneme Canyon appears to be more limited than in the area surrounding Mugu Lagoon, as historic seawater "plumes" near Port Hueneme have been swept east during non-drought periods by prevailing southeastward hydraulic gradients. The locations of the existing monitoring wells may be poorly positioned to document intrusion moving east from Port Hueneme (United, 2016).

2.7.1.10 SUBSIDENCE

Subsidence has been recognized by the USGS both as a potential consequence of groundwater-level decline and as a potential source of groundwater inflow (as a result of release of groundwater from pore spaces during compaction of layers and lenses of fine-grained sediments present within the UAS and LAS) to the groundwater system in the study area (Hanson and others, 2003). Although subsidence is not incorporated into the current version of the VRGWFM, a subsidence package is available for MODFLOW-NWT and could be applied to a future version of the VRGWFM if needed to simulate effects of potential future groundwater-level decline. For the historical calibration period of the VRGWFM, land subsidence has not been reported to be a significant problem in the study area, and the quantity of groundwater released throughout the study area was estimated by the USGS to be relatively small (3,700 AF/yr, occurring primarily during the late 1980s drought) compared to total groundwater outflows (142,000 AF/yr). However, as noted by the USGS, land subsidence can be expected to continue "…when water levels drop below previous maximum declines" (Hanson and others, 2003).

The potential relationship between subsurface fluid extractions (e.g., groundwater and hydrocarbons) and inelastic land subsidence has been known for several decades (e.g., Poland and Davis, 1969). Subsidence associated with fluid withdrawals includes the permanent compaction of fine-grained sediments due to the increase in the effective stress caused by the fluid removal. This process also releases groundwater present in the pore spaces between these fine-grained sediments. The hydrologic record in the study area has been punctuated by drought periods, sometimes lasting 2 to 5 years or longer, that are indicated in the hydrologic record by extreme low groundwater elevations in the Oxnard Plain, Pleasant Valley, and West Las Posas basins. It is well known that low groundwater levels can be the causal force that initiates the compaction of fine-grained deposits. The propagation of compaction to, or near, the land surface can result in subsidence. However, once the fine-grained sediments have been compacted, there is a low probability for additional subsidence unless the groundwater elevations decline below the historical lows for a significant length of time (a few months to years, typically).

Hanson (1994) discuss the likelihood of three potential causal factors for measured land subsidence of 2.6 feet during the period from 1939 to 1978 along a coastal traverse in the study area:

- Extraction of oil, gas, and brines from deep formations: estimated to account for most of (1.5 to 2.0 ft) the measured subsidence.
- Groundwater extraction from the UAS and LAS: subsidence from this potential source is not quantified, but anecdotal reports of subsurface collapse of well casings, the need to relevel fields, and lowering of levees along Calleguas Creek are cited as "indirect evidence that subsidence may be related to groundwater withdrawals" (Hanson and others, 2003).
- Tectonic activity: Hanson (1994) opines that a benchmark on the southern edge of the Oxnard Plain (Z 583) suggests 0.17 ft of tectonic-caused subsidence from 1939 to 1978.

The USGS reported that "Although the amount of subsidence from various sources remains unknown, ground-water withdrawals and oil and gas production probably are major causes of subsidence in the Oxnard Plain subbasin, and tectonic activity probably is a minor cause," and that groundwater released from fine-grained sediments during subsidence "can be a significant additional one-time source of water…in aquifer systems" (Hanson and others, 2003). However, excessive rates of land subsidence (as a result of groundwater withdrawals) would only be expected to occur in the future if groundwater elevations declined substantially below historic lows (as seen in the 1960s, 1980s, and 2010s). More recently, DWR (2014) prepared a summary document dealing with recent, historical, and future subsidence potential for groundwater basins in California. The stated intent of the document was to provide screening-level information with respect to potential for subsidence. The Oxnard Plain basin is listed with a medium-high potential, the West Las Posas basin is listed as having a medium-low potential, and the Pleasant Valley and Mound basins are listed as having a low potential.

2.7.2 GROUNDWATER OUTFLOW

Within the study area, groundwater discharges to water-supply wells, man-made drains (tile drains, ditches, storm drains, and older sewer lines), streams, the atmosphere (via ET), and the Pacific Ocean. Each of these components of groundwater outflow from the study area is described in more detail below.

2.7.2.1 PUMPING FROM WATER-SUPPLY WELLS

Groundwater pumping from water-supply wells is, by far, the largest component of estimated groundwater discharges (or outflows) from the overall groundwater system in the study area, and comprises 100 percent of the net discharge from the UAS and LAS in the study area (some discharge from the UAS and LAS to the Pacific Ocean occurs, but this is countered over the long-term by seawater intrusion; therefore, net inflow of seawater is occurring rather than net discharge). The average annual volume of groundwater pumped from water-supply wells during the period from 1985 through 2015 in the Mound, Oxnard Plain, Forebay, Pleasant Valley, and West Las Posas basins (most of the study area) was 117,000 AF. An additional 3,000 AF/yr, on average were each pumped from the margins of the study area that are outside of the boundaries of these groundwater basins (e.g., the part of Santa Paula basin that is in the active domain of the VRGWFM), for a total average pumping rate of 133,000 AF/yr in the entire study area. The next largest discharge component is ET (estimated to be 15,000 AF/yr), followed by discharge to manmade drainage systems and to the Santa Clara River (discussed later in this section); these discharge components solely affect the Semi-perched Aquifer, not the UAS or LAS. Similar to artificial recharge rates, groundwater pumping rates have been reported to local agencies throughout the period of interest (1985 through 2015), meaning that both the dominant recharge and discharge components required for input to the VRGWFM are well known.

Construction of water-supply wells in the study area began in 1870, when the first of many artesian wells reportedly were drilled in the Oxnard Plain basin; by the 1920s, however, due to drought and extraction of groundwater during the previous decades, groundwater elevations in the area had declined to depths that required installation of deeper wells equipped with pumps (Freeman, 1968). The USGS estimated that groundwater extraction in the study area increased rapidly from the 1920s to the 1950s, based on the expansion of irrigated agriculture shown on land-use maps for the region (Hanson and others, 2003). Since 1980 and 1985, respectively, United and the FCGMA have required semi-annual reporting of pumping by well owners within their service areas, improving the accuracy of pumping estimates in the study area. These records show a sharp rise in pumping rates during the 1980s, followed by slightly lower pumping rates from the 1990s to present. Reported annual volumes of groundwater pumped from wells in the study area since 1985 (when both FCGMA and United records of pumping become available, corresponding to the start of the historical calibration period selected for the VRGWFM) are shown on Figure 2-21.

