Report as of 2006 for 2003KS33B: "A Field Assessment of a Method for Estimation of Ground-Water Consumption By Phreatophytes"

Publications

- Conference Proceedings:
    - Arnold, D., and J.J. Butler, Jr., Salt-cedar control activities and water-table monitoring on the Arnold Ranch, Clark County, Kansas, an invited presentation to the CPR for Wetlands and Streams II Conference, Wichita, KS, Sept. 28, 2005.
    - Bauer, J., Evaluating the effectiveness of salt cedar control measures as a means of water conservation along the Cimarron River, Kansas, undergraduate honor's thesis, Department of Geological Sciences, University of Colorado at Boulder, October, 2005.
    - Butler, J.J., Jr., Whittemore, D.O., and G.J. Kluitenberg, Studies of ground-water consumption by phreatophytes in river valleys of Kansas (abstract), Trans. Kansas Academy Science, v. 108, no. 3/4, pp. 165-166, 2005.
    - Butler, J.J., Jr., Whittemore, D.O., and G.J. Kluitenberg, A field investigation of ground-water consumption by phreatophytes in river valleys of Kansas (abstract), 50th Annual Midwest Ground Water Conf., Program with Abstracts, Illinois State Geol. Survey OFS 2005-13, p. 18, 2005.
    - Butler, J.J., Jr., Whittemore, D.O., and G.J. Kluitenberg, A field investigation of ground-water consumption by phreatophytes, presentation at the 14th Annual Kansas Hydrology Seminar, Topeka, November 18, 2005.
    - Butler, J.J., Jr., Kluitenberg, G.J., Whittemore, D.O., Healey, J.M., and X. Zhan, Quantifying ground-water savings achieved by salt-cedar control measures: A demonstration project (abstract), Eos, v. 86, no. 18, Jt. Assem. Suppl., Abstract H33B-06, 2005
    - Keller, J., Shea, J., Bauer, J., Butler, J.J., Jr., Kluitenberg, G.J., and D.O. Whittemore, A field investigation of the influence of spatial variability in hydraulic properties on phreatophyte-induced fluctuations in the water table (abstract), 50th Annual Midwest Ground Water Conf., Program with Abstracts, Illinois State Geol. Survey OFS 2005-13, p. 19,

    2005.
  - Kluitenberg, G.J., Butler, J.J., Jr., and D.O. Whittemore, A field investigation of major controls on phreatophyte-induced fluctuations in the water table (abstract), Annual Meetings Abstracts [CD-ROM], ASA, CSSA, and SSSA, Madison, WI, 2005.
  - Shea, J., Bauer, J., Keller, J., Butler, J.J., Jr., Kluitenberg, G.J., Whittemore, D.O., Loheide, S.P., II, and W. Jin, An assessment of the vulnerability of native phreatophytes to replacement by invasive species in a mid-continent riparian setting (abstract), Eos, v. 86, no. 52, Fall Meet. Suppl., Abstract B23A-1037, 2005.
- Other Publications:
  - Bauer, J., Shea, J., Keller, J., Butler, J.J., Jr., Kluitenberg, G.J., and D.O. Whittemore, Diurnal water table fluctuations: An underutilized indicator of ground-water consumption by plants (abstract), Eos, v. 86, no. 52, Fall Meet. Suppl., Abstract B23A-1038, 2005.
  - Butler, J.J., Jr., Quantifying water consumption by phreatophytes in narrow riparian corridors, presentation to the University of Kansas Field Station & Ecological Reserves Seminar Series, March 11, 2005.
  - Butler, J.J., Jr., Diurnal water-table fluctuations: An underutilized indicator of groundwater consumption by plants, an invited presentation given as part of the Environmental Seminar Series at the Desert Research Institute, Reno, NV, November 4, 2005.
  - Butler, J.J., Jr., and D.O. Whittemore, Arkansas River phreatophytes, in Kansas Geological Survey Open-File Rept. 2005-17, pp. 4.9-4.12, 2005 (used for presentations for the 2005 Kansas Field Conference [Larned, June 9, 2005] and the Kansas Water Authority tour west of Garden City [August 10, 2005]).
  - Butler, J.J., Jr., Whittemore, D.O., and G.J. Kluitenberg, Ground water assessment in association with salt cedar control – Report on year one activities, Kansas Geological Survey Open-File Rept. 2005-19, 28 pp., 2005.
- Articles in Refereed Scientific Journals:
  - Butler, J.J., Jr., Kluitenberg, G.J., Whittemore, D.O., Loheide, S.P., II, Jin, W., Billinger, M.A., and X. Zhan, A field investigation of phreatophyte-induced fluctuations in the water

  table, Water Resour. Res., pending revisions.
  - Loheide, S.P., II, Butler, J.J., Jr., and S.M. Gorelick, Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment, Water Resour. Res., v. 41, W07030, doi:10.1029/2005WR003942, 2005.

Report Follows

KWRI PROGRESS REPORT – YEAR FOUR

Project Title: A Field Assessment of a Method for Estimation of Ground-Water Consumption by Phreatophytes: Impact of Shallow-Rooted Vegetation and Direct Evaporation From the Water Table
Duration of Reporting Period: March 1, 2006 - February 28, 2007
Federal Funding for Reporting Period: $37,280
Investigators and Affiliations: James J. Butler, Jr., Kansas Geological Survey (PI), Gerard J. Kluitenberg, Kansas State University (Co-PI), Donald O. Whittemore, Kansas Geological Survey (Co-PI).
Research Category: Statewide Competitive Grant
Descriptors: phreatophytes, ground water, evapotranspiration, water balance

PROBLEM AND RESEARCH OBJECTIVES

Low streamflows are an increasing problem in Kansas and other areas of the United States. As a result, smaller amounts of water are available for diversions to water supplies and wetlands, for inflows to reservoirs, for capture by wells in nearby aquifers, for sustaining aquatic wildlife, and for recreation. Stream-aquifer interactions play an important role in the generation and maintenance of low streamflows. Ground-water development in regional aquifers that discharge water to stream corridors and in alluvial aquifers immediately adjacent to streams is often a major factor responsible for low-flow periods. However, consumption of ground water by phreatophytes in riparian zones could also be an important contributor to reduction of stream flow. Recently, partly in response to concerns about water consumption, expensive measures for phreatophyte control have been advocated for stretches of rivers in western Kansas.

Present understanding of phreatophyte activity in stream-aquifer systems in Kansas is insufficient to assess the magnitude of that activity. This project is directed at refining methodologies for quantitative assessment of phreatophyte activity, and utilizing those methods to assess water savings as part of a demonstration of salt-cedar control measures along the Cimarron River. Specifically, the major objectives for the project are to 1) refine methodologies for quantifying the consumption of ground water by phreatophytes, and 2) use these methods to determine ground-water savings produced by control of invasive phreatophytes (salt cedar and Russian olive) along a portion of the Cimarron River in Kansas. An auxiliary objective of this work is to gather a detailed data set on the major fluxes in stream-aquifer systems that can serve as the basis for research proposals on the quantitative assessment of stream-aquifer interactions in settings common to the Great Plains.

The six activities proposed for the fourth year of this project were as follows:

1. Monitoring of water levels and meteorologic parameters at both the Larned Research Site and the Ashland Research Site;
2. Monitoring of vadose-zone moisture during the growing season at the Larned and Ashland sites using the neutron probe, and the testing and deployment of a new generation of capacitance sensors for measurement of volumetric water content at the Ashland site;
3. Determination of specific yield;

4. Assessing the rate of ground-water consumption by shallow-rooted vegetation and direct evaporation at the Ashland site;

5. Modeling of water flow under unsaturated and saturated conditions in the vicinity of selected wells at the Ashland site;

6. Reassessing the ground-water savings obtained through phreatophyte-control efforts at the Ashland site.

METHODOLOGY

This work is being done at two Kansas Geological Survey (KGS)/Kansas State University (KSU) research sites: the Larned Research Site (LRS) located adjacent to the United States Geological Survey stream-gaging station on the Arkansas River near Larned in central Kansas, and the Ashland Research Site (ARS) located along the Cimarron River south of Ashland in southwest Kansas (Figure 1). The KGS/KSU research team focused on the LRS in the first two years of the project and then expanded the scope of the project in year three to include the ARS. The vegetation at the LRS is dominated by phreatophytes that are native to the Arkansas River riparian zone (cottonwood, willow, and mulberry), while the ARS is dominated by invasive phreatophytes (salt cedar and Russian olive).

