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Results of Monitoring Water Levels in the Wetlands of Fourmile Branch near the F and H Areas of SRS: January to December 2001

by

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Executive Summary

Since 1996, a network of piezometers has been used to measure hydraulic head in the water-table aquifer (Upper Aquifer Zone of the Upper Three Runs Aquifer, or UAZ of the UTRA) along the groundwater outcrops (i.e. seeplines) near the F- and H-Areas. The piezometers were installed near the seepline to assess potential impacts of the F- and H-Area Groundwater Remediation Wastewater Treatment Units (WTUs) on the riparian wetlands located between the former F- and H-Area seepage basins and Fourmile Branch. The piezometers were installed in those areas expected to be most impacted by the remediation system.

The goals of the RCRA Part B Permit governing the WTUs are to 1) achieve a 70% reduction in the mass flux of tritium to Fourmile Branch within five years of Corrective Action Plan approval and reduce the discharge of other contaminants (metals and radionuclides other than tritium) to Fourmile Branch to levels less than the Groundwater Protection Standards (GWPS), and 2) reduce the discharge at the seepline of all contaminants to levels that are less than the GWPS by July 31, 2010. Because operation of the WTUs had the potential to dry portions of the nearby wetland areas, the purpose of the piezometer network was: 1) to establish baseline hydraulic head data for the water-table aquifer (UAZ) at the F- and H-Area seeplines prior to startup of the groundwater extraction/injection remediation system (completed), and 2) to observe the effects of the remediation system on the hydraulic head after system start-up (ongoing).

Hydraulic head was measured monthly using electric tape at each of the twenty-three piezometers. For the piezometers equipped with data loggers, hydraulic head was recorded every eight hours in addition to the monthly electric tape measurements. Results from 2001 were compared with previous years' results, including results recorded before the WTUs began operating (the baseline period).

The average hydraulic head at nearly all F-Area piezometers in 2001 decreased from 2000. Average decline in the average hydraulic head for the F-Area piezometers was 0.7 ft. The largest changes in average elevation for the F-Area piezometers occurred at locations FPZ002A and FPZ004A, with decreases of 1.4 ft and 1.3 ft, respectively, compared to 2000. The only location where average hydraulic head did not decrease was FPZ008A, where the average head was essentially unchanged. All locations exhibited decreases in hydraulic head compared to the baseline levels, with a maximum decline in average hydraulic head of 6.4 ft at location FPZ004A.

Hydraulic head at H-Area piezometers generally increased slightly from 2000 levels. The changes from 2000 average elevations ranged from a decrease of 0.2 ft at HPZ002A to an increase of 0.5 ft at HPZ003A. On the average, hydraulic head for H-Area piezometers increased 0.2 ft. The average hydraulic head at most of the piezometers was lower than the baseline level, but the HPZ003A, HPZ003B and HPZ006A locations, which are influenced by Fourmile Branch flows, exhibited higher hydraulic heads in 2001 than in the baseline period. HPZ003A/B and HPZ006A have exhibited little or no effect from operation of the WTUs in the past. Changes from the baseline period ranged from a 4.8 ft decrease at HPZ002A to a 0.8 ft increase at HPZ006A.

The average hydraulic head at the reference piezometers changed minimally from 2000 and did not show a clear trend in 2001. The average hydraulic head increased slightly at FHR002, decreased slightly at FHR003, and remained unchanged at FHR001. The average change in reference piezometer hydraulic head was a 0.1 ft increase. Compared with the first six months of data recorded at these sites (the baseline for the reference piezometers), average hydraulic heads were lower in 2001 by a range of 0.3 ft to 2.9 ft.

Rainfall in 2001 was the lowest rainfall recorded in both F and H Areas since this project began in 1996. Although rainfall during the first part of the year was close to the historical average (1985-2000) rainfall, less than one inch of rain per month fell during the last quarter of the year, bringing the year-end total well below average. Rainfall recorded in F Area was about 40 in., which was considerably less than the historical average of 49 in. Rainfall in H Area for 2001 was about 37 in, which also was considerably less than the historical average of about 52 in. A correlation analysis indicated that hydraulic head was strongly correlated to cumulative rainfall deficit/surplus at some locations.

Overall, the F-Area WTU extracted over 85 million gallons of groundwater in 2001, exceeding the amount extracted in 2000 by 1%. Continued full operation of the F-Area WTUs contributed to the overall decline in hydraulic head, especially at locations FPZ004A and FPZ002A. Total groundwater extracted by the H-Area WTU in 2001 was nearly 70 million gallons, about 4% less than in 2000. An extended outage in August and the resulting rise in hydraulic head near the extraction wells tempered the effects of the continuing drought at the H-Area piezometers in 2001. However, long term effects of WTU operation were still evident at locations HPZ002A, HPZ005A and HPZ005B. Strong negative correlation coefficients calculated for groundwater extraction volumes and hydraulic head at many locations supported the observations.

A time series analysis was performed on hydraulic head measurements at FPZ004A and HPZ002A. For FPZ004A, the volume of groundwater extracted, cumulative rainfall surplus/deficit, monthly rainfall, and the product of rainfall surplus/deficit and extraction were all statistically important factors in predicting hydraulic head, explaining 98% of the hydraulic head variation. However, after the F-Area WTU began full operation, minor changes in extraction rates did not appear to be an important factor. For HPZ002A, the volume of groundwater extracted and cumulative rainfall surplus/deficit were the only statistically important factors in predicting hydraulic head, explaining 93% of the hydraulic head variation. The same two factors were statistically important for predicting changes in hydraulic head even when looking only at the period of time since the H-Area WTU began full operation.

Wetlands are defined by the presence of hydric soils, saturated soil conditions during a portion of the growing season, and vegetation adapted to live in saturated soils. Lowering groundwater levels for a prolonged period could change the wetland hydrologic conditions and the vegetation growing in these areas. In many locations, the hydraulic head never reached the root zone during 2001. For nearly three years, the decline in hydraulic head at HPZ002A and HPZ005A/B kept the water table below levels required to sustain the herbaceous components of wetland vegetation. The water table remained below the root zone throughout 2001 at FPZ002A, as well, increasing the total time span in which the water table remained below root level to more than two years for that location. These hydrologic conditions may allow early successional species to germinate in these areas. However, these changes would not cause the areas to lose their wetland classification. In other areas, changes already have occurred. Nelson (2001) documented changes in herbaceous species diversity and establishment of early successional non-wetland species due to declines in water levels in recent years in the F- and H-Area tree kill zones, areas where tree mortality in seepline-fed wetlands downslope from the seepage basins was first identified in the 1970s. FPZ005A and HPZ001A are located in these tree kill areas. The water table has remained below the root zone for three years at FPZ004A and FHR002. These areas, also, could be subject to wetland vegetation changes if the trend continues. However, hydraulic head measurements at FPZ004A and FHR002 have remained below the root zone for the entire monitoring period except for 1998. The frequency of saturated soil conditions at these locations prior to 1996 is not known.

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Introduction

Seepage basins in the F and H Areas of the Savannah River Site (SRS) used to receive low-level radioactive wastewater from the nuclear materials separations facilities. This wastewater consisted mostly of sodium hydroxide, nitric acid, low levels of various radionuclides (primarily tritium) and some metals (Killian et al. 1985a, b). Discharges to the seepage basins were discontinued in 1988 and the basins were closed in accordance with an approved RCRA closure plan by February 1991.

As a result of basin operations, the aquifer beneath and down-gradient of the basins was contaminated. The contamination is located primarily in the Upper Aquifer Zone (UAZ) (i.e. the water-table aquifer) of the Upper Three Runs Aquifer (UTRA) and in the Lower Aquifer Zone (LAZ) of the UTRA. Near the seepage basins in both F and H Area, shallow groundwater flows toward Fourmile Branch. The UAZ discharges to the wetlands and Fourmile Branch, whereas the LAZ discharges primarily to Fourmile Branch. Contaminants originating from the seepage basins have been detected in shallow groundwater outcrops (i.e. the seepline) in the wetlands along Fourmile Branch near both F and H Areas (Haselow et al. 1990; Dixon et al. 1993; Dixon and Rogers 1993, Dixon et al. 1994).

Groundwater remediation wastewater treatment units (WTUs) were installed near F and H Areas in accordance with a Resource Conservation and Recovery Act (RCRA) Hazardous Waste Part B Permit to clean up the groundwater. The goals of the RCRA Part B Permit are to 1) achieve a 70% reduction in the mass flux of tritium to Fourmile Branch within five years of Corrective Action Plan approval and reduce the discharge of other contaminants (metals and radionuclides other than tritium) to Fourmile Branch to levels less than the Groundwater Protection Standards (GWPS), and 2) reduce the discharge at the seepline of all contaminants to levels that are less than the GWPS by July 31, 2010. The WTUs include a network of extraction and injection wells. Figures 1 and 2 show the locations of the wetlands near Fourmile Branch and the extraction wells for the water-table aquifer (the UAZ of the UTRA) in F Area and H Area, respectively. The extraction well numbers have the prefix "FEX" or "HEX."

Models simulating the operation of the WTUs predicted decreases in the water level of up to six feet at the seepline and in the wetlands nearby (Sadler 1995, Flach 1998). Decreases in water levels could result in drying of a portion of the wetlands, and an overall movement of the seepline towards Fourmile Branch. Chronic depression of the water table at portions of the wetlands affected by the extraction wells could alter the wetland plant and animal communities in this area.

Changes in water levels in and near the wetlands along Fourmile Branch have been monitored to assess the impacts of the F- and H-Area WTU remediation systems on the wetlands. The definition of wetlands differs from one federal agency to another. Under the U. S. Environmental Protection Agency (EPA) and the U. S. Corps of Engineers (USCOE) definition, an area must exhibit three attributes – hydric soil, hydrophytic vegetation and wetland hydrology – to be considered a wetland. An area is considered to have wetland hydrology if it is inundated or saturated to the surface continuously for at least 5% of the growing season in most years. For soil saturation to impact vegetation, it must occur within a major portion of the root zone (usually within 12 inches of the surface) (USCOE 1987).

To accomplish this monitoring, a network of piezometers was established in 1996 in and near the wetlands of Fourmile Branch in both F and H Areas (Dixon 1996). The purpose of the piezometer network was two-fold: 1) to establish baseline hydraulic head data for the water-table aquifer (the UAZ of the UTRA) at the F- and H-Area seeplines prior to startup of the groundwater extraction/injection remediation system (the pre-operational period), and 2) to observe the effects of the remediation system on the water table levels after system start-up. The first objective, developing a baseline, was completed in 1997. The second objective is ongoing. The purpose of this report is to present the results of the monthly and continuous hydraulic head elevations measured in 2001 at these piezometers.

Piezometer Installation and Instrumentation

Twenty-three water-table piezometers have been installed at seventeen locations in and near the wetlands of Fourmile Branch near F and H Areas since January 1996. During January and May of 1996, twenty of the piezometers were installed at fourteen locations in F (Figure 1) and H Areas (Figure 2). These piezometers were given the prefixes "FPZ" and "HPZ," respectively. The piezometers were installed near the current seepline, focusing on those areas expected to be most impacted by the remediation system. The location of the seepline varies with time depending on the elevation of the water table. At locations with heterogeneous stratigraphy, piezometers were installed in clusters so that the hydraulic head could be measured for each layer. The deeper piezometers were given well numbers with the suffix "A" and the shallower piezometers, the suffix "B."

In June 1997, three additional piezometers were installed in a reference area located in the wetlands of Fourmile Branch, but outside the area of influence of the remediation system. These piezometers have the prefixes "FHR" (Figure 3). Hydraulic head changes observed in these reference piezometers could be compared to changes observed in the FPZ and HPZ piezometers to help distinguish between natural variation in hydraulic head and treatment system impacts.

With the exception of FPZ003A, all piezometers were installed using hand augering equipment (3 1/4" bucket auger) in accordance with WSRC-3Q5 (Chapter 7) procedures. Installation methods are detailed in Dixon (1996). Piezometer FPZ003A, which is located in an upland area, was installed using a hollow stem augering method due to the depth to the water table at this location. Additional piezometer construction information can be found in Halverson (2000).

To investigate the natural water level variability and storm event influences in the Fourmile Branch riparian wetland system, nine piezometers were equipped with data logging equipment in 1996 to allow continuous water level monitoring. Five additional piezometers were equipped with data loggers in 1998. The three reference piezometers were equipped with data loggers in December 1999.

Methods

Water levels in the piezometers were measured monthly in 2001 using a manual electric water-level tape. From these measurements, the hydraulic head was determined for each location.

Water levels were measured and recorded every eight hours at the piezometers equipped with data loggers. In late summer, the data loggers were reprogrammed to take measurements hourly as recommended by the manufacturer to prolong battery life.

The data loggers in use during most of 2001 were In-Situ Inc. TROLL Model SP4000 units with 15 psig pressure transducers. An unusually long cold spell during the winter of 2000/2001 shortened the life of the data logger batteries. Battery levels in several data loggers dropped too low to sustain logger operation. As a result, data loggers from fourteen piezometers along the F and H-Area seeplines were removed during 2001 and sent back to the manufacturer's facilities for data recovery, battery replacement and recalibration during 2001. During this period, hydraulic heads at a few locations were recorded using back-up data loggers, In-Situ Inc.'s miniTROLL data loggers, with 15 psi pressure transducers. Monthly measurements with the electric water tape were continued during this period. For some piezometers, data recorded between the last data downloading and the time that the data logger quit functioning was recovered. By October 23, all the TROLL SP4000 data loggers were reinstalled in the piezometers.

The data loggers installed in HPZ003A and HPZ004A experienced calibration problems in the early part of 2001. Data from this period was deleted.

Status of the Wastewater Treatment Units

The monthly volumes of groundwater treated by the F-Area and H-Area WTUs (1997–2001) are shown in Table 1 and Table 2, respectively. Daily extraction (i.e. pumping) rates for 2001 are shown in Figure 4.

The F-Area Groundwater Remediation WTU began operating in shakedown mode in April 1997. The facility operated in this manner during the remainder of 1997 and all of 1998. Flow rates were limited due to system testing, and full-operation was not initiated. Pumping rates were not consistent due to significant system downtime. The total volumes of groundwater extracted in 1997 and 1998 were approximately 1.7 million gallons and 15 million gallons, respectively, in F Area (WSRC 1997a, 1998a&c, 1999a). In 1999, the F-Area WTU operated 57% of the time and extracted approximately 47 million gallons of water. In 2000, the F-Area WTU extracted nearly 85 million gallons of water, approximately twice the 1999 volume, and operated 94% of the time. Outages were few and of short duration.

In 2001, the F-Area WTU operated in a manner similar to 2000, extracting over 85 million gallons of water (Wells 2001, Long 2002), approximately 1% more than the 2000 total.

The H-Area WTU began operating in a shakedown mode in July 1997 and continued in this mode in 1998. Flow rates were limited due to system testing and limited injection well capacity, and there was significant system downtime (WSRC 1997b, 1998b&d, 1999b). Annual volumes extracted were approximately 1.2 million gallons and 15 million gallons in 1997 and 1998, respectively. In 1999, the H-Area WTU operated 82% of the time and extracted 58 million gallons of water. In 2000, the H-Area WTU extracted approximately 73 million gallons of water, approximately 30% more than in 1999, and operated 98% of the time.

In 2001, the H-Area WTU operated in a manner similar to 2000, extracting nearly 70 million gallons of water (Wells 2001, Long 2002). Total groundwater extracted in 2001 was about 4% less than in 2000. The decrease was primarily due to an extended outage in August.

Results and Discussion

Rainfall in 2001 was the lowest recorded since 1988. For the first half of the year, cumulative rainfall remained close to the long-term (1985-2000) average; however, less than one inch of rain per month fell during the last quarter of the year, bringing the year-end total well below average. Rainfall totals for 2001 were 39.8 inches (averaging 3.3 inches per month) measured at F Area and 37.3 inches (averaging 3.1 inches per month) measured at H Area. The average monthly rainfall calculated for the pre-operational period was 3.9 inches per month for both F Area and H Area. The long-term average annual rainfall is 49 inches in F Area and 51 inches in H Area. Monthly and cumulative rainfall amounts for 1996 through 2001 and the long-term average are shown in Figure 5 and Figure 6 for F Area and H Area, respectively. The 2001 total rainfall in F Area was 4% lower than the 2000 total rainfall and 19% lower than the long-term average. H-Area rainfall was 9% lower than the 2000 total rainfall and 28% lower than the long-term average.

Results from the monthly hydraulic head measurements for the period of September 1996 through December 2001 are presented in Table 3. Summary statistics for each location are presented in Table 4. Table 4 also presents summary statistics based on the data logger measurements for the period from January 2000 to December 2001.

Table 5 compares the hydraulic head measurements from 2001 with 2000 measurements for the "A" series (deeper wells) and reference piezometers. Maximum, minimum and average measurements at nearly all F-Area piezometers were lower in 2001 than in 2000. The average change in elevation across the piezometer network was a 0.7 ft decrease from 2000 levels. The largest differences in average elevation for F-Area piezometers occurred in FPZ002A and FPZ004A, with decrease of 1.4 ft and 1.3 ft, respectively, compared to 2000. On the average, the standard deviation for F-Area piezometers was roughly half of the 2000 levels.

For the H-Area piezometers, average hydraulic head measurements were higher for all but one piezometer, HPZ002A, which decreased by 0.2 ft. HPZ002A had the largest decrease in 2000 and in 1999. Water level elevation in the H-Area piezometer network increased an average of 0.2 ft from 2000 levels. Maximum and minimum hydraulic head measurements were also higher for most piezometers in 2001 than in 2000 (Table 5). On the average, the standard deviation for H-Area piezometers in 2001 decreased.

The reference piezometers did not show a clear trend. The average hydraulic head increased at FHR002 (0.5 ft), decreased slightly (0.2 ft) at FHR003 and remained constant at FHR001 (Table 5). The increase at FHR002 is in contrast to last year's results, when FHR002 exhibited the greatest decrease in average hydraulic head. From 2000 to 2001, the average change in average hydraulic head elevations over all three reference piezometers was a 0.1 ft increase.

Table 6 compares the 2001 groundwater elevations with baseline elevations. For F- and H-Area piezometers, the pre-operational period was used for the baseline (January 1996 through March 1997 for F Area and January 1996 through June 1997 for H Area) (WSRC 1997a, 1998c). For the reference piezometers, the first 6 months of data (July – December 1997) were used as a baseline. These baseline periods spanned less than two years. Thus, while the baseline data may be useful for comparison with current water levels, that data may not truly represent the long-term average water levels at these locations.

The 2001 minimum and average hydraulic head elevations were all lower than in the pre-operational period for the F-Area piezometers, though FPZ008A was only 0.2 ft lower. The largest change in average elevation for F-Area piezometers occurred in FPZ002A and FPZ004A, with decreases of 5.0 feet and 6.4 ft, respectively, compared to pre-operational levels. The average change in elevation across the piezometer network was a 2.6 ft decrease from pre-operational period levels. All F-Area piezometers except FPZ008A exhibited an increase in standard deviation in 2001 compared to the pre-operational period. On the average, the standard deviation for F-Area piezometers in 2001 was five times the pre-operational level.

In 2001, minimum and average hydraulic head elevations were lower for most H-Area locations compared to the pre-operational period (Table 6). The average hydraulic head elevation was higher at HPZ003A and HPZ006A compared to the pre-operational period. However, these piezometers are located within the wetlands bordering Fourmile Branch and could have been influenced by seasonal stream flows and periodic beaver-dam building activity. On the average, hydraulic head elevations in 2000 were 1.5 ft lower than in the pre-operational period. The largest changes in average elevation occurred in HPZ002A and HPZ005A, with decreases of 4.8 ft and 3.6 ft, respectively, compared with pre-operational levels. The standard deviation was higher in 2000 than in the pre-operational period for all H-Area piezometers. On the average, the standard deviation for H-Area piezometers in 1999 was nearly twice the pre-operational level.

Elevations at all the reference piezometers decreased in 2001 compared with the baseline, with declines ranging from 0.3 ft to 2.9 ft. (Table 5). FHR003 levels showed less variation from baseline levels than either FHR001 or FHR002. The greatest decrease from baseline occurred at FHR002, in spite of the increases seen this past year. The average decrease in average hydraulic head elevations over all three reference piezometers was 1.7 ft compared to baseline.

Hydrographs for each F- and H-Area piezometer location were created from the monthly measurements and are presented in Figures 7 through 20. Hydrographs for the reference locations are shown in Figures 21 through 23. Each hydrograph covers the entire monitoring period.

Hydrographs of the hydraulic head elevations, based on the data logger measurements, are shown in Figures 24 through 37 for the F- and

H-Area piezometers. Figures 38, 39 and 40 show the hydrographs from the data loggers at the reference piezometers. Elevations for the years 1996 to 2001 are plotted together. For periods in 2001 when the data loggers were not operating, monthly data are shown. Rainfall in 2001 is also plotted on each of these hydrographs for comparison with the 2001 elevation data.

Hydraulic head at FPZ002A (Figure 25) has remained below the plant root zone since September 1999. Hydraulic head at HPZ002A (Figure 33) has remained below the plant root zone for nearly three years. Hydraulic head at HPZ005A/B (Figures 19 and 36) also has remained below the root zone for the past three years except for two very short periods in 1999. The water table has remained below the root zone for three years at FPZ004A (Figure 27) and FHR002 (Figure 22), but since this study began in 1996, hydraulic head at these locations reached the root zone only during 1998 and the frequency of saturated soil conditions prior to 1996 is not known.

All three reference piezometers ended the year with hydraulic heads greater than at the beginning of the year, in spite of the fact that total rainfall in 2001 was actually less than in 2000. H-Area piezometers generally ended the year with similar or higher hydraulic head than at the beginning of the year, except for HPZ002A and HPZ005A, both known to be affected by the groundwater extraction. In contrast, F-Area piezometers generally ended the year with lower hydraulic heads.

Changes in hydraulic head elevations from 2000 to 2001 were not as dramatic as those seen from 1999 to 2000. Hydraulic head patterns for individual piezometers were similar to 2000 patterns, as well. Patterns were similar to FHR001 and FHR002 were evident in several seepline piezometers. Elevations at FPZ003A (Figure9), FPZ004A (Figure 10), HPZ001A (Figure 15), HPZ002A (Figure 16), HPZ004A (Figure 18) and HPZ005A (Figure 19) show general decline since early to mid 1998. However, overall decline at FPZ001A (Figure 7), FPZ002A (Figure 8), FPZ006A (Figure 12) and FPZ007A (Figure 13) did not begin until early to mid 1999, and decline at FPZ005A (Figure 11) did not begin until early 2000. In general, the closer a piezometer was to an extraction well, the earlier the hydraulic head decline began.

The maximum range of hydraulic head elevations in 2001, 6.2 ft, occurred at FHR002 (Table 4). This location has typically experienced a wide range in hydraulic head variance. FPZ003A and HPZ005A experienced similar variability, with ranges of 5.8 ft and 5.9 ft, respectively.