The locations and screened depths of water-supply wells in the Oxnard Plain and Pleasant Valley basins have shifted over time, largely in response to concerns about water quality—particularly seawater intrusion—but also in response to increasing urbanization of the region. Overdraft conditions and increasing seawater intrusion during a drought period from the late 1940s through the mid-1960s resulted in United constructing additional facilities to increase recharge to the aquifers and to decrease groundwater pumping in areas and aquifers most affected by seawater intrusion. In 1958, the PVP and a terminal reservoir were completed to deliver diverted surface water from the Santa Clara River to Pleasant Valley County Water District, which serves agricultural water to the portion of Pleasant Valley basin south of Highway 101. In 1986, United partnered with Ventura County to construct the PTP to convey Santa Clara River water to agricultural pumpers in the east-central area of the Oxnard Plain, thus reducing the amount of groundwater pumping in this critical area. A chronic pumping depression in the Oxnard Aquifer in this vicinity was a major concern, as these low water levels were expected to eventually draw saline water from the coastal areas to the center of the basin (SWRCB, 1979). In addition, five new wells were constructed to produce groundwater from the LAS, so that pumping in the UAS could be reduced. Although pumping the deep wells would exacerbate overdraft in the Fox Canyon Aquifer, the project was designed to address the more immediate concern of overdraft and saline intrusion in the UAS. In 2003, United constructed the Saticoy well field to pump down the groundwater mound that develops beneath the Saticoy recharge facility during periods of above-average recharge. Water pumped from the Saticoy well field is distributed to agricultural users on the PVP and PTP, in order to reduce pumping in those areas.

The FCGMA has been the agency with primary regulatory authority over groundwater extraction quantities in the Oxnard Plain (including Forebay), Pleasant Valley, and Las Posas basins since 1983. Their authority does not extend to the Mound basin. Following an allocation-establishment "base period" in the late 1980s, the FCGMA required a series of 5 percent pumping reductions, approximately every five years, to reduce pumping demands within its area of jurisdiction. Agricultural water users had the option of demonstrating efficient irrigation practices, thereby avoiding specified pumping reductions. Despite the implementation of these various measures to reduce pumping from the coastal basins, chronic overdraft conditions persisted in the aquifers of both the UAS and the LAS (FCGMA, 2015). In 2014, the FCGMA Board adopted Emergency Ordinance E, crafted in response to the severely depleted groundwater conditions in the coastal basins following a drought that began in spring 2011. Temporary extraction allocations were applied to wells within the FCGMA, adding additional pumping restrictions. In February 2015, Ventura County passed a well ordinance prohibiting the construction of new wells in overdrafted basins, including those within the study area. Construction of replacement wells is allowed, as the ordinance was intended to prevent increased groundwater use rather than to limit existing use.

Locations and relative magnitude of groundwater pumping as of 1985 and 2015 in the study area, from wells screened in aquifers of the UAS, LAS, and both systems, are shown on Figures 2-23 and 2-24. Groundwater pumping from the Semi-perched Aquifer is negligible. Many of the water-supply wells constructed in the study area are screened across multiple aquifers, because the objective of drilling a supply well is typically to yield a specified production rate of acceptable-quality groundwater, preferably without drilling any deeper than necessary (to minimize costs). Unfortunately, it can be difficult to delineate total groundwater pumping within each aquifer due to the large number of wells with screens that span multiple aquifers. Therefore, United generally maps pumping by system (UAS or LAS) rather than by individual aquifer. The most notable changes in pumping patterns from 1985 to 2015 are:

- Reduction in pumping from the UAS and a corresponding increase in pumping from the LAS in the south-central Oxnard Plain basin
- Reductions in pumping from the northeast and northwest quadrants of the City of Oxnard, where farms have been replaced by municipal and industrial development over the past 30 years

A small portion (relative to total recharge and discharge) of the groundwater withdrawn by water-supply wells in the study area is conveyed and used outside of the study area ("exported"). A long-term average of approximately 1,300 AF/yr of groundwater has been pumped from two water-supply wells operated by the Alta Mutual Water Company in the Forebay since the mid-1980s and exported to agricultural lands in and north of the Santa Paula basin. This is the single largest quantity of known groundwater exports from the study area. In addition, review of aerial photos suggest that a portion of the groundwater pumped from some wells just inside the study area boundaries may be used on nearby hillside orchards immediately outside of the study area along the northern margins of the Mound and West Las Posas basins, and the eastern margin of the Pleasant Valley basin. Agricultural return flows from these orchards most likely return to the study area as mountain-front recharge, meaning that the net effect of "exporting" the source water a short distance (typically less than ½ mile) to a hillside orchard would have little net impact on the water balance for the basin.

2.7.2.2 DRAINAGE

Tile drains were installed in the study area beginning in the early 20th century to remove shallow groundwater from the uppermost part of the Semi-perched Aquifer. Areas where tile drains are known or suspected to exist are shown on Figure 2-24. The long-term average discharge rate for groundwater via tile drains has been estimated to be approximately 8,000 AF/yr, while municipal drainage may account for another 700 AF/yr, as described below.

The surficial soils in the study area historically were alkaline due to poor drainage and evaporative concentration of salts. As a result, agricultural productivity was limited until 1918, when tile and other drainage systems began to be installed across much of the Oxnard coastal plain (Beller and others, 2011), leaching salts out of the soil and lowering groundwater levels below the root zone for row crops and orchards (Isherwood and Pillsbury, 1958). This improvement in drainage, combined with new pump technology, resulted in rapid expansion of irrigated agriculture during the subsequent three decades, and by 1947 over 93 percent of the irrigable area on the Oxnard coastal plain consisted of farmland (Isherwood and Pillsbury, 1958).

In 1958, Isherwood and Pillsbury noted that across the Oxnard coastal plain:

> *"Drainage from the area is accomplished by means of an extensive system of tile drains and a relatively small number of open ditches. Farm ditches are being replaced gradually by collector lines (Fig.1). The lateral tile lines usually discharge into collection lines from which the water flows to the district ditch system, thence to the ocean via one of the main drainage channels"* (clarified elsewhere in their report to be Revolon Slough and Calleguas Creek).

Figures in Isherwood and Pillsbury's (1958) report show tile drains and drainage ditches extending across nearly all of the Oxnard Plain and Pleasant Valley basins south of U.S. 101. Their study area did not extend north of U.S. 101. However, it can reasonably be assumed that other areas with shallow groundwater in the study area, most notably along the north bank of the Santa Clara River in the Mound basin and along Beardsley Wash in the far southwest portion of West Las Posas basin, likely also had some sort of drainage systems in place to reduce soil alkalinity and prevent waterlogging of the root zone for crops.