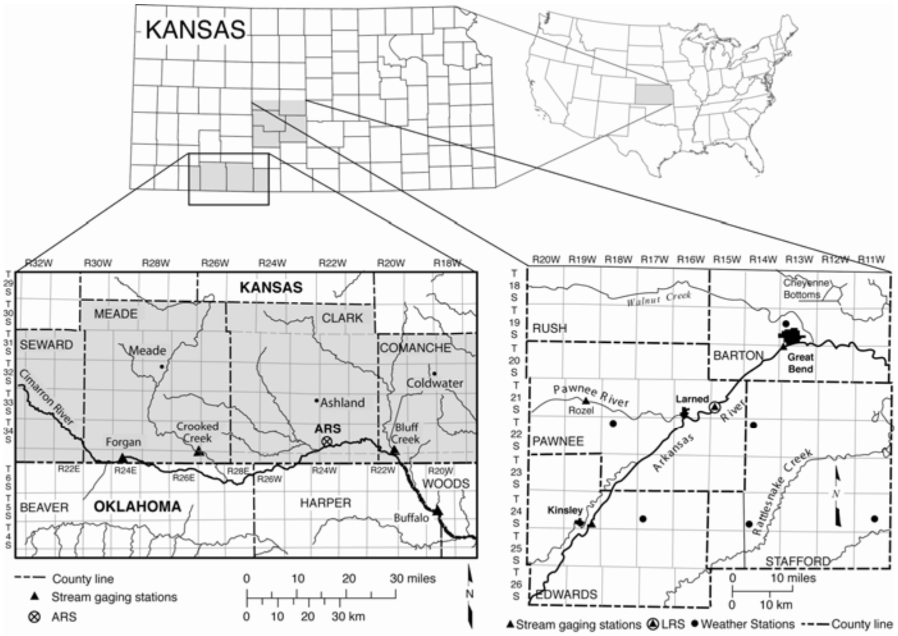

Figure 1 – Location map for sites used in this study.

A series of shallow wells have been installed at the LRS and ARS to monitor the position of the water table through time. All wells are equipped with integrated pressure transducer/datalogger units (In-Situ MiniTroll) that are programmed to take pressure-head readings every 15 minutes. Since riparian-zone wells can be overtopped during periods of high stream flow (at least

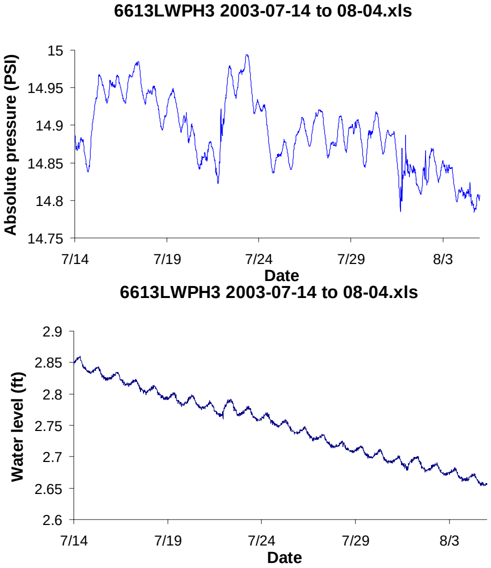

Figure 2 – Barometric pressure correction at LRS well LWPH3.

10 wells at the LRS and one at the ARS have been overtopped in the course of this project), absolute pressure sensors are used at most wells (12 out of 19 wells at the LRS and all six wells at the ARS) instead of the standard gauge-pressure sensors. The absolute-pressure sensors measure the pressure exerted both by the height of the overlying column of water in the well and by the atmosphere. The atmospheric pressure component is removed using data from a barometer at the site. Figure 2 displays records from an absolute-pressure sensor in the riparian zone at the LRS prior to and after the barometric pressure correction. Manual measurements of water levels in the monitoring wells are taken biweekly during the summer and bimonthly otherwise to assess the performance of the pressure sensors and, if necessary, to adjust the calibration parameters. Three barometers are maintained at each site, one of which is designated the site reference, to ensure data collection is not impacted by failure of a barometer. Barometer performance at each site is assessed through a comparison of the three site barometers. In addition, a handheld barometer is used to assess sensor performance during site visits.

A series of neutron-probe access tubes have been installed at each site (eight access tubes at the LRS and six at the ARS), so that volumetric water content can be measured at biweekly intervals during the growing season. Measurements in the access tubes are recorded with a neutron probe (Model 503 DR Hydroprobe Moisture Depth Gauge; Campbell Pacific Nuclear) using a count duration of 16 s and depth increments of either 0.076 m or 0.152 m. Standard counts are recorded in the field both prior to and after access tube measurements. The mean standard count for the duration of the study is used to convert each measured count to a count ratio (CR). The soil 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.

In the summer of 2006 (fourth year of project), a new generation of capacitance sensors for the measurement of volumetric water content, Decagon ECH$_2$O-TE sensors, was deployed in shallow pits at the ARS, each of which was adjacent to one of the ARS monitoring wells and neutron-probe access tubes. The sensors were used to monitor volumetric water content, bulk electrical conductivity, and temperature for 8-16 hours at a 5-min logging interval. A total of three pits were used and 15 probes were installed at differing depths (maximum depth of 1.07 m) in each pit. At the end of the monitoring period, the sensors were removed and soil samples were taken from each sensor location. The soil samples were transported to a KSU laboratory for measurement of volumetric water content. Prior to deployment, the electrical conductivity and temperature readings provided by the sensors were extensively evaluated at the KGS.

Vertical profiles of specific conductance and temperature within individual wells were measured approximately monthly during the summer and once in the spring and fall in the LRS riparian-zone wells using a YSI Model 30 meter and a 50-ft cable. Specific conductance and temperature were recorded at the same time interval as pressure head in two LRS and one ARS wells using integrated multiparameter probe/datalogger units (two In-Situ MP Troll 9000 units and one YSI 600SL Sonde).

Weather stations (Hobo Weather Station logger and sensors, Onset Computer Corp.) were in operation at both sites during year four. The weather stations are equipped with sensors to measure precipitation, air temperature, relative humidity, global irradiance [direct and diffuse solar irradiance], wind speed and direction, and barometric pressure. Data are averaged (air temperature, global irradiance, barometric pressure, and wind speed and direction) or summed (precipitation) and logged at a 15-minute interval. The only exception is the relative humidity sensor, which provides a single measurement at the end of the 15-minute interval. Potential evapotranspiration is calculated from the meteorologic data using the Penman-Monteith equation (Allen et al., 1998). The wind speed and direction sensor failed abruptly at the LRS in November of 2005, causing the datalogger to shut down. This sensor was replaced in year four.

A steady periodic analytical solution for water-table fluctuations produced by periodic forcing, such as diurnal variations in evapotranspiration, was developed in year four following the approach of Townley (1995). This solution was used to assess the impact of phreatophyte-control activities and uncut phreatophytes on water-table fluctuations measured in the ARS wells.

Additional funding was made available to project investigators in year four by the KGS for the purpose of developing a cooperative research program in ecohydrology with a plant physiologist at the University of Kansas (Joy Ward) and her postdoc (Jesse Nippert). During the 2006 growing season, travel monies were provided by this project and the KGS to allow Nippert to travel to the ARS to collect data on water movement within the salt cedar. Nippert gathered data on water pressure within leaves, water loss from leaves, sources of leaf water, and various other mechanisms and parameters related to photosynthesis. That data, in conjunction with the hydrologic data described earlier, allowed further insights to be obtained regarding water consumption by salt cedar.

MAJOR ACTIVITIES AND PRINCIPAL FINDINGS

The principal findings of the fourth year of the project will be briefly discussed in the context of the six activities proposed for year four:

Activity 1: Monitoring of water levels and meteorologic parameters at both the Larned Research Site and the Ashland Research Site – Pressure-head measurements were obtained at 15-minute intervals at 19 wells at the LRS and six wells at the ARS. Meteorologic parameters were measured at 15-minute intervals at weather stations at both sites. There was no flow in the Arkansas River at the LRS for most of year four. The three periods during which flow did occur were 8/20-9/8/06, 1/2-1/20/07, and 2/20/07 through the end of year four (2/28/07). One well in the LRS network, LWPH1, was destroyed as a result of high river flows during the late August event (plans are underway to replace it). There was flow in the Cimarron River at the ARS throughout

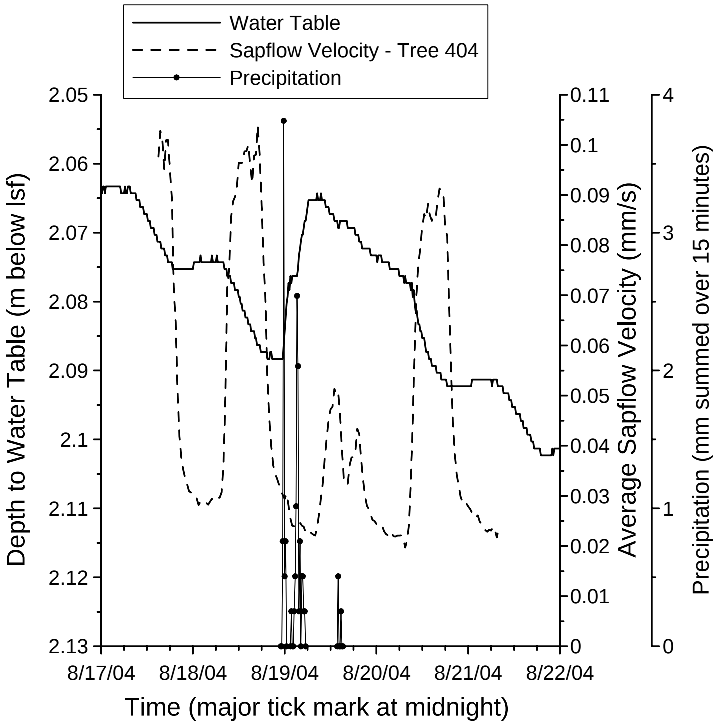

Figure 3A – Depth to water table from land surface at well LWPH2 in LRS with sapflow velocity from nearby cottonwood and precipitation from LRS weather station (from Butler et al., 2007).

much of the year. However, there was an extended period of no flow from late spring to late summer as a result of a period of anomalously hot and dry conditions. A paper primarily based on the LRS and ARS data was revised, accepted, and published in the journal *Water Resources Research* in year four (Butler et al., 2007). Figure 3A is a figure from that paper in which the link between the sapflow velocity measured in a LRS cottonwood and water-table fluctuations is illustrated (fluctuations are virtually nonexistent during period of low sapflow), while Figure 3B is a figure from the same paper that displays the diurnal water-table fluctuations typical of those observed during the growing season in five of the six wells at the ARS (all but well Ash32).