The fact that the monthly hydraulic head measurements at many of the F- and H-Area piezometers exhibited a pattern similar to those in the reference locations might indicate that the hydraulic head level changes in 2001 could be simply the result of natural causes. However, a comparison between changes in hydraulic head and changes in rainfall indicated that the extraction wells were at least partly responsible for the hydraulic head changes. For each piezometer, the difference between the annual average hydraulic head and the baseline is displayed for the years 1998 through 2001 in Figure 41. The differences between the baseline rainfall (annualized) and rainfall for 1998-2001 are also shown, as well as the annual volumes of groundwater extracted at the F-Area and H-Area WTUs. In F-Area, most hydraulic head responses approximate the rainfall changes in 1998, 1999 and 2001. However, the relatively large decreases in hydraulic head in 2000 were not reflected by rainfall, which remained essentially unchanged from 1999 levels. The change in extraction volumes from 1999 to 2000 in F Area (Figure 41), however, did explain the large decreases in hydraulic head. In H Area and the reference piezometers, the 2001 data generally did not seem to follow the rainfall pattern, with increases in hydraulic head in spite of decreases in rainfall compared with the baseline. The slight decrease in extraction volume from 2000 to 2001 in H Area (Figure 41) may provide a partial explanation.

To determine whether increased operation of the WTUs affected the hydraulic head at the seepline piezometers, the daily volume of groundwater extracted was plotted along with the hydrographs of piezometers that exhibited declining head levels. Effects were discernable at some piezometers, but because the outages at the WTUs were few and of short duration and frequently coincided with rainfall or periods when the data loggers had been removed for battery replacement, the effect of outages on the hydraulic head was not always clear. The effect was most pronounced at FPZ004A, HPZ002A and HPZ005A. These are the three piezometers closest to extraction wells. In addition, the extraction wells closest to FPZ004A and HPZ002A extracted more groundwater than the other extraction wells.

Figure 42 compares F-Area WTU groundwater extraction and hydraulic head at piezometer FPZ004A. The effect of the extraction on the hydraulic head could be seen clearly during three brief periods when the extraction pumps were shut down in the fall, a period with little rain to obfuscate the effect. During these times, the hydrographs showed rapid increases in hydraulic head that look different from the shorter-lived, nearly instantaneous increases brought about by rainfall events. Then the hydraulic head began to decline again when the extraction pumps resumed operating. For FPZ004A, hydraulic head increased by approximately 2.1 inches per day during the three-day outage in late October. A similar effect could be seen to a lesser degree at FPZ002A, FPZ005A, FPZ006A and FPZ007A.

Figure 43 shows the comparison between H-Area WTU groundwater extraction and hydraulic head at piezometer HPZ002A and HPZ005A. The hydraulic head response shows up clearly during the extended outage in August. Hydraulic head increases during the outage period averaged 1.3 in/day for HPZ002A and 0.7 in/day for HPZ005A.

The correlation data analysis tool in Excel was used to identify the strength of relationships between hydraulic head trends and operational, season and rainfall trends. Monthly average hydraulic heads were calculated and compared with monthly values for groundwater extraction, average daily high temperature (to identify seasonal trends), total rainfall, and variance between cumulative rainfall and the average cumulative rainfall (e.g. rainfall deficit or surplus, calculated using monthly rainfall averaged from 1985-2000 data). The population correlation calculation returns a coefficient (r) equal to the covariance of the two data sets divided by the product of their standard deviations.

The population correlation calculation can determine whether two ranges of data move together. If the two sets of data tend to increase together, r is positive. If one set tends to increase as the other tends to decrease, r is negative. The value of correlation coefficient lies between -1 and +1, inclusive. The sign of the correlation coefficient determines whether the correlation is positive or negative. The magnitude of the correlation coefficient determines the strength of the correlation. A value of +1 indicates perfect positive correlation, a value of –1 indicates perfect negative correlation and a value of zero indicates the two data sets are unrelated.

Results of the correlation calculations are shown in Table 7. Strong (defined for the purposes of this report as $0.7 \leq |r| \leq 1.0$) negative correlation existed between groundwater extraction volumes and hydraulic head for most F Area locations: FPZ001A, FPZ002A, FPZ004A, FPZ006A, FPZ007A and FPZ008A. Strong negative correlation also existed for H Area locations HPZ001A, HPZ002A and HPZ005A.The negative value indicated the expected result that higher volumes of groundwater extraction corresponded to lower hydraulic head elevations.

Correlation coefficients calculated for the reference piezometers and the remaining F- and H-Area piezometers, except HPZ003A and HPZ006A, were moderate (defined for the purposes of this report as $0.5 \leq |\rho| < 0.6$) or moderately strong ($0.6 \leq |\rho| < 0.7$) and negative. Correlation was the weakest at HPZ003A, with a correlation coefficient of -0.46. Results for HPZ006A differed from all other locations in that the correlation coefficient was positive, indicating that higher volumes of groundwater extraction correlated to higher hydraulic head elevations at that location.

FPZ001A, FPZ002A and FPZ004A hydraulic heads also were strongly correlated to cumulative rainfall deficit/surplus. Seasonal influence (i.e. correlation with temperature) was fairly low at all locations, with the strongest correlation occurring FPZ003A (r = -0.56)

HPZ006A results were notable, not only because of the positive correlation between head and extraction, but also because there was no correlation between hydraulic head elevation and either monthly rainfall (r = 0) or rainfall deficit (r = 0.02, Table 7). Also, HPZ006A was the only location with a positive correlation between hydraulic head and temperature, indicating that the elevation tended to rise when temperatures rose. However, the magnitude of the correlation coefficient was fairly low.

While the correlation coefficient is useful as an estimation of the strength of linear relationship between two data sets, the presence of a strong correlation does not necessarily indicate a cause and effect relationship between the two parameters. To further understand the relative effects of rainfall and extraction on the hydraulic head, two locations were chosen for further analysis. FPZ004A and HPZ002A were chosen because they showed the strongest correlation between hydraulic head and extraction. A time series analysis was performed on the collected data using JMP software. Two sets of analyses were run: the first covering the period January 1997 through December 2001 and the second covering the period from onset of full operation to December 2001.

For FPZ004A, the volume of groundwater extracted, cumulative rainfall surplus/deficit, monthly rainfall, and the product of rainfall surplus/deficit and extraction were all statistically important factors in predicting hydraulic head, explaining 98% of the hydraulic head variation. Plots of hydraulic head vs. each of these parameters are shown in Figure 44. A plot of actual vs. predicted hydraulic head is also shown in Figure 44.

When looking only at the period of full operation of the F-Area WTU (August 1999 through December 2001), however, the statistically important factors for predicting changes in hydraulic head were cumulative rainfall surplus/deficit, monthly rainfall and temperature, together explaining 94% of the variation. Minor changes in extraction rates during full operation of the WTU did not appear to be an important factor. A plot of the results for actual vs. predicted hydraulic head is shown in Figure 45.

Results were somewhat different for HPZ002A. The volume of groundwater extracted and cumulative rainfall surplus/deficit were the only statistically important factors in predicting hydraulic head, explaining 93% of the hydraulic head variation. Plots of hydraulic head vs. each of these parameters are shown in Figure 46. A plot of actual vs. predicted hydraulic head is also shown in Figure 46.

The same two factors were statistically important for predicting changes in hydraulic head even when looking only at the period of full operation of the H-Area WTU (May 1999 through December 2001). However, they explained only about 61% of the variation in hydraulic head during that period. A plot of the results for actual vs. predicted hydraulic head is shown in Figure 47. The difference between the results for HPZ002A and FPZ004A might have been due to fact that the H-Area WTU shut down for an extended period during the summer of 2001. The isolated point in Figure 47(c) represents that period of shutdown.

Conclusions

Average hydraulic heads at nearly all of the piezometers located near the F-Area seepline were lower in 2001 than in 2000 and the pre-operational period. In contrast, average hydraulic head in nearly all the H-Area piezometers increased in 2001 compared to 2000, though most were lower than the pre-operational elevations. Comparison of average hydraulic heads at the reference piezometers for 2001 vs. 2000 gave mixed results, though all locations had lower average elevations than in the pre-operational period. The greatest decreases in average hydraulic head continue to be in the piezometers closest to the F- and H-Area extraction wells.

For F Area, the declines in hydraulic head may be partly due to three consecutive years of low rainfall. For H Area, the slight increases appear to be primarily due to a prolonged outage of the extraction wells in the summer.

The continued operation of the WTUs in 2001 clearly affected the hydraulic head in piezometers located closest to the extraction wells. Strong negative correlation coefficients calculated for groundwater extraction volumes and hydraulic head at many locations supported the observations. Outage periods were visible on the hydrographs for piezometers FPZ004A, HPZ002A and HPZ005A. WTU outages resulted in increasing hydraulic head levels. Start-up after an outage resulted in declining hydraulic head levels at those locations. A similar effect could be seen to a lesser degree at FPZ002A, FPZ005A, FPZ006A and FPZ007A. Outages at the WTUs were few and of short duration in 2001; therefore, the effects of outages were less visible in the 2001 hydrographs than in the 1999 hydrographs, when outages were more frequent and typically of longer duration. This does not imply, however, that the overall effect of the WTUs on the hydraulic head was less in 2001 than in 1999.

A time series analysis was performed on hydraulic head measurements at FPZ004A and HPZ002A. For FPZ004A, the volume of groundwater extracted, cumulative rainfall surplus/deficit, monthly rainfall, and the product of rainfall surplus/deficit and extraction were all statistically important factors in predicting hydraulic head, explaining 98% of the hydraulic head variation. However, after the F-Area WTU began full operation, minor changes in extraction rates did not appear to be an important factor. For HPZ002A, the volume of groundwater extracted and cumulative rainfall surplus/deficit were the only statistically important factors in predicting hydraulic head, explaining 93% of the hydraulic head variation. The same two factors were statistically important for predicting changes in hydraulic head even when looking only at the period of time since the H-Area WTU began full operation.

WTU groundwater extraction probably was not the only cause of the decline in hydraulic head levels during 2001. Three consecutive year of below average rainfall could be a major contributor. Rainfall in 2001 was the lowest recorded since 1988. A correlation analysis indicated that hydraulic head was strongly correlated to cumulative rainfall deficit/surplus at some locations.

Wetlands are defined by the presence of hydric soils, saturated soil conditions during a portion of the growing season, and vegetation adapted to live in saturated soils. Lowering groundwater levels for a prolonged period could change the wetland hydrologic conditions and the vegetation growing in these areas. In many locations, the hydraulic head never reached the root zone during 2001. For nearly three years, the decline in hydraulic head at HPZ002A (Figure 33) and HPZ005A/B (Figure 36) kept the water table below levels required to sustain the herbaceous components of wetland vegetation. The water table remained below the root zone throughout 2001 at FPZ002A (Figure 25), as well, increasing the total time span in which the water table remained below root level to more than two years for that location. These hydrologic conditions may allow early successional species to germinate in these areas. However, these changes would not cause the areas to lose their wetland classification. In other areas, changes already have occurred. Nelson (2001) documented changes in herbaceous species diversity and establishment of early successional non-wetland species due to declines in water levels in recent years in the F- and H-Area tree kill zones, areas where tree mortality in seepline-fed wetlands downslope from the seepage basins was first identified in the 1970s. FPZ005A and HPZ001A are located in these tree kill areas. The water table has remained below the root zone for three years at FPZ004A and FHR002 (Figure 3). These areas, also, could be subject to wetland vegetation changes if the trend continues. However, hydraulic head measurements at FPZ004A and FHR002 have remained below the root zone for the entire monitoring period except for 1998. The frequency of saturated soil conditions at these locations prior to 1996 is not known.

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Table 1. Groundwater extraction (thousands of gallons) by the F-Area Groundwater Remediation Wastewater Treatment Unit, 1997 to 2001.

Well ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1997													
TOTAL	*0*	*0*	*0*	*10*	*29*	*29*	*40*	*411*	*189*	*235*	*173*	*560*	*1,676*
1998													
TOTAL	*570*	*547*	*390*	*0*	*0*	*0*	*1,214*	*3,468*	*2,448*	*3,137*	*1,680*	*1,173*	*14,627*
1999													
TOTAL	*842*	*573*	*913*	*4,621*	*4,626*	*1,106*	*1,397*	*3,883*	*6,739*	*7,615*	*6,565*	*7,683*	*46,562*
2000													
TOTAL	*7,586*	*6,093*	*7,593*	*7,363*	*6,404*	*7,302*	*7,529*	*6,624*	*6,381*	*7,530*	*7,231*	*7,098*	*84,739*
2001													
FEX-1	1,567	1,022	1,379	1,254	1,297	1,168	1,264	1,257	1,227	1,117	1,254	1,376	*15,181*
FEX-2	1,539	921	1,323	1,229	1,262	1,150	1,248	1,239	1,170	1,115	1,254	1,290	*14,742*
FEX-3	1,224	823	1,161	1,079	1,145	1,044	1,133	1,130	1,012	968	1,146	1,083	*12,947*
FEX-4	508	915	1,019	1,123	1,069	1,063	1,189	1,159	1,026	1,058	1,174	1,134	*12,434*
FEX-5	103	184	250	255	278	237	275	265	226	222	261	229	*2,786*
FEX-6	763	586	756	753	781	489	621	779	721	680	762	594	*8,282*
FEX-7	942	729	940	901	946	710	727	924	834	802	907	878	*10,240*
FEX-8	338	270	355	344	351	318	355	348	298	305	343	335	*3,960*
FEX-9	429	300	327	339	361	347	344	350	298	296	333	301	*4,024*
FEX-10	0	0	0	21	61	183	166	35	34	0	0	0	*499*
FEX-11	0	0	0	20	60	183	182	35	0	0	0	0	*480*
TOTAL	*7,413*	*5,750*	*7,510*	*7,318*	*7,611*	*6,892*	*7,504*	*7,521*	*6,846*	*6,563*	*7,434*	*7,220*	*85,576*

Sources: Long (2001, 2002), Wells (2001), WSRC (1997a, 1998a&c, 1999a&c, 2000a&c, 2001a)

Table 2. Groundwater extraction (thousands of gallons) by the H-Area Groundwater Remediation Wastewater Treatment Unit, 1997 to 2001.

Well ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1997													
TOTAL	*0*	*0*	*0*	*0*	*0*	*0*	*20*	*0*	*792*	*192*	*23*	*206*	*1,234*
1998													
TOTAL	*133*	*598*	*1,930*	*312*	*0*	*1,227*	*2,142*	*1,805*	*2,494*	*2,298*	*90*	*2,078*	*15,107*
1999													
TOTAL	*1,062*	*3,401*	*4,458*	*4,013*	*2,582*	*6,072*	*6,291*	*6,119*	*5,665*	*6,340*	*5,762*	*6,262*	*58,027*
2000													
TOTAL	*6,285*	*5,581*	*6,285*	*6,006*	*5,724*	*5,990*	*6,231*	*6,049*	*5,899*	*6,229*	*6,061*	*6,181*	*72,525*
2001													
HEX-1	961	905	993	930	992	974	937	434	981	1,100	1,017	1,064	*11,286*
HEX-2	0	0	0	0	0	0	0	0	0	0	0	0	
HEX-3	818	741	795	804	822	867	789	375	822	898	875	889	*9,496*
HEX-4	650	591	643	649	683	715	728	349	717	699	614	618	*7,655*
HEX-9	383	365	402	420	428	286	402	188	385	397	373	379	*4,407*
HEX-12	211	198	217	212	218	211	219	94	210	218	214	214	*2,435*
HEX-16	0	0	0	0	0	0	0	0	0	0	0	0	
HEX-17	1,643	1,538	1,722	1,638	1,689	1,750	1,846	727	1,564	1,673	1,825	1,871	*19,488*
HEX-18	1,220	1,221	1,265	1,191	1,192	1,107	1,191	508	1,044	1,219	1,078	1,162	*13,398*
HEX-19	147	136	159	169	99	142	151	21	65	108	112	102	*1,413*
TOTAL	*6,033*	*5,695*	*6,196*	*6,013*	*6,123*	*6,052*	*6,263*	*2,696*	*5,788*	*6,312*	*6,108*	*6,299*	*69,577*

Sources: Long (2001, 2002), Wells (2001), WSRC (1997b, 1998b&d, 1999b&d, 2000b&d, 2001b)

Table 3. Monthly water levels (feet, msl) at individual piezometers, January to December 2001.

Piezometer ID	Water Level Elevations												Ground Elevation
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
FPZ001A	196.0	196.1	196.3	195.9	195.4	195.7	195.9	195.0	195.5	194.6	194.9	194.7	197.90
FPZ002A	196.8	196.9	196.8	196.8	196.3	196.5	196.7	195.9	196.1	195.4	195.4	195.3	201.20
FPZ003A	189.1	188.2	189.3	187.7	185.8	187.3	187.3	185.7	185.8	185.0	185.3	185.4	194.00
FPZ004A	194.9	195.6	195.5	195.2	194.8	195.0	195.1	194.4	194.6	193.7	193.9	193.8	203.10
FPZ005A	190.2	190.2	190.4	190.0	189.6	189.9	190.6	189.2	189.9	188.7	189.4	189.1	190.90
FPZ005B	190.3	190.2	190.4	190.0	189.7	189.9	189.8	189.2	-	188.6	189.5	189.2	190.90
FPZ006A	188.5	188.6	188.8	188.2	187.4	188.0	187.9	187.0	187.8	186.6	187.2	187.0	189.40
FPZ006B	188.9	188.8	189.0	188.4	187.4	188.0	187.8	186.7	-	185.9	186.7	186.6	189.40
FPZ007A	190.7	191.4	191.6	190.9	190.2	190.9	191.5	190.1	190.6	189.5	191.3	189.9	194.50
FPZ007B	192.4	192.4	192.8	191.9	191.4	192.1	190.9	190.1	-	189.8	192.3	190.3	194.50
FPZ008A	187.5	187.5	187.6	187.4	187.4	187.4	187.5	187.4	187.5	187.3	187.5	187.4	187.40
FPZ008B	187.6	187.6	187.6	187.5	187.5	187.5	187.6	187.5	-	186.5	187.6	187.5	187.40
HPZ001A	202.1	202.1	202.1	202.0	201.9	201.9	202.5	201.5	202.0	201.6	202.0	202.0	202.40
HPZ002A	213.3	213.0	213.6	214.0	213.5	213.4	214.7	214.1	213.7	212.8	212.4	212.2	218.80
HPZ003A	201.1	201.1	201.2	201.2	201.0	201.2	201.3	201.1	201.3	201.2	201.2	201.2	200.40
HPZ003B	200.8	200.8	200.8	200.6	201.6	200.8	200.9	200.9	-	200.9	200.9	200.8	200.40
HPZ004A	209.2	209.2	209.3	209.3	209.2	209.1	209.2	209.2	209.2	209.3	209.1	209.0	210.70
HPZ005A	209.3	209.8	211.1	210.1	208.8	209.2	209.2	208.8	208.6	207.1	207.0	207.1	213.80
HPZ005B	209.3	209.9	211.3	210.1	208.7	209.2	209.3	208.8	-	208.2	207.8	207.8	213.80
HPZ006A	201.5	202.4	202.5	202.3	202.3	202.3	203.0	202.9	203.1	202.7	202.7	202.6	201.70
FHR001	265.2	265.6	266.9	268.5	267.4	267.5	267.2	266.5	266.5	265.9	265.7	265.6	269.90
FHR002	266.0	266.8	269.1	271.3	269.4	269.5	269.5	269.4	268.2	267.5	267.0	266.9	275.40
FHR003	219.7	219.7	219.7	219.8	219.6	219.6	219.7	219.6	219.7	219.7	219.7	219.7	220.50

Table 4. Maximum, minimum and average water level measurements from January to December 2001.

Piez. ID	Monthly Electric Tape Measurements						Continuous Measurements[b]					
	Max. Water Level (ft, msl)	Min. Water Level (ft, msl)	Avg. Water Level (ft, msl)	Change from 2000 Avg. (ft)[a]	Range (ft)	Std. Dev. (ft)	Max. Water Level (ft, msl)	Min. Water Level (ft, msl)	Avg. Water Level (ft, msl)	Change from 2000 Avg. (ft)[a]	Range (ft)	Std. Dev. (ft)
FPZ001A	196.3	194.6	195.5	-1.0	1.6	0.6	197.4	194.9	196.2	-0.5	2.5	0.5
FPZ002A	196.9	195.3	196.2	-1.3	1.6	0.6	196.9	195.1	196.0	-1.6	1.8	0.5
FPZ003A	189.3	185.0	186.8	-0.4	4.3	1.5	190.8	185.0	187.3	-0.2	5.8	1.9
FPZ004A	195.6	193.7	194.7	-1.5	1.8	0.6	195.4	193.7	194.5	-1.5	1.7	0.5
FPZ005A	190.6	188.7	189.8	-0.4	1.9	0.6	191.0	188.6	189.9	-0.5	2.4	0.7
FPZ005B	190.4	188.6	189.7	-0.6	1.8	0.5	NA	NA	NA	NA	NA	NA
FPZ006A	188.8	186.6	187.7	-0.2	2.2	0.7	189.2	186.3	187.8	-0.3	2.9	0.8
FPZ006B	189.0	185.9	187.6	-0.4	3.1	1.1	NA	NA	NA	NA	NA	NA
FPZ007A	191.6	189.5	190.7	-0.5	2.0	0.7	192.1	189.4	190.6	-0.5	2.7	0.7
FPZ007B	192.8	189.8	191.5	-0.9	3.0	1.1	NA	NA	NA	NA	NA	NA
FPZ008A	187.6	187.3	187.5	0.0	0.2	0.1	187.7	187.3	187.5	0.0	0.4	0.1
FPZ008B	187.6	186.5	187.4	-0.1	1.1	0.3	NA	NA	NA	NA	NA	NA
HPZ001A	202.5	201.5	202.0	0.1	1.0	0.2	202.2	201.4	201.9	0.1	0.8	0.2
HPZ002A	214.7	212.2	213.4	0.4[c]	2.4	0.7	215.2	212.2	213.3	-0.3	3.0	0.7
HPZ003A	201.3	201.0	201.2	0.4	0.4	0.1	202.0	201.2	201.2	0.0	0.8	0.1
HPZ003B	201.6	200.6	200.9	0.3	1.0	0.3	NA	NA	NA	NA	NA	NA
HPZ004A	209.3	209.0	209.2	0.3	0.3	0.1	209.9	208.6	209.2	-0.6	1.3	0.2
HPZ005A	211.1	207.0	208.8	0.4	4.2	1.3	212.7	206.7	209.0	0.1	6.0	1.5
HPZ005B	211.3	207.8	209.1	0.1	3.6	1.1	NA	NA	NA	NA	NA	NA
HPZ006A	203.1	201.5	202.5	0.1	1.6	0.4	203.5	202.4	202.7	0.1	1.1	0.1
FHR001	268.5	265.2	266.5	0.1	3.4	1.0	268.7	265.0	266.7	0.0	3.6	1.0
FHR002	271.3	266.0	268.3	0.0	5.3	1.5	272.2	266.0	268.6	0.5	6.2	1.6
FHR003	219.8	219.5	219.7	0.0	0.3	0.1	220.0	219.3	219.6	-0.2	0.6	0.1

[a] 2000 data were reported in Halverson (2001).
[b] Continuous measurements do not represent a full year of data because the data loggers were removed for battery replacement at some point during the year.
[c] Spurious data from July 2000 was deleted.
NA = Not Applicable

Table 5. Comparison of piezometer water-level statistics in 2000 and 2001.[a]

	Maximum			**Minimum**			**Average**			**Standard Deviation**		
Piezometer	2000 (ft, msl)	2001 (ft, msl)	Difference[b] (ft)	2000 (ft, msl)	2001 (ft, msl)	Difference[b] (ft)	2000 (ft, msl)	2001 (ft, msl)	Difference[b] (ft)	2000 (ft, msl)	2001 (ft, msl)	Difference[b] (ft)
FPZ001A	198.1	197.4	-0.7	195.6	194.6	-1.0	196.7	195.7	-1.0	0.6	0.5	-0.1
FPZ002A	199.3	196.9	-2.4	196.6	195.1	-1.4	197.6	196.3	-1.4	0.8	0.5	-0.3
FPZ003A	190.2	190.8	0.6	185.2	185.0	-0.2	187.4	187.1	-0.3	1.3	1.9	0.5
FPZ004A	197.8	195.6	-2.2	195.0	193.7	-1.3	196.1	194.8	-1.3	0.8	0.5	-0.3
FPZ005A	191.2	191.0	-0.1	189.1	188.6	-0.5	190.4	189.9	-0.5	0.5	0.7	0.2
FPZ006A	189.4	189.2	-0.2	186.6	186.3	-0.2	188.2	187.8	-0.4	0.6	0.8	0.2
FPZ007A	192.8	192.1	-0.7	189.7	189.4	-0.3	191.2	190.7	-0.5	0.7	0.7	0.0
FPZ008A	187.8	187.7	-0.1	187.1	187.3	0.2	187.5	187.5	0.0	0.1	0.1	-0.1
HPZ001A	202.5	202.2	-0.2	200.7	201.4	0.6	201.8	201.9	0.1	0.3	0.2	-0.1
HPZ002A	215.2	215.2	0.1	212.4	212.2	-0.3	213.5	213.3	-0.2	0.7	0.7	0.0
HPZ003A	201.4	202.0	0.6	200.2	201.0	0.7	200.8	201.2	0.5	0.4	0.1	-0.3
HPZ004A	209.7	209.9	0.2	207.2	208.6	1.4	208.9	209.2	0.3	0.8	0.2	-0.6
HPZ005A	212.1	212.7	0.6	207.2	206.7	-0.4	208.9	209.1	0.2	1.3	1.5	0.2
HPZ006A	205.0	203.5	-1.5	202.2	202.4	0.2	202.6	202.7	0.1	0.3	0.1	-0.1
FHR001	268.8	268.7	-0.1	265.0	265.0	0.0	266.7	266.7	0.0	1.2	1.0	-0.2
FHR002	271.6	272.2	0.6	266.0	266.0	0.0	268.1	268.6	0.5	1.8	1.6	-0.2
FHR003	220.4	220.0	-0.4	219.0	219.3	0.4	219.8	219.6	-0.2	0.2	0.1	-0.1

[a] 2001 data primarily based on data logger measurements, but hand measurements were substituted for months where no data logger data was available. 2000 data reported in Halverson (2001).
[b] Positive number indicates that the 2001 value was greater than the 2000 value. Negative number indicates the 2001 value was less than the 2000 value.