Reports specifying the depth of the tile drains installed in the study area were not found by United during a literature review, but tile drains are typically installed at depths ranging from 6 to 8 feet below land surface, to keep the water table below the root zone (personal communication, Jordan, 2015). Isherwood and Pillsbury (1958) installed 140 shallow (11-feet deep) piezometers at ½-mile spacing across the Oxnard coastal plain, and noted that "Mean depth to water (in the Semi-perched Aquifer) is 6.8 ft and shows little difference between January and June readings during the years 1953-1956." This depth to the water table in the Semi-perched Aquifer is consistent with installation of tile drains to depths ranging from 6 to 8 feet.

Since the Isherwood and Pillsbury (1958) investigation, the population of the Oxnard coastal plain has increased substantially, with a corresponding increase in land area developed for housing, commercial, and industrial uses, as discussed in Section 2.1. United staff have been told that the tile drains in the study area are typically destroyed when this land-use conversion occurs (personal communication, Smith, 2015). An extensive network of storm drains has been constructed within the Cities of Oxnard and Port Hueneme, many of which are observed to contain flowing water year round. Ingress of shallow groundwater into storm drains via weep holes, and into sewer lines via joints and cracks, likely occurs in developed areas within the study area, effectively acting in a similar manner to agricultural tile drains. Groundwater elevation data obtained from the state's Geotracker web site for the period from 1989 through 2015 indicates that Semi-perched Aquifer groundwater elevations in Oxnard and Port Hueneme are consistently about 8 feet below land surface, with little variation, consistent with Semi-perched Aquifer groundwater elevations in agricultural areas elsewhere on the Oxnard coastal plain. This similarity supports the occurrence of drainage in the Semi-perched Aquifer in municipal and industrial areas of the Oxnard coastal plain, as well as agricultural areas. Groundwater elevations in the Semi-perched Aquifer throughout the study area are discussed further in Section 2.9.

This smaller seasonal and annual variability of groundwater elevations observed in the Semi-perched Aquifer, compared to those in the UAS or LAS, in the Oxnard Plain and Pleasant Valley basins (described in Section 2.9) indicates that the drainage systems are very effective at removing recharge resulting from return flows and deep infiltration of precipitation, and that the Semi-perched Aquifer is poorly connected to the underlying aquifers of the UAS and LAS across much of the Oxnard coastal plain. Although some of the recharge that reaches the Semi-perched Aquifer migrates downward to deeper aquifers (Hanson and others, 2003) or discharges to naturally occurring surface-water bodies (see Sections 2.4 and 2.9), a substantial portion discharges to the tile and other drains in the study area.

Isherwood and Pillsbury (1958) estimated that discharge of irrigation return flows into agricultural drains in their investigation area 3, near Del Norte Boulevard and 5th Avenue, was approximately 1 acre-inch per acre (0.083 AF per acre) during a single irrigation cycle, with four irrigation cycles typically occurring per year. Agricultural land overlying the Oxnard Plain and Pleasant Valley basins combined was approximately 35,000 acres in 2015, suggesting that groundwater discharge to agricultural drains could presently be approximately 12,000 AF/yr, if Isherwood and Pillsbury's (1958) return-flow estimates from the 1950s were still applicable today. Given that the ITRC's (2010) evaluation suggests recent return flows across the Oxnard coastal plain are likely one-third smaller

(Section 2.7), discharge from agricultural drains could be closer to 8,000 AF/yr. Some of the recharge from irrigation returns and deep infiltration of precipitation that enters the Semi-perched Aquifer is known to migrate downward to aquifers of the UAS and LAS. Therefore, discharge from drains does not consist solely of irrigation return flows, and not all return flows discharge to drains.

United has not found references that provide estimates of the quantity of discharge to drains in areas of shallow groundwater within M&I portions in the study area (17,000 acres, primarily in the Cities of Oxnard and Port Hueneme). Water use per acre by the cities in the study area is about one-third less than water applied to agricultural land, and approximately half to two-thirds is typically applied to landscaping in most southern California cities, with the remainder being used indoors (ultimately directed to sewer lines and WWTPs). Therefore, it is likely that discharge of groundwater from the Semi-perched Aquifer to drains in municipal/industrial portions of the study area is smaller (on a per-acre basis) than discharge from tile drains in agricultural areas. Assuming the rate of M&I drainage per acre is half the rate of agricultural drainage, or 0.042 feet per year, then the total volume of M&I drainage would be approximately 700 AF/yr.

2.7.2.3 DISCHARGE TO STREAMS

As discussed in Section 2.3, shallow groundwater in the Semi-perched Aquifer discharges to natural surface-water bodies in the study area—the net discharge rate to most of these water bodies likely is small (less than a few hundred AF/yr), although they have typically not been quantified. However, a baseflow of 1,500 AF/yr has been estimated for the reach of the lower Santa Clara River below Victoria Avenue (Stillwater Sciences, 2017). The primary source of the shallow groundwater discharging to the Santa Clara River in this reach is agricultural return flows from irrigation of adjacent farmland (Figure 2-1).

2.7.2.4 EVAPOTRANSPIRATION (ET)

ET removes much of the water that falls as precipitation in Ventura County before it reaches the water table. The majority of ET occurs at land surface or within the root zone of the soil horizon, in the unsaturated zone. This near-surface ET does not directly affect groundwater levels or flow in the saturated zone, and thus is not explicitly included in most groundwater flow models. However, near-surface ET is included implicitly as part of net recharge calculations applied as input to the VRGWFM. Discharge of groundwater via ET from the saturated zone can occur where the water table is present at very shallow depths (typically within the upper 5 feet of the soil zone). Such conditions mostly occur in the study area where the Semi-perched Aquifer interacts with surface water bodies (Section 2.3), which is also where riparian vegetation is typically found in the study area. The U.S. Fish and Wildlife Service online "Wetlands Mapper" (https://www.fws.gov/wetlands/data/mapper.html) indicates that the combined area of riparian vegetation along stream channels within the study area, together with the coastal lakes and wetlands described in Section 2.3 of this report, could be as large as 4,600 acres (Figure 2-24). Applying the USGS estimates of ET rates as described below (1.1 to 5.2 feet per year) to this acreage results in calculated long-term annual average groundwater discharge as ET from the study area in the range from 5,100 to 24,000 AF/yr, with a midpoint of 15,000 AF/yr. It should be noted that nearly all of the riparian vegetation that takes up groundwater in the study area occurs in land overlying the Semi-perched Aquifer, which is rarely, if ever, pumped as a source of agricultural or M&I water supply.

