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Groundwater Level Declines at the Oasis of Mara, Joshua Tree National Park, 1940-2015

Natural Resource Report NPS/MOJN/NRR—2016/1242

ON THE COVER
Photograph of the Oasis of Mara in September 2015.
Photograph courtesy of Neil Frakes.

Groundwater Level Declines at the Oasis of Mara, Joshua Tree National Park, 1940-2015

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Contents

Figures

Page

Tables

Page

Executive Summary

The Oasis of Mara in Joshua Tree National Park (JOTR) is one of approximately 160 fan palm oases in North America. The oasis supports a diverse ecosystem, and is of great cultural significance. A paved interpretive trail rings the oasis, making it one of the most highly-visited sites in the park.

The Oasis of Mara is located in the Eastern Subbasin of the Joshua Tree Groundwater Basin, immediately to the south of Pinto Mountain Fault Zone. The fault impedes flow, forcing water to the surface. Historically, the oasis was a flowing spring with pools of water. However, the pools dried up in the 1940s due to declining groundwater levels. These declines reduced the extent of riparian vegetation in and around the oasis, and made the recruitment of new fan palms impossible. A 1974 USGS study (Swain 1974) found that "the principal cause of the decline probably is pumpage that exceeded natural recharge to the aquifer".

There was very little groundwater pumping in the Eastern Subbasin between 1960 and 1990. Water levels stabilized during these three decades, but they did not recover to their previous levels.

The Twentynine Palms Water District (TPWD) greatly increased its groundwater withdrawals from the Eastern Subbasin beginning in 1991. This increased pumping corresponded to a steep decline in groundwater levels in the subbasin. Currently, the groundwater level at the Oasis of Mara is more than 30 feet below ground surface in a monitoring well located 100 feet to the south of the oasis, with approximately half of that decline occurring since 1990.

Fan palm seeds require wet soil at the ground surface to germinate, and the maximum depth that fan palm roots can reach to access groundwater is approximately 13 feet. Therefore, declining groundwater levels threaten the survival of the fan palm oasis. JOTR has responded to the groundwater declines by irrigating the plants in the oasis. Given the magnitude of the groundwater declines the site, and the fact that groundwater levels did not rebound when pumping was greatly reduced for 30 years, it is likely that continued irrigation of the oasis is the best option for the survival of the palms and other riparian vegetation.

Acknowledgments

The data presented in this report was collected over several decades by the Resources Management staff at Joshua Tree National Park and the U.S. Geological Survey.

Introduction

Fan palms (*Washingtonia filifera*) are native to the Colorado Desert (a part of the Sonoran Desert) in the United States and Mexico. Mature fan palms require year-round water within 4 meters (13 feet) of the surface to survive, and their seeds can only germinate on damp soil, so they are found at persistent springs and streams (Cornett 2008). Many wildlife species are drawn to fan palm oases for access to a permanent source of water. The dense frond canopies of the fan palms also provide habitat to permanent and migratory animals (Cornett 2008). As a result, fan palm oases are much more diverse than the surrounding landscape, and many animals rely on the springs and streams that sustain them during the hot summer months.

There are approximately 160 fan palm oases in North America, five of which are within Joshua Tree National Park (JOTR). The Oasis of Mara is a fan palm oasis in JOTR near the park headquarters in Twentynine Palms, California (Figure 1). Currently, the oasis supports approximately seven hectares of riparian vegetation and a variety of wildlife, and is one of the most heavily visited sites in JOTR.

The Oasis of Mara has a rich history of human use dating back thousands of years. The earliest inhabitants of the area around Joshua Tree National Park were members of the Pinto Culture who arrived as early as 10,000 years ago (Dilsaver 2015). When Euro-Americans appeared in the late 1700s, the Serrano and Chemehuevi peoples were living at Oasis of Mara. By 1913, the native peoples had disappeared from the oasis as a result of forced relocation, first by Spanish missionaries and later by the Bureau of Indian Affairs (Dilsaver 2015).

Abundant water at the Oasis of Mara made it a natural hub for settlement and commercial activity. Patients with respiratory diseases were sent to convalesce in the dry desert air. With the advent of automobile travel, Twentynine Palms became accessible as a tourist destination. Many homesteaders bought properties in the burgeoning town and began to develop residential neighborhoods around the Oasis of Mara.

Historically, the oasis was a spring with water flowing to the surface. However, water ceased flowing in the mid-1940s due to water level declines. These declines reduced the extent of riparian vegetation in and around the oasis, and prevented the recruitment of new fan palms. JOTR began irrigating the site in the 1980s to keep the fan palms and other vegetation alive (Dilsaver 2015).

In 1973 and 1974, the USGS conducted a study of the oasis to determine why the springs had stopped flowing, and why some of the vegetation in the oasis was dying (Swain 1974). Since 1974, JOTR and the USGS have been monitoring water levels in the oasis using the wells installed during the USGS study. In this report, we present the results of this 40-year monitoring effort, and discuss the cause and management implications of continued groundwater declines at the Oasis of Mara. This report is focused on groundwater levels, and is intended to complement future ecological and botanical studies of the oasis.

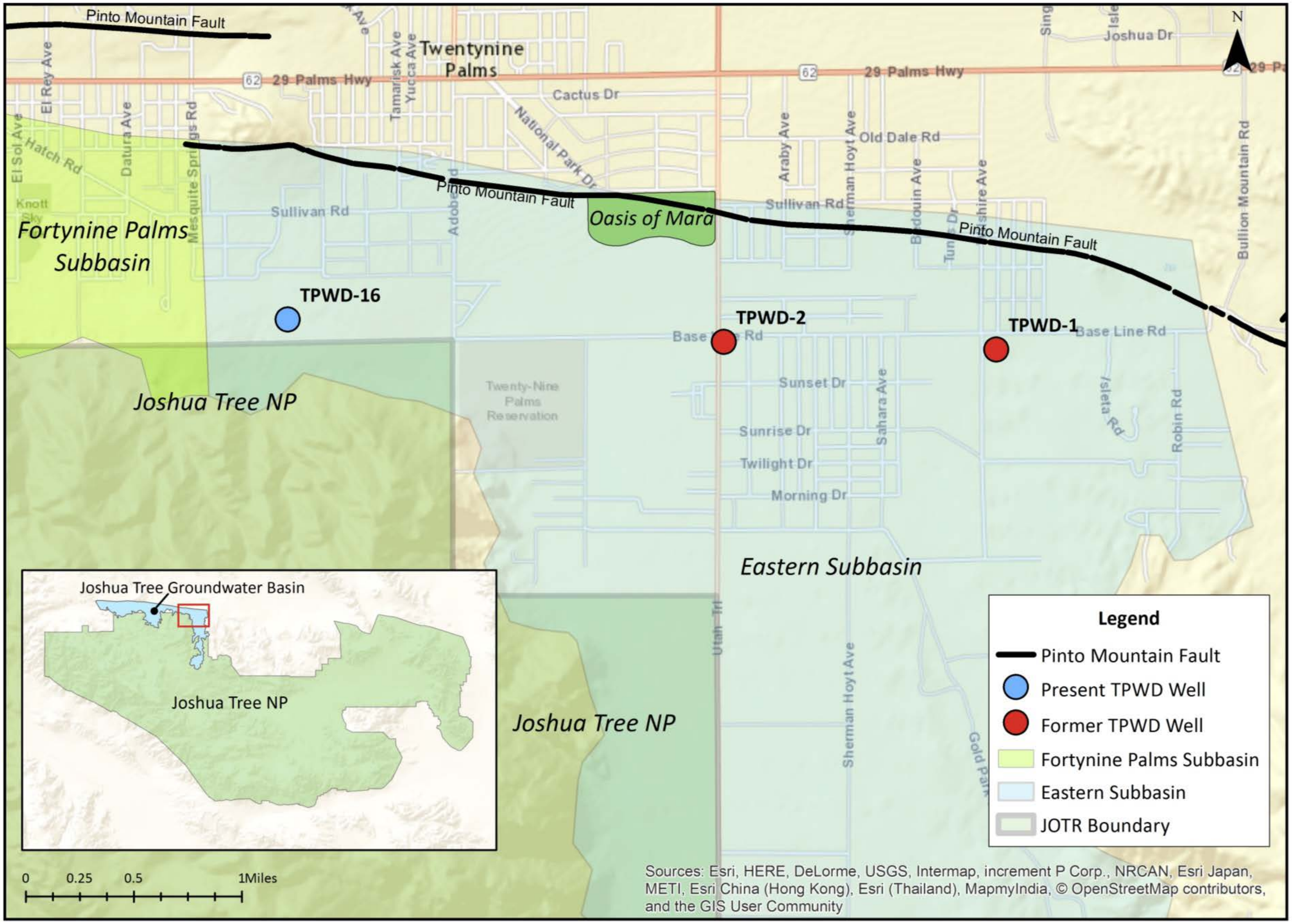

Figure 1. Map of the Oasis of Mara and Twentynine Palms Water District (TPWD) water supply wells.

Site Hydrogeology

The Oasis of Mara (Figure 1) lies along the Pinto Mountain Fault at the northern boundary of the Joshua Tree Groundwater Basin (CA DWR 2003). The basin receives recharge from rainfall in the mountains to the south, and groundwater flows from south to north. Historically a portion of this water was forced to the surface when it reached the fault, creating the springs in the oasis. While the fault acts as a low-permeability impediment to groundwater flow, there is some seepage across the fault to the Mesquite Lake Groundwater Basin (Kennedy/Jenks 2014, Li and Martin 2011). The Joshua Tree Groundwater Basin is the primary source of water for the communities in the area. The basin as a whole is in overdraft, with declines of tens of feet in some locations (Nishikawa et al. 2004).

The Oasis of Mara is located in the Eastern Subbasin of the Joshua Tree Groundwater Basin (Kennedy/Jenks 2014, Figure 1). The Eastern Subbasin is bounded by the Fortynine Palms Subbasin to the west and an outcrop of bedrock to the East. The exact nature of the boundary delineation between the Eastern Subbasin and the Fortynine Palms Subbasin is unknown, but water levels are currently tens of feet higher in the Eastern Subbasin than in the Fortynine Palms Subbasin (Kennedy/Jenks 2014). The numerical models of groundwater flow described in the Twentynine Palms Water District (TPWD) Groundwater Management Plan (Kennedy/Jenks 2014) assumes that there is no flow between the Eastern Subbasin and the Fortynine Palms Subbasin, but the document suggests that there may be “limited flow” between the subbasins.