Table 6. Comparison of the 2001 piezometer water-level statistics with baseline values.[a]

Piezometer	**Maximum**			**Minimum**			**Average**			**Standard Deviation**		
	Baseline[b] (ft, msl)	2001 (ft, msl)	Difference[c] (ft)	Baseline[b] (ft, msl)	2001 (ft, msl)	Difference[c] (ft)	Baseline[b] (ft, msl)	2001 (ft, msl)	Difference[c] (ft)	Baseline[b] (ft, msl)	2001 (ft, msl)	Difference[c] (ft)
FPZ001A	198.1	197.4	-0.7	197.8	194.6	-3.2	197.9	195.7	-2.2	0.1	0.5	0.5
FPZ002A	201.9	196.9	-5.0	201.0	195.1	-5.8	201.2	196.3	-5.0	0.2	0.5	0.3
FPZ003A[d]	191.2	190.8	-0.4	187.1	185.0	-2.1	188.9	187.1	-1.7	1.2	1.9	0.7
FPZ004A	202.5	195.6	-6.9	200.9	193.7	-7.2	201.2	194.8	-6.4	0.2	0.5	0.3
FPZ005A	191.3	191.0	-0.3	191.0	188.6	-2.4	191.1	189.9	-1.2	0.1	0.7	0.6
FPZ006A	189.8	189.2	-0.6	188.5	186.3	-2.2	189.2	187.8	-1.4	0.3	0.8	0.6
FPZ007A[d]	193.3	192.1	-1.2	192.7	189.4	-3.2	193.0	190.7	-2.4	0.2	0.7	0.6
FPZ008A[d]	187.7	187.7	0.0	187.6	187.3	-0.2	187.6	187.5	-0.2	0.1	0.1	0.0
HPZ001A[d]	202.4	202.2	-0.2	202.1	201.4	-0.7	202.3	201.9	-0.4	0.1	0.2	0.1
HPZ002A	218.8	215.2	-3.5	217.4	212.2	-5.3	218.0	213.3	-4.8	0.3	0.7	0.4
HPZ003A	201.6	202.0	0.4	200.4	201.0	0.6	201.2	201.2	0.1	0.3	0.1	-0.2
HPZ004A	210.5	209.9	-0.6	209.9	208.6	-1.3	210.1	209.2	-0.9	0.1	0.2	0.1
HPZ005A	213.7	212.7	-1.0	211.5	206.7	-4.8	212.7	209.1	-3.6	0.4	1.5	1.1
HPZ006A[d]	202.1	203.5	1.3	201.5	202.4	0.9	201.9	202.7	0.8	0.2	0.1	0.0
FHR001[d]	269.5	268.7	-0.8	267.7	265.0	-2.7	268.6	266.7	-1.9	0.6	1.0	0.4
FHR002[d]	273.6	272.2	-1.4	269.9	266.0	-3.9	271.5	268.6	-2.9	1.3	1.6	0.3
FHR003[d]	220.0	220.0	0.0	219.8	219.3	-0.5	219.9	219.6	-0.3	0.1	0.1	0.0

[a] 2001 data primarily based on data logger measurements, but hand measurements were substituted for months where no data logger data was available.
[b] Baseline data reported in Halverson and Dixon (1999). Baseline for FPZ and HPZ piezometers was the pre-operational period: 1/96 – 3/97 for F-Area piezometers and 1/96 – 6/97 for H-Area piezometers. Baseline for the reference piezometers (FHR) was the first six months of data, 7/97 – 12/97.
[c] Positive number indicates that the 2001 value was greater than the pre-operational period value. Negative number indicates the 2001 value was less than the pre-operational period value.
[d] Baseline values were based on monthly electric tape measurements because data loggers were not installed at that time.

Table 7. Population Correlation Coefficients for Monthly Hydraulic Head vs. Groundwater Extraction, Temperature, Rainfall, and Cumulative Rainfall Surplus/Deficit. Strong correlation coefficients are shown in bold.

	Correlation Coefficient			
Location	**Extraction**	**Avg. Daily High Temp**	**Rainfall**	**Cumulative Rainfall Surplus/Deficit**[a]
FPZ001A	**-0.72**	-0.12	0.24	**0.72**
FPZ002A	**-0.87**	-0.07	0.27	**0.78**
FPZ003A	-0.51	-0.56	0.34	0.25
FPZ004A	**-0.89**	-0.04	0.27	**0.74**
FPZ005A	-0.64	-0.26	0.32	0.40
FPZ006A	**-0.70**	-0.33	0.27	0.67
FPZ007A	**-0.85**	-0.20	0.33	0.67
FPZ008A	**-0.77**	-0.44	0.29	0.61
HPZ001A	**-0.73**	-0.45	0.16	0.20
HPZ002A	**-0.91**	-0.07	0.34	0.58
HPZ003A	-0.46	-0.37	0.17	0.31
HPZ004A	-0.64	-0.30	0.17	0.53
HPZ005A	**-0.83**	-0.23	0.40	0.47
HPZ006A	0.60	0.24	0.00	0.02
FHR001[b]	-0.69	-0.06	0.40	0.62
FHR002[b]	-0.67	-0.03	0.41	0.57
FHR003[b]	-0.57	-0.30	0.34	0.53

[a] Assumed to be zero at the beginning of the program in 1996.
[b] Correlation with H-Area data.

Table 8. Population Correlation Coefficients between Groundwater Extraction, Rainfall, and Cumulative Rainfall Surplus/Deficit.

		Extraction	**Rainfall**	**Cumulative Rainfall Surplus/Deficit**[a]
F Area	Rainfall	-0.34		
F Area	Cumulative Rainfall Surplus/Deficit[a]	-0.48	0.26	
F Area	Avg. Daily High Temperature	0.04	0.00	0.07
H Area	Rainfall	-0.23		
H Area	Cumulative Rainfall Surplus/Deficit[a]	-0.30	0.31	
H Area	Avg. Daily High Temperature	0.07	0.01	0.06

[a] Assumed to be zero at the beginning of the program in 1996.

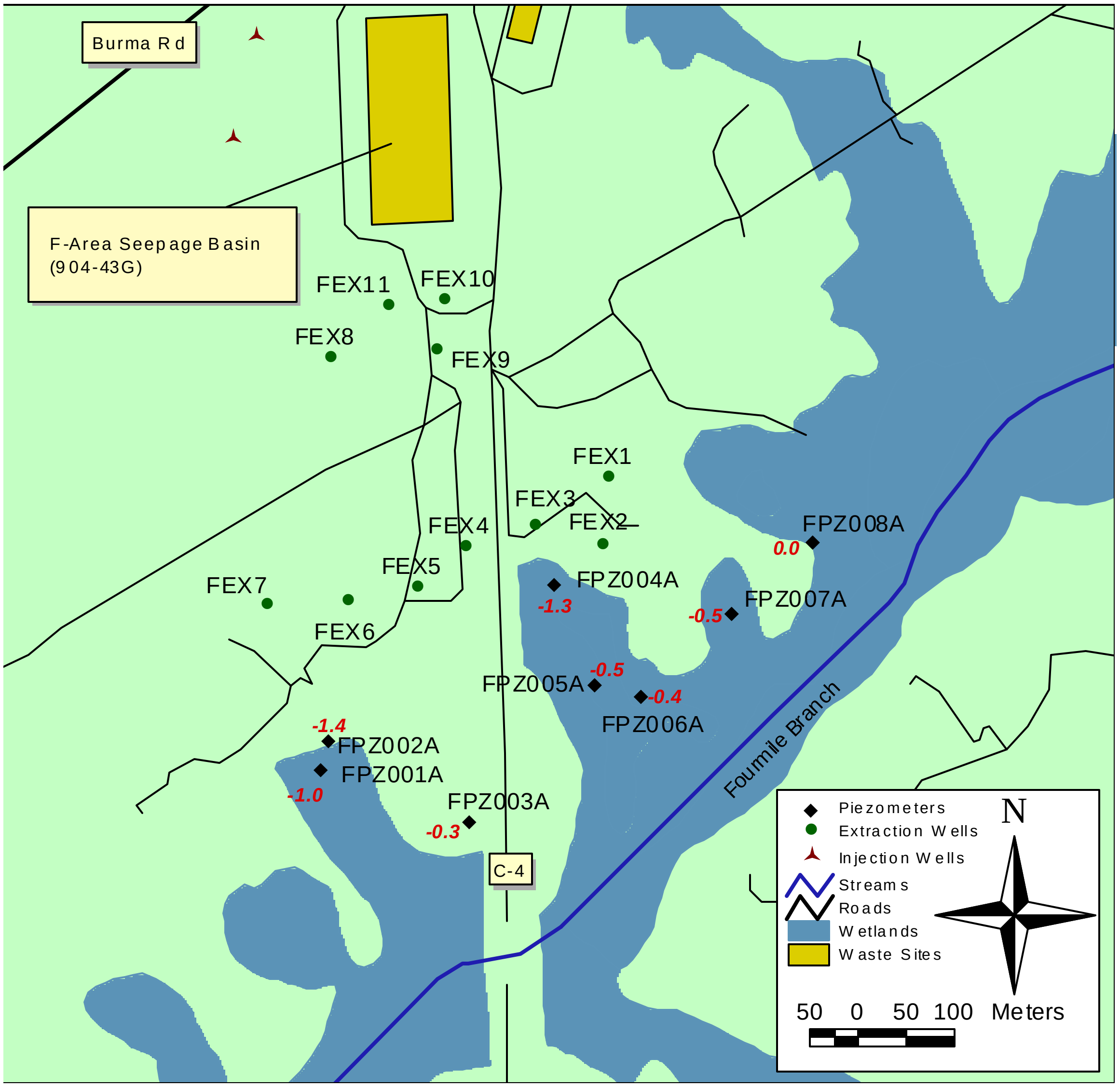


Figure 1. Extraction/injection well and piezometer locations for the water table aquifer (UAZ) in F-Area. Change in average hydraulic head elevation from 2000 to 2001 is shown in italics.

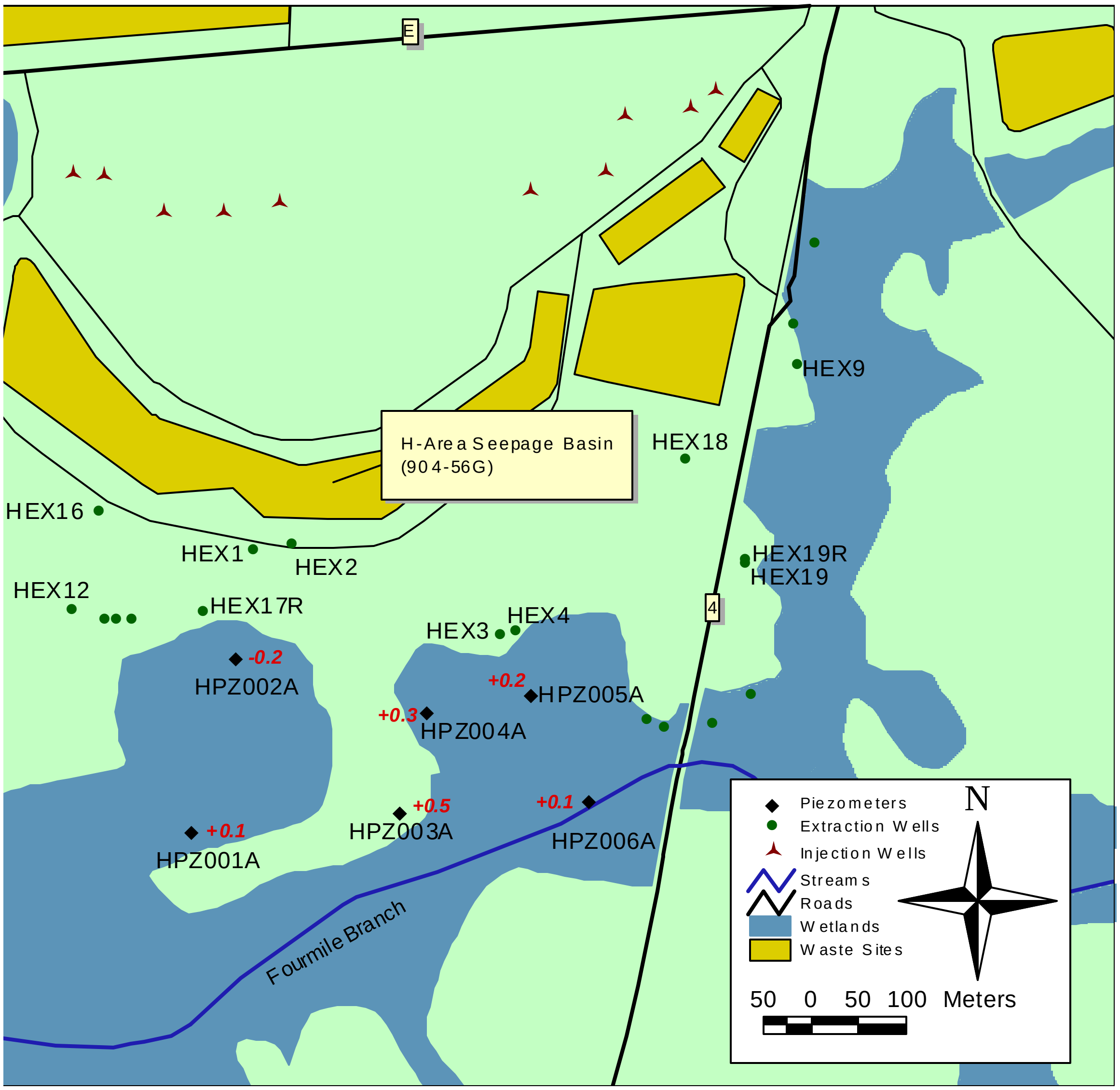


Figure 2. Extraction/injection well and piezometer locations for the water table aquifer (UAZ) in H-Area. Only operating extraction wells are labeled. Change in average hydraulic head elevation from 2000 to 2001 is shown in italics.

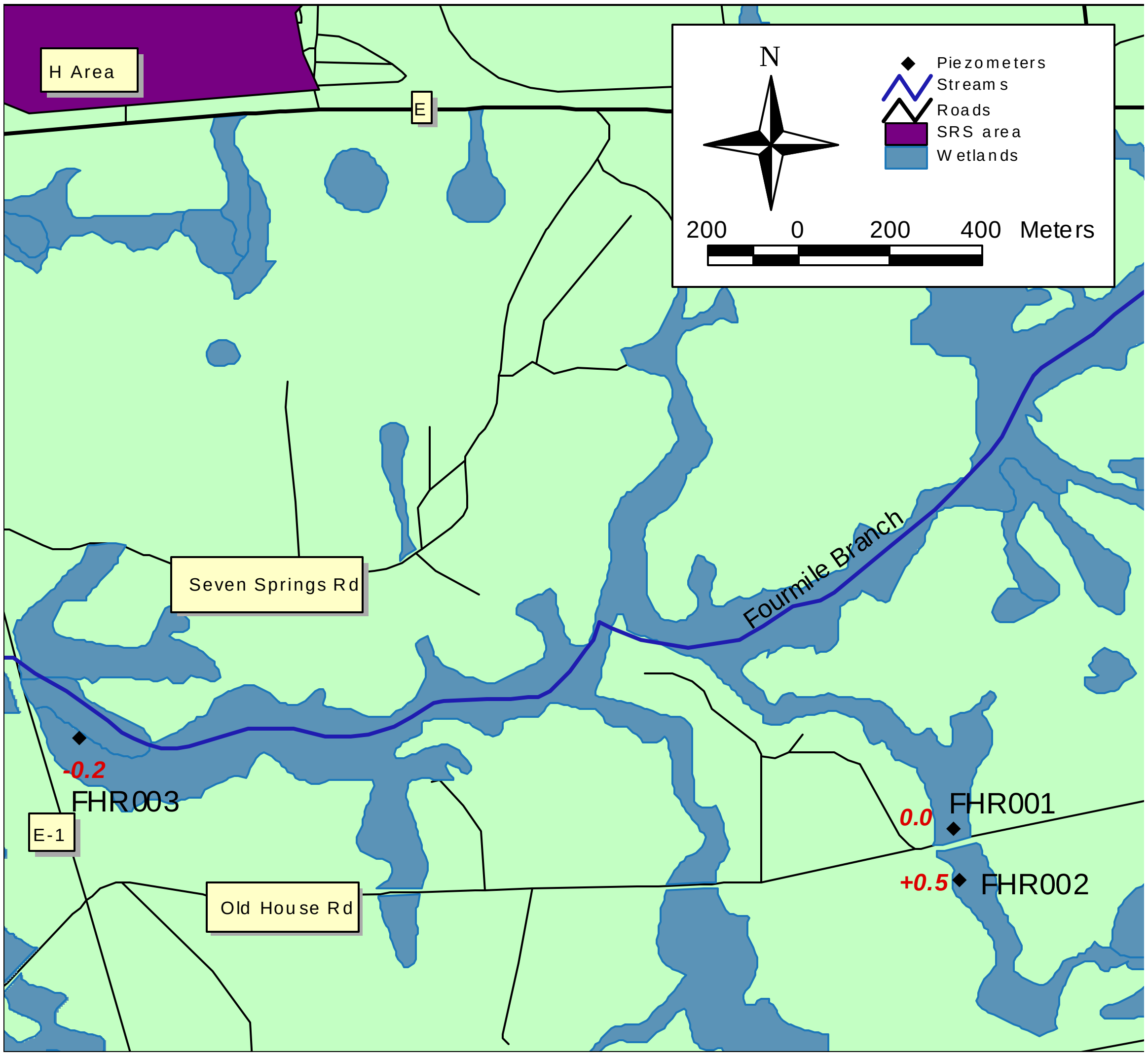
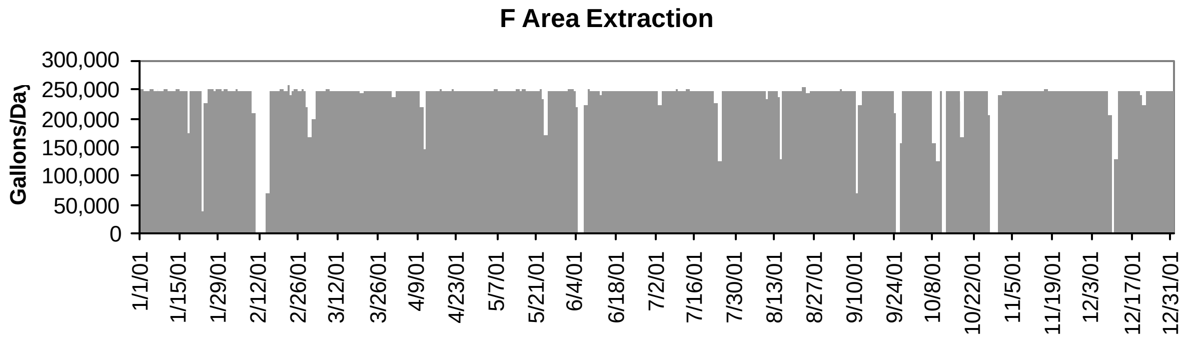


Figure 3. Reference piezometer locations. Change in average hydraulic head elevation from 2000 to 2001 is shown in italics.