The 2006 growing season was one of the hottest and driest on record for the vicinity of the ARS. Daily maximum (T_{max}) and minimum air temperature, as well as total daily precipitation, have been recorded in the town of Ashland (approx. 17 km north of ARS) since 1900 (data provided by Mary Knapp, KS state climatologist). The high mean T_{max} (31.2 °C) and low precipitation (251 mm) during the 2006 growing season (4/1-10/1/06) were comparable to the great droughts of the 1930's, the period of the driest and hottest consecutive growing seasons for the last century in the Ashland area. In the long-term data set (1900-2006), six years had total growing season precipitation $\leq$ 251 mm, and 20 years had mean $T_{max} \geq 31.2$ °C. However, only two years, 1934 and 1954, had both a mean $T_{max} \geq 31.2$ °C and precipitation $\leq$ 251 mm, the conditions recorded over the growing season in 2006. Thus, the hydrologic data from the 2006 growing season provided an excellent opportunity to assess the utilization of ground water by ARS vegetation during a severe drought.

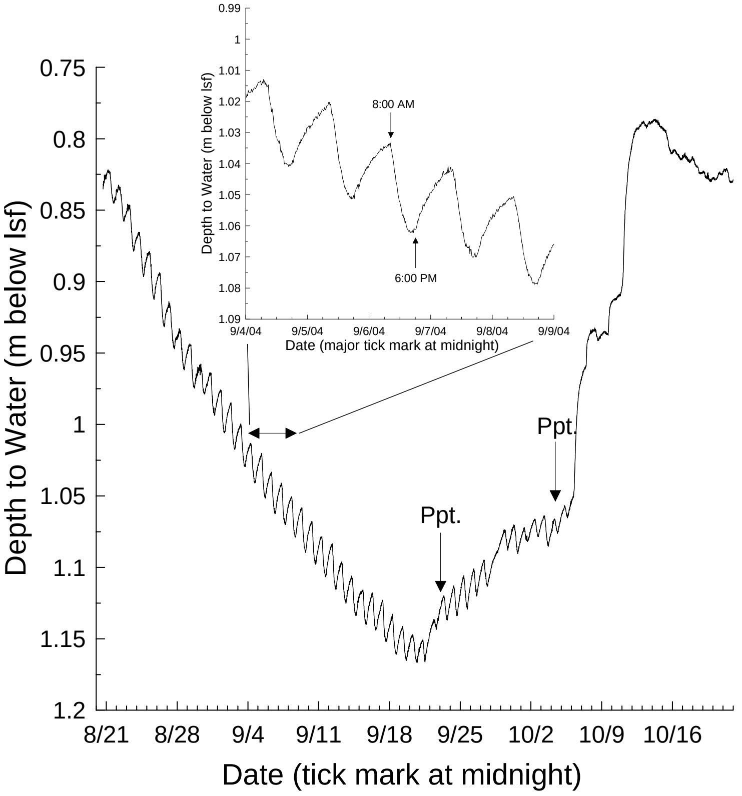

Figure 3B – Depth to water from land surface recorded at ARS well Ash22 from 8/20-10/22/04 (from Butler et al., 2007). Inset is expanded view of five days from the record. Rises in the water table after 9/21 are primarily due to rises in river stage produced by seasonal decreases in upstream irrigation pumping and plant water use, and by upstream precipitation (only the two precipitation events marked on the figure [Ppt.] occurred at the site and neither exceeded a total of 0.01 m; first frost did not occur until 11/3).

Figure 4A presents water-level and related data from well Ash31 that are representative of conditions observed at the ARS wells during the 2006 growing season. A clear diurnal pattern of water-level fluctuations can be seen in the late spring and early summer. However, at four of the five ARS wells that display diurnal fluctuations, the magnitude of these fluctuations significantly decreased after the water table fell past the lowest

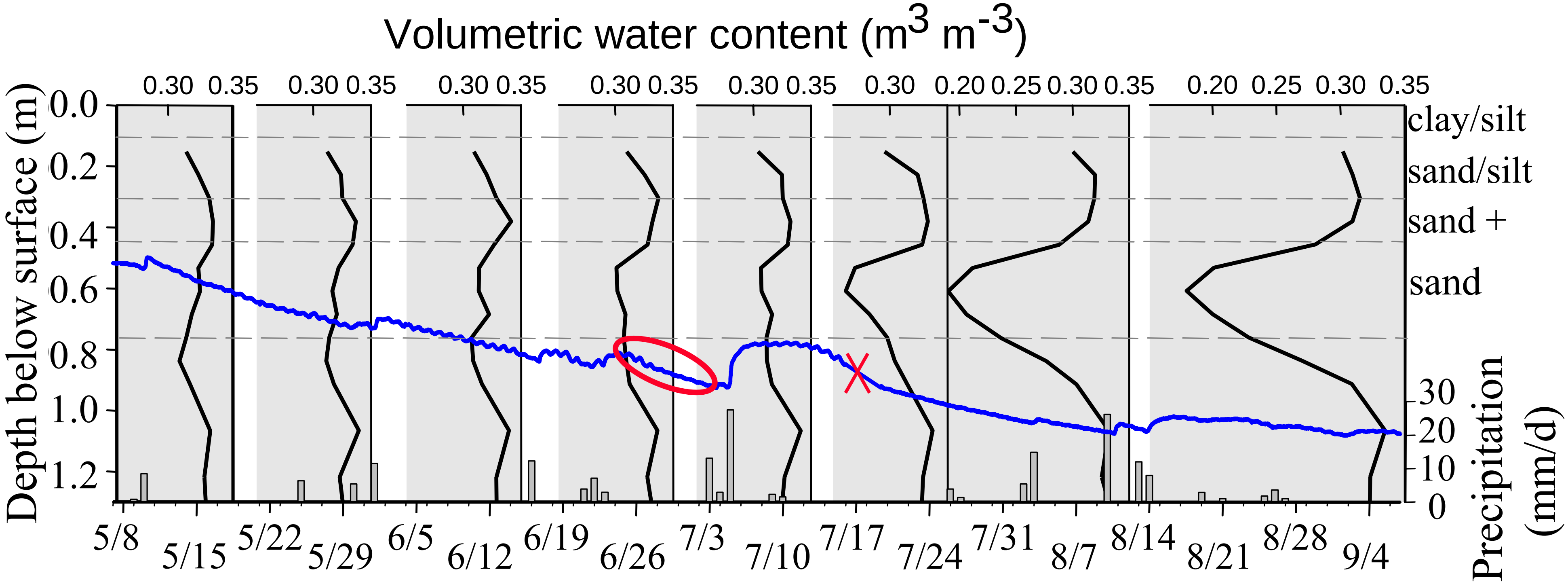

Figure 4A – Depth to the water table from land surface at well Ash31 (blue line, left y-axis) and related data for late spring and summer of 2006. Vertical black lines are volumetric water content (top x-axis) as a function of depth; intercept of the volumetric water content lines with the bottom x-axis is the date of measurement. Dashed horizontal lines delineate zones of similar soil texture (upper right y-axis); no information collected below lowest dashed line due to position of water table at time of soil sampling. Vertical bars are magnitude of daily precipitation (lower right y-axis). The ellipse indicates period of water table record expanded in Figure 4B. The X marks a four day interruption of water table monitoring (7/16-19) due to sensor malfunctioning as a result of premature battery failure.

position previously recorded during this study (Figure 4B), suggesting that the water table had fallen beyond the reach of the roots 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 LRS (Butler et al., 2007). This sizable reduction in the magnitude of the diurnal fluctuations observed at well Ash31 is accompanied by a large decrease in the volumetric water content in the sand interval centered at 0.6 m below land surface (Figure 4A), suggesting that the vegetation may have increasingly utilized vadose-zone water as the water table dropped beyond the reach of its roots. The plant physiology data collected by Nippert during the 2006 growing season revealed that the salt cedars functioned at near their physiologic maximum throughout this entire period. An article describing the ecohydrologic data collected at the ARS during the 2006 growing season is currently in the review process.

Activity 2: Monitoring of vadose-zone moisture during the growing season at the Larned and Ashland sites using the neutron probe, and the testing and deployment of a new generation of capacitance sensors for measurement of volumetric water content at the Ashland site – Vadose-zone moisture was monitored biweekly during the growing season at eight locations (four adjacent to monitoring wells) at the LRS and six locations (adjacent to monitoring wells) at the ARS, as in the previous years of this project. Figure 4A provides an example of the data that were obtained at the ARS through this monitoring.