The Eastern Subbasin aquifer consists of highly-transmissive alluvial fan deposits (i.e. sands and gravels) that are 160 to 750 feet thick (Kennedy/Jenks 2014). The recharge area for the Subbasin extends south into the park, and historically much of the flow through this portion of the aquifer discharged as springflow and evapotranspiration at the Oasis of Mara. Currently, the primary means of groundwater discharge is the pumping of TPWDwater supply well TPWD-16.

Groundwater Withdrawal History

The data regarding TPWD groundwater withdrawals in this section are drawn from a graph presented in the TPWD Groundwater Management Plan (Kennedy/Jenks 2014). The plan does not report pumping rates apart from the graph, and the authors have not reviewed TPWD files, so all reported TPWD groundwater withdrawal values are approximate.

1930s to 1959

Early settlers in the Twentynine Palms area used the Oasis of Mara and shallow wells as water sources. In 1941, more than 100 wells were in use in the Twentynine Palms area near JOTR (Lewis 1942). This number declined rapidly as groundwater levels declined and as more homes and businesses were supplied by the local water companies. Swain (1974) reports that only seven private wells were in use in the Twentynine Palms area south of the Pinto Mountain Fault in 1958, with an estimated the total groundwater of less than 20 acre-feet/year.

In the 1930s, two utility-scale water supply wells, currently known as TPWD-1 and TPWD-2, were drilled in the Eastern Subbasin (Figure 1). The first available pumping records (Kennedy/Jenks 2014) show that groundwater withdrawals from TPWD-1 and TPWD-2 ranged from approximately 150 to 300 acre-feet/year between 1953 and 1959.

1960 to 1990

The TPWD greatly reduced its groundwater withdrawals from the Eastern Subbasin after 1959. From 1960 until 1990, TPWD withdrawals from the Eastern Subbasin ranged from less than 10 to approximately 50 acre-feet per year (Kennedy/Jenks 2014). Swain (1974) reported that six of the seven private wells operating in the eastern Subbasin in 1958 had gone dry by 1974. Freckleton (1982) found only three private water wells in use in the Eastern Subbasin in 1981.

1991 to Present

In 1991, the TPWD installed municipal supply well TPWD-16, 1.5 miles to the southwest of the Oasis of Mara and 0.5 miles to the south of the Pinto Mountain Fault in the Eastern Subbasin (Figure 1). From 1992 to 2012, the water pumped from the Eastern Subbasin ranged from approximately 250 to 829 acre-feet per year (Kennedy/Jenks 2014). In 2012, the TPWD pumped 311 acre-feet from the Eastern Subbasin, all from TPWD-16. Groundwater withdrawals are expected to continue at a similar rate in the near future (Kennedy/Jenks 2014).

Monitoring Well Records

The monitoring wells located in and around the Oasis of Mara (Figure 2) include a hand-dug well first monitored by the USGS in 1917 (well J-1) and 11 monitoring wells (H-1 to H-2, J-2 to J-5, and K-1 to K-5) installed by the USGS as part of their 1974 investigation into the cause of the decline in water levels at the oasis (Swain 1994). The compiled USGS and NPS water level data from these 11 monitoring wells are included in Appendix A.

Figure 2. Map of monitoring well locations at the Oasis of Mara.

Wells in the Oasis of Mara

The earliest available measurements of groundwater level at the Oasis of Mara were made in a hand dug well located in the oasis (well J-1). The well was observed to be flowing in 1917, and water levels were measured from 1940 to 1974. Data from 1940 to 1958 are available from the USGS National Water Information System (NWIS). Data were also collected from 1958 to 1974, but the only record of these data is a graph produced by Swain (1974). MOJN has extracted these data points from the graph, but the accuracy of the recovered data is approximately ±0.3 feet in water level and approximately ±60 days in date of measurement. The 1958 to 1974 data are discussed further in Appendix B.

The USGS investigation in 1974 found that well J-1 was blocked, so they installed a monitoring well 4 feet to the east of the hand-dug well. Well J-5 was monitored from 1974 until it went dry in 1993.

Figure 3 combines water level records from well J-1 and well J-5 on a single graph. Throughout the 1940s, the water level was often above the ground surface (depths less than zero), indicating that the spring was flowing. By the late 1940s, groundwater level decline had begun, and the water level was approximately four feet below ground surface by 1958. From 1961 until 1970 water levels appeared decline more slowly, with the measured values ranging from 3.2 to 4.2 feet below ground (one measurement of 6.3 feet below ground was made in 1970). No measurements were made until 1974, when Swain found the well to be obstructed, but managed to make a water level measurement of 7.06 feet below ground. While the J-5 water level values are not necessarily directly comparable to the J-1 values, they exhibit the same pattern of slower decrease, with water levels varying from 4.5 to 7.25 feet below ground from 1974 to 1992. In 1993 the well, which had a depth of 8.44 feet, went dry.

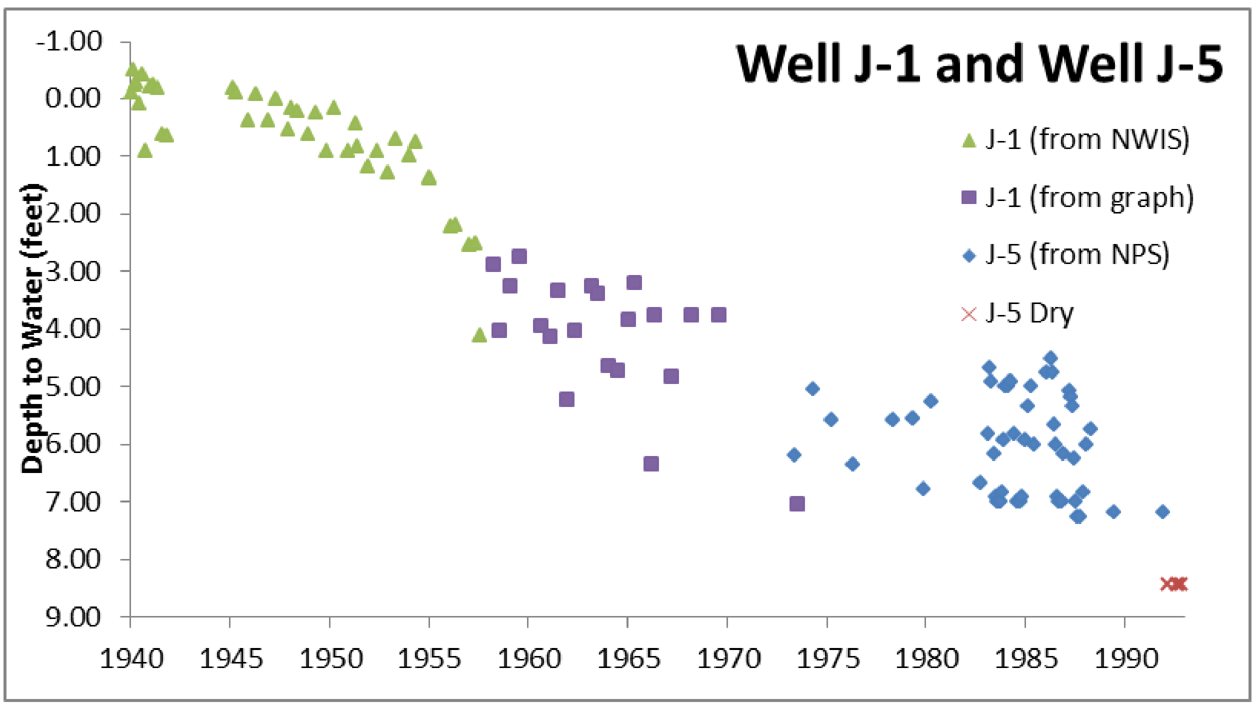

Figure 3. Water level data measured in Well J-1 (the hand-dug well) and in well J-5, which was installed 4 feet to the east of J-1. The data points labeled "from graph" are approximate values.

Wells to the South of the Oasis of Mara

The USGS installed 9 monitoring wells (Wells J-2 to J-4 and K-1 to K-5) approximately 100 feet or less to the south of the Oasis of Mara, inside the boundary of the Eastern Subbasin (Figure 2). Well K-1 has not been monitored since 1981, and may have been destroyed at some point. The water level record for Well J-2 is included below as an example (Figure 4) because it is the only well that has not yet gone dry. Water levels in J-2 decreased by approximately 1 foot from 1974 to 1978, increased by approximately one foot from 1978 to 1984, and then stabilized between 1984 and 1990. From 1992 to 2014, water levels declined 13.27 feet, approximately 0.6 feet per year. For the purposes of brevity, the water level records for the other wells located to the south of the Oasis of Mara are not reproduced here, but they can be found in appendix A, and exhibit the same behavior: relative stability from 1974 to 1990, then a steep decline. However, the other seven wells have gone dry.