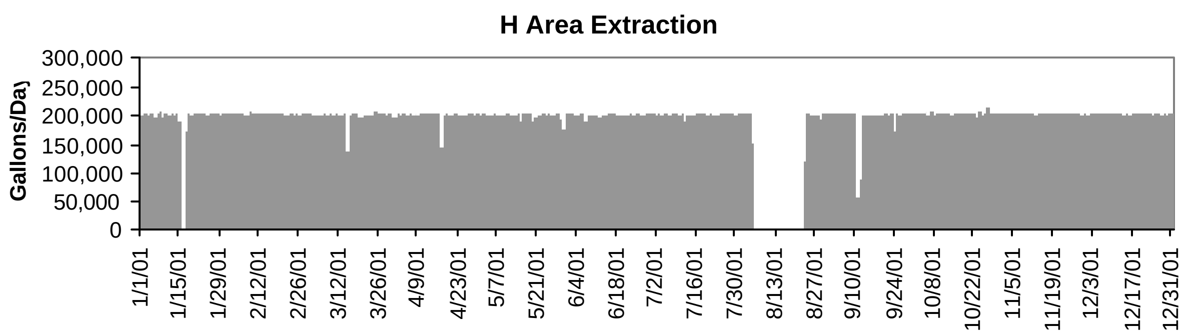
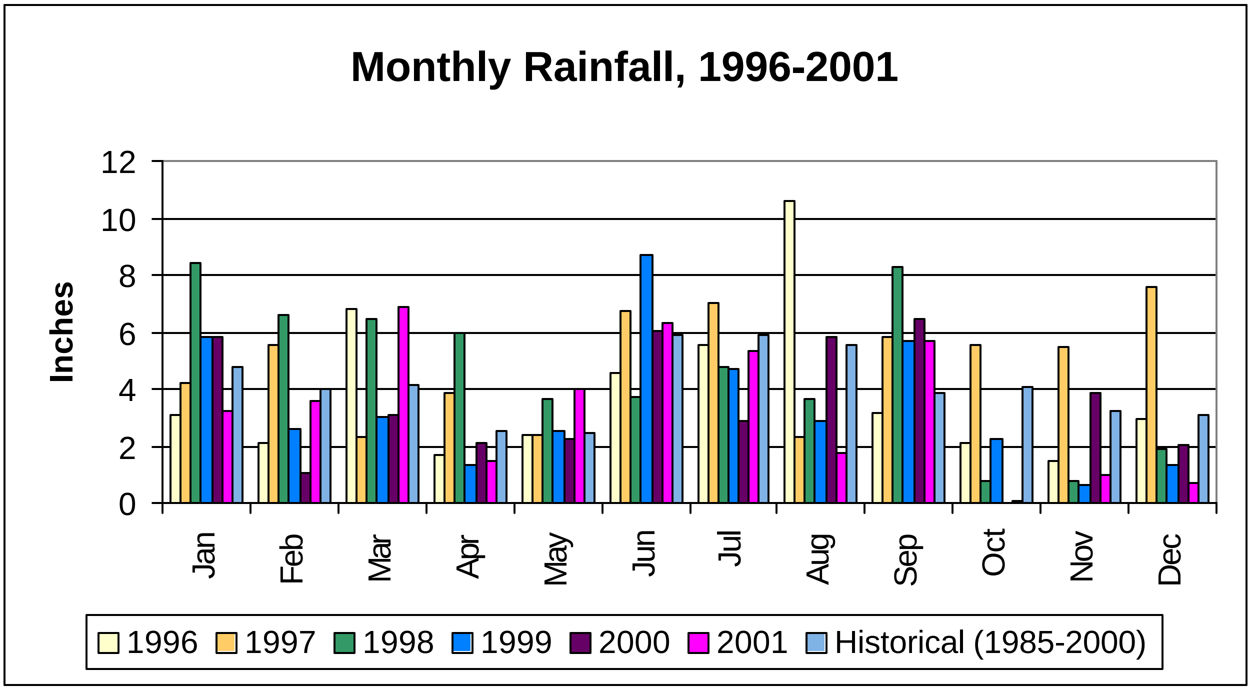


Figure 4. Groundwater extraction rates (gal/day) in F Area and H Area, 2001.



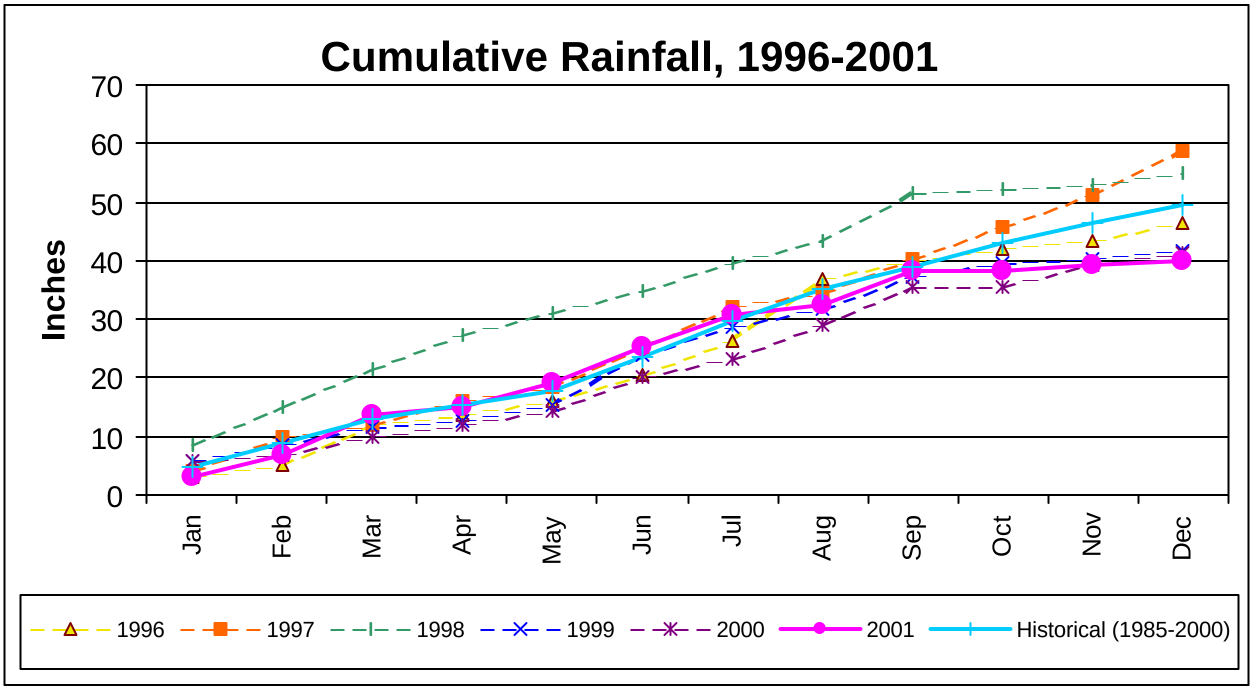


Figure 5. Monthly and cumulative rainfall (inches) in F Area, 1996 to 2001.

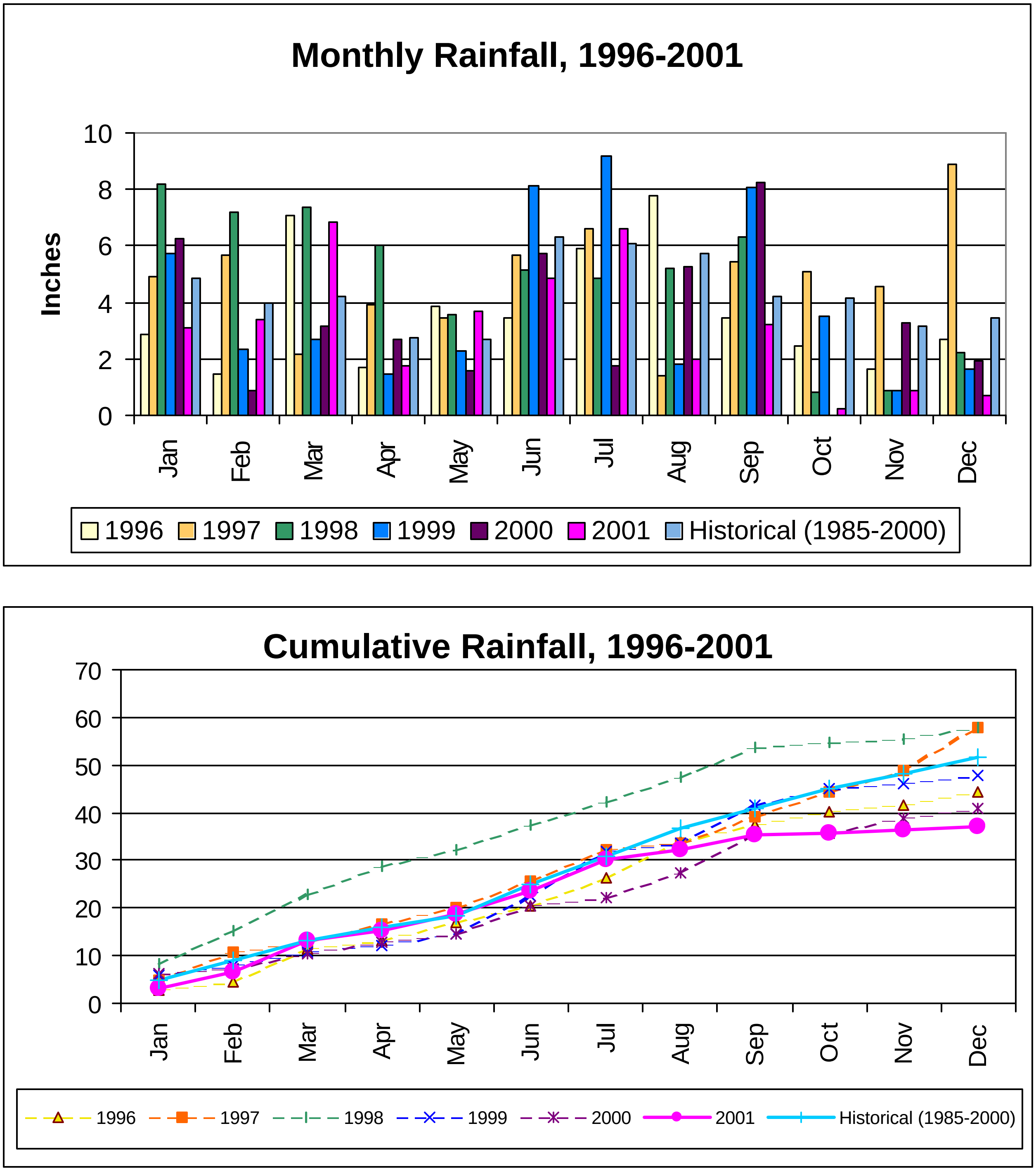


Figure 6. Monthly and cumulative rainfall (inches) in H Area, 1996 to 2001.

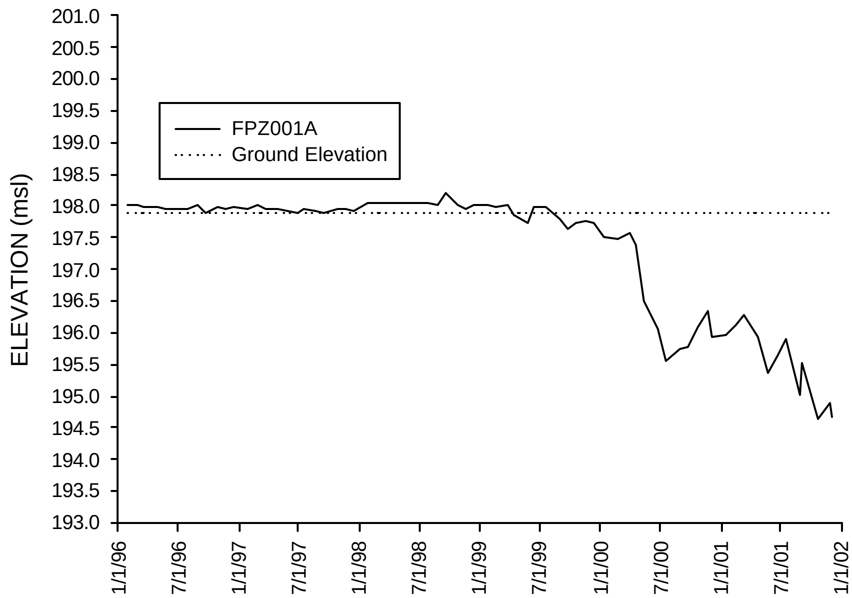


Figure 7. Monthly hydraulic head elevations (ft, msl) at FPZ001A, January 1996 to December 2001.

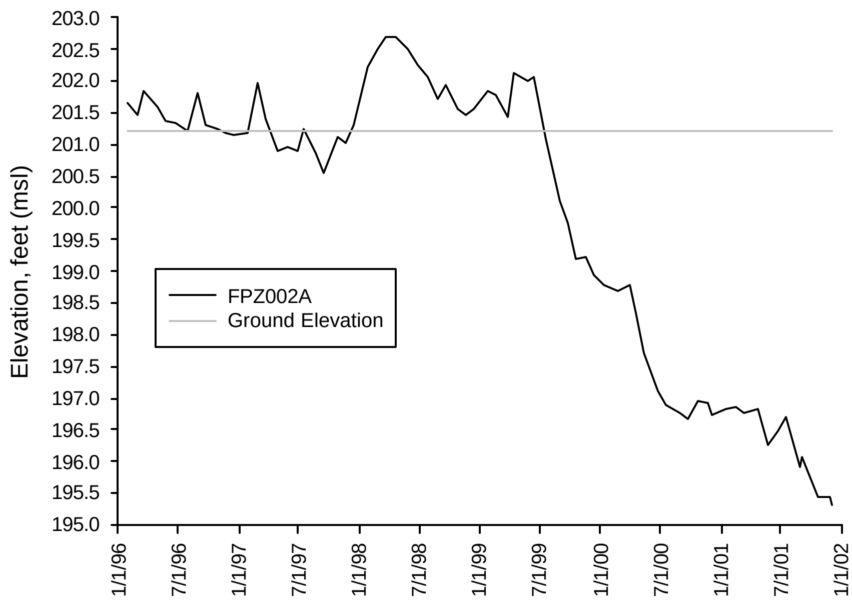


Figure 8. Monthly hydraulic head elevations (ft, msl) at FPZ002A, January 1996 to December 2001.

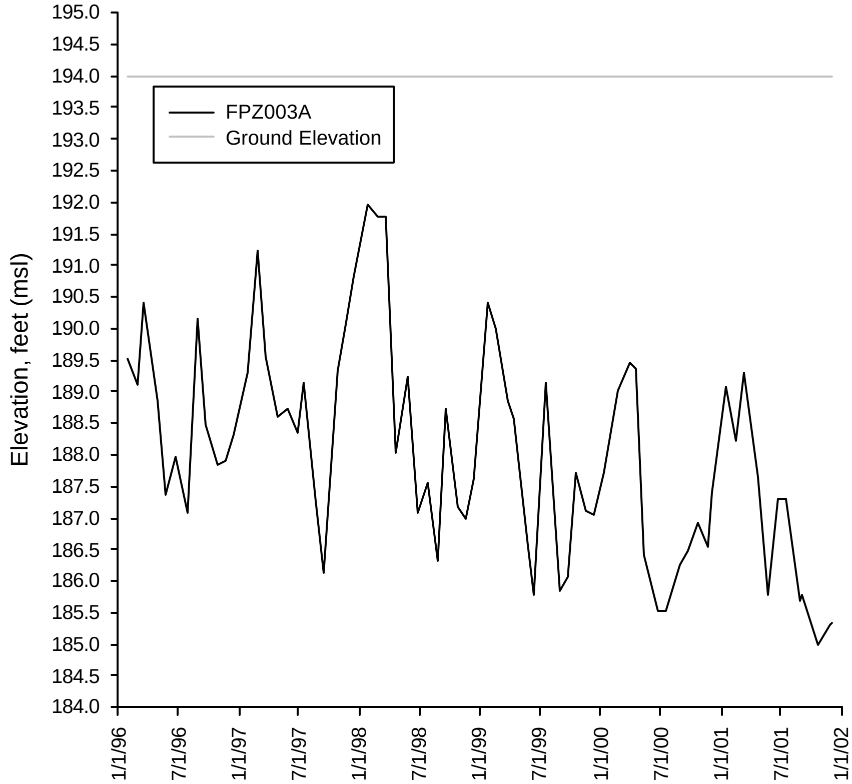


Figure 9. Monthly hydraulic head elevations (ft, msl) at FPZ003A, January 1996 to December 2001.

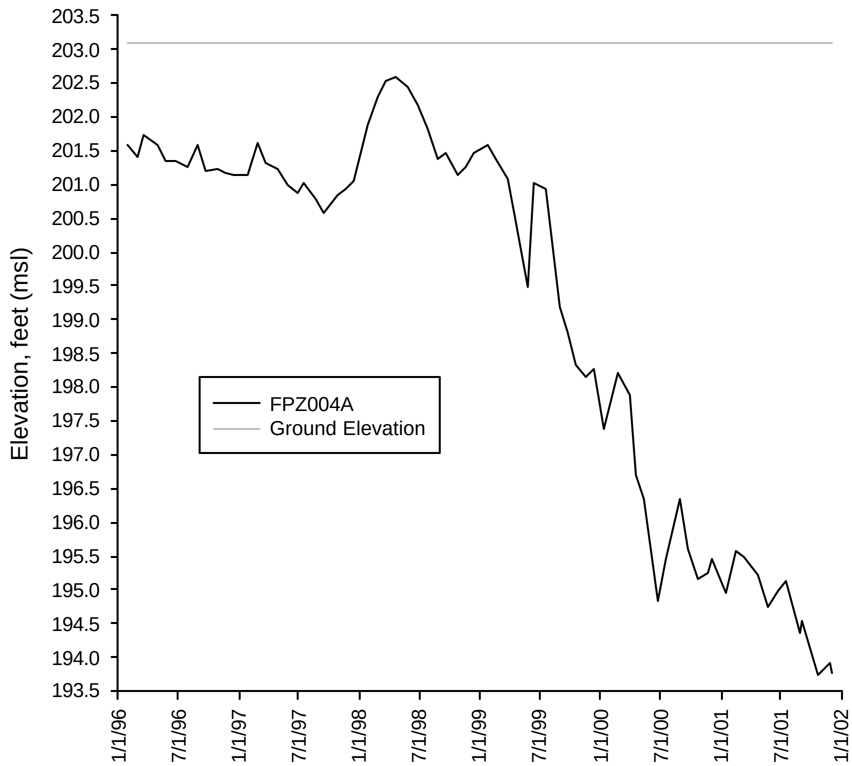


Figure 10. Monthly hydraulic head elevations (ft, msl) at FPZ004A, January 1996 to December 2001.

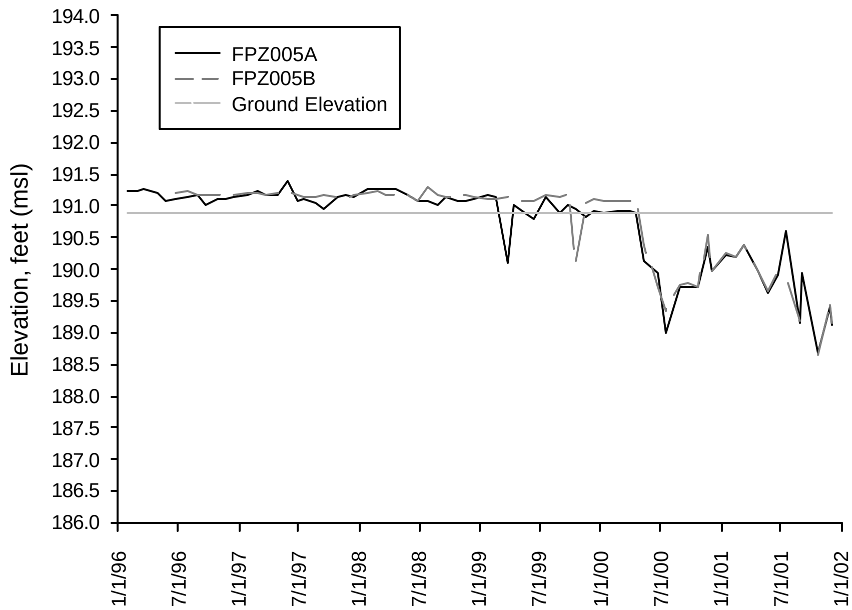


Figure 11. Monthly hydraulic head elevations (ft, msl) at FPZ005A and FPZ005B, January 1996 to December 2001

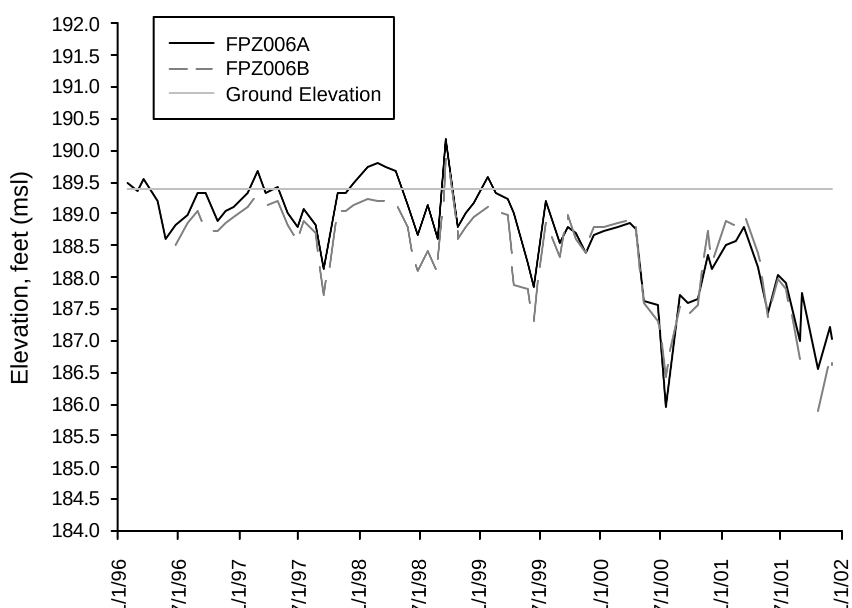


Figure 12. Monthly hydraulic head elevations (ft, msl) at FPZ006A and FPZ006B, January 1996 to December 2001.

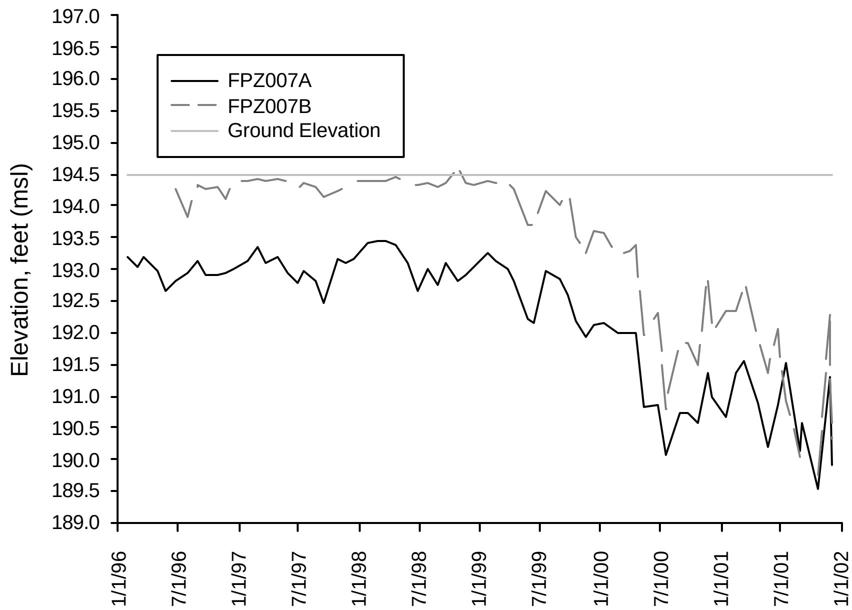


Figure 13. Monthly hydraulic head elevations (ft, msl) at FPZ007A and FPZ007B, January 1996 to December 2001.

