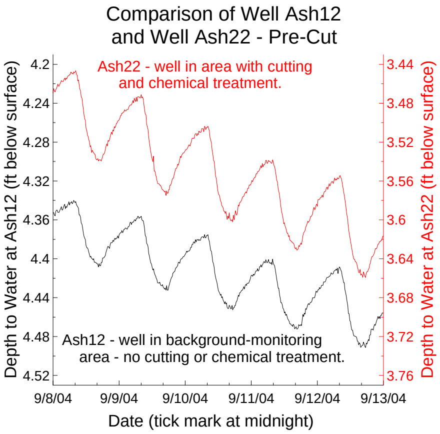
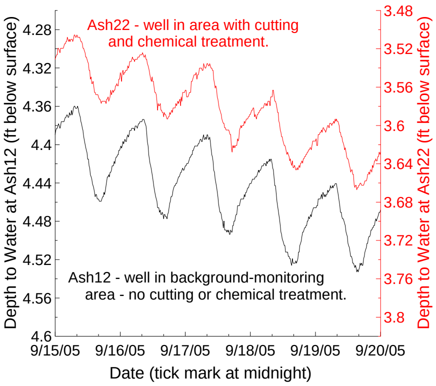
Kansas Geological Survey

GROUND-WATER ASSESSMENT IN ASSOCIATION WITH SALT-CEDAR CONTROL – REPORT ON PHASE TWO ACTIVITIES

Comparison of Well Ash12 and Well Ash22 - Pre-Cut



Comparison of Well Ash12 and Well Ash22 - Post-Cut



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Project: Ground-Water Assessment in Association with Salt-Cedar Control
Phase Two Duration: August 1, 2005 to August 31, 2006
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KWO Contract Number: 06-112 Phase Two Funding: $5,000

EXECUTIVE SUMMARY

The primary objective of this project was to use water-table fluctuations to estimate the impact of various salt-cedar control activities on the ground-water resources of the Cimarron River alluvial aquifer at a site in Clark County, Kansas. Previous work by this research team has shown that diurnal (daily) fluctuations in the water table can be utilized both as a diagnostic indicator of phreatophyte activity and for quantifying ground-water consumption by phreatophytes. This contract was developed to extend the work of the team to exploit an opportunity presented by a Kansas Alliance of Wetlands and Streams (KAWS) demonstration project focused on investigating the effectiveness of various salt-cedar control measures. Funding for this contract was provided by the Kansas Water Plan through the Kansas Water Office. This contract was supplemented by funds from the Kansas Water Resources Institute and the Kansas Geological Survey.

The KAWS demonstration project is being carried out in an area of salt-cedar infestation along the Cimarron River south of Ashland, Kansas. Four experimental plots were established in pasture on the north side of the Cimarron River. One plot (Plot 1) is used for monitoring background (unaltered) conditions, while the other three plots (Plots 2-4) are for application of different salt-cedar control measures. Application of control measures began in mid-March of 2005 and is continuing. The first total clearing of salt cedars (mulch cutting) from Plots 2 and 3 was completed on August 9, 2005. Treatment of salt-cedar regrowth in Plot 2 with a herbicide-diesel mix was completed in mid-August of 2005. Plot 3 was cut again shortly after the end of this reporting period.

Six shallow wells were installed in Plots 1-3 in August 2004. All wells have submersible pressure sensors to allow monitoring of water levels at a 15-min interval. A weather station was installed in October 2004 to monitor meteorological conditions at the same 15-min interval and provide estimates of the potential for evapotranspiration on a daily basis. A neutron-probe access tube was installed adjacent to each well in August 2004 to allow measurement of the volumetric water content above the water table. Water content is measured approximately biweekly during the growing season.

The relative ground-water savings gained through the control activities were estimated using a ratio method specifically developed for this project by the research team. The method is based on diurnal water-table fluctuations and ratios of the empirical equation of White [1932]. Application of this method to data from wells in Plots 2 and 3 showed that ground-water consumption was reduced, relative to what would have been expected in the absence of the control activities, by 23-56% (three-well average of 40%) one month after the total clearing of the salt cedar in Plots 2 and 3. A follow-up analysis using data from June 2006, ten months after completion of treatment, showed that ground-water consumption in Plots 2 and 3 during that period was reduced by 2-27% (three-well average of 17%). Thus, the reductions in ground-water

consumption achieved from salt-cedar control appear to be decreasing with time, despite the severe drought conditions experienced during the 2006 growing season at the site. This decreased reduction may be a result of increased growth (and thus water use) of grasses, forbs, and small bushes due to greater exposure to sunlight and wind after the removal of the large phreatophytes, and regrowth of salt cedar. Further work is needed to assess the relative importance of ground-water consumption by these and other mechanisms to better understand the impact of the control measures.

These results demonstrate that long-term monitoring is critical for assessing the ultimate ground-water savings gained through salt-cedar control. If control activities are undertaken for the express purpose of "salvaging" ground water, monitoring networks, such as that established for this project, must be in place prior to commencement of control activities so that the hydrologic impact of those activities can be assessed. Collection of water-level, water-content, and meteorologic data will continue at this site as long as funding permits in order to ascertain the ultimate ground-water savings achieved with the control activities.

INTRODUCTION

Consumption of ground water by phreatophytes in riparian corridors is thought to be one factor responsible for stream-flow reductions in the Cimarron Basin and elsewhere in western Kansas. Extensive phreatophyte-control measures, primarily focusing on invasive species such as salt cedar (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*), are being considered in response to concerns about the impact of phreatophytes on surface- and ground-water resources (Salt Cedar and Russian Olive Control Demonstration Act passed by 109th Congress and signed by President Bush in October 2006). At present, there is no generally accepted means of quantifying the ground-water savings that might be gained through these control measures. Recently, a team of Kansas Geological Survey (KGS) and Kansas State University (KSU) researchers demonstrated that diurnal fluctuations in the water table can be utilized both as a diagnostic indicator of phreatophyte activity and for quantifying ground-water consumption by phreatophytes [Butler et al., 2007]. This Kansas Water Office (KWO) contract was directed at extending that previous work to assess the use of water-table fluctuations as a tool for quantifying ground-water savings achieved through phreatophyte-control measures.

The KWO contract was developed to exploit an opportunity presented by a Kansas Alliance of Wetlands and Streams (KAWS) demonstration project focused on investigating the effectiveness of various salt-cedar control measures. The demonstration project is being carried out in an area of salt-cedar infestation along the Cimarron River south of Ashland, Kansas (Figure 1). Four experimental plots have been established on the north side of the Cimarron River on pastureland of the Arnold Ranch (Figure 2a). One area (Plot 1) is to remain unaltered during the project, while different salt-cedar control measures are being applied in the other three areas. The salt cedar has been cut and chemically treated in Plot 2, and cut in Plots 3 and 4. When weather conditions permit, the salt cedar will be burned in Plot 4. All cutting has been done with the Arnold Ranch's HydroAx unit (Figure 2b). Cutting with this unit, which shreds the salt cedar, will be referred to as "mulch cutting" for the remainder of this report. Note that the Ashland Research Site (ARS) is the designation for the area on the Arnold Ranch where the work described in this report was carried out.

The Arnold Ranch has been owned and operated by the Arnold family since its establishment in the late 1800s. According to the Arnold family, salt cedar was first noted on the ranch after the flood of 1939. The salt cedar sprouted on wet sand deposited by that flood and its distribution across the area has changed little since then. Dave Arnold, the ranch owner and operator, clear cut (mulch cutting) an area that included Plots 1-3 in the fall of 1996. The heterogeneous pattern of salt cedar and Russian olive growth observed in Plots 1-3 at the start of this project (mid-August 2004) was not a function of how the plots were cut in 1996. That distribution was most likely a reflection of spatial variations in underlying soil conditions.

As described in the Year One Report for this project [Butler et al., 2005 – henceforth, Y1 Report], six wells were installed in Plots 1-3 (wells were not placed in Plot 4 because of concerns about possible damage to wells from the planned burning) and equipped with submersible pressure sensors to monitor water-table responses in the vicinity of the most common phreatophyte communities at the site. A neutron-probe access tube was emplaced adjacent to each well so that volumetric water content in the vadose zone (interval between the water table and the land surface) could also be measured. A weather station was installed on the north end of Plot 3 to monitor meteorological conditions and provide estimates of the potential for evapotranspiration. Water-level and meteorologic data are collected at 15-min intervals, while the volumetric water content in the vadose zone is measured biweekly during the growing season.

In the reporting period for this contract, the first round of salt-cedar control activities was completed in Plots 2 and 3. Control activities began in March 2005. At that time, Plots 2-4 were clear cut of salt cedar and Russian olive except for circles ranging from 70-100 ft in radius about the four monitoring wells in Plots 2 and 3 (Figure 2a). The radii of those circles of vegetation were reduced to 45 ft at three of the four wells on June 3, 2005 (Figures 2a, 3 and 4a). The salt cedar was completely cleared about well Ash32 on June 3rd because of the lack of any plant-induced water-table responses at that well since the start of monitoring in August 2004. The circles at the other three wells in Plots 2 and 3 were reduced to 20 ft on June 27, 2005 (Figure 4b). On July 11, 2005, all plants except one were cut in the three remaining circles. One salt cedar was left adjacent to wells Ash21 and Ash22 (Figure 4c), and one Russian olive was left adjacent to well Ash31. The final plant from each plot was removed on August 9, 2005 (Figures 4c-d). Approximately two weeks after the July 11th cutting, a herbicide (Remedy EC) and diesel mix at a 1:4 ratio for Remedy and diesel, respectively, was applied to the salt cedar regrowth (Figure 5a) in Plot 2 except for that in the immediate vicinity of wells Ash21 and Ash22, which was treated after the final cutting. The effectiveness of the herbicide application varied across the plot. In certain portions of Plot 2, the application appeared to have killed most of the above-surface salt cedar (Figure 5b). In 2006, there was a considerable degree of salt-cedar regrowth across Plots 2 and 3 (Figure 5c). All vegetation in Plot 3 was mowed with a brush hog shortly after the end of this contract period on September 9, 2006.

The salt-cedar regrowth in 2006 was noteworthy because the 2006 growing season was one of the hottest and driest on record for the Ashland area. Daily maximum and minimum air temperatures, as well as total daily precipitation, have been recorded in the city of Ashland since the year 1900 (data provided by Mary Knapp, KS state climatologist). The high maximum daily air temperature (T_{max}) and low precipitation during 2006 were comparable to the great droughts of the 1930's. The mean T_{max} and total precipitation for the 2006 growing season at Ashland were 88.2 °F and 9.88 inches, respectively. In the long-term data set (1900-2006), six years had total growing season precipitation $\leq$ 9.88 inches, and 20 years had a mean $T_{max} \geq 88.2$ °F. However, only two years, 1934 and 1954, had both a mean $T_{max} > 88.2$ °F and total growing season precipitation < 9.88 inches [Nippert et al., 2007, in review]. As a result of the drought conditions, the Cimarron River channel was dry from early June of 2006 to the end of the reporting period (Figure 5d); a dry channel for that length of time has rarely been observed on the Arnold Ranch (Dave Arnold, personal communication).

A number of tasks not funded by this contract were also performed by the KGS/KSU research team to increase the value of the project results. These tasks, which included soil sampling in the vicinity of each of the wells in September 2005, monitoring of various plant physiology parameters and analyses of the stable isotopic composition of plant-stem water during the 2006 growing season [Nippert et al., 2007, in review], and a mathematical analysis of the lateral propagation of water-table fluctuations [Jin et al., 2007], will be briefly summarized in the Related Activities section of this report.

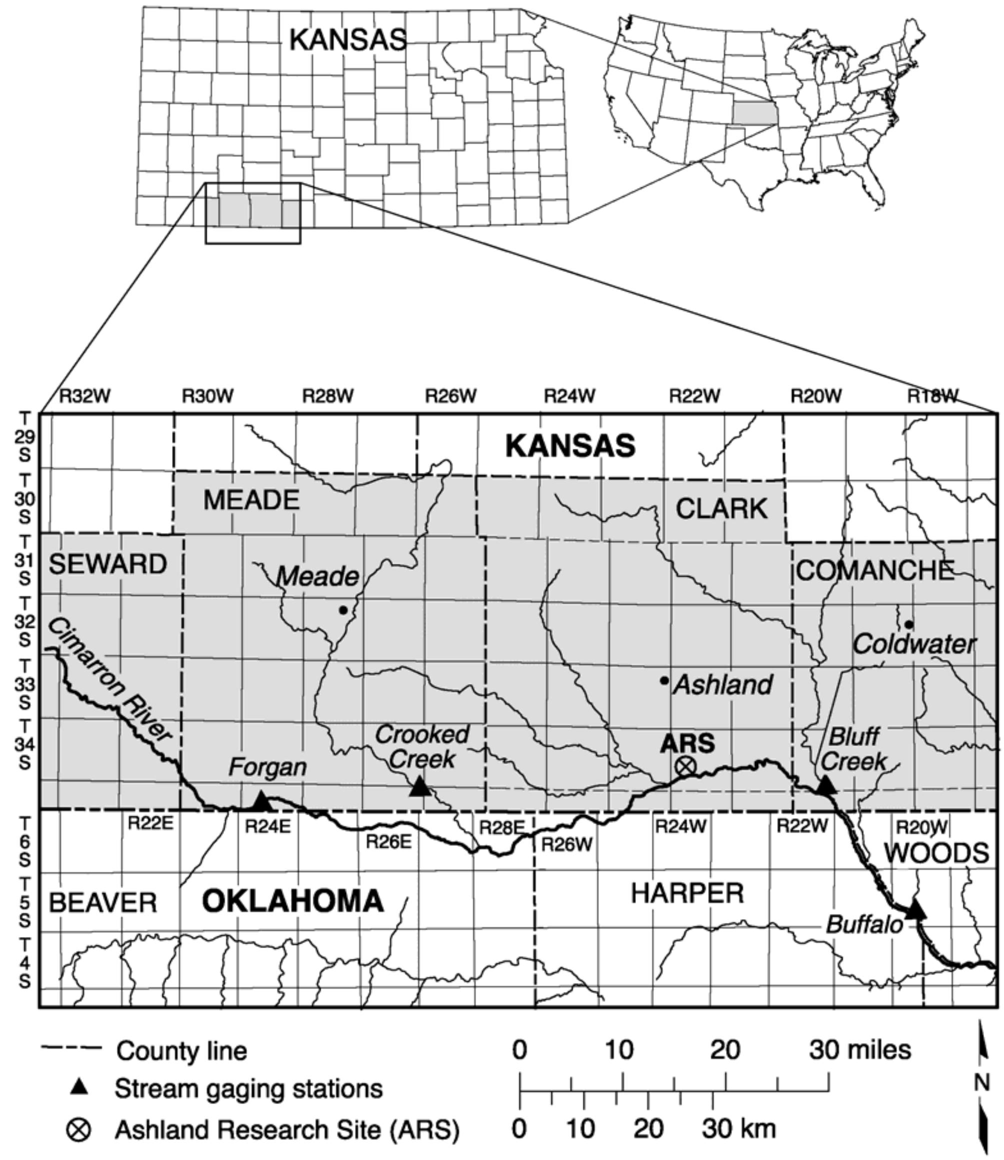


Figure 1 – Location map of the Ashland Research Site (ARS). The Ashland Research Site is the designation for the area on the Arnold Ranch where the work described in this report was carried out.

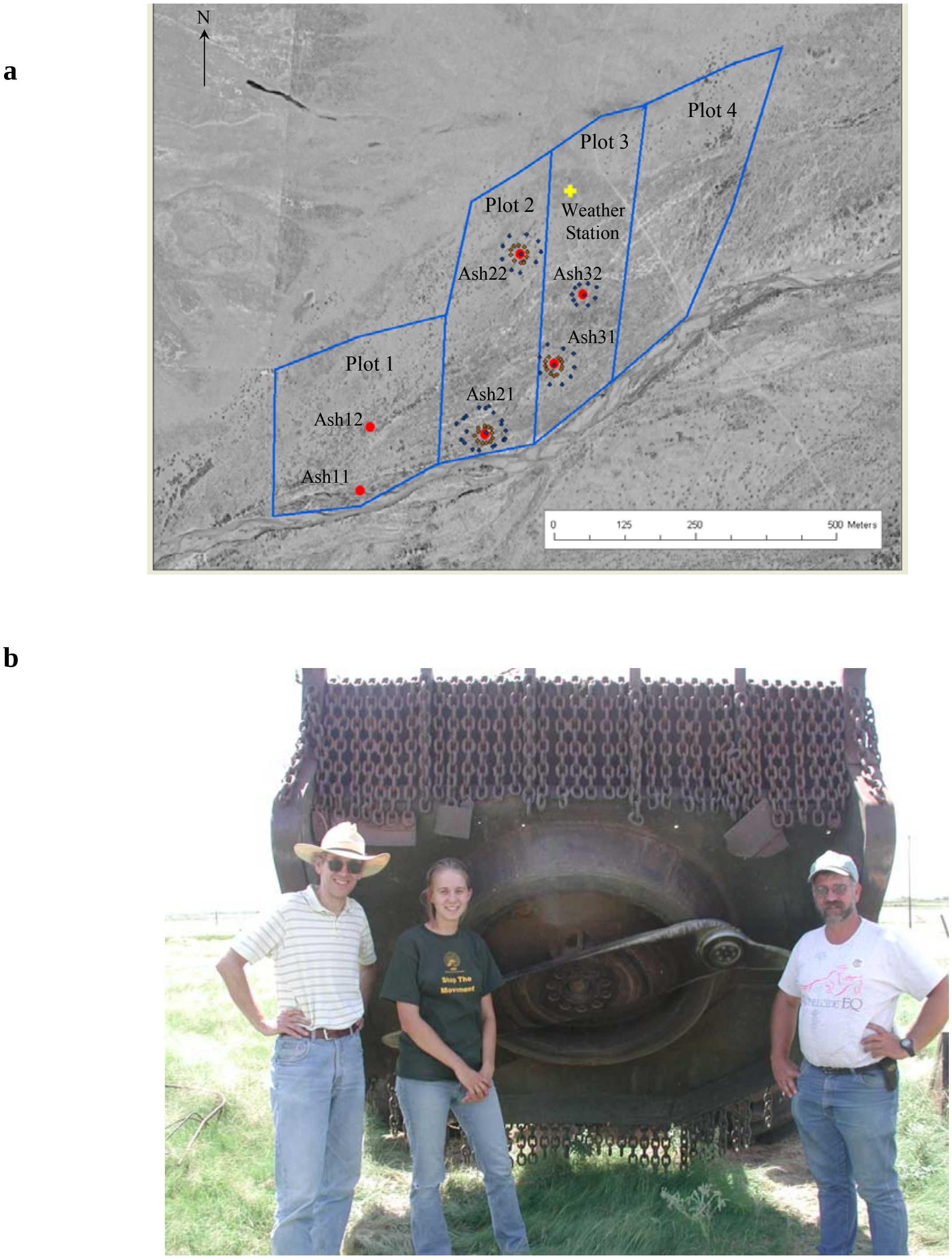


Figure 2 – a) Aerial photo of ARS with locations of the experimental plots, monitoring wells (red circles), and weather station. The circles about each well in Plots 2 and 3 denote boundaries of vegetation circles remaining after mid-March 2005 and June 3, 2005, cuttings (circle boundaries recorded with handheld GPS unit; vegetation completely cleared around well Ash32 on June 3); b) Underside of HydroAx unit, the cross bar weighs 450 lbs and spins at 950 rpm, the small wing-like attachments on either side of the central bar weigh 37 lbs each and rotate as well.