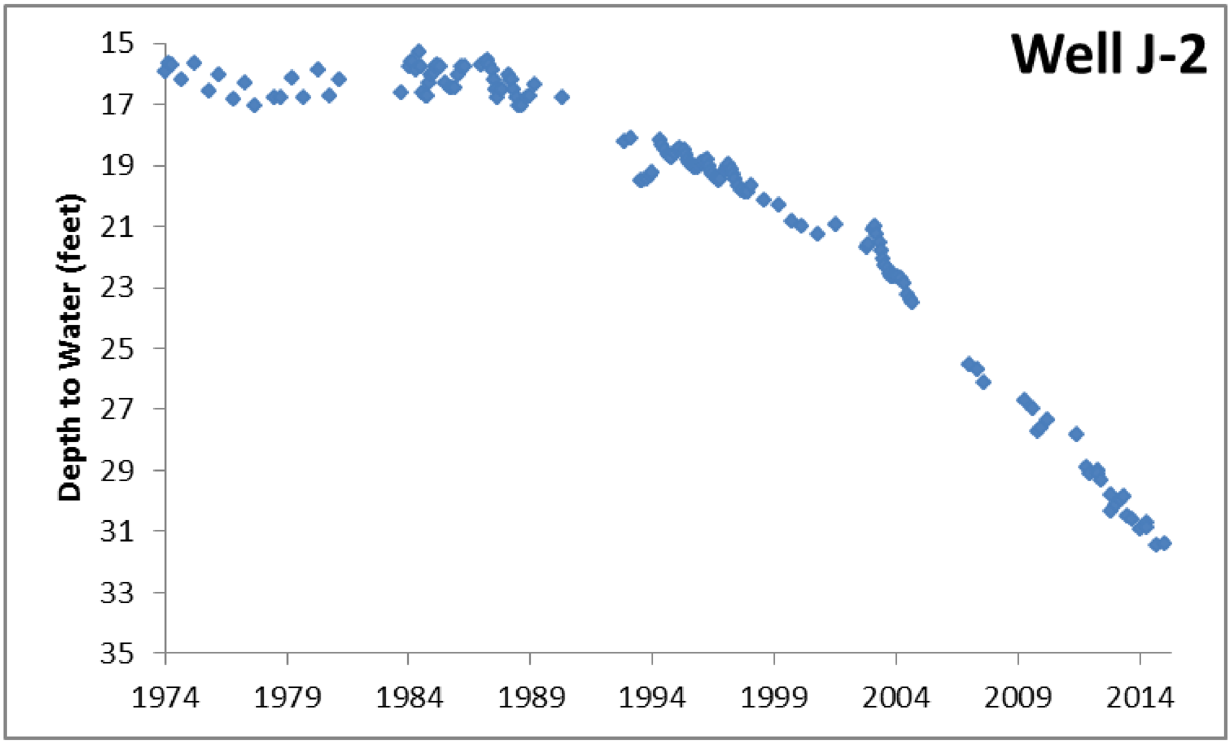

Figure 4. Water level data measured in monitoring well J-2.

Wells to the North of the Oasis of Mara

The USGS installed two monitoring wells immediately to the north of Pinto Mountain Fault, just outside of the Eastern Subbasin but within the area where oasis vegetation has historically been found. The water levels in these wells are approximately 30 feet deeper than to the south of the fault, indicating that the fault may act as an impediment to groundwater flow. The water level record for Well H-1 is included below as an example (Figure 5). Similar to well J-2, water levels in well H-1 decrease by approximately 1 foot from 1974 to 1978, increase by approximately one foot from 1978 to 1984, and then stabilize or slightly increase between 1984 and 1990. The water level in well H-1 also began to decline after 1992. However, the rate of decline is lower (6.59 feet from 1994 to 2014, or approximately 0.3 feet per year), and the water level rises slightly between late 2000 and early

2003. These differences confirm that the area to the north of the fault is part of a different groundwater basin than the area to the south of the fault. The water level record for other well to the north of the oasis, well H-2, which went dry in 1996, is given in Appendix A.

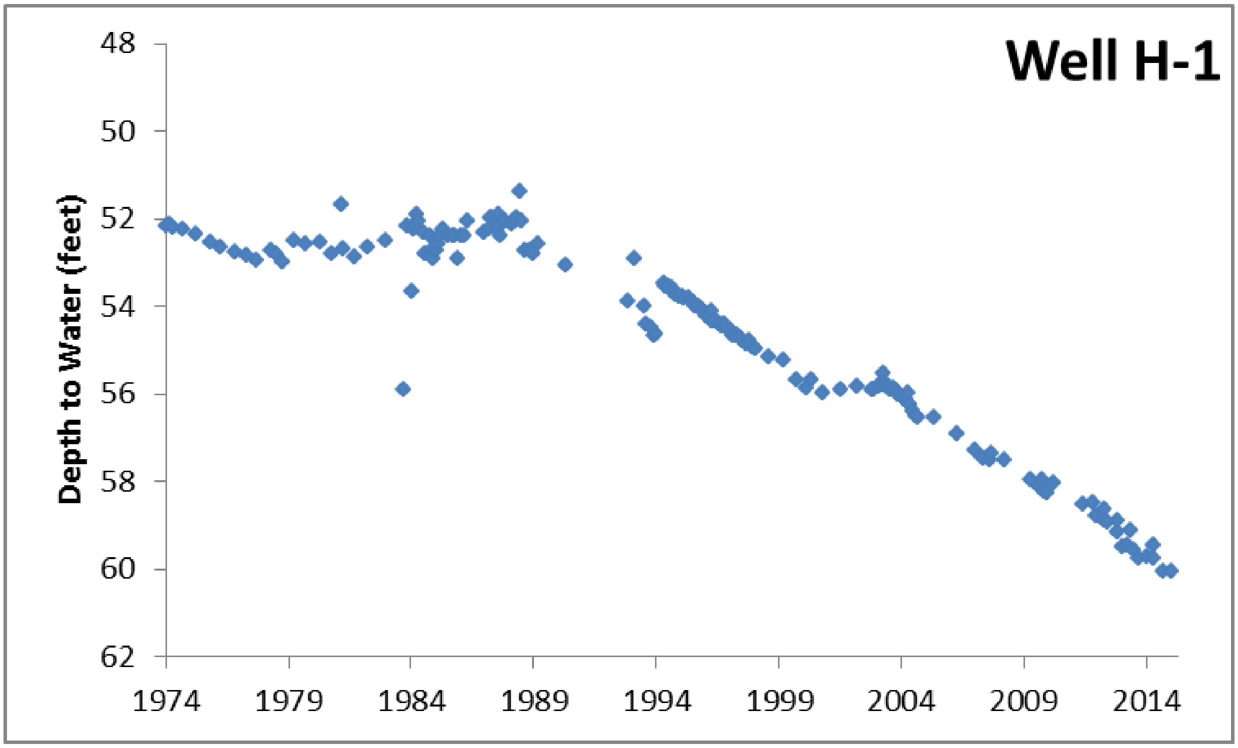

Figure 5. Water level data measured in monitoring well H-1.

Discussion

Many groundwater basins in California and across the Western United States are in overdraft, that is, more water is being pumped from them than is being recharged. Basins in overdraft experience declining groundwater levels, which can decrease or eliminate flow to springs. Groundwater levels in the vicinity Oasis of Mara declined in the 1940s and 1950s, largely in response to large-scale groundwater withdrawals, causing the springs in the oasis to run dry. Groundwater withdrawals were greatly reduced from 1960 to 1990, and water levels declined slowly or stabilized as a result. In 1991, TPWD began pumping from well TPWD-16. At approximately the same time, groundwater levels in wells near the oasis began to decline by approximately 0.6 feet each year, a decline that continues today. Given the timing, the proximity, and the history of declines due to groundwater withdrawal, it is likely that the declines are the result of pumping at TPWD-16.

The TPWD began pumping from two additional water supply wells located in the Fortynine Palms Subbasin, TPWD-14 and TPWD-17, in 1988. Withdrawals from those wells, located approximately 3.5 miles to the west of the Oasis of Mara, have drawn down water levels in monitoring wells in the eastern half of the Fortynine Palms Subbasin by approximately 80 feet since the early 1990s. While the numerical groundwater models in the TPWD Groundwater Management Plan (Kennedy/Jenks 2014) assume no flow between the Eastern Subbasin and the Fortynine Palms Subbasin, the document suggests that there may be “limited flow” between the subbasins. It is possible that the decline in water levels in the Fortynine Palms Subbasin has induced some seepage from Eastern Subbasin, potentially contributing some component to the decline in water levels observed near the Oasis of Mara.

It has been suggested (e.g., Dilsaver 2015) that groundwater declines at the Oasis of Mara may have been partly caused by the Joshua Tree Earthquake (April 22, 1992) or the Landers Earthquake (June 28, 1992). No data are available from May 1990 until November 1992, so the immediate response to the earthquake cannot be seen. Changes in water levels in wells are often observed in monitoring wells during earthquakes. However, the effects of the earthquakes generally last for a period of minutes to months (e.g., Roeloffs 1998, Chia et al. 2001, Roeloffs et al. 2003). We consider it extremely unlikely that the multi-decadal decline in water level at the Oasis of Mara was caused by an earthquake.

No water levels have been measured in wells located in the oasis since 1993, when the water level decreased to more than eight feet below ground surface. Water levels in wells approximately 100 feet to the south of the oasis have fallen approximately 0.6 feet per year since the early 1990s. If the water level beneath the oasis experienced a similar rate of decline, it would be more than 20 feet below the ground surface, below the depths that can be reached by the roots of the fan palm (Cornett 2008).

Pumping rates in the Eastern Subbasin were greatly reduced from 1960 to 1990. Water levels in this period declined more slowly or stabilized, but did not reverse the declines caused by the previous 20 to 25 years of higher groundwater withdrawals. This suggests that reducing groundwater withdrawal rates likely would not return flowing water to the Oasis of Mara for many decades. Therefore, the best option for the survival of the fan palms is continued irrigation of the oasis.

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Appendix A: Compiled Water Level Data from the Oasis of Mara

Overview

Table A-1 lists the wells included in this report. Drillers logs and construction details for each well are provided by Swain (1974) and reproduced in Appendix A of this report. Levels were run April 30, 1974. Any possible shifts in land surface elevation or casing elevation since that time would be small compared to the observed water level declines.

Table A-1. Monitoring wells at the Oasis of Mara.