Hypothetically, ET could also discharge groundwater from the aquifers of the UAS and LAS where they outcrop at land surface in the Forebay, West Las Posas, and parts of the Pleasant Valley basins, but only in the situation where groundwater in these aquifers occurs within approximately 5 feet of land surface. This situation is rare in the study area and is not known to result in discharge of a significant quantity of groundwater. Roots of some trees take up water at depths greater than 5 feet, but the quantities are minor compared to the volumes of water evaporated from near-surface soil or taken up and transpired by the shallow-rooted crops, landscaping, and other vegetation that occur across most of the study area. Similar to deep infiltration of precipitation, ET is variable over time and location, since it is highly dependent on complex interactions between many of the same climate, soil, hydrologic, and vegetation inputs. Therefore, estimates of ET at a given location or time are typically subject to substantial uncertainty similar to deep infiltration of precipitation. Unlike deep infiltration of precipitation, discharge of groundwater as ET occurs primarily where (and when) groundwater is present within approximately 5 feet of land surface, whereas deep infiltration of precipitation can occur virtually any place or time where land surface is permeable. Within much of the study area, depth to the water table in the shallow aquifer system is maintained 6 to 8 ft bgs, which is below the root zone of most plants, by tile drains or other drainage systems, and can occur as deep as 150 ft bgs where the Clay Cap is not present. Therefore, the locations where ET can directly remove groundwater from the saturated zone of aquifers within the study area are limited, as are the potential volumes of groundwater discharge as ET.

The USGS estimates of average annual ET rates for the study area ranged from 1.1 to 5.2 feet per year, all assumed to occur within riparian zones and floodplains along the Santa Clara River and Calleguas Creek (Hanson and others, 2003). This range of estimated ET rates is consistent with the reported annual average pan evaporation rate of 63.2 inches (5.3 feet) on the Oxnard coastal plain (Section 2.2)—80 percent of the pan evaporation rate is generally considered to be representative of the maximum evaporation rate possible from an open water body. Transpiration from phreatophytic plants around such water bodies could make total ET somewhat higher than this value. Where groundwater does not discharge directly to land surface, actual ET rates can be expected to be less than the maximum (open water) evaporation rate, declining to small values in areas where the water table is deeper than 5 feet (the limit of most plant roots as well as the effects of direct evaporation of soil moisture to the atmosphere). The area of riparian zones and floodplains along the Santa Clara River and Calleguas Creek watersheds as of 1969 was estimated by the USGS to be 2,265 acres (Hanson and others, 2003); however, that estimate included stream reaches beyond the current study area of the VRGWFM. The USGS did not consider ET from wetlands and surface water bodies fed directly by the Semi-perched Aquifer, which was not explicitly simulated in their model.

DBSA (2017a) estimated the annual average volumes of groundwater removed via ET by riparian vegetation in the Pleasant Valley and West Las Posas basins to be approximately 1,700 and 700 AF/yr (rounded to the nearest 100 AF/yr), respectively, based on the following data and assumptions:

- 4 ft/yr of ET from native riparian vegetation
- 24 ft/yr of ET from non-native *Arundo donax* (arundo)
- 274 acres of riparian vegetation in the Pleasant Valley basin, 20 percent of which consists of arundo
- 138 acres of riparian vegetation in the West Las Posas basin, 10 percent of which consists of arundo

DBSA (2017a) did not estimate ET from riparian vegetation in the Oxnard Plain basin (because virtually all groundwater discharge as ET from the Oxnard Plain basin is assumed to occur in the Semi-perched Aquifer), or from the Mound basin (which was outside of their study area).

2.7.2.5 GROUNDWATER DISCHARGE TO THE OCEAN

As described in Section 2.7.1, groundwater in the Oxnard Plain and Mound basins can discharge to the Pacific Ocean when and where the potentiometric head of groundwater in the aquifer is greater than that of seawater at the submarine outcrop. During most of the latter half of the 20th century, a net influx of seawater has occurred in the UAS and LAS, particularly near the heads of the Mugu and Hueneme submarine canyons (Section 2.7.1). Small volumes of groundwater may discharge to the ocean in the Mound and northwestern Oxnard Plain basins during periods of relatively high groundwater elevations (discussed further in Sections 2.8.1), but such outflows have not previously been quantified.

Groundwater elevations in the Semi-perched Aquifer are nearly always above sea level; therefore, groundwater in the study area would be expected to discharge from the Semi-perched Aquifer to the Pacific Ocean. The rate of such discharge has not been studied extensively because groundwater in the Semi-perched Aquifer is not typically considered an important water resource (due to its poor quality). Quantification of groundwater discharge from the Semi-perched Aquifer to the ocean may prove difficult using traditional approaches (based on hydraulic gradients and conductivities) because of the complicating effects of tidal reversals and groundwater discharge via ET in the coastal surface-water bodies and wetlands that occur along much of the coastline in the study area.

2.8 GROUNDWATER OCCURRENCE AND MOVEMENT

This section summarizes the observed effects that the hydrostratigraphic framework, coupled with groundwater recharge and discharge have had on groundwater occurrence and movement within the basins and subbasins of the study area, focusing primarily on the historic calibration period of the VRGWFM, 1985 through 2015. Details regarding historical groundwater conditions in the study area are provided by Mukae and Turner (1975) and Mann (1959). In addition, Hanson and others (2003) estimated groundwater levels and movement in Ventura County from predevelopment to the early 1990s, based on data synthesis and modeling.

2.8.1 GROUNDWATER ELEVATIONS

Hydrographs showing changes in groundwater elevations over time, combined with maps showing typical groundwater elevations, can help illustrate groundwater occurrence and movement in an aquifer system. Accordingly, hydrographs for selected representative wells in each groundwater basin in the study area are shown on Figures 2-25, 2-26, and 2-27. A location map for selected wells in the Semi-perched Aquifer is provided on Figure 2-28, and groundwater-elevation contour maps prepared by United staff for the UAS and LAS in fall 2012 are provided on Figures 2-29 and 2-30. Groundwater-level contours for the UAS and LAS during fall 2012 were selected for inclusion in this report because 2012 was the most recent year when groundwater elevations were not extensively influenced by anomalously wet or dry conditions. Fall is the period when groundwater elevations in the study area are typically at seasonal lows, and 2012 is now recognized as the first year of an exceptional drought throughout California. However, inspection of the hydrographs shown on Figures 2-26 and 2-27 indicates that groundwater elevations during fall 2012, while slightly lower than long-term averages, were still within their typical ranges. Therefore, the groundwater-level contour maps shown on Figures 2-29 and 2-30 are suitable for their intended purpose in this report, which is to provide the reader with a conceptual representation of recent "typical" hydraulic conditions in the UAS and LAS across the study area (those portions with sufficient data for contouring). Insufficient data were available for United to interpolate groundwater elevation contours for 2012 in the Semi-perched Aquifer across most of the study area. However, comparison of land-surface elevations to groundwater elevations at wells screened in the Semi-perched Aquifer where the Clay Cap exists, as shown on Figure 2-31, indicates a close correlation exists. Specifically, the depth to groundwater measured in most wells screened in the Semi-perched Aquifer consistently occurs at depths of 5 to 10 feet below land surface, as discussed further below.

