

**Kansas Water Resources Research Institute  
Annual Technical Report  
FY 2006**

## **Introduction**

The Kansas Water Resources Institute is part of a national network of water resource institutes in every state and territory of the U.S. established by law in the Water Resources Research Act of 1964. The network is funded by a combination of federal funds through the U.S. Department of the Interior/Geological Survey (USGS) and non-federal funds from state and other sources. KWRI is administered by the Kansas Center for Agricultural Resources and the Environment (KCARE) at Kansas State University. An Administrative Council composed of representatives from participating higher education or research institutions, state agencies, and federal agencies assists in policy making. The Mission of KWRI is to: -Develop and support research on high priority water resource problems and objectives, as identified through the state water planning process; -Facilitate effective communications among water resource professionals; -Foster the dissemination and application of research results. We work towards this mission by: -Providing and facilitating a communications network among professionals working on water resources research and education, through electronic means, newsletters, and conferences; -Supporting research and dissemination of results on high priority topics, as identified by the Kansas State Water Plan, through a competitive grants program.

## **Research Program**

Our mission is partially accomplished through our competitive research program. We encourage the following through the research that we support: interdisciplinary approaches; interagency collaboration; scientific innovation; support of students and new young scientists; cost-effectiveness; relevance to present and future water resource issues/problems as identified in the State Water Plan; dissemination and interpretation of results to appropriate audiences. In implementing our research program, KWRI desires to:

- Be proactive rather than reactive in addressing water resource problems of the state;
- Involve the many water resources stakeholders in identifying research needs and utilize their input to prioritize the water resources research needs of the state;
- Foster collaboration among state agencies, federal agencies, and institutions of higher education in the state on water resource issues;
- Leverage additional financial support from state, private, and other federal sources;
- Be recognized in Kansas as a major institution to go to for water resources research.

# A Field Assessment of a Method for Estimation of Ground-Water Consumption By Phreatophytes

## Basic Information

<b>Title:</b>	A Field Assessment of a Method for Estimation of Ground-Water Consumption By Phreatophytes
<b>Project Number:</b>	2003KS33B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2008
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	2nd District
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Groundwater, Water Use, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	James J. Butler, Gerard J. Kluitenberg, Donald Whittemore

## **Publication**

## **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).

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

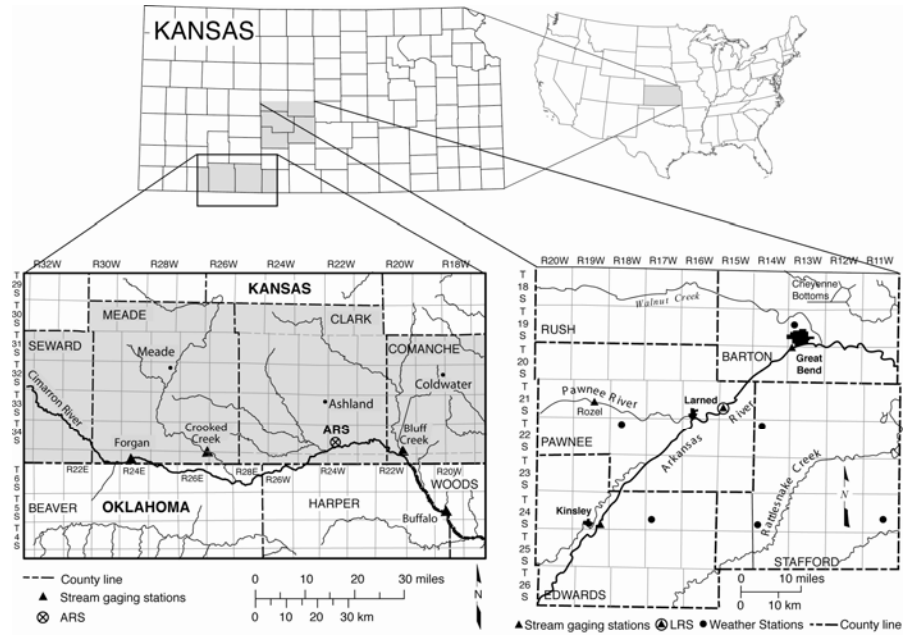


Figure 1 – Location map for sites used in this study.

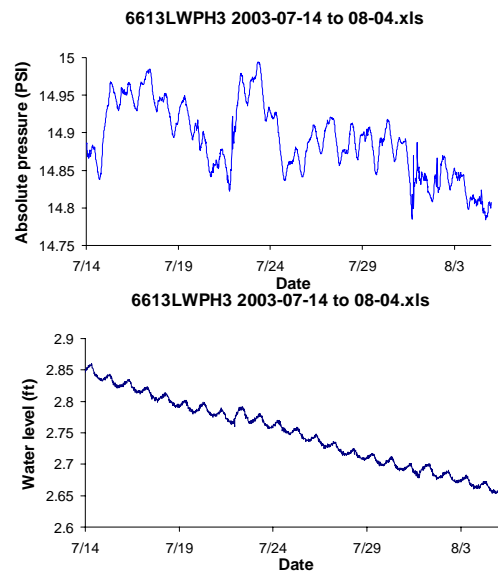


Figure 2 – Barometric pressure correction at LRS well LWPH3.

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 ( $\text{m}^3 \text{m}^{-3}$ ),  $\theta$ , corresponding to each measured count ratio is calculated with the calibration equation  $\theta = 0.2929 \times \text{CR} - 0.0117$ , 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<sub>2</sub>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

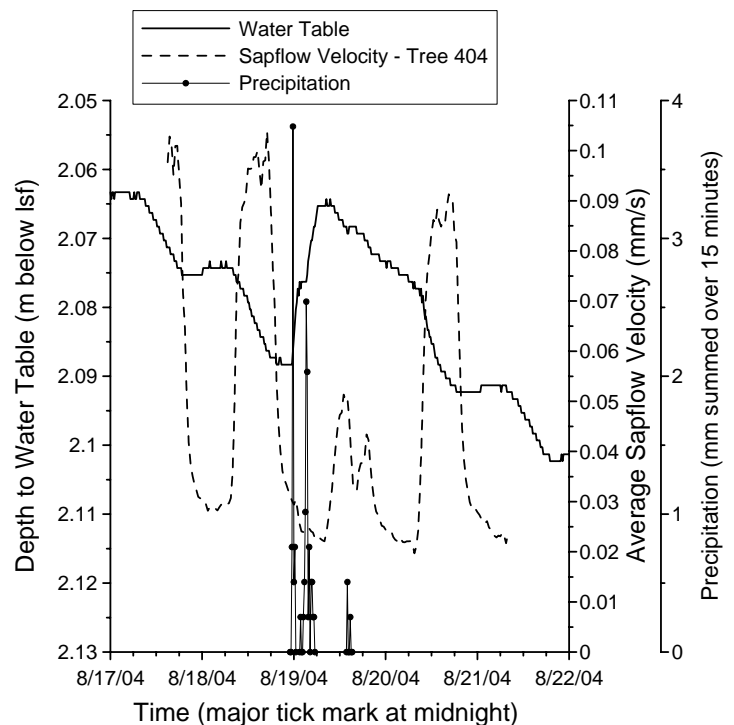


Figure 3A – Depth to water table from land surface at well LWPH2 in LRS with sapflow velocity from nearby cottonwood and precipitation from LRS weather station (from Butler et al., 2007).

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 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

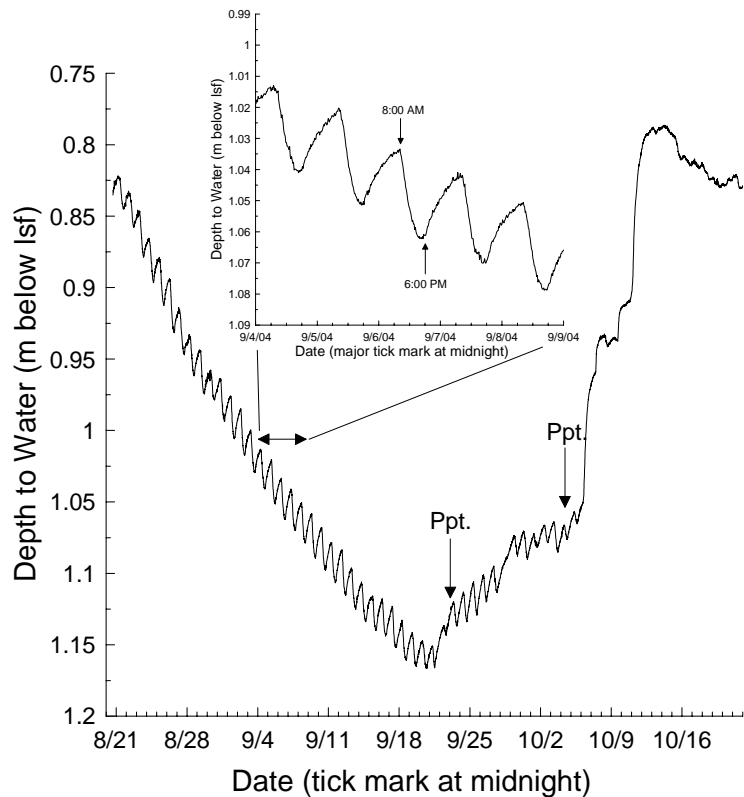


Figure 3B – Depth to water from land surface recorded at ARS well Ash22 from 8/20-10/22/04 (from Butler et al., 2007). Inset is expanded view of five days from the record. Rises in the water table after 9/21 are primarily due to rises in river stage produced by seasonal decreases in upstream irrigation 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).

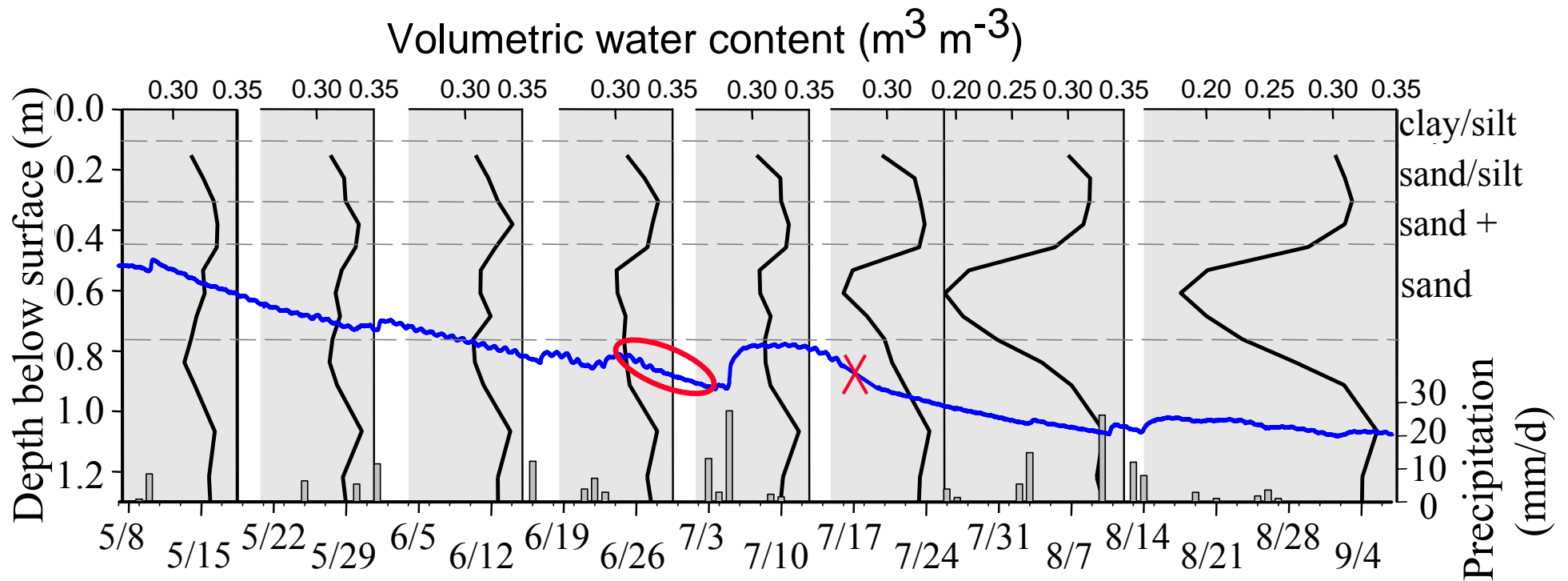


Figure 4A – Depth to the water table from land surface at well Ash31 (blue line, left y-axis) and related data for late spring and summer of 2006. Vertical black lines are volumetric water content (top x-axis) as a function of depth; intercept of the volumetric water content lines with the bottom x-axis 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<sub>2</sub>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

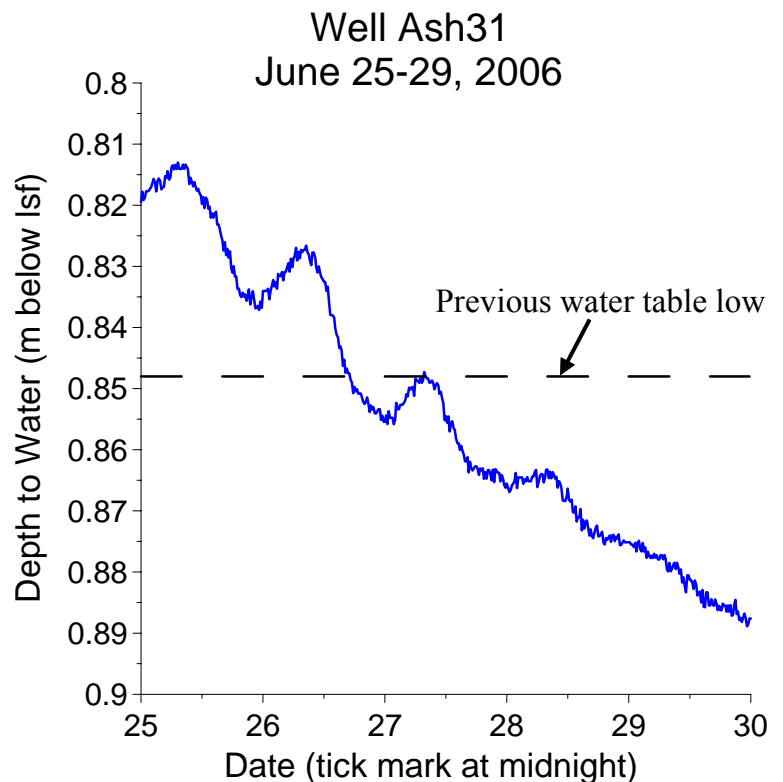


Figure 4B – Depth to the water table from land surface at well Ash31 for the period in late June of 2006 indicated by the ellipse in Figure 4A.

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.

Activity 3: 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.

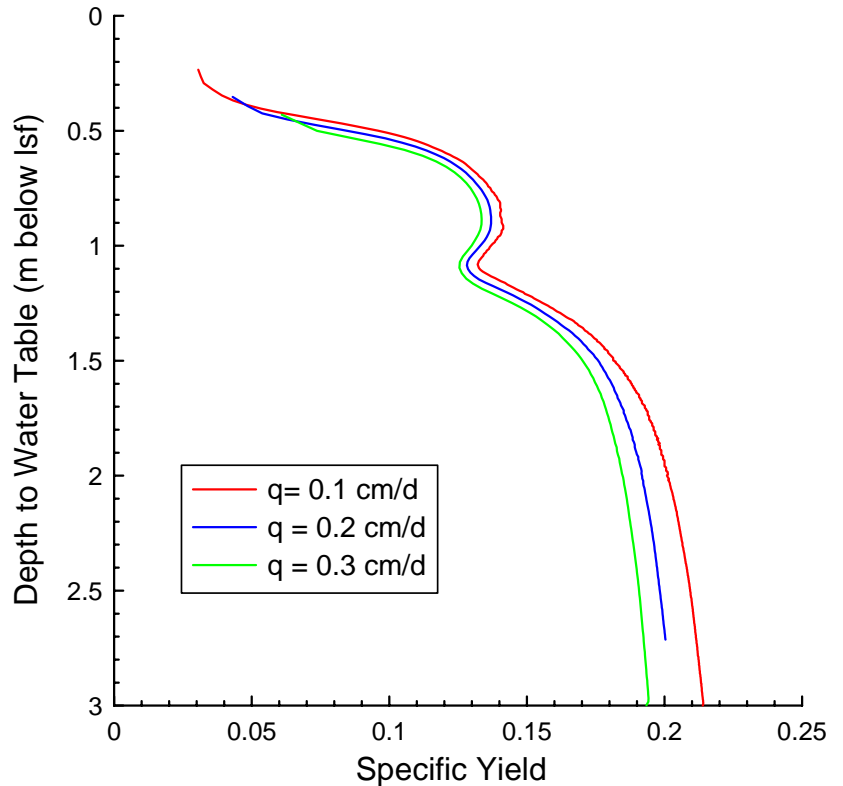


Figure 5 – Example of specific yield ( $S_Y$ ) estimates for the case of a falling water table at well Ash12. Estimates of  $S_Y$  are shown as a function of depth to the water table for three different fluxes ( $q$ ) across the water

Activity 4: 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.

Activity 5: 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.

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

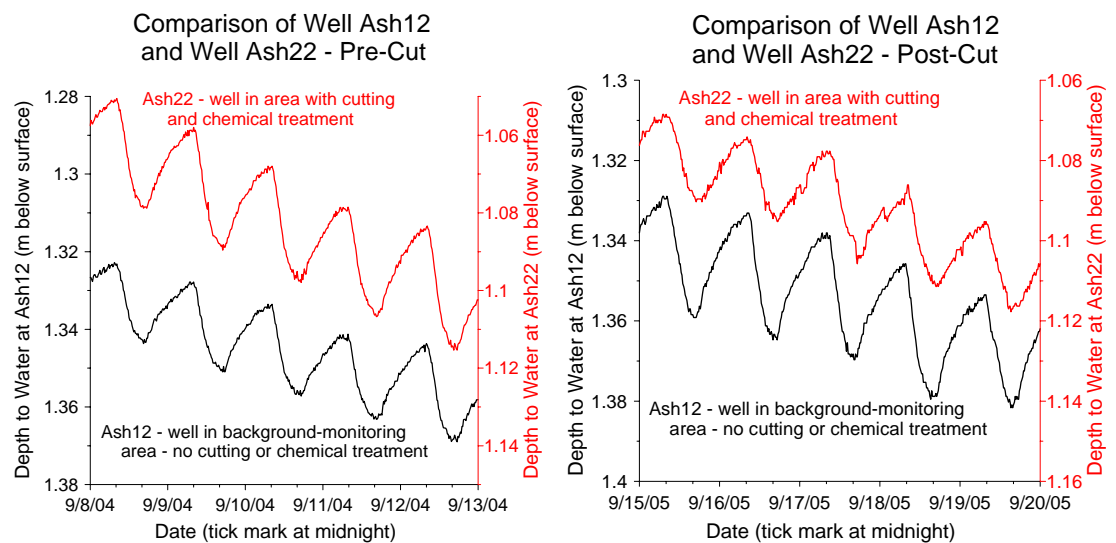


Figure 6 – Depth to the water table from land surface at wells Ash12 and Ash22 prior to (A – left figure) and after (B- right figure) clear cutting all invasive phreatophytes from Plot 2 in August of 2005. Data for Ash12 included to show the pattern of fluctuations observed in Plot 1 where no control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

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.

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

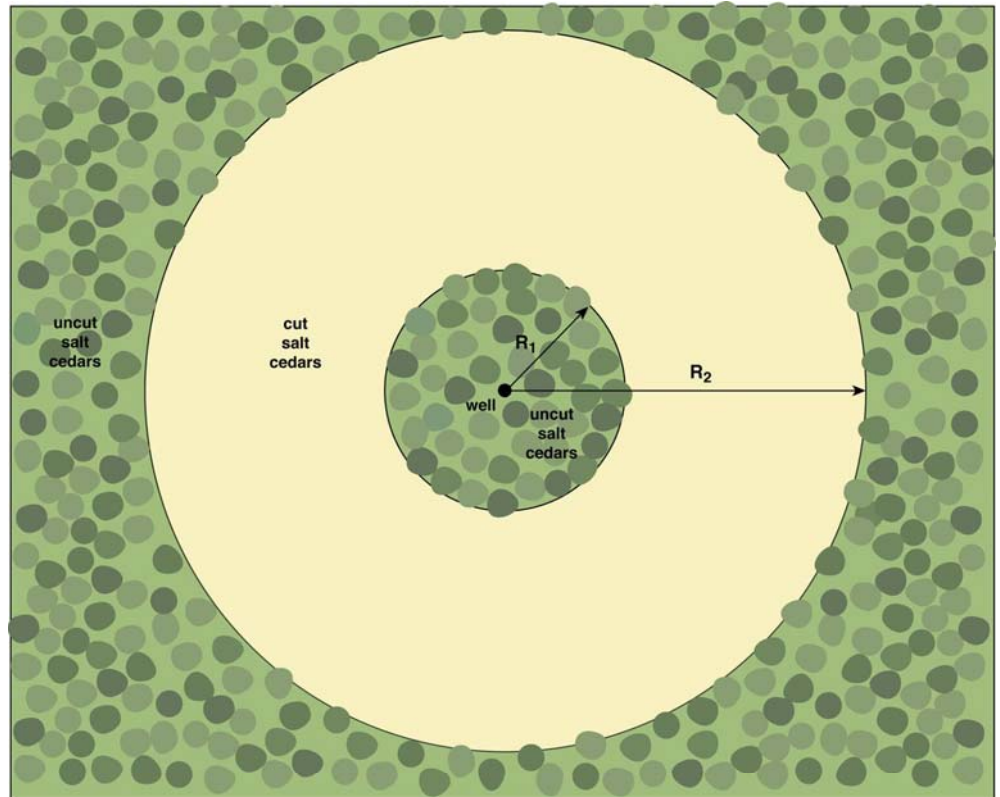


Figure 7A – Schematic areal view of configuration of cut and uncut salt cedars around wells Ash21, Ash22, and Ash31 during the 2005 cutting period (not to scale).

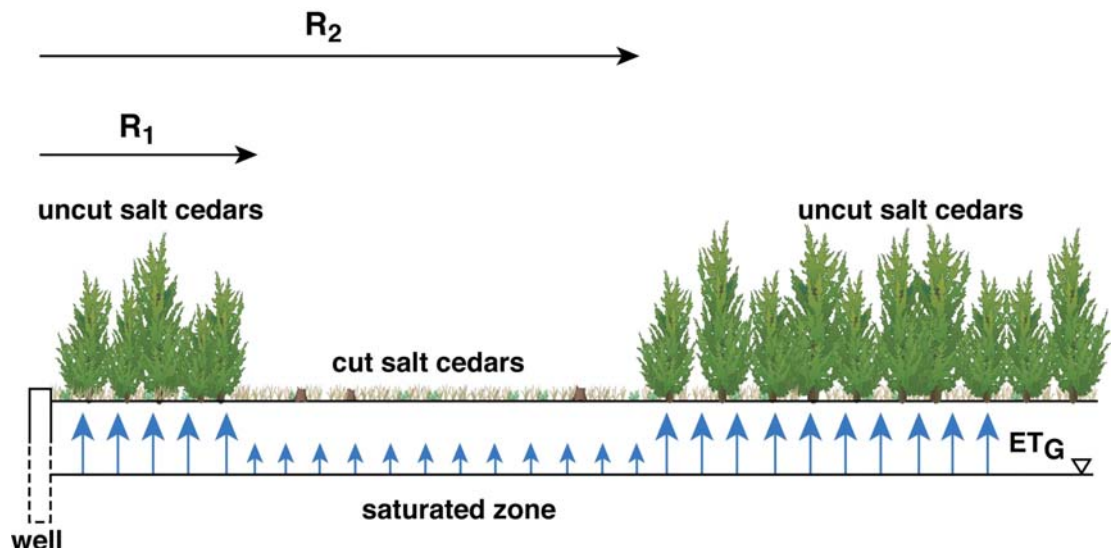


Figure 7B – Schematic cross-sectional view of the vicinity of wells Ash21, Ash22, and Ash31 during the 2005 cutting period (not to scale). Well at left is at center of Figure 7A.  $ET_G$  is the evapotranspirative consumption of ground water, differences in heights of arrows indicate relative differences 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

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

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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## PAPERS AND PRESENTATIONS

- Butler, J.J., Jr., An ecohydrologic investigation of groundwater consumption by phreatophytes, an invited presentation to the Environmental Resources and Policies Program, Southern Illinois Univ., Carbondale, IL, March 8, 2006.
- 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<sub>2</sub>O-TE Sensors**

### **Summary**

On 6/28- 6/30/06, a KGS/KSU research team conducted a field assessment of the Decagon ECH<sub>2</sub>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.

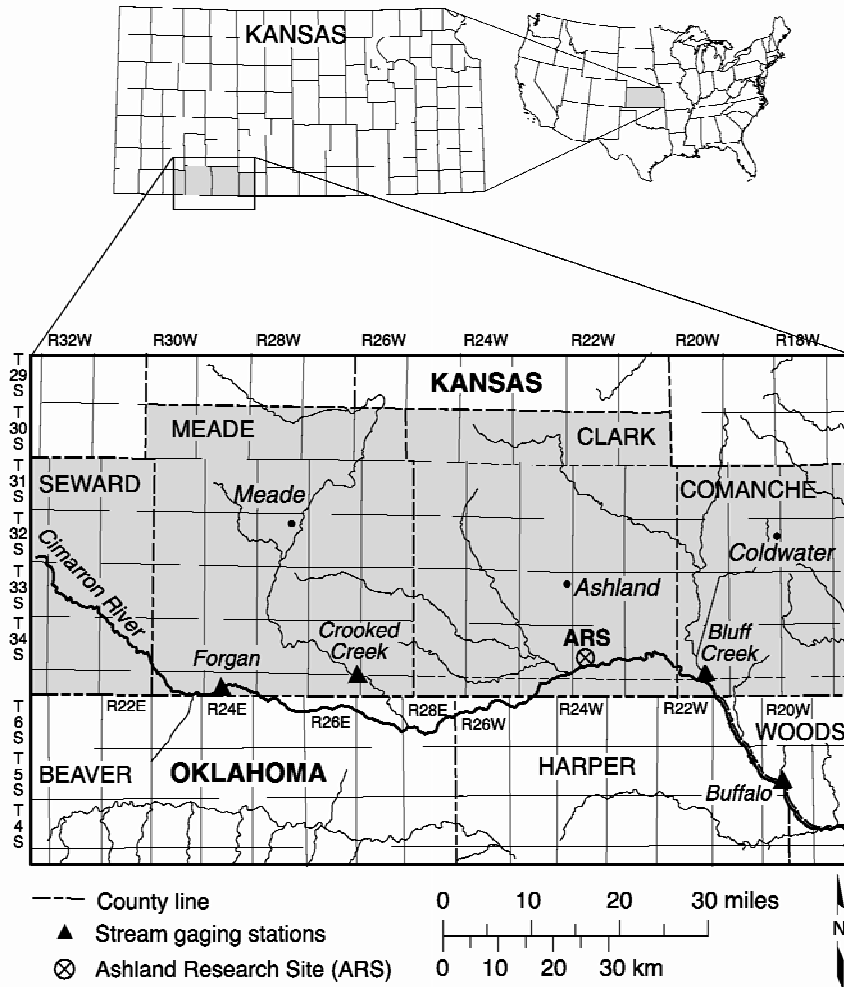


Figure 1 – Location map of the Ashland Research Site (ARS).

## 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<sup>3</sup>, giving a total sample volume of 181 cm<sup>3</sup>. 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.

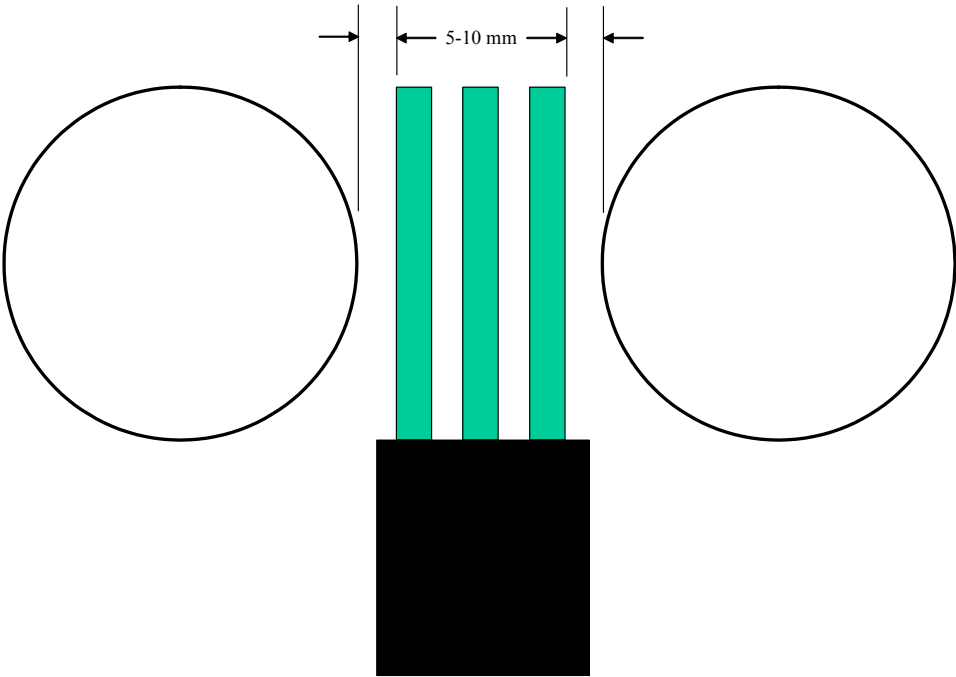


Figure 3 – Top view of sampling rings relative to sensor.



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<sup>3</sup> (mean = 1.57 g/cm<sup>3</sup>). This corresponds to a range of 0.39 to 0.46 in total porosity, if a particle density of 2.65 g/cm<sup>3</sup> 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<sup>3</sup> (mean = 1.41 g/cm<sup>3</sup>), 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<sup>3</sup> (mean = 1.54 g/cm<sup>3</sup>), 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 Isf [inches]	Sensor Average VWC [m3/m3]	Sensor Average Temp [C]	Sensor Average EC [dS/m]	Samples VWC	Absolute Difference	Within Specs?
<b>PIT ASH21</b>							
24	6	<b>0.21</b>	25.30	0.77	<b>0.14</b>	0.07	N
37	12	<b>0.54</b>	23.60	3.09	<b>0.29</b>	0.25	N
39	18	<b>0.81</b>	21.67	4.14	<b>0.42</b>	0.39	N
16	24	<b>0.39</b>	21.47	1.46	<b>0.36</b>	0.03	N
31	30	<b>0.25</b>	21.07	0.39	<b>0.27</b>	0.03	Y
40	6	<b>0.21</b>	21.53	0.78	<b>0.14</b>	0.07	N
33	12	<b>0.69</b>	20.90	3.06	<b>0.33</b>	0.36	N
25	18	<b>0.36</b>	20.53	0.84	<b>0.36</b>	0.00	Y
34	24	<b>0.13</b>	20.52	0.08	<b>0.17</b>	0.04	N
38	30	<b>0.26</b>	20.65	0.65	<b>0.28</b>	0.03	Y
45	6	<b>0.11</b>	21.00	0.43	<b>0.13</b>	0.02	Y
42	12	<b>0.75</b>	20.67	3.57	<b>0.32</b>	0.43	N
18	18	<b>0.14</b>	20.52	0.30	<b>0.31</b>	0.18	N

26	24	<b>0.22</b>	20.35	0.29	<b>0.23</b>	0.00	Y
41	30	<b>0.33</b>	20.50	0.74	<b>0.22</b>	0.10	N
<b>PIT ASH22</b>							
9	6	<b>0.70</b>	26.72	3.22	<b>0.34</b>	0.36	N
30	9	<b>0.27</b>	28.58	0.60	<b>0.21</b>	0.06	N
22	12	<b>0.33</b>	26.12	0.98	<b>0.15</b>	0.18	N
23	15	<b>0.31</b>	26.87	1.21	<b>0.14</b>	0.18	N
21	18	<b>0.41</b>	24.00	1.31	<b>0.16</b>	0.25	N
35	6	<b>0.68</b>	30.37	1.69	<b>0.30</b>	0.39	N
15	9	<b>0.21</b>	29.52	0.33	<b>0.19</b>	0.02	Y
3	12	<b>0.46</b>	28.13	2.55	<b>0.18</b>	0.28	N
12	15	<b>0.35</b>	26.55	1.11	<b>0.16</b>	0.19	N
32	18	<b>0.76</b>	25.22	5.57	<b>0.28</b>	0.48	N
28	6	<b>0.69</b>	23.15	2.45	<b>0.29</b>	0.40	N
8	9	<b>0.38</b>	23.88	1.13	<b>0.22</b>	0.15	N
11	12	<b>0.31</b>	23.07	1.12	<b>0.15</b>	0.16	N
6	15	<b>0.31</b>	22.93	1.41	<b>0.14</b>	0.17	N
10	18	<b>0.73</b>	21.90	5.63	<b>0.26</b>	0.47	N
<b>PIT ASH32</b>							
4	6	<b>0.01</b>	33.60	0.02	<b>0.04</b>	0.03	Y
7	12	<b>0.03</b>	31.13	0.01	<b>0.03</b>	0.00	Y
2	18	<b>0.11</b>	28.42	0.06	<b>0.06</b>	0.05	N
44	24	<b>0.06</b>	27.52	0.03	<b>0.07</b>	0.01	Y
19	30	<b>0.10</b>	25.93	0.04	<b>0.07</b>	0.03	Y
29	36	<b>0.08</b>	25.32	0.04	<b>0.07</b>	0.01	Y
20	42	<b>0.09</b>	24.32	0.09	<b>0.19</b>	0.10	N
1	6	<b>0.14</b>	35.53	0.08	<b>0.06</b>	0.08	N
17	12	<b>0.04</b>	33.38	0.03	<b>0.03</b>	0.01	Y
5	18	<b>0.02</b>	31.05	0.02	<b>0.02</b>	0.01	Y
27	24	<b>0.11</b>	28.72	0.08	<b>0.06</b>	0.05	N
43	30	<b>0.09</b>	25.70	0.05	<b>0.09</b>	0.00	Y
13	36	<b>0.09</b>	25.53	0.04	<b>0.06</b>	0.03	Y
36	42	<b>0.15</b>	25.30	0.16	<b>0.16</b>	0.01	Y
14	12	<b>0.08</b>	33.23	0.13	<b>0.02</b>	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 inches	Elec. cond. 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 inches	Total sand (2.00-0.05 mm)	Total silt (50.0-2.0 $\mu$ m)	Total clay ( < 2.0 $\mu$ m )	Textural class
			----- % -----			
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.

# A Real-Time Permittivity Sensor for Simultaneous Measurement of Multiple Water-Quality Parameters

## Basic Information

<b>Title:</b>	A Real-Time Permittivity Sensor for Simultaneous Measurement of Multiple Water-Quality Parameters
<b>Project Number:</b>	2005KS40B
<b>Start Date:</b>	3/1/2005
<b>End Date:</b>	2/28/2008
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	2
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Water Quality, None, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Naiqian Zhang, Philip Barnes, Gerard J. Kluitenberg, Andrew Ziegler



## **Publication**

**Project Title:**

A Real-time Permittivity Sensor for Simultaneous Measurement of Multiple Water-Quality Parameters

**Start Date:** March 1, 2006

**End Date:** February 28, 2007

**Investigators and Affiliations:**

Naiqian Zhang, Professor, Biological and Agricultural Engineering Department, Kansas State University

**Keywords:** Sensor, Water Quality, Water Contaminants, Nutrient, Pesticide.

## Problem and Research Objectives

This is the second year of the project. The main objective of the research work is to develop a novel, frequency-response permittivity sensor to measure multiple properties of surface and ground water that are crucial to water quality.