Well	USGS Code	Easting	Northing	Elevation of Ground Surface (ft)	Casing Stick-Up (ft)	N or S of Fault?	Screen Interval (ft below surface)	Sediment in Screen Interval
H-1	340741116022001	588555	3776850	1960.75	0.11	N	75-77	Gravel, clay
H-2	340741116022002	588555	3776850	1960.75	0.46	N	53.6-55.6	Clay, some sand
J-2	340738116021701	588591	3776750	1973.27	0.21	S	34.2-36.2	Clay
J-3	340739116021701	588589	3776758	1972.02	0.46	S	33-35	Sand
J-4	340739116021702	588591	3776758	1972.02	0.37	S	24.5-26.5	Clay
J-5	340741116022003	588557	3776829	1960.48	[no data]	S	6.63-8.63	Clay, silty sand
K-1	340740116023001	588277	3776795	1970.48	[no data]	S	27.35-29.35	Clay
K-2	340739116023001	588277	3776780	1972.09	0.07	S	35-37	Clay
K-3	340739116023002	588277	3776780	1972.09	0.31	S	23-25	Silty sand
K-4	340739116023003	588282	3776766	1973.13	0.50	S	34.3-36.3	Clay
K-5	340739116023004	588282	3776766	1973.13	0.33	S	25.6-27.6	Silty sand

Data Sources

USGS data were obtained from the USGS National Water Information System (NWIS). The USGS data extend from 1974 to 2014. The data from 1974 to 1981 are identical to data from NPS data sheets discussed below, so it is not clear which agency collected these data.

The NPS data were taken from a variety of paper data sheets, reports, and print-outs of spreadsheets found in JOTR Resource Management files. The data extend from 1974 to 2015, and appear to have been collected with different frequencies using different methods over the years. Most of the data have a nominal precision of a hundredth of a foot, but some of the measurements were recorded to the nearest half-inch or inch. In some cases, only the month of the measurement was recorded- these events have been assigned a nominal date of the 15th of the month for plotting purposes.

Wells K-4 and K-5

Well K-4 and well K-5 were installed in the same borehole at different depths. According to Swain (1974), K-4 is screened from 34.3 to 36.3 feet below ground surface and K-5 is screened from 25.6 to 27.6 feet below ground surface. However, the deepest measurement recorded in K-4 is 24.52 feet (Figure A-10), while water was observed in well K-5 at depths greater than 30 feet by both the USGS and the NPS (Figure A-11). It is likely that the two wells were confused at some point, possibly by Swain. Notes in the margin of one of the NPS field sheets indicate that JOTR staff believed the total depth of K-4 was 25.42 feet in 1993. The two water level records track each other very closely in the period before the water level fell below the screened interval of the shallower well, so there is no obvious way to determine which measurements were made in which well. We have chosen to use the more recent nomenclature (K-4 for the shallow well and K-5 for the deeper well) to maintain consistency with the USGS and JOTR staff, but care should be taken in using these data.

Water Data and Graphs

Figures A-1 to A-11 show the compiled water level data for the 11 wells in the Oasis of Mara installed by the USGS in 1973 and 1974. These data are given in Table A-2, below.

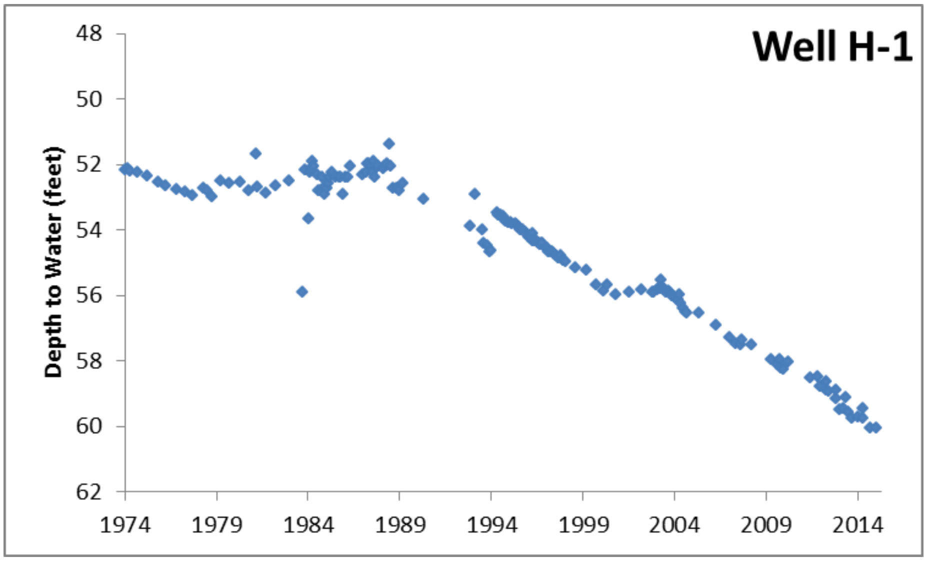

Figure A-1. Water level data from monitoring well H-1.

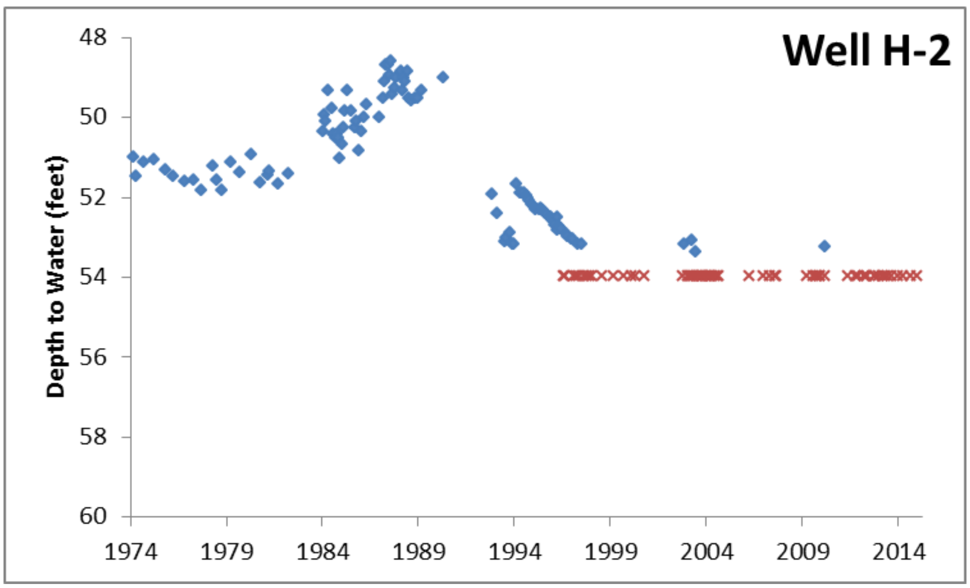

Figure A-2. Water level data from monitoring well H-2.

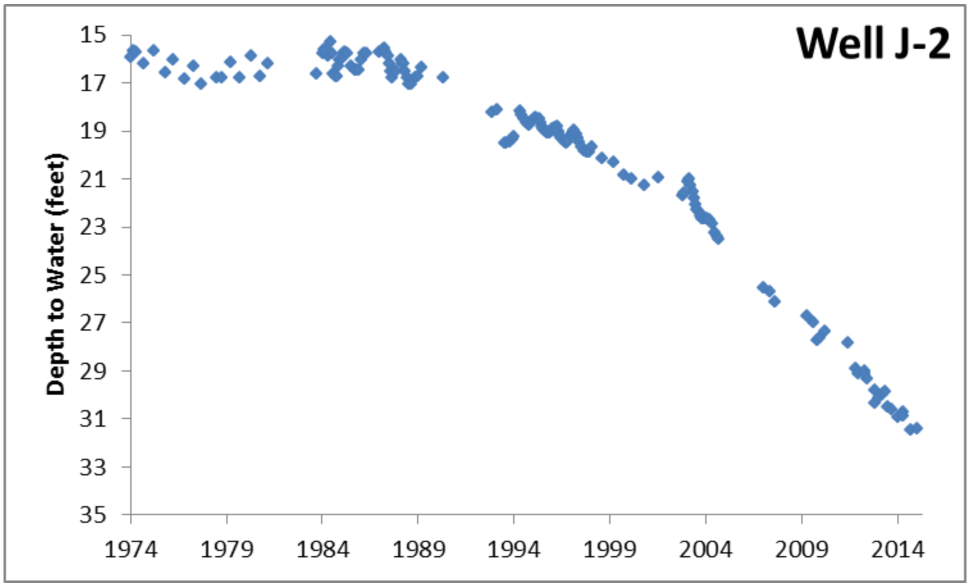

Figure A-3. Water level data from monitoring well J-2.

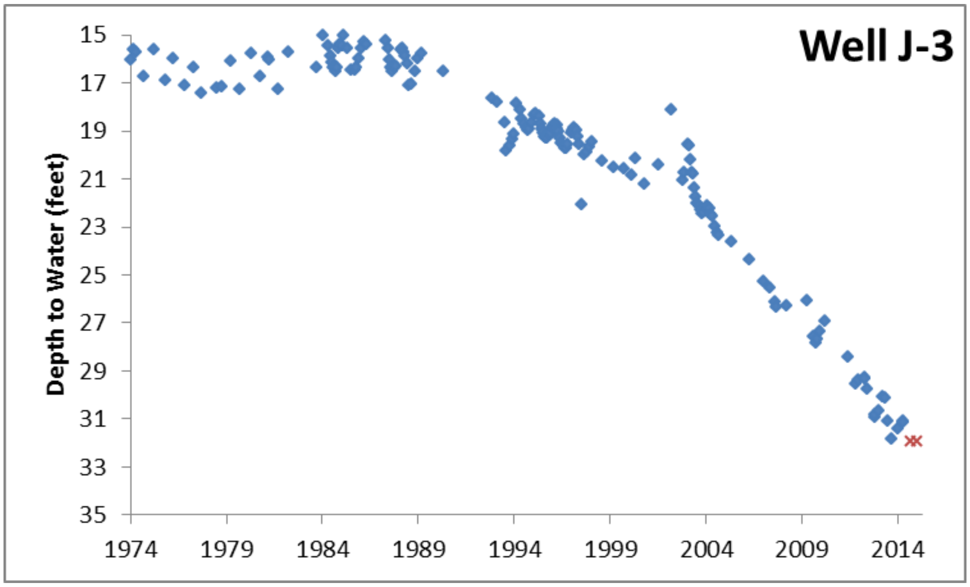

Figure A-4. Water level data from monitoring well J-3.