2.8.1.1 SEMI-PERCHED AQUIFER

Most of the groundwater-level data available for the Semi-perched Aquifer in the study area were obtained from monitoring wells installed during the 1990s at leaking underground storage tank (UST) remediation sites associated with fueling facilities. Monitoring wells at these sites are typically screened to depths of just 5 to 40 feet below "first water," which is within the Semi-perched Aquifer in much of the study area. These groundwater elevation data were downloaded by United from the California State Water Resources Control Board's (SWRCB) "GeoTracker" on-line database (https://geotracker.waterboards.ca.gov/). Many of these leaking UST sites closed or reduced their frequency of monitoring after 2009 in response to SWRCB Resolution 2009-0042. The pace of site closures increased further after California adopted a low-threat UST closure policy in 2012. Because of the site closures and reductions in monitoring frequency associated with these policy changes, the availability of groundwater elevation data from the Semi-perched Aquifer diminished rapidly after 2009. United attempted to obtain widely-distributed (spatial and temporal) groundwater elevation data from the Semi-perched Aquifer, trying to avoid both "clustering" (excessive data over a small area or timeframe) and large gaps between data points. Data were commonly available for three to twenty (and occasionally more) monitoring wells at each UST or other remediation site in GeoTracker, and most sites were smaller than 1 acre in area. A review of the available data indicated that groundwater elevations within the Semi-perched Aquifer varied little (from a few inches or feet) across each site. Therefore, data from only one or two representative wells at each site were downloaded by United. There were many UST or other remediation sites in urban and suburban areas, typically clustered on multiple corners of a street intersection, or aligned along a single street in a business district. There were very few sites with available data in agricultural areas. Unfortunately, no useful data (for this evaluation) were available for the period from 1985 through 2015 in the West Las Posas basin.

As can be seen on Figure 2-25, groundwater elevations at most wells screened in the Semi-perched Aquifer varied by less than 3 feet on a seasonal basis, and less than 10 feet between longer-term dry and wet periods. Groundwater levels in the Semi-perched Aquifer vary least in the Oxnard Plain and western Pleasant Valley basins, where the Clay Cap is present, and vary most near the margin of the Forebay, in the Mound basin, and in northeastern Pleasant Valley basin, where the aquitard between the Semi-perched Aquifer and underlying aquifers consists of discontinuous silts and clays. Where the Clay Cap is absent, the water table in the shallow aquifer system is typically deeper, tile drains are less likely to be needed or present, and the hydraulic connection to underlying aquifers is greater, resulting in larger variations in groundwater elevation.

Where the Clay Cap is present, groundwater elevations in the Semi-perched Aquifer have a high degree of correlation with land-surface elevations, as shown on Figure 2-31. This figure indicates that groundwater elevations are consistently about 5 to 10 feet below land surface (average is 8.6 feet below land surface) in the Semi-perched Aquifer, excluding wells that are located along the margins of the Forebay, in the Mound basin, West Las Posas basin, and northeast Pleasant Valley basin, where the Clay Cap is missing and where the uppermost aquifer consists of discontinuous silt and clay lenses. Near the coastline, groundwater elevations in the Semi-perched Aquifer tend to fall in the range from +2 to +5 ft msl, sufficiently above sea level to suggest that discharge from the Semi-perched Aquifer to the ocean generally occurs, rather than seawater intrusion into this aquifer.

The close correlation between groundwater elevations and land-surface elevations, as well as the stability of groundwater elevations, in the Semi-perched Aquifer across most of the Oxnard coastal plain is largely a result of two factors. First, the Clay Cap provides a degree of hydraulic separation between the Semi-perched Aquifer and the underlying Oxnard Aquifer; therefore, the large variations in groundwater elevations occurring in the Oxnard Aquifer as a result of United's recharge operations as well as pumping for agricultural and municipal supply have little effect on groundwater levels in the Semi-perched Aquifer. Second, subsurface tile drains and other drainage systems installed across the Oxnard coastal plain (see Section 2.8) quickly remove pulses of recharge that would otherwise cause groundwater elevations in the Semi-perched Aquifer to rise closer to land surface than the typical depth of 5 to 10 feet.

2.8.1.2 UPPER AQUIFER SYSTEM

Early newspaper accounts suggest that the confined aquifers of the UAS on the Oxnard coastal plain were first drilled for water supply wells in the early 1870s. Artesian conditions existed on the Oxnard coastal plain at this time, persisting through the turn of the century. However, the water demands associated with expanding irrigated agriculture on the plain, along with the growing population and industrial demand, lowered the artesian pressure in the UAS. By the early 1900s, widespread artesian conditions were generally absent, requiring wells to be fitted with pumps to lift water from below land surface (Freeman, 1968). Since that time, artesian conditions have periodically returned to parts of the Oxnard Plain basin during wet climatic cycles. Documentation of groundwater levels in the aquifers of the Oxnard Plain basin are sparse until the early 1930s, but artesian conditions were documented in Oxnard city well #9 during the winters of 1917, 1919, 1922 and 1923 (Jamison, 1928). The early 1940s was a wet period, and widespread artesian conditions likely existed at that time. The year 1945 marked the beginning of a long dry period during which water levels fell across the Oxnard coastal plain. Widespread artesian conditions were again present in the UAS on the Oxnard coastal plain in the late 1990s following the completion of the Freeman Diversion and high precipitation totals in 1992, 1995 and 1998. As recently as the 2000s, artesian conditions periodically existed in coastal areas surrounding Port Hueneme and in the northwest Oxnard Plain, and are more common in UAS wells than in wells with deeper screened intervals. As can be seen on Figure 2-26, groundwater elevations at most wells screened in the UAS fluctuate 5 to 20 feet seasonally, and 40 to 100 feet between longer-term dry and wet periods. During the calibration period of the VRGWFM (1985 through 2015), the effects of two major droughts can be seen in groundwater elevations shown on these hydrographs, with significant groundwater-level declines in the late 1980s and early 2010s.