## Methodology

### 1. Sensor improvement

Considering the effect of corrosion on measurement, we made two new sensors using aluminum alloy and stainless steel (Figure 1). Geometry of the sensor probe was modified to further enhance the capacitive effect. Sealing of the probe was also improved to achieve complete waterproof.



Figure 1. Sensor probes made of (a) aluminum alloy and (b) stainless steel

### 2. Hardware design

A printed circuit board (Figure) was designed and fabricated. User interface with a keypad and a LCD screen was also designed. The hardware was integrated into a portable box (Figure 3), which was designed for field tests.

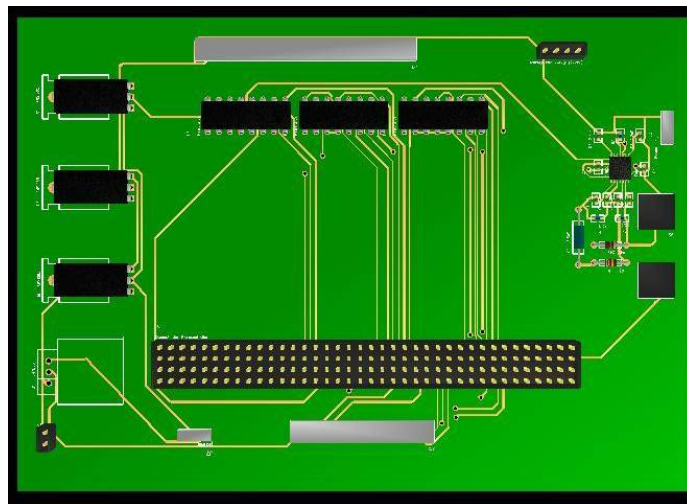


Figure 2. Printed Circuit Board for signal processing



**Figure 3. Signal conditioning/processing and user interface**

### **Significant Findings**

Four water tests were conducted for the sensor. Findings from the tests are reported below.

#### *1. Test in three separate Potassium solutions*

A modified sensor probe (Figure 1) was tested in water solutions of three potassium salts,  $\text{KNO}_3$ ,  $\text{KH}_2\text{PO}_4$ , and  $\text{KCl}$ . The experiment was conducted in two steps. During the first step, we tested the solutions in high salt concentrations (3,500 – 35,000 ppm). The goal was to identify FR signatures of individual cation and anions. For each salt, 11 solution samples with increasing concentration were prepared in deionized water. Frequency-response data were then taken three times using the sensor. Calibration models for predicting the salt concentrations were established for individual salts. Results are shown in Table 1.

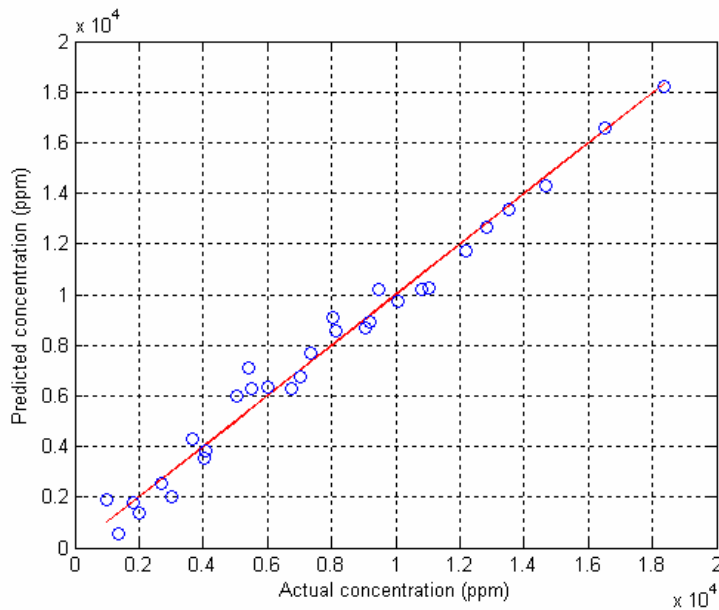
**Table 1. Prediction results for three salt solutions at high concentrations  
(3,500 – 35,000 ppm)**

Salt type	R-square value	RMS error (ppm)
$\text{KH}_2\text{PO}_4$	0.9985	390
$\text{KNO}_3$	0.9848	1273
$\text{KCl}$	0.9927	857

In order to test the sensor's ability to recognize specific ions in water solutions, FR data for all three salts were combined to establish PLS models to quantitatively predict individual ions. The results are shown in Table 2. The prediction results for potassium ion across three salt types are shown in Figure 4.

**Table 2. Prediction results for ions and cation in three salt solutions at high concentrations (3,500 – 35,000 ppm)**

Anion/Cation	R-square	RMS error (ppm)
K <sup>+</sup>	0.9801	640
Cl <sup>-</sup>	0.9532	1109
NO <sub>3</sub> <sup>-</sup>	0.9649	1238
PO <sub>4</sub> <sup>-</sup>	0.8323	3078



**Figure 4. Prediction result for potassium ion concentration in three high-concentration salt solutions**

The second step of the experiment was to test salt solutions at low concentrations (0-4 ppm). The salt tested was potassium nitrate. Samples of 11 concentrations were prepared using a dilution procedure. Three independent sets of samples were prepared. One set was used for calibration; the others for validation. The results are shown in Table 3. These results prove that the sensitivity of the sensor is sufficient for measuring nutrient residual in water at the environmentally- and physiologically-relevant concentration level.

**Table 3. Prediction results for K<sup>+</sup> in three salt solutions at low concentrations (0-4 ppm)**

Data set	R-square	RMS error (ppm)
Training data set	0.9988	0.041
Validation data set 1	0.9217	0.775
Validation data set 2	0.8710	1.408

#### Frequency signature

Conventional multivariate analysis tools, such as partial least square (PLS) method, have been proven effective in spectroscopic data analysis. In order to reduce the number of frequencies used in the model, “signature frequencies” for a specific agent, at which the frequency response of the agent possesses distinguishable patterns from other agents, should be selected. One way to select the signature frequencies is to locate the peaks (both positive and negative) in the loading factors (principal components) derived from the PLS analysis for that specific agent.

From the first three principal components (PC) derived from the PLS analysis on potassium cation (K<sup>+</sup>) using 33 solution samples of KCl, KNO<sub>3</sub>, and KH<sub>2</sub>PO<sub>4</sub> (11 samples for each), 30 signature frequencies were selected from 606 frequencies originally used in the FR data. PLS models established using the 30 signature frequencies were tested in samples of individual and combined salt solutions to predict the concentrations of potassium cation (K<sup>+</sup>). As shown in Table 4, the 30 signature frequencies did a very good job in detecting the cation concentration with high R<sup>2</sup> values and low RMS errors, especially for the KCl and KH<sub>2</sub>PO<sub>4</sub> solutions. This result indicates that, once correctly identified, the signature frequencies can be used to detect specific ions in water samples with unknown pollutants. The reduced number of frequencies would not only speed up the measurement, it would also avoid overfitting of the prediction models.

**Table 4. Prediction results for K<sup>+</sup> in different salt solutions using a PLS model established based on 30 “signature frequencies”**

Solutions tested	Number of samples tested	R <sup>2</sup>	RMS error (ppm)
KCl	11	0.9909	503
KNO <sub>3</sub>	11	0.8084	4401
KH <sub>2</sub> PO <sub>4</sub>	11	0.9999	25
KCl, KNO <sub>3</sub> , and KH <sub>2</sub> PO <sub>4</sub>	33	0.9071	1383

When the 30 signature frequencies obtained using high-concentration solutions were used to predict low-concentration (0-4 ppm) KNO<sub>3</sub> solutions, the R<sup>2</sup> value for the training data set was basically unchanged. For validation, the R<sup>2</sup> value slightly decreased for data set 2 but increased for data set 3 (Table 5). The difference between these two was greatly reduced. This demonstrates the effectiveness of the frequency signature in describing the FR patterns of specific types of ions and in avoiding model overfitting.

**Table 5. Effectiveness of frequency signature in reducing the number of frequencies while achieving better prediction for low concentration (0-4ppm) KNO<sub>3</sub>.**

Data set	Data set 1 (Training)		Data set 2 (Validation)		Data set 3 (Validation)	
Frequencies used	606 (original)	30 (Signature)	606 (original)	30 (Signature)	606 (original)	30 (signature)
R <sup>2</sup> values	0.9991	0.9992	0.9560	0.9153	0.8207	0.9140

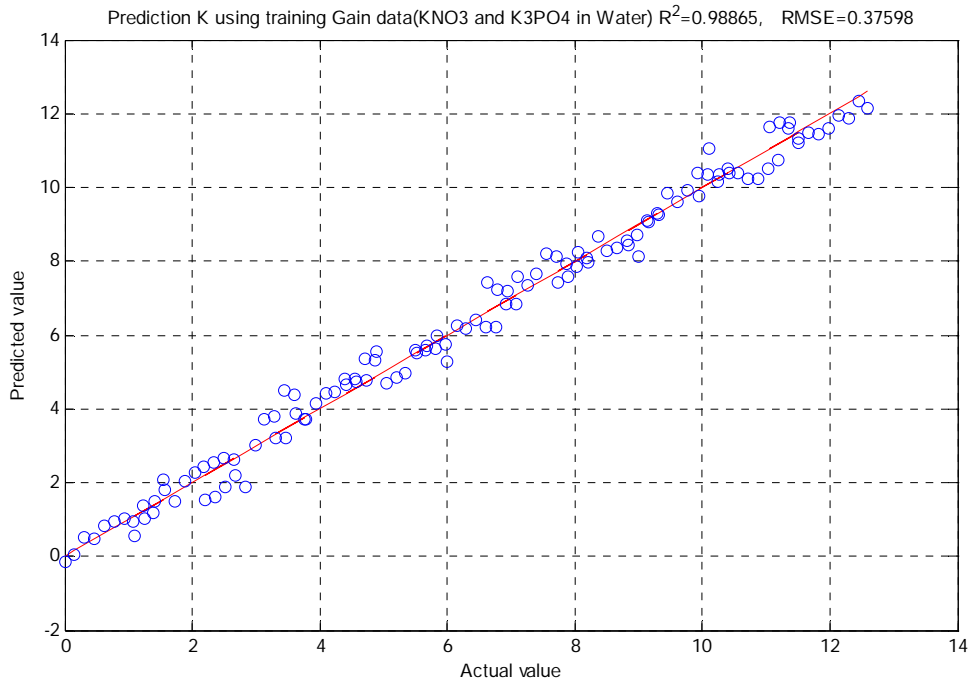
2. Detecting potassium ion in mixed salt solutions

Two sets of 121 mixed Potassium Phosphate (K<sub>3</sub>PO<sub>4</sub>) and Potassium Nitrate (KNO<sub>3</sub>) solutions were prepared by blending 11 Potassium Phosphate solutions (0-20ppm) with 11 Potassium Nitrate solutions (0-4 ppm). One set was used for training and the other validation. Models were established to predict the concentration of potassium ions in the mixed solutions. The results are list in table 6. Figures 5 and 6 demonstrate the prediction results for potassium ion for the training and validation data sets, respectively.

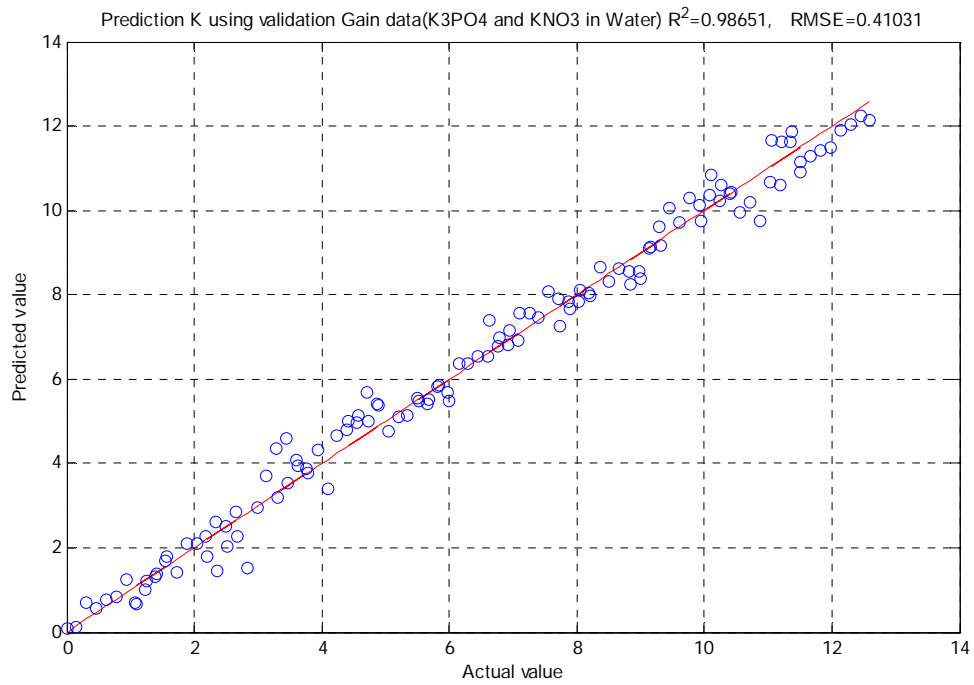
It can be noted from Table 6 that, when 30 “signature frequencies” were used, high prediction accuracy was maintained.

**Table 6. Predicting potassium ion concentration in mixed salt solutions**

	Data type	R-square	RMS error (ppm)
Training	Gain	0.9887	0.376
	Gain (30 “signature frequencies”)	0.9708	0.603
	Phase	0.9878	0.390
	Gain and phase	0.9885	0.379
Validation	Gain	0.9886	0.410
	Gain (30 “signature frequencies”)	0.9645	0.679
	Phase	0.9880	0.430
	Gain and phase	0.9878	0.436



**Figure 5. Prediction K<sup>+</sup> using training gain data**



**Figure 6 Prediction K<sup>+</sup> using validation gain data**

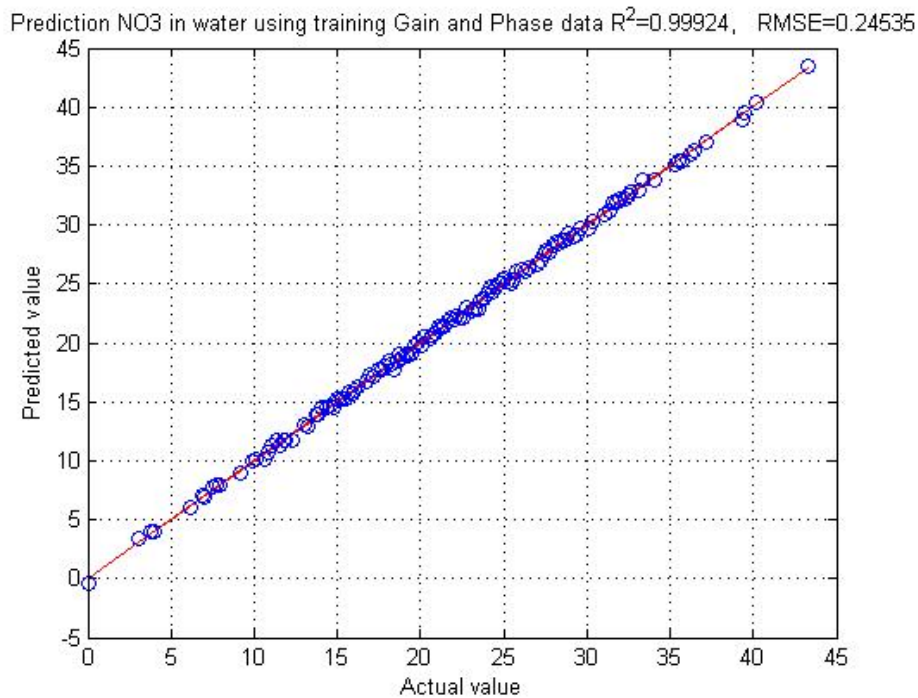


3. Simultaneously detecting nitrate and three salts in mixed salt solutions

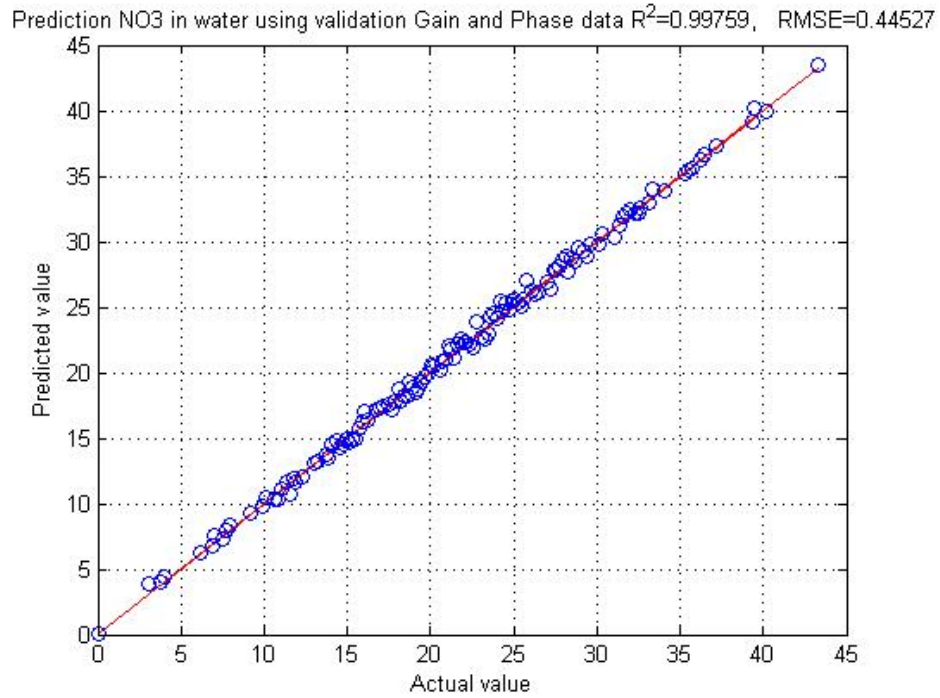
Two sets of 125 mixed salt solutions were prepared. These included combinations of five Potassium Nitrate ( $KNO_3$ ) concentrations, five Calcium Nitrate ( $Ca(NO_3)_2$ ) concentrations, and five Ammonium Nitrate ( $NH_4NO_3$ ) concentrations. The five concentrations were 0, 5, 10, 15, and 20 ppm. One set of the 125 mixed solutions were used as the training data set, where as the other for validation. The goal was to predict the nitrate concentration, as well as concentrations of Potassium Nitrate, Calcium Nitrate, and Ammonium Nitrate, simultaneously, in all samples. The results are shown in Tables 7 through 10. Figure 8 shows the prediction using both gain and phase training data.

**Table 7. Predicting Nitrate concentration in blends of three salt solutions**

Data set		R-square	RMSE (ppm)
Training	Gain	0.9987	0.320
	Phase	0.9990	0.284
	Gain+Phase	0.9992	0.245
Validation	Gain	0.9973	0.481
	Phase	0.9971	0.484
	Gain+Phase	0.9976	0.445



**Figure 7. Prediction result using both gain and phase data for the training data set**



**Figure 8. Prediction result using both gain and phase data for the validation data set**

**Table 8. Predicting Potassium Nitrate concentration in blends of three salt solutions**

Data set		R-square	RMSE (ppm)
Training	Gain	0.9001	2.235
	Phase	0.6887	3.945
	Gain+Phase	0.8805	2.444
Validation	Gain	0.5744	4.894
	Phase	0.4322	5.954
	Gain+Phase	0.6380	4.386

**Table 9. Predicting Calcium Nitrate concentration in blends of three salt solutions**

Data set		R-square	RMSE (ppm)
Training	Gain	0.9025	2.207
	Phase	0.8278	2.934
	Gain+Phase	0.8757	2.493
Validation	Gain	0.6488	4.447
	Phase	0.5663	4.727
	Gain+Phase	0.6464	4.220

**Table 10. Predicting Ammonium Nitrate concentration in blends of three salt solutions**

Data set		R-square	RMSE (ppm)
Training	Gain	0.9704	1.217
	Phase	0.9564	1.476
	Gain+Phase	0.9632	1.357
Validation	Gain	0.8794	2.817
	Phase	0.8828	2.943
	Gain+Phase	0.8960	2.819

It can be seen from Tables 7-10 that the prediction result is better for nitrate than for the potassium, calcium, and ammonium ions. This is probably because that nitrate is the only anion in the mixed solutions, whereas all other ions are all cations. It is more difficult to discriminate between same types of ions because their roles in ionic conduction are similar. However, more accurate detection of individual types of ions is possible if “signature frequencies” for individual ion types are identified. We will further work in this area.

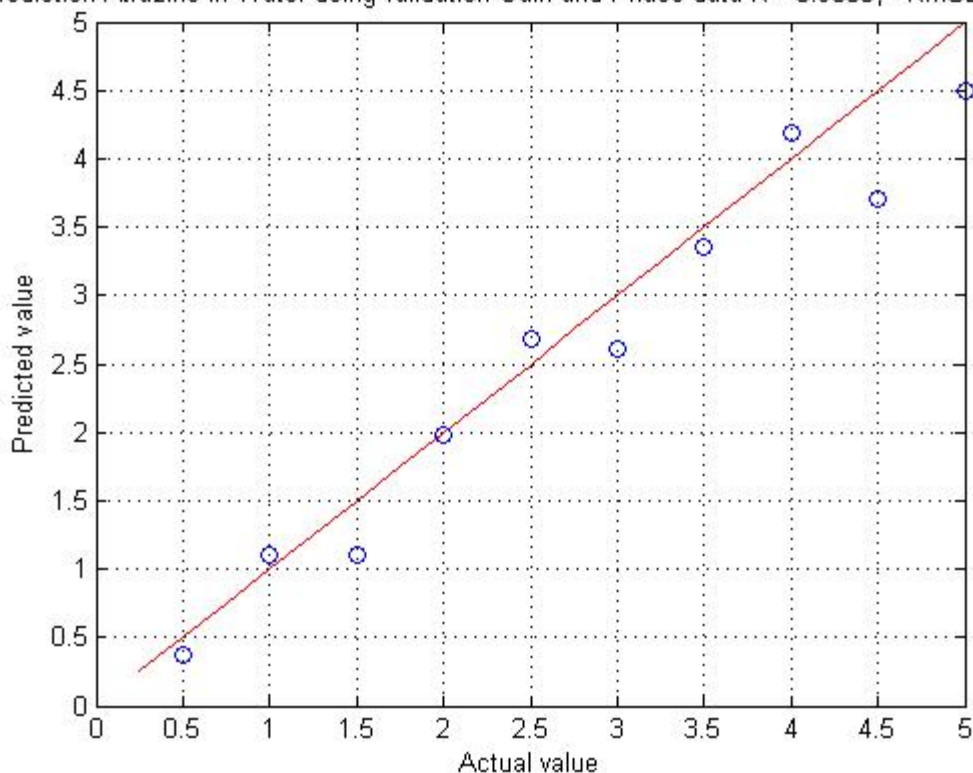
#### 4. Measuring atrazine concentration in water

Water solutions of atrazine at 10 concentrations (0-5 ppm) were tested using the sensor. Two sets of samples were prepared for training and validation purposes, respectively. Results shown in Table 11 and Figure 9 are promising.

**Table 11. Predicting Ammonium Nitrate concentration in blends of three salt solutions**

Data set		R-square	RMSE (ppm)
Training	Gain	0.9949	0.103
	Phase	1.0000	0.001
	Gain+Phase	1.0000	0.002
Validation	Gain	0.9694	0.396
	Phase	0.9456	0.375
	Gain+Phase	0.9558	0.365

Prediction Atrazine in Water using validation Gain and Phase data  $R^2=0.9558$ ,  $RMSE=0.3652$



**Figure 9. Predicted and actual atrazine concentrations (ppm) in deionized water for the validation data set.**

#### **Publications and Presentations**

Zhang, N. 2007. Invited speech: "The potential of a novel frequency-response permittivity sensor in measuring soil and water properties". Proceedings of the Dahlia Greidinger Symposium 2007, "Advanced Technologies for Monitoring Nutrient and Water Availability to Plants". March 12-13, Haifa, Israel.

#### **Information Transfer**

U.S. Patent (Pending):

Zhang, N. "Frequency-response sensors and associated signal conditioning/processing for real-time and simultaneous measurement of multiple properties of dielectric materials", 2007.

#### **Student Support**

Ning Tang: Graduate Research Assistant, studying for M.S. degree in BAE.

# Fate of Nitrate Beneath Fields Irrigated with Treated Wastewater in Ford County, Kansas Using Field Data and Preferential Flow Modeling -- Year 3

## Basic Information

<b>Title:</b>	Fate of Nitrate Beneath Fields Irrigated with Treated Wastewater in Ford County, Kansas Using Field Data and Preferential Flow Modeling -- Year 3
<b>Project Number:</b>	2005KS45B
<b>Start Date:</b>	3/1/2005
<b>End Date:</b>	2/28/2008
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	2nd
<b>Research Category:</b>	Biological Sciences
<b>Focus Category:</b>	Models, None, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Marios Sophocleous, Margaret A. Townsend, Fred Vocasek, Tom Willson, John Zupanic

## Publication

1. Sophocleous, M. A., Townsend, M. A., Willson, T., and Vocasek, F., 2006, Fate of nitrate beneath fields irrigated with treated wastewater in Ford County, Kansas: 23'd Annual Water and the Future of Kansas Conference, Topeka, KS, March 16,2006.
2. Sophocleous, M. A., Townsend, M. A., Willson, T., and Vocasek, F., 2006, Preferential flow and transport of nitrate beneath fields irrigated with treated wastewater in Ford County: Geological Society of America, GSA Abstracts with Program, v. 38, no. 7, p. 40
3. Townsend, M. A., Macko, S. A., Sophocleous, M. A., Vocasek, F., Schuette, D., and Ghijsen, R., 2006, Documenting seasonal variation at a wastewater irrigation site through stable isotopes: Geological Society of America, GSA Abstracts with Program, v. 38, no. 7, p. 40.
4. Sophocleous, M. A., Townsend, M. A., and Vocasek, F., 2007, Treated wastewater and nitrate transport beneath irrigated fields near Dodge City, Kansas: Water and the Future of Kansas Conference, March 15,2007, Topeka, KS.
5. Townsend, M. A., Macko, S. A., Sophocleous, M. A., Vocasek, F., Schutte, D., and Ghijsen, R., 2007, Variations in water chemistry and plant uptake of nitrogen at a wastewater irrigation site: Water and the Funlre of Kansas Conference, March 15, 2007, Topeka, KS.

# Treated Wastewater and Nitrate Transport Beneath Irrigated Fields near Dodge City, Kansas

Marios Sophocleous<sup>1</sup>, Liwang Ma<sup>2</sup>, Margaret Townsend<sup>1</sup>, Fred Vocasek<sup>3</sup>, Ashok KC<sup>1</sup>, John Willson<sup>4</sup>, and David Schuette<sup>3</sup>

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**Lawrence, KS, June 2007**

Second-year Progress Report to KWRI  
(March 1, 2006 – February 28, 2007)

**Keywords:** wastewater fertigation; dye tracer; macropores; RZWQM model; sensitivity analysis; nitrogen use efficiency; nitrogen management scenarios

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- 6. Student Support**
- 7. Acknowledgments**
- 8. References**

# Treated Wastewater and Nitrate Transport Beneath Irrigated Fields near Dodge City, Kansas

Marios Sophocleous<sup>1</sup>, Liwang Ma<sup>2</sup>, Margaret Townsend<sup>1</sup>, Fred Vocasek<sup>3</sup>, Ashok KC<sup>1</sup>, John Willson<sup>4</sup>, and David Schuette<sup>3</sup>

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<sup>3</sup> Servi-Tech Agri/Environmental Consulting Services, Dodge City, KS

<sup>4</sup> Formerly at Kansas State University, Garden City Experiment Station

## 1. Problem and Research Objectives

With increasingly limited ground-water resources, reuse of treated wastewater provides an alternative source of water for irrigation of crops and landscaping. In addition, utilization of the nutrients in recycled wastewater as fertilizer results in less application of fertilizer to a plant system.

A long-term irrigation project using treated municipal wastewater has been ongoing south of Dodge City in Ford County since the mid-1980s (Fig. 1). The Dodge City Wastewater Treatment Plant (DCWTP) consists of three covered anaerobic digesters and three aeration basins. The treated water is stored in storage lagoons with a capacity of more than 2800 acre-ft. A pumping system, consisting of several electric, centrifugal pumps distributes the water to irrigate more than 2700 acres of cropland in 25 fields (Fig. 1). The system is managed by Operations Management International (OMI) and the agronomic firm Servi-Tech, Inc., under contracts with the City.

Use of the treated wastewater, which includes inputs from both the municipality of Dodge City and its meat-packing plant, has resulted in relatively high soil nitrate-nitrogen concentrations (10–50 mg/kg) in the soil profile at the sites irrigated with this treated wastewater effluent as well as in nitrate-nitrogen concentrations in ground water from monitoring wells in the area exceeding the safe drinking-water limit of 10 mg/L (Zupancic and Vocasek, 2002). Evaluation of the environmental impact of such land-use strategies needs to be made in order to determine if and when this process may impact usable ground water at depth and what management changes may need to be made to slow the downwards nitrogen (N) migration.



The study area overlies the High Plains aquifer with depth to water in the range of 75 to 150 ft. The overlying soils are predominantly Harney and Ulysses silt loams (Dodge et al., 1965). Although this area has a deep water table and soils with a silty clay component, there is evidence that nitrate is migrating to those depths through the vadose zone. USGS National Water-Quality Assessment and other studies in the central High Plains aquifer region indicate that nitrate from fertilizer sources and animal waste has reached the Ogallala portion of the High Plains aquifer most likely due to increased recharge from irrigation but also because of preferential flow processes (U.S. Geological Survey, 2004).

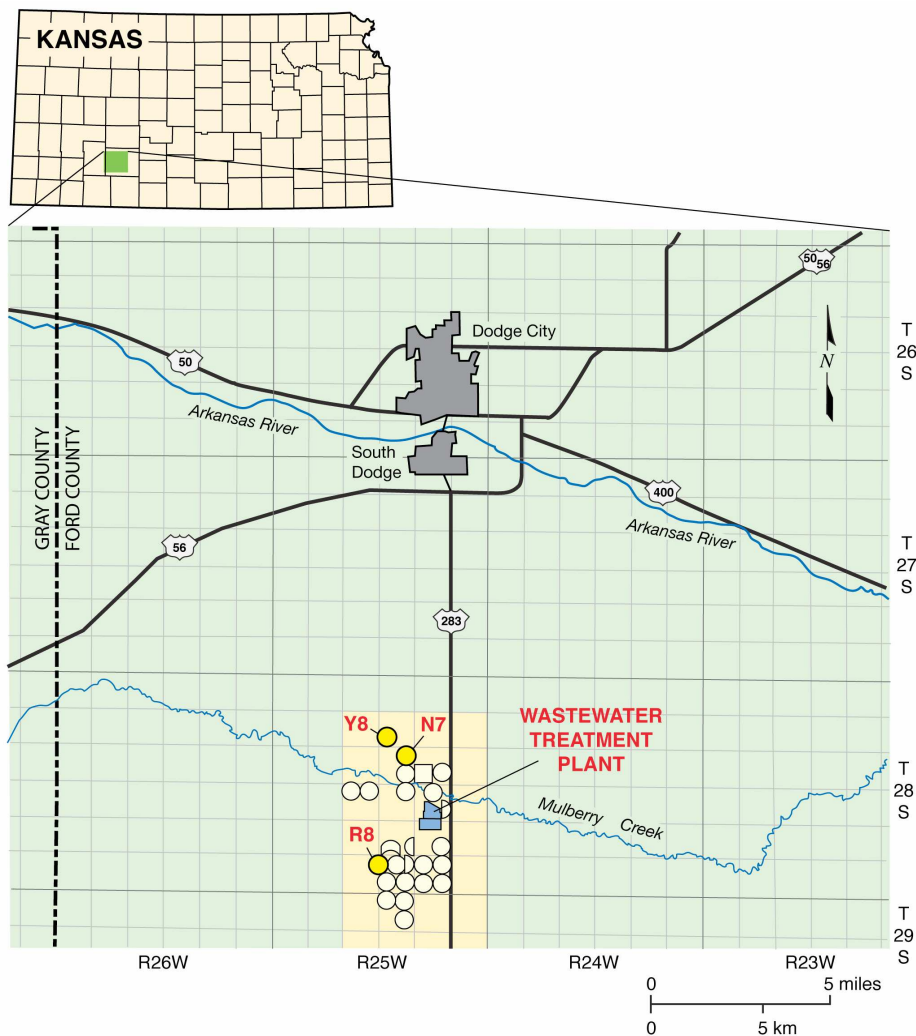


Figure 1. Location of the study area. Circular areas indicate irrigated fields.

It is now generally recognized that preferential flow occurs to some degree in most soils (Shipitalo and Edwards, 1996). In some soils, macropores can serve as important pathways for preferential flow that allow rapid gravitational flow of the free water available at the soil surface or above an impeding soil horizon, thus bypassing the soil matrix. Short-circuiting to ground water through macropores is of serious concern because of the possibilities of rapid transport of a portion of fertilizers, pesticides, and other chemicals applied on the soil surface. As macropore development, preservation, and continuity can be strongly affected by soil management, such concerns have been exacerbated by the growing practice of minimum or no tillage, which (1) allows chemical solutes in surface water applied on the soil to accumulate and to enter macropores at the surface, and (2) leaves plant residues on the surface as well as no tillage also enhancing worm activity and allowing worm holes and other macropore channels to stay open at the surface (Ahuja et al., 1993).

Therefore, the objectives of this project are

- 1) to conduct field sampling and other analyses to study and document the impact of treated wastewater irrigation in the area south of Dodge City; and
- 2) to employ sophisticated numerical modeling of N fate and transport that also account for preferential flow to identify key parameters and processes that influence N losses, thus facilitating evaluation of the environmental impact of different land-use practices.

## **2. Methodology**

### **2.1 Field Monitoring/Field Experiments**

To analyze this nitrogen-leaching problem further, we established two main monitoring sites, one in each of the two major loess-derived soil series in the project area, the Harney and the Ulysses soils (Fig. 2; the Harney silt loams are the bluish and greenish colors in the slide, whereas the Ulysses silt loams are the reddish and purplish colors). One of the sites, the R8 in Harney soils, has a long-term treated wastewater irrigation history (since 1986), whereas the other site, N7 in Ulysses soils, has a short-term treated

wastewater irrigation history (since 1998). In addition, a third, control site, Y8, without any wastewater irrigation record, has also been established (Fig. 2). Crop-history records indicate that corn (*Zea mays* L.) was planted at site N7 each year since 1998, and at site R8 since 2003. From 1997 to 2002, site R8 was planted in alfalfa (*Medicago sativa*). During 2005, sites N7 and R8 were planted in corn, whereas site Y8 was planted in sorghum (milo). During 2006, all three sites were planted in corn.