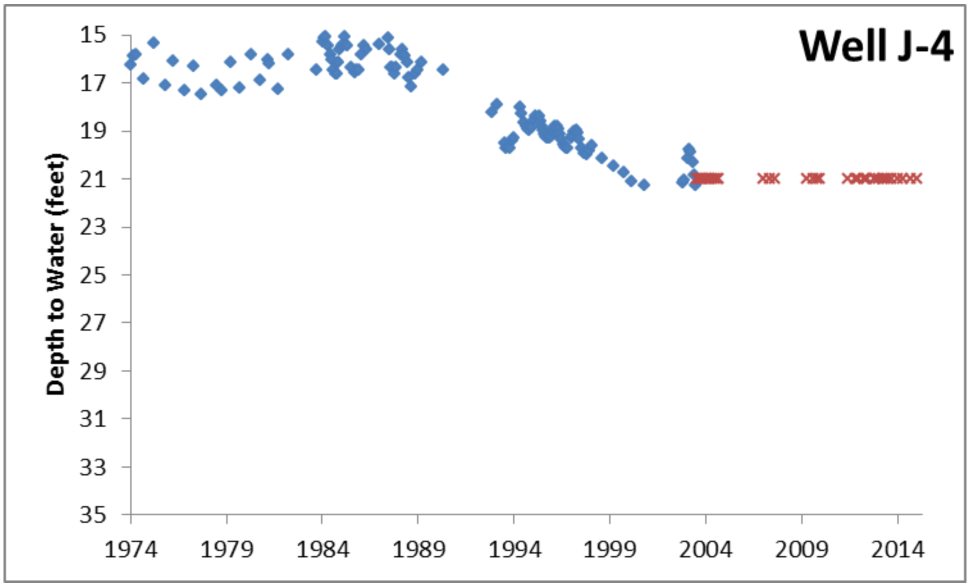

Figure A-5. Water level data from monitoring well J-4.

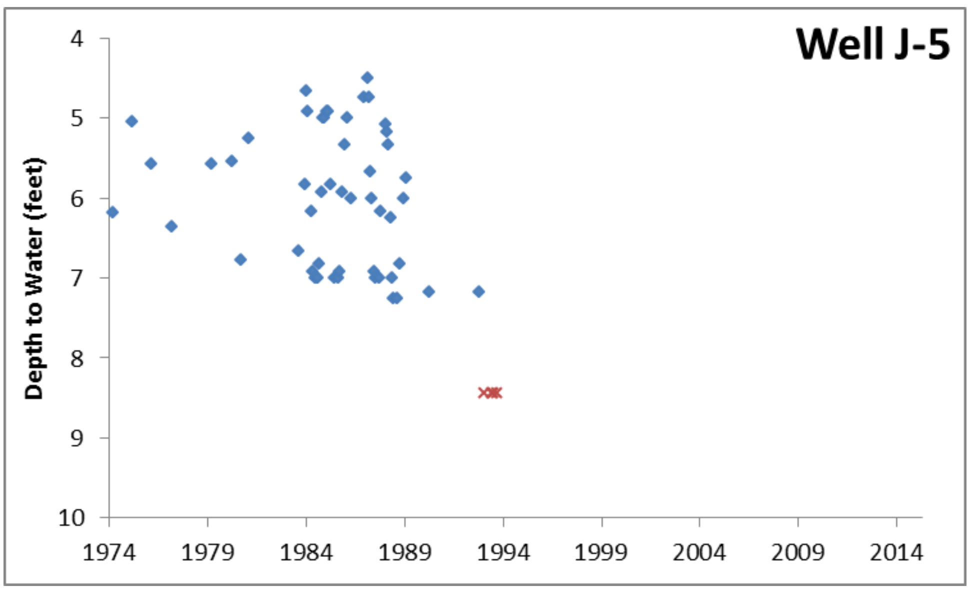

Figure A-6. Water level data from monitoring well J-5.

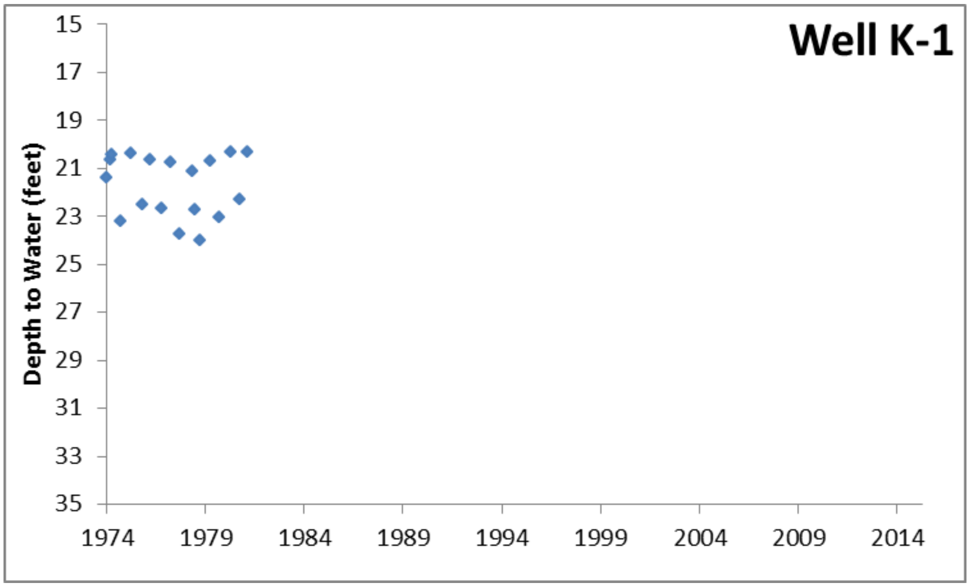

Figure A-7. Water level data from monitoring well K-1.

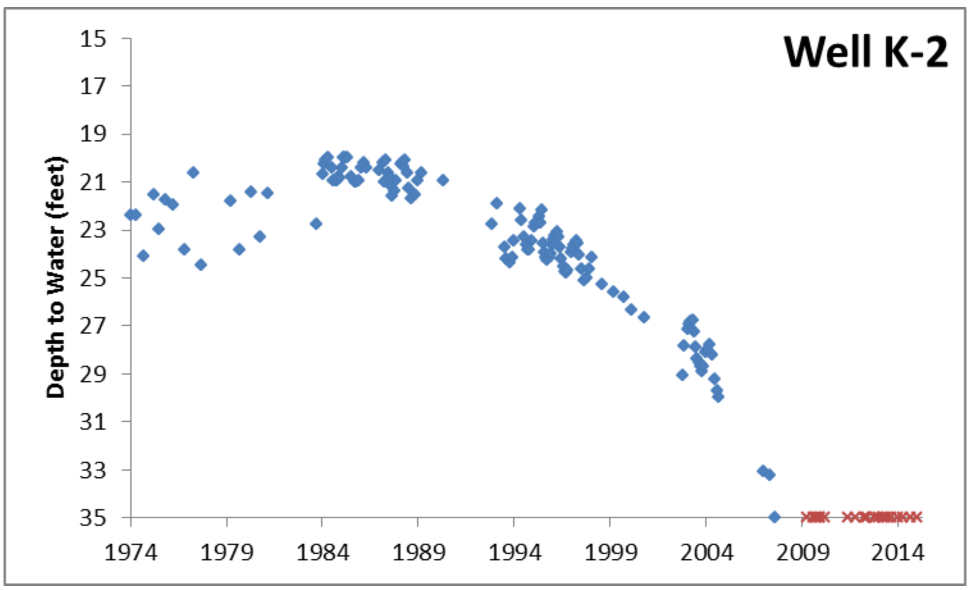

Figure A-8. Water level data from monitoring well K-2.

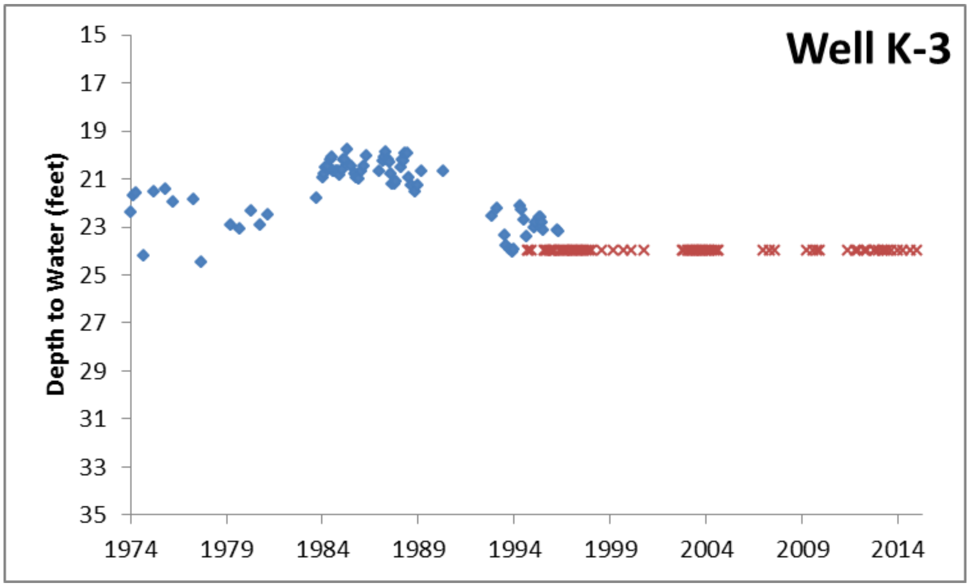

Figure A-9. Water level data from monitoring well K-3.