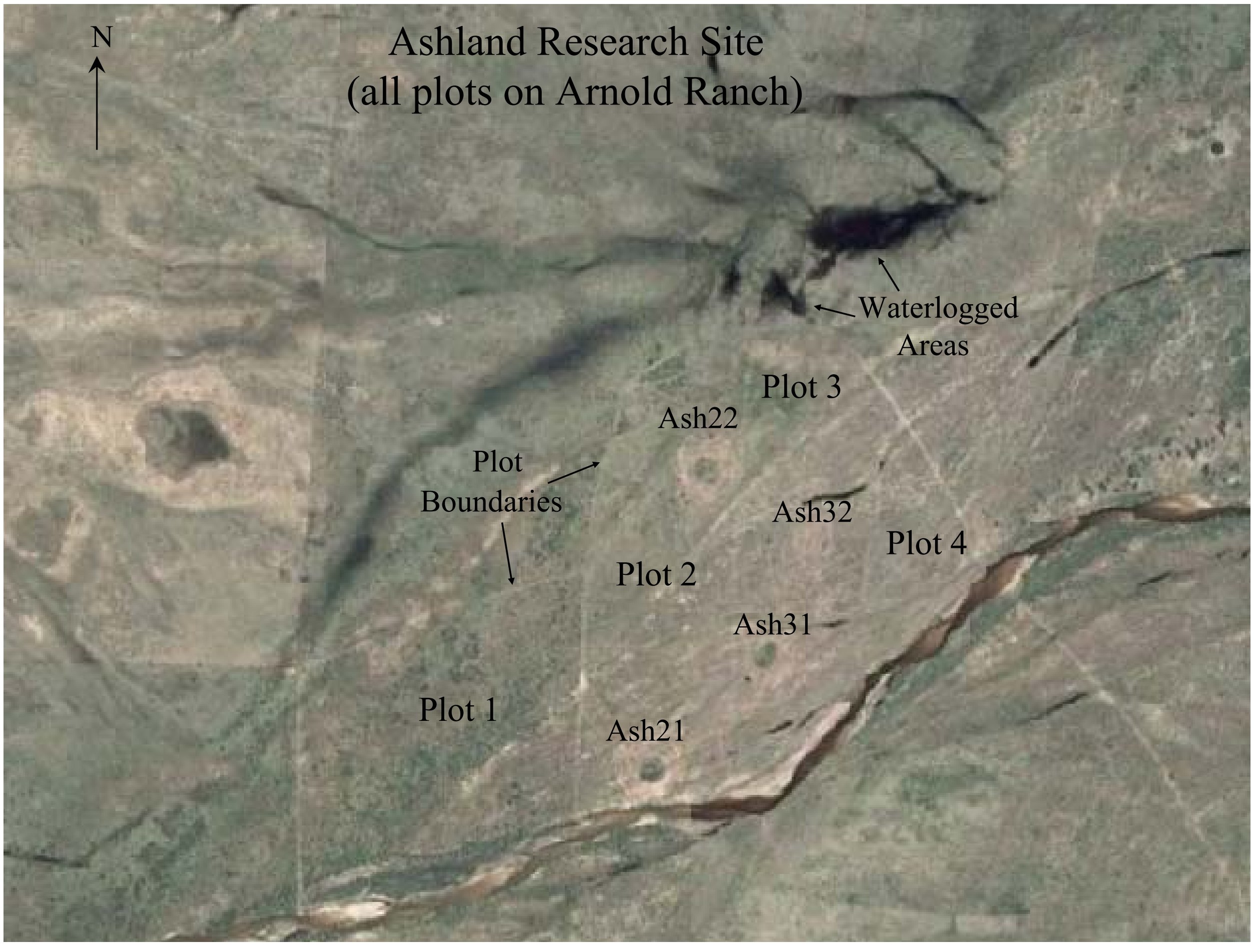


Figure 3 - Aerial photo of ARS sometime in period June 10-27, 2005, showing boundaries of vegetation circles remaining after June 3rd cutting (photo downloaded from Microsoft Virtual Earth site on June 9, 2008). The bare annular rings around wells Ash21, Ash22, and Ash31 indicate the area cut on June 3rd. The lack of a vegetated core at well Ash32 is due to the low vegetation density at that well. Plot boundaries are thin white lines of cut vegetation; boundaries between Plots 2 and 3 and Plots 3 and 4 are only visible for a limited portion of their extent. Note the extensive waterlogged areas most likely as a result of heavy precipitation on June 10 and 12, 2005.

a b

c d

Figure 4 – a) Photo (6/16/05) of vegetation circle (radius of 45 ft) around well Ash22 following June 3rd cutting (view looking north, ATV on left for scale, pole visible at center of plot is 8.5 ft in height; note remnants of cut salt cedar in foreground in this and following photos); b) Photo (6/27/05) of vegetation circle (radius of 20 ft) around well Ash22 following June 27th cutting (view looking north); c) Photo (8/9/05) of HydroAx approaching large salt cedar remaining as the single plant near well Ash22 following July 11th cutting (view looking north); d) Photo (8/9/05) of area around well Ash22 immediately after final cutting (view looking north).

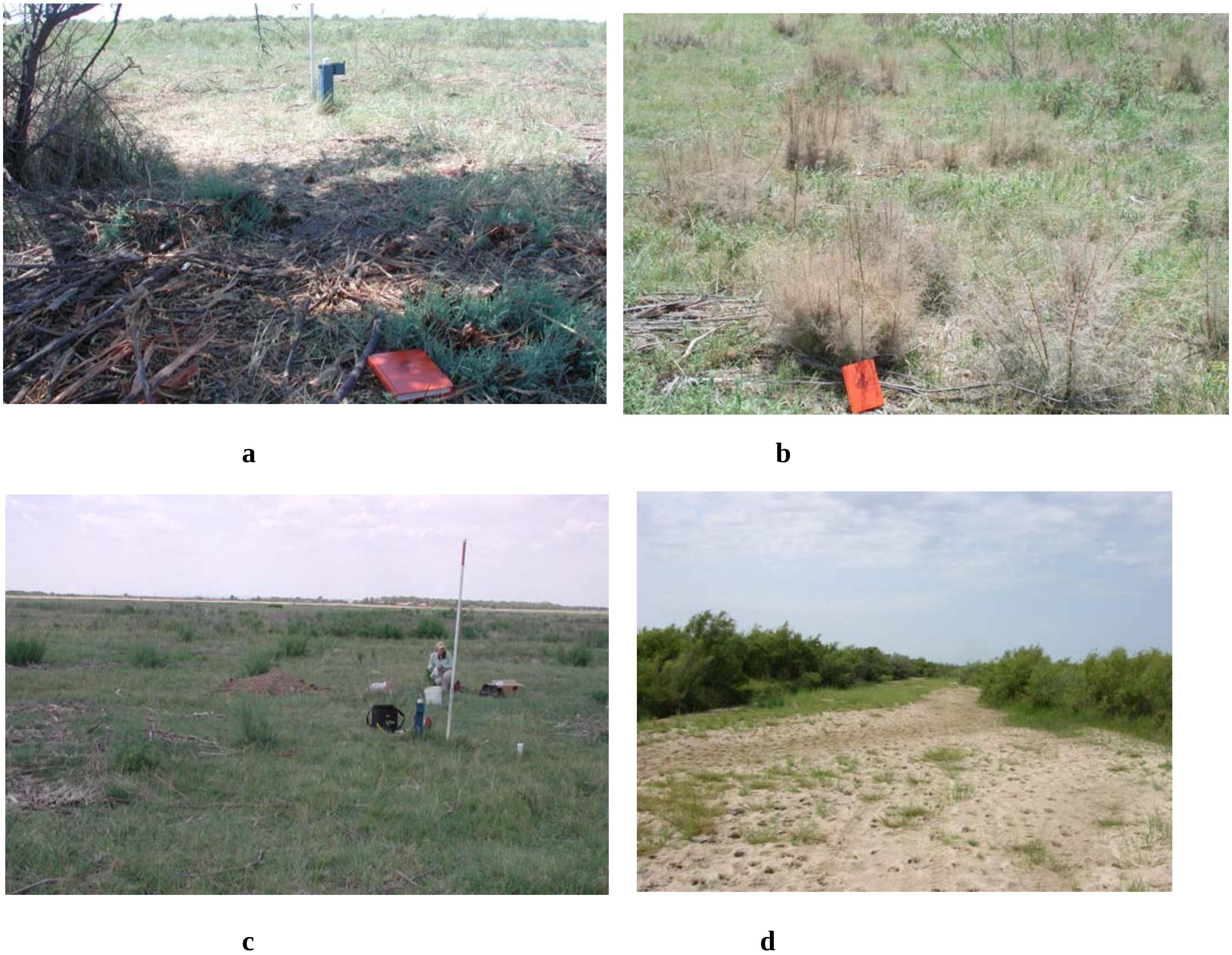


Figure 5 – a) Photo (8/9/05) of salt-cedar regrowth in immediate vicinity of final remaining salt cedar at well Ash22 (view looking southwest toward well Ash22, field notebook for scale, regrowth occurred following July 11th cutting); b) Photo (8/9/05) of treated salt-cedar regrowth in Plot 2 (photo taken 45-50 ft southwest of well Ash22, field notebook for scale, regrowth occurred following June 3rd cutting); c) Photo (6/29/06) of salt-cedar regrowth at well Ash22 near end of reporting period (view looking north); d) Photo (6/29/06) of Cimarron River channel in vicinity of well Ash11 (view looking west, note dense salt-cedar stands on channel banks).

REPORT OVERVIEW

The following report is divided into three main sections: 1) Data Management, Processing, and Overview; 2) Initial Analysis of Ground-Water Savings Produced by Salt-Cedar Control; and 3) Related Activities. The first section describes data management and processing procedures, presents an overview of the water-level and meteorologic data that have been collected in the project, and summarizes the procedures for and results from the neutron logging. The second section presents an initial analysis of the ground-water savings produced by salt-cedar control using changes in water-table fluctuations prior to and following application of control measures. The third section describes related activities at the ARS funded through sources other than this contract.

1) DATA MANAGEMENT, PROCESSING, AND OVERVIEW

The first five tasks listed in the scope of work outlined in the KWO contract involved the management, processing, and analysis of the pressure-sensor, weather-station, and neutron-probe data. Those tasks, all of which are ongoing and will continue through the life of the project, are as follows:

Task 1 - Data collection from six ground-water monitoring wells in the Cimarron River alluvial aquifer
Task 2 - Download data from pressure sensors and weather station
Task 3 - Processing and analysis of pressure-sensor and weather-station data
Task 4 - Neutron logging
Task 5 - Processing of neutron logging

Each of these tasks is described in this section.

Task 1 – Data collection from six ground-water monitoring wells in the Cimarron River alluvial aquifer

Data collection continued from all six ground-water monitoring wells through the contract period. The descriptions of Tasks 2 and 3 will provide more details concerning the data collection. Further information about the wells and sensors can be found in the Y1 Report.

Task 2 – Download data from pressure sensors and weather station

The eight sensors (five absolute-pressure miniTrolls, one absolute-pressure Troll 9000, and two baroTrolls, In-Situ Inc.) used for water-level monitoring are downloaded each time the research team visits the ARS. Those visits are approximately every two to three weeks during the growing season and every two months at other times. Downloading is done using a hand-held (Rugged Reader, In-Situ Inc.) or laptop computer. Cables and software for downloading the sensors have also been provided to Dave Arnold and he has helped download during the winter. Each time the sensors are downloaded, the status of the internal batteries and memory are checked. Low (<30% capacity) batteries are changed. If the amount of occupied memory appears to be significantly increasing download time, the memory is cleared. Each time the memory is cleared, the sensor is reprogrammed and the monitoring program is restarted. A member of the research team must confirm that the monitoring program has actually restarted prior to departure from the site. When the research team downloads a sensor, a depth-to-water measurement is also taken with an electric tape (Model 101, Solinst Canada Ltd.) as a check on sensor operation and calibration. The same electric tape was used for all the depth-to-water measurements taken in this reporting period. All eight sensors functioned well throughout the contract period, but data from the sensor in well Ash22 appeared to become “noisier” with time.

The weather station is also downloaded each time the research team visits the site. The downloading is done using a laptop computer. When the research team downloads the weather station, a hand-held unit (Kestrel 3500 Pocket Weather Meter, Nielsen Kellerman Inc.) is used to measure air temperature, relative humidity, wind speed, and atmospheric pressure to check the operation of the weather station sensors. During the winter, Dave Arnold also helps download the weather station and forwards that information to the research team.

Task 3 – Processing and analysis of pressure-sensor and weather-station data

Pressure-sensor data

After downloading, the pressure-sensor data are forwarded to staff at the KGS for processing. Dr. Xiaoyong Zhan performed that processing early in the reporting period, while Butler and KGS students under his guidance performed the processing for the remainder of the contract period after Dr. Zhan’s departure from the KGS. As described in the Y1 Report, processing involves removing the atmospheric-pressure component from the pressure sensors submerged in the water column, and then appending the new data to the existing master file. The atmospheric-pressure measurements were obtained from a barometer in the air space above the water in well Ash12 for the entire length of the contract period. The processed data are currently stored in Excel worksheets. Efforts to move the data into an Oracle database were suspended after the departure of Dr. Zhan.

In this report, processed pressure-sensor data through September 7, 2006, are presented. The analysis of the pressure-sensor data for estimation of ground-water savings achieved through salt-cedar control activities will be discussed in Section 2 of this report. Data from each well will be presented here to illustrate the temporal pattern of water-table variations observed at the site and to discuss the minor problems that were encountered during the monitoring. In addition, these data will be used to illustrate the changes in water-table fluctuations recorded at four of the six wells during the summer 2006 drought.

Figures 6-11 are plots of depth to water (henceforth, well hydrographs) recorded at each of the wells for the entire contract period. Ash11 (Figure 6) had the largest variation in water-table elevation over this period (4.38 ft) due to its location in a low-lying area prone to flooding near the river channel. Although absolute-pressure sensors were used in all wells to avoid sensor failure resulting from well overtopping during high flows of the Cimarron River, only well Ash11 was overtopped during the contract period (see mid-June 2005 peak on Figure 6). As described in the Y1 Report, the sensing port for the barometer in well Ash12, as well as that for the backup barometer in well Ash32, was submerged due to an unanticipated rise in the water table in late 2004. That submergence produced the horizontal line on the water-level plot for well Ash12 (Figure 7) and impacted the water-level readings for all the wells for that same time period (11/16/04 to 1/13/05). The barometers were repositioned in both wells in early 2005. Following the repositioning, the barometer at well Ash12 has only been submerged for two days (6/16-6/18/05), which were during the highest Cimarron River stage for the contract period.

The well hydrographs for the contract period show a consistent pattern across the site: a water-table low in mid-September 2004, water-table highs in mid-February and mid-June 2005, a water-table low in late summer of 2005, and then a falling water table through most of the spring and summer of 2006. The elevations of the 2004 and 2005 water-table lows were similar, but the water table fell well beyond those lows in 2006. Although there is no stream gage at the Ashland site, the hydrograph at well Ash11 should provide a reasonable depiction of stage changes in the adjacent Cimarron River. The Ash11 hydrograph is characterized by many abrupt and short-lived changes in water level that are reflective of transient stage changes in the river. These stage-induced changes in water level are dampened and broadened as they propagate through the aquifer to the other wells. The Ash32 hydrograph (Figure 11) reveals that many of the short-lived changes are difficult to discern at distance from the river.