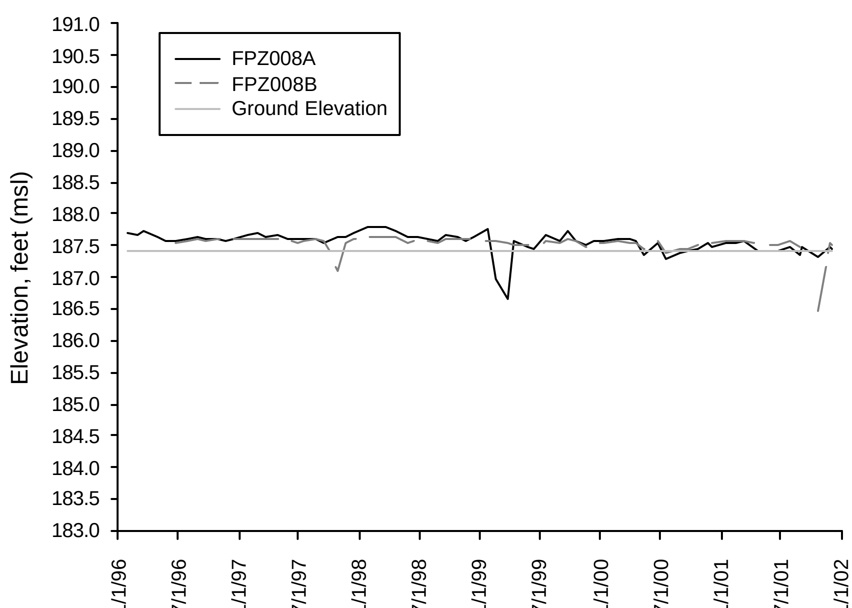


Figure 14. Monthly hydraulic head elevations (ft, msl) at FPZ008A and FPZ008B, January 1996 to December 2001.

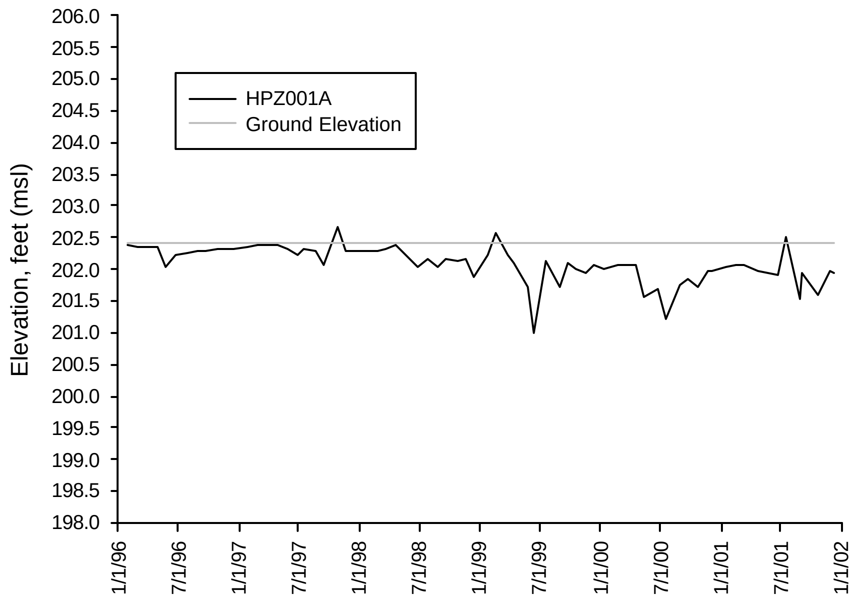


Figure 15. Monthly hydraulic head elevations (ft, msl) at HPZ001A, January 1996 to December 2001.

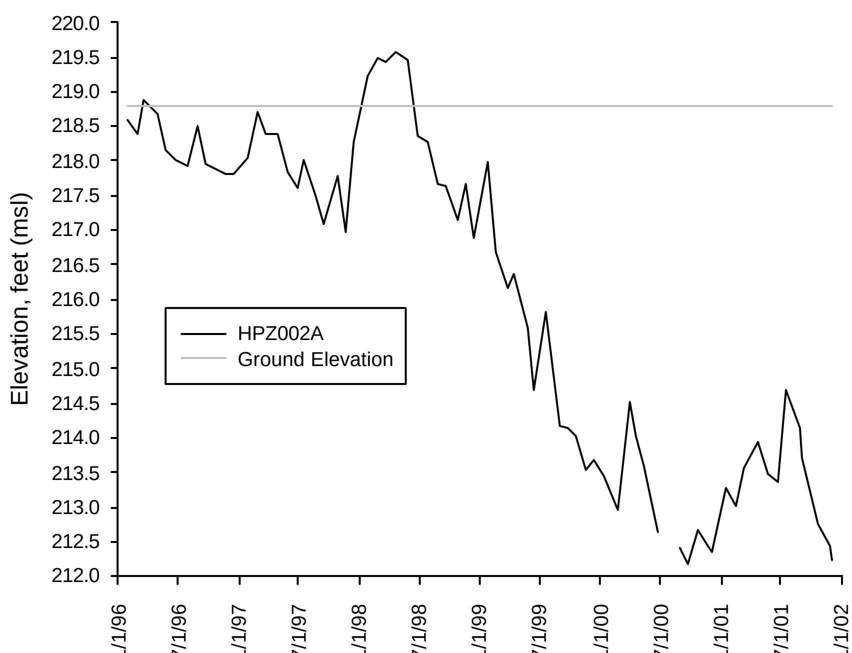


Figure 16. Monthly hydraulic head elevations (ft, msl) at HPZ002A, January 1996 to December 2001.

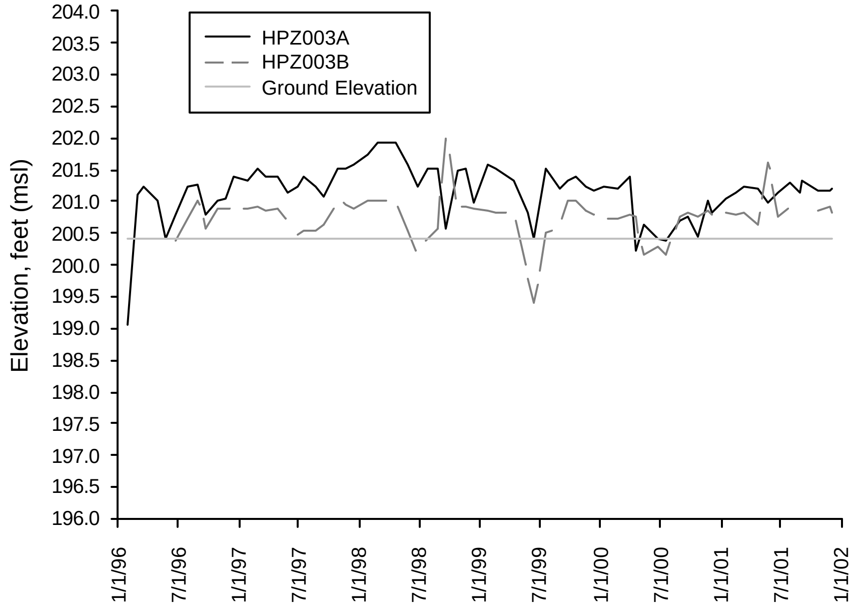


Figure 17. Monthly hydraulic head elevations (ft, msl) at HPZ003A and HPZ003B, January 1996 to December 2001.

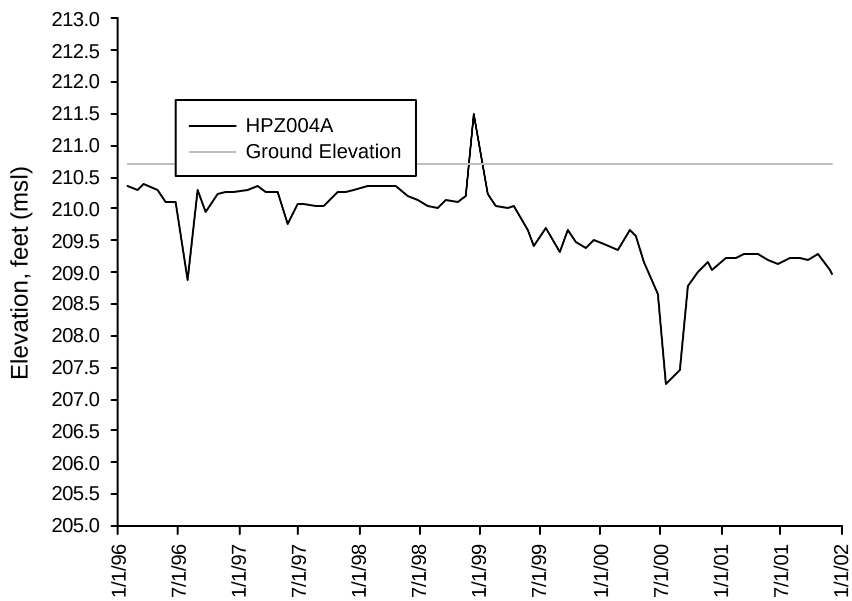


Figure 18. Monthly hydraulic head elevations (ft, msl) at HPZ004A, January 1996 to December 2001.

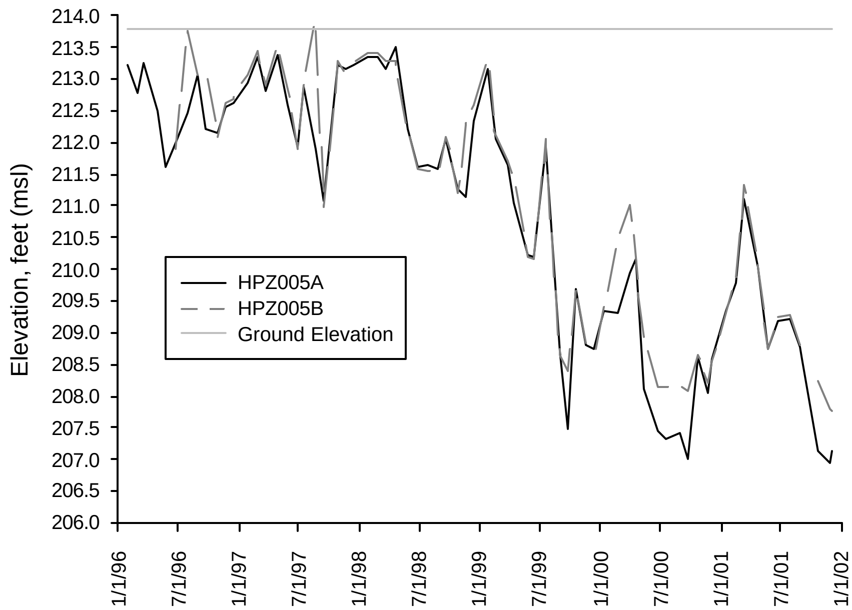


Figure 19. Monthly hydraulic head elevations at HPZ005A and HPZ005B (ft, msl), January 1996 to December 2001.

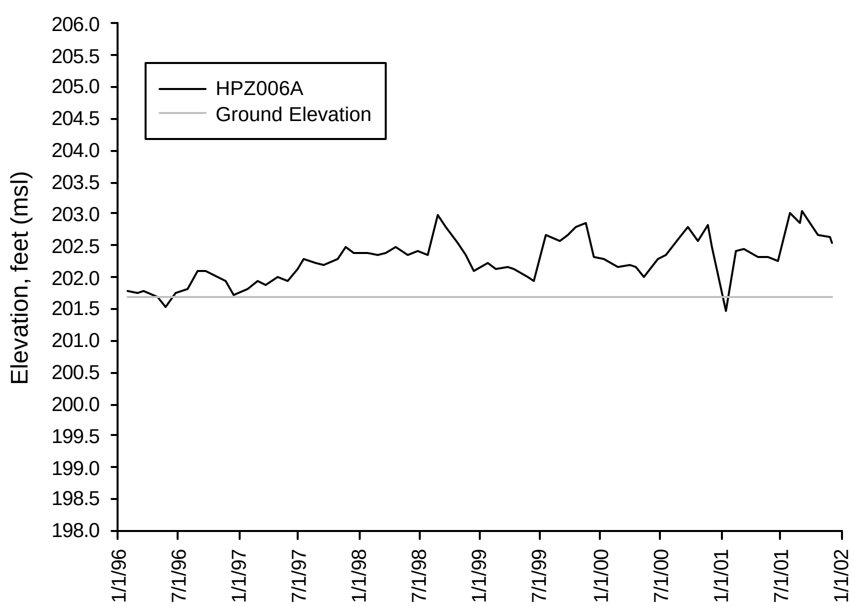


Figure 20. Monthly hydraulic head elevations (ft, msl) at HPZ006A, January 1996 to December 2001.

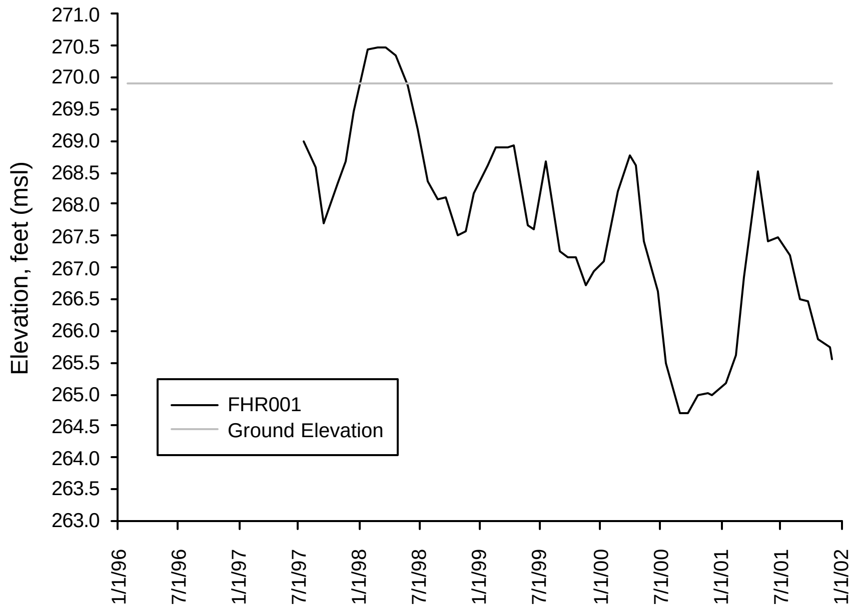


Figure 21. Monthly hydraulic head elevations (ft, msl) at FHR001, July 1997 to December 2001.

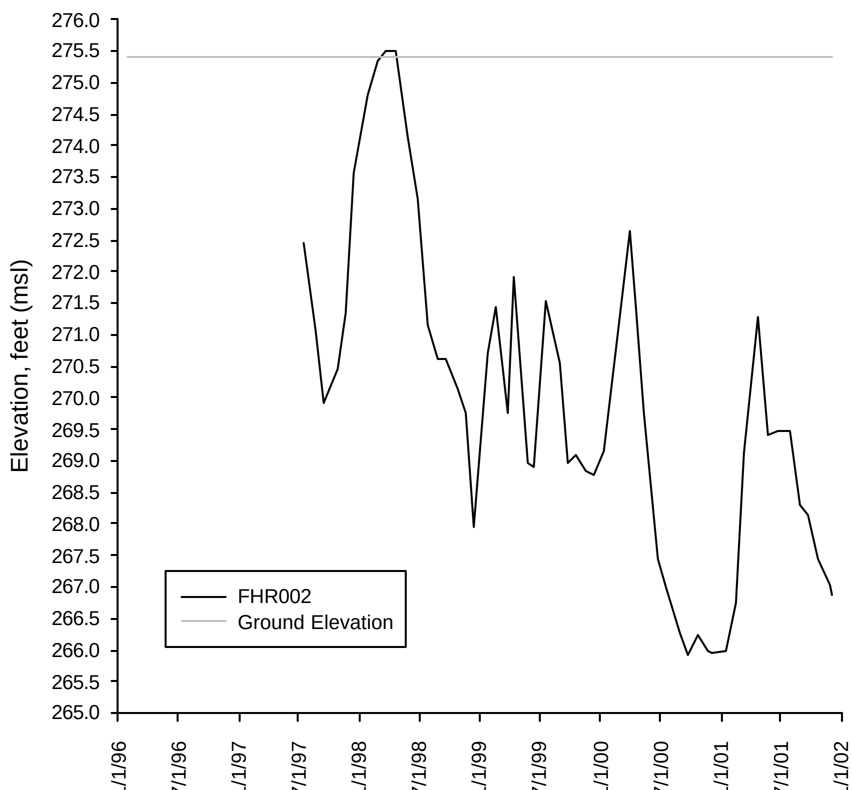


Figure 22. Monthly hydraulic head elevations (ft, msl) at FHR002, July 1997 to December 2001.

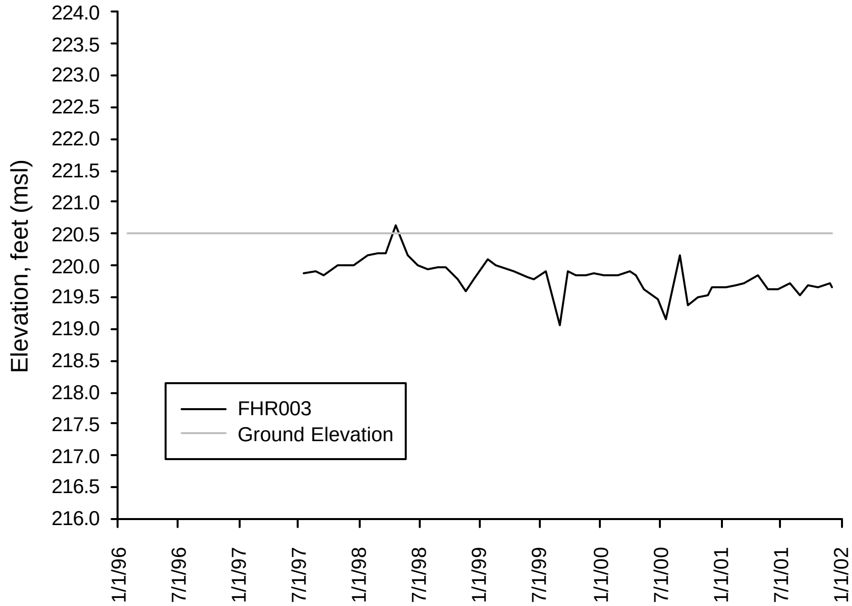


Figure 23. Monthly hydraulic head elevations (ft, msl) at FHR003, July 1997 to December 2001.

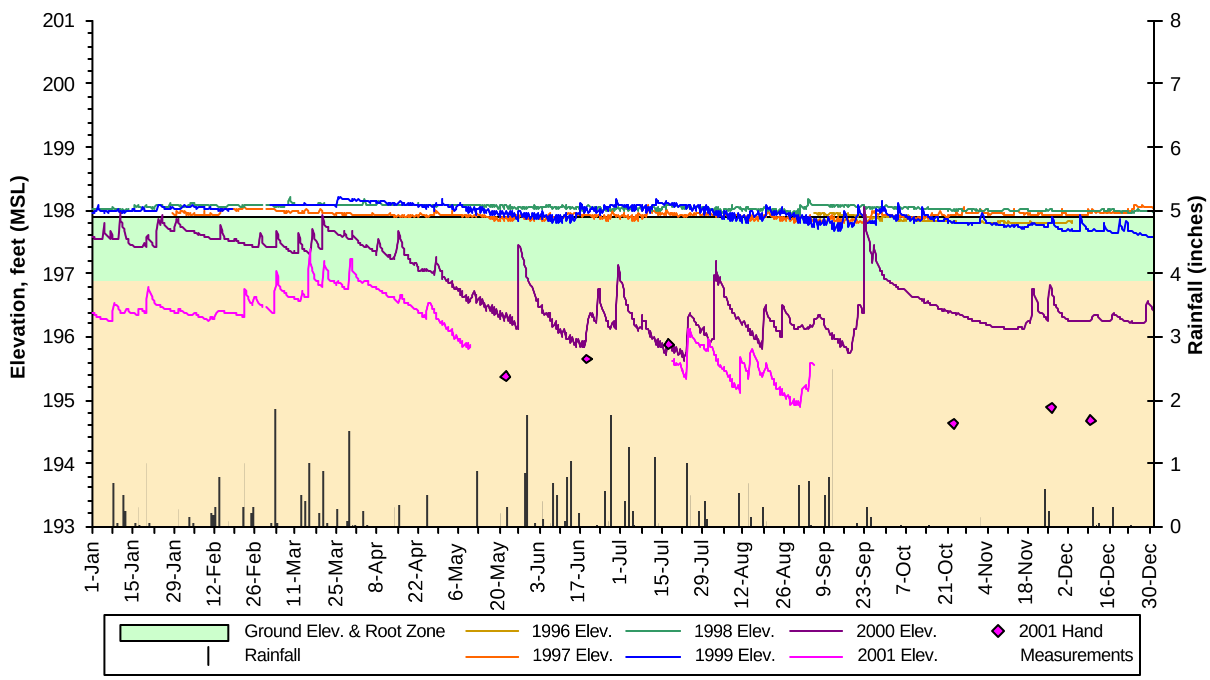


Figure 24. Comparison of hydraulic head elevation and rainfall at FPZ001A (F Area) in 2001.

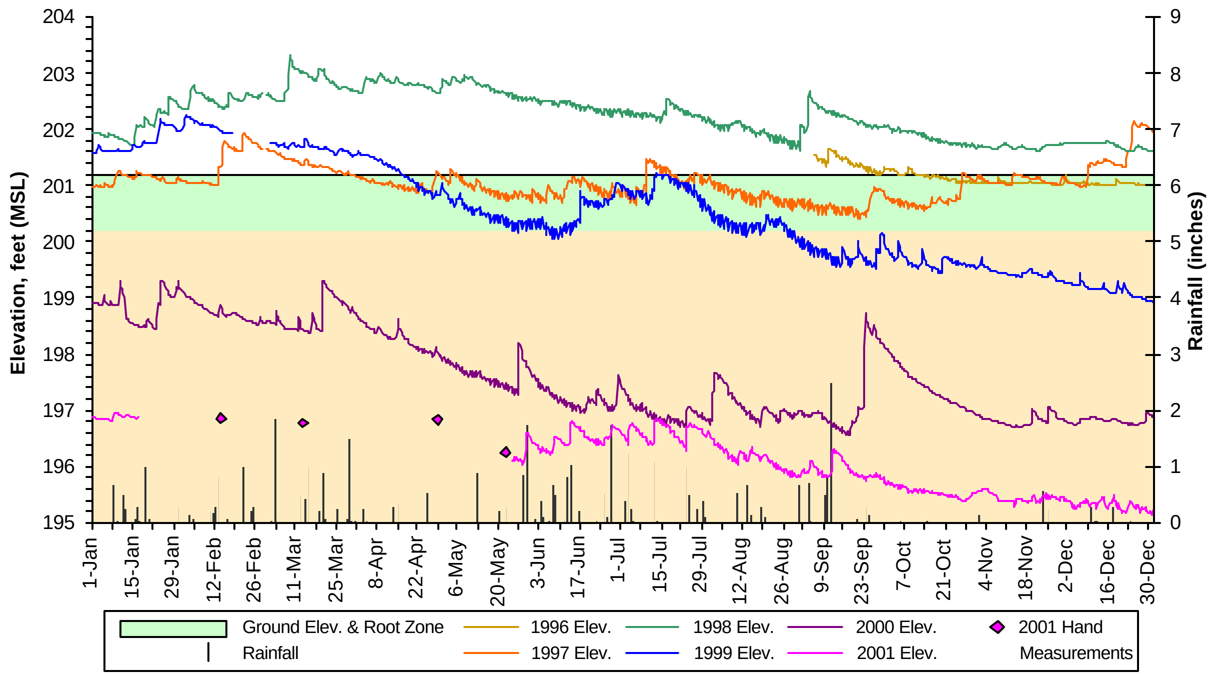


Figure 25. Comparison of hydraulic head elevation and rainfall at FPZ002A (F Area) in 2001.