The neutron-probe data provide valuable information about vertical and temporal changes in volumetric water content. However, the coarse resolution, in both time and space, does limit the insights that can be obtained from these data. An important emphasis of year four was the investigation of the capability of a new generation of capacitance probes (Decagon ECH$_2$O-TE) to provide measurements of volumetric water content at the same 15-minute interval as the water-level and meteorological sensors, even in the presence of the high soil and water salinity at the ARS (Butler et al., 2005). Nachabe et al. (2005) have demonstrated the potential use of such information for estimation of ground-water consumption by phreatophytes. An extensive period of probe evaluation was carried out in the KGS laboratories (assessment of temperature and electrical conductivity [EC] measurements) and at the ARS (assessment of volumetric water

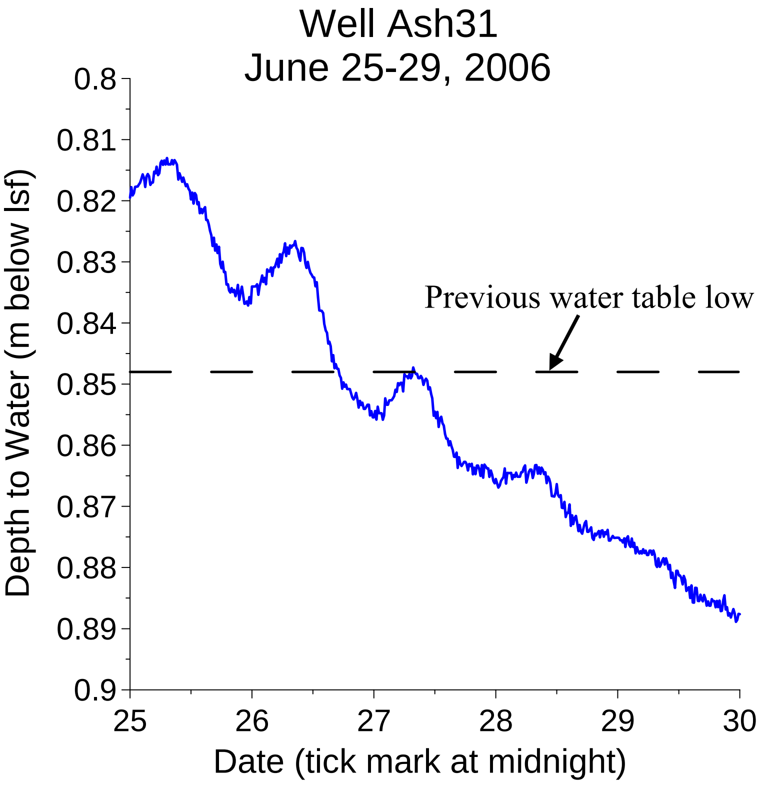

Figure 4B – Depth to the water table from land surface at well Ash31 for the period in late June of 2006 indicated by the ellipse in Figure 4A.

content measurements). The temperature measurements were found to be within the stated specifications in all tests performed at the KGS. However, the EC measurements were found to be in error as a result of incorrect calibration relationships for moderate to high electrical conductivities. After two rounds of correction of calibration relationships by the manufacturer, the EC measurements were found to be within the stated specifications. After passing the temperature and EC assessments performed in the KGS laboratories, the probes were deployed at the ARS.

A total of 45 probes were installed in three pits at the ARS (15 probes installed at differing depths in each pit). Out of those 45 probes, only 16 had volumetric water content readings close (i.e. within the reported accuracy specification of the sensors) to laboratory determined volumetric water content measurements from soil samples taken at the same locations in the pit. Twenty-two of the 29 sensors that were not in agreement with the soil sample measurements were in materials with bulk EC values greater than 0.5 dS/m. Twenty-four sensors had EC values greater than 0.5 dS/m, only two of those had volumetric water content readings close to the laboratory measurements of the soil samples. Not one sensor with a bulk EC value greater than 0.85 dS/m had a volumetric water content reading close to the soil sample measurement. As a result of the poor performance of the sensors in the ARS pits, the decision was made not to deploy these sensors at the ARS. Alternative approaches for obtaining volumetric water content data at the same 15-minute interval as the water-level and meteorological sensors are currently under consideration. The Appendix provides further information about the field assessment of the Decagon probes at the ARS.

<u>Activity 3</u>: Determination of specific yield – The analysis of volumetric-water-content and water-level data (Skaggs et al., 1978; Romano and Santini, 2002) can result in reasonable estimates of specific yield (S_Y) as shown in previous years of this project (McKay et al., 2004; Keller et al., 2005). However, that approach does not appear viable at the ARS because the finer texture of the ARS sediments do not allow the periods of rapid soil-moisture change required by the method (needed so that soil-moisture changes due to drainage/wetting will dominate over changes produced by plant water use). Instead, S_Y estimates were obtained for the ARS by simulating vertical water movement and then using the simulated results to evaluate the terms in Eq. [22] of Raats and Gardner (1974). Numerical simulations of one-dimensional vertical water movement were performed with HYDRUS-1D (Simunek et al., 2005) for a range of fluxes and for both falling and rising water tables. The soil hydraulic properties required for those simulations were estimated using ROSETTA (ver. 1.2), a software package for evaluating the hierarchical pedotransfer functions of Schaap et al. (1998, 2001). Specifically, hydraulic properties were estimated with the ROSETTA pedotransfer function model that uses soil particle size (sand, silt, and clay percentages) as input. Particle size data were obtained from soil samples collected in the vicinity of each of the ARS wells in the third year of this project (see Year Three Report). The KSU Soil Characterization Laboratory completed particle size analysis of those samples early in year four.

Example results for well Ash12 (Figure 5) show that S_Y generally increases with increasing depth to water for the case of a falling water table. Whereas uniform soil results in a monotonic increase in S_Y with increasing depth to water, the results for well Ash12 clearly show deviations from monotonic behavior. This is a direct result of vertical variations in soil texture, which cause soil hydraulic properties to vary with depth throughout the profile. The results in Figure 5 also show that specific yield depends on the magnitude of the flux across the water table. In addition, well Ash12 results for the case of a rising water table (not shown) revealed that estimates of S_Y are influenced by the direction of water table movement. It is clear from these results that S_Y is not a static property. For a given water table depth and soil texture, specific yield varies with the direction of water table movement and the magnitude of the flux across the water table. A distinct advantage of the method described here for estimating S_Y is that it explicitly accounts for transient effects due to the motion of the water table and the flux of water across the water table.

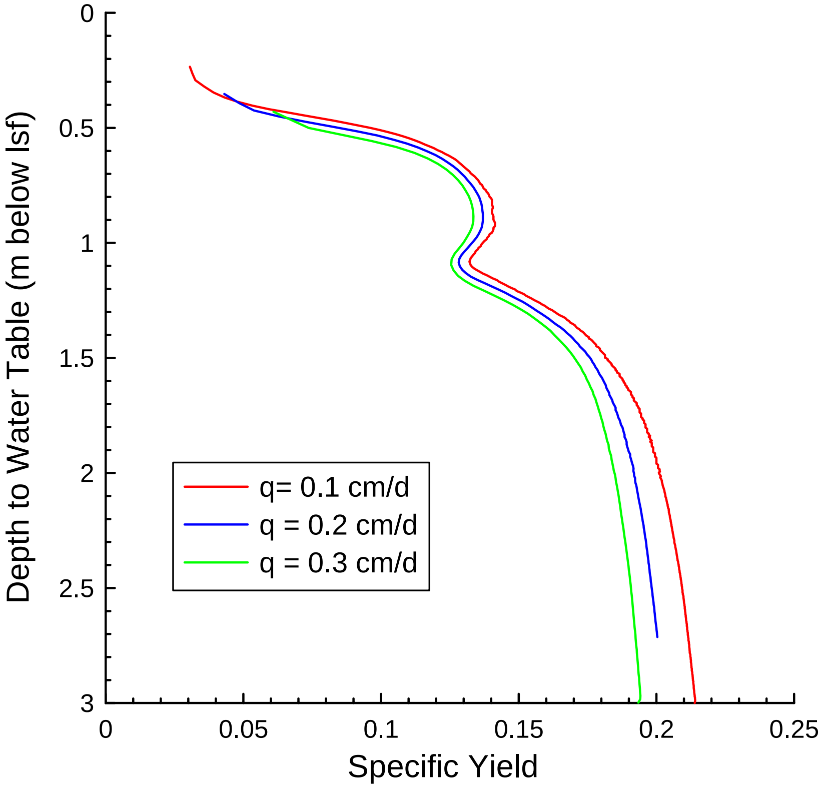

Figure 5 – Example of specific yield (S_Y) estimates for the case of a falling water table at well Ash12. Estimates of S_Y are shown as a function of depth to the water table for three different fluxes (q) across the water

<u>Activity 4</u>: Assessing the rate of ground-water consumption by shallow-rooted vegetation and direct evaporation at the Ashland site – Limited progress was made on this activity in year four as a result of the unsuitable weather conditions during the 2006 growing season and the unexpectedly large amount of time required for the sensor assessment described in Activity 2 in the early summer of 2006. In late June of 2006, the diurnal fluctuations virtually ceased at two (Ash21 and Ash31) of the three wells that were to be used for this activity (e.g., Figure 4B), thus making it impossible to pursue the planned experiments after that time. However, some insight into the relative contributions of ground-water consumption by shallow-rooted vegetation and direct evaporation was obtained from the analytical solution described in Activity 5 and previously collected water-level data.