Figures 12-17 provide expanded views of the well hydrographs for (a) the three months during the late spring and summer of 2005 (period of majority of treatment activities in Plots 2 and 3), and (b) the last three months of the contract period (summer 2006 drought). The (a) hydrographs demonstrate that water-table fluctuations continued throughout the treatment period both in the unaltered area (Plot 1) and the altered areas (Plots 2 and 3) for those wells that displayed diurnal fluctuations in the pre-treatment monitoring period (all wells except Ash32, see Y1 Report). The continuation of diurnal water-table fluctuations at wells in the treatment area (Figures 14a-16a) indicates that evapotranspirative consumption of ground water did not cease as a result of the treatment activities, an issue that will be discussed further in Section 2. The (b) hydrographs demonstrate that at four of the wells (Ash11, Ash12, Ash21, and Ash31) the amplitude of the diurnal fluctuations abruptly diminished as the water table dropped during the 2006 drought (Figures 12b-14b and Figure 16b). These abrupt and large decreases in amplitude occur in the vicinity of the elevation of the 2004 and 2005 water-table lows. One possible interpretation is that the water table had fallen beyond the reach of the roots of much of the phreatophytic vegetation at the ARS, an interpretation similar to that proposed earlier to explain the disappearance of diurnal fluctuations with declines in the water table at the KGS/KSU research group's Larned Research Site [Butler et al., 2007].

Weather-station data

After downloading, the weather-station data are forwarded to staff at the KGS for processing. Dr. Xiaoyong Zhan performed that processing early in the reporting period, while Butler and KGS students under his guidance performed the processing for the remainder of the contract period after Dr. Zhan's departure. As described in the Y1 Report, processing involves appending the new data to the existing master file, and calculating the reference evapotranspiration parameter (ET_0 – Allen et al. [1998]) based on the Penman-Monteith equation [Campbell and Norman, 1998] to characterize the potential for evapotranspiration when water is not a limiting factor. The data are currently stored in Excel worksheets. Efforts to move the data into an Oracle database were suspended after the departure of Dr. Zhan.

Figure 18 displays the reference evapotranspiration parameter for the entire period during which the weather station was operating. The low ET_0 in the late fall and winter months and the high in the late spring and summer are as expected. The sizable short-term temporal variations in ET_0 observed throughout the contract period also are as expected and are a product of changing meteorological conditions.

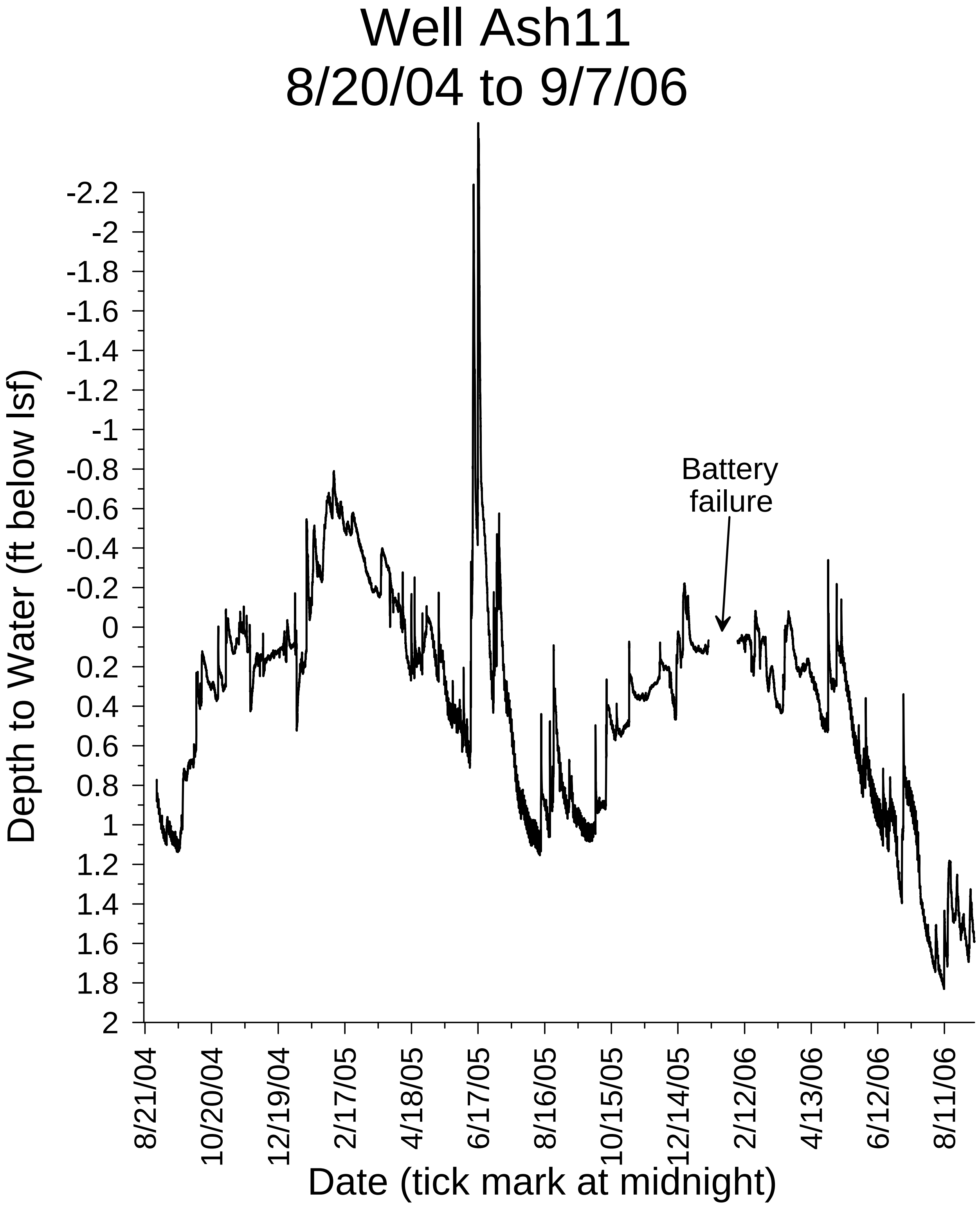


Figure 6 - Depth to water from land surface recorded in well Ash11 for the entire contract period (well Ash11 is in Plot 1 [unaltered area], see Figure 5a in Y1 Report for a photograph of well and surrounding vegetation). Note the monitoring gap from 1/10/06 to 2/5/06 that was caused by battery failure.

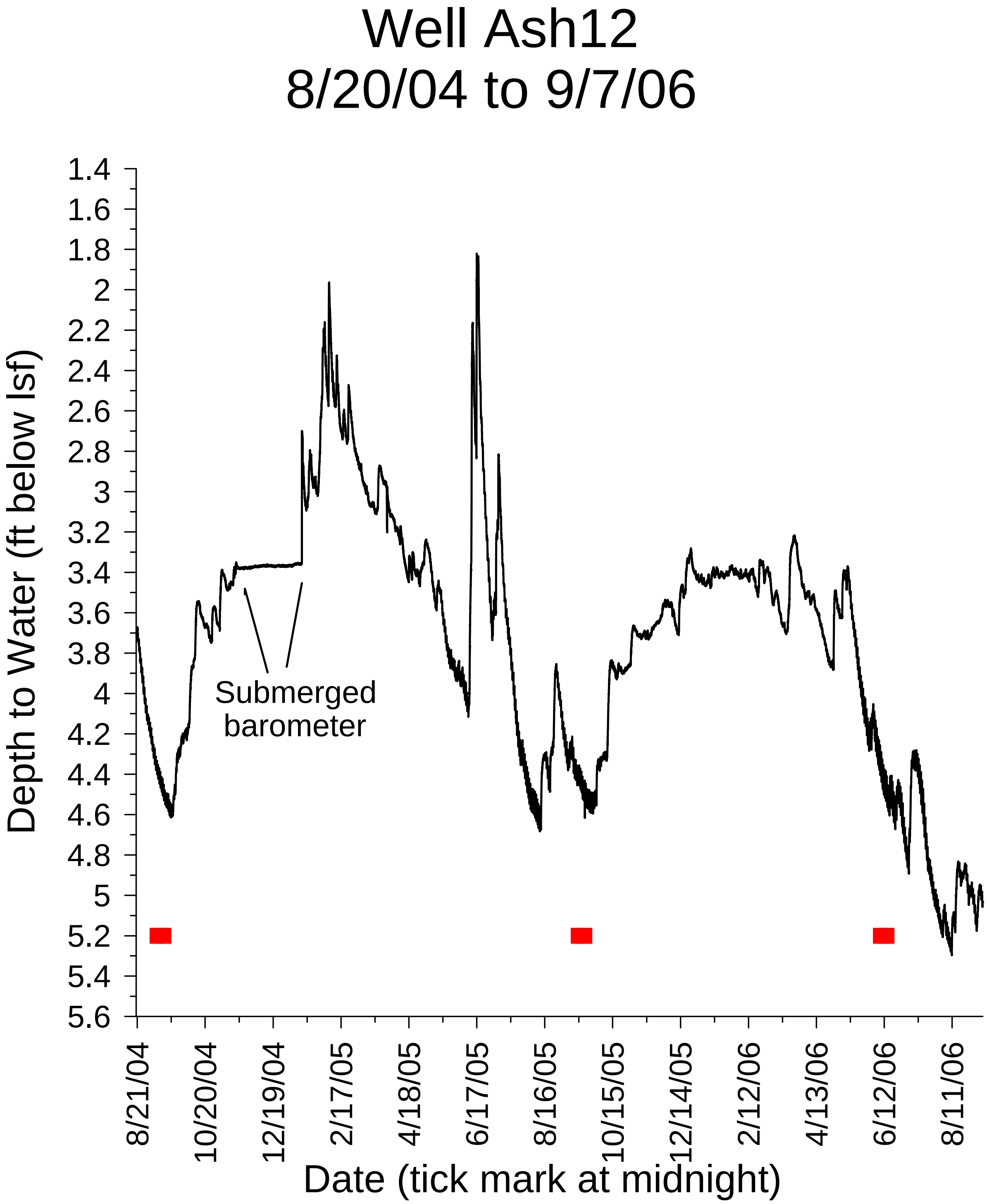


Figure 7 - Depth to water from land surface recorded in well Ash12 for the entire contract period (well Ash12 is in Plot 1 [unaltered area], see Figure 6a in Y1 Report for a photograph of well and surrounding vegetation). A barometer in the air column in well Ash12 was used to correct the absolute-pressure sensors in all wells for the entire contract period; the barometer was submerged from 11/16/04 to 1/13/05, producing a horizontal line on the water-level plot for well Ash12 (see Y1 Report for further details). Thick red lines indicate periods used in analyses described in Section 2.

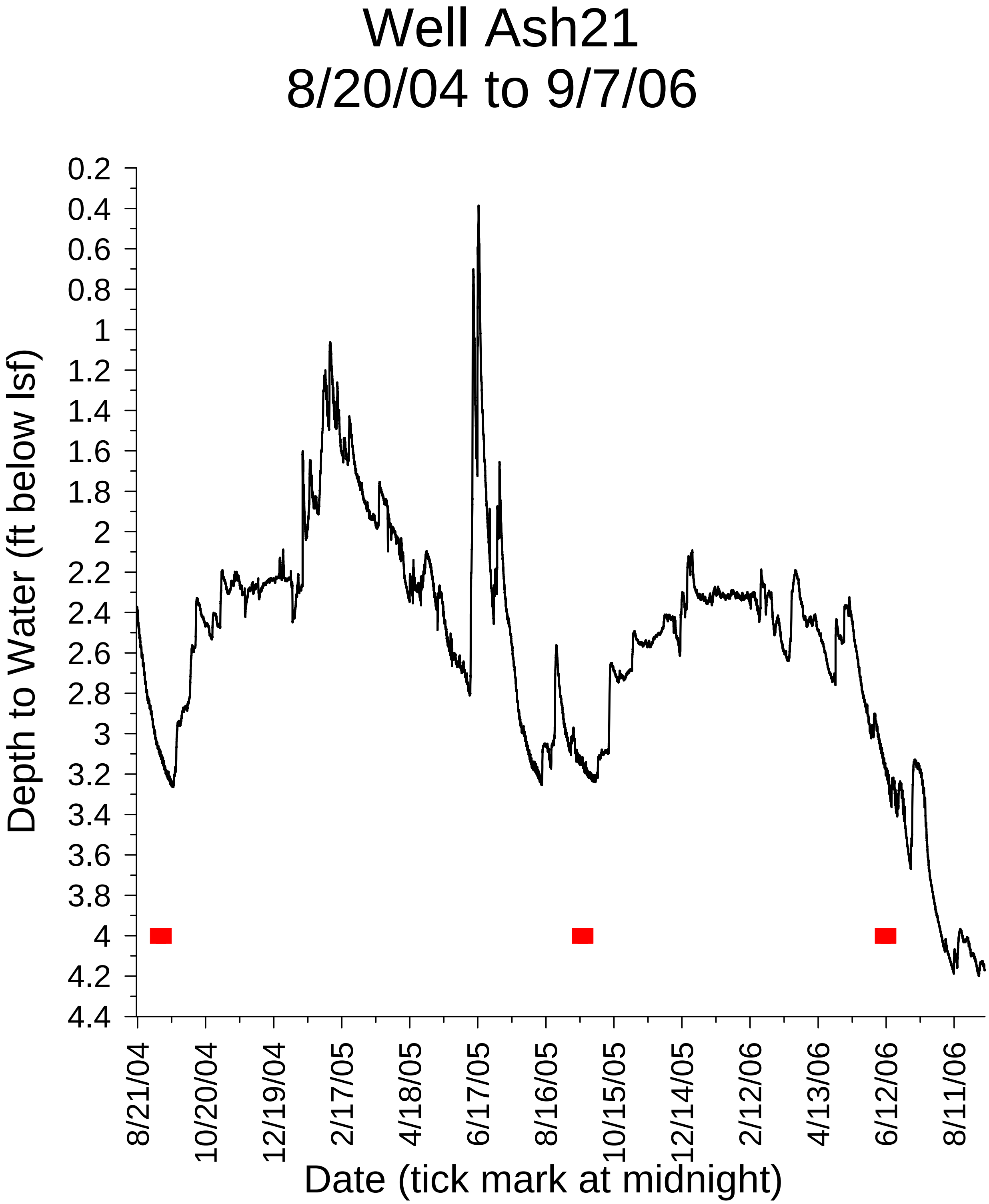


Figure 8 - Depth to water from land surface recorded in well Ash21 for the entire contract period (well Ash21 is in Plot 2 [area of mulch cutting and chemical treatment], see Figure 7a in Y1 Report for a photograph of well and surrounding vegetation). Thick red lines indicate periods used in analyses described in Section 2.

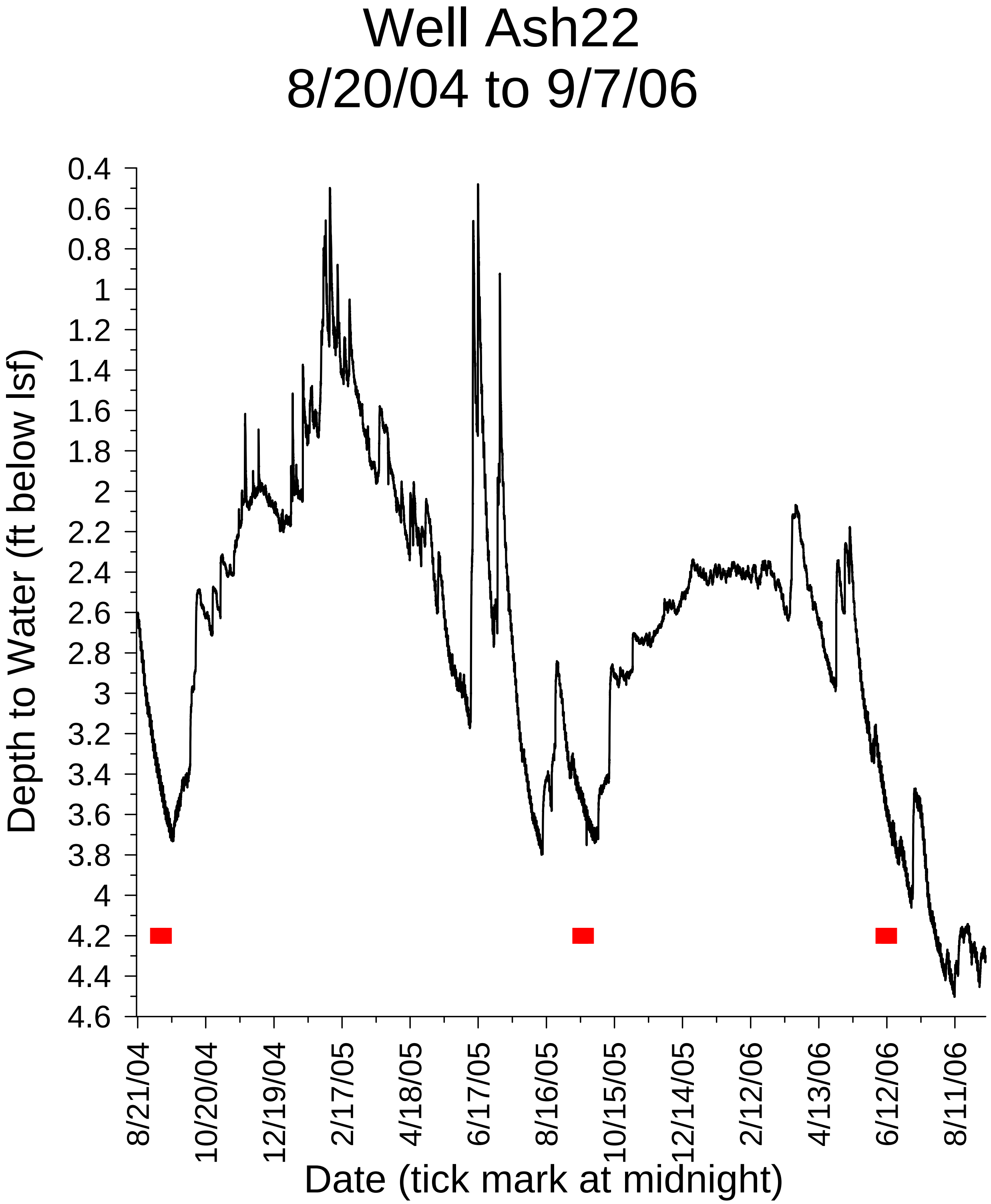


Figure 9 - Depth to water from land surface recorded in well Ash22 for the entire contract period (well Ash22 is in Plot 2 [area of mulch cutting and chemical treatment], see Figure 8a in Y1 Report for a photograph of well and surrounding vegetation). Thick red lines indicate periods used in analyses described in Section 2.