We collected several deep cores, down to 15.2 m, from each of the sites for a number of physical and chemical analyses using a truck-mounted Giddings probe. The textural, soil hydraulic, and additional physical and chemical analyses were performed by NRCS personnel at the Lincoln, NE, National Soils Laboratory. Core nitrogen and carbon and related analyses were conducted at the KSU and Servi-Tech Soil Analysis Laboratories. Tables and figures of analyzed values are presented in Sophocleous et al. (2006) and are summarized by model simulation layer in section 2.3.

The soil bulk density down to 15.2 m was determined from collected cores of known diameter by cutting the core in 15.2-cm (6-inch) increments, weighing them in the field, and then oven-drying them in the lab. For a smoother bulk density profile estimation, a three-consecutive 15.2-cm core-sample moving average was obtained down to 15.2 m.

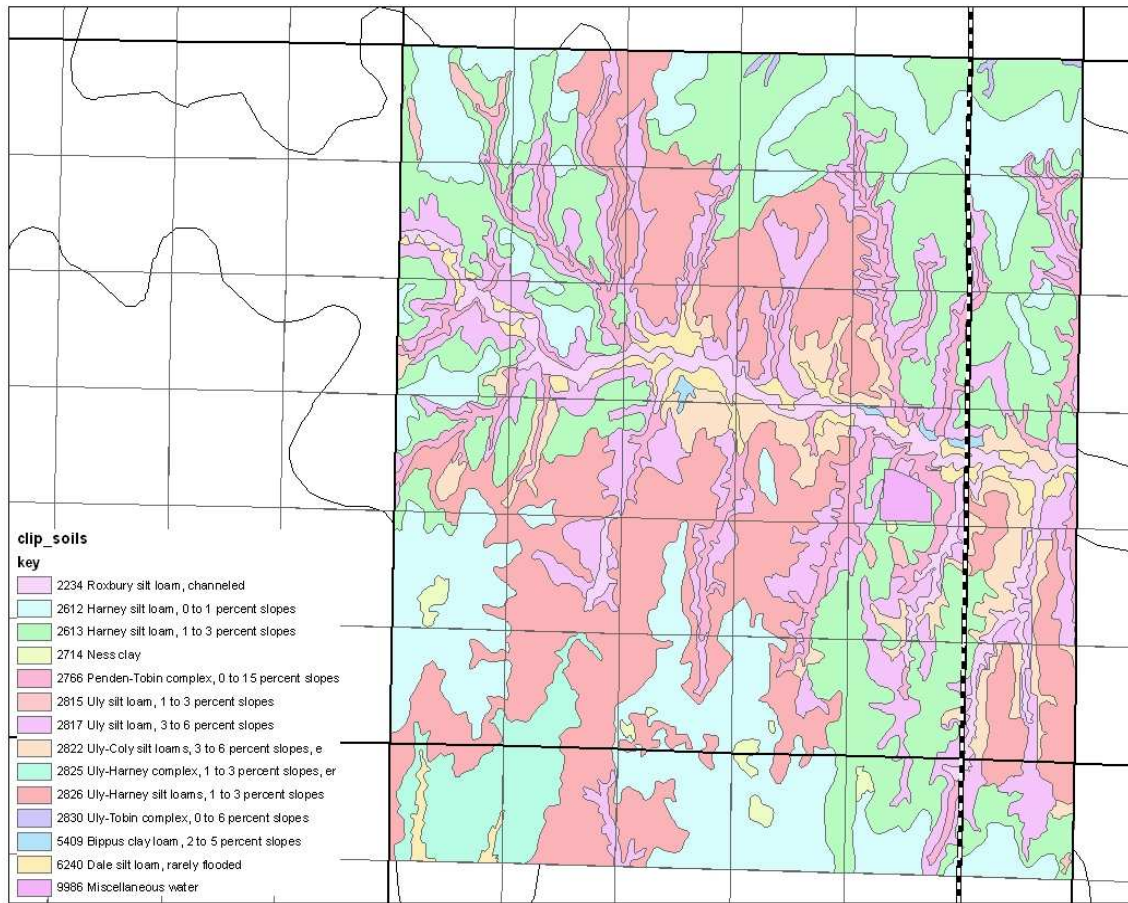


Figure 2. Map of soils in Ford County at study sites (data downloaded from the NRCS Geospatial Data Gateway at <http://soildatamart.nrcs.usda.gov>).

A neutron probe (Campbell Pacific Nuclear (CPN) 503DR Hydroprobe) is used to collect moisture-data profiles to 15.2-m depth. Aluminized steel pipe was used for the neutron probe access tube. The neutron probe was calibrated in the field as follows: a 15.2-m hole was cored with the Giddings probe, and the access tube was snugly inserted down the hole. The collected core was cut in 15.2-cm increments, weighed in the field, and taken to the Servi-Tech, Inc., soils lab for oven-drying and re-weighing. Following access-tube installation, neutron profile readings were taken in 15.2-cm increments within the root zone (180 cm) and in 30.48-cm increments from the bottom of the root zone to 15.2 m. At each site, two field corner (180- by 180-cm) plots were selected as additional calibration plots in which a 305-cm access was installed in each. One plot was used for the neutron-moisture calibration at the dry end-end of the moisture range, whereas the other plot was periodically wetted by applying measured amounts of water

for neutron probe calibration at the wet end of the moisture range. Periodically, 244-cm-long cores were collected from within the corner, calibration plots were done with the Giddings probe, and moisture content was calculated by oven-drying for comparison with neutron readings. Additional details of neutron access tube installation and probe calibration are presented in Sophocleous et al. (2006). Periodic measurements of neutron probe-based soil water content down to 15.2 m were conducted throughout the growing seasons for 2005 and 2006.

A small number of suction lysimeters were also installed in all sites at various depths, mainly at shallow (152–183 cm) and intermediate depths (518–793 cm) for occasional analyses of pore waters.

We also sampled most of the existing monitoring wells in the area (shown in Fig. 9) to check any impacts on the relatively deep water table, which ranges from about 21 m close to Mulberry Creek to more than 45 m deep as one goes away from the usually dry Mulberry Creek (Fig. 1). Additional water samples from monitoring, domestic, and irrigation wells and wastewater lagoons were periodically collected by OMI and occasionally KGS personnel.

To explain deep occurrences of nitrogen concentrations through possible preferential pathways, we conducted two dye-tracer experiments in each of the two major soil types in the study area in which we established our study sites (site R8 in Harney soil, and site N7 in Ulysses soil). A literature search for a suitable dye tracer (Flury and Fluhler, 1994, 1995; Flury et al., 1994; Petersen et al., 1997; Schwartz et al., 1999; Flury and Wai, 2003) revealed that the brilliant-blue food-coloring dye (FD&C Blue 1, tri-phenyl-methane dye) would be a suitable tracer because of its desirable properties of mobility and distinguishability in soils, and also because of its non-toxicity.

The steps we followed in conducting the dye-tracer tests at sites R8 and N7 are as follows: we rented a 3785-liter (1000-gallon) water tank and filled it with 1514 liters (400 gallons) of water. We then added a carefully pre-weighted total quantity of 6,056.7 grams

of brilliant-blue powder dye (3,028.4 grams per 757 liters {200 gallons} of water) and mixed it well to obtain a dye concentration of 4 g/L (which was also employed in the studies cited above). We prepared two 91.4-cm by 152.4-cm (3-ft by 5-ft) wooden rectangular frames of 91.4-cm height for flooding the sites with the dye solution as shown in Figure 3.



Figure 3. Wooden rectangular frame for flooding the site with dye solution.

## 2.2 Numerical Model Employed

The USDA-ARS developed a Root Zone Water Quality Model (RZWQM), which is a comprehensive agricultural systems model intended as a research tool to investigate the effects of agricultural management on crop production and environmental quality (Ahuja et al., 2000). The RZWQM is an integrated physical, biological, and chemical process model that simulates plant growth, and the movement and interactions of water, nutrients, and pesticides over and through the root zone at a representative area of an

agricultural cropping system. It is a one-dimensional (vertical into the soil profile) model designed to simulate conditions on a unit-area basis.

The reasons we chose to evaluate the RZWQM model are because, in addition to having been extensively tested nationally and internationally (Ahuja et al., 2000; Abrahamson et al., 2005; Malone et al., in press), it contains special features of interest to this study, such as macropore flow as well as an exchange component between the soil matrix and macropore walls; a wide variety of management effects, such as evaluation of conservation tillage, residue cover and conventional tillage, methods and timing of water applications as well as fertilizer and pesticide applications, and different crop rotations; and a user-friendly interface that can be initially set up with a minimum dataset using readily available data, as well as other features.

The RZWQM consists of six subsystems or processes that define the simulation program: 1) physical processes 2) soil chemical processes 3) nutrient processes 4) pesticides processes 5) plant growth processes and 6) management processes. Information about the RZWQM processes is calculated at daily and sub-hourly time scales as shown in Figure 4.

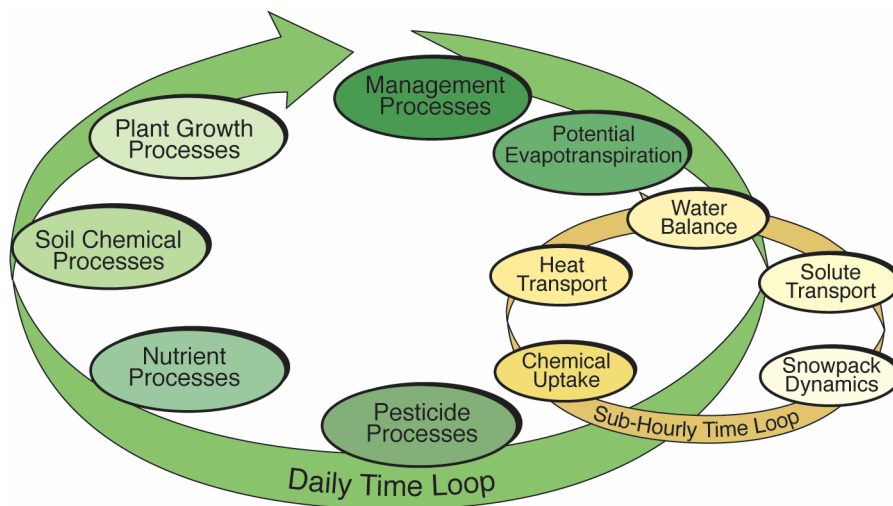


Figure 4. Execution sequence for RZWQM (adapted from Ahuja et al., 2000).

Management effects on the system (such as tillage, addition of chemicals or irrigation water) are calculated first. A daily estimate of potential ET is then determined (based on an extended Shuttleworth-Wallace potential ET module (Farahani and Ahuja, 1996) that considers the effects of surface-crop residue cover on soil evaporation and partitions evaporation into the bare soil and residue-covered fractions) so that the evaporation and transpiration fluxes can be applied to the soil surface and plant roots, respectively.

The sub-hourly time loop is then executed to calculate the transport and fate of the water-controlled processes. These processes include infiltration and runoff, soil water distribution, chemical transport, actual evaporation and transpiration, plant nitrogen uptake, and others.

The water flow processes in the RZWQM are divided into two phases: 1) infiltration into the soil matrix and macropores and macropore-matrix interaction during a rainfall or an irrigation event, modeled by using the Green and Ampt approach; and 2) redistribution of water in the soil matrix following infiltration, estimated by a mass-conservative numerical solution of the Richards' equation. Rainfall or irrigation water in excess of the soil-infiltration capacity (overland flow) is routed into macropores if present. The maximum macropore flow rate and lateral water movement into macropores in the surrounding soil are computed using Poiseuilles' law and the lateral Green-Ampt equation, respectively. Macropore flow in excess of its maximum flow rate or excess infiltration is routed to runoff. In the RZWQM, water can only enter the macropores at the surface. High-intensity rainfalls generally yield greater water flow and chemical transport in macropores than low-intensity rainfalls (Shipitalo and Edwards, 1996), and this is true with the RZWQM as well.

Continuing along the daily loop, pools of carbon and nitrogen are transformed by the nutrient processes (Ma et al., 1998). The soil carbon/nitrogen dynamics module of the RZWQM model (Hanson et al., 1999) contains two surface residue pools (fast and slow decomposition), three soil humus pools (slow, medium, and fast decomposition),



and three soil microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs). It simulates N mineralization, nitrification, denitrification, ammonia volatilization, urea hydrolysis, methane production, and microbial population. These processes are functions of soil pH, soil O<sub>2</sub>, soil microbial population, soil temperature, soil water content, and soil ion strength. Despite the complexity of this organic matter/N-cycling component, good estimates of initial soil carbon content and nitrogen are generally the only site-specific parameters needed. The required inputs (e.g. fast pool, slow pool) are then usually determined through an initiation wizard and calibration.

Finally, after accounting for all the physical and chemical changes to the system throughout the day, the plant-growth processes determine crop production. The RZWQM has a generic plant-growth component that can be parameterized to simulate different crops. Both individual plant growth through seven phenological growth stages (dormancy, germination, emergence, 4-leaf plant, vegetative growth, reproductive growth, and senescence), and population development (controlled by the Leslie matrix {Hanson, 2000}) are simulated. The RZWQM also provides a second option submodel for simulation of crop growth referred to as the Quickplant model. However, Quickplant is not a detailed growth model, and it is recommended (Ahuja et al., 2000) that it only be used when simulating crop production is not the primary aim of the modeler. Details on all aspects of the model can be found in Ahuja et al. (2000).

As mentioned previously, the RZWQM is a research-grade complex tool that was designed to analyze soil and plant processes only within the root zone. However, for our application, we had to modify and extend the RZWQM to deal with deeper vadose-zone processes, and in discussing this extension with the RZWQM developers in the Agricultural Research Service Systems-Research Unit in Fort Collins, CO, ours may be the first RZQWM application to depths beyond the root zone. Soil-horizon depths are converted to a numerical grid with a maximum thickness of 5 cm and 1 cm for the top soil layer. These numerical layers are used for solving the Richards equation during redistribution. During infiltration, 1-cm soil layers are used for the Green-Ampt equation (Ahuja et al., 2000). This model can simulate a soil profile of up to 30 m. A unit gradient

was assumed for the lower boundary condition at 10.8 m for site N7 and 4.84 m for site R8.

### 2.3 Outline of Some Model Input Requirements

To simulate the transport of water and chemicals, the soil profile must be well defined in its depth, horizon delineation, physical properties (bulk density, particle density, porosity, and texture), and hydraulic properties. A detailed description of site soil horizons and related physical and chemical properties is presented in Sophocleous et al. (2006). Because of model limitations, we had to combine a number of soil horizons into a maximum of 10 layers. The soil physical properties by layer used as initial conditions for model simulations {based on NRCS National Soils Lab (Lincoln, NE)-analyzed soil-core measurements that were presented in Sophocleous et al. (2006)} are shown in Tables 1 and 2 for sites N7 and R8, respectively.

The hydraulic properties are defined by the soil water characteristic or retention curves, and the unsaturated hydraulic conductivity function. Those relationships are described by functional forms suggested by Brooks and Corey (1964) with slight modifications (Ahuja et al., 2000).

The volumetric soil water content ( $\theta$ ) versus the capillary pressure head or matric suction head ( $\psi$ ) relationship representing the water retention or characteristic curve is formulated as follows:

$$\theta(\psi) = \theta_s - A_1 |\psi| \text{ for } \psi \leq \psi_a \quad (1)$$

$$\theta(\psi) = \theta_r + B |\psi|^{-\lambda} \text{ for } \psi > \psi_a \quad (2)$$

where  $\theta_s$  and  $\theta_r$  are the saturated and residual soil-water contents ( $\text{cm}^3/\text{cm}^3$ ), respectively;  $\psi_a$  is the air-entry or bubbling suction head (cm);  $\lambda$  is the pore-size distribution index (and represents the logarithmic slope of the water retention curve);  $A_1$  and  $B$  are constants, where  $B = (\theta_s - \theta_r - A_1 \psi_a) \psi_a^\lambda$  and  $A_1$  was set to zero in our case, thus reducing equations (1) and (2) to the Brooks and Corey (1964) model. Figure 5

displays a schematic of a typical soil-water retention curve with a number of the above-mentioned parameters indicated.

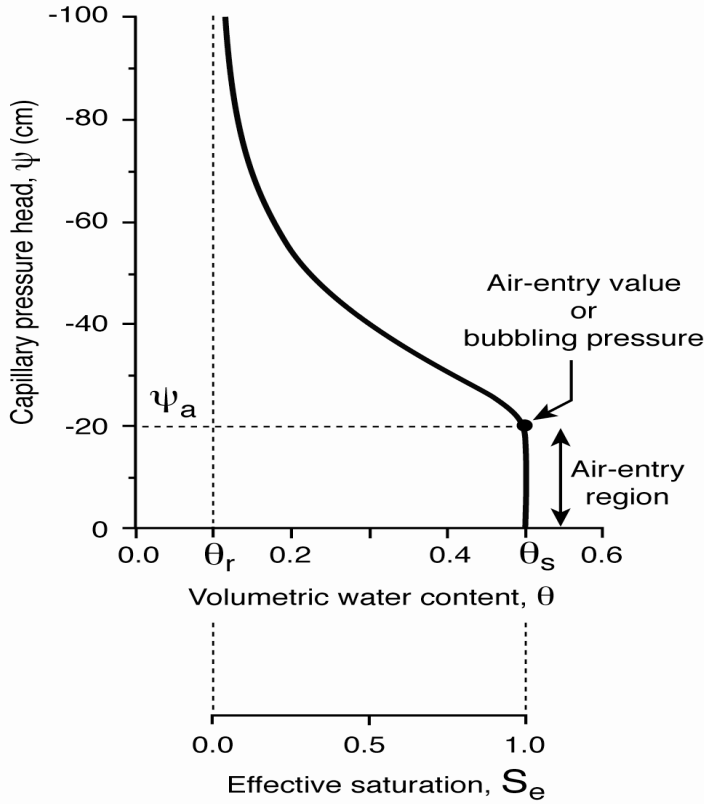


Figure 5. Schematic of a typical soil-water retention curve.

The hydraulic conductivity ( $K$ ) versus matric suction head ( $\psi$ ) relationship representing the unsaturated hydraulic conductivity function is formulated as follows:

$$K(\psi) = K_s |\psi|^{-N_1} \quad \text{for } \psi \leq \psi_a \quad (3)$$

$$K(\psi) = K_2 |\psi|^{-N_2} \quad \text{for } \psi > \psi_a \quad (4)$$

where  $N_1$ ,  $N_2$ , and  $K_2$  are constants and  $K_2 = K_s |\psi_a|^{-N_2}$ ,  $N_2 = 2 + 3\lambda$ , and  $N_1$  was set to zero in our case, thus reducing equations (3) and (4) to the Brooks and Corey (1964) model, where the effective saturation,  $S_e$  is defined as

$$S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$$

Table 1. Soil physical properties for site N7 by layer based on measurements by the NRCS National Soils Lab (Lincoln, NE) that are presented in Sophocleous et al. (2006)

Layer	Soil Type	Horizon Depth (cm)	Bulk Density (g/cm <sup>3</sup> )	Porosity <sup>a</sup>	Sand fraction	Silt fraction	Clay fraction	K <sub>s</sub> <sup>b</sup> (cm/hr)	1/3-bar W.C. <sup>c</sup>	1/10-bar W.C. <sup>c</sup>	15-bar W.C. <sup>c</sup>
1	Silty loam	0-23	1.280	0.517	0.056	0.686	0.258	1.3163	0.2260	0.3637	0.1305
2	Silty clay loam	23-74	1.470	0.445	0.027	0.621	0.352	0.3911	0.2540	0.4037	0.1690
3	Silty clay loam	74-168	1.300	0.509	0.033	0.624	0.343	0.7268	0.2710	0.4037	0.1617
4	Silty clay loam	168-221	1.240	0.532	0.114	0.558	0.328	0.9829	0.2390	0.4037	0.1410
5	Silty clay loam	221-363	1.380	0.479	0.115	0.554	0.331	0.2266	0.2070	0.3742	0.1215
6	Silty clay loam	363-625	1.420	0.464	0.090	0.610	0.300	0.5431	0.2340	0.4037	0.1185
7	Silty loam	625-848	1.350	0.491	0.126	0.631	0.243	0.7048	0.2855	0.3637	0.1070
8	Silty loam	848-889	1.380	0.479	0.141	0.638	0.221	0.6966	0.2855	0.3637	0.1260
9	Silty loam	889-945	1.410	0.468	0.267	0.513	0.220	0.6966	0.2480	0.2961	0.0960
10	Loam	945-1079	1.520	0.426	0.344	0.416	0.240	0.1463	0.2335	0.2961	0.1015

<sup>a</sup> calculated assuming a particle density of 2.65 g/cm<sup>3</sup>

<sup>b</sup> saturated hydraulic conductivity (K<sub>s</sub>)

<sup>c</sup> soil water content (W.C.)

Table 2. Soil physical properties for site R8 by layer based on measurements by the NRCS National Soils Lab (Lincoln, NE) that are presented in Sophocleous et al. (2006)

Layer	Soil Type	Horizon Depth (cm)	Bulk Density (g/cm <sup>3</sup> )	Porosity <sup>a</sup>	Sand fraction	Silt fraction	Clay fraction	K <sub>s</sub> <sup>b</sup> (cm/hr)	1/3-bar W.C. <sup>c</sup>	1/10-bar W.C. <sup>c</sup>	15-bar W.C. <sup>c</sup>
1	Silty clay loam	0-16	1.420	0.464	0.041	0.643	0.316	0.4480	0.4463	0.4037	0.2107
2	Silty clay loam	16-29	1.490	0.438	0.036	0.659	0.305	0.4452	0.4216	0.4037	0.2107
3	Silty clay loam	29-50	1.280	0.517	0.023	0.599	0.378	0.1553	0.4928	0.4037	0.2107
4	Silty clay	50-68	1.210	0.543	0.017	0.553	0.430	0.0890	0.5182	0.4251	0.2513
5	Silty clay loam	68-90	1.260	0.525	0.021	0.592	0.387	0.2799	0.5002	0.4037	0.2107
6	Silty clay loam	90-140	1.520	0.426	0.030	0.627	0.343	0.8501	0.4280	0.4037	0.2107
7	Silty clay loam	140-260	1.620	0.389	0.152	0.502	0.346	0.3237	0.4049	0.3890	0.2107
8	Silty clay loam	260-300	1.610	0.392	0.194	0.483	0.323	0.1543	0.3806	0.3920	0.2107
9	Clay loam	300-410	1.530	0.423	0.217	0.494	0.289	0.2968	0.4230	0.3742	0.1882
10	Silty clay loam	410-484	1.540	0.419	0.188	0.496	0.316	0.1308	0.4380	0.4037	0.2107

<sup>a</sup> calculated assuming a particle density of 2.65 g/cm<sup>3</sup>

<sup>b</sup> saturated hydraulic conductivity (K<sub>s</sub>)

<sup>c</sup> soil water content (W.C.)

The RETention Curve (RETC) computer program (van Genuchten et al., 1991) for describing the hydraulic properties of soils as well as the neural network program ROSETTA (Schaap et al., 2001) were employed to fit the parameters for several analytical models such as the Brooks and Corey (1964) and van Genuchten functions (van Genuchten, 1980) to experimentally measure water retention and hydraulic conductivity data for input into the RZWQM. (The correspondence of the van Genuchten parameters  $\alpha$  and  $n$  to the Brooks and Corey parameters  $\psi_a$  and  $\lambda$  is as follows:  $\alpha = 1/\psi_a$ , and  $n = \lambda + 1$ .)

The model also requires detailed meteorological data on a daily basis, and rainfall data in breakpoint increments. Hourly precipitation and other meteorological data (except for solar radiation) were obtained from the Dodge City Municipal Airport weather station, some 17 km northeast of the study sites, whereas daily solar radiation data were obtained from the Garden City Agricultural Experiment Station some 80 km west-northwest of Dodge City, operated by Kansas State University. The model also requires specification of land-use practices such as planting and harvesting dates, specification of irrigation and fertilization events, as well as the chemical quality of irrigation. The daily precipitation and irrigation events during the 2005 irrigation season for site N7 are shown in Figure 6.

The physically based nature of RZWQM necessitates a good deal of data from the user to adequately parameterize and initialize the model. From experience, users do not have enough data to completely describe the state of an agricultural cropping system. To facilitate use of the model, the RZWQM allows for input options where certain parameters are estimated from easily determined soil properties (e.g., soil texture) or obtained from default value tables if measured data are not available.

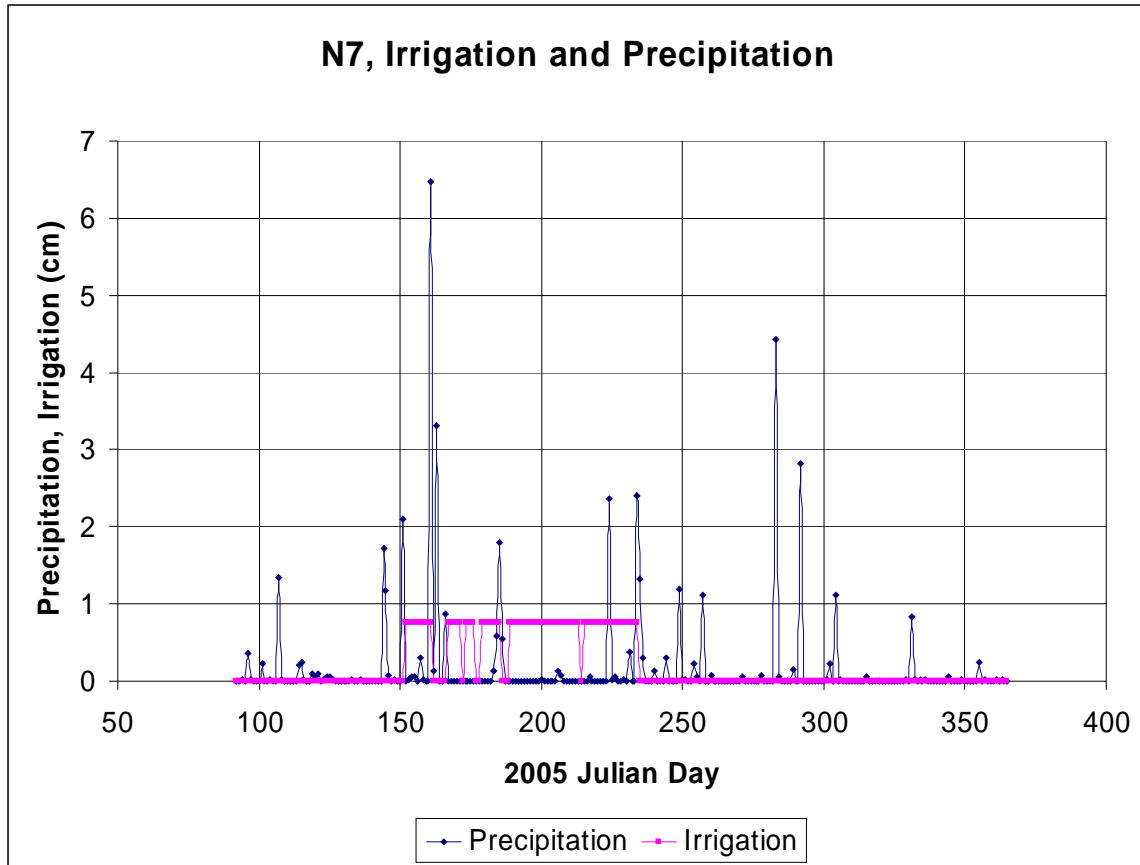


Figure 6. Daily precipitation and irrigation events during the 2005 irrigation season at site N7.

## 2.4 Model Calibration Procedures

### 2.4a General Procedures

For accurate simulations, RZWQM must be calibrated for soil hydraulic properties, nutrient properties, and plant-growth parameters for the site and crops being simulated (Hanson et. al., 1999), as there are significant interactions among the different model components. The number of parameters and processes in the RZWQM are so numerous that it is exceedingly difficult to decide which ones to optimize and what optimization scheme might be appropriate, if at all feasible. As a result, such agricultural system models as the RZWQM are usually parameterized by trial-and-error or iterative processes (Ahuja and Ma, 2002). In this report, we followed the detailed procedures for calibrating the RZWQM as laid out by Hanson et al. (1999) and Ahuja and Ma (2002).

The model requires establishment of initial C/N pool sizes for the fast and slow decomposition residue pools; slow, medium, and fast decomposition humus pools; and the three microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs) (Hanson et al., 1999). No laboratory procedures were known to effectively determine the sizes of these pools (Ahuja and Ma, 2002). Therefore, because previous management at a site determines the initial state of a soil in terms of its organic matter and microbial populations, simulations with previous management practices will usually create a better initial condition for these parameters (Ma et al., 1998). After entering all the model inputs and parameters, we began by estimating the three humus organic-matter pool sizes (based on measured organic-carbon depth profiles) at 5, 10, and 85%, respectively, for fast, medium, and slow pools and set the microbial pools at 50,000, 500, and 5000 organisms per gram of soil, respectively, for aerobic heterotrophs, autotrophs, and facultative heterotrophs, as recommended by Ahuja and Ma (2002). RZWQM was initialized for the organic-matter pools by running the model for 12 years prior to the 2005-06 actual simulation periods. A 12-year initialization run was suggested by Ma et al. (1998) to obtain steady-state conditions for the faster soil organic pools. The only parameters that we adjusted after the initialization procedure were the soil nitrate and soil ammonium nitrate for the analysis period (2005-06) as we had available measured values of those quantities from the sites before corn was planted in the spring of 2005.

#### 2.4b Sensitivity Analysis

To identify key model parameters and sources of simulation errors resulting from parameter uncertainty, we conducted extensive sensitivity analysis. A sensitivity analysis is usually done by varying (perturbing) model parameter values around their base values independently. The range of the perturbation may be a specific percentage around a base value (Walker et al., 2000; Ma et al., 2000).

Different sets of model input parameter groups were perturbed, such as 1) hydraulic properties 2) organic matter/nitrogen cycling parameters 3) plant-growth parameters, and 4) irrigation water and fertilization rates. The purpose is to identify key



(sensitive) model input parameters under western Kansas conditions in terms of corn production and NO<sub>3</sub>-N leaching, so as to guide calibration and measurement efforts.

#### 2.4c Calibration Strategy

Following the sensitivity analysis, which identified the most sensitive or critical parameters affecting model output, the model calibration strategy we adopted was as follows: the RZWQM was first calibrated for soil hydraulic properties by adjusting one or more of the most sensitive hydraulic parameters from the sensitivity analysis, then for the N-nutrient properties as outlined in the “General Procedures” section, and finally for the plant-growth parameters for the site and crops being simulated. Because plant production was part of the N balance and tightly coupled to the other processes, we followed the procedure for calibrating plant growth recommended for the model by Hanson (2000) when using the generic plant-growth submodel. This procedure is based on adjustments to five relatively sensitive plant parameters (see also section 3.4 on sensitivity analysis results further on for additional explanations) including active N uptake rate ( $\mu_l$ ), the proportion of daily respiration as a function of photosynthesis ( $\Phi$ ), the specific leaf density, i.e., the biomass to leaf area conversion coefficient ( $C_{LA}$ ), and the age effect for plants during the propagule stage and the seed-development stage ( $A_p$  and  $A_s$ ). We based adjustments of these parameters for corn within the range of values used for calibration of the Management Systems Evaluation Areas (MSEA) sites in the midwestern USA (Hanson, 2000). Because the nitrogen-related and plant-growth parameters are difficult to measure with independent experiments, an accurate description of the water-related processes is required to minimize N-simulation errors.

Calibration targets were the measured-profile soil water contents using the neutron probe and the core-sampled nitrate profiles. Field measurement errors are typically >10%; therefore, it is unrealistic to match the observed data any more closely (Hanson et al., 1999). Both qualitative and quantitative methods were used to evaluate the model. Three statistics were used to evaluate the simulation results: (i) root mean squared error (RMSE) between simulated and observed values, eq. (5); (ii) relative root

mean square error (RRMSE), i.e., RMSE relative to the mean of the observed values, eq. (6); and (iii) mean relative error (MRE) or bias, eq. (7).

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2} \quad (5)$$

$$\text{RRMSE} = \text{RMSE} \times \frac{100\%}{O_{avg}} \quad (6)$$

$$\text{MRE} = \frac{1}{n} \sum_{i=1}^n \frac{(S_i - O_i)}{O_i} \times 100\% \quad (7)$$

where  $S_i$  is the  $i$ th simulated value,  $O_i$  is the  $i$ th observed value,  $O_{avg}$  is the average of observed values, and  $n$  is the number of data pairs.

The RMSE reflects the magnitude of the mean difference between simulated and experimental results, whereas the RRMSE standardizes the RMSE and expresses it as a percentage that represents the standard variation of the estimator (Abrahamson et al., 2005). The MRE indicates if there is a systematic bias in the simulation. A positive value indicates an overprediction and a negative value an underprediction.

### 3. Significant Findings

#### 3.1 Soil Nitrate Profiles

Our coring at the sites indicated relatively high nitrate-N concentrations in the soil profile at all sites sampled as seen in Figure 7 for sites N7, R8, and Y8, respectively. Each curve represents a different soil core analyzed that was collected at the time indicated in the figures.

For site R8 (with a long-term wastewater irrigation history—since 1986) we see (Fig. 7a) a high nitrate peak of about 40 mg/kg around 60 cm, which decreases sharply in the depth interval of 380 to 580 cm, possibly due to previously planted alfalfa roots consuming the nitrate at those depths, as the R8 site was under alfalfa cultivation from 1997 to 2002. The nitrate increases again reaching a secondary maximum near the depth

of 880 cm, then following a decrease near the 940-cm level, it progressively increases with depth down to more than 1500 cm. It seems that a previous nitrate front has reached down to 1500 cm, with yet older fronts reaching even deeper, indicating that nitrate may have already penetrated down to those depths.