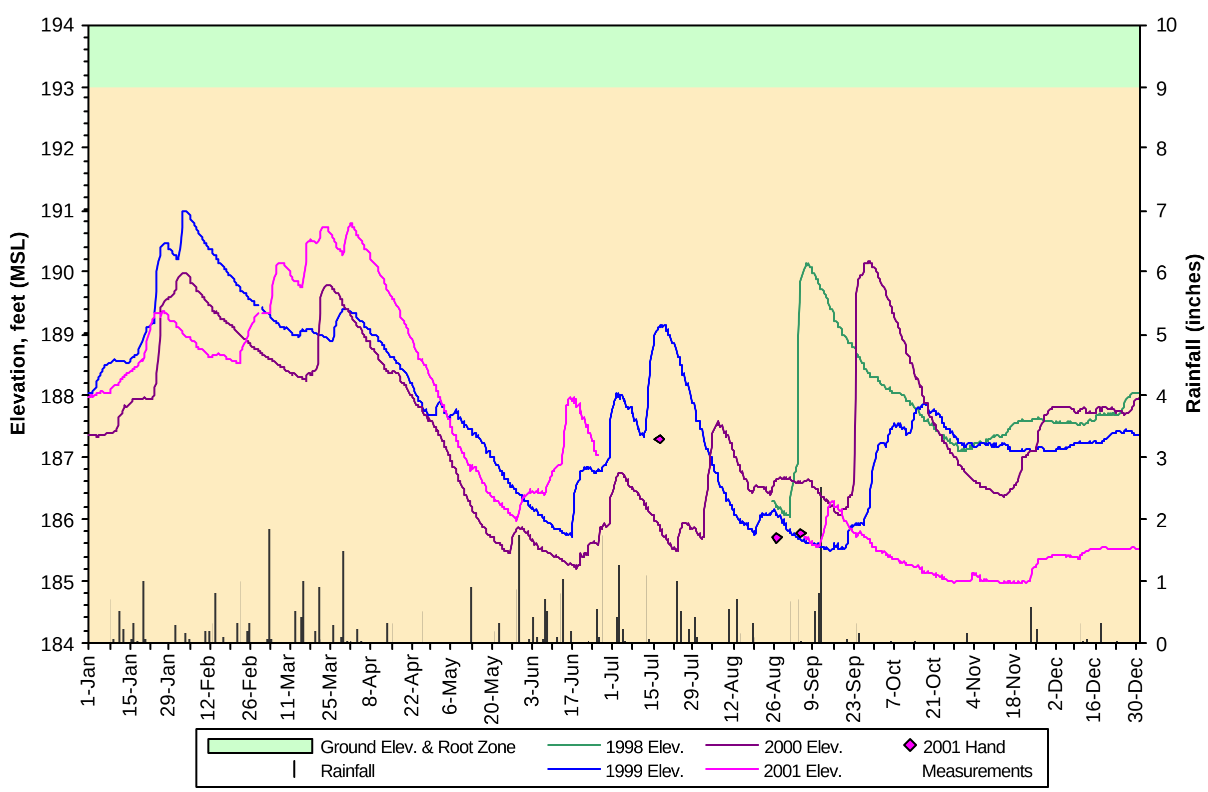


Figure 26. Comparison of hydraulic head elevation and rainfall at FPZ003A (F Area) in 2001.

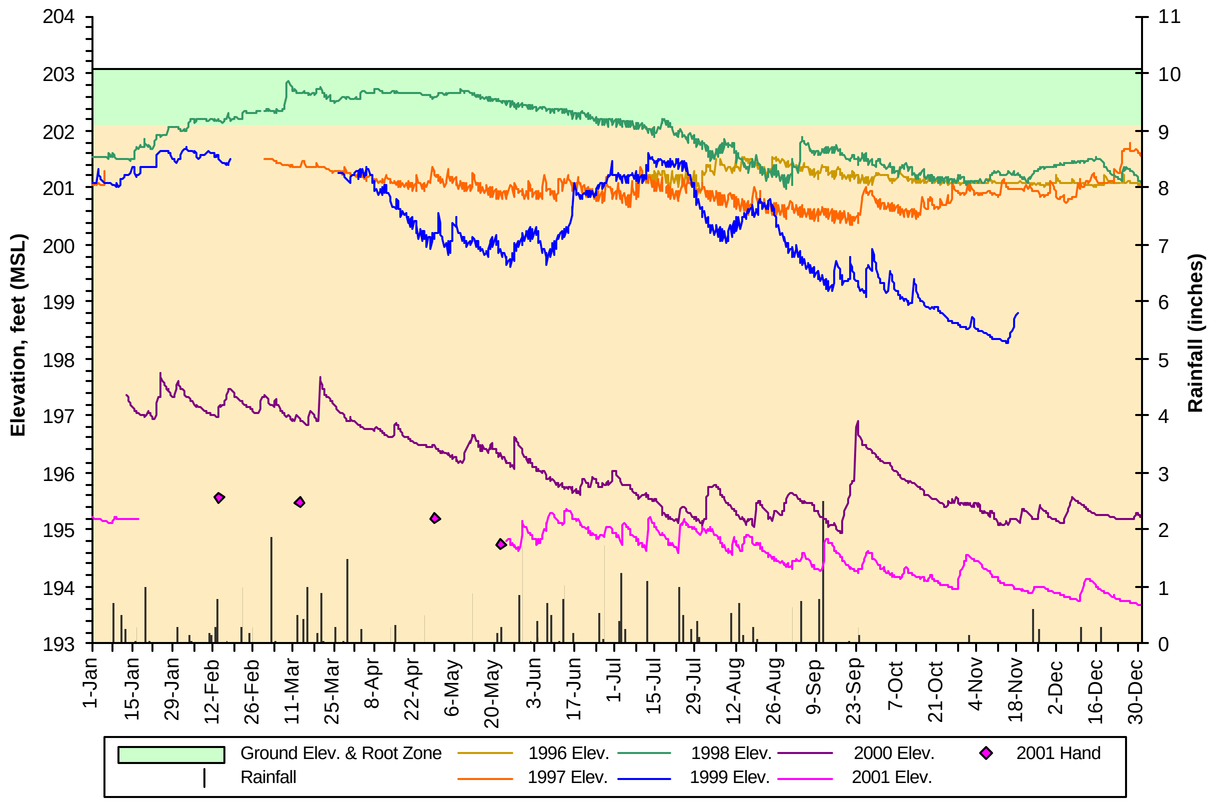


Figure 27. Comparison of hydraulic head elevation and rainfall at FPZ004A (F Area) in 2001.

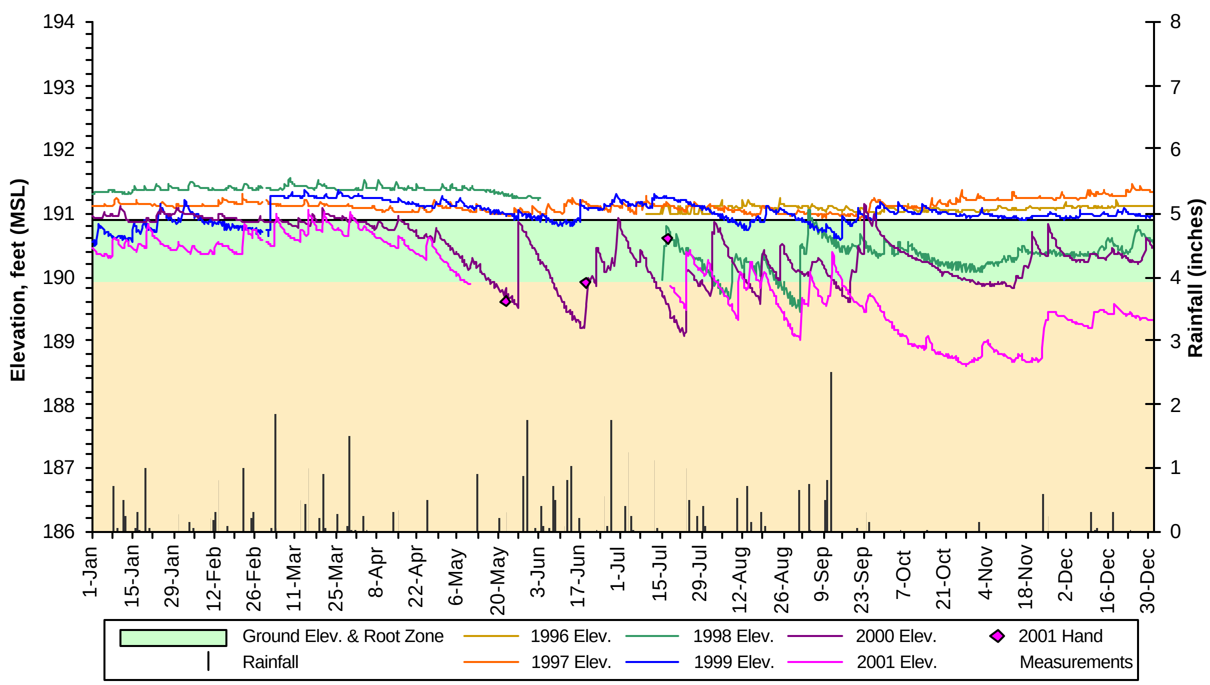


Figure 28. Comparison of hydraulic head elevation and rainfall at FPZ005A (F Area) in 2001.

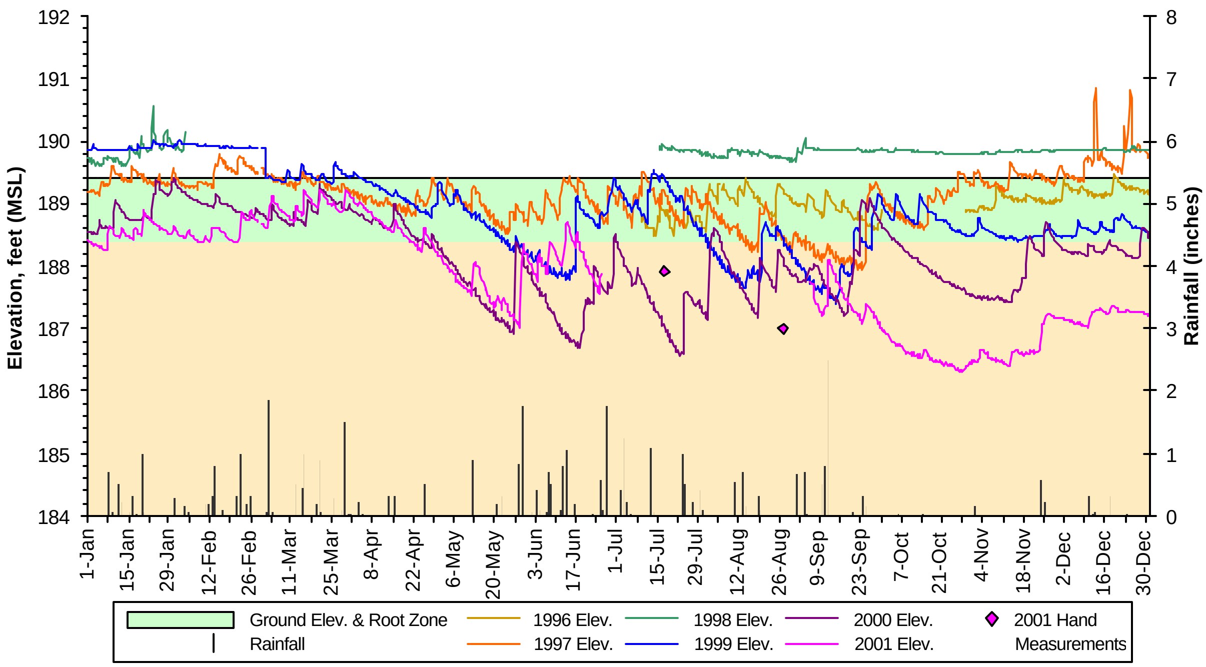


Figure 29. Comparison of hydraulic head elevation and rainfall at FPZ006A (F Area) in 2001.

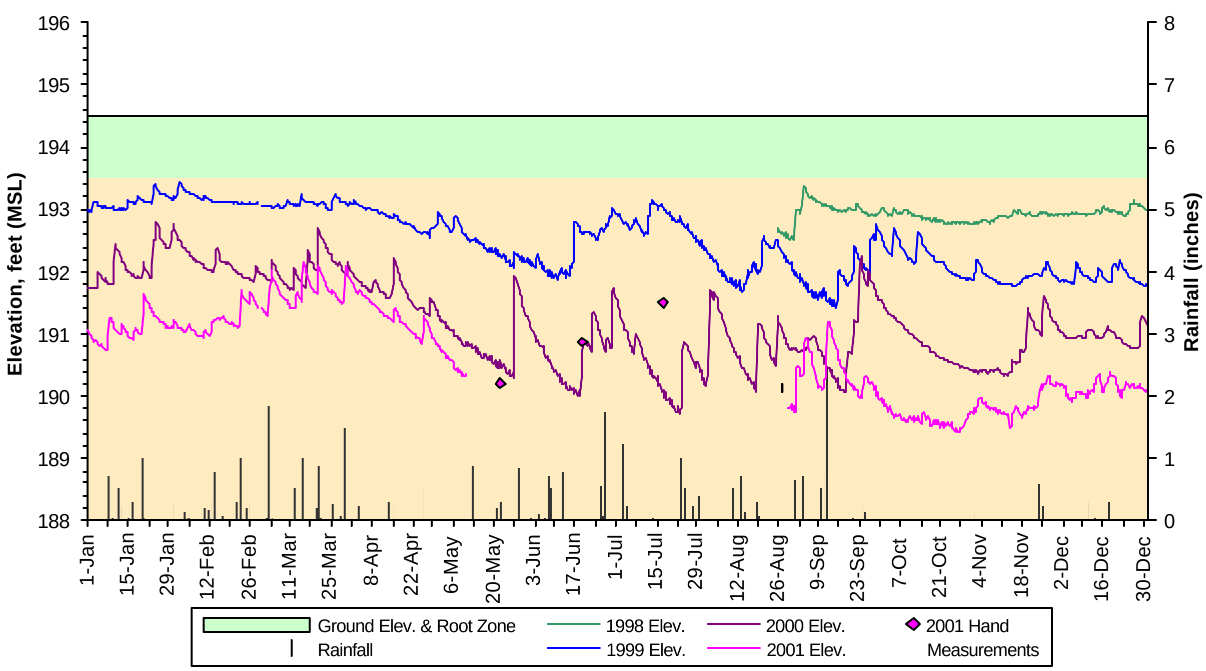


Figure 30. Comparison of hydraulic head elevation and rainfall at FPZ007A (F Area) in 2001.

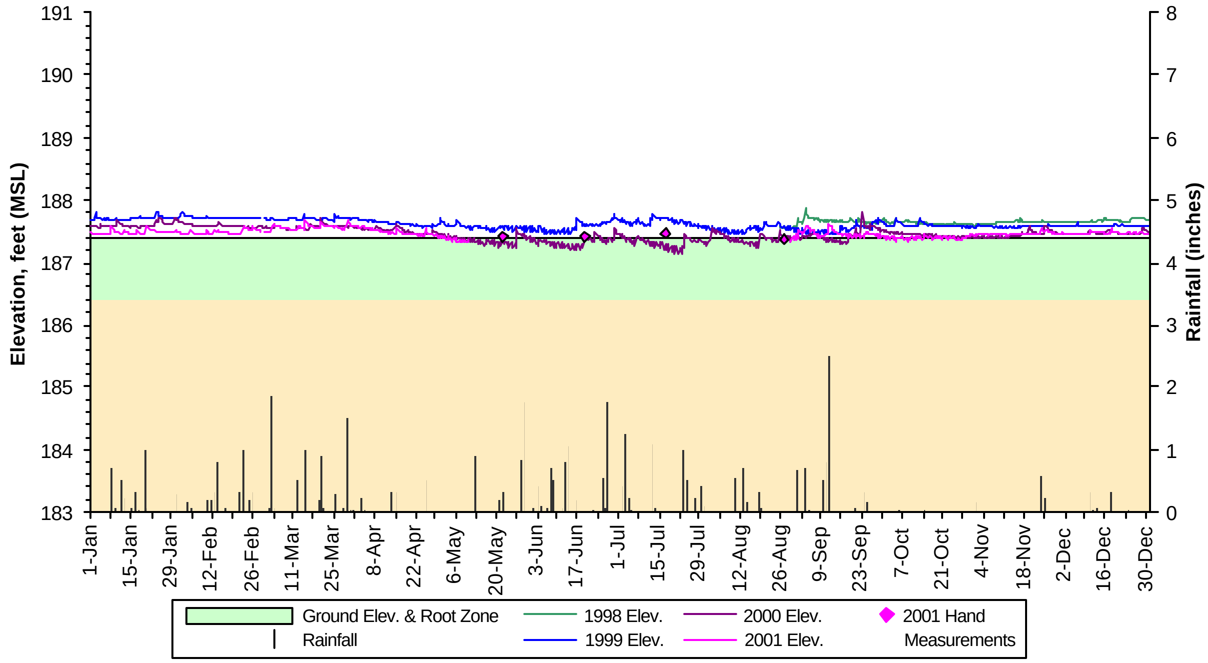


Figure 31. Comparison of hydraulic head elevation and rainfall at FPZ008A (F Area) in 2001.

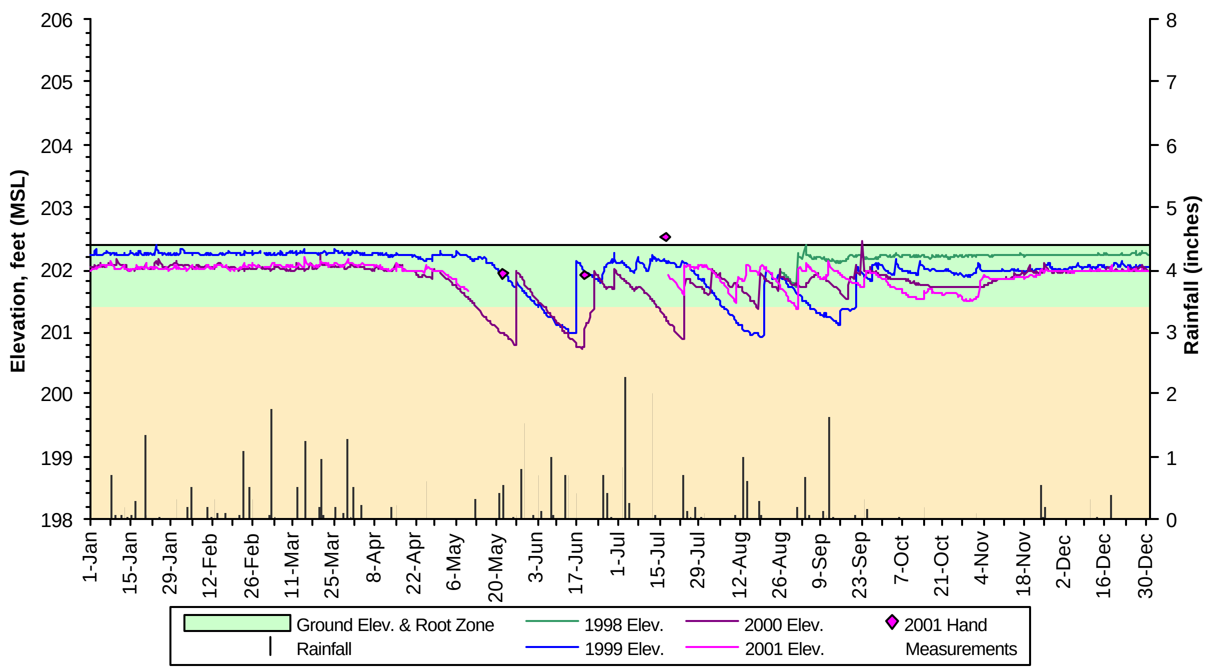


Figure 32. Comparison of hydraulic head elevation and rainfall at HPZ001A (H Area) in 2001.

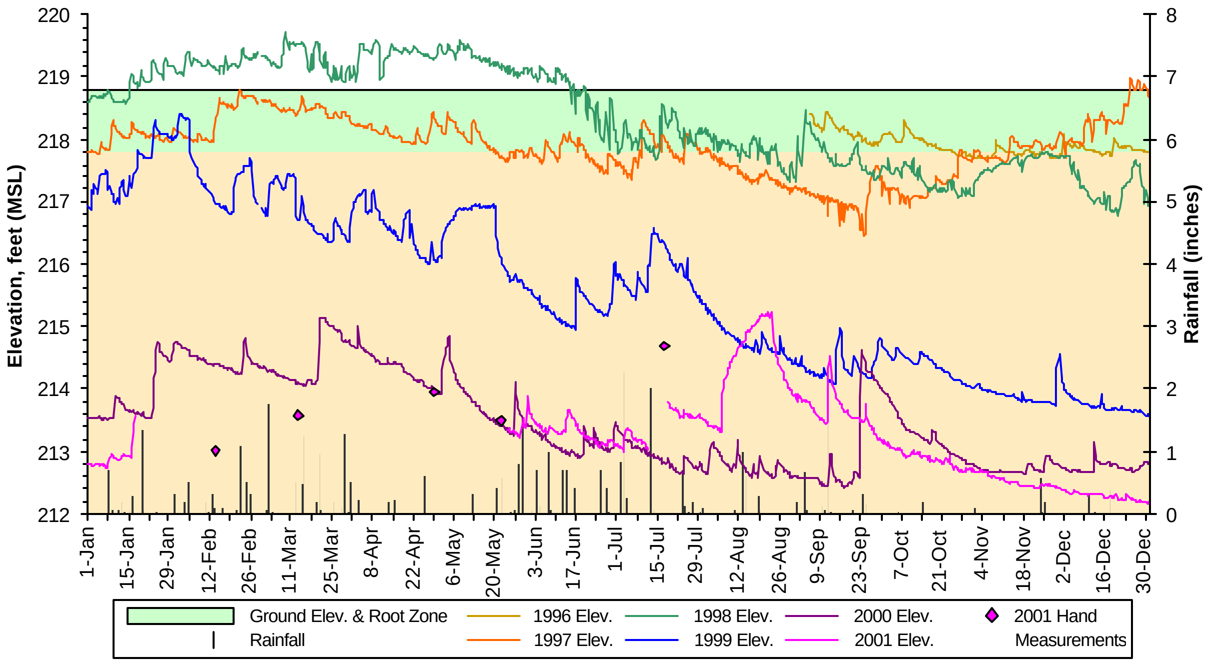


Figure 33. Comparison of hydraulic head elevation and rainfall at HPZ002A (H Area) in 2001.