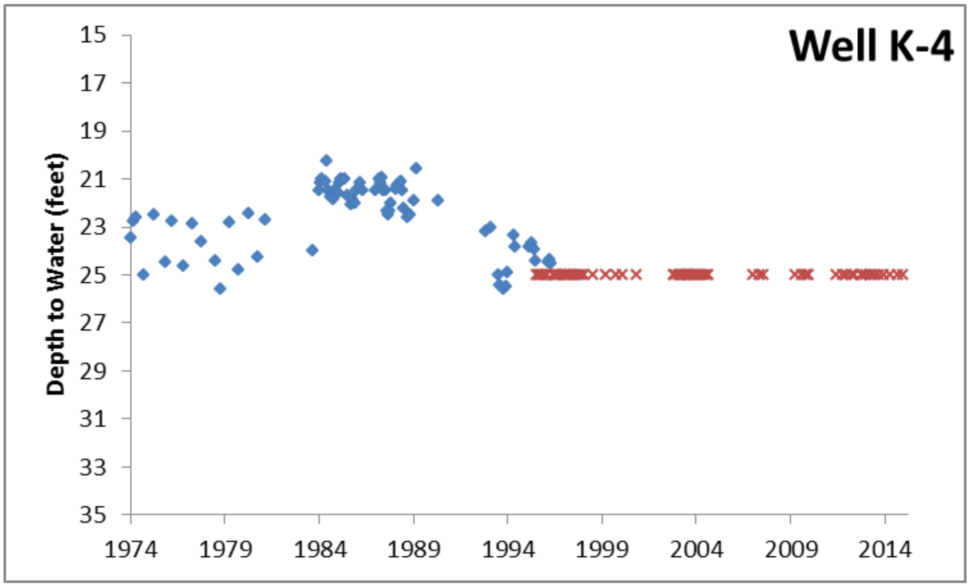

Figure A-10. Water level data from monitoring well K-4.

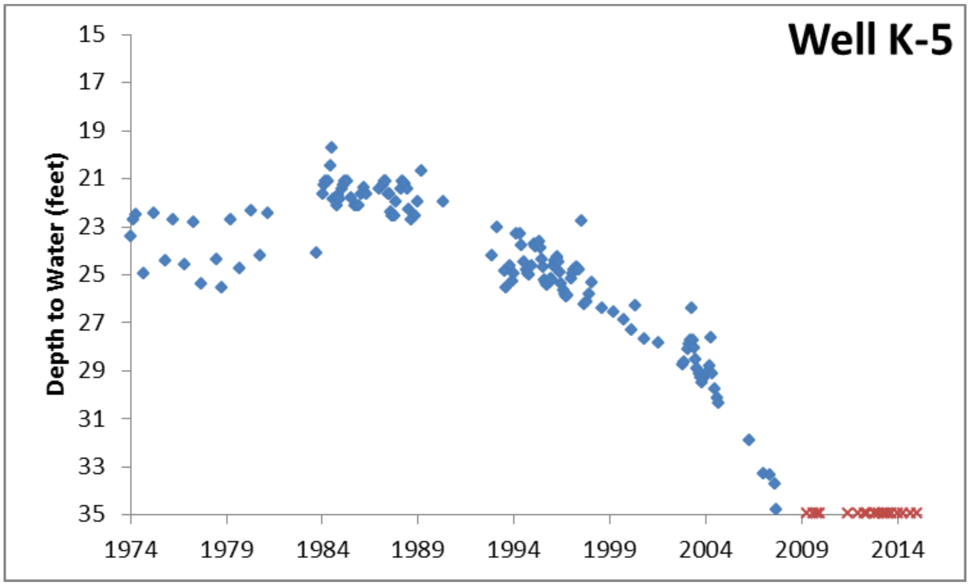

Figure A-11. Water level data from monitoring well K-5.

Table A-2. Water level measurements for all wells from 1973 to 2014. A "*" indicates events for which only the month and year were recorded; these events have been assigned a nominal date of the 15th of the month for plotting purposes.

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
12/1/1973	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	28	32	21	[no data]	23
12/4/1973	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	21.02	[no data]	22.53
1/15/1974	61.7	[no data]	15.94	16.03	16.24	[no data]	21.37	22.4	22.41	23.48	23.47
1/17/1974	52.15	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
3/20/1974	52.14	51.01	15.64	15.63	15.86	[no data]	20.63	[no data]	21.67	22.77	22.74
4/30/1974	52.19	51.51	15.7	15.7	15.84	6.19	20.44	22.41	21.61	22.59	22.55
9/27/1974	52.23	51.14	16.17	16.72	16.86	[no data]	23.2	24.07	24.18	24.99	24.99
4/8/1975	52.33	51.1	15.64	15.59	15.36	5.05	20.38	21.55	21.53	22.5	[no data]
4/15/1975	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	22.48
7/15/1975*	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	22.99	[no data]	[no data]	[no data]
11/13/1975	52.52	51.33	16.57	16.91	17.08	[no data]	22.49	21.73	21.43	24.49	24.48
3/26/1976	52.63	51.49	16.01	15.98	16.08	5.57	20.63	21.95	21.98	22.76	22.76
11/5/1976	52.75	51.64	16.82	17.12	17.29	[no data]	22.66	23.84	[no data]	24.62	24.63
4/20/1977	52.83	51.59	16.31	16.35	16.31	6.36	20.77	20.6	21.87	22.88	22.87
10/6/1977	52.96	51.86	17.05	17.43	17.48	[no data]	23.73	24.45	24.46	23.61	25.43
5/13/1978	52.71	51.25	[no data]	[no data]	[no data]	[no data]	21.12	[no data]	[no data]	[no data]	[no data]
7/13/1978	52.79	51.61	16.78	17.21	17.09	[no data]	22.71	[no data]	[no data]	24.41	24.4
10/12/1978	52.97	51.85	16.79	17.18	17.31	[no data]	23.99	[no data]	[no data]	25.59	25.58
4/10/1979	52.49	51.14	16.16	16.08	16.13	5.57	20.72	21.81	22.92	22.83	22.78
10/5/1979	52.56	51.41	16.77	17.25	17.23	[no data]	23.03	23.82	23.08	24.78	24.78
4/24/1980	52.52	50.97	15.9	15.76	15.81	5.55	20.33	21.45	22.35	22.46	22.41
10/17/1980	52.78	51.66	16.71	16.75	16.87	6.78	22.28	23.27	22.9	24.26	24.24
3/10/1981	51.68	51.46	16.17	15.95	16.02	5.25	20.33	21.48	22.5	22.71	22.48
4/9/1981	52.68	51.39	[no data]	16.06	16.21	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
10/2/1981	52.88	51.71	[no data]	17.24	17.26	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
4/16/1982	52.65	51.45	[no data]	15.74	15.84	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
12/27/1982	52.51	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
9/15/1983*	55.89	60.54	16.62	16.37	16.46	6.67	[no data]	22.76	21.81	24	24.17
11/18/1983	52.16	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
1/15/1984*	53.64	50.37	15.79	15.04	15.3	5.83	[no data]	20.68	20.94	21.5	21.67
2/15/1984*	52.22	49.96	15.62	14.87	15.13	4.67	[no data]	20.26	20.77	21.17	21.34
3/15/1984*	52.14	50.12	15.62	14.96	15.05	4.92	[no data]	20.1	20.52	21	21.17
4/17/1984	51.9	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
5/15/1984*	52.06	49.37	15.87	15.46	15.46	6.17	[no data]	20.01	20.44	21.08	21.17
6/15/1984*	-0.11	47.54	15.29	15.87	15.8	6.92	[no data]	[no data]	20.19	20.25	20.5
7/15/1984*	52.31	49.79	15.79	16.12	16.05	7	[no data]	20.43	20.11	21.5	19.75
8/15/1984*	52.81	50.46	16.62	16.37	16.46	7	[no data]	20.93	20.69	21.75	21.92
9/15/1984*	52.81	50.54	16.71	16.54	16.63	7	[no data]	20.93	20.69	21.67	21.84
10/15/1984*	52.39	50.46	16.71	16.37	16.63	6.83	[no data]	20.93	20.69	21.83	22.17
11/15/1984*	52.72	50.54	16.29	15.54	16.13	5.92	[no data]	20.76	20.69	21.5	21.75
12/15/1984*	52.89	51.04	16.04	15.37	15.63	5	[no data]	20.85	20.86	21.58	21.92
1/15/1985*	52.72	50.71	15.96	15.46	15.46	5	[no data]	20.43	20.61	21.58	21.5
2/15/1985*	52.56	50.29	15.79	15.04	15.38	4.92	[no data]	20.01	20.19	21.17	21.34
3/15/1985*	52.39	49.87	15.71	14.87	15.05	4.92	[no data]	20.01	20.19	21	21.17
5/15/1985*	52.22	49.37	15.79	15.54	15.46	5.83	[no data]	20.01	19.77	21	21.17
7/15/1985*	52.39	49.87	16.29	16.46	16.38	7	[no data]	20.76	20.44	21.67	21.84
9/15/1985*	52.39	50.29	16.46	16.46	16.55	7	[no data]	21.01	20.77	22.08	22.17
10/15/1985*	52.39	50.12	16.46	16.37	16.46	6.92	[no data]	21.01	20.94	21.83	22.17
12/15/1985*	52.89	50.87	16.46	15.96	16.46	5.92	[no data]	20.93	21.02	22	22.17
1/15/1986*	52.39	50.37	16.04	15.54	15.8	5.33	[no data]	20.43	20.69	21.5	21.67
3/15/1986*	52.39	50.04	15.79	15.29	15.46	5	[no data]	20.18	20.44	21.17	21.42
5/15/1986*	52.06	49.71	15.79	15.37	15.63	6	[no data]	20.43	20.02	21.5	21.67
1/15/1987*	52.31	50.04	15.71	14.95	15.38	4.75	[no data]	20.51	20.69	21.5	21.5
3/15/1987*	52.22	49.54	15.62	14.79	14.96	4.5	[no data]	20.18	20.27	21	21.34
4/15/1987*	51.97	49.12	15.54	14.62	14.71	4.75	[no data]	21.01	20.11	21.17	21.17
5/15/1987*	51.97	48.71	15.706	15.21	14.96	5.67	[no data]	20.1	19.86	20.92	21.17