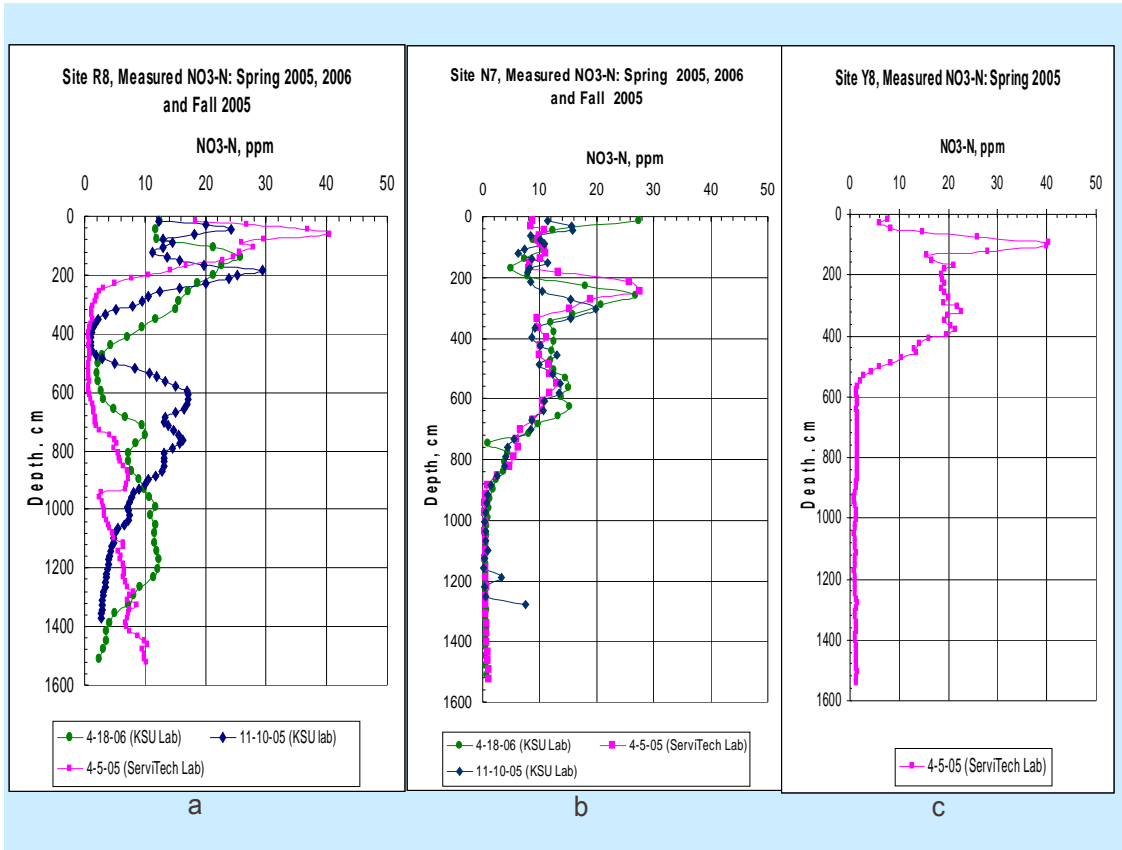


Figure 7. Measured soil profile Nitrate-Nitrogen during Spring 2005 for all study sites (a –R8, b – N7, and c –Y8), and during Fall 2005 and Spring 2006 for sites R8 and N7.

For site N7 (with wastewater irrigation history since 1998) we see (Fig. 7b) a deeper nitrate peak (of less than 28 mg/kg, i.e., not as high as that at site R8) around the 240-cm-depth level. Then, the nitrate distribution progressively decreases to a minimal background level by the time we reach near 900 cm, indicating that nitrate penetrated down to near 900 cm but no further.

Finally, for site Y8 (without any wastewater irrigation), we see (Fig. 7c) a high nitrate peak near the 100-cm level, but by the time we reach the 550-cm depth level, nitrate goes back to minimal background level.

### 3.2 Wastewater and Ground-water Quality

The sites were periodically LEPA-sprinkle irrigated from mid-May until the latter part of August during 2005 and 2006. The general quality of the treated wastewater effluent applied at the sites during 2005 and 2006 is shown in Figure 8. The chloride concentrations (in green) were around the 300 mg/L level but further increased during the second half of the 2006 year, and the Total Kjeldahl Nitrogen concentrations (TKN, in blue) were generally above the 80 mg/L level. The treated wastewater effluent was analyzed by both the OMI and Servi-Tech labs, and the chemical analysis results are presented in Appendix A (Tables A1 and A2, respectively). Noticeable differences are evident in the resulting wastewater constituents from the two labs.

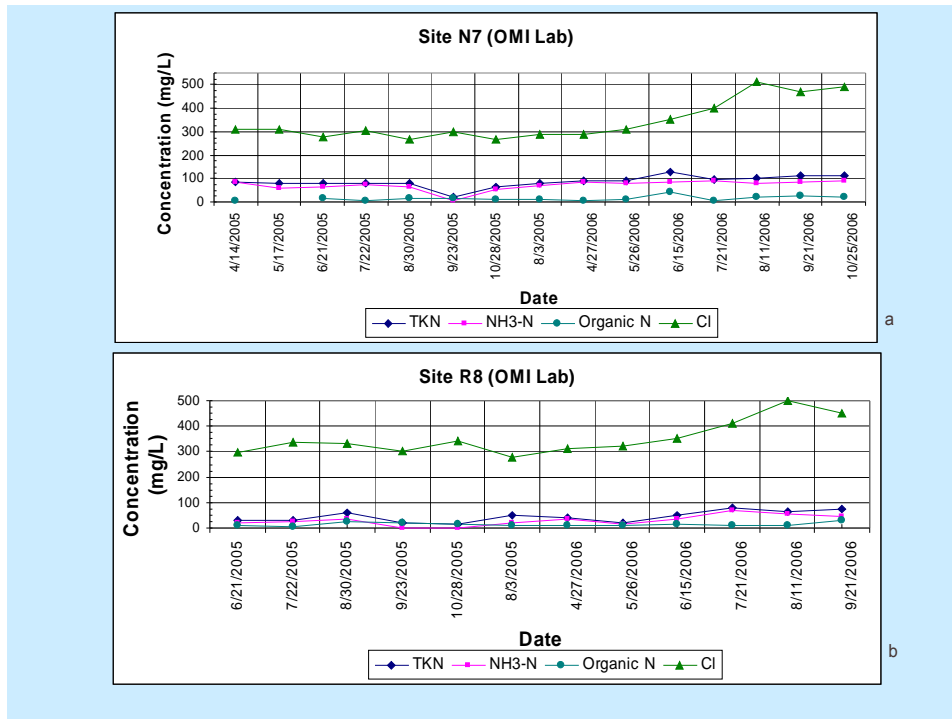


Figure 8. Treated effluent irrigation water chloride, total Kjeldahl nitrogen, and nitrate-nitrogen concentration time series applied to sites N7 (a) and R8 (b) during 2005 and 2006.

Figure 9 shows the ground-water nitrate-N concentrations from the November 2005 survey sampling, where wells shown in red exceed the safe drinking-water limit for nitrate-N of 10 mg/L. Notice that most of the wells have more than 2 mg/L nitrate-N in the ground water. This indicates (Mueller and Helsel, 1996) that anthropogenic sources have begun to impact the ground water in the area.

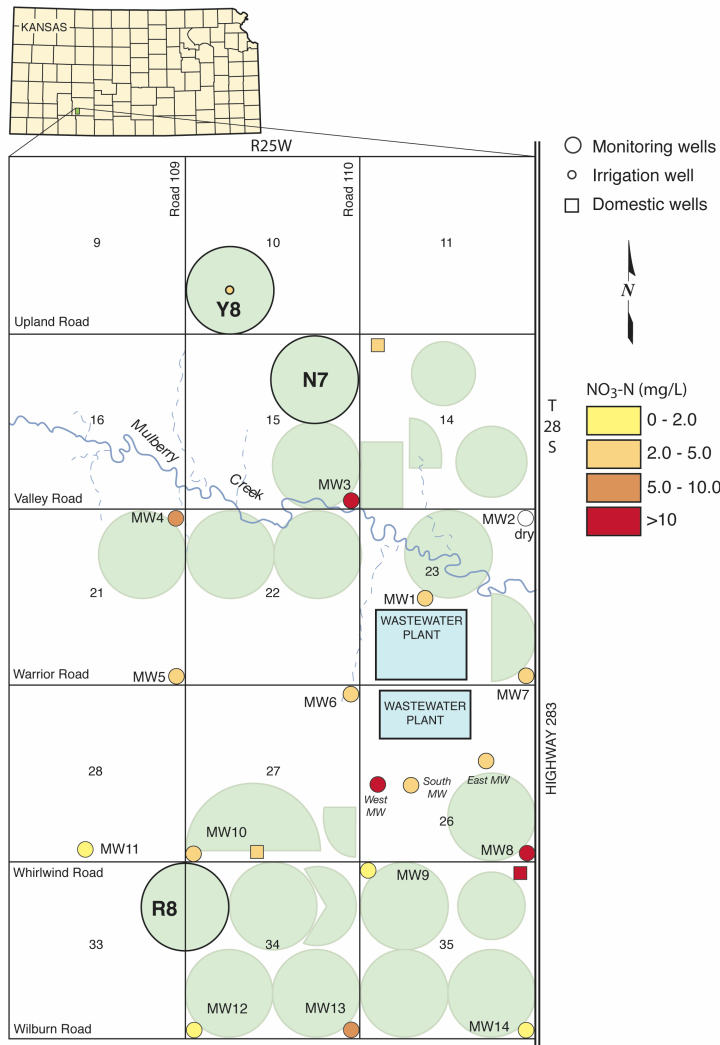


Figure 9. Ground-water nitrate-nitrogen concentrations during November 2005. Numbers at the center of square blocks are Section numbers in the Township and Range system of land classification. Green circles/semicircles are irrigated fields.

Figure 10 displays a trilinear diagram showing the average water quality of the irrigation water applied in both R8 and N7 sites marked as the A circle, the shallow- and intermediate-depth suction lysimeter-sampled pore water from both sites marked as the B

circle, as well as sampled domestic, monitoring, and irrigation wells in the area. The sampled populations of applied wastewater, pore water from suction lysimeters, and monitoring and domestic wells form distinct groups in the trilinear diagram.

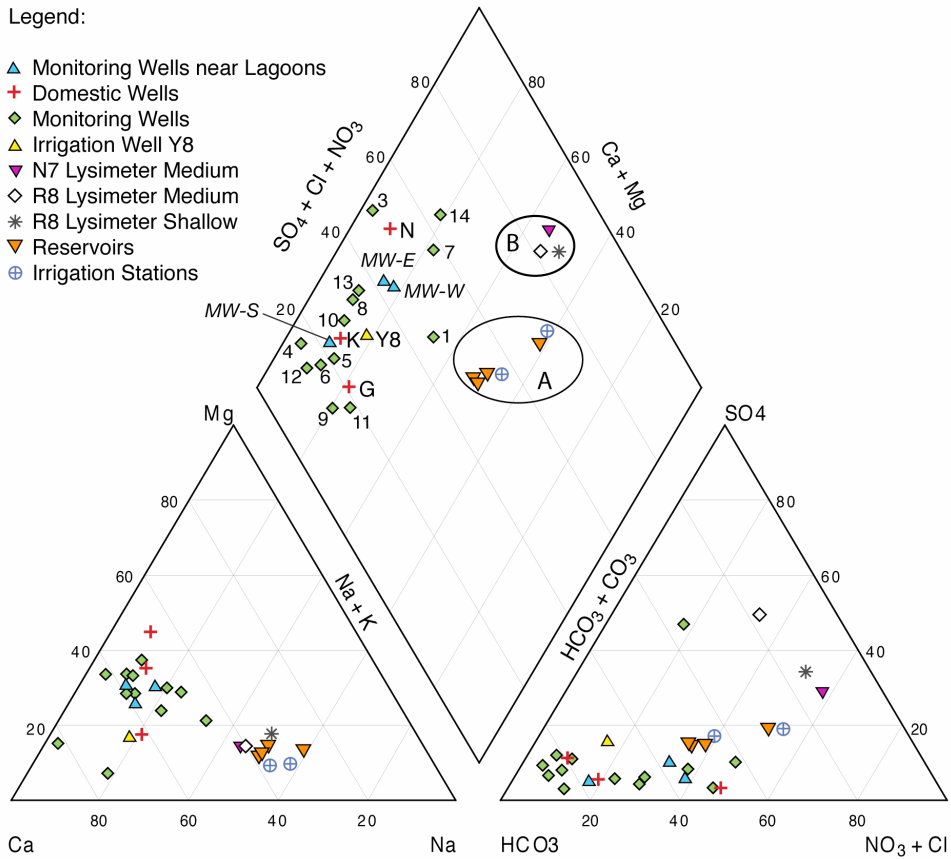


Figure 10. Trilinear diagram showing the average 2005 water quality of irrigation water applied in sites R8 and N7 (circle A), the shallow and intermediate-depth suction lysimeter-sampled pore water from sites R8 and N7 (circle B), and the domestic, monitoring, and irrigation wells sampled in the area.

### 3.3 Dye-tracer Experiment Results

We observed numerous macropores in the cores collected during sampling, not only in the upper soil profile but also at depths down to more than 9 m. Figure 11 displays a small sampling of the observed macropores from the sites. Because of the occurrence of such macropores and of the relatively high nitrate concentrations observed at the various wells sampled in the area, we run the two brilliant-blue dye experiments at the sites that were briefly described in section 2.1.

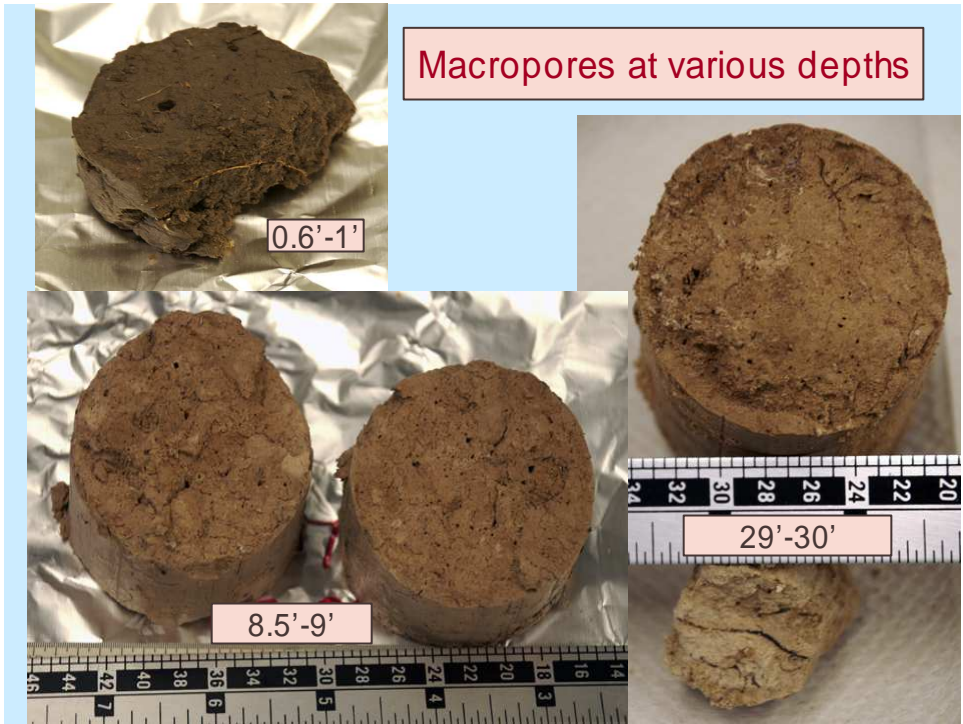


Figure 11. Soil cores at various depths from the study sites showing macropores. Numbers indicate depth in feet.

For the site R8 in Harney soil, the dye solution penetrated down to approximately 200 cm and formed a more-or-less uniform “finger front” at the bottom as shown in Figure 12. The right-hand-side picture in Figure 12 shows a closer-up view of the dye-tracer movement through the blocky-structure soil layers of the Bt horizons (at approximately the 50- to 100-cm depth interval) where the tracer dye moved along the spaces between the blocky soil aggregates and concentrated in numerous fingers in the lower soil layer that did not exhibit the heavy blocky structure of the Bt horizons above.



Figure 12. Uniform finger front from brilliant-blue dye-tracer experiment at site R8. The right-hand-side image shows in more detail the dye moving through the inter-soil block structure spaces of the Bt horizon and accumulating below that blocky layer into numerous fingers.

For site N7 in Ulysses soil, the dye pattern was different, forming a giant funnel front ending in a big finger down to approximately 200 cm, as shown in Figure 13. Closer examination of a side finger, indicated in Figure 13, showed that the dye finger formed along a decaying root channel, as did other fingers examined in both sites.

The observed macropores at depth are probably due to the existence of deep-rooted prairie grasses that dominated the landscape prior to agricultural development. The currently practiced no-till land-use treatment further enhances worm activity near the soil surface, thus maintaining macropores open at the soil surface. Because of the existence of such preferential-flow pathways, the macropore option of the RZWQM was employed. As a result of the observed macropores throughout the soil profile in both sites, macropores were uniformly distributed through all simulated layers using an average estimated pore radius of 0.1 cm and a percentage of macropores of 0.1%.



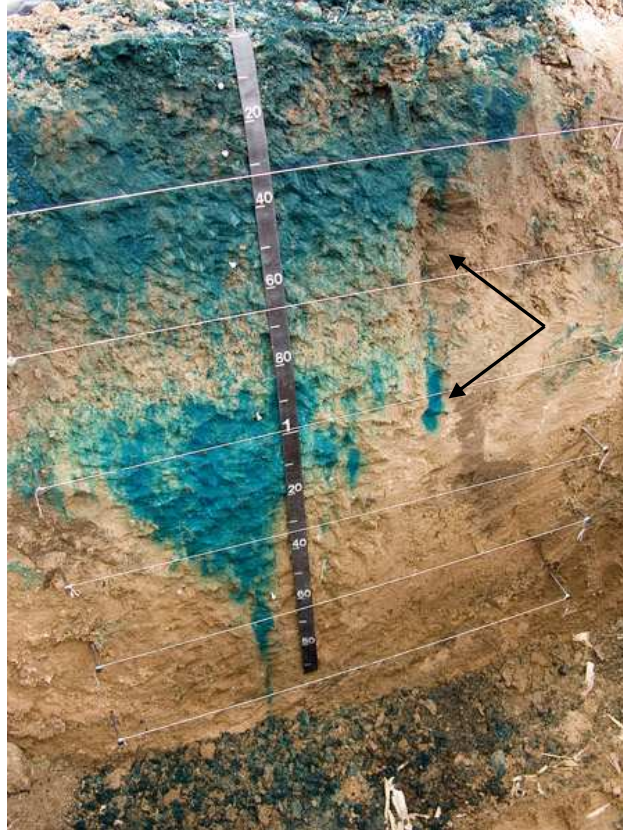


Figure 13. Funnel front pattern from brilliant-blue dye-tracer experiment at site N7 and side finger formed along a decaying root channel (indicated by the two arrows).

### 3.4 Sensitivity Analysis Results

A sampling of the hydraulic and crop-parameter sensitivities is shown in Figures 14 and 15, respectively. For the sensitivity analysis of hydraulic properties, the response variable considered was the soil-water content, whereas for the sensitivity analysis of crop parameters, the response variable considered was the soil nitrate-nitrogen.

For hydraulic parameters, bulk density, saturation water content ( $\theta_s$ ), and the Brooks and Corey parameters  $\lambda$  and  $\psi_a$  were the most sensitive, whereas saturated hydraulic conductivity (Ksat) and residual water content ( $\theta_r$ ) were the least sensitive.

For the macropore parameters, the total macroporosity fraction and the average size of pore radii were the most sensitive (Fig. 16). Macroporosity had minimal effect on soil water content, but had appreciable effect on nitrogen distribution. Macropore flow is generated only during heavy rainfall events in the model. The major hydrologic effect of introducing macropores in the model is to reduce surface runoff.

Ahuja and Williams (1991) and Williams and Ahuja (2003) found that the soil water retention curves as described by the Brooks and Corey equations could be simply described by the pore size distribution index,  $\lambda$ . The importance of  $\lambda$  was used for scaling water infiltration and redistribution (Kozak and Ahuja, 2005) and for scaling evaporation and transpiration across soil textures (Kozak et al., 2005). Because of the relatively high sensitivity of parameters  $\theta_s$  and  $\lambda$ , both of which are fitted (as opposed to experimentally measured) parameters, we decided to use primarily the  $\lambda$ -parameter and secondarily the  $\theta_s$  parameter to calibrate our model.

For the plant-growth parameters, the specific leaf density,  $C_{LA}$  (i.e., the amount of biomass needed to obtain a leaf area index, LAI = 1), the proportion of daily respiration as a function of photosynthesis,  $\Phi$  (that maintains N uptake while decreasing biomass accumulation), the propagule age effect,  $A_p$  (that may result in increased photosynthesis efficiency during propagule development and thus increased yield, while above-ground biomass is kept constant), the luxurious nitrogen uptake factor (that starts 100 days after corn planting and allows the crop to take up exactly as much N or more or less than it needs), and the maximum depth of roots were the most sensitive. The seed-age effect (same as propagule-age effect but affects photosynthesis later in growing season), minimum leaf stomatal resistance (that is resistance to movement of water through leaf stomata), and the nitrogen sufficiency index (i.e., the fraction of the difference between the ideal and minimum N content of the crop) were the least sensitive.

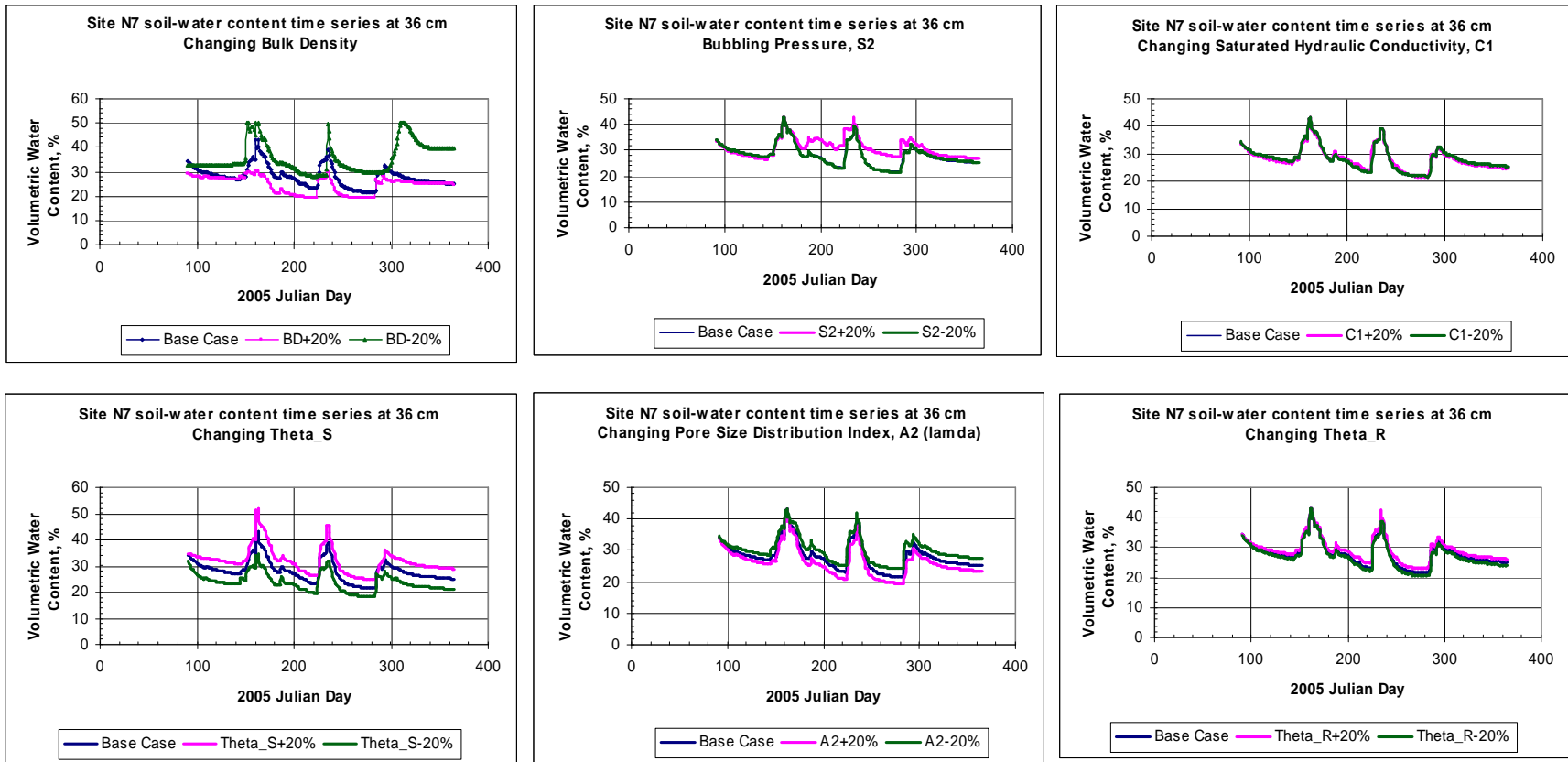


Figure 14. Sensitivity analysis of selected hydraulic parameters as exemplified for a random root-zone depth of 36 cm for site N7. Each variable was increased or decreased by 20% around a base (measured or estimated) initial value.

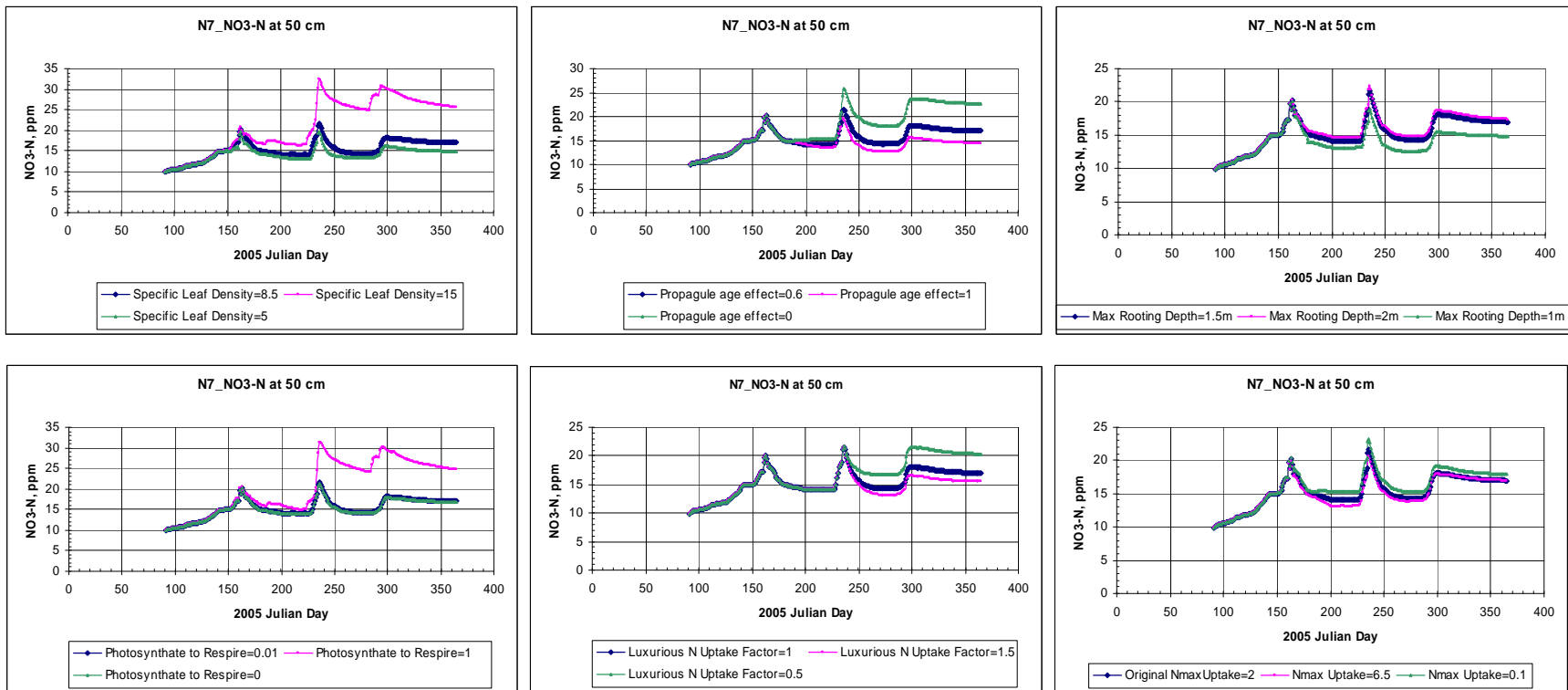


Figure 15. Sensitivity analysis of selected crop-growth parameters as exemplified for a random root-zone depth of 50 cm for site N7. Each variable was increased or decreased by a certain amount around an estimated base or initial value.

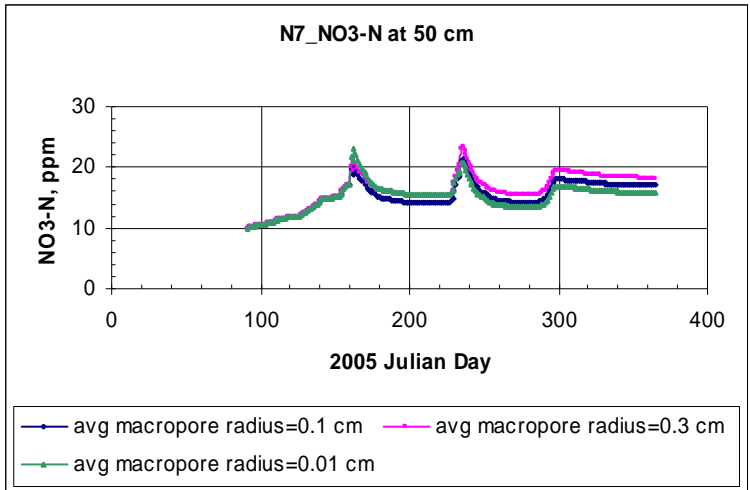
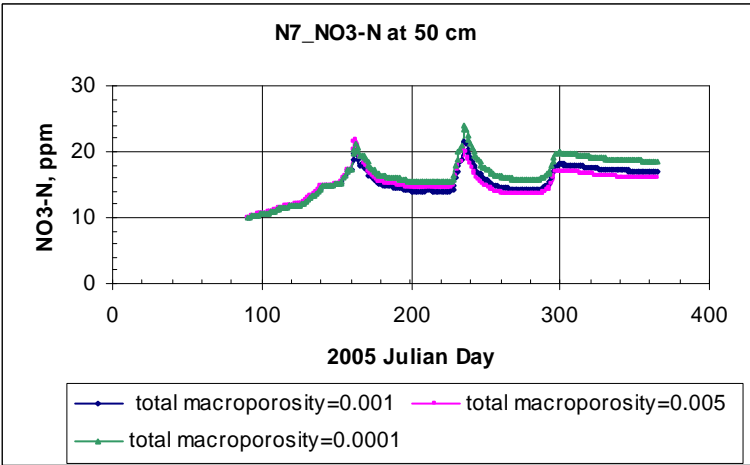


Figure 16. Macropore sensitivity analysis as exemplified for a random root-zone depth of 50 cm for site N7.

For the organic matter/nitrogen-cycling parameters, the aerobic heterotroph microbial population (that is, organisms capable of deriving carbon and energy from organic compounds, and growing only in the presence of molecular oxygen) and the transition and fast humus were the most sensitive parameters, as shown in Figure 17.

Of course, the irrigation and fertilization rates were very sensitive inputs.

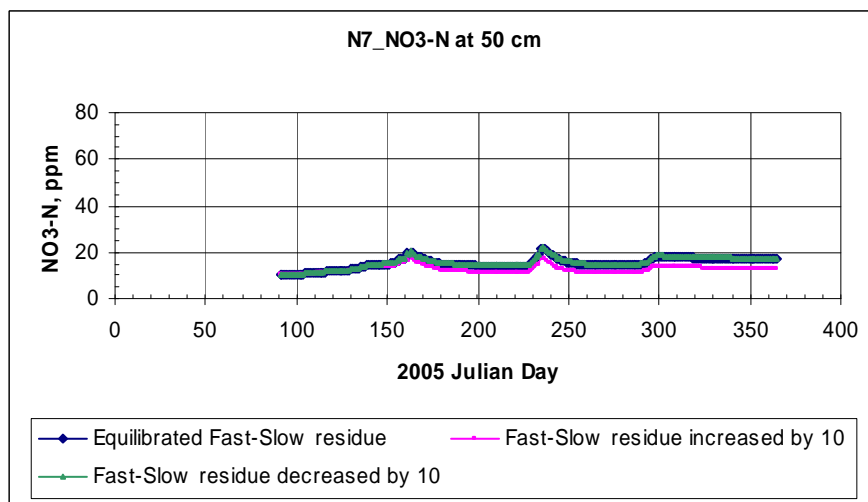
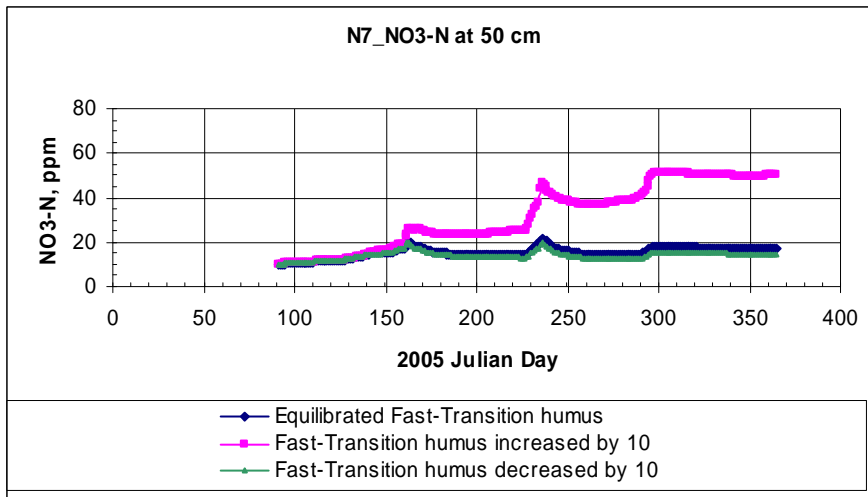
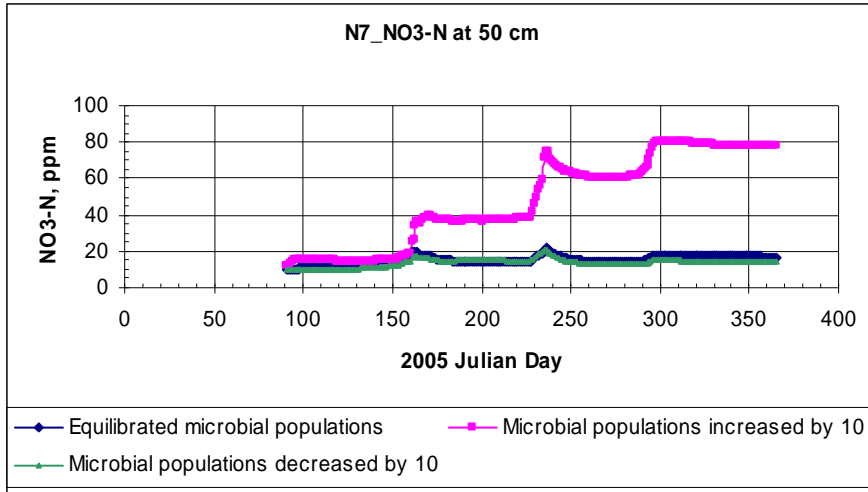


Figure 17. Sensitivity analysis of organic matter pools as exemplified for a random root-zone depth of 50 cm for site N7. The size of each pool was increased or decreased by one order of magnitude around the equilibrium base value.

### **3.5 Model Calibration and Simulation Results**

The simulated and observed moistures for the various individual layers are shown in Figures 18 and 19, for sites N7 and R8, respectively. Although for the upper layers of the soil in both sites the RRMSE and other error measures were relatively high, they much improved at increasing depths, as shown in the figures for the deeper layers. In addition, the simulation results, especially for site R8, show a slight negative bias or underprediction, as indicated by the negative value of the MRE statistic. In order to economize space from here onwards, we present simulation results from site N7 in more detail (for which we have relatively more detailed hydraulic-property data, resulting in generally and relatively somewhat better simulation results than for site R8).