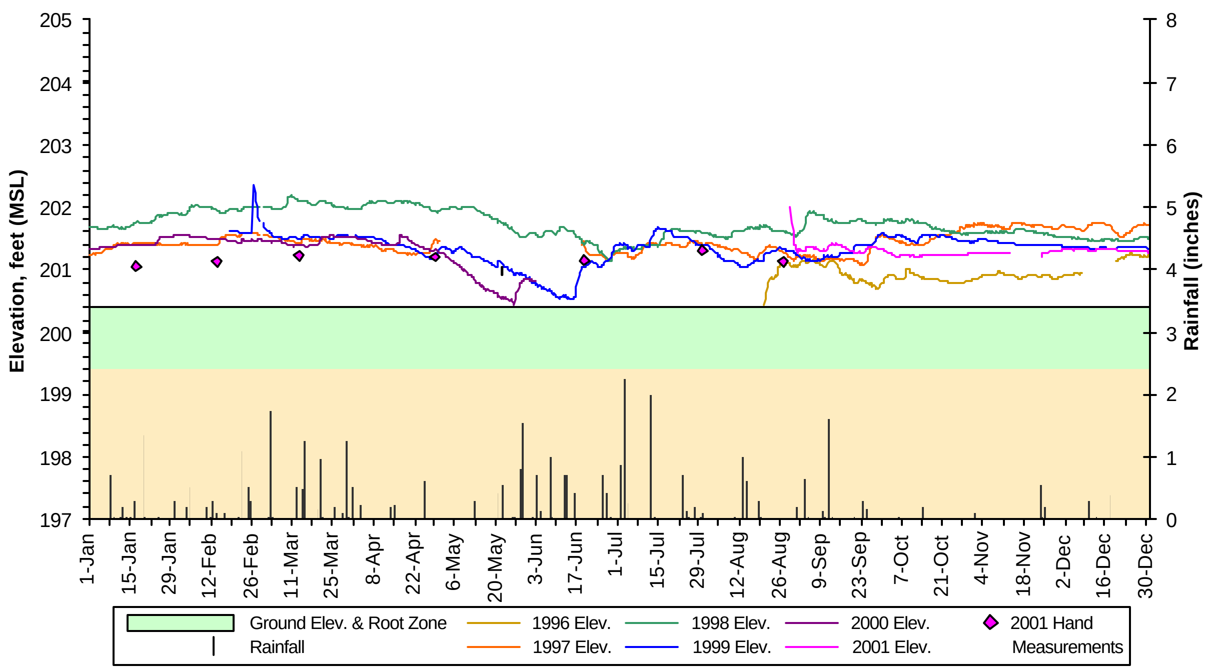


Figure 34. Comparison of hydraulic head elevation and rainfall at HPZ003A (H Area) in 2001.

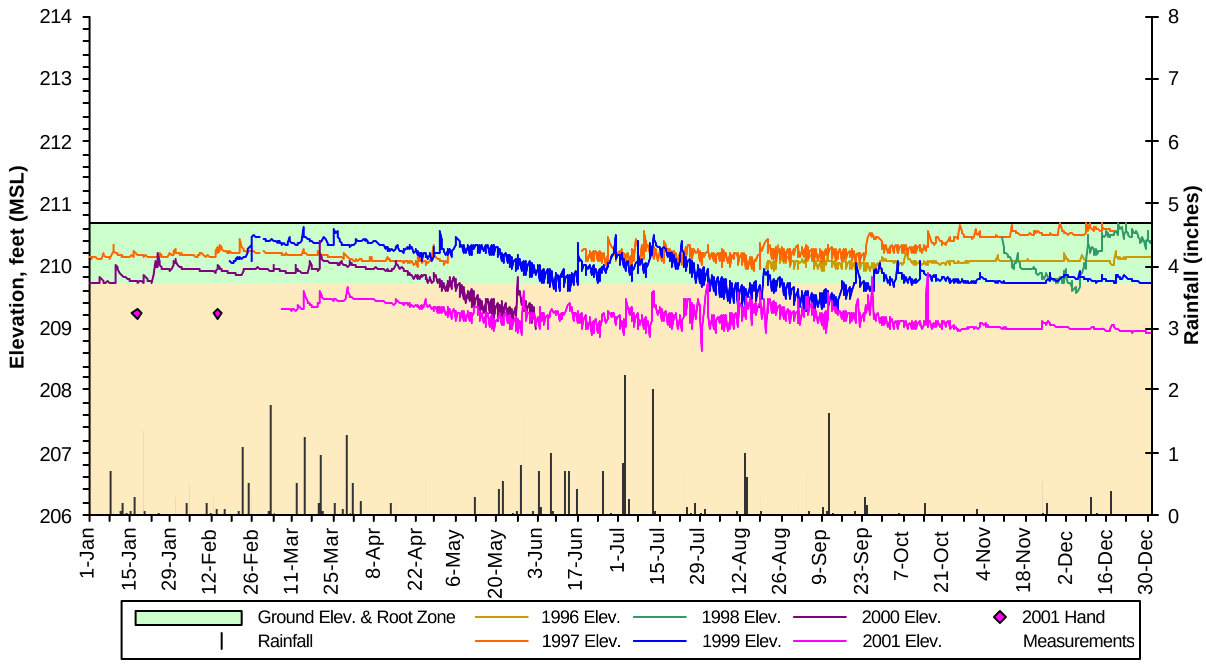


Figure 35. Comparison of hydraulic head elevation and rainfall at HPZ004A (H Area) in 2001.

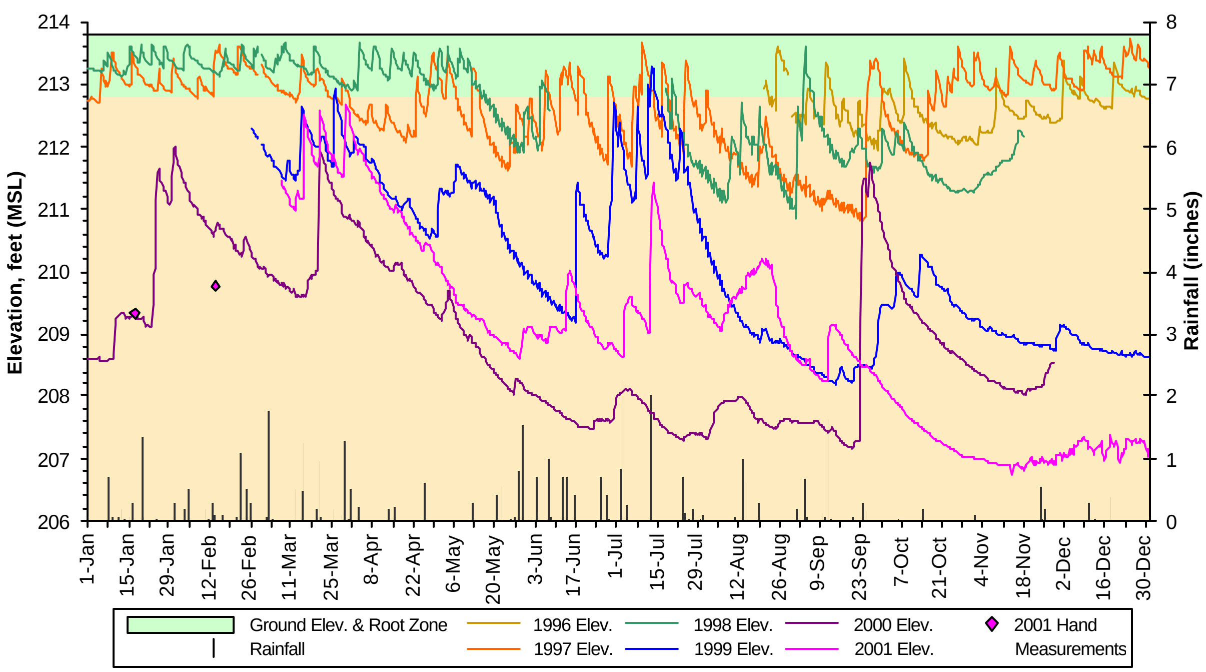


Figure 36. Comparison of hydraulic head elevation and rainfall at HPZ005A (H Area) in 2001.

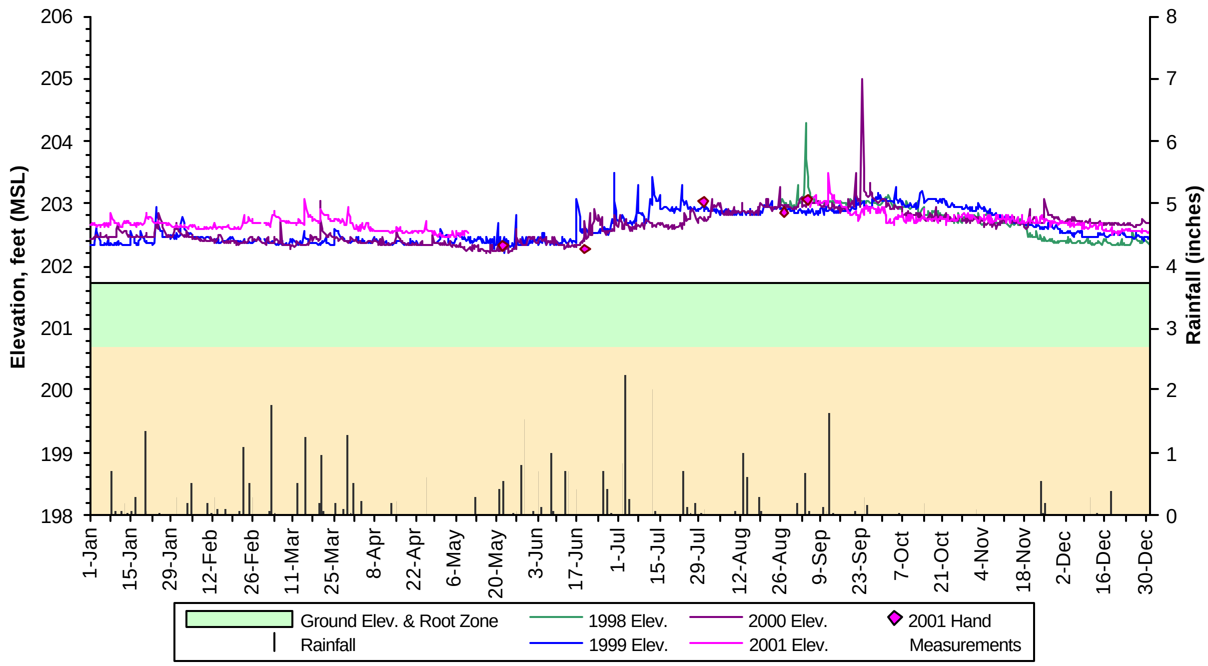


Figure 37. Comparison of hydraulic head elevation and rainfall at HPZ006A (H Area) in 2001.

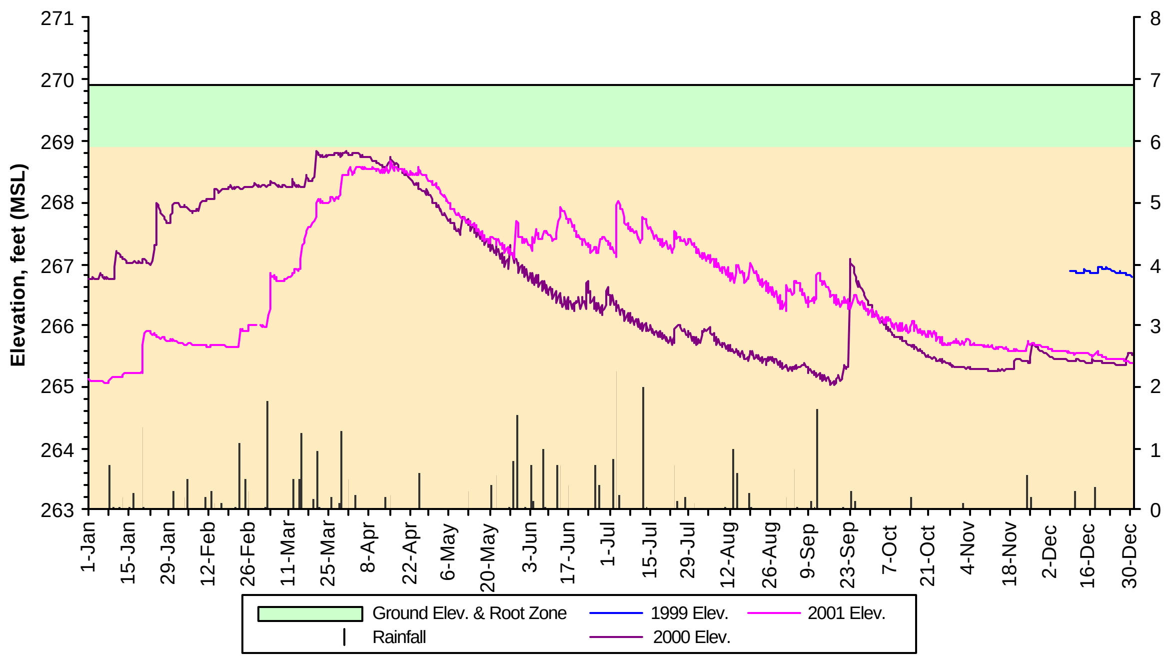


Figure 38. Comparison of hydraulic head elevation and rainfall (H Area) at FHR001 in 2001.

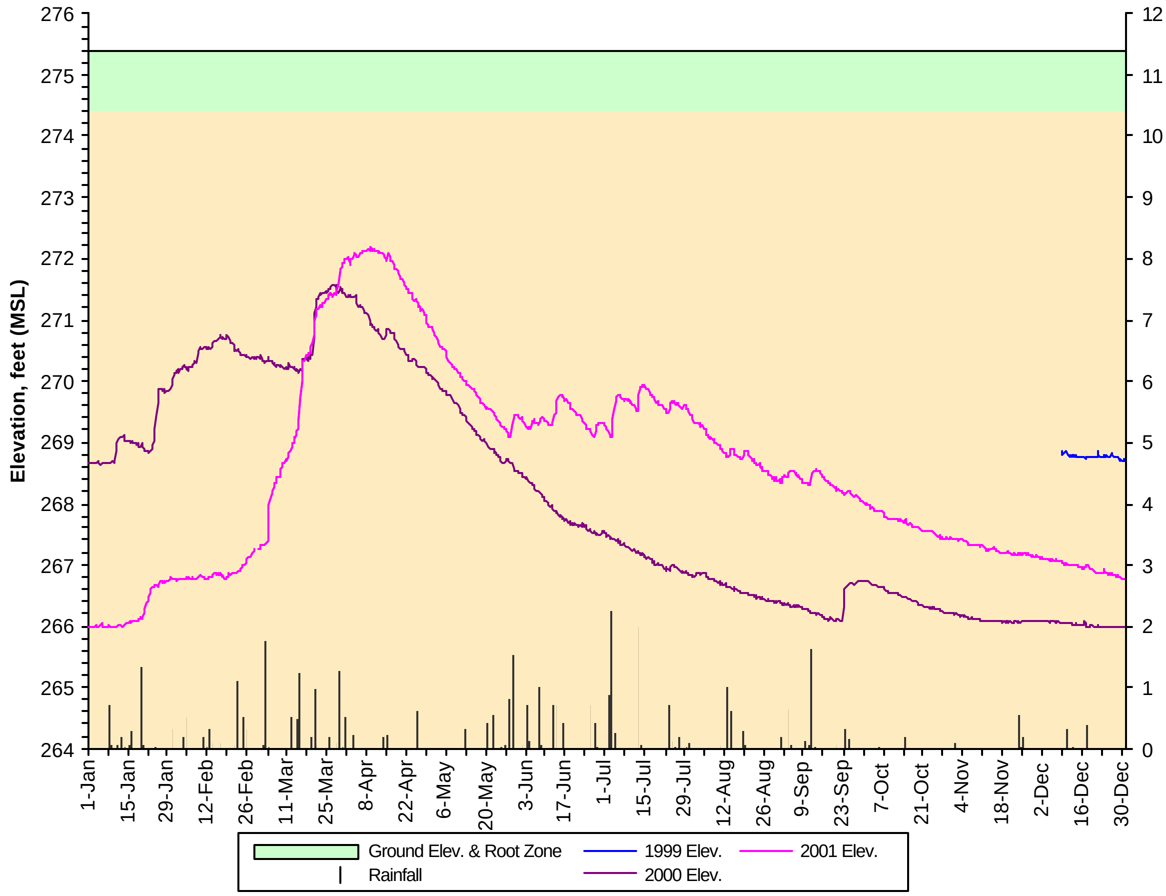


Figure 39. Comparison of hydraulic head elevation and rainfall (H Area) at FHR002 in 2001.

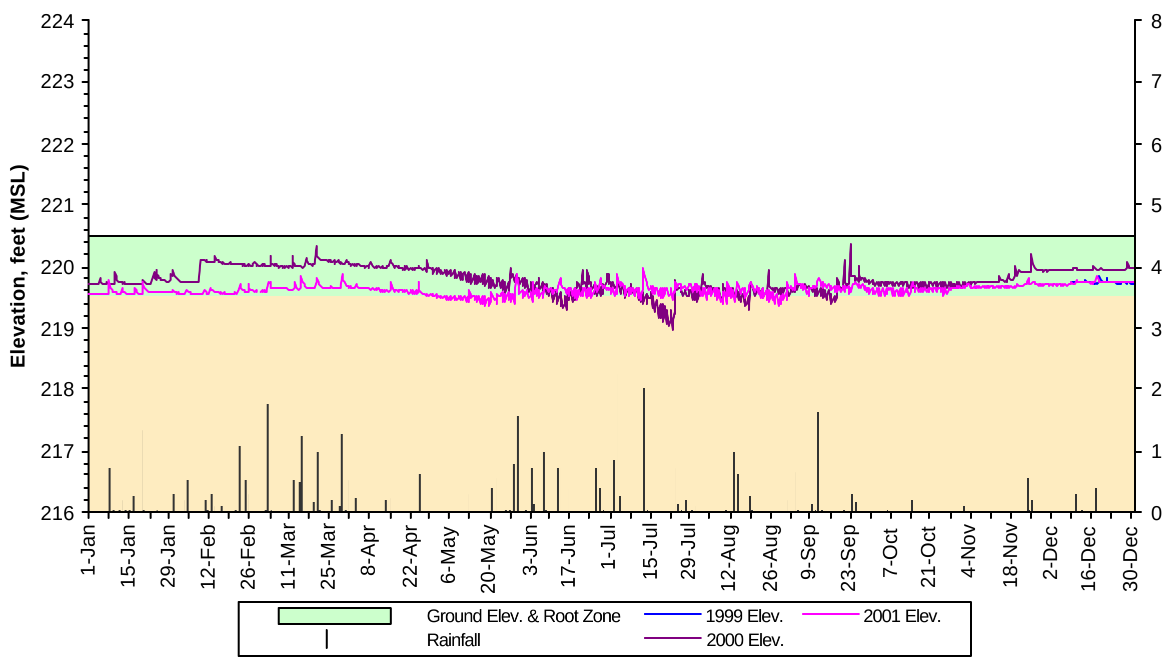


Figure 40. Comparison of hydraulic head elevation and rainfall (H Area) at FHR003 in 2001.

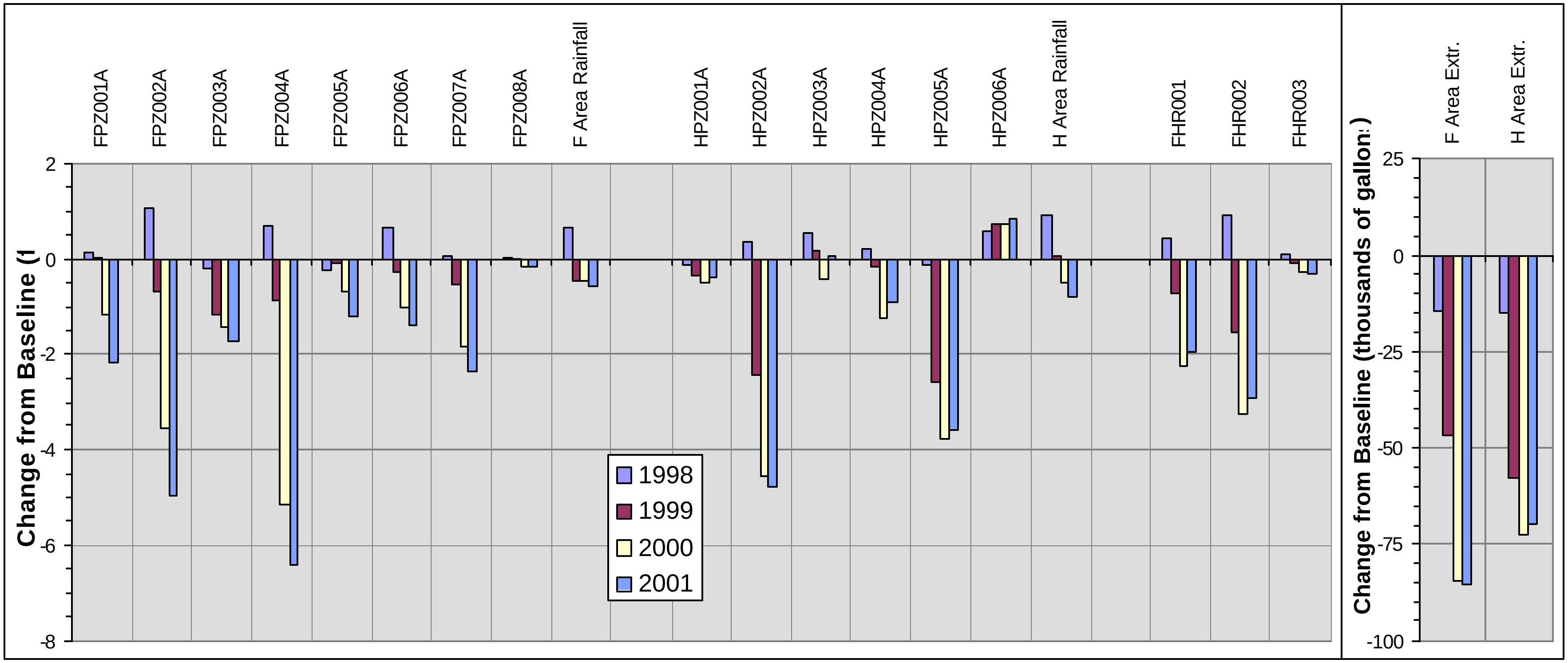


Figure 41. Changes from the baseline period for annual average hydraulic head elevations and annual rainfall (1998-2001) compared with groundwater extraction. Extraction is shown as negative volumes for comparison purposes.