Groundwater elevation contours for the UAS in fall 2012 are shown on Figure 2-29. In the UAS across most of the study area, groundwater elevations in the Mugu Aquifer are similar to or a few feet lower than those in the Oxnard Aquifer. On the southern Oxnard Plain, and most notably in the area surrounding Mugu Lagoon, groundwater levels in the Mugu Aquifer may be as much as 30 feet lower than in the Oxnard Aquifer. Figure 2-29 indicates groundwater flow occurring radially from recharge areas in the Forebay to surrounding areas. Recharge from the Forebay serves to raise or sustain water levels in wells on the Oxnard Plain, countering the decline in groundwater elevations resulting from groundwater extractions. When groundwater levels are high across the study area, groundwater may flow past the coastline to the offshore extension of the aquifers, or exit the system at near-shore submarine canyons as discharge to the sea. By fall 2015, 3 years into an exceptional drought, UAS groundwater elevations were below sea level across much of the Oxnard Plain and Pleasant Valley basins. The hydraulic gradient in the interior of the basin was still nearly flat, and the lowest Oxnard Aquifer water levels were recorded in the Forebay near United's El Rio spreading grounds where the O-H well field is in operation (United, 2017a).

2.8.1.3 LOWER AQUIFER SYSTEM

Strategies implemented in the past to mitigate saline intrusion in the UAS in the Oxnard Plain basin included delivery of surface water to agriculture with the goal of reduced groundwater pumping (starting in the 1950s), and a shift of pumping from the UAS to the LAS (starting in the 1980s). These mitigation strategies raised groundwater levels in the UAS, but did not help with overdraft in the LAS. As can be seen on Figure 2-27, groundwater elevations at most wells screened in the LAS fluctuate 10 to 60 feet seasonally, and 50 to 100 feet between longer-term dry and wet periods. Similar to groundwater levels in the UAS, the effects of droughts in the late 1980s and early 2010s are apparent in these hydrographs.

Groundwater elevation contours for the LAS in fall 2012 are shown on Figure 2-30; these contours indicate groundwater flow occurring radially from recharge areas in the Forebay to surrounding areas, similar to the UAS. A “mound” of groundwater associated with recharge of surface-water flows in the Arroyo Las Posas has also been observed in the northern Pleasant Valley basin, under the City of Camarillo. Groundwater elevations in the LAS in this area rose from -140 ft msl in 1993 to +120 ft msl in 2012, and then gradually decreased to +40 ft msl in 2015 in response to diminishing flows in Arroyo Las Posas (Bachman, 2016). By fall 2015, groundwater elevations in the LAS were below sea level throughout most of the Oxnard Plain and Pleasant Valley basins. The highest groundwater levels were recorded in the northern Forebay and the northern Pleasant Valley basins, which are areas of recharge. An area of more than three square miles had groundwater elevations deeper than -150 ft msl. LAS groundwater elevations at the coast near Mugu Lagoon were measured at -98 ft msl. LAS piezometers surrounding Port Hueneme recorded groundwater levels ranging from -19 to -40 ft msl (United, 2017a).

2.8.2 GROUNDWATER FLOW CONDITIONS SUMMARIZED BY BASIN

Although the groundwater basins in the study area are interconnected, they have distinctive characteristics that can affect the occurrence and movement of groundwater within each basin. This section summarizes groundwater flow conditions in each groundwater basin or subbasin.

2.8.2.1 FOREBAY SUBBASIN

The Forebay subbasin occupies 10 square miles of the northern portion of Oxnard Plain basin and is where most of the groundwater recharge to the Oxnard Plain basin occurs. Recharge in the Forebay benefits all of the other basins in the study area (Oxnard Plain, Mound, West Las Posas, Pleasant Valley). The shallow sediments of the Forebay are dominated by coarse-grained, permeable alluvial deposits of the ancestral Santa Clara River. The distinguishing feature of the Forebay is the absence of the Semi-perched Aquifer and Clay Cap. This allows unimpeded groundwater recharge of the UAS. In the area of the Forebay between United’s Saticoy and El Rio recharge facilities, the LAS has been uplifted and truncated along its contact with the UAS (Mann, 1959). This allows rapid transmission of recharge to the underlying LAS. In the southern portions of the Forebay the LAS becomes more hydraulically isolated from the UAS.

Reported extractions of groundwater from the Forebay in 2015 totaled 19,400 acre-feet, which was 21 percent less than the average annual extraction rate of 24,600 AF/yr (1985 through 2015). United's O-H well field is the largest pumping center in the basin, delivering water to coastal areas for M&I use as part of a management strategy to move pumping away from coastal areas vulnerable to saline intrusion. As of 2015, approximately 62 percent of pumping in the Forebay was from the UAS, 26 percent was from the LAS, and 12 percent was from wells screened in both the UAS and the LAS.

During 2015, only 2,645 acre-feet of water was spread (artificially recharged) at United's spreading grounds in the Forebay (in contrast to an average of 48,000 AF/yr of artificial recharge on average since construction of the Freeman Diversion in 1991). United artificially recharges nearly twice as much water per year, on average than is withdrawn from wells in the Forebay. Natural infiltration of surface water from the Santa Clara River and deep percolation of rainfall and return flows provide additional recharge in the Forebay.

Changes in groundwater elevation in the Forebay affect hydrostatic head in the confined aquifers extending from the margins of the Forebay, through the Oxnard Plain basin, to the coastal and offshore portions of the aquifers of the UAS and LAS. Higher groundwater levels in the Forebay associated with wet periods, such as those that occurred during the late-1990s and mid-2000s, are beneficial, as they maintain seaward hydraulic gradients from the Forebay to coastal areas. In the dry conditions that have prevailed since 2012, groundwater elevations in the Forebay have fallen to record lows, resulting in flattened hydraulic gradients and only minor groundwater flow out of the Forebay. Groundwater underflow ***into*** the Forebay occurs from the Santa Paula basin. The quantity of inflow is limited to some degree by relatively low horizontal hydraulic conductivities across the Oak Ridge and Country Club faults, which form the boundary between these two basins. Mann (1959) estimated average groundwater underflow from the Santa Paula basin to the Forebay for WY 1937 through 1957 to be approximately 1,800 AF/yr. DBSA (2017b) estimated underflow from the Santa Paula basin to the Forebay for WY1999 through 2012 to be much greater, at 7,400 AF/yr. This large difference in underflow estimates may be partly due to different hydrogeologic conditions during the different timeframes evaluated, and partly due to different assumptions regarding the conceptual model for groundwater flow from Santa Paula basin to the Forebay.