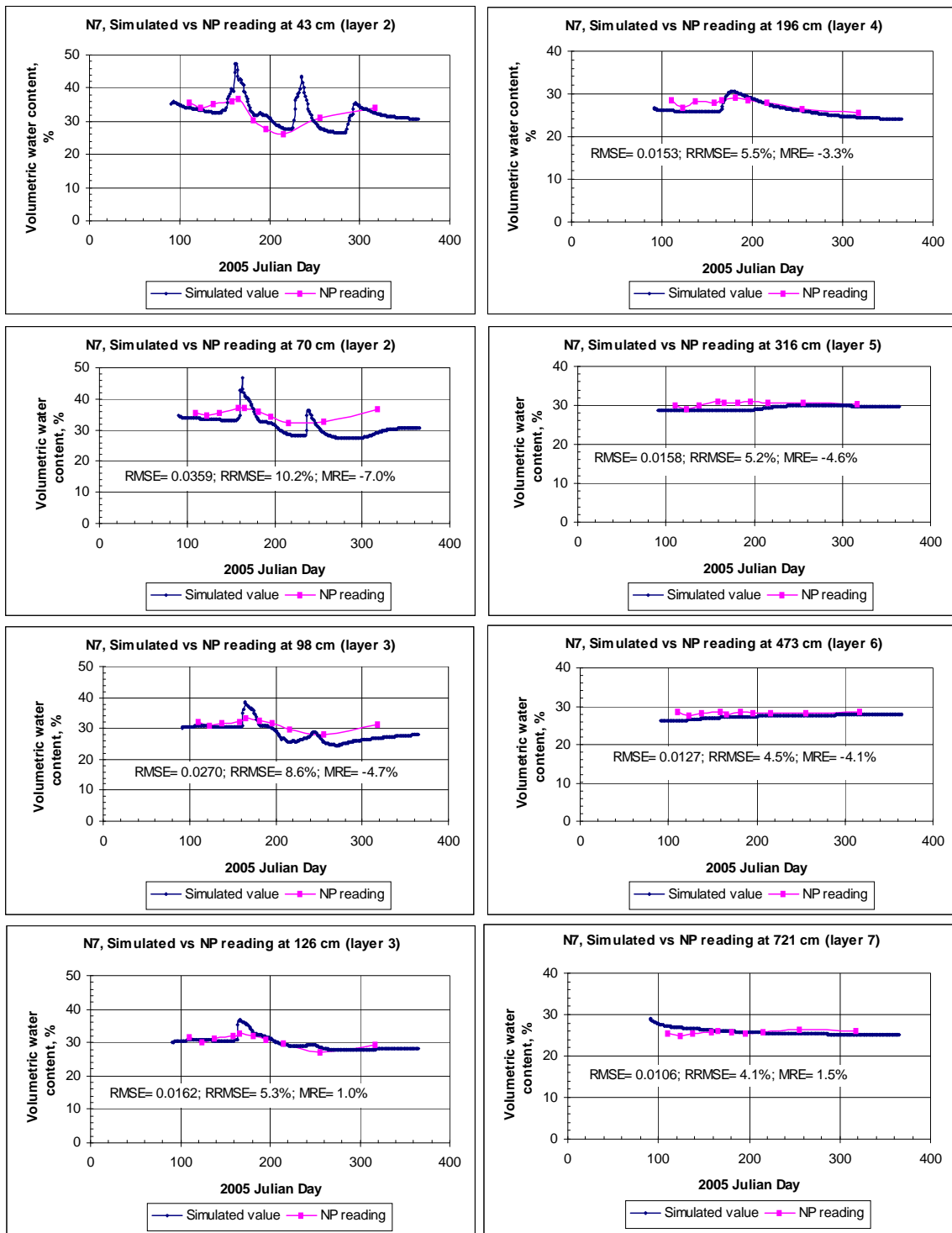


Figure 18. Comparison of model-simulated and field-measured soil water contents at various soil depths for site N7. Three statistical indices, root mean square error (RMSE), relative RMSE (RRMSE), and mean relative error (MRE), all defined in the text, are used to quantify the goodness of fit of model parameterization.



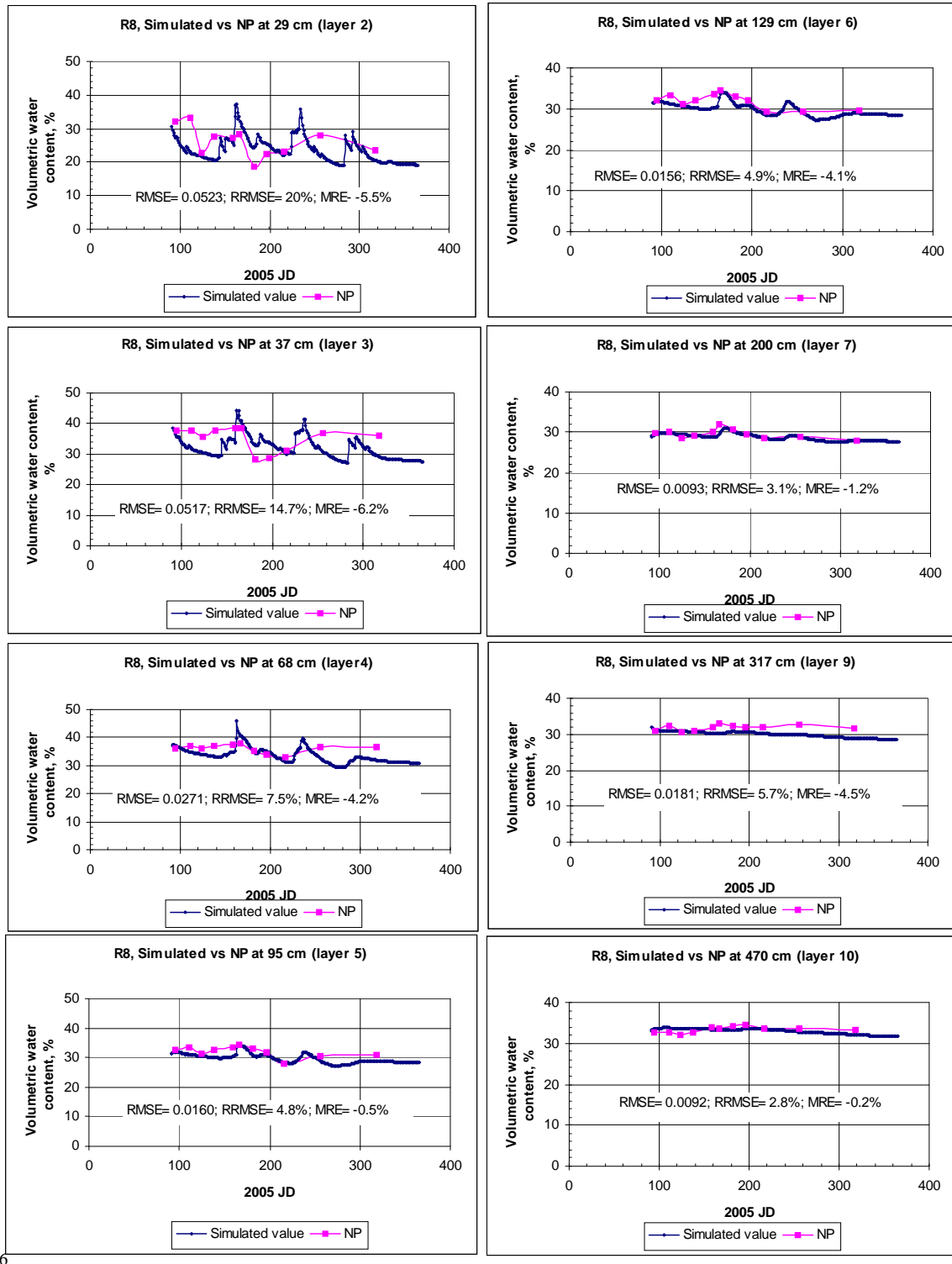


Figure 19. Comparison of model-simulated and field-measured soil water contents at various soil depths for site R8. Three statistical indices, root mean square error (RMSE), relative RMSE (RRMSE), and mean relative error (MRE), all defined in the text, are used to quantify the goodness of fit of model parameterization.

The simulated cumulative water budget components for the 2005 growing season are shown in Figure 20, where you notice that the runoff component is negligible during 2005.

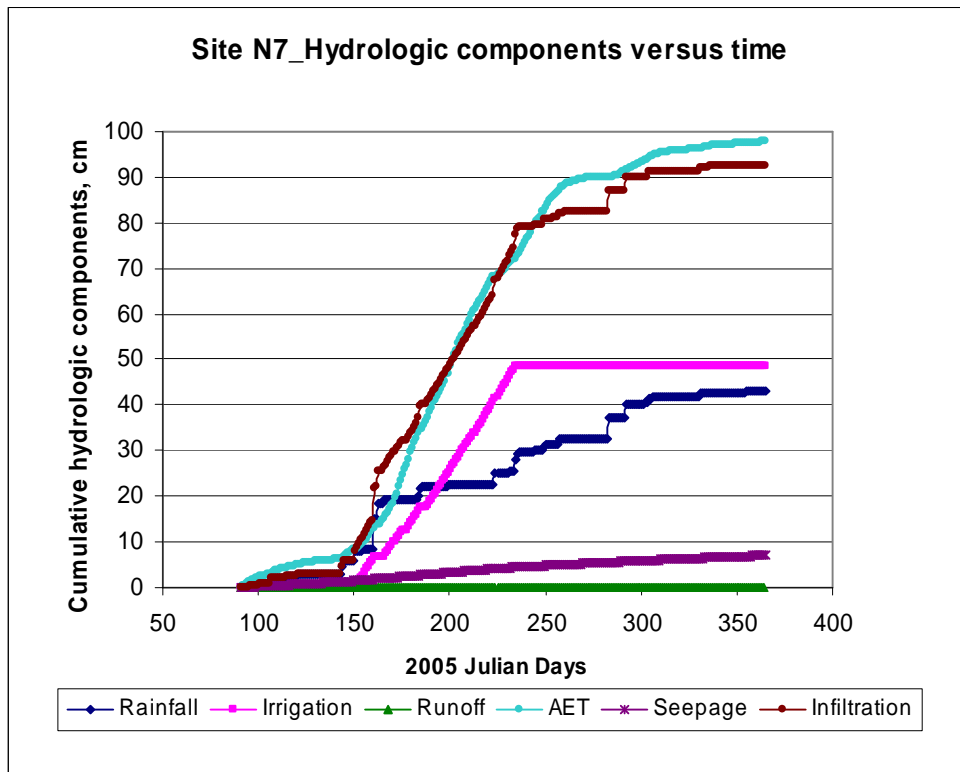


Figure 20. Simulated cumulative hydrologic components for site N7 during the 2005 growing season.

The simulated and measured soil nitrate profiles in the fall of 2005 in sites N7 and R8, both of which were planted in corn in April and harvested at the end of September are shown in Figure 21. For the case of site N7, the model approximated the main patterns of the nitrate depth profile fairly well, but not the observed detailed patterns. The results for site R8 were not as good as those for site N7, although they may be considered acceptable. As mentioned previously, we did not have hydraulic property data for the deeper R8 soil profile (only down to ~4.8 m), and as explained in the section on water-retention parameters in Sophocleous et al. (2006), some outside lab-determined hydraulic property data for that site were questionable.

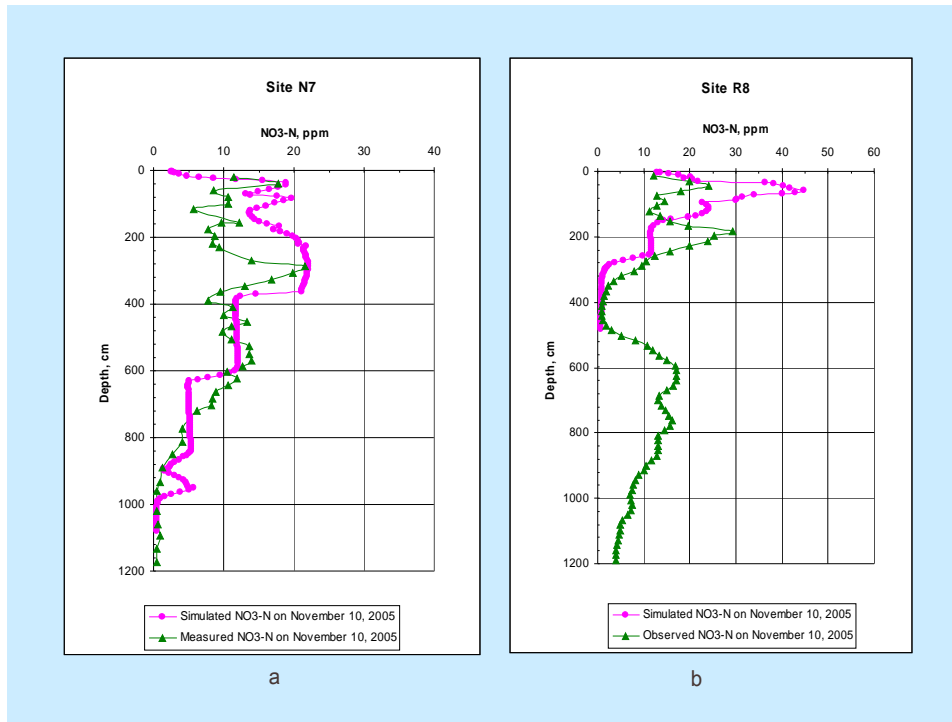


Figure 21. Measured and simulated soil nitrate-nitrogen profiles at (a) site N7 (simulated depth 1080 cm) and (b) site R8 (simulated depth 484 cm) during the soil-sampling date of November 10, 2005, following corn harvest.

The simulated temporal distribution of nitrogen losses are shown in Figure 22, whereas the simulated spatial and temporal nitrogen uptake are shown in Figure 23.

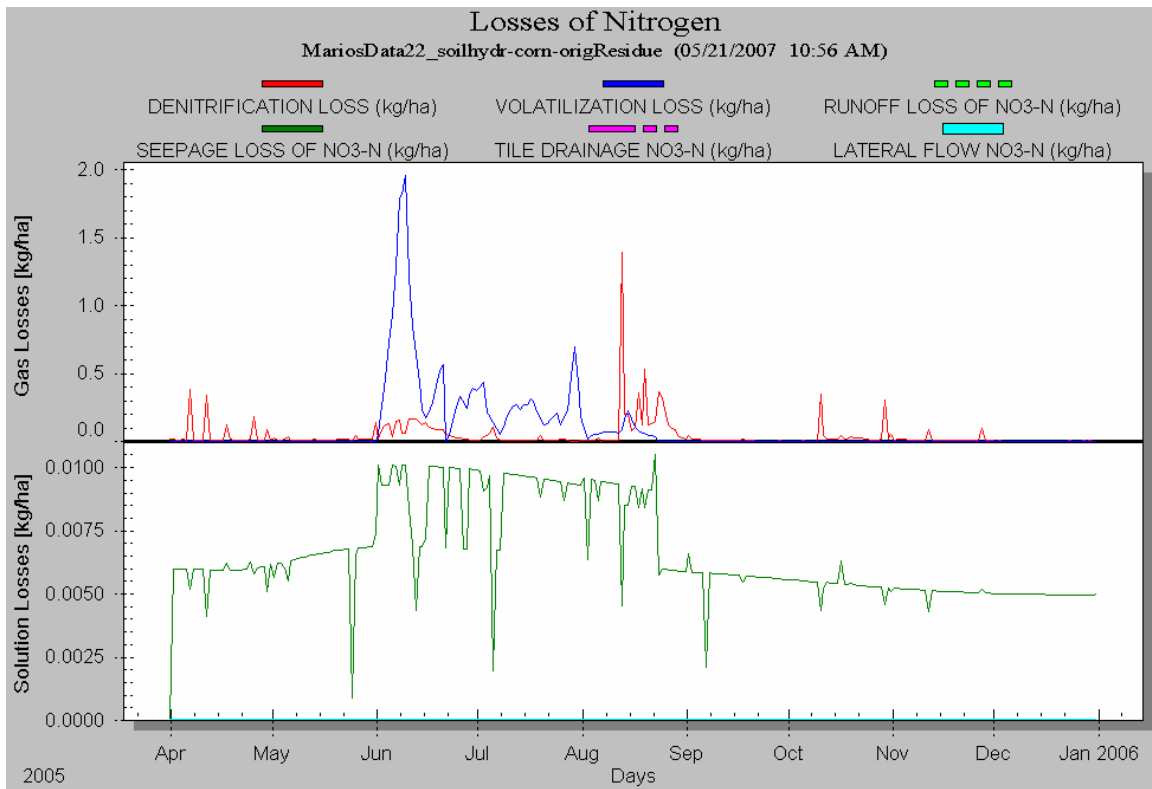


Figure 22. Simulated temporal distribution of nitrogen losses (volatilization, denitrification, deep seepage) at site N7 during the 2005 corn-growing season.

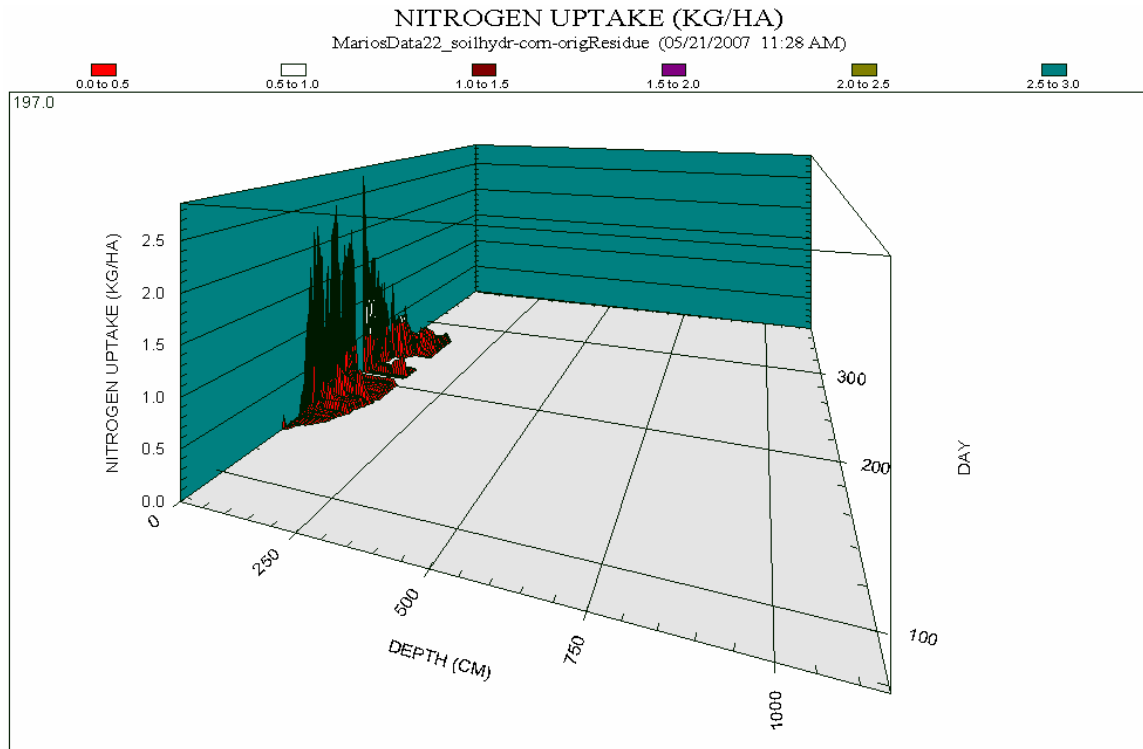


Figure 23. Three-dimensional diagram indicating the simulated spatial and temporal distribution of nitrogen uptake.

The model-estimated soil nitrogen balance is shown in Figure 24. The major source of nitrogen is the applied wastewater effluent that added more than 312 kg/ha during 2005 at site N7. The major nitrogen losses are from plant uptake, and secondarily from volatilization and deep seepage. Mineralization (that is, conversion of organic nitrogen that is present in soil organic matter, crop residues, and applied effluent to inorganic nitrogen, such as ammonium nitrogen, as a result of microbial decomposition) is the major transformation of nitrogen. However, large amounts of nitrate exist in the unsaturated soil profile as can be seen from Figure 7. The model-estimated storage of nitrate-nitrogen in the 10.8-m-deep soil profile analyzed in this model was more than 1500 kg/ha.

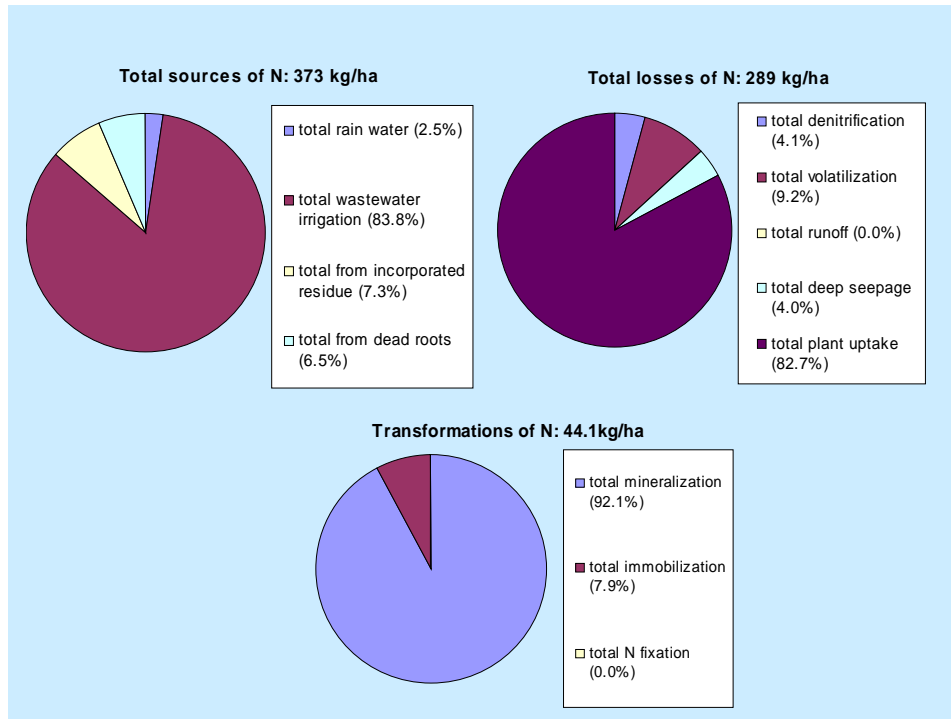


Figure 24. Simulated soil nitrogen balance components for site N7 during the 2005 growing season.

### 3.6 Management Scenarios Results

Once an agricultural system is adequately calibrated and tested, it has the potential for use in evaluation of alternative crop-soil management practices for the location of interest in terms of their production potential and impact on the environment (Hu et al., 2006). Because of the limited data we had available for calibrating and checking the RZWQM model, the results presented here should be considered preliminary.

Historical and current sampling of nitrogen in the soil at the wastewater-irrigated sites shows increased accumulation of inorganic nitrogen in the soil profile with time (see also Fig. 7), which indicates that the inorganic nitrogen left in the soil at harvest is not taken up completely by the subsequent crop. This residual nitrogen is subject to leaching to ground water when rainfall, especially of high intensity that enhances macropore flow, occurs between crop seasons. Numerical simulations indicated consistent increases in

nitrogen losses due to volatilization (primarily) and deep seepage and denitrification (secondarily) with increased nitrogen application rates (see also Figs. 22-24).

Nitrogen Use Efficiency (NUE) is a term used to indicate the relative balance between the amount of fertilizer N taken up and used by the crop versus the amount of fertilizer N “lost.” Nitrogen Use Efficiency in this report is defined as follows (Hu et al., 2006):

$$\text{NUE} = \frac{(\text{Plant N uptake under a particular N treatment}) - (\text{Plant N uptake under no N fertilization})}{(\text{amount of N applied})} \quad (8)$$

The RZWQM model was run with a zero-N treatment, and the results were used in the NUE computations.

Differences in predicted grain yields, plant N uptake, residual soil profile N, volatilization, and other N losses with different irrigation and fertilization treatments were analyzed using the RZWQM model and are summarized in Table 3. There is some uncertainty as to the total amount of fertilization applied in the fields. According to OMI lab analyses (see also Fig. 8 and Appendix A), the total N applied during the 2005 irrigation season was 434.5 kg/ha. According to Servi-Tech lab analyses (Appendix A, F. Vocasek, March 2007 written communication), the total was 312.4 kg/ha. To somewhat resolve this discrepancy, we adopted the Servi-Tech total but employed the OMI lab proportions of NO<sub>3</sub>, NH<sub>3</sub>, and organic nitrogen constituents of treated wastewater applied for irrigation (fertigation). The N balance components and NUE for both of the totals mentioned above are shown in Table 3. In addition, several management scenarios were simulated using reduced fertilization treatments of 50% of those OMI- and Servi-Tech-based wastewater-N totals mentioned above, as well as 75% and 50% reduced irrigation totals while maintaining the same irrigation scheduling.

We see that reducing fertilization by 50% using the same 2005 irrigation scheduling increases NUE while keeping relative crop yield nearly constant with a decrease of only 1% of maximum simulated yield (see Table 3, items 2, 5, 8, 11, and 14). Lowering fertigation from 435 kg/ha (Table 3, item 10) to 312 kg/ha (Table 3, item 1), to

217 kg/ha (Table 3, item 11), to 157 kg/ha (Table 3, item 2) consistently increased NUE (10.5%, 17.1%, 31.9%, 42.2%, respectively). Reducing irrigation total amount while keeping fertilization levels at 157 kg/ha further increases NUE from 42.2% (at full irrigation amount—Table 3, item 2) to 48.1% (at 75% of full irrigation amount—Table 3, item 5) to only 48.2% (at 50% of full irrigation amount—Table 3, item 8). This last result indicates that such a drastic irrigation reduction (50%) may not be necessary, as nearly the same NUE is obtained with 75% irrigation reduction.

It seems that reducing the fertilization levels at the study sites to around 150 kg/ha increases the NUE significantly. Such lower fertilization rates can be achieved by blending treated wastewater effluent with freshwater from the underlying High Plains aquifer. In addition, decreasing the amount of irrigation water applied by approximately 25%, while using reduced fertilization rates, further increases NUE.



Table 3. Nitrogen inputs and losses predicted by RZWQM for the 2005 crop season for site N7 for current irrigation, 75% irrigation, and 50% irrigation, and various levels of nitrogen fertilization through the irrigation LEPA system.

Description of method			Total N Input (kg/ha)					Total N losses (kg/ha)								NUE <sup>c</sup> %
	Crop yield (kg/ha)	Percent change in crop yield	Storage (10.8m-profile)	Rain	Ferti-gation <sup>b</sup>	Mineral-ization	Percent change in mineral-ization	Plant uptake	Percent change in plant uptake	Deep seep-age	Percent change in deep seepage	Denitri-fication	Percent change in denitri-fication	Volatili-zation	Percent change in volatili-zation	
1. Full rate irrigation <sup>a</sup> , full rate fertilization <sup>b</sup>	6030.3	-----	1518.5	9.4	312.4	40.6	-----	239.0	-----	11.6	-----	11.9	-----	26.5	-----	17.12
2. Full rate irrigation, 50% fertilization	5961.8	-1.14	1465.8	9.4	156.9	40.9	0.73	251.8	5.32	11.6	0.0	7.8	-34.59	5.1	-80.66	42.19
3. Full rate irrigation, zero fertilization	5198.8	-13.79	1426.3	9.4	-----	40.9	0.71	185.6	-22.37	11.6	-0.00	5.4	-54.15	0.01	-99.95	-----
4. 75% irrigation, full rate fertilization	6067.9	-----	1519.7	9.3	312.4	42.8	-----	236.6	-----	11.6	-----	10.5	-----	30.7	-----	17.47
5. 75% irrigation, 50% fertilization	6006.7	-1.01	1469.6	9.3	156.9	43.1	0.56	257.5	8.82	11.6	0.00	7.3	-30.55	5.9	-80.72	48.08
6. 75% irrigation, zero fertilization	5367.5	-11.54	1427.8	9.3	-----	43.4	1.37	182.0	-23.06	11.6	0.01	5.3	-49.63	0.01	-99.96	-----
7. 50% irrigation, full rate fertilization	6002.8	-0.46	1519.7	9.3	312.4	44.5	9.44	222.7	-6.85	11.5	-0.71	9.9	-16.77	38.6	45.38	13.75
8. 50% irrigation, 50% fertilization	5969.8	-1.00	1472.0	9.3	156.9	44.7	9.95	255.3	6.81	11.5	-0.71	7.0	-41.08	7.4	-72.28	48.18
9. 50% irrigation, zero fertilization	5507.7	-8.67	1428.5	9.3	-----	45.2	11.16	179.7	-24.82	11.5	-0.71	5.2	-56.11	0.01	-99.95	-----

<sup>a</sup> Full rate of 2005-season irrigation = 48.55 cm

<sup>b</sup> Full rate of 2005-season fertigation = 312.4 kg/ha

<sup>c</sup> Nitrogen Use Efficiency

Description of method			Total N Input (kg/ha)					Total N losses (kg/ha)								NUE <sup>f</sup> %
	Crop yield (kg/ha)	Percent change in crop yield	Storage (10.8m-profile)	Rain	Ferti-gation <sup>e</sup>	Mineral-ization	Percent change in mineral-ization	Plant uptake	Percent change in plant uptake	Deep seep-age	Percent change in deep seepage	Denitri-fication	Percent change in denitri-fication	Volatili-zation	Percent change in volatili-zation	
10. Full rate irrigation <sup>d</sup> , full rate fertilization <sup>e</sup>	6054.4	-----	1559.6	9.4	434.5	40.6	-----	231.3	-----	11.6	-----	15.0	-----	58.7	-----	10.52
11. Full rate irrigation, 50% fertilization	6017.8	-0.60	1486.1	9.4	217.3	40.8	0.42	254.9	10.20	11.6	0.0	9.1	-39.12	11.3	-80.83	31.91
12. Full rate irrigation, zero fertilization	5198.8	-14.1	1426.3	9.4	-----	40.9	0.80	185.6	-19.77	11.6	-0.00	5.4	-63.76	0.01	-99.98	-----
13. 50% irrigation, full rate fertilization	5995.0	-0.98	1553.1	9.3	434.5	44.4	9.37	237.8	2.80	11.5	-0.71	12.1	-19.67	84.4	43.75	13.36
14. 50% irrigation, 50% fertilization	5978.8	-1.25	1489.6	9.3	217.3	44.5	9.74	240.5	3.96	11.5	-0.71	8.0	-46.58	16.2	-72.39	27.96
15. 50% irrigation, zero fertilization	5507.7	-9.03	1428.5	9.3	-----	45.2	11.25	179.7	-22.30	11.5	-0.71	5.2	-65.31	0.01	-99.98	-----

<sup>d</sup> Full rate of 2005-season irrigation = 48.55 cm

<sup>e</sup> Full rate of 2005-season fertigation = 434.5 kg/ha

<sup>f</sup> Nitrogen Use Efficiency

## **Publications and Presentations**

- Sophocleous, M. A., Townsend, M. A., Willson, T., and Vocasek, F., and Zupancic, J., 2006, Fate of nitrate beneath fields irrigated with treated wastewater in Ford County, Kansas: First-year Progress Report to KWRI, 62 p.
- Sophocleous, M. A., Townsend, M. A., Willson, T., and Vocasek, F., 2006, Fate of nitrate beneath fields irrigated with treated wastewater in Ford County, Kansas: 23<sup>rd</sup> Annual Water and the Future of Kansas Conference, Topeka, KS, March 16, 2006.
- Sophocleous, M. A., Townsend, M. A., Willson, T., and Vocasek, F., 2006, Preferential flow and transport of nitrate beneath fields irrigated with treated wastewater in Ford County: Geological Society of America, GSA Abstracts with Program, v. 38, no. 7, p. 40.
- Townsend, M. A., Macko, S. A., Sophocleous, M. A., Vocasek, F., Schuette, D., and Ghijssen, R., 2006, Documenting seasonal variation at a wastewater irrigation site through stable isotopes: Geological Society of America, GSA Abstracts with Program, v. 38, no. 7, p. 40.
- Sophocleous, M. A., Townsend, M. A., and Vocasek, F., 2007, Treated wastewater and nitrate transport beneath irrigated fields near Dodge City, Kansas: Water and the Future of Kansas Conference, March 15, 2007, Topeka, KS.
- Townsend, M. A., Macko, S. A., Sophocleous, M. A., Vocasek, F., Schutte, D., and Ghijssen, R., 2007, Variations in water chemistry and plant uptake of nitrogen at a wastewater irrigation site: Water and the Future of Kansas Conference, March 15, 2007, Topeka, KS.

Note: A journal manuscript based on this report and additional ongoing work is under preparation.

## **Information Transfer**

See Publications and Presentations above. In addition, Dodge City TV broadcasting news services recorded our dye-tracer experiments in November 2005 and interviewed co-PI Fred Vocasek on this project. See also Student Support below.

## **Student Support**

A graduate student in the School of Engineering of the University of Kansas is being supported by this project. Main duties include data processing and numerical modeling. An MS non-thesis project based on this study is now being pursued by the graduate student (Ashok KC). An additional hourly student from Kansas State University based in the Garden City Agricultural Experiment Station has been supported for conducting periodic neutron moisture-content readings at the field sites.

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## **APPENDIX A**

Effluent composition (nutrient variables) applied at the study sites N7 and R8 during 2005 and 2006.