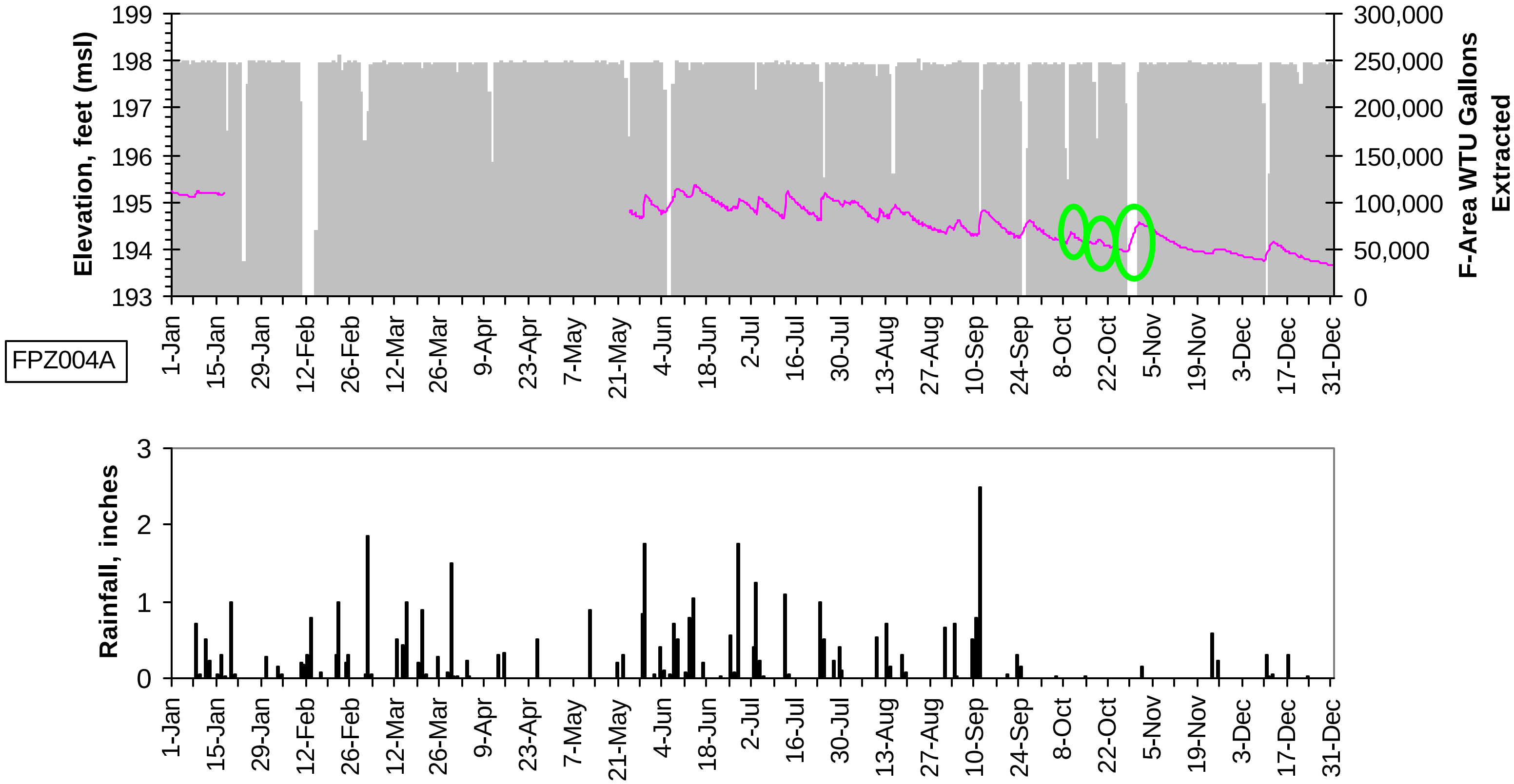


Figure 42. F-Area WTU extraction volume compared to FPZ004A hydraulic head elevations and rainfall.

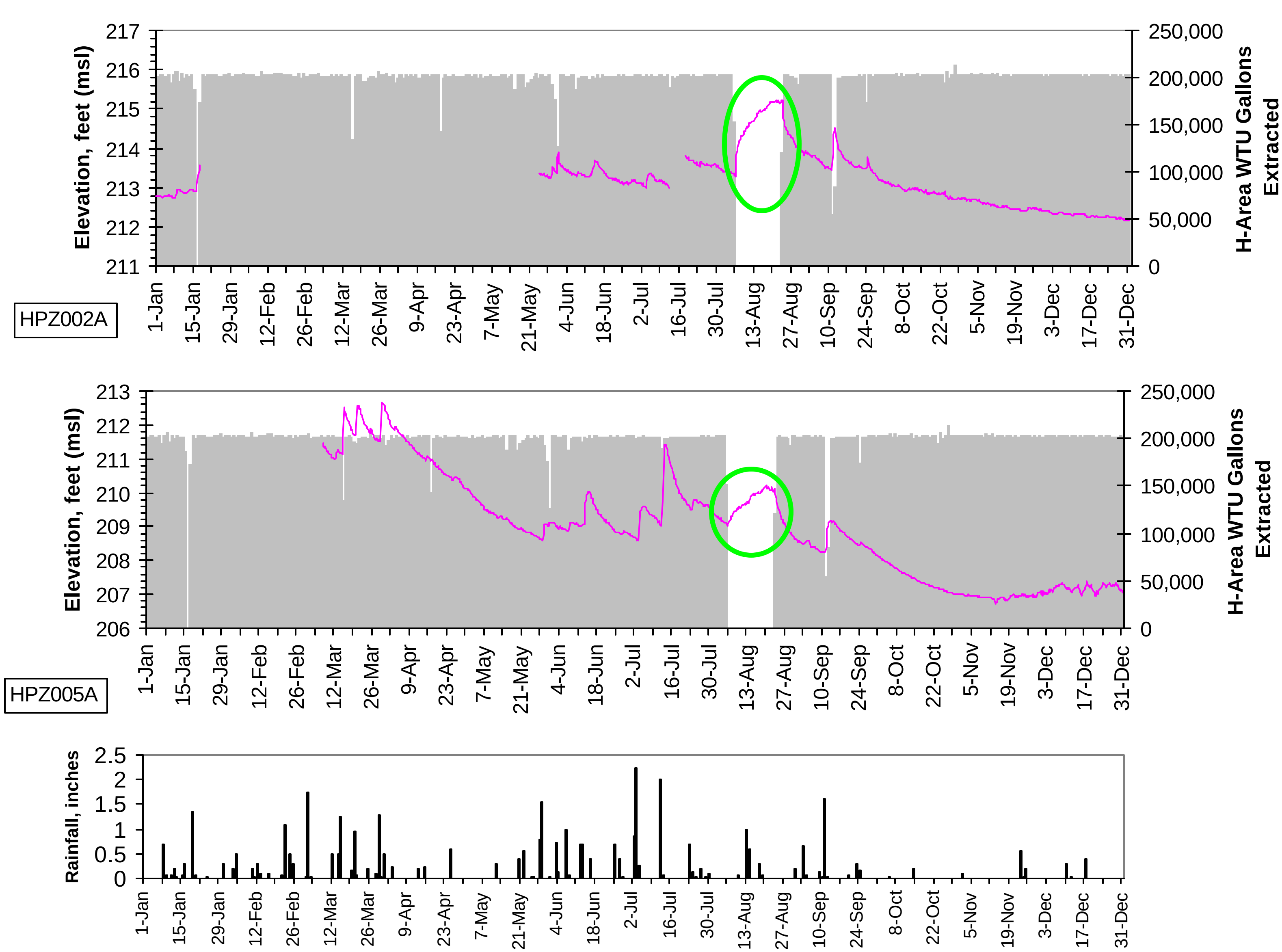
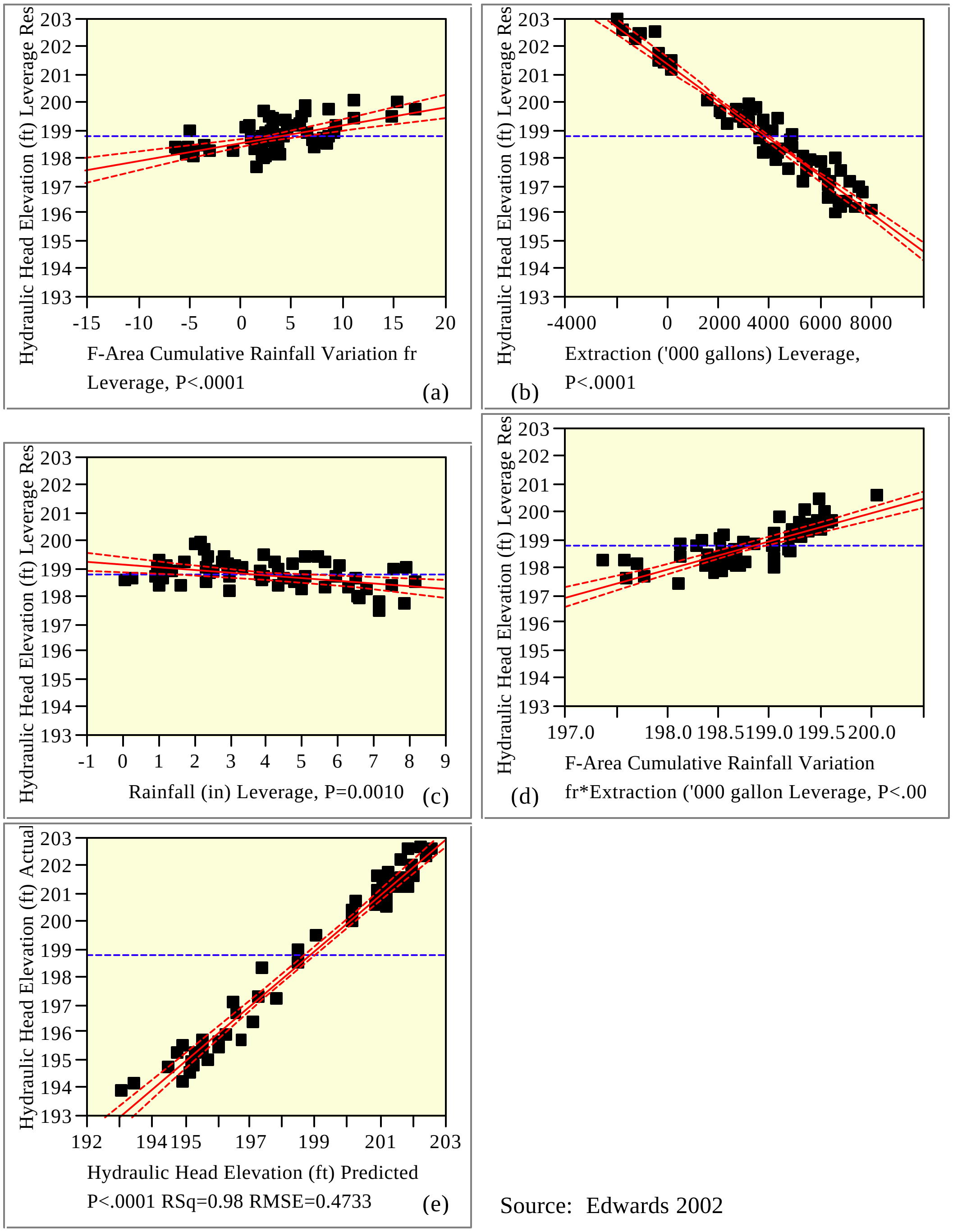
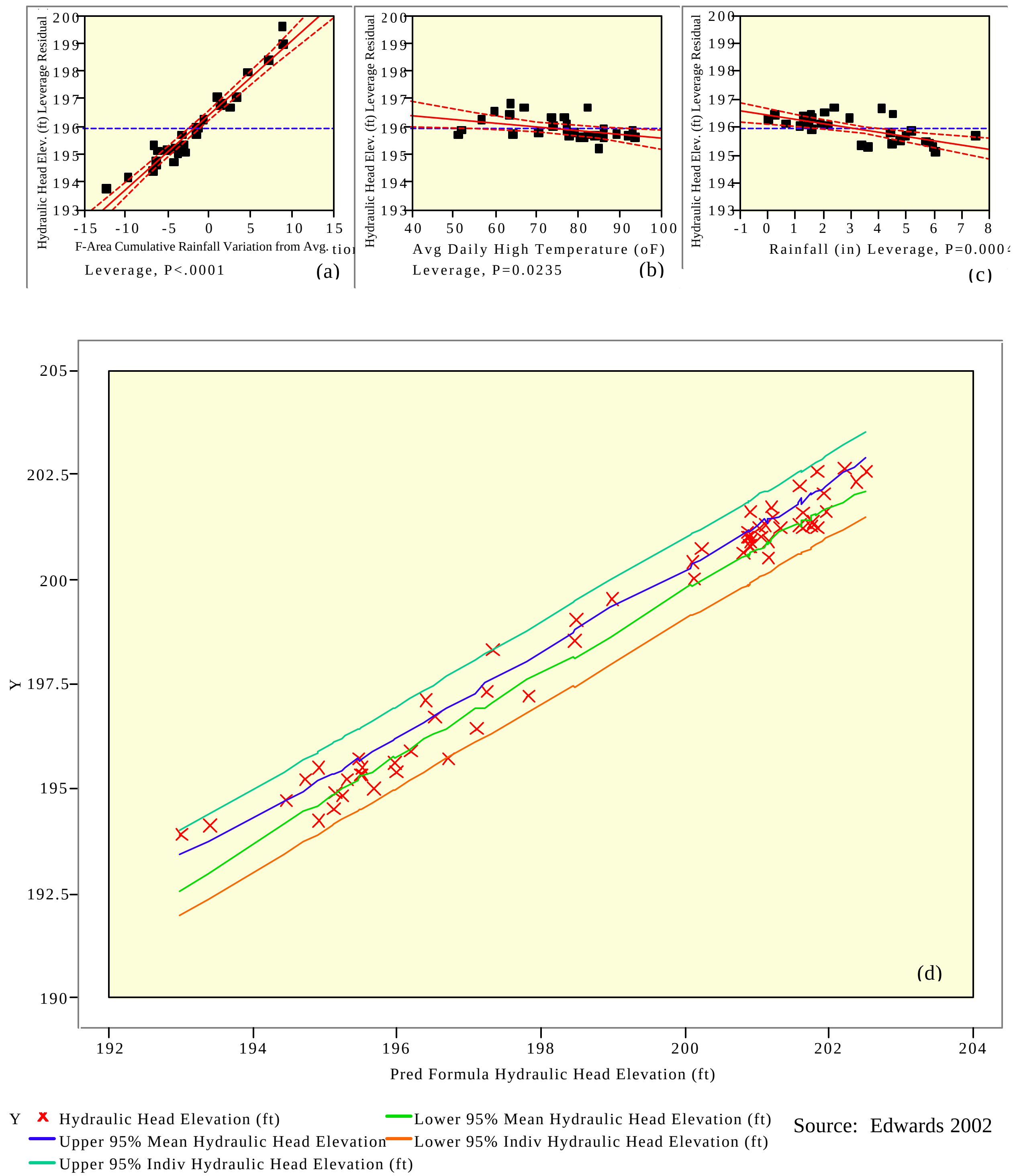


Figure 43. H-Area WTU extraction volume compared to HPZ002A and HPZ005A hydraulic head elevations and rainfall.



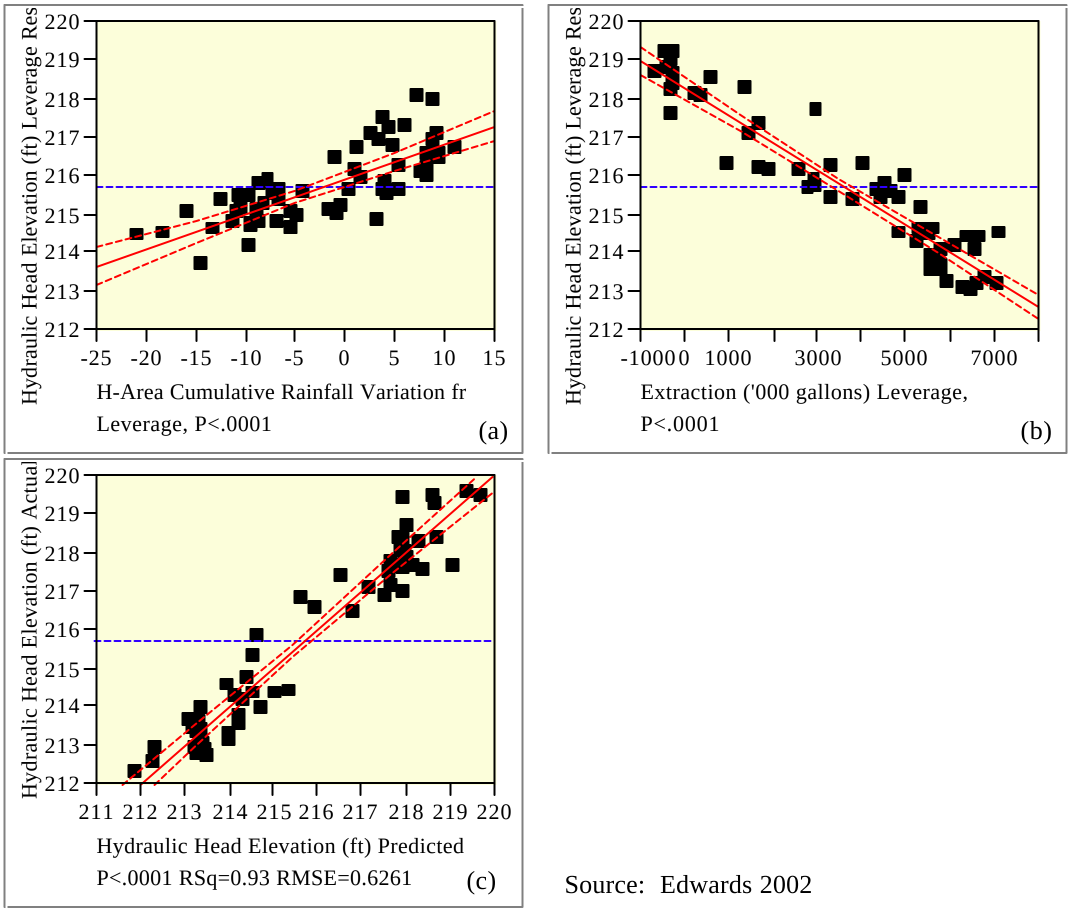
Source: Edwards 2002

Figure 44. Leverage plots of hydraulic head at FPZ004A vs. rainfall surplus/deficit (a), F-Area extraction (b), rainfall (c), and rainfall surplus/deficit times extraction (d) and modeling results showing actual vs. predicted hydraulic head (e) for the period January 1997 through December 2001.



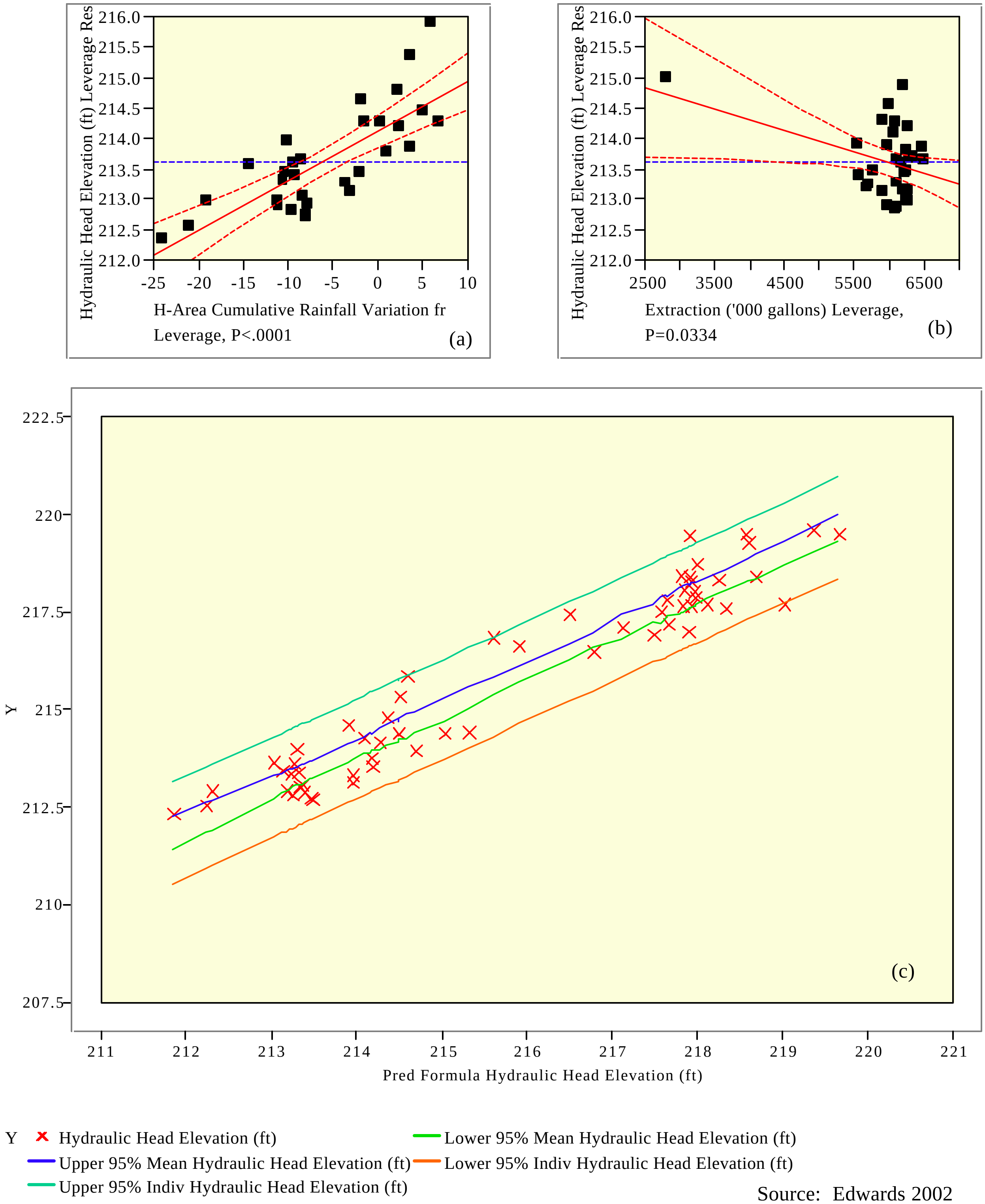
Source: Edwards 2002

Figure 45. Leverage plots of hydraulic head at FPZ004A vs. rainfall surplus/deficit (a), temperature (b), and rainfall (c) and plot of best model results for predicting hydraulic head at FPZ004A during full operation of the F-Area WTU (d). Based on data from August 1999 to December 2001.



Source: Edwards 2002

Figure 46. Leverage plots of hydraulic head at HPZ002A vs. rainfall surplus/deficit (a) and H-Area extraction (b), and modeling results showing actual vs. predicted hydraulic head (c) for the period January 1997 through December 2001. Source: Edwards 2002



Source: Edwards 2002

Figure 47. Leverage plots of hydraulic head at HPZ002A vs. rainfall surplus/deficit (a) and H-Area extraction (b), and plot of best model results for predicting hydraulic head at HPZ002A during full operation of the H-Area WTU (c). Based on data from May 1999 to December 2001.