2.8.2.2 OXNARD PLAIN BASIN

The Oxnard Plain basin (excluding the Forebay) occupies approximately 75 square miles of the Oxnard coastal plain (Figure 2-1). The aquifers of the Oxnard Plain basin are continuous with those of the Forebay, described above; however, the Clay Cap and Semi-perched Aquifer overlie the principal aquifers across most of the Oxnard Plain basin, limiting direct hydraulic connection between land surface and the underlying aquifers. The tile drains and other drainage systems constructed across much of the Oxnard coastal plain further limit hydraulic connection from land surface to the underlying aquifers of the UAS and LAS. Therefore, the largest source of recharge for these aquifers in the Oxnard Plain basin is lateral groundwater flow from the Forebay, rather than deep percolation of rainfall or irrigation return flows directly on the Oxnard coastal plain. While the physical movement of groundwater out of the Forebay is fairly slow, the pressure response in the confined aquifers of the Oxnard Plain basin is rapid. When groundwater elevations are below sea level along the coastline, there can be significant lateral inflow of seawater into the aquifers, mixing with or displacing fresh water (United, 2016). In areas near Port Hueneme and Mugu Lagoon, where submarine canyons extend nearly to the coastline, the fresh-water aquifers are likely in direct contact with seawater a short distance offshore. Consequently, these are areas where seawater intrusion has historically been observed.

Vertical gradients commonly exist between aquifers in the Oxnard Plain basin, resulting in some degree of vertical groundwater movement through low-permeability aquitards that occur between the major aquifers. When LAS groundwater levels are substantially lower than UAS groundwater levels (creating a downward gradient), there is leakage of UAS groundwater into the LAS through the various aquitards that separate the aquifer units, through wells that are screened across both aquifer systems, and in areas where the aquitards are thin or absent (areas of mergence). Likewise, a downward gradient can exist between the Semi-perched Aquifer and the Oxnard Aquifer when hydraulic heads in the Oxnard Aquifer are lowered, either regionally by drought conditions or locally by pumping wells. The movement of poor quality groundwater from the Semi-perched Aquifer to the Oxnard Aquifer has been documented in some locations, with abandoned or improperly constructed wells being a notable pathway for this downward flow (Izbicki and others, 1992; Stamos and others, 1992; Predmore, 1993). Conversely, during rare periods of artesian conditions, upward vertical gradients may exist between deeper confined aquifers and the Semi-perched Aquifer.

Deposits comprising the aquifers of the LAS are generally finer-grained than those of the UAS, resulting in lower hydraulic conductivities, and have been more extensively deformed by folding and faulting. An uneven distribution of pumping, along with structural and stratigraphic changes within the LAS, results in varied hydraulic heads among the deep wells across the Oxnard Plain. Faulting and uplift associated with the Sycamore fault, and changes in LAS stratigraphy, are believed to prevent or limit direct contact of the LAS with seawater in the area offshore from Mugu Lagoon (Izbicki, 1996; Hanson and others, 2003).

Reported 2015 groundwater extractions from the Oxnard Plain basin totaled 59,600 acre-feet, which was 8 percent greater than the long-term average annual extraction rate of 55,200 AF/yr (1985 through 2015). Groundwater withdrawals from the Oxnard Plain basin are somewhat variable, with less demand in years when surface water is available for agricultural water supply (via the PTP). Water supply wells are common throughout the agricultural areas of the Oxnard Plain basin, with few wells located in the City of Oxnard. In the western part of the Oxnard Plain basin most of the pumping occurs from the UAS, while in the eastern part of the Oxnard Plain basin most of the pumping occurs from the LAS (Figure 2-23).

2.8.2.3 PLEASANT VALLEY BASIN

The Pleasant Valley basin, with an area of 33 square miles, is bounded to the south and east by the Santa Monica Mountains, to the north by the Camarillo Hills, and to the west by the Oxnard Plain basin (Figure 2-1). The Bailey fault is a major structural feature that trends NE near the base of the Santa Monica Mountains, and the Springville fault bounds the basin along the Camarillo Hills to the north (Figure 2-10). The Pleasant Valley basin is differentiated from the Oxnard Plain basin by a general lack of productive UAS aquifers (Turner, 1975). In Pleasant Valley basin, much of the UAS is fine grained and not extensively pumped for groundwater supply (Turner, 1975; Hanson and others, 2003). UAS deposits in the Pleasant Valley basin are approximately 400 feet thick and consist of sediments from the Calleguas Creek watershed, a smaller and less mountainous drainage than that of the Santa Clara River, which deposited the coarser UAS deposits of the Oxnard Plain basin. Some coarse-grained UAS deposits do exist in the Pleasant Valley basin, but these deposits tend to be thin or discontinuous. For this reason, limited pumping in the Pleasant Valley basin occurs from wells screened in the UAS (Figure 2-23).

The LAS in the Pleasant Valley basin is composed of the Hueneme, Fox Canyon, and Grimes Canyon Aquifers to depths greater than 1,500 ft. The Hueneme Aquifer is relatively thin in the Pleasant Valley basin and composed of alternating layers of sand and finer-grained deposits. The Fox Canyon and Grimes Canyon Aquifers are composed of thick sequences of relatively uniform marine sand. The Fox Canyon Aquifer is the major water-bearing unit in the Pleasant Valley basin. In Pleasant Valley basin the LAS is surrounded and underlain by partly consolidated marine deposits and volcanic rocks, which typically do not yield a sufficient quantity or quality of groundwater to wells for most uses.

Under pre-development conditions in the Pleasant Valley basin, groundwater movement was likely from recharge areas in the northeast toward the Oxnard Plain basin to the southwest. Groundwater underflow into the Pleasant Valley basin occurs from the East Las Posas basin through the “Somis Gap” in the Camarillo Hills, along the northern boundary of Pleasant Valley basin. Recent groundwater modeling by Intera Geoscience and Engineering Solutions (2017) suggests that the average rate of underflow from the East Las Posas basin to the Pleasant Valley basin was approximately 700 AF/yr in 1983, increasing to approximately 1,900 AF/yr by 2000 (due to increased wastewater discharges in upstream basins), and then declining to 1,400 AF/yr by 2015 (in response to the recent drought and conservation measures that reduced upstream wastewater discharges). Little groundwater underflow occurs from Santa Rosa basin to the Pleasant Valley basin due to the presence of shallow bedrock that acts as a flow constriction between the basins. The rate and direction of groundwater underflow between the Oxnard Plain and Pleasant Valley basins is variable over time, location, and depth, largely as a result of variations in recharge rates and groundwater withdrawals that have occurred in each basin over seasonal to multi-year time frames.

Reported 2015 groundwater extractions from the Pleasant Valley basin totaled 17,800 acre-feet, which was 14 percent greater than the average annual extraction rate of 15,600 AF/yr (1985 through 2015). Most water-supply wells in the Pleasant Valley basin are screened in the LAS (Figure 2-23), due to the abundance of fine-grained sediments and discontinuous nature of the UAS in the Pleasant

Valley basin. Similar to the Oxnard Plain basin, groundwater withdrawals from the Pleasant Valley basin are somewhat variable, with less demand in years when surface water is available for agricultural water supply (via the PVP and from Conejo Creek). Also similar to the Oxnard Plain basin, water supply wells are common throughout the agricultural areas of the Pleasant Valley basin, with a lower density of wells in the City of Camarillo.