<u>Activity 5</u>: Modeling of water flow under unsaturated and saturated conditions in the vicinity of selected wells at the Ashland site – This activity was a major focus of the latter half of year four. As described in previous reports (e.g., Butler et al., 2005), the ARS is subdivided into four plots of approximately four hectares each in which different salt-cedar control measures are being applied. Control measures are not used in Plot 1 (wells Ash11 and Ash12) so that data unaffected by those measures can be obtained throughout the project. Water-level data collected prior to any control activities clearly indicate that the magnitude of the water-table fluctuations is highly dependent on the apparent vitality of the phreatophyte community in the vicinity of each well

(Butler et al., 2005, 2007). Salt-cedar control measures began to be implemented at the ARS in March of 2005. At that time, Plots 2-4 were clear cut except for circles ranging from 20-30 m in radius, centered at each well. The radii of those circles of vegetation were progressively reduced through repeated cuttings in the summer of 2005 until the vegetation circles were completely removed on August 9, 2005. Only the invasive phreatophytes were cut at the site; grasses, forbs, and low-lying bushes were largely unaffected. A chemical treatment (Remedy and diesel-fuel mix) was applied to the salt-cedar regrowth in Plot 2 (wells Ash21 and Ash22) following the cutting, but no chemical treatment was applied in Plot 3 (wells Ash31 and Ash32). Water levels, volumetric water content, and meteorological parameters were monitored before, during, and after these control activities. Note that no wells were installed in Plot 4 because of the eventual planned burn in that plot.

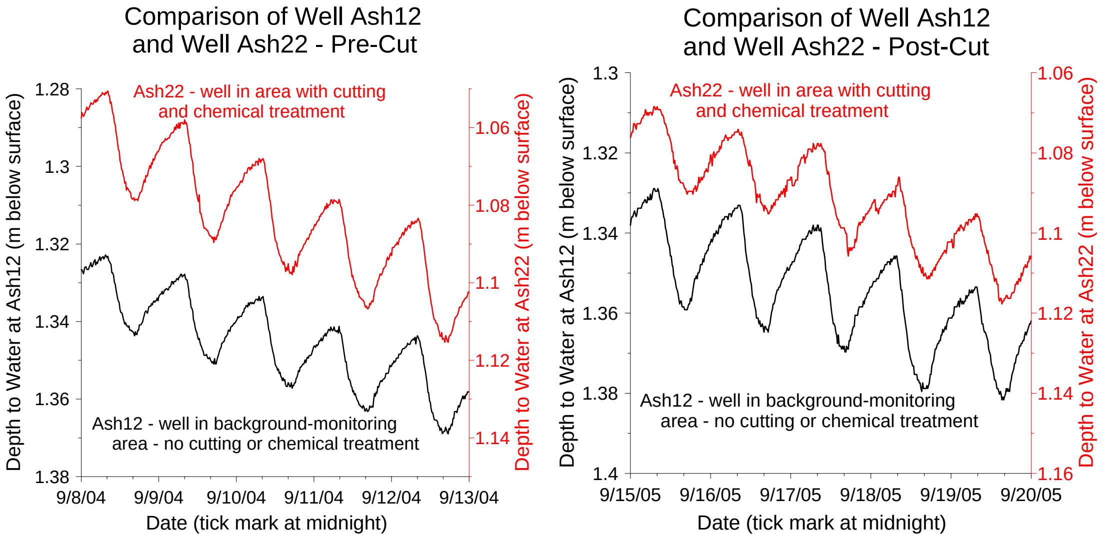

Figure 6 – Depth to the water table from land surface at wells Ash12 and Ash22 prior to (A – left figure) and after (B- right figure) clear cutting all invasive phreatophytes from Plot 2 in August of 2005. Data for Ash12 included to show the pattern of fluctuations observed in Plot 1 where no control activities were applied.

The initial expectation was that the diurnal fluctuations would virtually cease after the cutting. However, as illustrated in Figure 6 for well Ash22, that expectation was not realized at any of the ARS wells at which fluctuations were observed prior to cutting (Ash21, Ash22, and Ash31). Possible explanations for the continued fluctuations include ground-water consumption by the uncut grasses, forbs, and small bushes, and by direct evaporation from the water table in the vicinity of the well, and ground-water consumption by invasive phreatophytes outside of the cut area. In order to assess the possibility of this latter mechanism, steady periodic analytical solutions for water-table fluctuations produced by diurnal variations in evapotranspiration were developed by extending the general approach described in Townley (1995) to the configuration illustrated in Figures 7A-B. 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 fluctuations at the central well produced by the invasive 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 6A-B show that such a difference was not observed. Thus, it is considered unlikely that ground-water consumption by invasive phreatophytes outside the cut circle is producing the diurnal fluctuations observed after completion of cutting and chemical treatment.

Development of periodic analytical solutions for consideration of configurations similar to that at the LRS and for unsaturated conditions is ongoing.

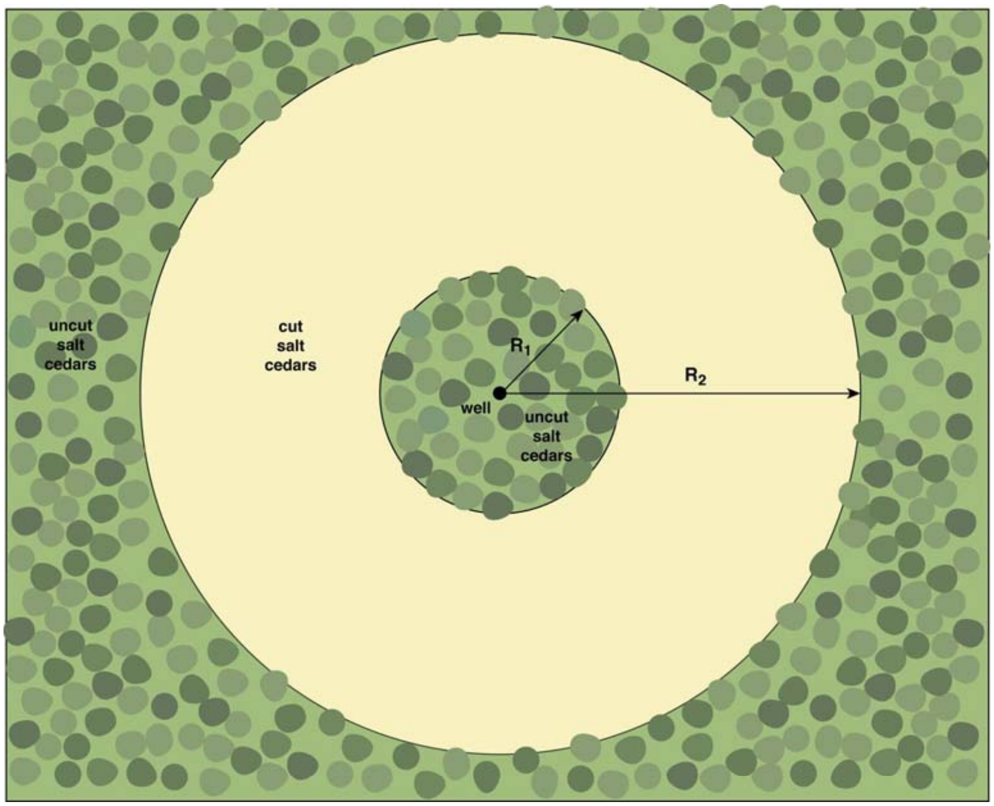

Figure 7A – Schematic areal view of configuration of cut and uncut salt cedars around wells Ash21, Ash22, and Ash31 during the 2005 cutting period (not to scale).

Activity 6: Reassessing the ground-water savings obtained through phreatophyte-control efforts at the Ashland site – The ground-water savings achieved through phreatophyte-control activities at the ARS were estimated using an approach, developed in this work, based on ratios of the White equation (White, 1932; Loheide et al., 2005). This approach is illustrated in Figure 8 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 (midnight to 4 A.M.) recovery of water levels expressed as a daily rate, and s is the net change in water-table position over one day expressed