Table A1. Effluent composition, irrigation stations, nutrient variables (OMI Lab)

Sample location	Sample date	TKN	NH <sub>3</sub> -N	NO <sub>3</sub> -N	Organic-Nitrogen	PO <sub>4</sub> -P
		mg/L	mg/L	mg/L	mg/L	mg/L
Irrigation station#1 (irrigating site N7)	4/14/05	88.0	85.0	0.7	3.0	11.4
	5/17/05	79.0	57.9	7.3		10.8
	6/21/05	81.0	64.0	27.0	17.0	9.6
	7/22/05	81.0	76.9	0.0	4.1	10.7
	8/30/05	80.0	65.3	1.7	14.7	9.8
	9/23/05	20.0	4.5	23.4	15.5	8.9
	10/28/05	65.0	55.2		9.8	10.4
	8/3/05	80.0	70.0	<1.0	10.0	
	4/27/06	91.0	85.7	0.0	5.3	11.2
	5/26/06	90.0	80.9	0.0	9.1	10.8
	6/15/06	130.0	86.3	0.0	43.7	11.7
	7/21/06	95.0	90.2	0.0	4.8	12.5
	8/11/06	100.0	80.2	0.0	19.8	13.9
	9/21/06	110.0	85.8	0.0	24.2	17.0
10/25/06	110.0	90.0	0.0	20.0	16.7	
Irrigation station #2 (irrigating site R8)	6/21/05	30.0	18.8	13.8	11.2	10.0
	7/22/05	29.0	26.2	22.8	2.8	10.9
	8/30/05	57.0	33.3	0.8	23.8	8.6
	9/23/05	20.0	0.3	24.8	19.7	6.2
	10/28/05	15.0	0.4		14.6	4.8
	8/3/05	50.0	20.0	20.0	10.0	26.0
	4/27/06	40.0	32.5	3.6	7.5	8.7
	5/26/06	20.0	12.4	25.6	7.7	9.2
	6/15/06	51.0	36.9	0.0	14.1	10.9
	7/21/06	79.0	68.2	1.0	10.8	11.3
8/11/06	65.0	54.2	0.0	10.8	12.0	
9/21/06	72.0	42.5	1.3	29.5	11.3	



Table A2. 2005 effluent composition, irrigation stations, nutrient variables (Servi-Tech Lab)					
		TKN	NH <sub>3</sub> -N	NO <sub>3</sub> -N	PO <sub>4</sub> -P
Sample location	Sample date	mg/L			
Irrigation station #1 (irrigating site N7)	4/14/05	88	85	0.7	11.4
	5/17/05	79	58	7.3	10.8
	6/21/05	81	64	27.0	9.6
	7/22/05	81	77	0.0	10.7
	8/30/05	80	65	1.7	9.8
	9/23/05	20	5	23.4	8.9
	10/28/05	65	55	0.0	10.4
Irrigation station #2 (irrigating site R8)	6/21/05	30	19	13.8	10.0
	7/22/05	29	26	22.8	10.9
	8/30/05	57	33	0.1	8.6
	9/23/05	20	0	24.8	6.2
	10/28/05	15	0	0.0	4.8
2005 mean values					
Irrigation station #1 (N7)		70.6	58.4	8.6	10.2
Irrigation station #2 (R8)		30.2	15.6	12.3	8.1
Irrigation station #1 (irrigating site N7)	4/27/06	91	86	0.0	11.2
	5/26/06	90	81	0.0	10.8
	6/15/06	130	86	0.0	11.7
	7/21/06	95	90	0.0	12.5
	8/11/06	100	80	0.0	13.9
	9/04/06	110	86	0.0	17.0
	10/25/06	110	90	0.0	16.7
Irrigation station #2 (irrigating site R8)	4/27/06	40	33	3.6	8.7
	5/26/06	20	12	25.6	9.2
	6/15/06	51	37	0.0	10.9
	7/21/06	79	68	1.0	11.3
	8/11/06	65	54	0.0	12.0
	9/04/06	72	43	1.3	11.3
	10/25/06				
2006 mean values					
Irrigation station #1 (N7)		103.7	85.6	0.0	13.4
Irrigation station #2 (R8)		54.5	41.2	5.3	10.6

# Assessment of Seasonal, Pumping Induced Water Quality Changes in the Ozark Plateaus Aquifer System, Southeast Kansas and Southwest Missouri -- Year 2

## Basic Information

<b>Title:</b>	Assessment of Seasonal, Pumping Induced Water Quality Changes in the Ozark Plateaus Aquifer System, Southeast Kansas and Southwest Missouri -- Year 2
<b>Project Number:</b>	2006KS50B
<b>Start Date:</b>	3/1/2006
<b>End Date:</b>	2/28/2008
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	2nd
<b>Research Category:</b>	Ground-water Flow and Transport
<b>Focus Category:</b>	None, None, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Peter Allen MacFarlane, Rudolf T Ghijsen

## **Publication**

1. Macfarlane, P.A., and Ghijssen, R., 2007, Assessment of seasonal pumping-induced water quality changes in the Ozark Plateaus aquifer system: Water and the Future of Kansas Conference Proceedings, Topeka, Kansas, March 15,2007, p. 19.
2. Macfarlane, P.A., and Ghijssen, R., 2007, Assessment of seasonal pumping-induced water quality changes in the Ozark Plateaus aquifer system: Water and the Future of Kansas Conference, Topeka, Kansas, March 15,2007.

ASSESSMENT OF SEASONAL, PUMPING-INDUCED WATER QUALITY CHANGES IN  
THE OZARK PLATEAUS AQUIFER SYSTEM, SOUTHEAST KANSAS AND  
SOUTHWEST MISSOURI

Start Date

March 1, 2006

End Date

February 29, 2008

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Key Words:

Ozark Plateaus aquifer system, Springfield Plateau aquifer system, Ozark aquifer, water quality,  
pumping stress

## **Problem and Research Objectives**

The Ozark Plateaus aquifer system consists of the Springfield Plateau and underlying Ozark aquifers and historically has been the single most important source of water in the Tri-State region of southeast Kansas, southwest Missouri and northeast Oklahoma. Concerns have been raised by the Kansas water agencies and the Tri-State Coalition (a multi-state organization consisting of water-related interest groups from the Tri-state region) that the available supply from the Ozark aquifer may become inadequate, rendered unusable, or require additional water treatment in the near future because of future overdevelopment. In response, the Division of Water Resources, Kansas Department of Agriculture (DWR) has instituted a moratorium on new appropriations from the aquifer system in southeast Kansas. The Southeast Kansas Ozark Aquifer Water Supply Study was also conducted by the Kansas Geological Survey to redesign a new water-level monitoring network.

Many southeast Kansas and southwest Missouri water supplies withdraw water from a 40-60-km wide transition zone in the Ozark aquifer separating low dissolved solids calcium-bicarbonate ground waters to the east from sodium chloride brines to the west (Figure 1). These supplies withdraw water using single or multi-aquifer wells. Two earlier regional studies indicated significant short and long-term changes in the chemical quality of produced water from these wells. It is unclear if the observed variability results from quality degradation in the Ozark, the Springfield Plateau, or both aquifers over the entire transition zone due to long-term use or if short-term variability in pumping stress is the dominant influence on water quality. The former implies eastward movement of poorer quality water whereas the latter implies local upconing of poorer quality water from the lower part of the aquifer. The data needed to evaluate these mechanisms is currently unavailable. Earlier studies were done in the 1970s and early 1980s and no synoptic sampling has since been carried out to assess how these changes have progressed within the transition zone in southeast Kansas and southwest Missouri.

The goal of this proposed project is to assess the influence of pumping on the temporal variability in the quality of water produced in single and multi-aquifer wells in two small areas within the Ozark aquifer transition zone in Crawford and Cherokee counties in southeast Kansas and Barton and Vernon counties in southwest Missouri. Toward this end, the first year of the project has focused on characterizing the magnitude and timing of the changes in the geochemistry of the Ozark Plateaus aquifer system relative to pumping stress at 9 sites within the transition zone in southeast Kansas. The project has also addressed the temporal aspects of water quality change within the Ozark aquifer transition in the 25 years since previous investigations were reported.

The project addresses the following Kansas Water Plan objectives:

By 2015, achieve sustainable yield management of Kansas surface and ground water sources outside of the Ogallala aquifer and areas specifically exempt by regulation.

By 2010, ensure that all public water suppliers have the technical, financial, and managerial capability to meet their needs and Safe Drinking Water Act requirements.

By 2010, less than 5 percent of public water suppliers will be drought vulnerable.

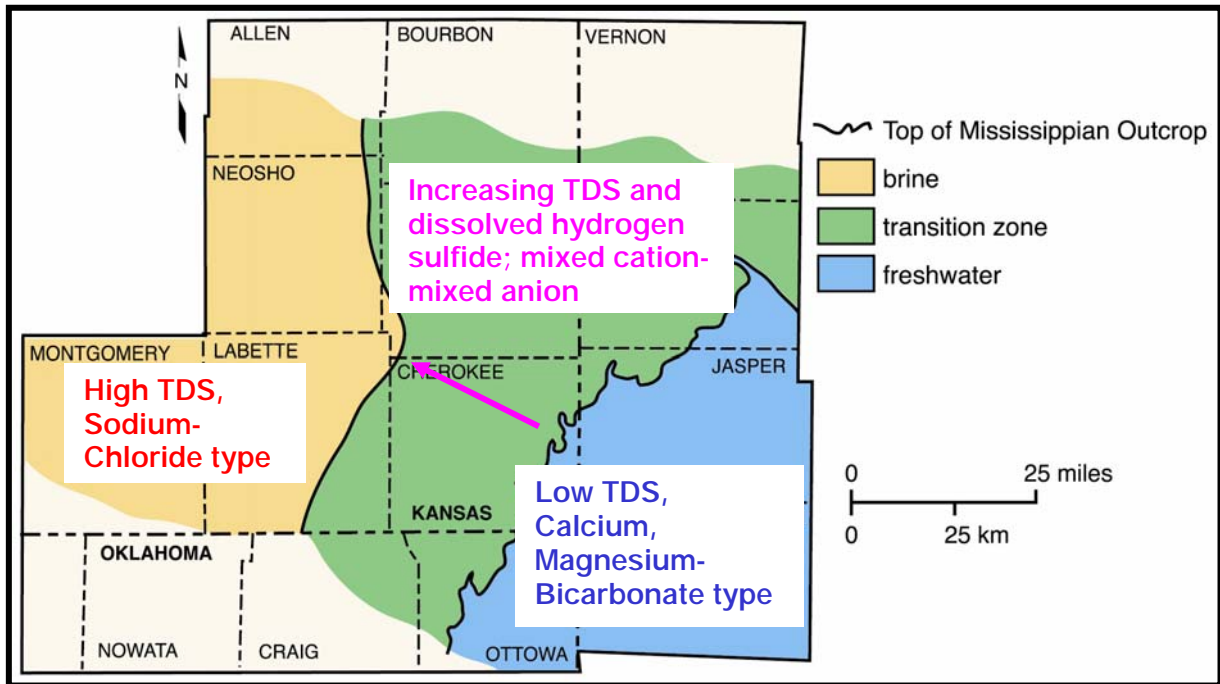


Figure 1. Extent and characterization of the three water quality provinces in the Ozark aquifer in the Tri-State region of southeast Kansas, southwest Missouri, and northeast Oklahoma. Taken from Macfarlane and Hathaway (1987).

## Methodology

*Well selection:* In the initial plan two sets of nearby wells located within the Ozark aquifer transition zone were to be selected for water sampling. Each set was to consist of an Ozark, Springfield Plateau, and multi-aquifer well and ideally the wells in each set were to be located within a few kilometers of each other. However, difficulty was experienced in securing Springfield Plateau aquifer wells for incorporation in the study. As an alternative, nine municipal and rural water district wells located within the Ozark aquifer water-quality transition zone were selected for monthly water sample collection and water-level monitoring (Figure 2, Table 1).

*Water sampling and water-level measurements:* The wells were visited monthly to collect water samples and water-level data. On arrival at the well site the depth to water from surface was measured and the owner/operator was asked when the well was last pumped, if the well had not been pumping. Depth to water measurements were made with a chalked and unweighted steel tape. In October 2006 an In Situ mini-TROLL was installed in an observation in the City of Pittsburg wellfield and set to collect and store for later downloading a measurement every 15 minutes for continuous monitoring (Figure 3).

After the pump was turned on, the sampling port (tap, usually) was opened and the water was allowed to flow. As the water flowed from the sampling point, ground-water temperature and specific conductance were monitored. Samples were not collected until both parameters stabilized and at least one well volume of water had been pumped out. Ground-water

temperature, specific conductance, and pH were measured on site and recorded prior to collection of a water sample. Unfiltered 1 L samples were collected in numbered Nalgene

Table 1. Water supply wells sampled for water quality during the first year of the project.

Water supply	Well Number	Aquifer	Township S	Range E	Sec.	Qualifier
Cherokee RWD 3	1	Ozark	34	24	17	SWSWSE
Columbus	4	Ozark	32	23	13	NENENW
Brock	1	Springfield Plateau	31	25	5	SWNWSE
Weir	1	Ozark Plateaus	31	24	27	NWSESW
Pittsburg	10	Ozark	30	25	28	NENESE
Girard	3	Ozark	30	24	21	NESENE
Crawford Co. RWD 1C	North well	Ozark	30	24	2	SESESE
Crawford Co. RWD 4	3	Ozark Plateaus	31	24	16	NENENE
Crawford Co. RWD 5	1	Ozark Plateaus	30	25	23	SESWSW

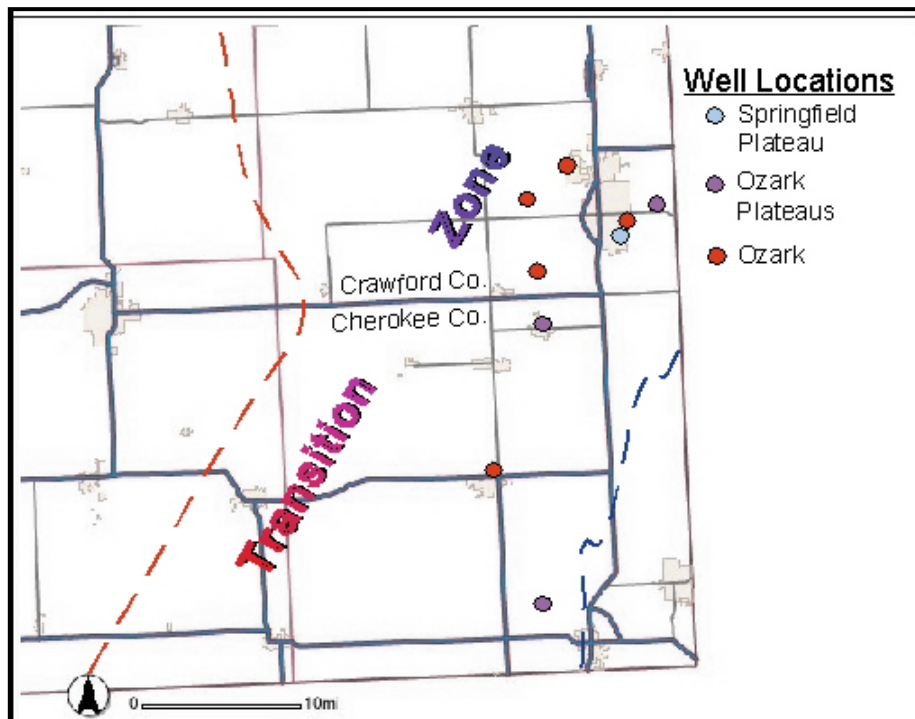


Figure 2. Distribution and construction of water supply wells sampled within the Ozark aquifer transition zone.

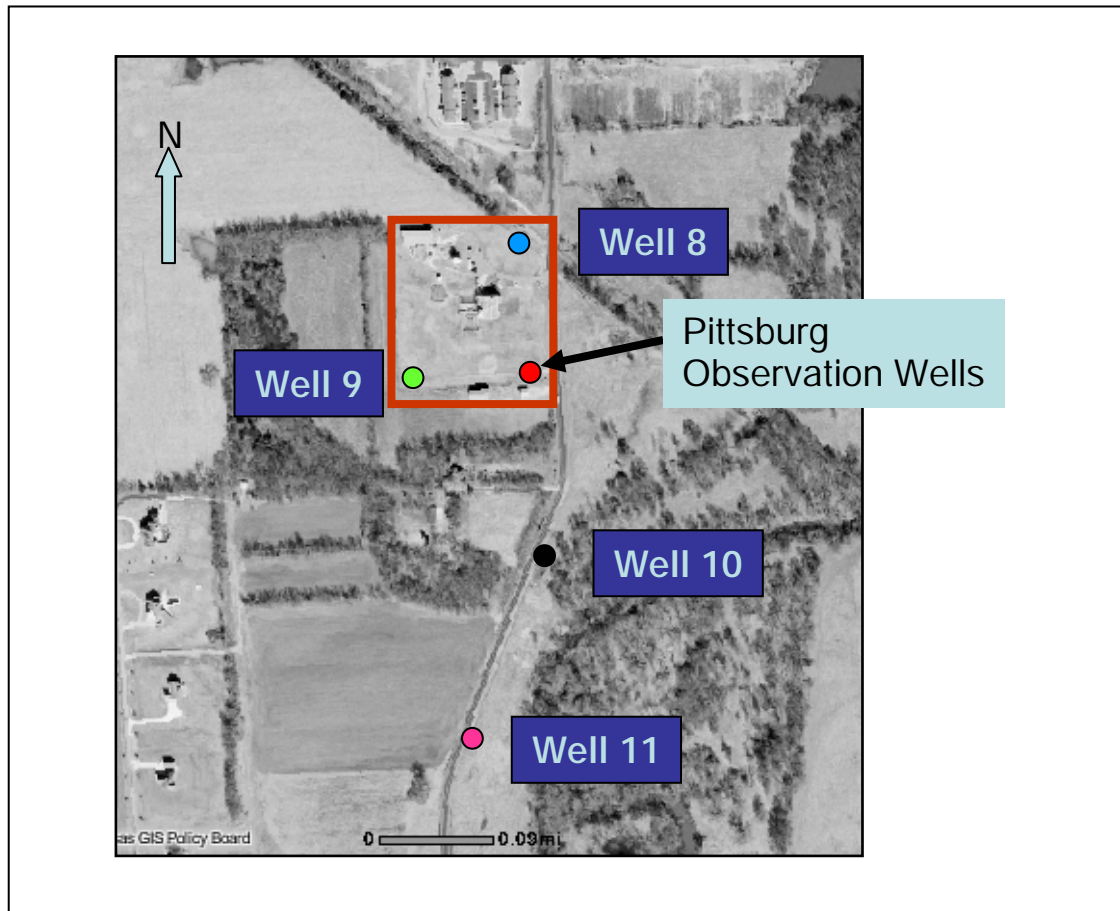


Figure 3. Layout of the City of Pittsburg wellfield with respect to the observation wells.



plastic bottles and stored on ice until their return to the KGS Analytical Services laboratory to be logged in for analysis.

*Water analysis:* After the samples had been logged in, they were filtered using 0.45 µm filter paper to remove suspended sediment prior to chemical analysis. Analyses were completed to determine major and selected minor constituent concentrations using standard atomic absorption and ion chromatographic techniques. pH and bicarbonate were determined in the laboratory using a titrimeter. Concentrations of dissolved silica, calcium, magnesium, sodium, potassium, strontium, and boron were determined using the ICP. Chloride and sulfate were determined using the Alpkem instrument. Fluoride was determined using an ion-specific electrode.

*Pumpage data:* With the exception of the City of Pittsburg, monthly pumpage data were not generally available from most supplies by the end of the first year of the project the DWR.

*High-frequency specific conductance monitoring:* In the project proposal, a downhole sonde was to be inserted in each monitored multi-aquifer well to monitor changes in specific conductance in the zone where waters from both aquifers mix in the well. The high-frequency specific conductance data were to be used to (1) help characterize short-term impacts of pumping on water quality associated with short-term variability (less than one month) in the amount of pumping at each site and (2) develop insight into longer-term water quality changes. This part of the project could not be completed because access to the interior of the well was limited. The probes were generally larger in diameter than that of the access hole. Furthermore, insertion was likely to be unsuccessful because of the danger of getting the sonde entangled in the pumping equipment and cables already suspended in the well. As a result this part of the project was abandoned.

*Data analysis:* The water chemistry data have been used to determine water types and create constituent ratio and time series plots for well sampled. Bar graphs of monthly amounts of ground water pumped from the Pittsburg wellfield were also prepared and compared to the time series water chemistry plots.

## **Results**

The results of the first year of sampling show that the quality of produced water fluctuated in some wells but not others (Figures 4-8). Samples from City of Pittsburg well 8, Crawford Co. Consolidated Rural Water District (RWD) 1, City of Columbus well 4 and Cherokee Co. RWD 3, well 1, showed increases in chloride and a depression of the sulfate concentration in summer months relative to the samples collected during the rest of the year. Cherokee Co. RWD 3 also exhibited increases in bicarbonate and sodium, which suggests an increase in the relative amount of water being drawn into the well from the Springfield Plateau aquifer during periods of more intense pumping. The Springfield Plateau aquifer well is located within a mile of the Pittsburg wellfield. The chemical quality of the water it produces differs significantly from the water produced by the well 8 in the Pittsburg wellfield.

The chemical data from analysis of 1980 water samples from wells tapping the Ozark aquifer near the sodium-chloride type water brine zone have low sulfate to chloride ratios relative to

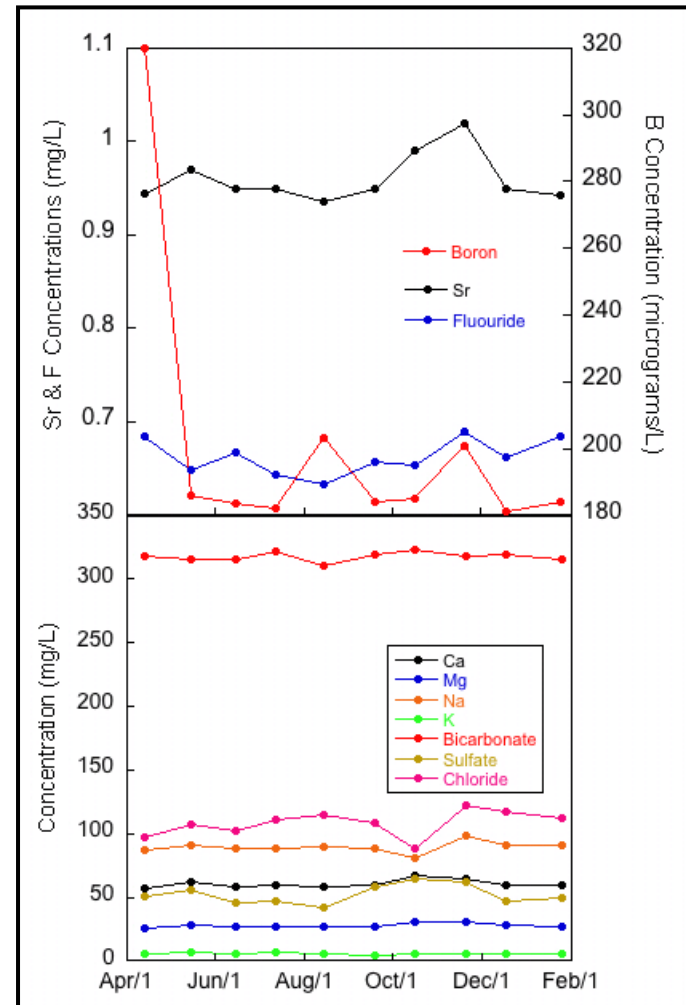
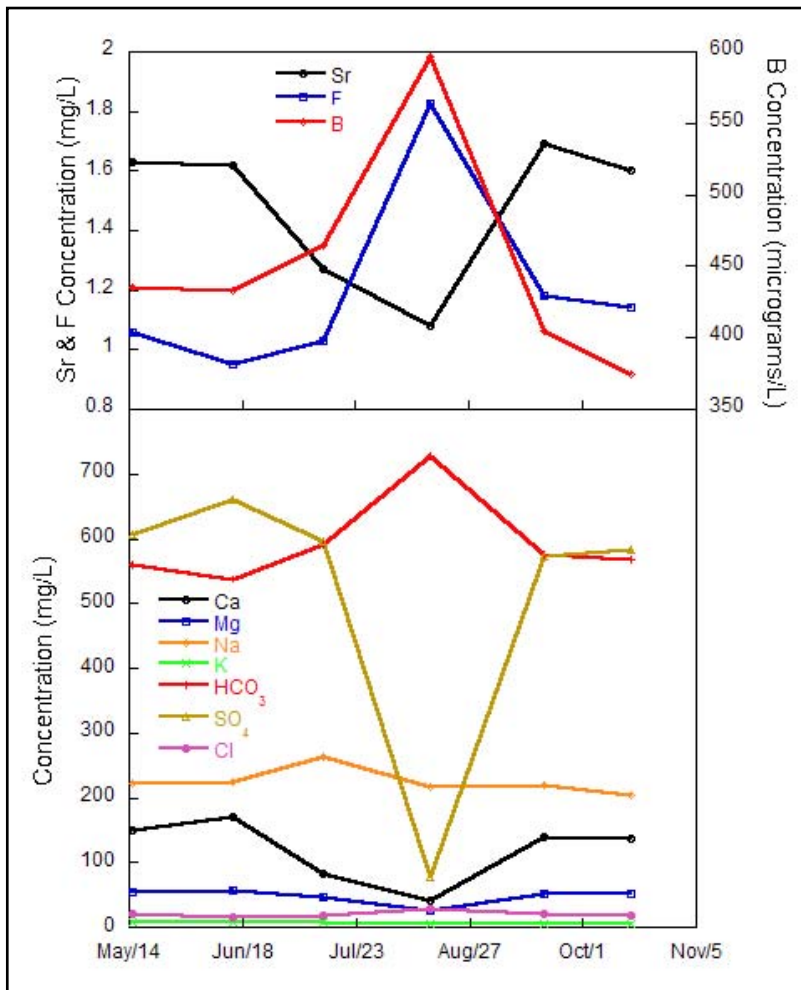


Figure 4. Monthly fluctuations in water chemistry from samples collected from the Springfield Plateau aquifer well at Pittsburg (left) and the Ozark aquifer well, the City of Pittsburg, well 8 (right).

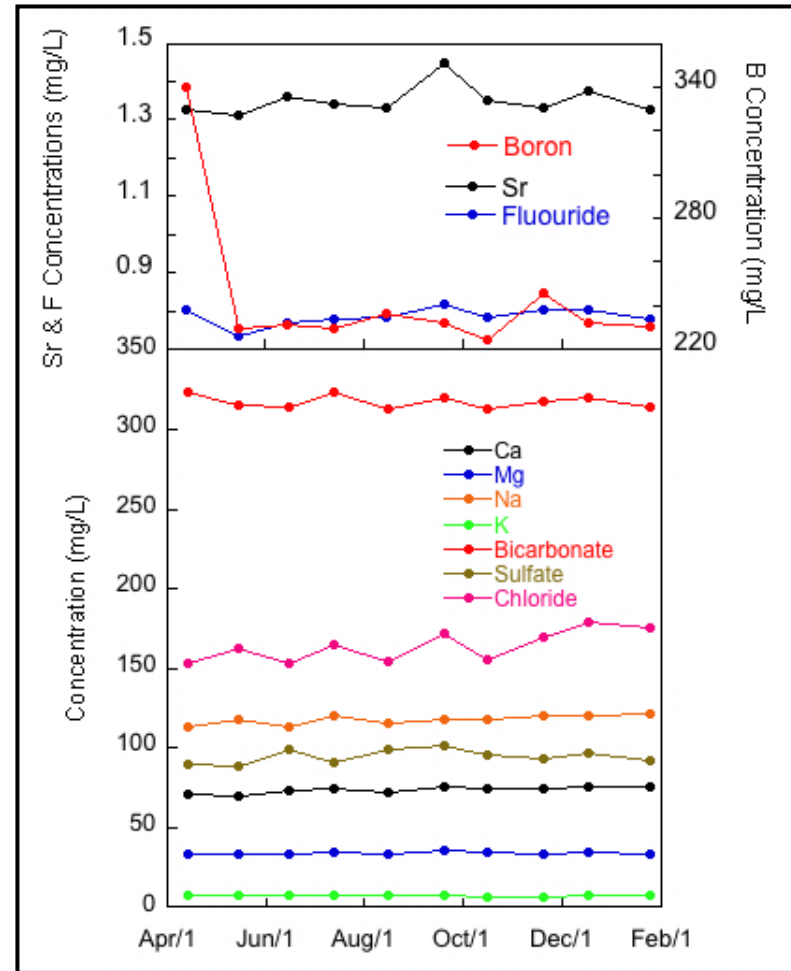
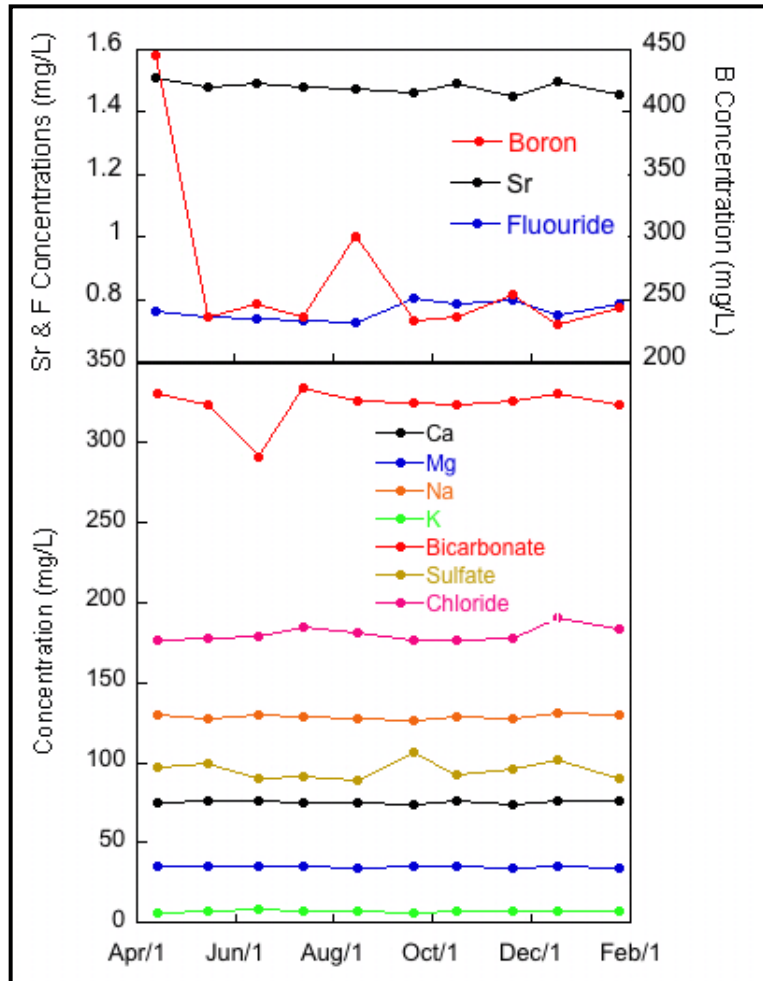


Figure 5. Monthly fluctuations in water chemistry from samples collected from Crawford Co. Consolidated RWD 1, well 1 (left) and the City of Girard, well 3 (right).

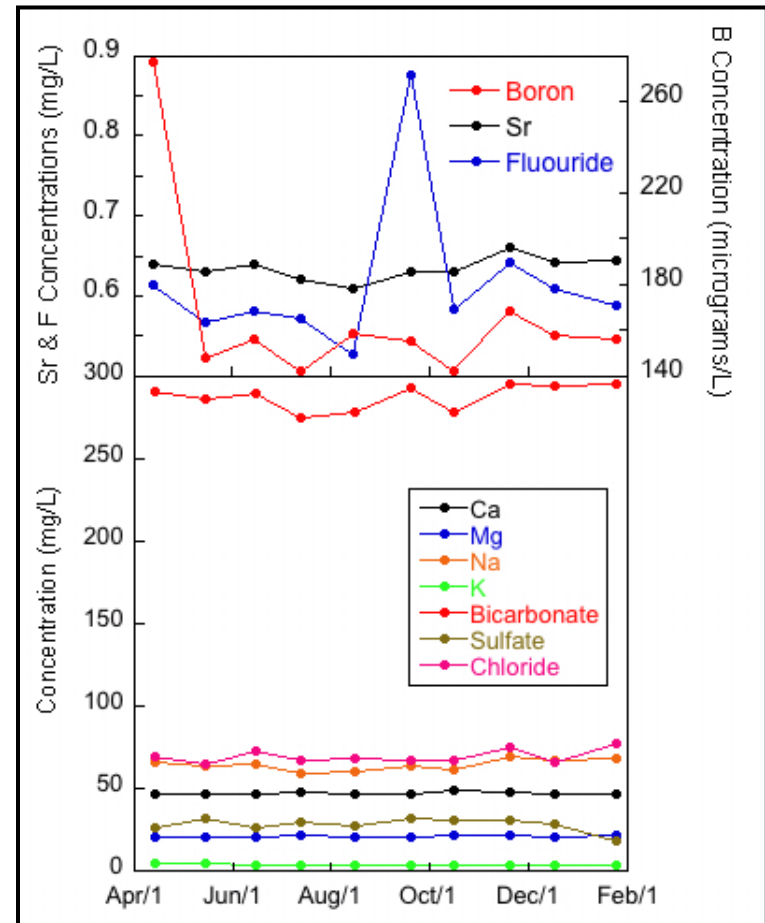
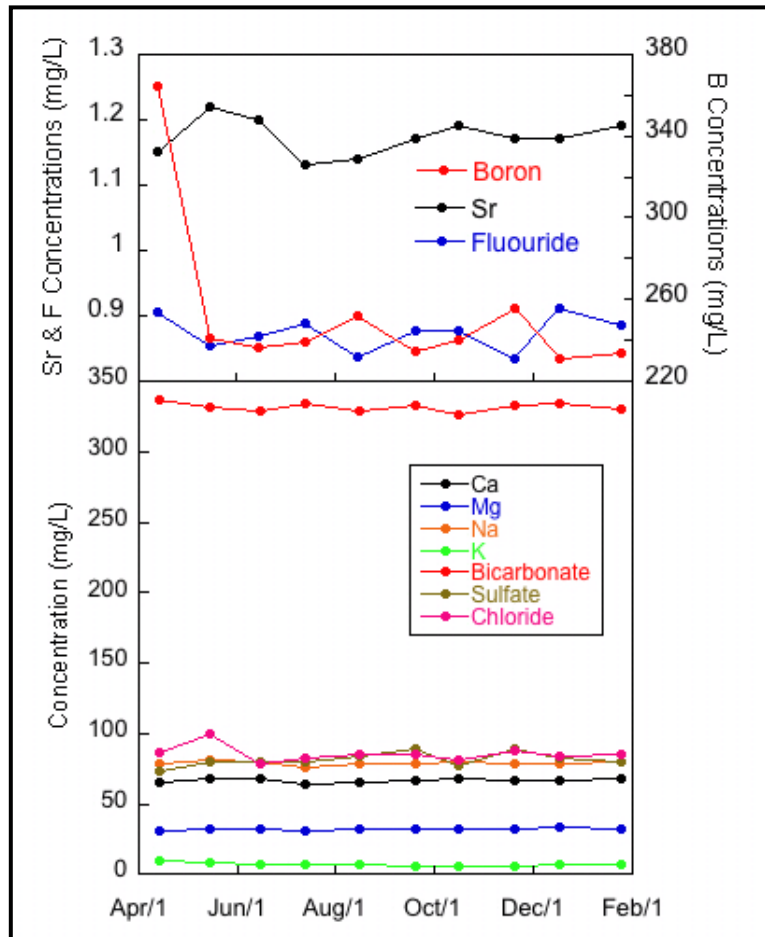


Figure 6. Monthly fluctuations in water chemistry from samples collected from Crawford Co. RWD 4, well 3 (left) and the Crawford Co. RWD 5, well 1 (right).