Over the previous two decades, groundwater levels recorded in at least two wells in northern Pleasant Valley basin rose more than 250 feet (United, 2017a). The degree to which this large recharge mound serves to recharge the LAS in the central portion of the basin is not well established, as the distribution of wells available for groundwater-level monitoring in the northern Pleasant Valley basin is limited. The City of Camarillo has plans to construct a large-scale desalter to treat and utilize this groundwater, which tends to be more mineralized than the older and deeper groundwater native to the basin. This groundwater mound has decreased in size since 2012 as flow in Arroyo Las Posas has diminished.

2.8.2.4 MOUND BASIN

The principal fresh water-bearing strata of the Mound basin are the upper units of the San Pedro Formation and the overlying Pleistocene-age deposits that are interpreted to be correlative with the Mugu Aquifer of the Oxnard Plain basin. These strata extend several miles westward offshore from the coast, and are overlain and confined by Pleistocene-age clay approximately 300 feet in thickness. The sediments of the basin have been warped into a syncline (Ventura-Santa Clara River syncline) that is oriented in an east-west direction approximately parallel to Highway 126 (Figure 2-10). Structural disruption along the Oak Ridge fault in the southern portion of the basin has resulted in considerable uplift and erosion of the San Pedro Formation and younger sediments. This disruption is the cause of the topographic “mounds” near the intersection of Victoria Avenue and U.S. 101, for which the basin is named. The Montalvo anticline (Figure 2-10) has traditionally been used to define the southern extent of the basin. These structural features generally offset only the deeper LAS units of the adjacent Oxnard Plain basin. The deposits of the UAS overlie the faults and folds along the southern margins of the Mound basin, but the character of the deposits change as they extend to the north, becoming more thin-bedded and fine-grained (United, 2012).

The limited number of wells in the Mound basin, especially in the northern half of the basin, complicates efforts to ascertain its primary sources of recharge. The USGS (Hanson and others, 2003) indicated that some mountain-front (bedrock) recharge to the Fox Canyon Aquifer occurs as a result of precipitation falling on San Pedro Formation outcrops in the hills along the northern margin of the Mound basin (Figure 2-10), as discussed in Section 2.7. There is general agreement that the basin benefits from groundwater underflow from the Forebay and Oxnard Plain to the south, especially during periods of high groundwater levels in the Oxnard Plain basin and from Santa Paula basin, to the east (Geotechnical Consultants, Inc., 1972; Fugro West, Inc., 1996; United 2012). Mann (1959) suggested that there is little underflow from the Santa Paula basin to the Mound basin, although more recent studies suggest it may be significant (Fugro West, Inc., 1996; United, 2012; DBSA, 2017b).

Reported 2015 groundwater extracted from the Mound basin totaled 6,600 acre-feet, which was 12 percent less than the average annual extraction rate of 7,500 AF/yr (1985 through 2015). Locations for water-supply wells in the Mound basin are shown on Figure 2-23.

Groundwater flow in the Mound basin is generally to the west and southwest. The limited number and distribution of wells with groundwater-level records complicates efforts to contour groundwater elevations in the basin. During periods of drought and increased pumping, an elongate pumping depression forms in the southern portion of the basin that significantly modifies groundwater gradients. Groundwater elevations fall below sea level in this area during dry periods, creating a landward hydraulic gradient and groundwater flux, but saline intrusion has not been observed in the Mound basin to date. Fresh groundwater is likely present in the offshore portions of the aquifers extending south and west from the Mound basin; when landward hydraulic gradients form in the basin during dry periods, fresh water is drawn inland rather than seawater. The volume of fresh water present in aquifers offshore from the Mound basin is uncertain.

2.8.2.5 WEST LAS POSAS BASIN

The West Las Posas basin is located east of the Oxnard Plain basin, between South Mountain and the Camarillo Hills (Figure 2-1). The West Las Posas basin mostly consists of a broad alluvial plain sloping to the south, and approximately three quarters of its surface watershed area is drained by Beardsley Wash, which flows southwest to the Oxnard Plain basin. The eastern one-quarter of the watershed drains southeast to the Arroyo Las Posas, then into the Pleasant Valley basin through the Somis Gap. Tree crops (orchards) are the dominant land use in this agricultural area.

Most groundwater production in the West Las Posas basin is from the LAS (Figure 2-23). Reported 2015 groundwater extraction from the West Las Posas basin totaled 15,800 acre-feet, which was 9 percent greater than the long-term average annual extraction rate of 14,500 AF/yr (1985 through 2015). The UAS is present only along the western margin of the West Las Posas basin.

Beneath most of the Las Posas Valley (including the West and East Las Posas basins), the upper San Pedro Formation consists of low permeability sediments with lenses of permeable sediments which are age-equivalent to the Hueneme Aquifer of the Oxnard Plain basin (DWR, 1975b). The permeable lenses form isolated, yet locally important, water sources. The water-bearing zones in the upper San Pedro Formation do not appear to be well connected. Some recharge to the deeper Fox Canyon Aquifer may result from downward leakage from the upper San Pedro Formation. Mukae (1988) wrote that many wells in the West Las Posas basin are screened in the Fox Canyon Aquifer, making it the principal water-bearing unit, but United’s mapping of HSUs in the basin includes extensive mapping of the Grimes Canyon Aquifer, most notably in the southern portion of the basin (which may have been mapped as Fox Canyon Aquifer by Mukae, 1988). The Fox Canyon Aquifer is exposed almost continuously along the southern flank of South Mountain. South of the outcrop, beds of the Fox Canyon Aquifer dip below land surface and are folded into a series of anticlines and synclines. Groundwater in the Fox Canyon Aquifer exists under confined conditions beneath the valley and unconfined conditions at the valley margins where the Fox Canyon Aquifer is folded upward and exposed at the surface.

Much of the groundwater present in the LAS in the western portion of the West Las Posas basin results from eastward underflow from the Oxnard Plain basin, although there may be a limited quantity of groundwater underflow in the opposite direction in the shallower aquifers. Limited underflow from the East Las Posas and Pleasant Valley basins may also occur, suggested by northward and eastward hydraulic gradients near the boundaries of these basins with the West Las Posas basin. Recent groundwater modeling of the East and South Las Posas basins (Intera, 2018) suggests that less than 100 AF/yr of groundwater underflow occurs from East Las Posas basin to West Las Posas basin.

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