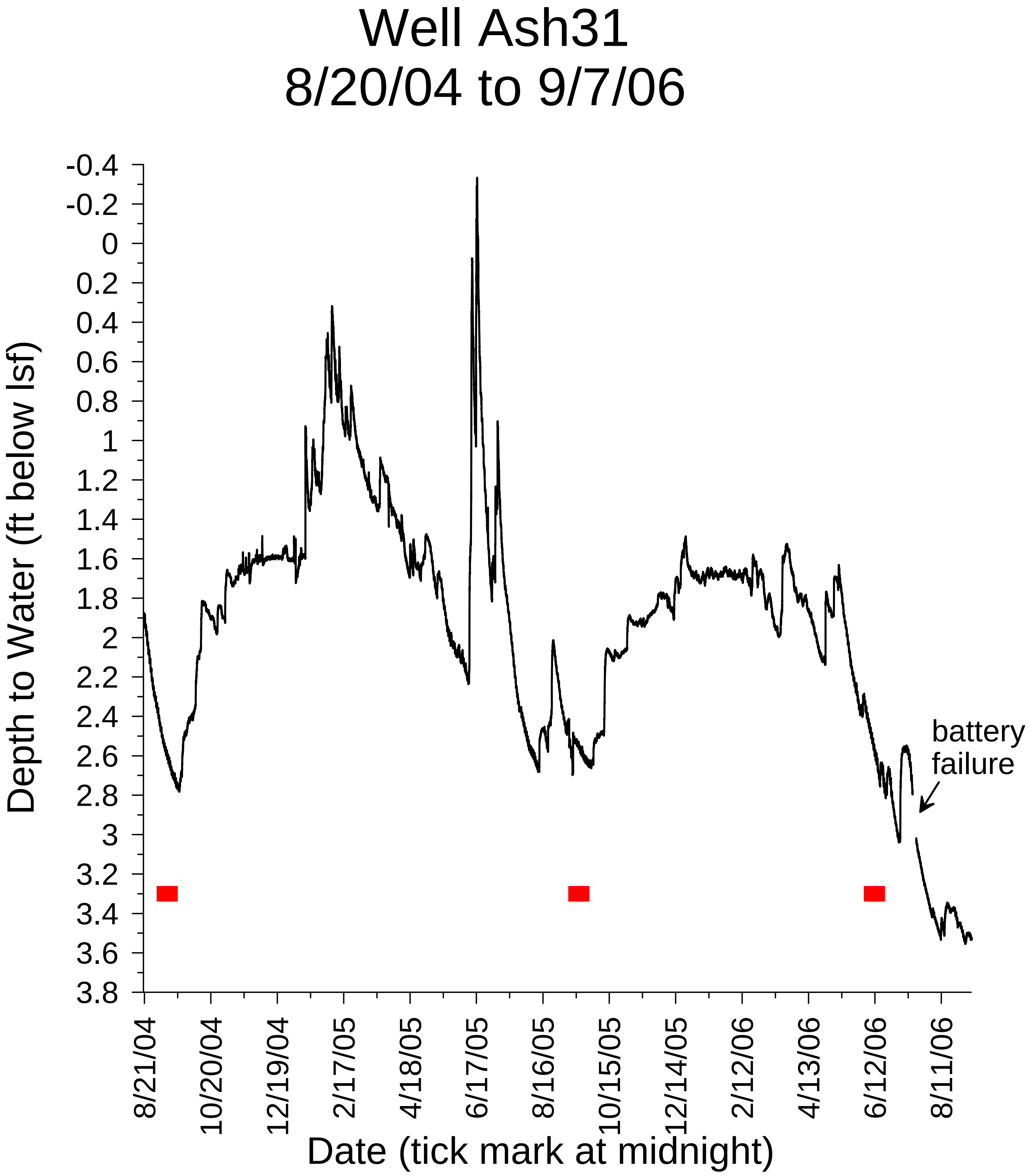


Figure 10 - Depth to water from land surface recorded in well Ash31 for the entire contract period (well Ash31 is in Plot 3 [area of mulch cutting only], see Figure 9a in Y1 Report for a photograph of well and surrounding vegetation). Note the monitoring gap from 7/16/06 to 7/19/06 that was a result of premature battery failure. Thick red lines indicate periods used in analyses described in Section 2.

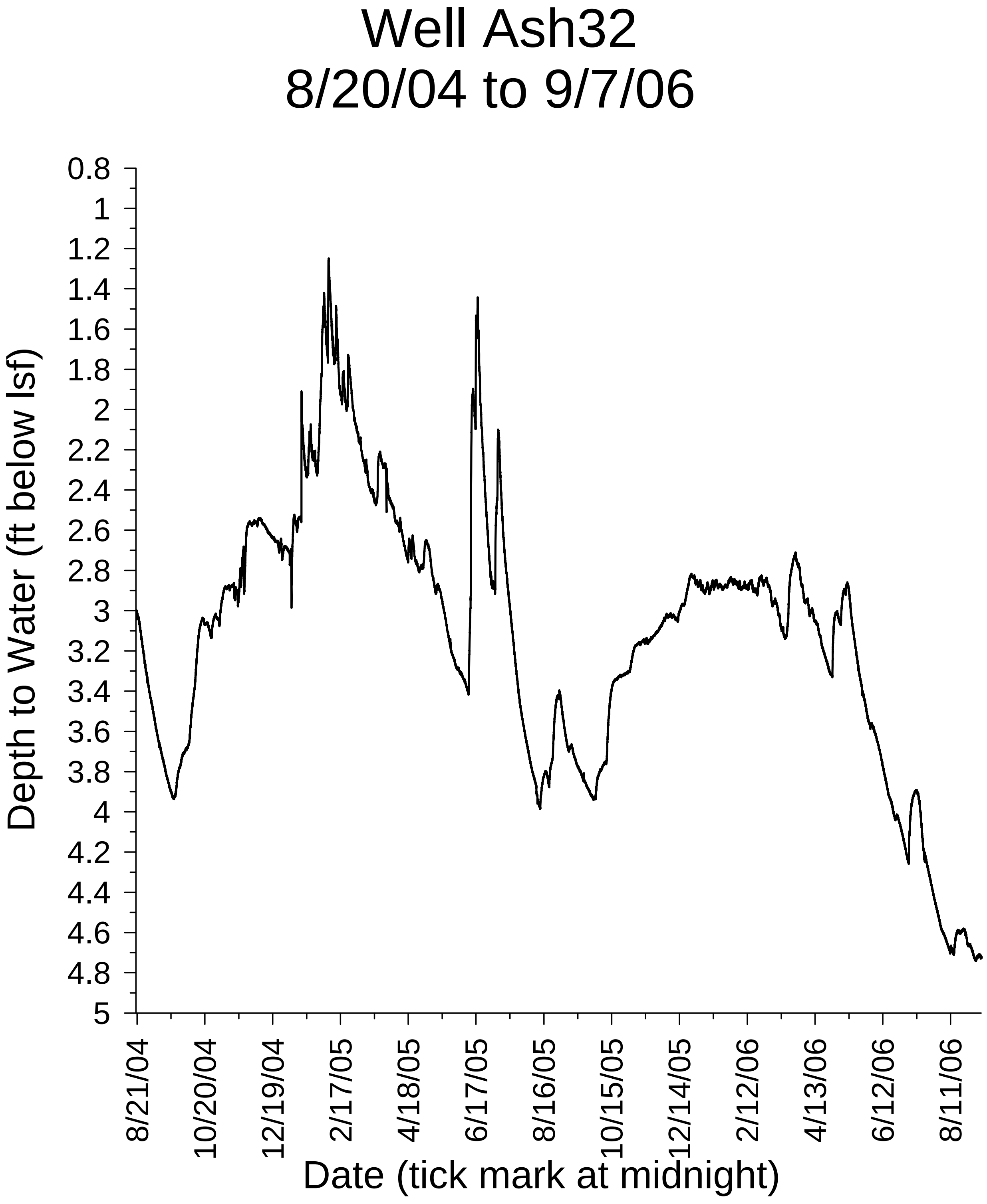


Figure 11 - Depth to water from land surface recorded in well Ash32 for the entire contract period (well Ash32 is in Plot 3 [area of mulch cutting only], see Figure 10a in Y1 Report for a photograph of well and surrounding vegetation).

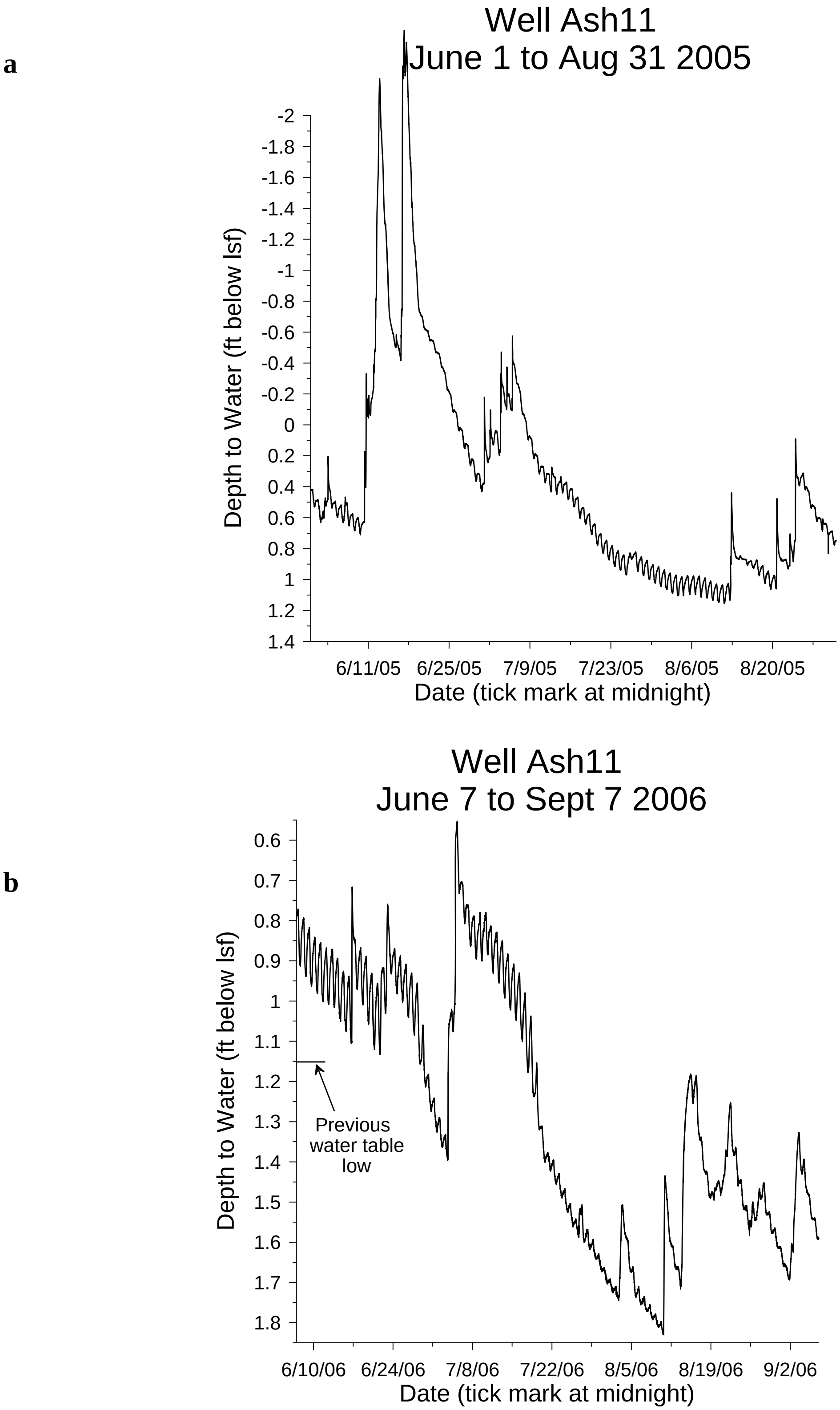


Figure 12 - Depth to water recorded in well Ash11 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period.

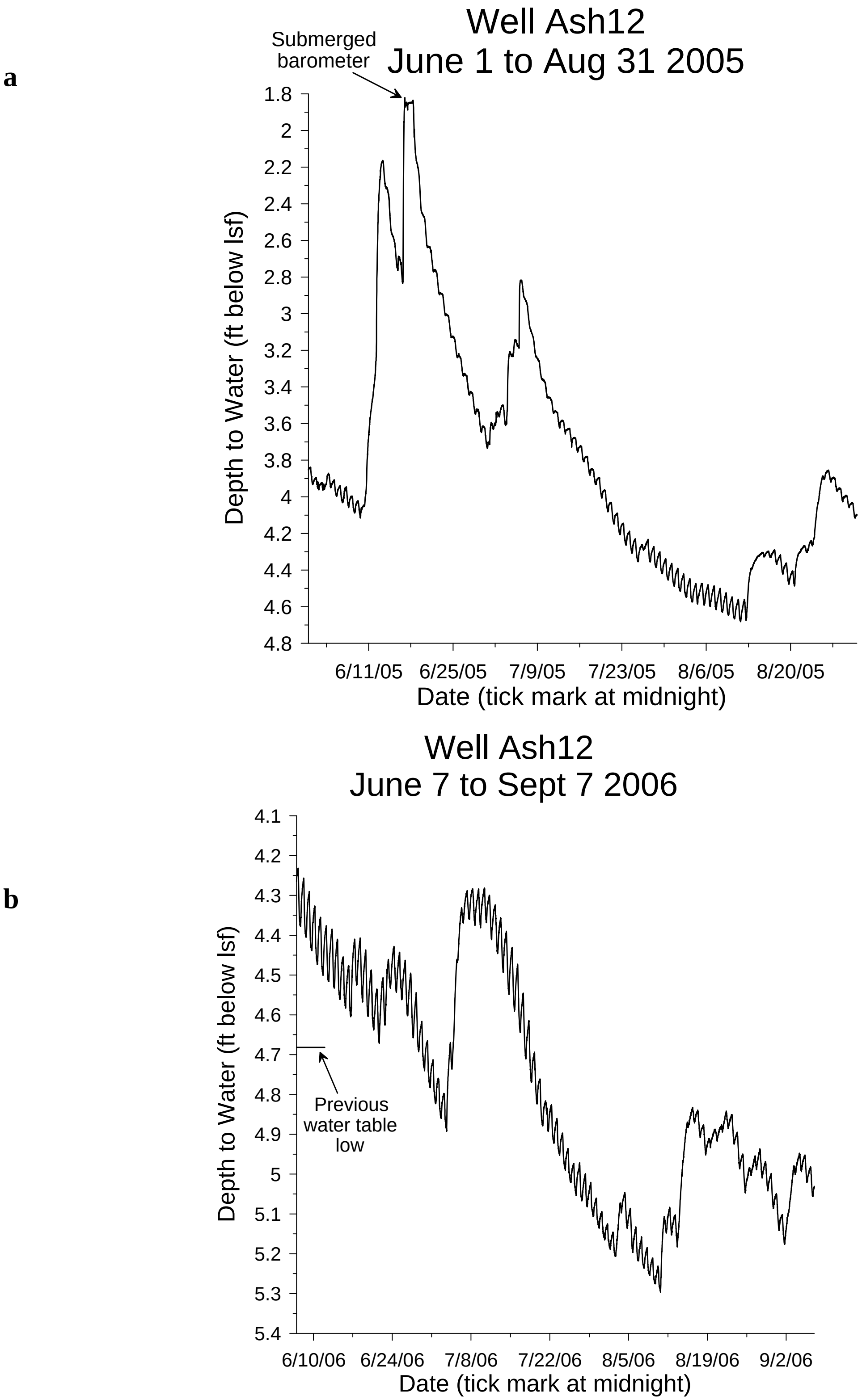


Figure 13 - Depth to water recorded in well Ash12 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period. Note the brief period of barometer submergence in mid-June of 2005 due to the highest water-table position during the contract period.