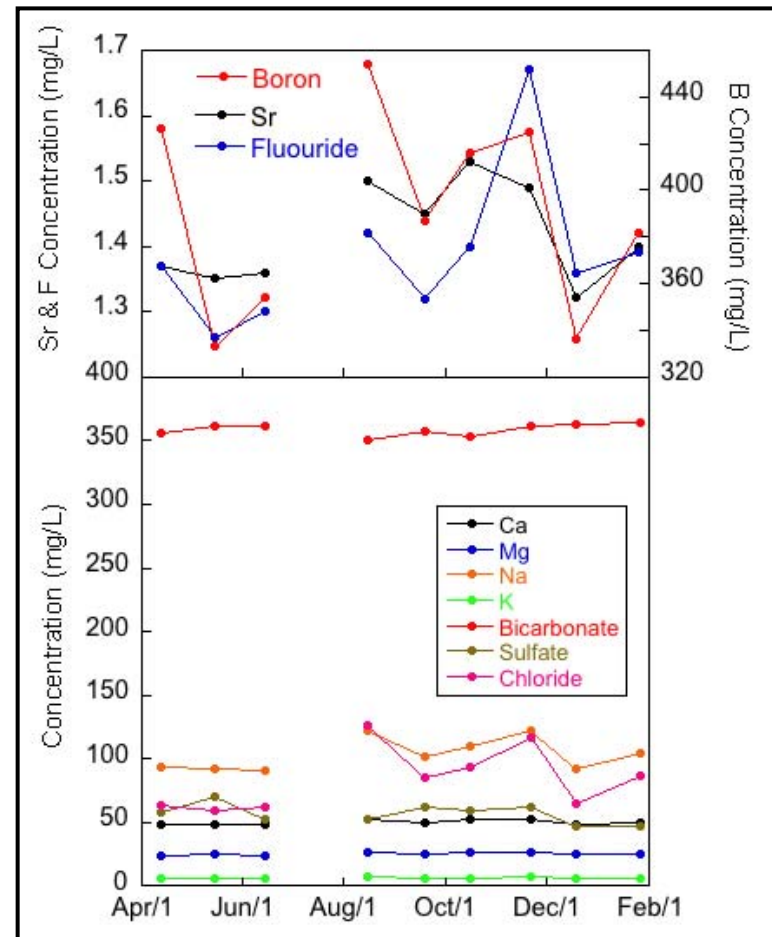
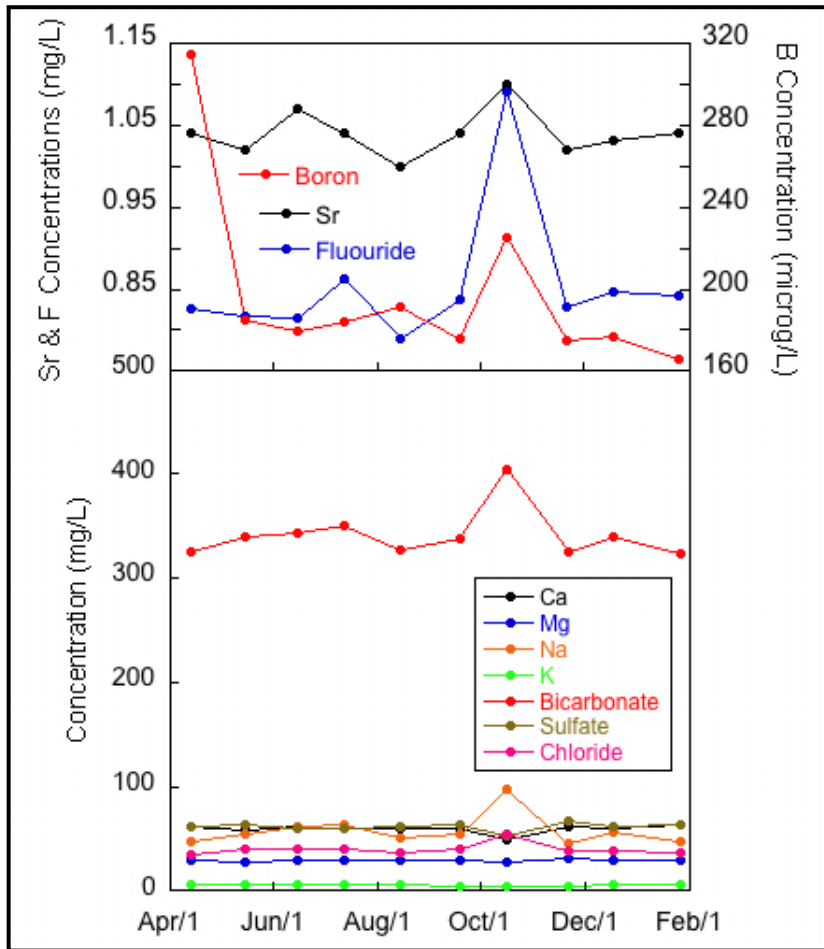


Figure 7. Monthly fluctuations in water chemistry from samples collected from the City of Weir (left) and the City of Columbus, well 4 (right).

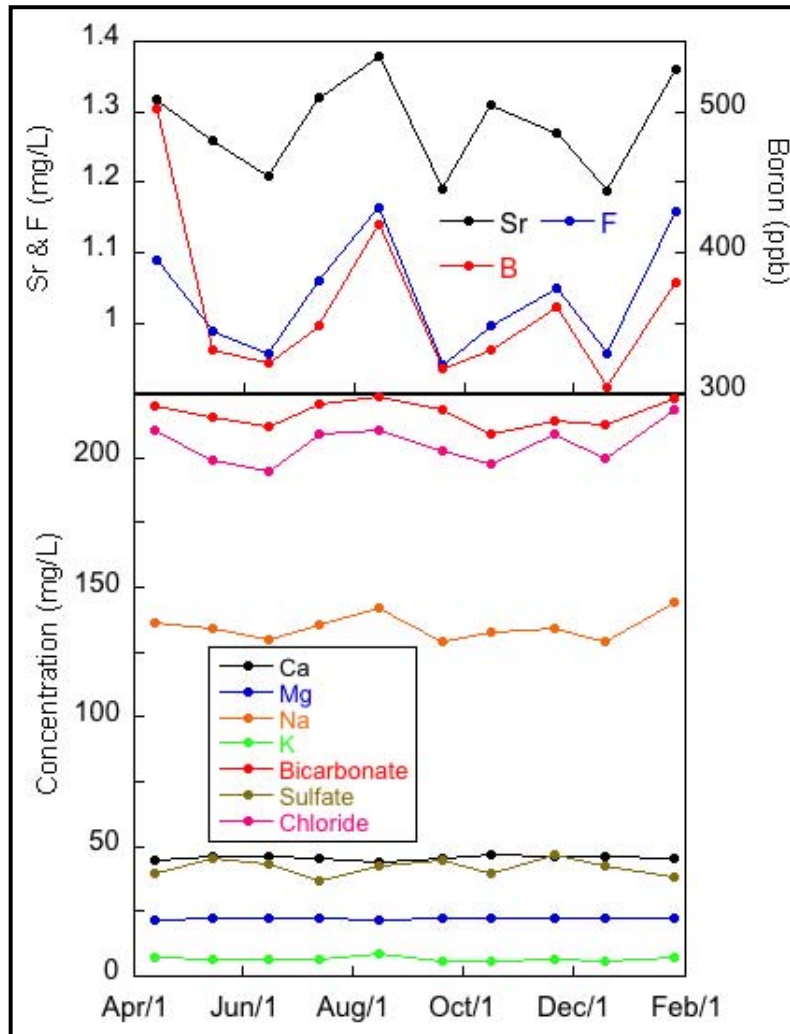


Figure 8. Monthly fluctuations in water chemistry from samples collected from Cherokee Co. RWD 3, well 1.

samples collected from wells located near the low total dissolved solids, calcium-bicarbonate type water zone (Figure 9). The samples collected from this project plot nearer the freshwater samples on the chloride vs. sulfate/chloride graph, clearly following a linear trend in log-log space. Fluctuations in the ratio of sulfate to chloride in the samples collected from the City of Pittsburg well 8 are negatively correlated with the monthly quantity of water withdrawn by all of the wells in the city's field (Figure 10). The negative correlation of the sulfate to chloride ratio and potentiometric surface elevations with monthly pumpage suggests the possibility of upconing of poorer quality ground water in response to reduced fluid pressures in the shallower parts of the Ozark aquifer when pumping from the city's wellfield is more intense.

Comparison of the water chemistry data from this project with the 1980 data indicates that water quality has markedly changed for some of the supplies sampled in this study but not others (Figures 11-14).

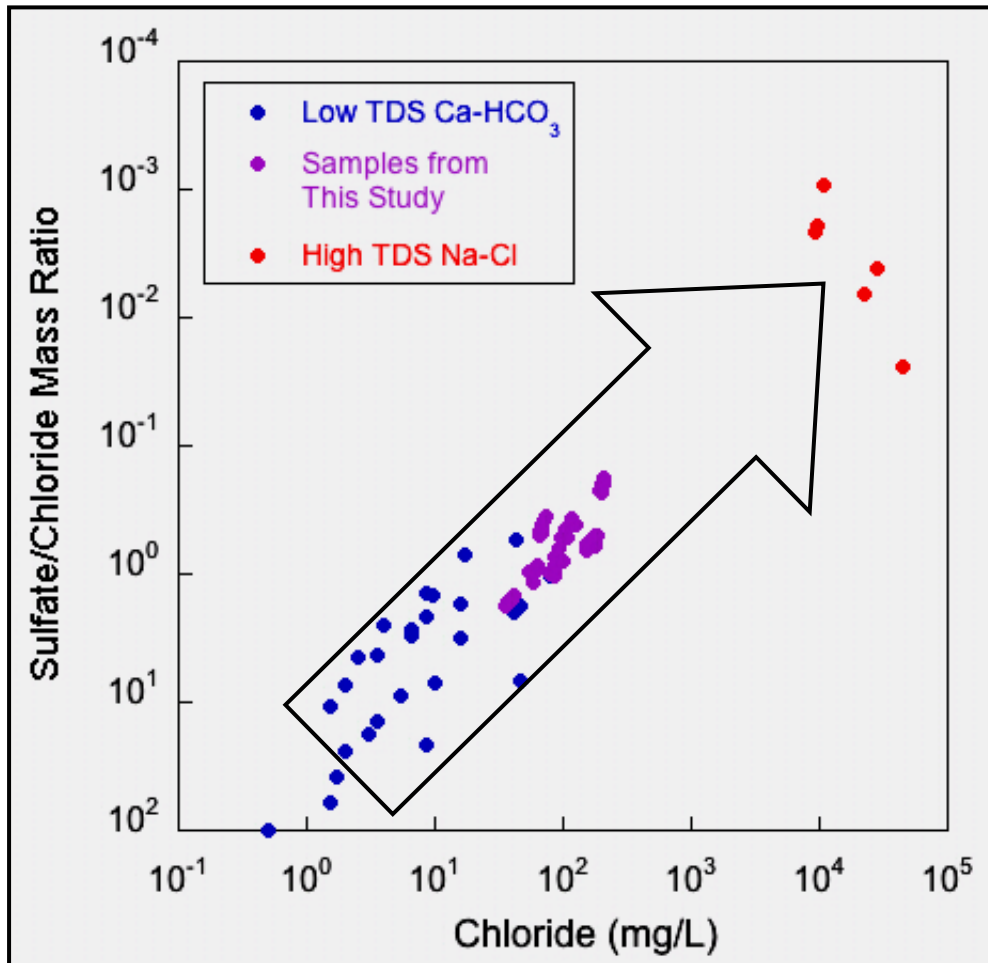


Figure 9. Chloride vs. the ratio sulfate to chloride for the 1980 samples from the low TDS calcium-bicarbonate and sodium-chloride brine portions of the Ozark aquifer and the monthly samples collected in this study.



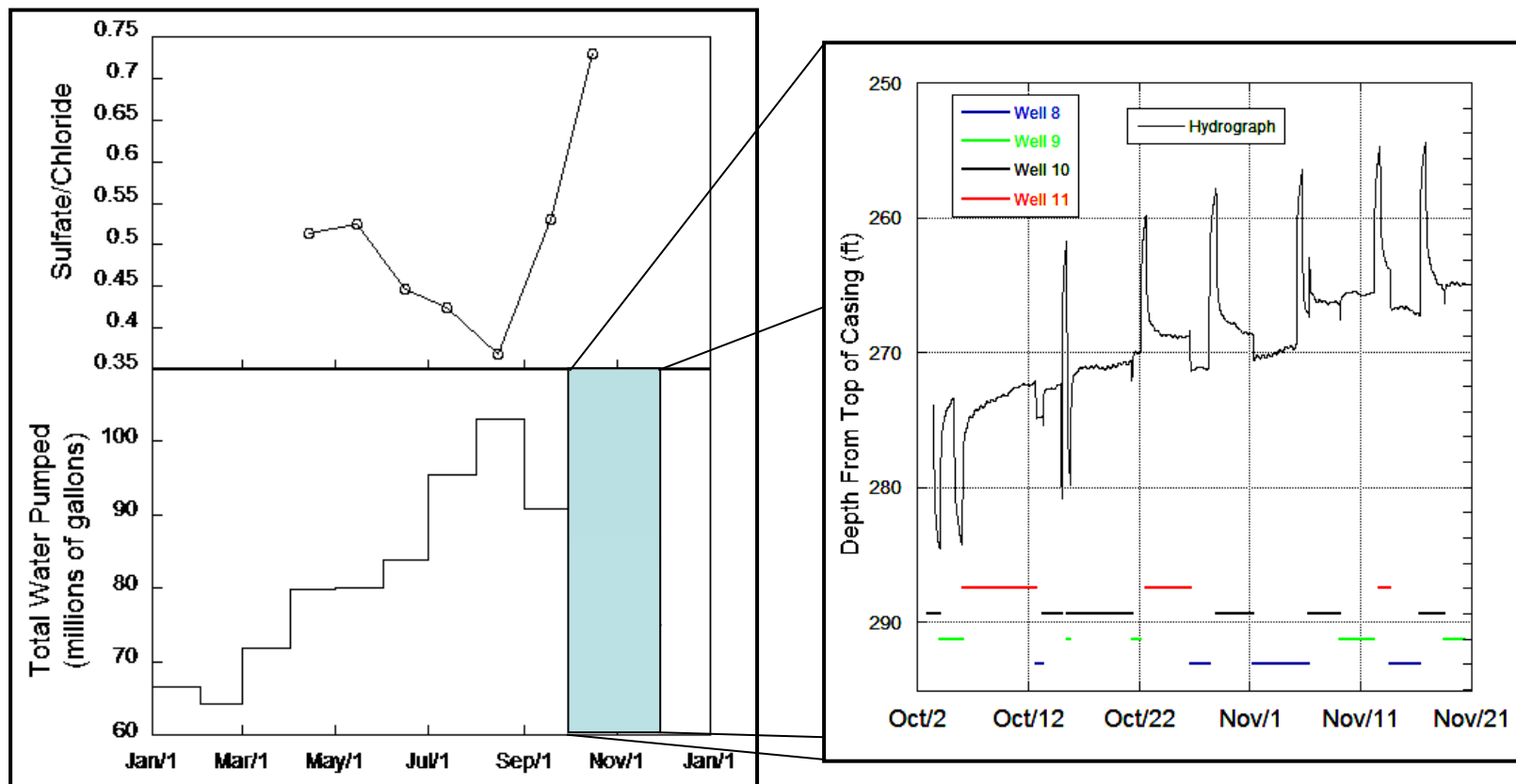


Figure 10. The ratio of sulfate to chloride in monthly water samples from the City of Pittsburg well 8 is negatively correlated with monthly pumpage from Pittsburg’s wellfield. Shown on the right is the hydrograph from the Ozark aquifer monitoring well in the Pittsburg wellfield (Figure 3) derived from high-frequency monitoring.

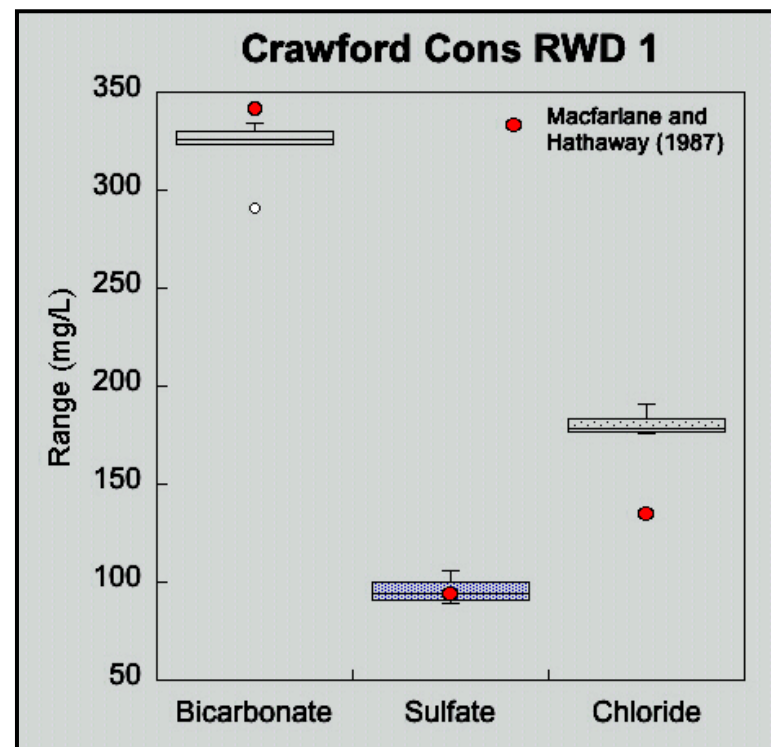
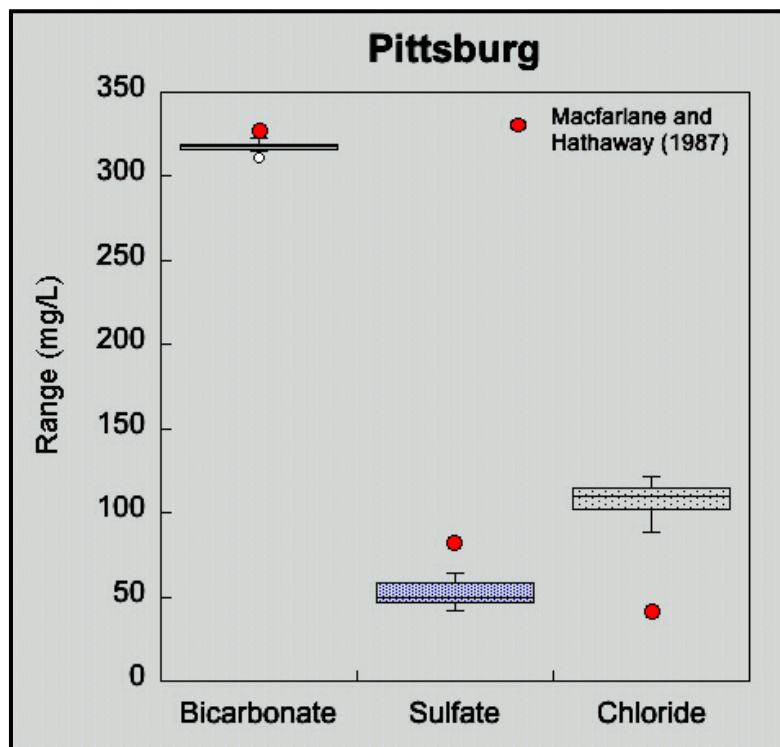


Figure 11. Comparison of the range of bicarbonate, sulfate, and chloride concentrations with 1980 values for the City of Pittsburg well 8 and Crawford Co. Consolidated RWD 1 using box plots.

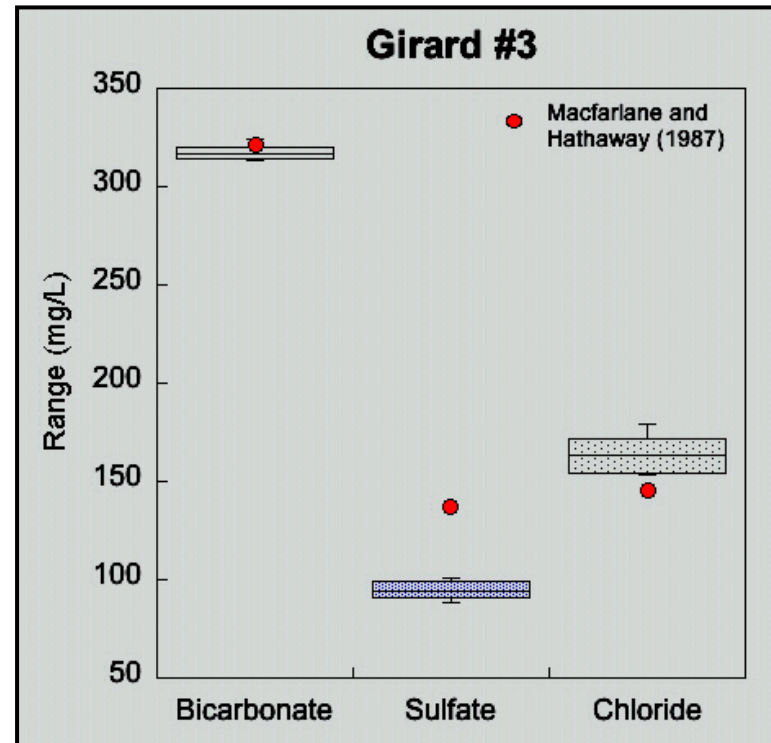
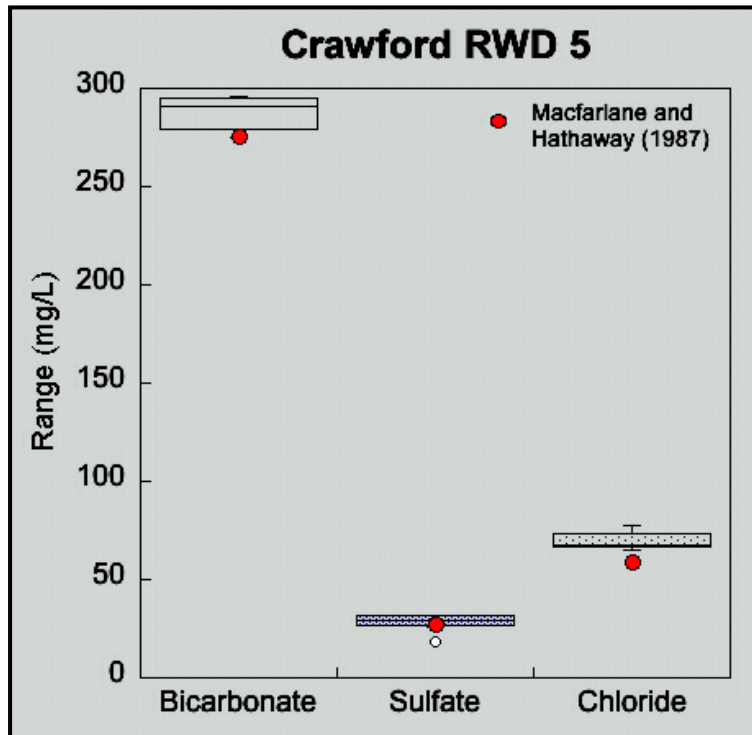


Figure 12. Comparison of the range of bicarbonate, sulfate, and chloride concentrations with 1980 values for Crawford Co. RWD #5 well 1 and the City of Girard well 3 using box plots.

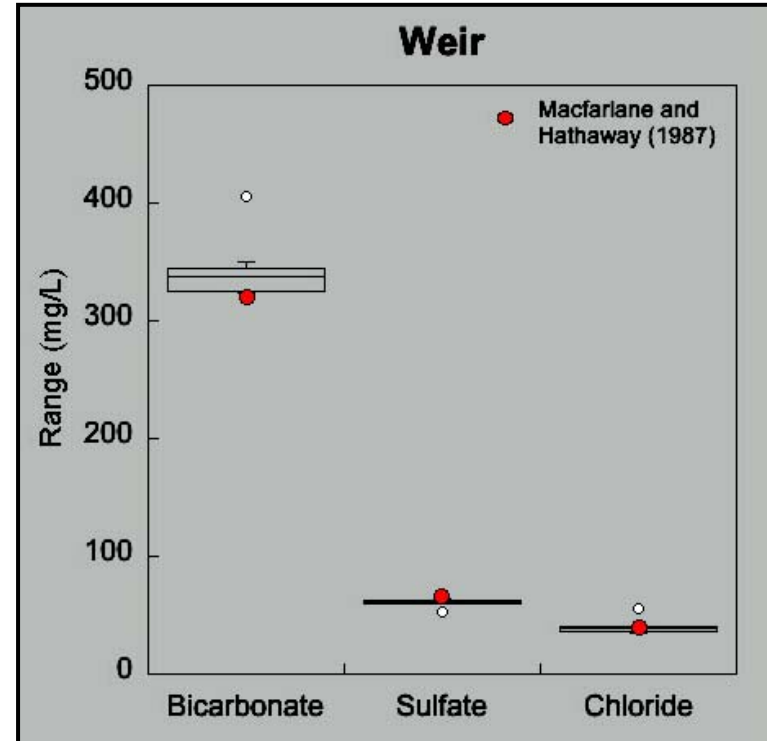
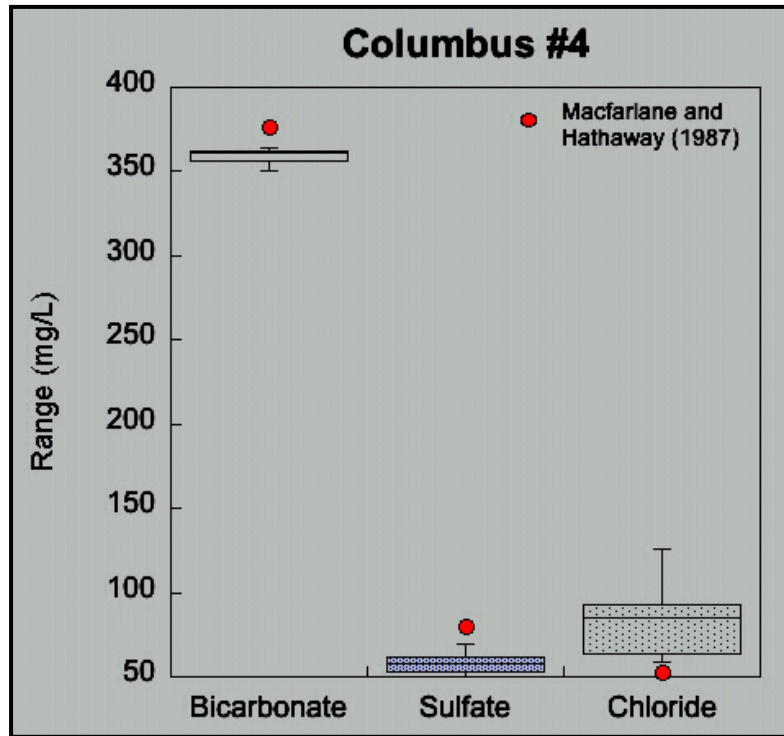


Figure 13. Comparison of the range of bicarbonate, sulfate, and chloride concentrations with 1980 values for the City of Columbus well 4 and the City of Weir using box plots.

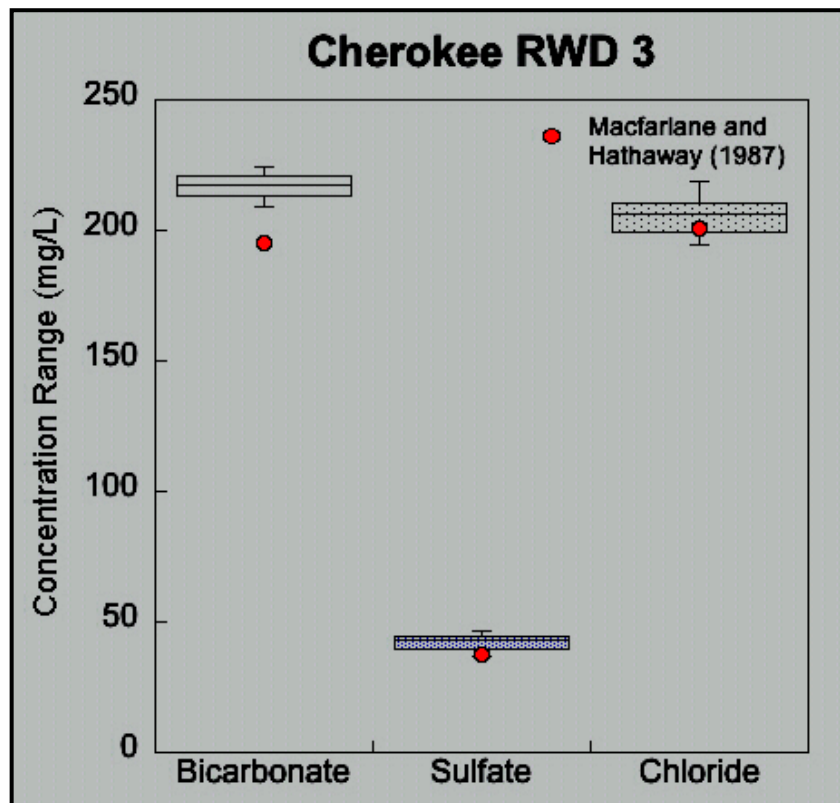


Figure 14. Comparison of the range of bicarbonate, sulfate, and chloride concentrations with 1980 values Cherokee Co. RWD 3 using box plots.

**Publications and Presentations**

Macfarlane, P.A., and Ghijsen, R., 2007, Assessment of seasonal pumping-induced water quality changes in the Ozark Plateaus aquifer system: Water and the Future of Kansas Conference Proceedings, Topeka, Kansas, March 15, 2007, p. 19.

Macfarlane, P.A., and Ghijsen, R., 2007, Assessment of seasonal pumping-induced water quality changes in the Ozark Plateaus aquifer system: Water and the Future of Kansas Conference, Topeka, Kansas, March 15, 2007.

**Information Transfer**

Project results were disseminated through and formal/informal meetings with state and local water agencies and public meetings, and with colleagues conducting the USGS Simulation of the Groundwater Flow System and Water-Quality Assessment in the Kansas Missouri and Oklahoma Tri-State Area project. Whenever possible attempts were made to discuss the results with municipalities and rural water districts in the Tri-State region.

**Student Support**

No students were funded by this project.

# Variations in Nitrogen Water Chemistry at a Wastewater Irrigation Site, Dodge City, Kansas (Part B)

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## Variations in Nitrogen Water Chemistry at a Wastewater Irrigation Site, Dodge City, Kansas (Part B)

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## **Variations in Nitrogen Water Chemistry at a Wastewater Irrigation Site, Dodge City, Kansas (Part B)**

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### **Abstract**

As part of the Kansas Water Resources Institute study at the Dodge City wastewater treatment area for 2006-07 the variation in nitrogen water chemistry was investigated. In the previous study in 2005-06 the water chemistry was found to vary in concentration between the spring 2005 and fall 2005 sampling times. A similar variation was found for the fall 2005 to spring 2006 sampling. Statistically significant trend variation in nitrate and chloride concentrations was found for a number of the monitoring wells at the treatment site. The nitrogen-15 natural-abundance method and additional water chemistry methods were used to determine sources of the nitrate observed in the seventeen monitoring wells and sampled domestic wells in the study area and plants grown at all three sites.

### **Introduction**

The purpose of the water-chemistry evaluation of the Kansas Water Resources Institute study is to identify the sources of nitrate in ground water using the nitrogen-15 natural-abundance isotope method. The nitrate-N concentrations have been increasing in the monitoring well samples since 1990. The values are generally above 2 mg/L (as nitrogen), which is above the USGS National Water Quality Assessment Program limit for water not impacted by human activities (Mueller and Helsel, 1996). Many of the samples have nitrate-N values above the U.S. EPA drinking-water limit of 10 mg/L.

The study area is the Dodge City wastewater treatment site approximately 19 km (12 mi) south of Dodge City, Kansas (Fig. 1). A schematic of the treatment process is shown in Figure 2. The input stream is from both the city wastewater and the meat packing industry wastewater. The waste flows into a collection area and then is sent to three covered anaerobic lagoons (Fig. 2). From there the water is released to an aerobic lagoon where the water is mixed with air to increase release of ammonia gas. The aerobic lagoon water is then released to storage lagoons. From these lagoons water is then land applied using sprinkler irrigation generally during the crop-growing season from April through October.

The two irrigated sites that were investigated in this study are sites R8 and N7 (Fig. 1) with Y8 as a non-wastewater irrigated cropland as a control site. The sites were selected based on length of wastewater treatment: R8 was started in 1986 and N7 was started in 1996, soil properties, and a prior history of soil coring for nitrate and chloride profiles done by Servi-Tech (Zupancic and Vocasek, 2002).

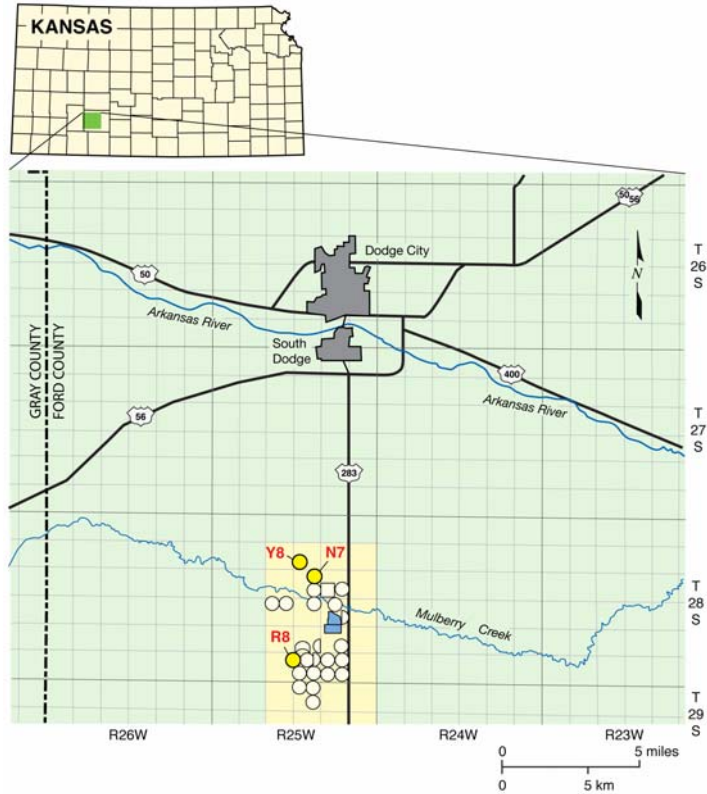


Figure 1. Location of study area south of Dodge City, Kansas. Sites N7 and R8 are wastewater irrigated, site Y8 is not wastewater irrigated.

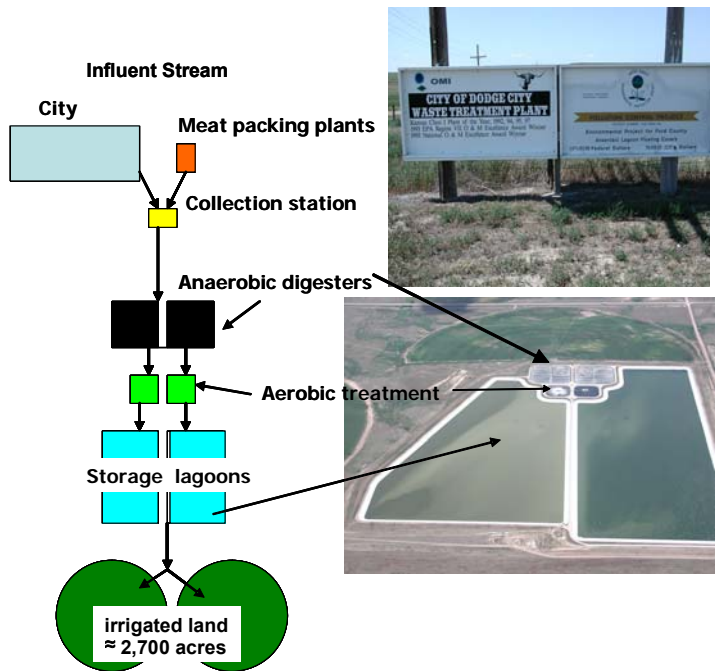


Figure 2. Schematic of waste-treatment process at Dodge City wastewater-treatment facility.