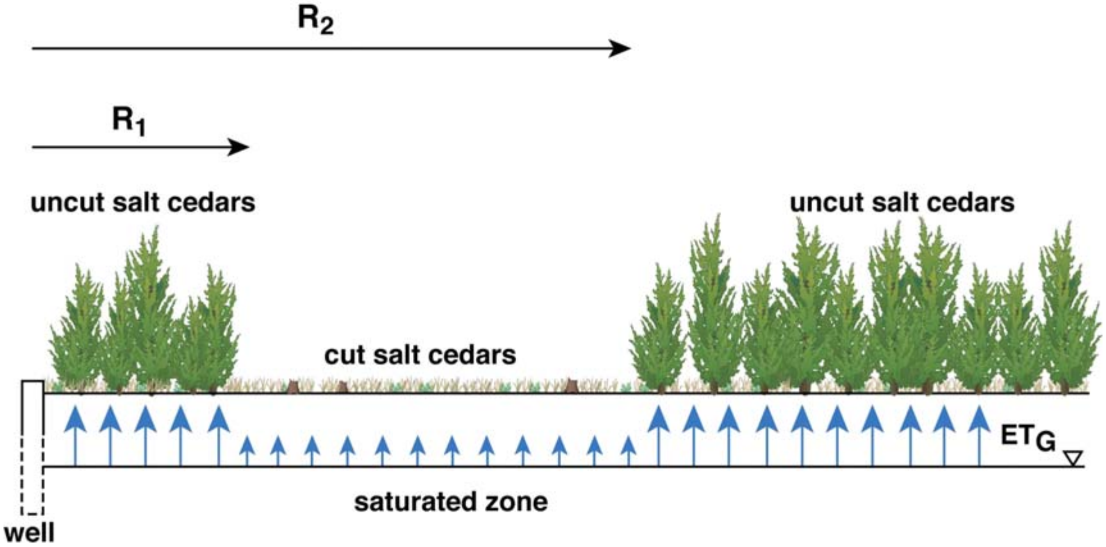

Figure 7B – Schematic cross-sectional view of the vicinity of wells Ash21, Ash22, and Ash31 during the 2005 cutting period (not to scale). Well at left is at center of Figure 7A. ET_G is the evapotranspirative consumption of ground water, differences in heights of arrows indicate relative differences in ET_G between cut and uncut regions. Vegetation in area of cut salt cedars primarily consists of grasses, forbs, and small bushes.

as a daily rate (by convention positive with decrease in water-table elevation). The ratio in the numerator of the left-hand side of the expression in Figure 8 characterizes the changes in ET_G at Ash22 between the pre-cut and post-cut periods. A similar ratio in the denominator of the left-hand side characterizes the changes in ET_G at Ash12 between these same periods. The changes in Ash12 reflect the impact on ET_G of factors other than the phreatophyte-control activities. The right-hand side of the expression in Figure 8 is obtained by substituting the White equation for each ET_G term. Because the same depth intervals were used for the pre-cut and post-cut periods (e.g., Figure 6), S_Y cancels out in both the numerator and the denominator.

The reductions in ET_G calculated with the ratio approach illustrated in Figure 8 varied between the three wells (Ash21, Ash22, and Ash31) from 23-56% in the month immediately following cutting (time intervals shown in Figure 6 – average of three wells was 40%) . However, an analysis using the same depth intervals in 2006 (June 9-13) found that the reductions varied from 2-42% (average of three wells was 22%). Thus, the reduction in ET_G gained from the phreatophyte-control activities appears to be decreasing with time, despite the severe drought conditions experienced during the 2006 growing season. This decreased reduction in ET_G may be a result of 1) increased growth (and thus water use) of grasses, forbs, and small bushes due to increased exposure to sunlight as a result of the removal of the large phreatophytes, 2) increased direct evaporation from the water table due to the increased exposure of the land surface to sunlight, and 3) regrowth of salt cedar (both plots have experienced regrowth following the initial application of control activities). Future work of this project will be directed at assessing the relative importance of ground-water consumption by these various mechanisms. Unless the impact of these mechanisms is better understood, it will be difficult to reliably estimate the potential water savings to be achieved through control of invasive phreatophytes. Note that the salt cedar regrowth in plot 3 was cut on September 7, 2006. Monitoring will

$$\frac{\left(\dfrac{ET_{G_{post-cut}}}{ET_{G_{pre-cut}}}\right)_{Ash22}}{\left(\dfrac{ET_{G_{post-cut}}}{ET_{G_{pre-cut}}}\right)_{Ash12}} \Rightarrow \frac{\left(\dfrac{S_Y(r+s)_{post-cut}}{S_Y(r+s)_{pre-cut}}\right)_{Ash22}}{\left(\dfrac{S_Y(r+s)_{post-cut}}{S_Y(r+s)_{pre-cut}}\right)_{Ash12}}$$

Figure 8 – Example of approach for using diurnal water-table fluctuations to estimate changes in ground-water consumption by vegetation following clear cutting of invasive phreatophytes about wells in Plots 2 and 3 in August of 2005. Data for Ash12, well in Plot 1 where no control activities were applied, used to assess impact of changes on ground-water consumption at the ARS due to factors other than clear cutting of phreatophytes.

continue at the ARS throughout this project so that the ultimate reduction in ET_G achieved through phreatophyte-control measures can be assessed.

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Butler, J.J., Jr., Overview of research at the Larned Research Site, presentation to the South Asian Water Resources Delegation, Larned Research Site, Dec. 6, 2006.

Butler, J.J., Jr., What the heck is a phreatophyte? A field investigation of ecohydrologic processes in stream-aquifer systems, 2007 Henry Darcy Distinguished Lecture Series – presented at Emporia State University (Jan. 31, 2007) and Kansas State University (Feb. 15, 2007).

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INFORMATION TRANSFER

Eleven presentations concerning this project were presented at various venues both within and outside of Kansas during year four, including the 2006 Tamarisk Research Conference in Fort Collins, Colorado. Two of these presentations were part of the 2007 Henry Darcy Distinguished Lectureship that was awarded to James Butler. Early in year five, Butler presented additional Darcy lectures on this project at universities and research institutes in the United States, China, Taiwan, the Netherlands, Germany, Austria, Spain, and the United Kingdom. Additional lectures will be presented later in the year at universities and research institutes in the United States and Canada. One manuscript describing the results of the field investigation of phreatophyte-induced fluctuations in the water table was published in the journal *Water Resources Research*. An additional manuscript on the summer 2006 work at the Ashland Research Site is currently in review.

STUDENT SUPPORT

Three students participating in the Applied Geohydrology Summer Research Assistantship Program of the Kansas Geological Survey were partially supported from this grant during the summer of 2006. These students contributed to the aspects of the project involving water-level and vadose-zone monitoring, conductance measurements, Decagon probe laboratory and field assessment, and weather-station upkeep. One student, Angela Cook from the University of Colorado at Boulder, presented a poster on a portion of the summer work at the Fall Conference of the American Geophysical Union in San Francisco in December of 2006. One KSU undergraduate participating in the Agronomy Undergraduate Research Assistantship Program assisted with vadose-zone monitoring and Decagon probe field assessment.

Appendix - Report on Field Assessment of Decagon ECH$_2$O-TE Sensors

Summary

On 6/28- 6/30/06, a KGS/KSU research team conducted a field assessment of the Decagon ECH$_2$O-TE sensors at the Ashland Research Site in southwestern Kansas. We installed the sensors in pits adjacent to three monitoring sites and monitored volumetric water content, bulk electrical conductivity, and temperature for 8-16 hours using a 5-min logging interval. A total of three pits were used and 15 probes were installed at differing depths in each pit. At the end of the monitoring period, the sensors were removed and soil samples were taken from the same depth intervals. The samples were then taken to the lab for measurement of volumetric water content. Out of the 45 sensors, only 16 had soil moisture readings close (i.e. within the reported accuracy specifications of the sensors) to the soil moisture measurements obtained in the laboratory. Twenty-two of the 29 sensors that were not in agreement with the measurements were in materials with bulk EC values greater than 0.5 dS/m. Twenty-four sensors had EC values greater than 0.5 dS/m – only two of those had soil moisture values close to the measurements. Not one sensor with a bulk EC value greater than 0.85 dS/m had a soil moisture reading close to the measurement. In the following sections, we provide further details about the site and the sampling methods.

Site Overview

The Ashland Research Site (ARS) is located along the Cimarron River in southwestern Kansas a few miles north of the Oklahoma border (Figure 1). Since August of 2004, the Kansas Geological Survey and Kansas State University have been studying water-use by phreatophytes and the efficacy of various salt-cedar control measures at the site. We have installed a network of shallow water-table wells and neutron-probe access tubes along with a weather station. Each well is paired with a neutron-probe access tube that is located within 5 ft of the well. The well and access tube pairing will be designated as a monitoring site in this report. We monitor water-table position and various meteorological parameters at a 15-minute interval throughout the year, while soil moisture is measured on a biweekly basis during the growing season. We want to use the Decagon sensors to obtain information on temporal variations in soil moisture over the same time interval used for the water-level and meteorological data.