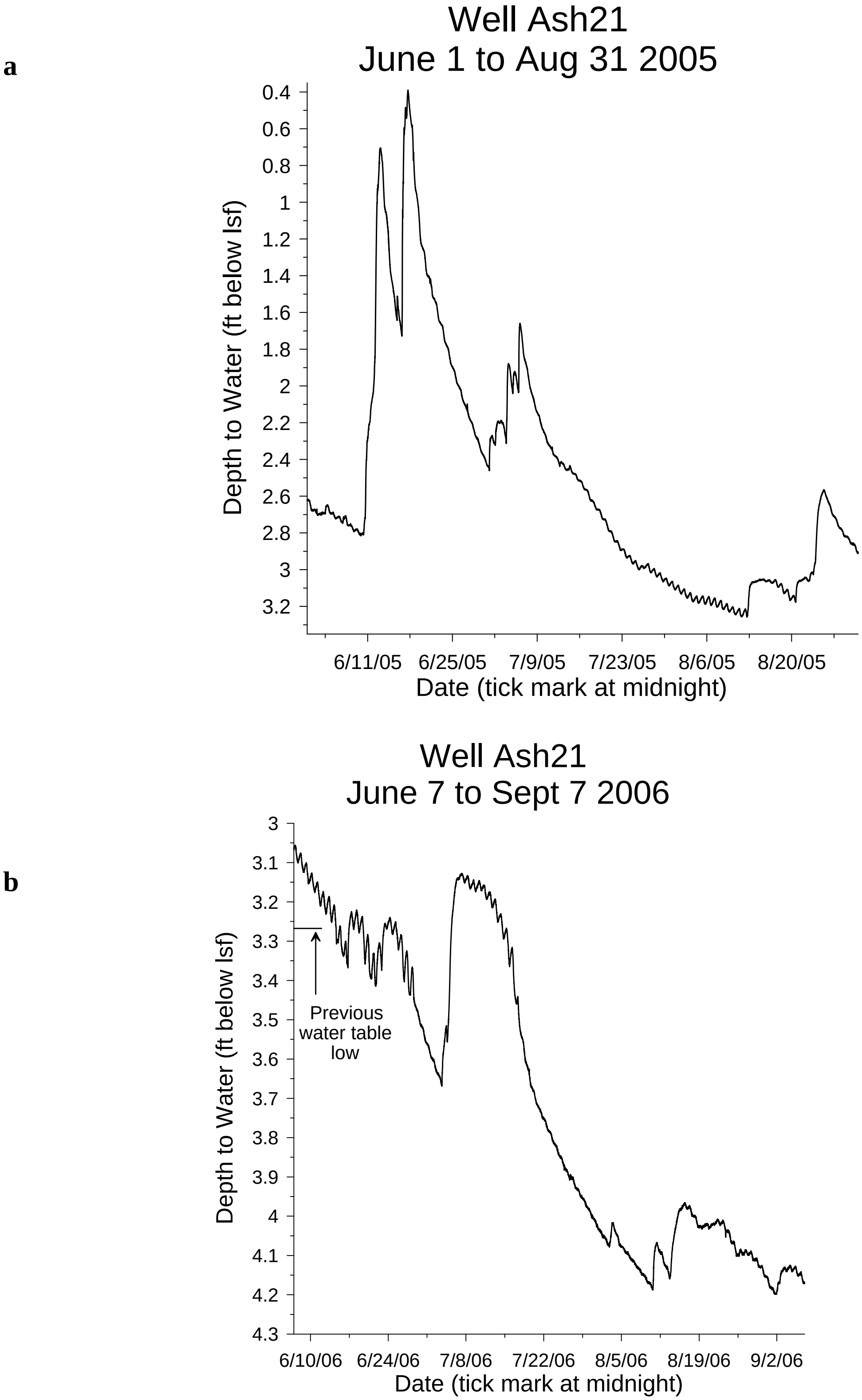


Figure 14 - Depth to water recorded in well Ash21 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period.

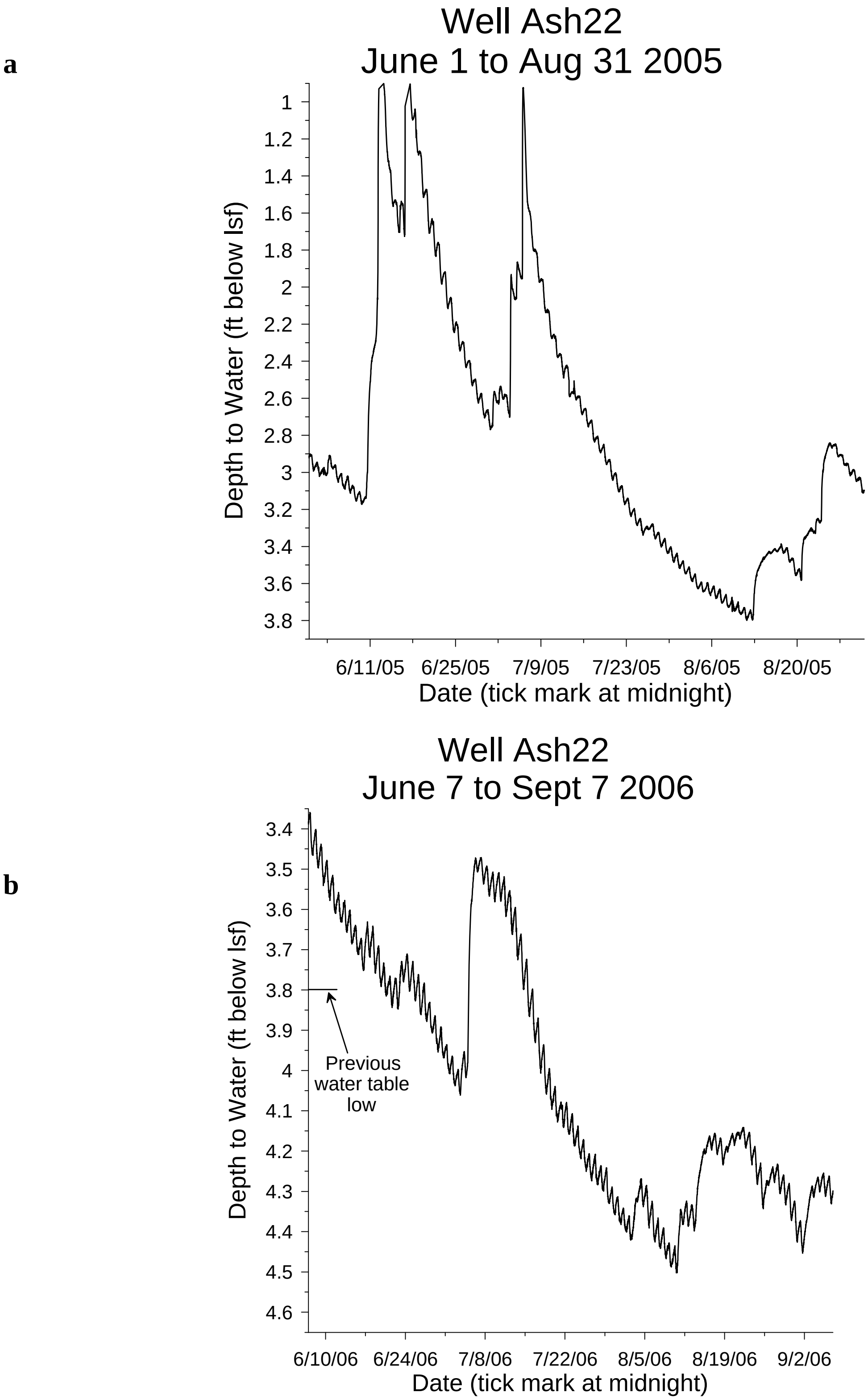


Figure 15 - Depth to water recorded in well Ash22 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period.

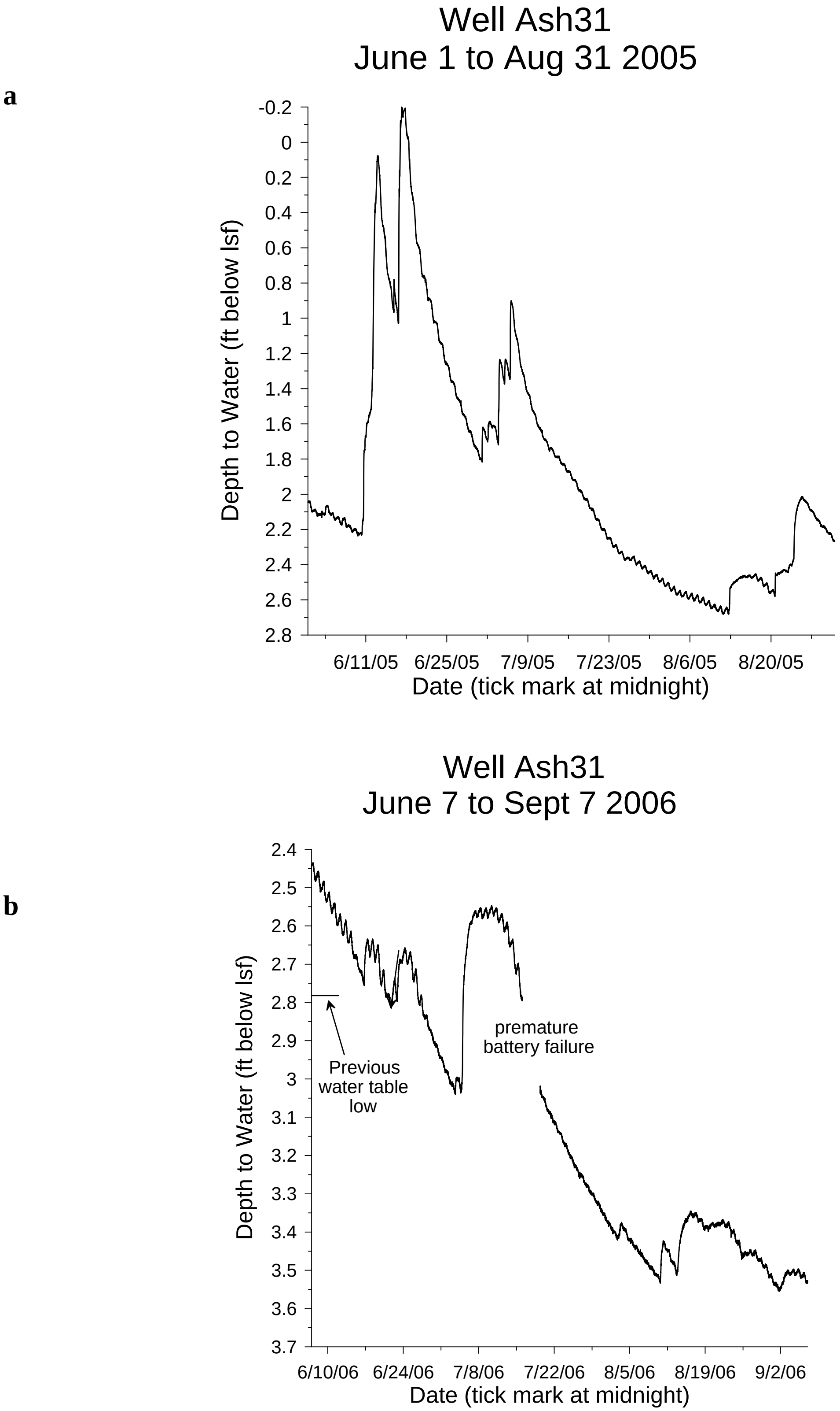


Figure 16 - Depth to water recorded in well Ash31 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period.

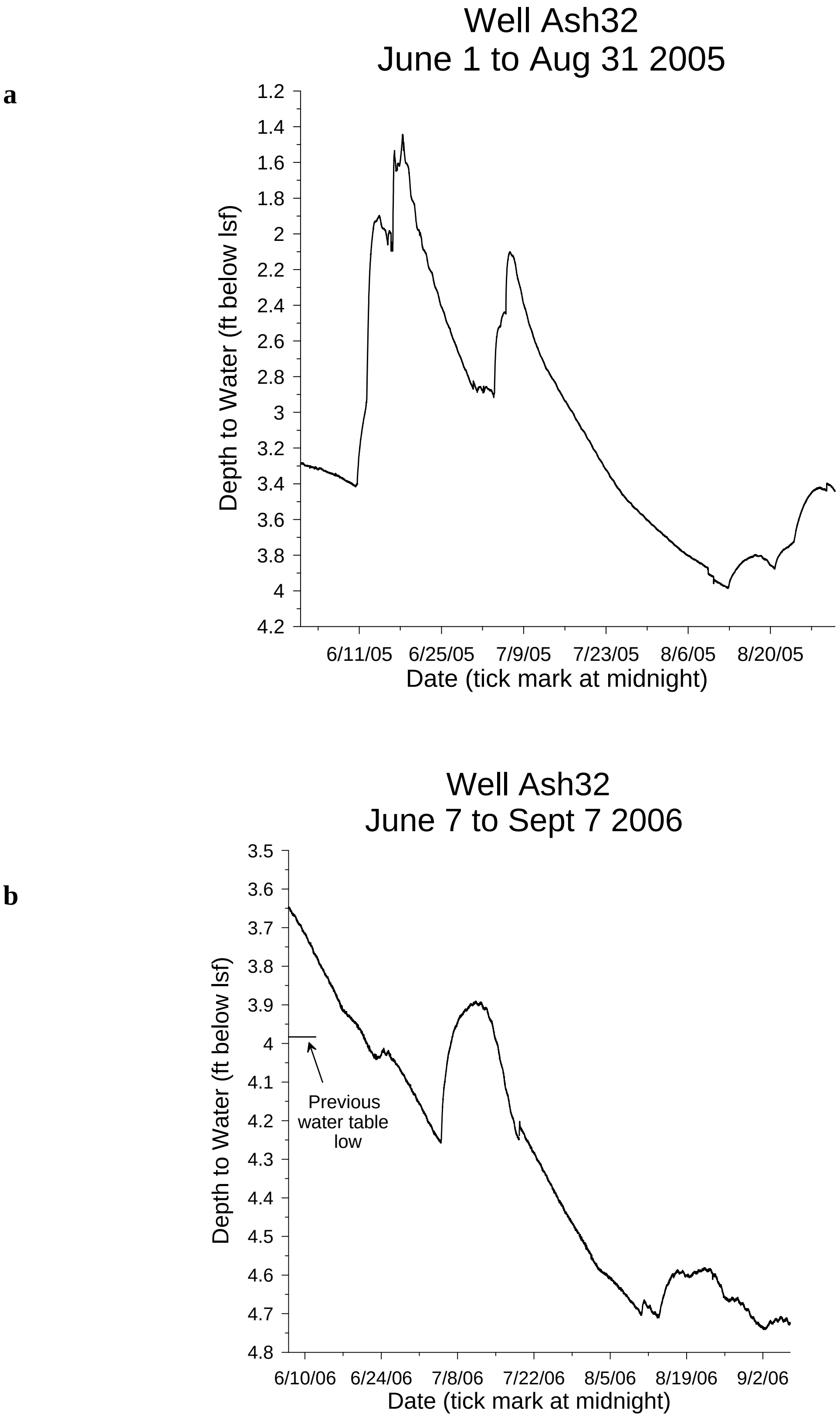


Figure 17 - Depth to water recorded in well Ash32 for (a) the three months during the late spring and summer of 2005 when the majority of treatment activities occurred in Plots 2 and 3, and (b) the last three months of the contract period.

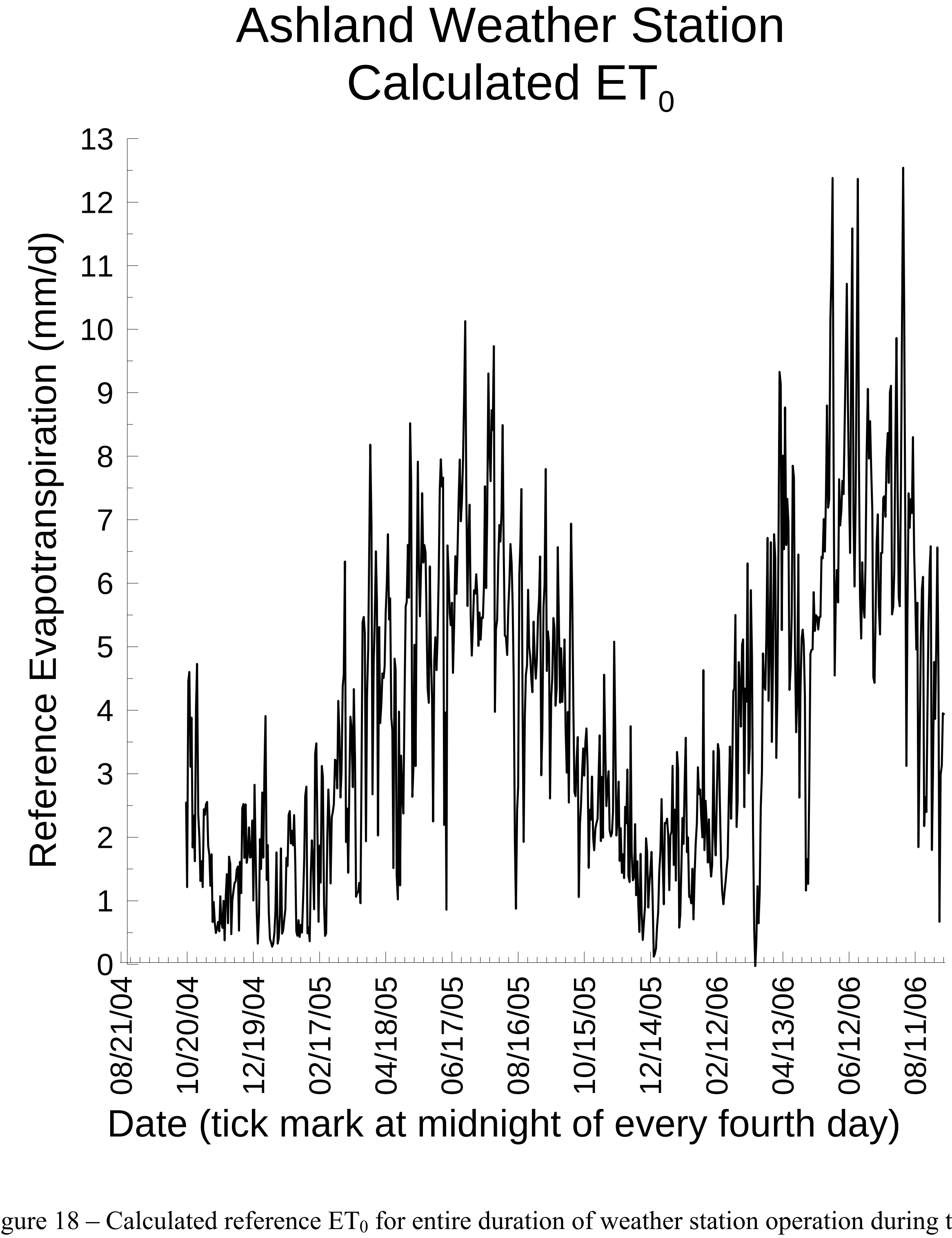


Figure 18 – Calculated reference ET_0 for entire duration of weather station operation during the contract period. ET_0 characterizes the potential for evapotranspiration when water is not a limiting factor. See Figure 12 of Y1 Report for photographs of the weather station.