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
6/15/1987*	52.06	48.71	15.87	15.54	15.13	6	[no data]	20.6	20.19	21.5	21.67
7/15/1987*	52.22	48.96	16.21	16.04	15.63	6.92	[no data]	20.76	20.29	21.5	21.67
8/15/1987*	51.89	48.62	16.54	16.37	16.38	7	[no data]	21.18	20.81	22.33	22.42
9/15/1987*	52.39	49.46	16.79	16.54	16.38	[no data]	[no data]	21.6	21.19	22.5	22.59
10/15/1987*	52.06	49.29	16.54	16.37	16.63	7	[no data]	21.35	21.19	22.33	22.59
11/15/1987*	52.06	49.04	16.54	16.29	16.38	6.17	[no data]	20.93	21.11	22	22
2/15/1988*	52.14	48.87	16.04	15.62	15.8	5.08	[no data]	20.26	20.52	21.42	21.5
3/15/1988*	52.06	49.37	16.21	15.54	15.63	5.17	[no data]	20.18	20.19	21.25	21.17
4/15/1988*	52.06	49.04	16.21	15.71	15.8	5.33	[no data]	20.35	20.27	21.17	21.2
5/15/1988*	51.97	49.12	16.54	15.87	15.88	6.25	[no data]	20.1	19.94	21.08	21.25
6/15/1988*	51.39	48.87	16.79	16.21	16.13	7	[no data]	20.6	19.94	21.5	21.5
7/15/1988*	52.06	49.54	17.04	17.12	16.8	7.25	[no data]	21.26	20.94	22.25	22.34
9/15/1988*	52.72	49.62	17.04	17.04	17.13	7.25	[no data]	21.68	21.27	22.58	22.75
11/15/1988*	52.72	49.54	16.79	16.54	16.63	6.83	[no data]	21.51	21.52	22.5	22.59
1/15/1989*	52.806	49.54	16.71	15.96	16.46	6	[no data]	20.93	21.27	21.92	22
3/15/1989*	52.56	49.37	16.37	15.79	16.13	5.75	[no data]	20.6	20.69	20.58	20.75
5/15/1990*	53.06	49.04	16.79	16.54	16.46	7.17	[no data]	20.93	20.69	21.91	22
11/15/1992*	53.89	51.96	18.21	17.62	18.21	7.17	[no data]	22.76	22.52	23.17	24.25
2/15/1993*	52.89	52.42	18.12	17.77	17.92	8.44 (dry)	[no data]	21.89	22.23	23.04	23.09
7/15/1993*	53.99	53.14	19.49	18.65	19.53	dry	[no data]	23.73	23.34	25	24.92
8/15/1993*	54.39	53.04	19.49	19.84	19.74	dry	[no data]	24.18	23.79	25.45	25.57
10/15/1993*	54.47333	52.92	19.46	19.62	19.73	dry	[no data]	24.35	23.94	25.58	24.67
12/15/1993*	54.68167	53.21	19.37	19.33	19.38	[no data]	[no data]	24.14	24.065	25.5	25.34
1/15/1994*	54.64	53.21	19.21	19.12	19.3	[no data]	[no data]	23.43	23.94	24.92	25
3/3/1994	[no data]	51.69	[no data]	17.83	18	[no data]	[no data]	[no data]	[no data]	[no data]	23.33
5/6/1994	53.46	51.92	18.15	18.12	[no data]	[no data]	[no data]	22.11	22.14	23.35	23.34
6/10/1994	53.55	51.91	18.35	18.47	18.29	[no data]	[no data]	22.61	22.28	23.82	23.83
7/21/1994	53.53	51.93	18.49	18.72	18.63	[no data]	[no data]	23.3	22.73	[no data]	24.52
8/25/1994	53.59	51.99	18.64	18.87	18.82	[no data]	[no data]	23.62	23.39	[no data]	24.85

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
9/23/1994	53.64	52.04	18.72	18.96	18.94	[no data]	[no data]	23.81	dry	[no data]	25.02
10/25/1994	53.72	52.12	18.74	18.9	18.99	[no data]	[no data]	23.81	dry	[no data]	25.04
11/30/1994	53.75	52.2	18.62	18.63	18.84	[no data]	[no data]	23.45	dry	[no data]	24.68
1/26/1995	53.77	52.28	18.48	18.34	18.52	[no data]	[no data]	22.86	23.05	[no data]	23.79
2/27/1995	53.8	52.32	18.45	18.28	18.4	[no data]	[no data]	22.68	22.83	23.83	23.86
4/27/1995	53.82	52.34	18.49	18.4	18.38	[no data]	[no data]	22.42	22.62	23.67	23.67
5/30/1995	53.86	52.3	18.64	18.69	18.58	[no data]	[no data]	22.71	22.62	23.94	23.94
6/28/1995	53.88	52.35	18.79	18.93	18.8	[no data]	[no data]	22.16	22.79	24.4	24.39
7/18/1995	53.92	52.36	18.89	19.08	18.95	[no data]	[no data]	23.54	23.11	dry	24.76
8/15/1995	53.98	52.4	18.99	19.23	19.14	[no data]	[no data]	23.95	dry	dry	25.27
9/12/1995	53.98	52.42	19.03	19.27	19.24	[no data]	[no data]	24.13	dry	dry	25.35
10/6/1995	53.98	52.47	19.06	19.3	19.31	[no data]	[no data]	24.27	dry	dry	25.47
11/14/1995	54.05	52.53	19.05	19.17	19.31	[no data]	[no data]	24.13	dry	dry	25.35
12/6/1995	54.09	52.54	19.02	19.08	19.23	[no data]	[no data]	23.99	dry	dry	25.21
1/11/1996	54.14	52.6	18.93	18.85	19.04	[no data]	[no data]	23.62	dry	dry	25.26
2/5/1996	54.22	52.62	18.91	18.75	18.92	[no data]	[no data]	23.42	dry	dry	24.67
3/4/1996	54.23	52.72	18.84	18.71	18.81	[no data]	[no data]	23.22	dry	24.47	24.46
4/4/1996	54.31	52.85	18.79	18.73	18.81	[no data]	[no data]	23.08	23.16	24.35	24.33
4/23/1996	54.1	52.52	[no data]	18.93	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	24.35
5/7/1996	54.32	52.74	19	19.03	18.89	[no data]	[no data]	23.27	23.17	24.52	24.51
6/5/1996	54.31	52.78	19.16	19.3	19.14	[no data]	[no data]	23.74	dry	dry	24.96
7/3/1996	54.34	52.8	19.29	19.52	19.34	[no data]	[no data]	24.21	dry	dry	25.41
8/6/1996	54.39	dry	19.38	19.61	19.57	[no data]	[no data]	24.52	dry	dry	25.71
9/4/1996	54.43	dry	19.46	19.7	19.67	[no data]	[no data]	24.71	dry	dry	25.88
10/3/1996	54.39	52.93	19.49	19.73	19.73	[no data]	[no data]	24.79	dry	dry	25.98
11/5/1996	54.42	53.01	19.45	19.57	19.74	[no data]	[no data]	24.69	dry	dry	25.9
1/14/1997	54.56	53.07	19.17	19.08	19.3	[no data]	[no data]	23.96	dry	dry	25.19
2/3/1997	54.57	53.08	19.1	18.99	19.19	[no data]	[no data]	23.8	dry	dry	25.01
3/3/1997	54.68	dry	18.99	18.84	19.02	[no data]	[no data]	23.59	dry	dry	24.83

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
4/3/1997	54.66	dry	19.12	18.96	18.97	[no data]	[no data]	23.44	dry	dry	24.73
5/2/1997	54.68	53.2	19.27	19.22	19.09	[no data]	[no data]	23.56	dry	dry	24.79
6/2/1997	54.69	dry	19.45	19.54	19.36	[no data]	[no data]	24.04	dry	dry	24.85
7/8/1997	54.76	53.21	19.64	22.04	19.7	[no data]	[no data]	24.63	dry	dry	22.82
9/2/1997	54.84	dry	19.84	19.96	19.94	[no data]	[no data]	25.11	dry	dry	26.27
10/14/1997	54.78	dry	19.87	19.87	19.96	[no data]	[no data]	25.01	dry	dry	26.18
12/8/1997	54.93	dry	19.86	19.69	19.85	[no data]	[no data]	24.64	dry	dry	25.85
2/3/1998	54.95	dry	19.68	19.44	19.6	[no data]	[no data]	24.13	dry	dry	25.35
8/5/1998	55.16	dry	20.17	20.26	20.14	[no data]	[no data]	25.28	dry	dry	26.42
3/20/1999	55.24	dry	20.3	20.51	20.45	[no data]	[no data]	25.61	dry	dry	26.62
10/5/1999	55.67	dry	20.83	20.58	20.74	[no data]	[no data]	25.82	dry	dry	26.92
2/15/2000	55.87	dry	20.99	20.86	21.1	[no data]	[no data]	26.33	dry	dry	27.33
5/1/2000	55.66	dry	[no data]	20.13	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	26.35
11/2/2000	55.98	dry	21.28	21.21	21.27	[no data]	[no data]	26.68	dry	dry	27.73
7/26/2001	55.9	[no data]	20.92	20.42	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	27.9
3/11/2002	55.82	[no data]	[no data]	18.13	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
10/31/2002	55.9	dry	21.67	21.07	21.16	[no data]	[no data]	29.04	dry	dry	28.78
11/27/2002	55.9	53.19	21.59	20.73	21.06	[no data]	[no data]	27.81	dry	dry	28.66
1/30/2003	55.83	dry	21.09	19.56	20.14	[no data]	[no data]	27.12	dry	dry	28.13
2/28/2003	55.8	dry	21	19.61	19.78	[no data]	[no data]	26.93	dry	dry	27.94
3/28/2003	55.77	dry	21.26	20.2	19.89	[no data]	[no data]	26.79	dry	dry	27.8
4/24/2003	55.52	53.12	[no data]	20.73	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	26.45
4/30/2003	55.75	dry	21.53	20.79	20.32	[no data]	[no data]	26.77	dry	dry	27.79
6/3/2003	55.78	dry	21.8	21.37	20.84	[no data]	[no data]	27.22	dry	dry	28.08
7/1/2003	55.82	53.39	22.07	21.74	21.25	[no data]	[no data]	27.91	dry	dry	28.59
7/31/2003	55.88	dry	22.28	21.99	dry	[no data]	[no data]	28.38	dry	dry	28.96
8/28/2003	55.85	dry	22.41	22.14	dry	[no data]	[no data]	28.52	dry	dry	29.17
9/30/2003	55.89	dry	22.55	22.27	dry	[no data]	[no data]	28.68	dry	dry	29.33
10/30/2003	55.93	dry	22.63	22.43	dry	[no data]	[no data]	28.89	dry	dry	29.56