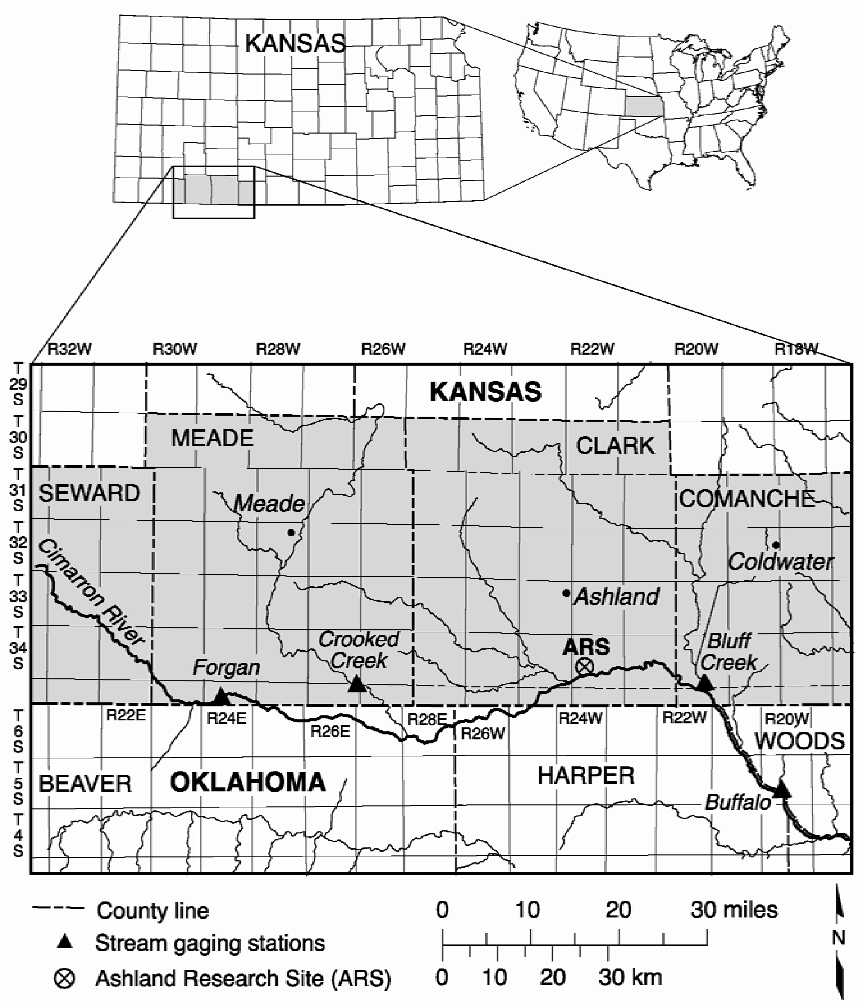

Figure 1 – Location map of the Ashland Research Site (ARS).

Installation and Sampling Procedures

Sensor Installation

On the evening of 6/28 and the morning of 6/29, we dug two pits (Ash32 and Ash21) at the site with a backhoe and one shallow pit (Ash22) with shovels. Each pit was adjacent (within 15-20 ft) to the monitoring site from which it derived its name. Beginning in the morning of 6/29, we installed 15 sensors in each pit (Figure 2) following the instructions outlined in the sensor manual. In general, sensor installation went smoothly. Once installed, the sensors were programmed to log at a 5-minute interval. During daylight hours, we periodically went to each pit and sprayed the pit faces with a light mist of water to prevent excessive drying of the soil exposed at the pit faces.

Figure 2 – Pit Ash22 with installed sensors

Sensor Removal and Soil Sampling

We began to remove the sensors late in the afternoon of 6/29. We removed the sensors in the order in which they were installed. All the sensors were removed from pit Ash32 in the late afternoon of 6/29. The sensors were removed from pits Ash21 and Ash22 in the morning and early afternoon of 6/30. As the sensors were removed, soil samples were taken adjacent to the position of the sensors using a pair of sampling rings. Figure 3 shows the orientation (top view) of sampling rings relative to the sensor. The sampling rings were made from thin-wall aluminum tubing. The height of each ring was 5.0 cm, the diameter was 4.8 cm, so the volume of each was 90.5 cm^3, giving a total sample volume of 181 cm^3. The bottom edge of each ring was beveled to form a cutting edge. The rings were placed in position after forming a smooth, level surface approximately 2.5 cm above the level of the sensor "blades" (Figure 4 shows surface immediately prior to sampling at pit Ash32). Rings were vertically driven into the soil by tapping. A small block of wood was placed on the ring, and then a hammer was used to deliver light blows to the block. After insertion, the bottom edge of the rings ended up approximately 2.5 cm below the level of the sensor "blades". In soil layers with higher clay content, a light coating of WD-40 was applied to the exterior of the sampling rings. Care was taken to avoid getting lubricant on the interior surface of the rings. We experienced little to no problems with compaction of the samples. The position of the rings was adjusted slightly in a few instances to avoid roots and other irregularities.

The sensor was removed after the rings were driven to depth and a small masonry trowel was inserted beneath a ring to shear off the sample and lift it out. Additional trimming (with edge of trowel) was required on occasion to ensure that the bottom of the sample was level with the bottom of the sampling ring. The soil from both rings was placed in a soil moisture tin that was stored in an insulated container.

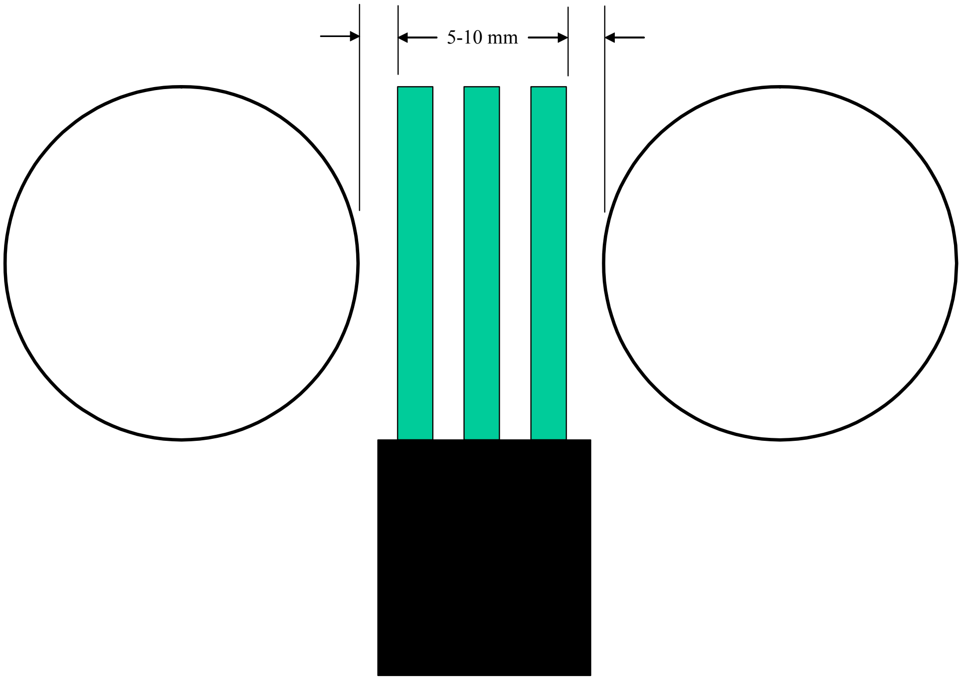

Figure 3 – Top view of sampling rings relative to sensor.

Figure 4 – Gerard Kluitenberg preparing a level surface prior to taking a soil sample at pit Ash32. Sampling ring can be seen on left side of ledge.

Soil Moisture Determination

Soil moisture tins remained in the insulated container until they could be weighed. Samples were weighed in the field after all the samples were removed from a pit and checks (i.e. some samples were weighed immediately after removal from pit) were performed to ensure that the samples did not lose water before weights were recorded. A calibration weight was used to confirm that transport of the balance to the ARS did not affect balance calibration. The samples were then transported back to KSU.

Samples were weighed in Kluitenberg's laboratory at KSU (using the same balance) after drying at 105 deg C for 36 hours. Weight checks were performed to confirm that moisture loss had ceased prior to final weight determinations. Gravimetric water content was calculated as mass of water per mass of oven-dried soil material. Mass of oven-dried soil material and total sample volume (combined volume of two rings) was used to calculate bulk density. Volumetric water content was calculated as the product of the gravimetric water content and the bulk density.

Comparison of Soil Moistures from Sensors and Samples

Table 1 presents the comparison of the soil-moisture readings from the sensors with the values determined in the lab. The reported sensor values are averages obtained over the last 25 minutes prior to sensor removal. The temperature and bulk EC values from the sensors are also reported. At pit Ash21, five sensors each were placed on three pit faces at six-inch intervals beginning at six inches below land surface. At pit Ash22, five sensors each were placed on three pit faces at three-inch intervals beginning at six inches below land surface. At pit Ash32, seven sensors each were placed on two pit faces at six-inch intervals beginning at six inches below land surface with one additional sensor being placed on the second pit face a foot below land surface.

At pit Ash21, five of the 15 sensors performed within specifications. There appeared to be a pattern of poorer agreement as the bulk EC increased. Some of the average soil moisture values from the sensors were also deemed to be outside of the range of physical plausibility for materials at that pit. Bulk density for this pit ranged from 1.42 to 1.63 g/cm^3 (mean = 1.57 g/cm^3). This corresponds to a range of 0.39 to 0.46 in total porosity, if a particle density of 2.65 g/cm^3 is assumed.

At pit Ash22, only one of the 15 sensors performed within specifications and that was the one in the interval of lowest bulk EC at that pit. Some of the average soil moistures from the sensors were again deemed to be outside of the range of physical plausibility for materials at that pit. Bulk density for this pit ranged from 1.27 to 1.55 g/cm^3 (mean = 1.41 g/cm^3), which corresponds to a range of 0.41 to 0.52 in total porosity. As is shown by the sample data in Tables 3 and 4, pit Ash22 had the highest EC and highest percentage of fine textured material of the three pits.

At pit Ash32, 10 of the 15 sensors performed within specifications. The bulk EC values at this pit were relatively low. The most common characteristic of the sensors functioning outside of specs was the relatively high EC of the material in which they had been placed. Only one of the six intervals with the highest bulk EC values reported at the pit had a sensor that performed within specs. Bulk density for this pit ranged from 1.35 to 1.66 g/cm^3 (mean = 1.54 g/cm^3), which corresponds to a range of 0.37 to 0.49 in total porosity.