Task 4 – Neutron logging

As described in the Y1 Report, profiles of volumetric water content versus depth are obtained with a neutron probe (Model 503 DR Hydroprobe Moisture Depth Gauge; Campbell Pacific Nuclear) in the access tube adjacent to each well. At the start of the project, a depth increment of 0.5 ft was used for the entire 10 ft spanned by the access tubes. In mid-summer 2005, a finer depth increment of 0.25 ft was used from 0.5-3.0 ft to better resolve the profiles in the vicinity of the water table. A count duration of 16 s was used at all depths. Standard counts are recorded in the field both prior to and after access tube measurements. Logging is done by Kluitenberg or students under his supervision. The research team travels to the ARS for neutron logging approximately every two to three weeks during the growing season.

Task 5 – Processing of neutron logs

The neutron logging data are processed at KSU by Kluitenberg. The mean standard count for the duration of the study is used to convert each measured count to a count ratio (CR). The volumetric water content ($m^3\ m^{-3}$), θ, corresponding to each measured count ratio is calculated with the calibration equation $\theta = 0.2929 \times CR - 0.0117$, which is based on laboratory calibrations and an adjustment for PVC pipe. However, the calculated water contents are subject to revision because of the possible sensitivity of the neutron probe results to soil salinity. As shown by the direct-push electrical conductivity (EC) logs presented in the Y1 Report, the soils at the ARS have very high EC readings as a result of near-surface soil salinity, which may have affected the results of the neutron logging. An assessment of the impact of the soil salinity at the ARS on the neutron log results is planned for the near future.

Figures 19-22 display results of neutron logging at access tubes adjacent to wells Ash12, Ash21, Ash22, and Ash31, respectively. These profiles are shown because the adjacent wells are used in the analyses discussed in Section 2. At all four wells, the volumetric water contents from the 8/10/06 profiles were the lowest measured over the contract period, a reflection of the severity of the 2006 drought at the ARS. Although the presented profiles may be influenced by salinity as indicated in the previous paragraph, the total porosity values below the water table appear reasonable at all of the ARS access tubes. Note the great similarity between all but one of the profiles acquired from the Ash31 access tube. This agreement most likely is due to the shallow depth to water and the fine near-surface sediments in the vicinity of well Ash31.

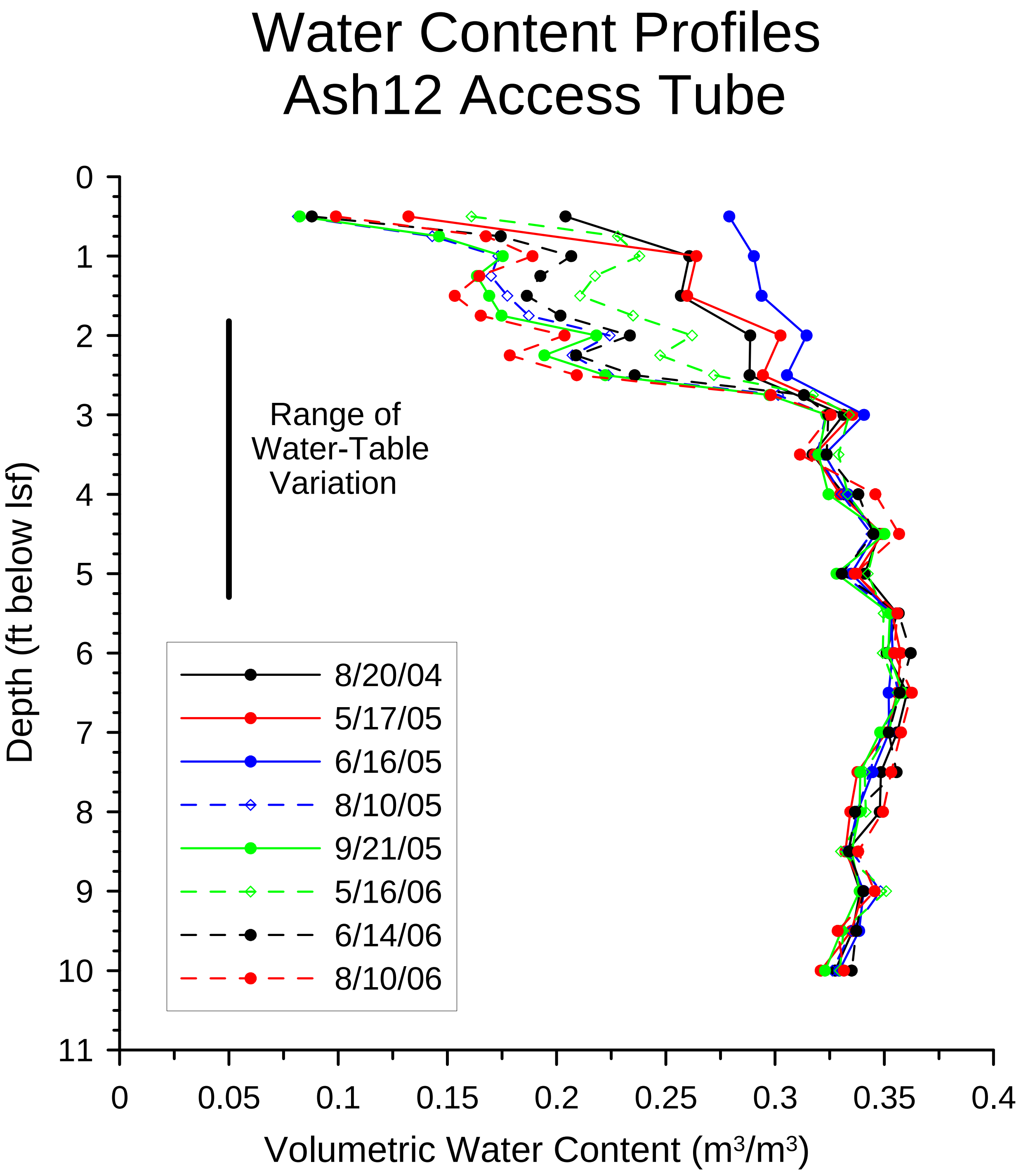


Figure 19 – Volumetric water content versus depth plot from neutron-probe access tube adjacent to well Ash12 for selected periods during the contract period. The vertical black line displays the range of water-table positions over the contract period.

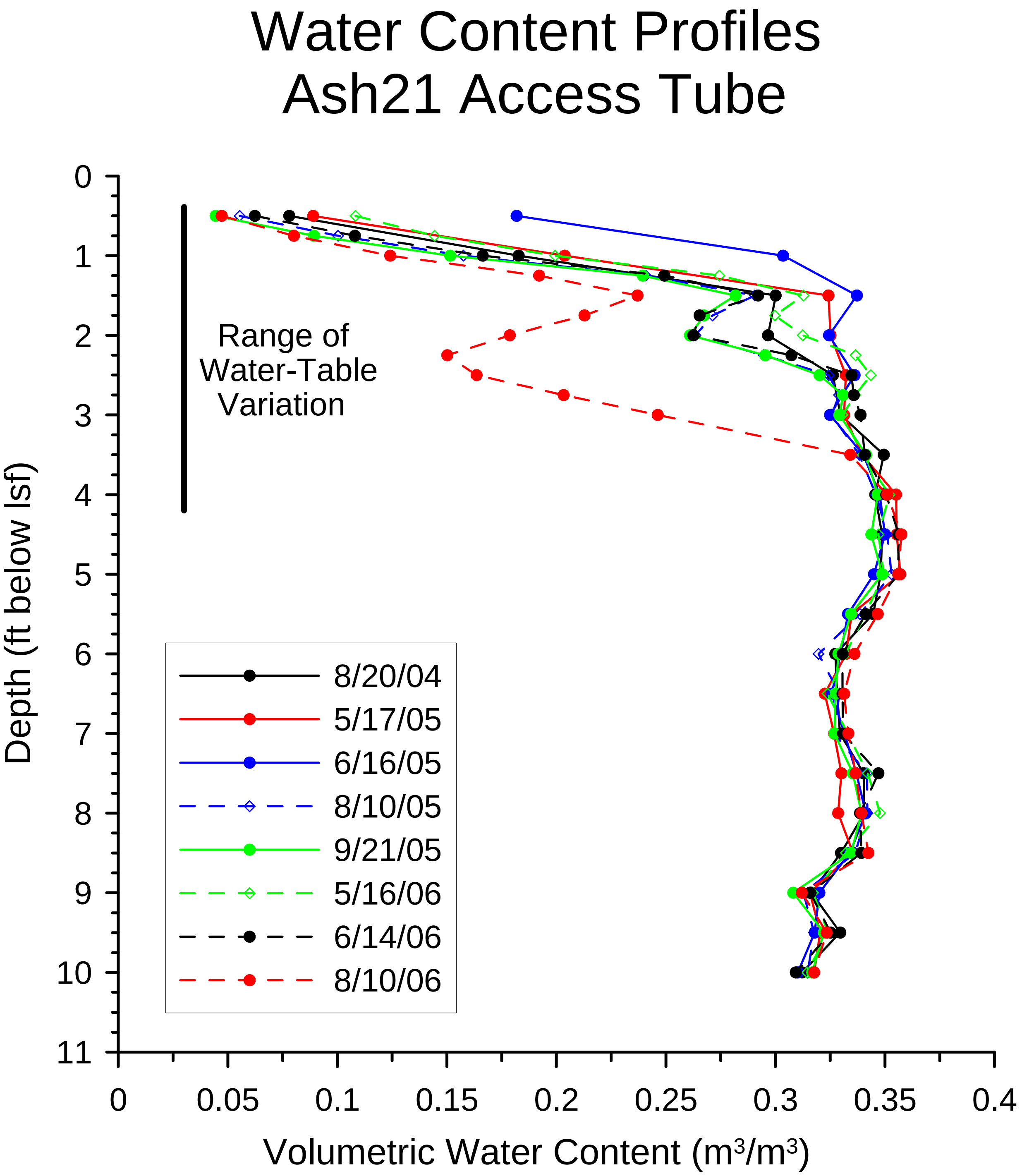


Figure 20 – Volumetric water content versus depth plot from neutron-probe access tube adjacent to well Ash21 for selected periods during the contract period. The vertical black line displays the range of water-table positions over the contract period.

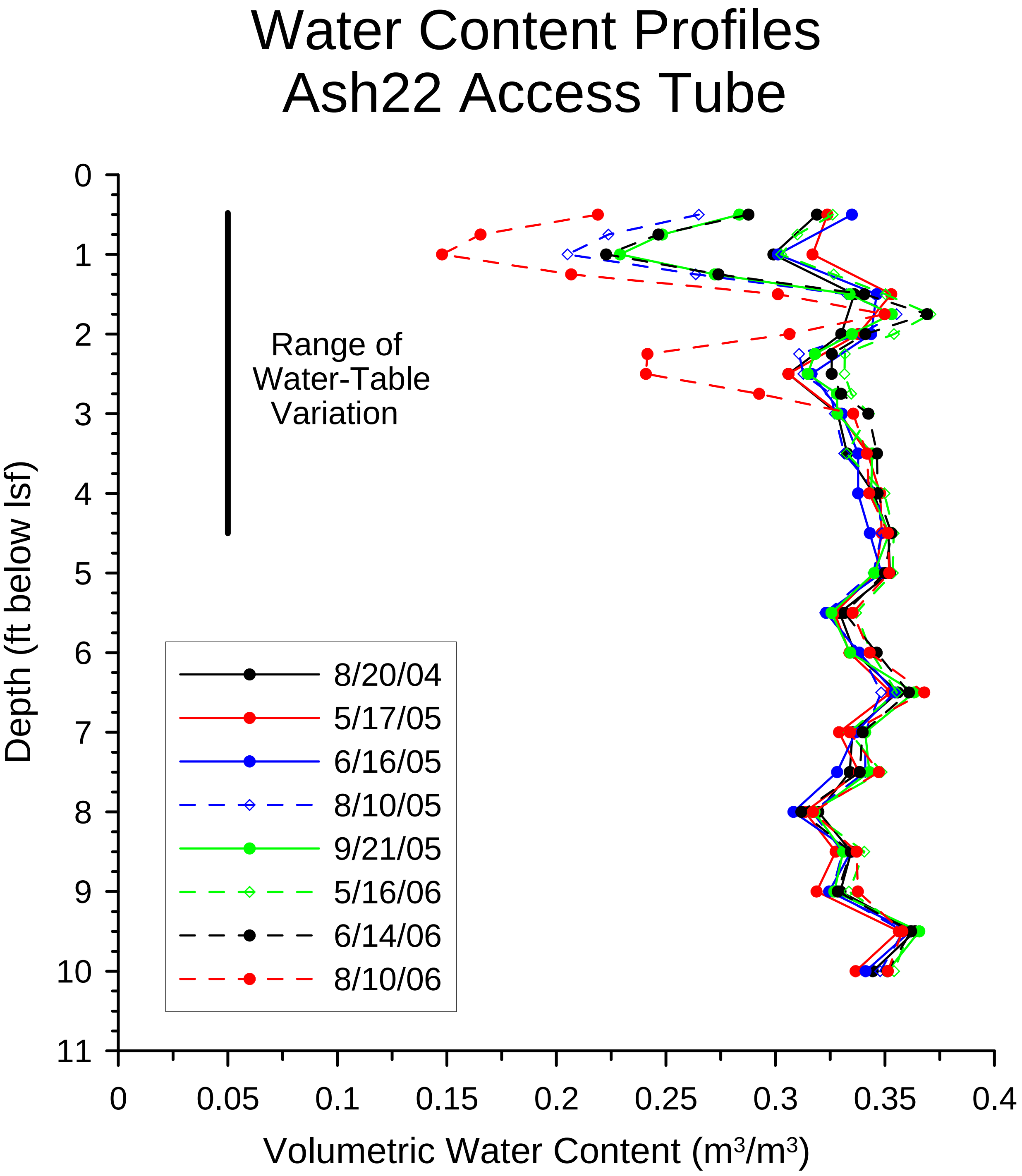


Figure 21 – Volumetric water content versus depth plot from neutron-probe access tube adjacent to well Ash22 for selected periods during the contract period. The vertical black line displays the range of water-table positions over the contract period.

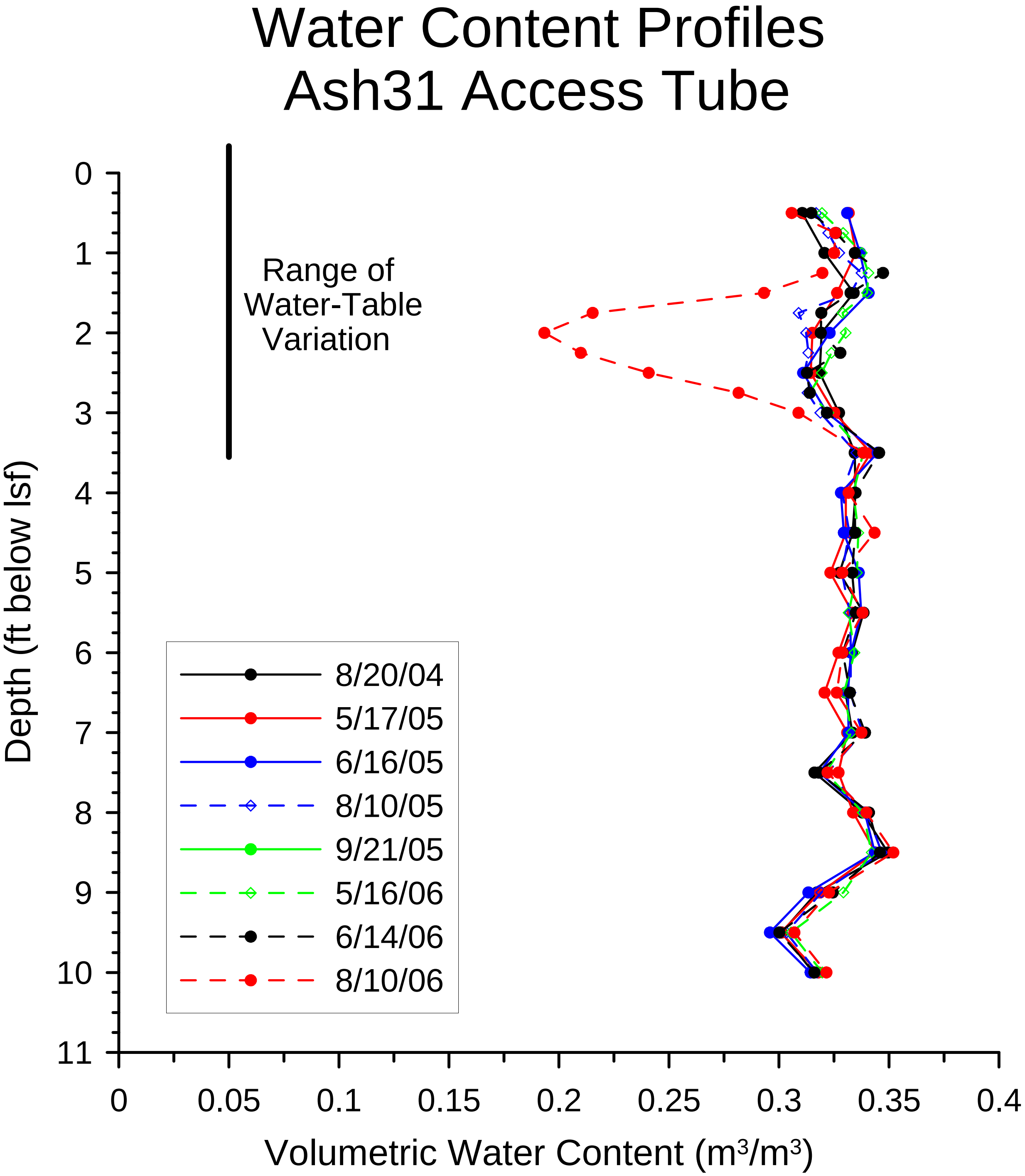


Figure 22 – Volumetric water content versus depth plot from neutron-probe access tube adjacent to well Ash31 for selected periods during the contract period. The vertical black line displays the range of water-table positions over the contract period.