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
11/25/2003	56	dry	22.65	22.41	dry	[no data]	[no data]	28.7	dry	dry	29.38
1/15/2004	56.06	dry	22.66	22.22	dry	[no data]	[no data]	28.12	dry	dry	29.21
2/2/2004	56.08	dry	22.65	22.14	dry	[no data]	[no data]	28.01	dry	dry	29.1
4/1/2004	56.12	dry	22.71	22.25	dry	[no data]	[no data]	27.77	dry	dry	28.87
4/19/2004	55.98	dry	[no data]	22.47	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	27.68
5/4/2004	56.22	dry	22.88	22.53	dry	[no data]	[no data]	28.21	dry	dry	29.14
7/1/2004	56.38	dry	23.22	22.97	dry	[no data]	[no data]	29.2	dry	dry	29.81
8/3/2004	56.48	dry	23.42	23.23	dry	[no data]	[no data]	29.69	dry	dry	30.2
9/1/2004	56.53	dry	23.5	23.34	dry	[no data]	[no data]	29.94	dry	dry	30.39
5/12/2005	56.53	[no data]	[no data]	23.63	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
4/19/2006	56.92	dry	[no data]	24.38	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	31.96
1/5/2007	57.27	dry	25.53	25.29	dry	[no data]	[no data]	33.05	dry	dry	33.31
5/11/2007	57.45	dry	25.72	25.53	dry	[no data]	[no data]	33.21	dry	dry	33.37
8/15/2007	57.49	dry	26.13	26.11	dry	[no data]	[no data]	34.99	dry	dry	33.78
9/17/2007	57.34	dry	[no data]	26.33	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	34.82
3/31/2008	57.5	[no data]	[no data]	26.3	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
4/23/2009	57.97	dry	26.72	26.07	dry	[no data]	[no data]	dry	dry	dry	dry
8/18/2009	58.1	dry	26.98	27.56	dry	[no data]	[no data]	dry	dry	dry	dry
10/6/2009	57.94	dry	[no data]	27.83	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
10/30/2009	58.2	dry	27.72	27.68	dry	[no data]	[no data]	dry	dry	dry	dry
12/15/2009	58.25	dry	27.63	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	dry	[no data]
12/21/2009	[no data]	[no data]	[no data]	27.34	dry	[no data]	[no data]	dry	dry	dry	dry
3/19/2010	58.03	53.27	27.33	26.9	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
6/9/2011	58.52	dry	27.85	28.44		[no data]	[no data]				
10/19/2011	58.49	dry	28.9	29.56	dry	[no data]	[no data]	dry	dry	dry	[no data]
12/22/2011	58.79	dry	29.1	29.36		[no data]	[no data]				
4/10/2012	58.64	dry	28.99	29.28	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
4/12/2012	58.87	dry	29.11	29.31		[no data]	[no data]				
6/4/2012	58.93	dry	29.32	29.76		[no data]	[no data]				

Date	H-1 level	H-2 level	J-2 level	J-3 level	J-4 level	J-5 level	K-1 level	K-2 level	K-3 level	K-4 level	K-5 level
10/29/2012	59.14	dry	30.33	30.94		[no data]	[no data]				
11/1/2012	58.9	dry	29.81	30.84	dry	[no data]	[no data]	dry	dry	dry	dry
1/8/2013	59.47	dry	30.14	30.67		[no data]	[no data]				
3/13/2013	59.45	dry	29.97	30.08		[no data]	[no data]				
5/10/2013	59.1	dry	29.84	30.15	dry	[no data]	[no data]	dry	dry	dry	dry
7/11/2013	59.56	dry	30.48	31.11		[no data]	[no data]				
9/5/2013	59.76	dry	30.62	31.82		[no data]	[no data]				
12/30/2013	59.71	dry	30.95	31.43		[no data]	[no data]				
4/16/2014	59.44	[no data]	30.72	31.08	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]	[no data]
4/21/2014	59.76	dry	30.9	31.12		[no data]	[no data]				
9/16/2014	60.05	dry	31.48	dry		[no data]	[no data]				
1/5/2015	60.03	dry	31.39	dry		[no data]	[no data]				

Appendix B: Approximate Water Level Data for Well J-1 from 1959-1974

Figure 3 in (Swain 1974) includes a graph showing water level measurements made in the hand-dug well in the Oasis of Mara (well J-1) between 1940 and 1974. The USGS National Water Information System (NWIS) has data from 1939 to 1958 that correspond to points on the graph, but no data from 1958 to 1974. he only record of these data which we are aware of is the graph in Swain (1974), reproduced in Figure B-1, below.

We extracted the approximate well levels from the figure by measuring the positions of the data points on the graph (Table B-1). Because the vertical and horizontal scales on the graph extend over large ranges (40 feet and 39 years, respectively), small inaccuracies due to drafting errors in the original pen-and-ink drawing can introduce significant uncertainty into the extracted data. For instance, the circular markers for each data point have a diameter corresponding to 0.5 feet on the vertical axis. We estimate that the uncertainty in the data is ±0.5 mm on the original figure, or approximately ±0.3 feet of water level and ±60 days for the measurement date.

The approximate water level data given below can be used to illustrate how water level has changed over several decades. However, these data are not appropriate for many quantitative analyses.

Table B-1. Approximate water level data for well J-1 extracted from graph in Swain (1974).

Approximate Date	Approximate Depth to Water
3/20/1959	2.88
7/21/1959	4.02
1/23/1960	3.26
7/27/1960	2.76
8/2/1961	3.96
2/4/1962	4.15
6/8/1962	3.33
12/10/1962	5.22
4/13/1963	4.02
2/16/1964	3.26
6/19/1964	3.39
12/22/1964	4.65
6/26/1965	4.72
12/28/1965	3.83
5/1/1966	3.20
3/7/1967	6.36
5/7/1967	3.77
3/12/1968	4.84
3/18/1969	3.77
7/26/1970	3.77
6/19/1974	7.06

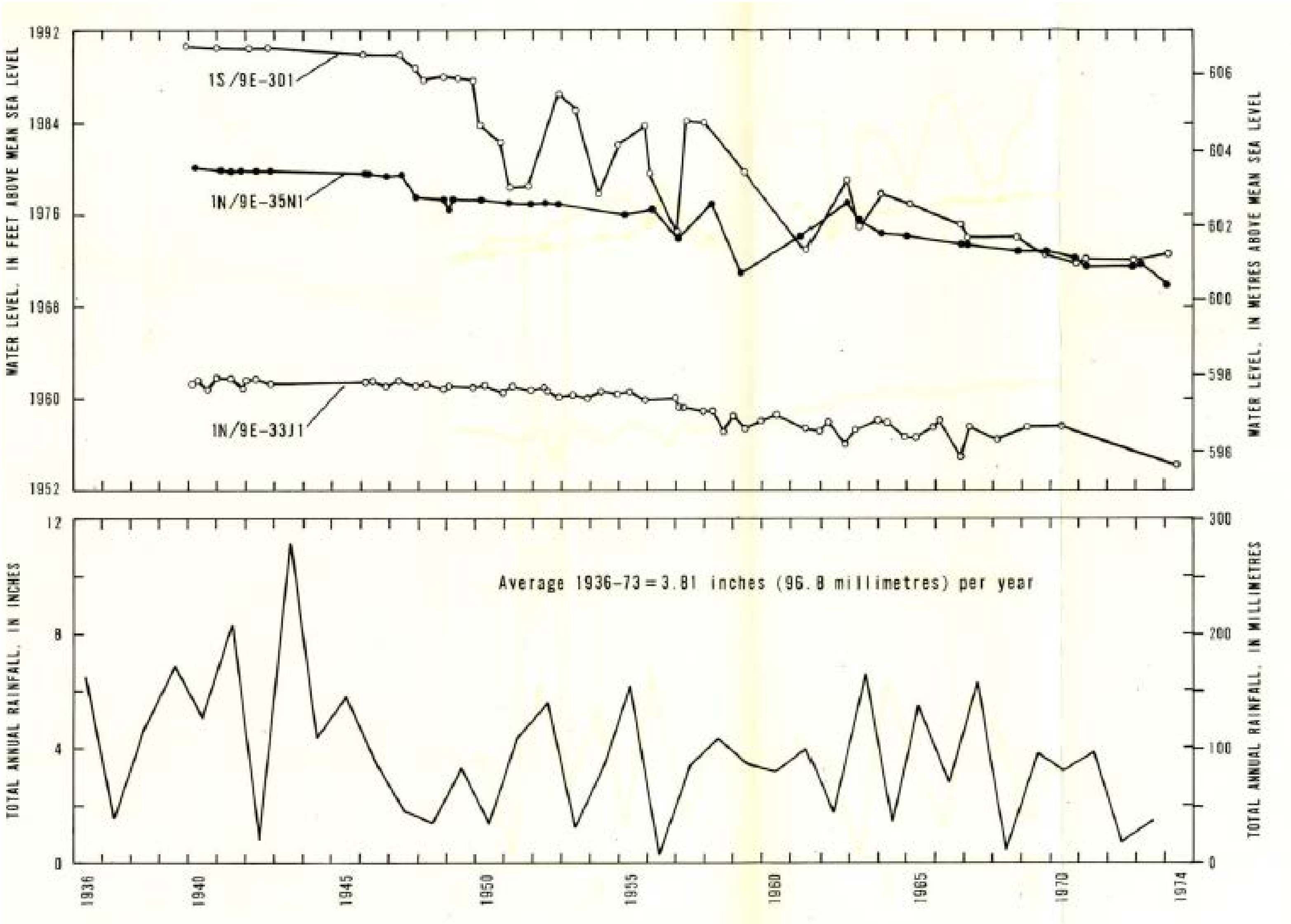

FIGURE 3.--Hydrographs of ground-water levels and rainfall near the Oasis of Mara.

Figure B-1. Reproduction of Figure 3 from Swain (1974) at approximately the original size. Well J-1 is the bottom-most hydrograph in the upper figure, labeled “1N/9E-33J1”.

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