Table 1 – Sensor and Sample Comparison of Volumetric Water Content

Sensor #	Depth below lsf [inches]	Sensor Average VWC [m3/m3]	Sensor Average Temp [C]	Sensor Average EC [dS/m]	Samples VWC	Absolute Difference	Within Specs?
PIT ASH21							
24	6	**0.21**	25.30	0.77	**0.14**	0.07	N
37	12	**0.54**	23.60	3.09	**0.29**	0.25	N
39	18	**0.81**	21.67	4.14	**0.42**	0.39	N
16	24	**0.39**	21.47	1.46	**0.36**	0.03	N
31	30	**0.25**	21.07	0.39	**0.27**	0.03	Y
40	6	**0.21**	21.53	0.78	**0.14**	0.07	N
33	12	**0.69**	20.90	3.06	**0.33**	0.36	N
25	18	**0.36**	20.53	0.84	**0.36**	0.00	Y
34	24	**0.13**	20.52	0.08	**0.17**	0.04	N
38	30	**0.26**	20.65	0.65	**0.28**	0.03	Y
45	6	**0.11**	21.00	0.43	**0.13**	0.02	Y
42	12	**0.75**	20.67	3.57	**0.32**	0.43	N
18	18	**0.14**	20.52	0.30	**0.31**	0.18	N

26	24	**0.22**	20.35	0.29	**0.23**	0.00	Y
41	30	**0.33**	20.50	0.74	**0.22**	0.10	N
PIT ASH22							
9	6	**0.70**	26.72	3.22	**0.34**	0.36	N
30	9	**0.27**	28.58	0.60	**0.21**	0.06	N
22	12	**0.33**	26.12	0.98	**0.15**	0.18	N
23	15	**0.31**	26.87	1.21	**0.14**	0.18	N
21	18	**0.41**	24.00	1.31	**0.16**	0.25	N
35	6	**0.68**	30.37	1.69	**0.30**	0.39	N
15	9	**0.21**	29.52	0.33	**0.19**	0.02	Y
3	12	**0.46**	28.13	2.55	**0.18**	0.28	N
12	15	**0.35**	26.55	1.11	**0.16**	0.19	N
32	18	**0.76**	25.22	5.57	**0.28**	0.48	N
28	6	**0.69**	23.15	2.45	**0.29**	0.40	N
8	9	**0.38**	23.88	1.13	**0.22**	0.15	N
11	12	**0.31**	23.07	1.12	**0.15**	0.16	N
6	15	**0.31**	22.93	1.41	**0.14**	0.17	N
10	18	**0.73**	21.90	5.63	**0.26**	0.47	N
PIT ASH32							
4	6	**0.01**	33.60	0.02	**0.04**	0.03	Y
7	12	**0.03**	31.13	0.01	**0.03**	0.00	Y
2	18	**0.11**	28.42	0.06	**0.06**	0.05	N
44	24	**0.06**	27.52	0.03	**0.07**	0.01	Y
19	30	**0.10**	25.93	0.04	**0.07**	0.03	Y
29	36	**0.08**	25.32	0.04	**0.07**	0.01	Y
20	42	**0.09**	24.32	0.09	**0.19**	0.10	N
1	6	**0.14**	35.53	0.08	**0.06**	0.08	N
17	12	**0.04**	33.38	0.03	**0.03**	0.01	Y
5	18	**0.02**	31.05	0.02	**0.02**	0.01	Y
27	24	**0.11**	28.72	0.08	**0.06**	0.05	N
43	30	**0.09**	25.70	0.05	**0.09**	0.00	Y
13	36	**0.09**	25.53	0.04	**0.06**	0.03	Y
36	42	**0.15**	25.30	0.16	**0.16**	0.01	Y
14	12	**0.08**	33.23	0.13	**0.02**	0.06	N

Soil Information

Soil Type

The ARS is located in an area mapped as a Lincoln-Krier complex, which means it contains a mixture of both Lincoln and Krier soils. A detailed description of these soils can be found in the Clark County soil survey (USDA-SCS, 1982). Note that the descriptions of the Lincoln and Krier series are for typical pedons. They capture the distinguishing characteristics of these series, but are not exact descriptions of Lincoln and Krier pedons in the Lincoln-Krier complex at the ARS. We did not attempt to identify the soils in each pit as we did not feel qualified to do so.

Soil Texture

On September 20-21, 2005, we collected soil samples at each monitoring site. At each site, four sampling locations were identified at a distance of approximately 10 feet from the water-table well. Sampling locations were distributed as uniformly as possible around each well (ideal arrangement forming a square); however, the spatial arrangement varied from well to well due to the presence of salt cedar plants (live plants as well as crowns of treated plants) and landscape features.

Samples were collected (2.75-inch-diameter bucket auger) from all four sampling locations in 6-inch depth intervals from the soil surface to the maximum depth allowable due to the presence of the water table. The samples obtained from the four sampling locations were combined (composited) by depth interval in plastic buckets. That is, all four samples from the 0- to 6-inch depth interval were combined in a bucket, all four samples from the 6- to 12-inch depth interval were combined in a bucket, and so on. After samples were obtained from all four locations, all of the soil material in each bucket was transferred to a sample bag, labeled with well number and depth interval.

The samples were transported to the laboratory and dried at 50 °C for one week. Samples were crushed and then passed through a 2-mm sieve. Large root fragments were removed and discarded prior to crushing. Small root fragments were removed and discarded during the sieving process. The material that passed through the 2-mm sieve was returned to the original sample bag.

A sample splitter was used to obtain a subsample of approximately 16 ounces (liquid volume basis) for particle size analysis and a subsample of approximately 32 ounces (liquid volume basis) for chemical analysis.

The subsamples for chemical analysis were submitted to the KSU Soil Testing Laboratory. Table 2 contains results for the electrical conductivity of the solution extracted from a saturated paste.

Sample number	Well number	Depth interval	Elec. cond.
		inches	dS/m
12	Ash 21	0-6	3.53
13	Ash 21	6-12	6.62
14	Ash 21	12-18	11.32
15	Ash 21	18-24	6.58
16	Ash 21	24-30	5.10
17	Ash 21	30-36	4.15
18	Ash 22	0-6	11.81
19	Ash 22	6-12	14.33
20	Ash 22	12-18	11.14
21	Ash 22	18-24	12.30

22	Ash 22	24-30	13.96
23	Ash 22	30-36	12.25
24	Ash 22	36-42	13.00
25	Ash 22	42-48	5.01
31	Ash 32	0-6	3.55
32	Ash 32	6-12	2.96
33	Ash 32	12-18	2.59
34	Ash 32	18-24	1.45
35	Ash 32	24-30	1.60
36	Ash 32	30-36	2.20
37	Ash 32	36-42	2.52
38	Ash 32	42-48	2.37

Table 2 – Electrical conductivity of saturated extract

The subsamples for particle size analysis were analyzed at the KSU Soil Characterization Laboratory. All samples were subject to a pretreatment step of salt washing (removal of soluble salts). In addition, several samples were subject to a pretreatment step for removal of organic matter. Amounts of total sand and the various sand fractions (very fine, fine, medium, coarse, and very coarse sand) were determined by sieving. Amounts of total clay, fine silt, and medium silt fractions were determined using sedimentation analysis in conjunction with the pipette method. The amount of coarse silt in each sample was determined by difference. Particle size analysis results are shown in Table 3.

Sample number	Well number	Depth interval	Total sand (2.00-0.05 mm)	Total silt (50.0-2.0 μm)	Total clay (< 2.0 μm)	Textural class
		inches		%		
12	Ash 21	0-6	83.8	11.1	5.1	lfs
13	Ash 21	6-12	84.1	11.3	4.6	lfs
14	Ash 21	12-18	82.0	14.0	4.0	lfs
15	Ash 21	18-24	93.2	3.8	3.0	s
16	Ash 21	24-30	94.0	5.8	0.2	fs
17	Ash 21	30-36	97.0	3.0	0.0	fs
18	Ash 22	0-6	16.5	52.6	30.9	sicl
19	Ash 22	6-12	53.8	39.6	6.7	vfsl
20	Ash 22	12-18	68.8	25.5	5.7	vfsl
21	Ash 22	18-24	24.9	45.5	29.6	cl
22	Ash 22	24-30	41.0	33.2	25.8	l
23	Ash 22	30-36	86.5	9.5	4.0	lfs
24	Ash 22	26-42	76.6	19.0	4.4	lfs
25	Ash 22	42-48	93.4	6.6	0.0	fs
31	Ash 32	0-6	59.7	34.0	6.3	vfsl
32	Ash 32	6-12	76.8	19.4	3.8	lvfs

33	Ash 32	12-18	88.6	10.5	0.9	fs
34	Ash 32	18-24	95.9	3.0	1.1	s
35	Ash 32	24-30	96.8	3.2	0.0	s
36	Ash 32	30-36	96.8	3.2	0.0	s
37	Ash 32	26-42	96.6	3.4	0.0	s
38	Ash 32	42-48	97.6	2.4	0.0	s

Table 3 – Soil textural information from the vicinity of the three pits.