2) INITIAL ANALYSIS OF GROUND-WATER SAVINGS PRODUCED BY SALT-CEDAR CONTROL

An initial analysis of the ground-water savings produced by salt-cedar control was performed using diurnal water-table fluctuations and ratios of the White equation. White [1932] proposed an empirical method for estimation of evapotranspirative consumption of ground water using hydrographs from wells screened across the water table and the following equation (Figure 23):

$$ET_G = S_Y(r+s) \tag{1}$$

where ET_G is the evapotranspirative consumption of ground water expressed as a daily rate, S_Y is the readily available specific yield (dimensionless), r is the net inflow calculated from the night-time recovery expressed as a daily rate, and s is the net change in water-table position over one day expressed as a daily rate (by convention positive with decrease in water-table elevation). Loheide et al. [2005], through a series of numerical simulations, have demonstrated that the White method will provide reasonable estimates of ET_G when reliable estimates of the readily available specific yield are available. They identified uncertainty in S_Y as the major source of error in ET_G estimates. Unfortunately, however, reliable estimates of S_Y can be difficult to obtain in the field.

The analysis approach developed for this project by the research team was specifically designed to reduce the impact of the S_Y uncertainty. This approach uses ratios of equation (1) to calculate the relative reduction in ET_G produced by the control activities as illustrated for well Ash22 in equation (2):

Relative Reduction in ET_G at well Ash22 =

$$1-\frac{\left(\dfrac{ET_{G_{post}}}{ET_{G_{pre}}}\right)_{Ash\ 22}}{\left(\dfrac{ET_{G_{post}}}{ET_{G_{pre}}}\right)_{Ash\ 12}} = 1-\frac{\left(\dfrac{[S_Y(r+s)]_{post}}{[S_Y(r+s)]_{pre}}\right)_{Ash\ 22}}{\left(\dfrac{[S_Y(r+s)]_{post}}{[S_Y(r+s)]_{pre}}\right)_{Ash\ 12}} \tag{2}$$

where *pre* indicates period prior to application of control measures and *post* designates period after application. The ratio in the numerator on the left-hand side of the second line of equation (2) is the relative change in ET_G at Ash22 between the pre-treatment and post-treatment periods. A similar ratio in the denominator of the left-hand side is the relative change in ET_G at Ash12 between those same periods. The relative change in ET_G at Ash12, a well in the background-monitoring area (Plot 1), is included to account for the impact of factors other than the phreatophyte-control activities. The right-hand side of the second line of equation (2) is obtained by substituting equation (1) for each ET_G term on the left-hand side, as illustrated in Figure 24.

There are two key aspects of equation (2). First, ET_G changes at a well where control measures have been applied are calculated relative to changes at a well in the background-monitoring area where those measures have not been applied. The use of a ratio of ratios allows the relative impact of the control activities to be separated from that of meteorological factors. Second, the water table at a given well must be within the same vertical interval for the two periods used in the ratios in equation (2). This allows one to assume that S_Y is not changing between those periods, and thus justifies canceling out S_Y from the numerator and the denominator of each ratio. The ratio method therefore also removes the influence of uncertainty about S_Y from the analysis, a critical aspect of this approach. The use of the same depth interval is based on the assumption that lithologic characteristics of the intervals, which are not changing between the two periods, are the primary controls on S_Y. In reality, however, S_Y is also highly dependent on volumetric water contents in the vadose zone. Thus, for the assumption of a constant S_Y to be strictly valid for the periods used in the analyses, the water-table position must be in the same vertical interval and the water content profiles must be similar. Otherwise, S_Y cannot be removed from the ratios of equation (2) and uncertainty about S_Y will dominate the analysis, making it difficult to reach defensible conclusions.

The initial expectation for the impact of the control activities was that the diurnal water-table fluctuations would virtually cease as a result of the mulch cutting and herbicide application. However, as illustrated for well Ash22 in Figures 25 and 26, that expectation was not realized at any of the wells in Plots 2 and 3 at which fluctuations were observed in the pre-treatment monitoring period (see Figures 14b-16b). Possible explanations for the continued fluctuations include ground-water consumption by the uncut grasses, forbs, and small bushes in the vicinity of the well, and by direct evaporation from the water table in that same area, and ground-water consumption by phreatophytes outside of the treated area. An analysis to assess the importance of this latter mechanism has been performed by the research team. That analysis, which is described in the Related Activities Section, indicates that it is highly unlikely that ground-water consumption by phreatophytes outside of the treated area is responsible for the post-treatment diurnal fluctuations in the water table observed in Plots 2 and 3 at the ARS.

The ET_G reductions, relative to what would have been expected in the absence of control activities, calculated with equation (2) for two post-treatment time periods are given in percentage form in Table 1. The reductions varied between the three wells from 23-56% (average of three wells was 40%, post-treatment 1) in the month immediately following the treatment (Figure 25b). An analysis using the same depth intervals in 2006 (Figure 26), ten months after treatment, found that the reductions varied from 2-27% (average of three wells was 17%, post-treatment 2). Thus, the reductions in ET_G gained from the phreatophyte-control activities appear to be decreasing with time, despite the severe drought conditions experienced during the 2006 growing season at the ARS. This decreased reduction in ET_G may be a result of increased growth (and thus water use) of grasses, forbs, and small bushes from greater exposure to sunlight and wind after the removal of large phreatophytes (see Ash22 Pre-treatment and Post-treatment photographs in Figure 24), and regrowth of salt cedar (both plots have experienced regrowth following control activities, see Figure 5c). Further work is needed to assess the relative importance of ground-water consumption by these and other mechanisms to better understand the effectiveness of the control measures.

The ratio method used to calculate the percentage reductions in ET_G depends on three critical assumptions. The validity of each assumption for the ARS analyses will be briefly discussed in the following paragraphs.

Assumption One: The White method can provide reasonable estimates of the evapotranspirative consumption of ground water.

As discussed earlier, the simulation study of Loheide et al. [2005] demonstrated that the White method can provide reasonable estimates of ET_G when reliable estimates of S_Y are available. Although S_Y is not known at the ARS, the use of the ratio method removes S_Y from the calculations. Thus, the White method should be valid at the ARS when used in a ratio format.

Assumption Two: The water table at a given well was within the same vertical interval for all periods used in the analysis.

The analysis summarized in Table 1 utilized three times periods: 9/8-9/12/04 (pre-treatment), 9/15-9/19/05 (post-treatment 1), and 6/9-6/13/06 (post-treatment 2). As illustrated in Figures 25a-b and 26 for wells Ash12 and Ash22, the water table at a given well was essentially in the same vertical interval for all three periods at all ARS wells used in the analyses.

Assumption Three: The volumetric water content profiles at a given access tube were the same for the three periods used in the analysis.

The volumetric water content profiles for the four wells used in the analyses of Table 1 are given in Figures 19-22. The three profiles pertinent to the analyses are the 8/20/04, 9/21/05, and 6/14/06 profiles. The 9/21/05 and 6/14/06 profiles were acquired one to two days after the end of the analysis interval, so they can be considered representative of volumetric water contents over the analysis period. The 8/20/04 profiles were obtained 18 days before the start of the analysis period, so they are not necessarily representative of that period. However, there was no significant precipitation and the water table continuously declined over those 18 days (Figures 7-10). Given our extensive experience at the ARS with changes in water content profiles during periods of water-table decline without rainfall, we have some confidence in the way the 8/20/04 profiles changed over that 18-day period. An assessment of the overall viability of this third assumption at each access tube is as follows:

Ash12 Access Tube – For all three periods, the profiles agree at depths below 2.5 ft. The 9/21/05 and 6/14/06 profiles are in close agreement except for the upper 1.5 ft of the profile. The 9/8-9/12/04 profiles would be expected to be close to the profiles for the other two intervals because of gravity drainage and the lack of precipitation after the 8/20/04 profile. Thus, the profiles are assumed to have been in reasonable agreement for the analysis periods.

Ash21 Access Tube – The 9/21/05 and 6/14/06 profiles are in reasonable agreement. The 9/8-9/12/04 profiles would be expected to be close to the profiles for the other two intervals because of gravity drainage and the lack of precipitation after the 8/20/04 profile. Thus, the profiles are assumed to have been in reasonable agreement for the analysis periods.

Ash22 Access Tube – The 9/21/05 and 6/14/06 profiles are in very good agreement. The 9/8-9/12/04 profiles would be expected to be close to the profiles for the other two intervals because of gravity drainage and the lack of precipitation after the 8/20/04 profile. Thus, the profiles are assumed to have been in good agreement for the analysis periods.

Ash31 Access Tube – Profiles from this access tube are in close agreement for all three periods. Thus, the profiles are assumed to have been in very good agreement for the analysis periods.

In conclusion, all of the critical assumptions underlying the ARS analyses appear to be valid for the three analysis periods.

Well	Analysis Period	
	Post-Treatment 1 9/15 – 9/19/05	Post-Treatment 2 6/9 – 6/13/06
Ash21	23	2
Ash22	41	27
Ash31	56	22
Average	**40**	**17**

Table 1 – Initial estimates of percentage reductions in ground-water consumption, relative to what would have been expected in the absence of control activities, calculated with equation (2) and data from one month (9/15-9/19/05) and ten months (6/9-6/13/06) after completion of treatment activities. Reported values are based on five-day averages for wells Ash21 and Ash31, and a three-day average for well Ash22. A shorter time average was used at well Ash22 because of the considerable amount of sensor noise at well Ash22 on certain days during the post-treatment periods (e.g., compare Ash22 data from Figure 25a with Ash22 data from Figures 25b and 26).

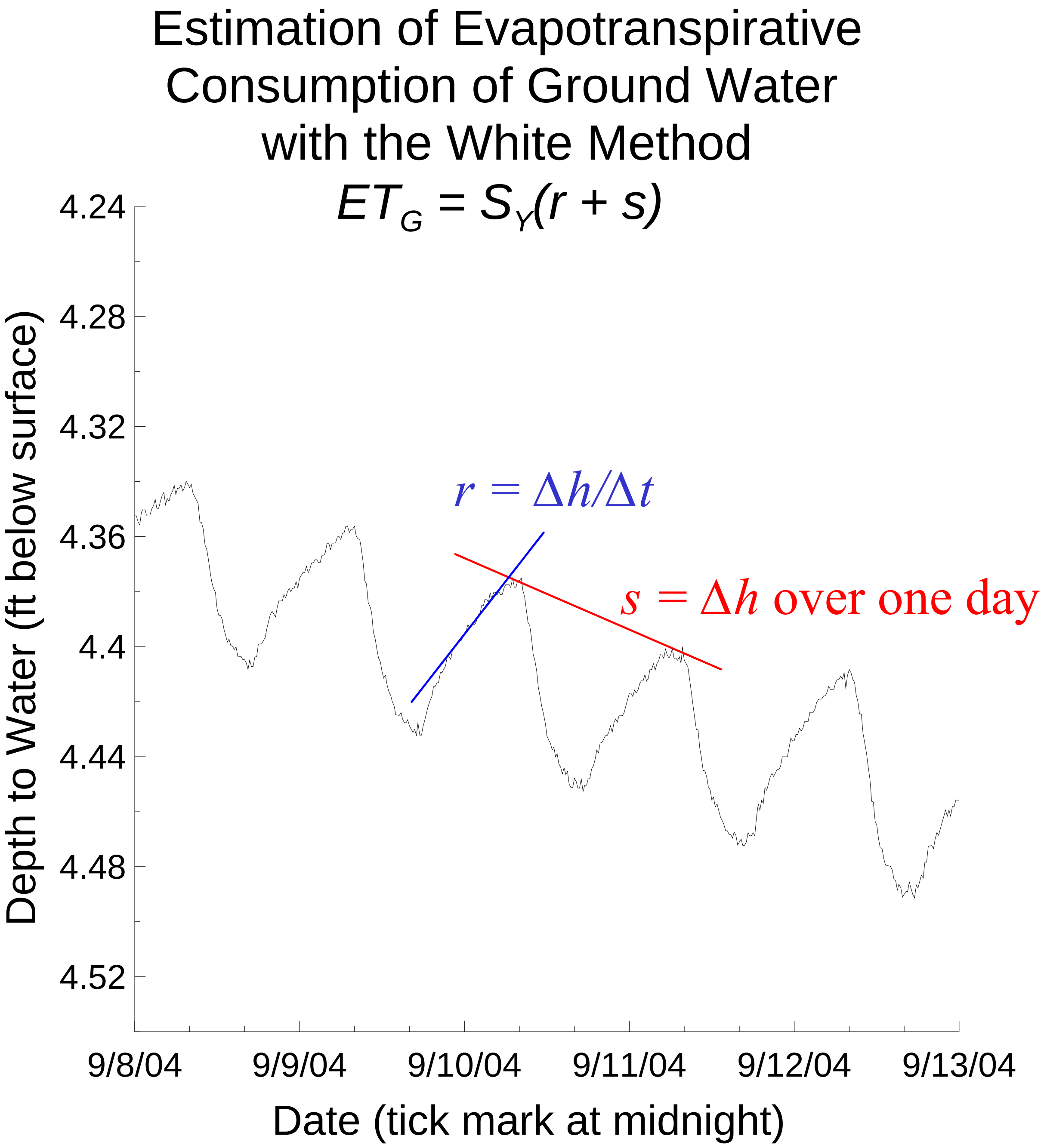
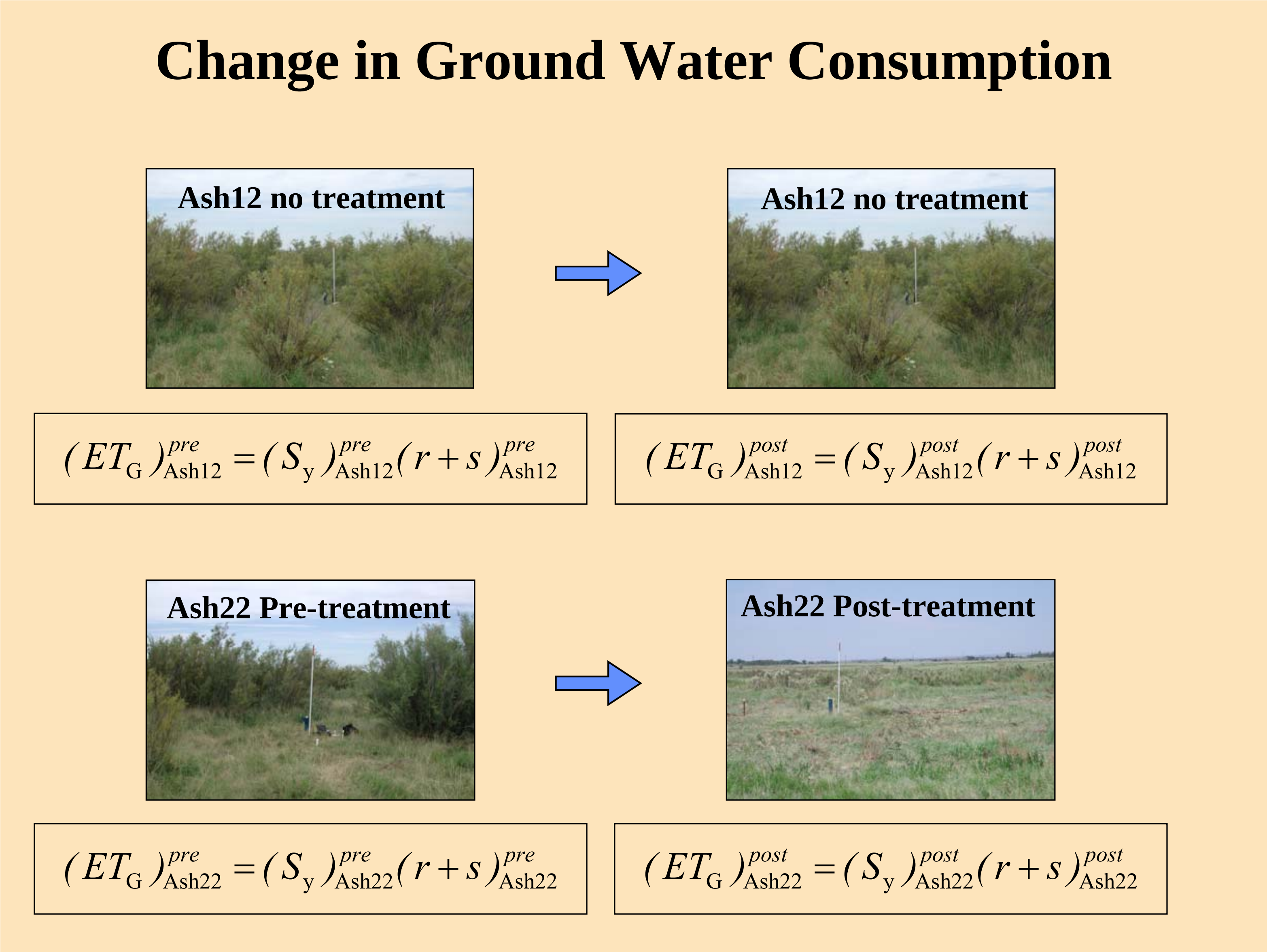


Figure 23 – Illustration of the White method using water-level data from well Ash12. ET_G is the evapotranspirative consumption of ground water expressed as a daily rate, S_Y is the readily available specific yield (dimensionless), r is the net inflow calculated from the night-time recovery expressed as a daily rate, and s is the net change in water-table position over one day expressed as a daily rate (by convention positive with decrease in water-table elevation).



Change in Ground Water Consumption

Ash12 no treatment → **Ash12 no treatment**

$$(ET_{\mathrm{G}})^{pre}_{\mathrm{Ash12}} = (S_{\mathrm{y}})^{pre}_{\mathrm{Ash12}}(r+s)^{pre}_{\mathrm{Ash12}}$$

$$(ET_{\mathrm{G}})^{post}_{\mathrm{Ash12}} = (S_{\mathrm{y}})^{post}_{\mathrm{Ash12}}(r+s)^{post}_{\mathrm{Ash12}}$$

Ash22 Pre-treatment → **Ash22 Post-treatment**

$$(ET_{\mathrm{G}})^{pre}_{\mathrm{Ash22}} = (S_{\mathrm{y}})^{pre}_{\mathrm{Ash22}}(r+s)^{pre}_{\mathrm{Ash22}}$$

$$(ET_{\mathrm{G}})^{post}_{\mathrm{Ash22}} = (S_{\mathrm{y}})^{post}_{\mathrm{Ash22}}(r+s)^{post}_{\mathrm{Ash22}}$$

Figure 24 – Illustration of the use of the White method to calculate evapotranspirative consumption of ground water prior to (*pre*) and following (*post*) treatment activities at the ARS. Quantities in expressions are defined in main text and Figure 23.

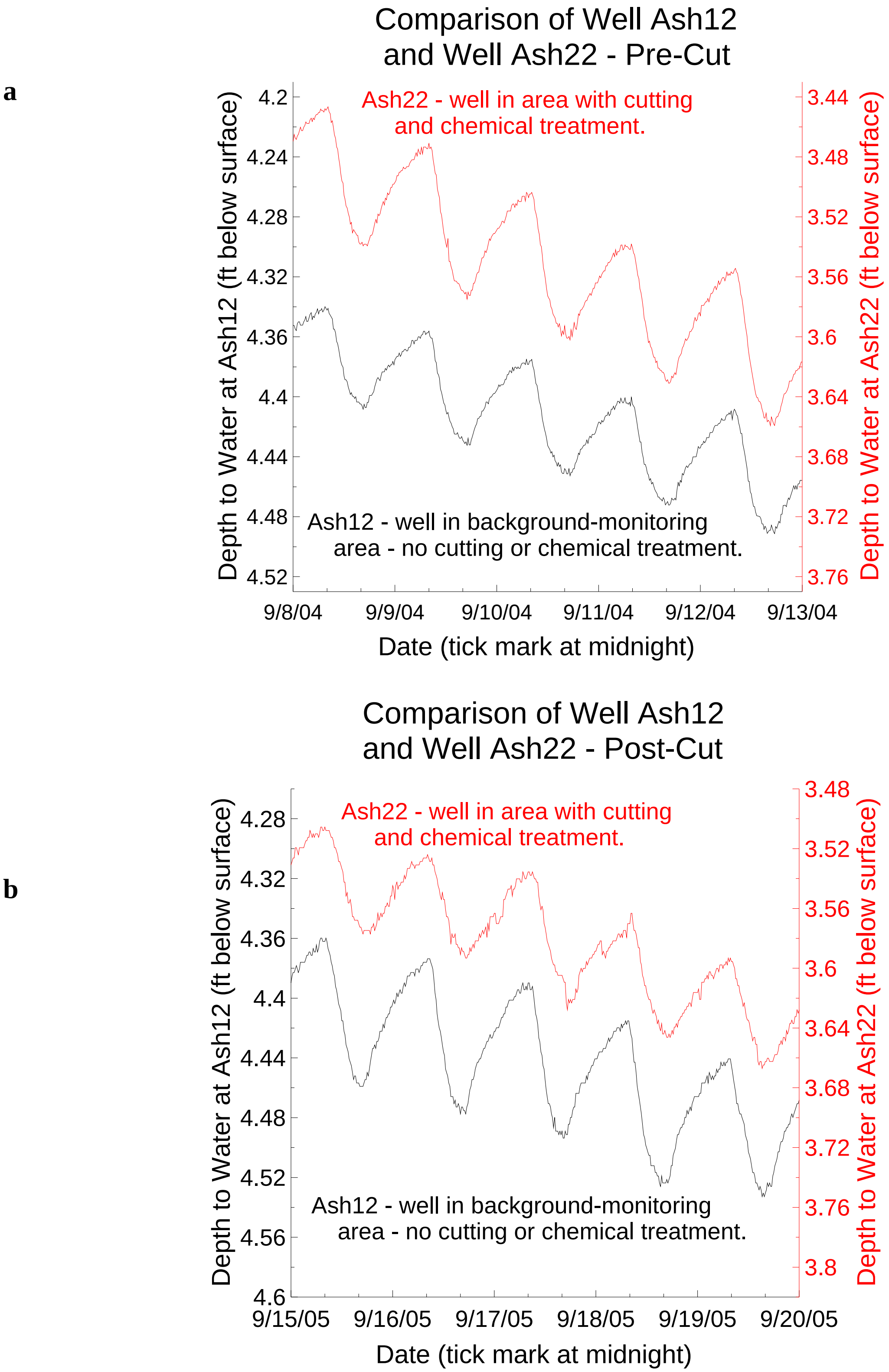


Figure 25 - Depth to water recorded in wells Ash12 and Ash22 prior to (a) and one month after (b) mulch cutting and chemical treatment (herbicide application) in Plot 2 in the summer of 2005. Data for Ash12 included to illustrate pattern of water-table fluctuations observed in Plot 1, the background-monitoring area, where no phreatophyte-control activities were applied.

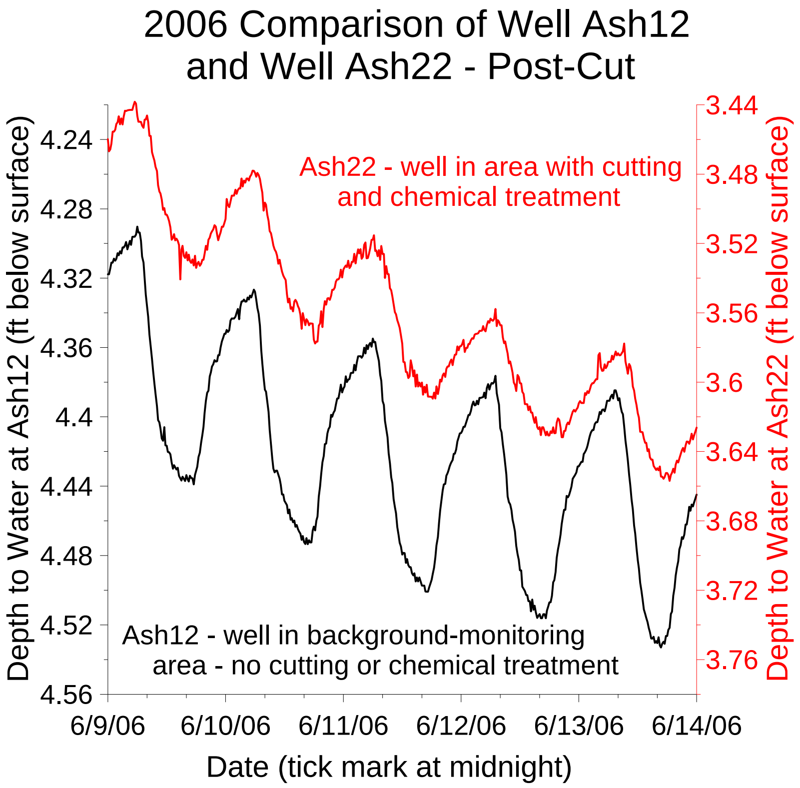


Figure 26 - Depth to water recorded in wells Ash12 and Ash22 in June 2006, approximately ten months after completion of mulch cutting and chemical treatment in Plot 2.

3) RELATED ACTIVITIES

A number of activities that were not funded through this contract have been carried out at the ARS. The most relevant of these activities are briefly summarized here.

a) Soil sampling at the Ashland Research Site – Soil samples were collected near each of the six wells at the ARS on September 20-21, 2005. At each well, samples were collected in 6-inch depth intervals from the soil surface to the maximum depth allowable due to the presence of the water table. The samples were analyzed in KSU laboratories for particle-size distribution and soil chemical properties. An example of the analysis results (particle-size distribution) are presented in Table 2. Further details can be found in Kluitenberg [2007]. This work was funded by the Kansas Water Resources Institute (KWRI).

b) Analysis of impact of ground-water consumption by phreatophytes outside of treated area – Ground-water consumption by phreatophytes outside of the treated area could be one factor responsible for the post-treatment diurnal fluctuations in the water table observed in Plots 2 and 3 (Figures 25b and 26). In order to assess the likelihood of this mechanism, steady periodic analytical solutions for water-table fluctuations produced by diurnal variations in evapotranspiration were developed by extending the approach described in Townley [1995] to the configuration illustrated in Figure 27. Of particular interest is the solution for which R_1 goes to zero (vegetation circle completely removed). Substituting reasonable parameters for the ARS into that solution revealed that diurnal fluctuations produced by phreatophytes outside the circle of cut vegetation should greatly differ in both amplitude and phase from those produced by vegetation in the immediate vicinity of the well. The data plotted in Figures 25 and 26 show that such a difference was not observed. Thus, it is considered highly unlikely that ground-water consumption by phreatophytes outside the treated area is producing the diurnal fluctuations observed after completion of mulch cutting and chemical treatment. Development of the periodic analytical solutions was funded by the KWRI and the KGS, and is described in Jin et al. [2007].

c) Measurement of physiological responses of salt cedar – Repeated physiological measurements of salt cedar were conducted on individual plants growing in Plots 1 and 3 in the summer of 2006. Surrounding each well, five salt cedars were randomly selected for repeated measurements throughout the summer. Each salt cedar was within a 5-m radius of the well, and the light-saturated photosynthetic rate, stomatal conductance to water, leaf water potential, leaf fluorescence, and leaf transpiration were measured on each plant. On the same days as the physiological measurements, samples of plant stems, soil, and ground water were collected for oxygen stable isotopic analyses. This work, which is described further by Nippert et al. [2007, in review], was funded by the KWRI and the KGS.

d) Technology transfer – Over forty five presentations on this project were given at various venues both within and outside of Kansas. Thirty six of the presentations were part of the 2007 Henry Darcy Distinguished Lectureship that was awarded to Butler. Those lectures were presented in 11 countries on three continents. Presentations in Kansas or in the immediate vicinity included lectures at the University of Kansas, Kansas State University, Emporia State University, University of Missouri at Kansas City, Oklahoma State University, and the 2006 Tamarisk Research Conference in Colorado. The travel costs for the presentations were provided by the National Ground Water Research and Educational Foundation, the Desert Research Institute, Southern Illinois University, the University of South Carolina, the KGS, the KWRI, and KSU.

Table 2 - Particle size distribution of the fine fraction of the 38 soil samples submitted to the KSU Soil Characterization Laboratory. Results are reported as a percentage of total soil material below 2 mm in size.

Well no.	Depth interval	Sample number	Total sand (2.00-0.05 mm)	Total silt (50.0-2.0 µm)	Total clay (< 2.0 µm)
	inches		-------------------------------	%	-------------------------------
Ash 11	0-6	1	90.9	5.1	4.0
Ash 11	6-12	2	96.4	6.1	0.0
Ash 11	12-18	3	97.6	2.4	0.0
Ash 12	0-6	4	61.8	31.8	6.4
Ash 12	6-12	5	46.3	43.3	10.4
Ash 12	12-18	6	76.0	21.4	2.6
Ash 12	18-24	7	68.5	27.7	3.8
Ash 12	24-30	8	67.5	26.5	6.0
Ash 12	30-36	9	64.1	28.2	7.7
Ash 12	36-42	10	54.7	36.6	8.7
Ash 12	42-48	11	71.4	21.8	6.8
Ash 21	0-6	12	83.8	11.1	5.1
Ash 21	6-12	13	84.1	11.3	4.6
Ash 21	12-18	14	82.0	14.0	4.0
Ash 21	18-24	15	93.2	3.8	3.0
Ash 21	24-30	16	94.0	5.8	0.2
Ash 21	30-36	17	97.0	3.0	0.0
Ash 22	0-6	18	16.5	52.6	30.9
Ash 22	6-12	19	53.8	39.6	6.7
Ash 22	12-18	20	68.8	25.5	5.7
Ash 22	18-24	21	24.9	45.5	29.6
Ash 22	24-30	22	41.0	33.2	25.8
Ash 22	30-36	23	86.5	9.5	4.0
Ash 22	36-42	24	76.6	19.0	4.4
Ash 22	42-48	25	93.4	6.6	0.0
Ash 31	0-6	26	19.2	59.1	21.7
Ash 31	6-12	27	67.3	28.2	4.5
Ash 31	12-18	28	86.0	12.6	1.4
Ash 31	18-24	29	93.4	5.6	1.0
Ash 31	24-30	30	96.2	3.7	0.1
Ash 32	0-6	31	59.7	34.0	6.3
Ash 32	6-12	32	76.8	19.4	3.8
Ash 32	12-18	33	88.6	10.5	0.9
Ash 32	18-24	34	95.9	3.0	1.1
Ash 32	24-30	35	96.8	3.2	0.0
Ash 32	30-36	36	96.8	3.2	0.0
Ash 32	36-42	37	96.6	3.4	0.0
Ash 32	42-48	38	97.6	2.4	0.0

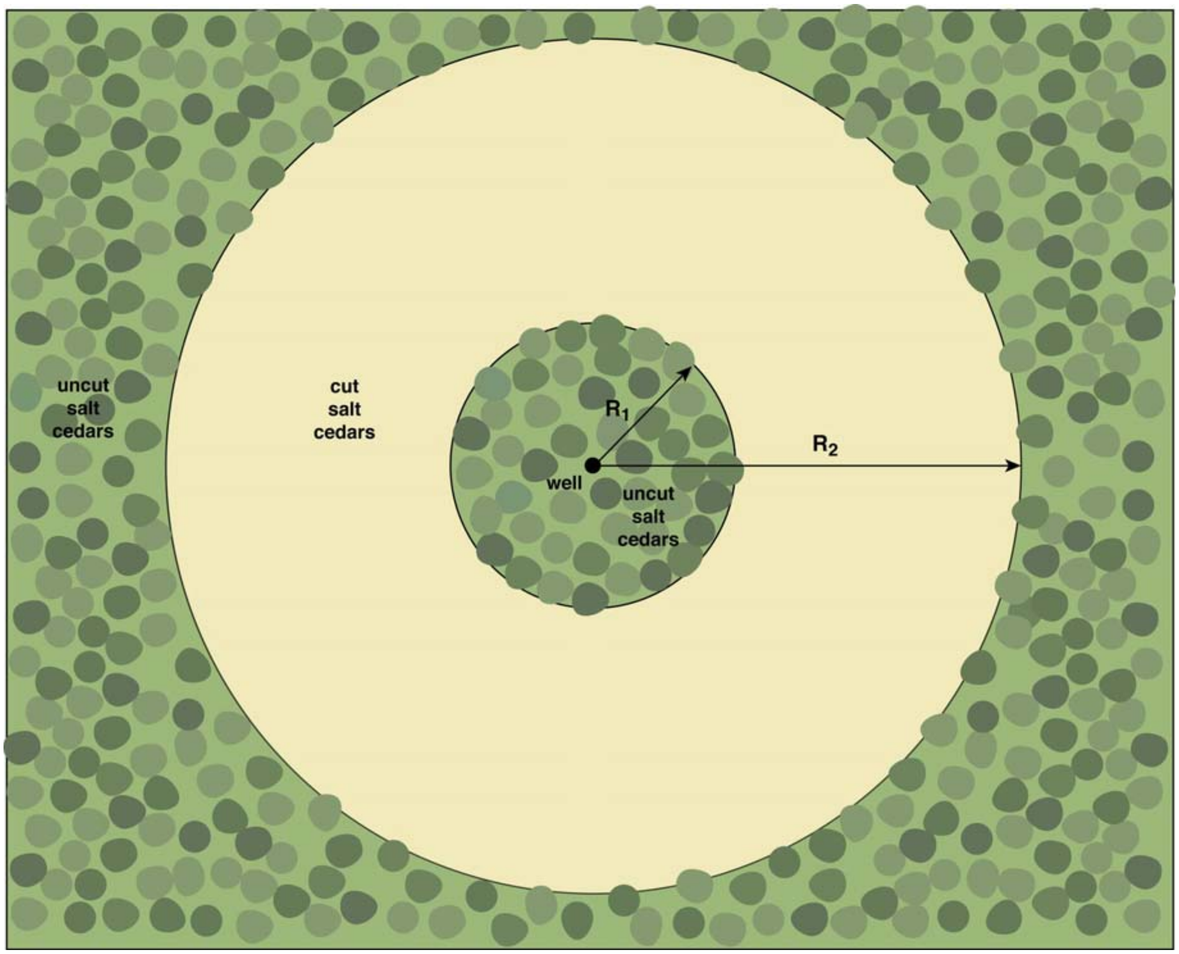


Figure 27 –Schematic areal view (not to scale) of configuration of cut and uncut salt cedars around wells Ash21, Ash22, and Ash31 during the 2005 treatment period (see Figure 3 for aerial photograph of ARS during the treatment period and Figures 4a-d for sequence of photographs of cut vegetation in the vicinity of well Ash22).

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