## Methods

### Water Sampling

There are seventeen monitoring wells in the study area (Fig. 3). Most of these wells were installed by CH2M-Hill OMI, Inc. with well records available at the Kansas Geological Survey (KGS) <http://www.kgs.ku.edu/Magellan/WaterWell/index.html> (verified May 2007). These wells were sampled five times from the spring of 2005 to the spring of 2007. In addition, domestic wells near sites N7 and R8 were sampled twice. Other wells in the area were sampled in the summer of 2006. All analyses through 2006 are listed in Appendix A.

The monitoring wells were sampled by personnel from CH2M-Hill OMI, Inc. in the fall and spring of each year. Each well was pumped for several hours in order to clean out the well bore and sample fresh aquifer water. Samples collected for the KGS were stored in 1-L polyethylene bottles and an additional sample was collected for nitrate and other anion analyses in a 250-ml polyethylene bottle with 2-ml of HCl acid for preservation. All samples were stored on ice while in the field and in a refrigerator until shipment to the KGS with ice and ice packs. An additional 1-L to 500-ml sample was collected for isotope analysis. This sample was frozen at the CH2M-Hill OMI laboratory and sent frozen to the KGS where it was stored frozen until sent to the University of Virginia for isotope determination.

Samples were also collected by the KGS from domestic and irrigation wells in the area. Wells were pumped until the specific conductance and temperature were stable with three readings every 5 minutes; usually this took at most 20 minutes. Samples were collected in 500-ml polyethylene bottles for cations, specific conductance, pH, and temperature. A 200-ml sample was collected in a 250-ml polyethylene bottle with 2-ml HCL for preservation for nitrate and anion analyses. Samples were stored on ice until returned to the KGS where they were refrigerated until analyzed.

### Sample Analysis

In the laboratory the KGS filtered the water samples through 0.45- $\mu$ m membrane filter paper before analysis. Specific conductance was measured to estimate chloride concentrations and determine dilution factors for the optimum concentration range of the analytical method for bromide, iodide, and chloride measurement. Chloride, sulfate, bromide, total inorganic iodine, and iodate concentrations were determined using automated colorimetric methods on a Technicon AutoAnalyzer II. Dissolved iodide was computed from the total inorganic iodine and iodate concentrations and used to correct for its effect on the measured bromide in the analytical method. Nitrate content was determined on the AutoAnalyzer using an ultraviolet spectrophotometric method. Bicarbonate content was computed from an alkalinity determination using an automated titrimer. Cation concentrations were measured using an inductively coupled argon plasma spectrometer. Only conductance, chloride, bromide (along with iodine species for bromide correction), and sulfate were determined in the untreated and treated wastewater samples. Charge-balance errors calculated for the well waters for which measurements of all major and substantial minor constituents were completed were all <2% and averaged 1.0%. As a part of its quality assurance steps, the KGS participates in the standard reference water program of the U.S. Geological Survey.

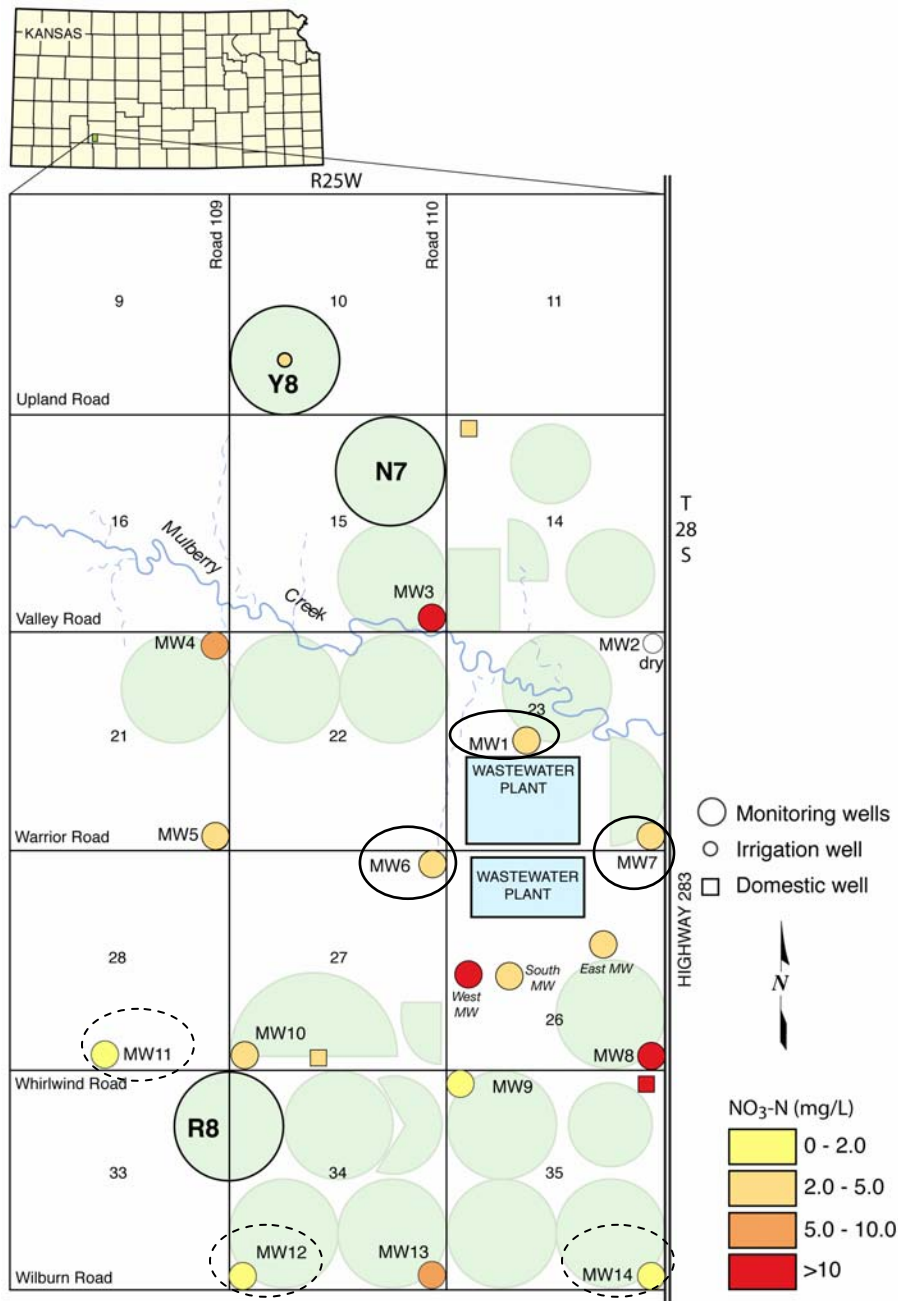


Figure 3. Location of monitoring and domestic wells located at study area. Solid black lines indicate monitoring wells with quarterly nitrate-N and chloride sampling. Dashed black lines indicate wells with decreasing trend in nitrate-N or chloride concentrations from 1985 to 2005.

Servi-Tech Laboratories, Inc., performed complete analyses on the lagoon samples. Laboratory information and chemical data for the ground water and wastewater samples are listed in Appendix A. The table includes the total dissolved solids (TDS) content calculated from the major and minor constituent concentration. In the TDS computation, the bicarbonate was multiplied by 0.4917 to approximate the carbonate that would be left in the residual solids after evaporating to dryness (Hem, 1985).

## Nitrogen-15 Analytical Methods

The nitrogen-15 isotopic composition in the waters was determined at the Department of Environmental Sciences, University of Virginia. Samples of the dried nitrate-containing salts dissolved in the waters were combusted at high temperature to nitrogen gas for analysis of their isotopic compositions. The  $\delta^{15}\text{N}$  was determined on a Micromass Optima isotope ratio mass spectrometer (IRMS) coupled with an elemental analyzer (EA), with an overall precision better than 0.5 ‰. The data are reported relative to a standard (atmospheric  $\text{N}_2$ ) defined to be 0 ‰, and expressed in  $\delta$  notation as

$$\delta_{\text{sample}}(\text{‰}) = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$$

where  $\delta_{\text{sample}}$  represents  $\delta^{15}\text{N}$ , and R is the molar ratio of the heavier ( $^{15}\text{N}$ ) to the lighter ( $^{14}\text{N}$ ) isotope for the standard or sample (Hoefs, 2001). The analyses were run on nitrate in all samples except the wastewater samples, which have ammonium as the dominant nitrogen form.

## Statistical Methods

Nonparametric statistical methods were used for determining if variation occurred between sampling periods and for trend analysis. Splus version 7.02 for Windows (2005) and SAS version 9.1 (2002-03) were used for the statistical analysis. All tests used  $\alpha = 0.10$  for comparison of the calculated  $p$  values. If the  $p$  value is less than  $\alpha = 0.10$  then the alternate hypothesis for the test is accepted.

The Shapiro-Wilk test for goodness of fit to a normal distribution was used to evaluate the data. All of the tested parameters except bicarbonate, magnesium, and boron for the seasonal sampling periods showed a non-normal distribution (Appendix B). For the Shapiro-Wilk test, if the calculated  $p$  value is less than  $\alpha = 0.10$  then the data is considered non-normal in distribution. Because most of the tested parameters had a non-normal distribution, non-parametric statistical methods were used.

The Kruskal-Wallis Rank Sum difference test around the median value was used to determine if the sampling periods were representative of different populations. The Kendall test for trend and the Kendall seasonal test for trend were used to determine if observed increased values were statistically significant for both the inorganic analyses and the isotope values.

## Water Chemistry Results

### Observed Trends in Nitrate and Chloride Data

Monitoring wells 1, 6, and 7 were installed in the early 1990s and were monitored quarterly for nitrate-N and chloride as indicators of potential wastewater leaching to the ground water (Fig.3, black circles). The quarterly monitoring was only continued for these wells until 1999 because of changes in permit regulations to sampling of two times per year.

MW #1 is located north of the lagoons, MW #7 is located east of the lagoons, and MW #6 is located west of the lagoons. Figure 3 also shows the irrigation circles where wastewater is

applied. MW #6 is not located near any wastewater irrigated circles and the water chemistry is probably representative of background water quality in the area.

Figure 4 (a, b, c) shows the variation of the quarterly nitrate-N values for wells 1, 6, and 7, and Figure 5 (a, b, c) shows the variation for quarterly chloride values. The seasonal Kendall test for trend was used to evaluate the presence of trend for samples from all six wells. For both the nitrate-N and chloride, an increasing trend was noticed for MW#7. MW #1 showed a decreasing trend for nitrate-N and an increasing trend for chloride. MW #6 shows no trend for either constituent. This result is expected for MW #6 in that its location is not near any sites of active irrigation, and therefore no immediate source of undiluted wastewater present within the pumping radius of this well (Fig. 3) is known.

Tables 1 (chloride) and 2 (nitrate-N) indicate seasonal trend for all of the monitoring wells from 1985 to 2005. The Seasonal Kendall test for trend shows an increasing trend for the two constituents in a number of the monitoring wells. The wells with samples with increasing concentrations are located within the area of wastewater irrigation. Samples from monitoring wells 11, 12, and 14 show decreasing trends for nitrate-N and/or chloride (Fig. 3 dashed black lines). These wells are located near the edges of the wastewater irrigation fields and may be impacted by regional ground-water chemistry.

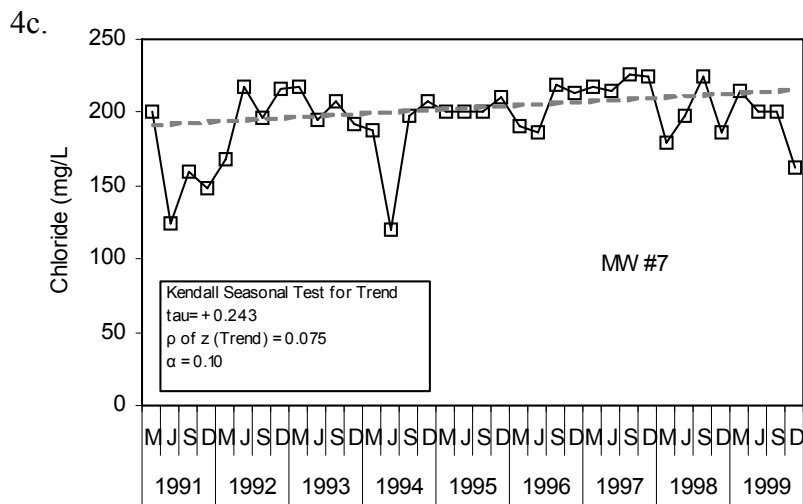
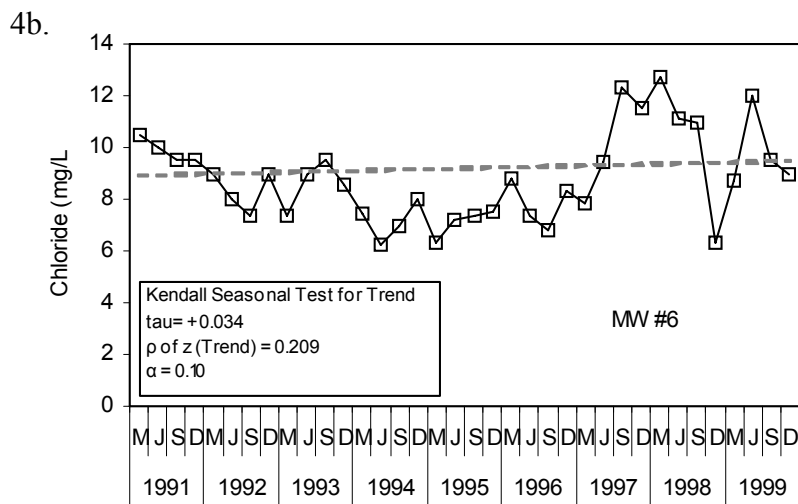
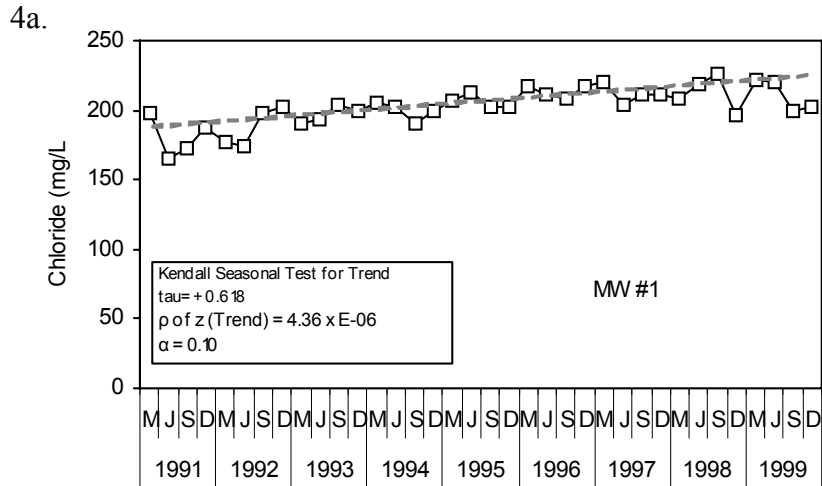


Figure 4. Kendall seasonal test for trend for monitoring wells 1 (4a), 6 (4b), and 7 (4c) for quarterly sampling from 1991 to 1999. MW #1 and MW #7 show increasing trends in concentration. MW #6 shows no trend.



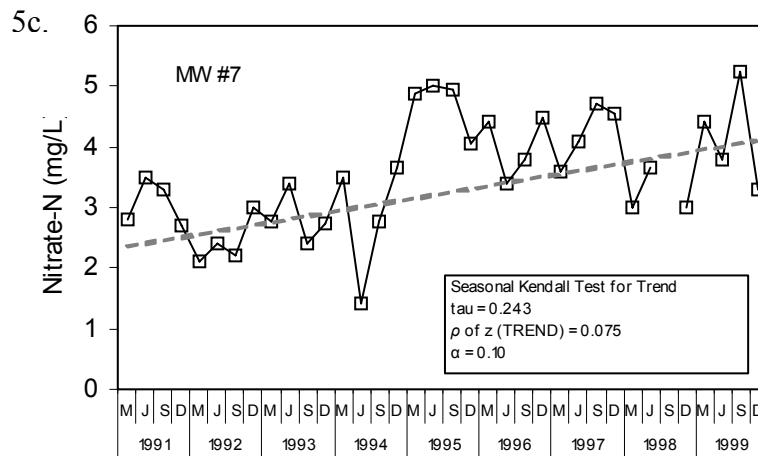
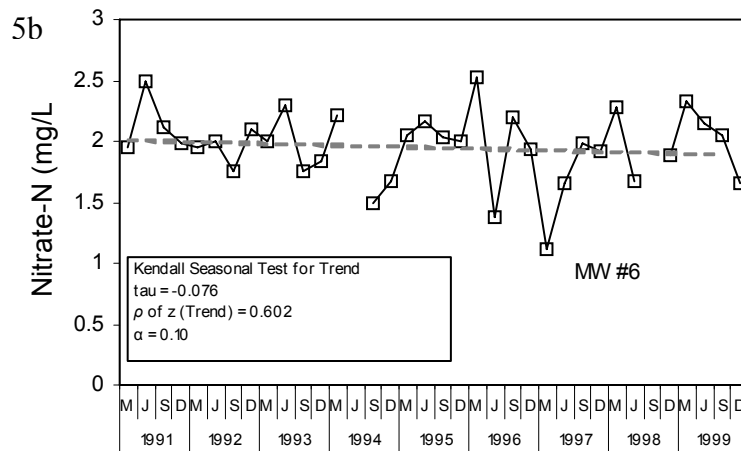
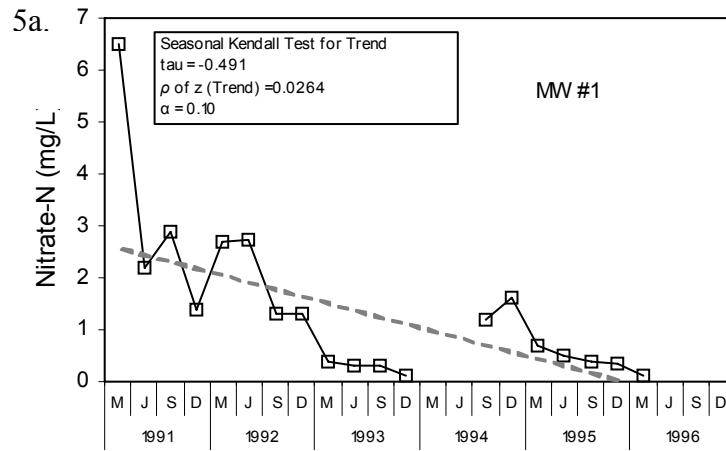


Figure 5 a, b, c. Seasonal Kendall test for trend shows a decreased trend in nitrate-N concentration for MW #1 (a) for 1991 to 1996, no trend for MW #6 (b), and an increasing trend for MW #7 (c).

Table 1. Seasonal Kendall test for trend for chloride concentrations 1985 to 2005.

<b>ID</b>	<b>tau</b>	<b>p value</b>	<b>Trend</b>
MW 1	0.176	0.276	
MW 2	0.389	0.018	increasing
MW 3	0.605	0.0001	increasing
MW 4	-0.037	0.868	
MW 5	-0.133	0.414	
MW 6	-0.219	0.173	
MW 7	0.3	0.0605	increasing
MW 8	0.486	0.002	increasing
MW 9	0.443	0.005	increasing
MW 10	0.366	0.022	increasing
MW 11	-0.348	0.029	decreasing
MW 12	-0.133	0.413	
MW 13	0.228	0.155	
MW 14	-0.366	0.022	decreasing

Table 2. Seasonal Kendall test for trend for nitrate-N concentrations 1985 to 2005.

<b>ID</b>	<b>tau</b>	<b>p value</b>	<b>Trend</b>
MW 1	-0.205	0.358	
MW 2	0.295	0.074	increasing
MW 3	0.367	0.022	increasing
MW 4	0.181	0.263	
MW 5	0.328	0.039	increasing
MW 6	0.1	0.605	
MW 7	0.319	0.045	increasing
MW 8	0.324	0.043	increasing
MW 9	0.485	0.002	increasing
MW 10	0.314	0.048	increasing
MW 11	-0.281	0.079	decreasing
MW 12	-0.438	0.005	decreasing
MW 13	0.038	0.832	
MW 14	-0.057	0.739	

## Trilinear Diagrams

Trilinear Piper diagrams are a method for evaluating changes in water chemistry (Hem, 1985). Work in 2005-06 (Sophocleous et al., 2007) showed that the ground water is a calcium bicarbonate water type except in those parts of the study area that were impacted by long-term wastewater application (Figures 5 and 6).

Variation in the general water chemistry is illustrated by the variation in where wells plot on the diagrams. The ground water was sampled three times (fall 2005, spring 2006, and fall 2006). The wells with stable similar water chemistry for fall 2005 and fall 2006 with spring 2006 are shown in figures 5 and 6 as a separate symbol (green star). These wells are: 1, 4, 5, 6, 11, and 12 for the fall 2005 and fall 2006 time period and wells 4, 5, 6, 9, 10, 11, 12, 14, and West and South for the fall 2006 and spring 2006. The samples from the other monitoring wells show variation in the Piper diagram plot between the sampling periods.

The variation reflected in the graphs is an indication of the variation in the irrigation water chemistry as well as the potential variation in the regional ground water that mixes with the applied water. The parameters that had most spatial variation among the wells are shown in Appendix C. The Kruskal-Wallis test was used on all chemical parameters to see if variation showed up among the wells spatially and temporally.

The three domestic wells sampled during the study also show variation between the fall 2005 and spring 2006 sampling. The occurrence of chemical variation during the years of study suggests that the processes are not stable and that inputs and biological impacts are different at different periods of time. This type of variability needs to be considered when evaluating the methods to control or improve water quality by crop and land-use changes. The number of samples collected is too small to be evaluated statistically.

The two diagrams also show the variation of the wastewater samples collected in the summer of 2005 and the fall of 2006. In addition, the diagrams have the city influent and meat-packing plant influent shown on the diagrams. The city influent is more similar to the ground water of the area as would be expected than is the meat-packing waste. The chemistry of the lagoons shows that the mixing of the two waters makes the wastewater more similar to the meat packing chemistry. This is probably due to the much higher chloride and sulfate concentrations from the packing plants (Appendix A). The chemistry of the wastewater plots in slightly different areas of the graphs depending upon the season of sampling. The variation in the chemistry with time of year is a reflection of the impact of temperature and biological degradation on the chemistry of the water. The differences in the chemistry show up more explicitly in the measured nitrogen-15 isotope values that will be discussed in a later section.

Statistically, the water samples from the monitoring across the area are spatially different. However, the results for the short-term chemistry (seasonal differences) do not show a statistical difference between the sampling periods. Results for the Kruskal-Wallis test are given in Appendix C.

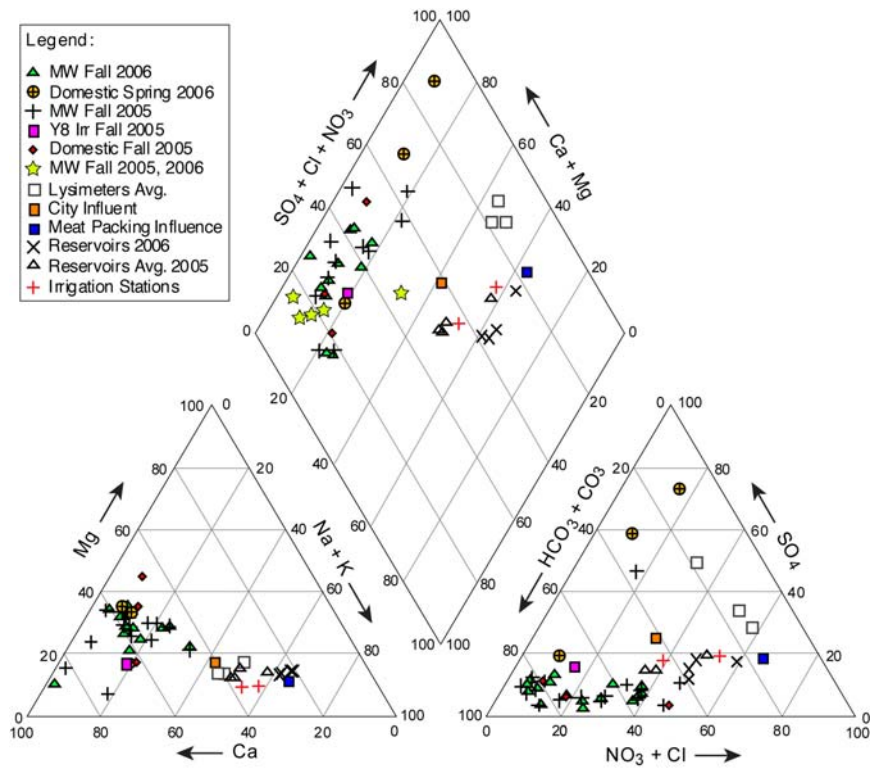


Figure 5. Trilinear diagram of fall 2005 and fall 2006 water chemistry from wells, wastewater, lysimeters, and domestic wells in the area of the Dodge City wastewater irrigation site.

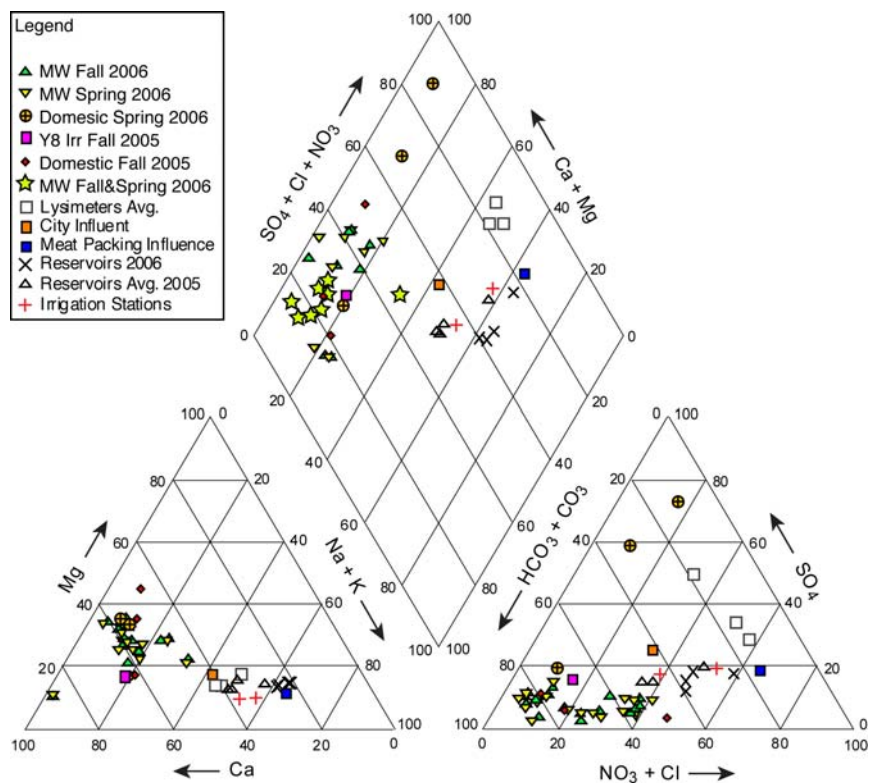


Figure 6. Trilinear diagram of fall 2006 and spring 2006 water chemistry from wells, wastewater, lysimeters, and domestic wells in the area of the Dodge City wastewater-irrigation site

## Background on the Nitrogen-15 Isotope Method

Natural-abundance nitrogen-isotope analysis is frequently used to assist in determining sources of nitrogen to ground water. The isotope analysis involves establishing the ratio of nitrogen-15 ( $^{15}\text{N}$ ) to nitrogen-14 ( $^{14}\text{N}$ ) on the nitrogen in nitrate compared to the ratio observed in the standard, atmospheric nitrogen (air). Comparisons of these values indicate if there is more (positive) or less (negative)  $^{15}\text{N}$  in the sample. The values thus indicate whether the sample is enriched (+) or depleted (-) in relation to the standard.

Isotopic values are reported as  $\delta^{15}\text{N}$  in per mil (‰) (Hoefs, 2001):

$$\delta^{15}\text{N} (\text{‰}) = \frac{(^{15}\text{N}/^{14}\text{N})_{\text{sample}} - (^{15}\text{N}/^{14}\text{N})_{\text{standard}}}{(^{15}\text{N}/^{14}\text{N})_{\text{standard}}} \times 1000 \quad (1)$$

Figure 7 illustrates the range of  $\delta^{15}\text{N}$  values for various sources of nitrogen and associated processes affecting the  $^{15}\text{N}$  abundance (Heaton, 1986). Generally, biological activities use  $^{14}\text{N}$  preferentially, resulting in an increased  $\delta^{15}\text{N}$  value in the remaining nitrogen. Previous work has shown that nitrate from commercial fertilizer sources has  $\delta^{15}\text{N}$  values of -2 to +8‰, from soil nitrogen a range of +5 to +7‰, and from animal waste generally greater than +10‰ (Heaton, 1986; Herbel and Spalding 1993). Other information such as dissolved oxygen, salinity, iron, and manganese concentrations, and proximity to potential sources aids in source determination.

Ground water impacted by fertilizer frequently has measurable nitrate-N also (generally greater than 3 mg/L in Kansas). Because of possible volatilization of anhydrous ammonia when the chemical pH is above 8, and nitrification of ammonium by bacteria, the  $\delta^{15}\text{N}$  values frequently are in the +2 to +8 ‰ range.

Other sources such as human-septic waste or animal waste have  $\delta^{15}\text{N}$  values starting around +5 ‰. Because animal waste has a high ammonia component, the release of the ammonia when the waste is produced causes an immediate enrichment of the  $\delta^{15}\text{N}$  because the lighter ammonia containing  $^{14}\text{N}$  is preferentially released by volatilization. As a result, the  $\delta^{15}\text{N}$  of the remaining nitrogen is much higher, in the range of +10 ‰ or more. Nitrate-N values are generally also high (usually more than 10 mg/L) in animal-waste sources.

Nitrogen volatilization also can occur in soils and rocks with carbonate zones. Carbonates can increase the pH of water towards 8.5, which means the water is more basic. In this pH range nitrate can be converted to ammonia gas by a chemical reaction. The lighter  $\delta^{14}\text{N}$  isotope is preferentially released with the gas. The remaining nitrogen becomes enriched with a higher value  $\delta^{15}\text{N}$ .

Another process that can result in an enriched  $\delta^{15}\text{N}$  value is denitrification. In this process, bacteria degrade nitrate to nitrogen gases that are released to the atmosphere. The  $^{14}\text{N}$  of the nitrate is preferentially utilized resulting in  $\delta^{15}\text{N}$  enrichment in the remaining nitrate. Signs of possible denitrification are low nitrate values and enriched  $\delta^{15}\text{N}$  values. Table 1 lists the range of  $\delta^{15}\text{N}$  values and the types of sources usually identifiable with the method.

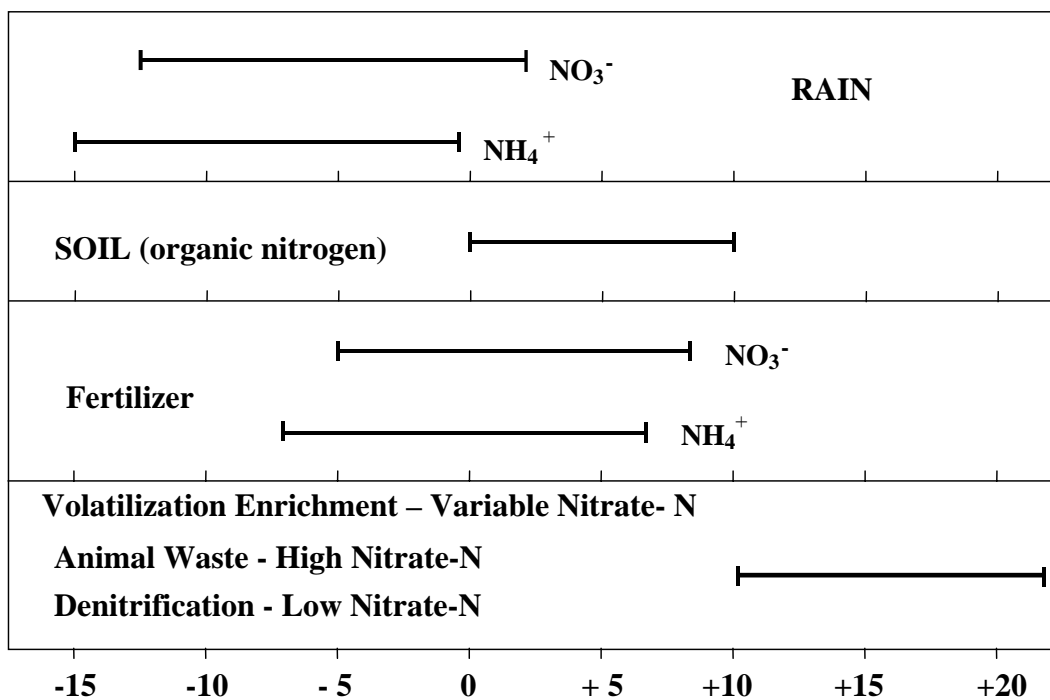


Figure 7. Range of  $\delta^{15}\text{N}$  signatures for different sources of nitrogen (Heaton, 1986; Townsend et al., 1994).

Table 4. Range of nitrogen-15 and nitrogen sources

$\delta^{15}\text{N}$ Values	Nitrogen Sources
< 8 ‰	Fertilizer (Nitrate-N usually > 2 mg/L)
8 to 10 ‰	Mixed sources (Variable range of nitrate-N)
> 10 ‰	Animal waste (Nitrate-N > 10 mg/L); volatilization or long-term nitrification of fertilizer from a spill (Nitrate-N > 10 mg/L); or denitrification (Nitrate-N < 1 mg/L)

## Nitrogen-15 Natural Abundance Results for the Dodge City Site

The nitrogen-15 isotope natural abundance method was used to determine the sources of the nitrate that was measured in the ground water from the monitoring and domestic wells in the area. Figure 8 shows the  $\delta^{15}\text{N}$  values and nitrogen concentrations for the monitoring, domestic, and irrigation wells and the reservoir nitrogen concentrations. The monitoring, domestic and irrigation wells are reported as nitrate-N. The reservoir values are reported as total nitrogen and as ammonium-N.

The graph shows that variation occurs in the reservoir samples between the fall sampling and the summer sampling. The summer values from July 2005 show lower  $\delta^{15}\text{N}$  values although the nitrogen content is similar to the fall 2006 samples. The lower  $\delta^{15}\text{N}$  values are most likely related to the seasonal impacts on the lagoon chemistry. During the late fall/winter time period the temperature of the ponds decreases and the activity of the bacteria in terms of denitrification of nitrogen in the lagoons also decreases. Also the volatilization enrichment process, because of release of ammonia as a gas, decreases with decreased temperature. Both of these processes utilize  $^{14}\text{N}$  which is the lighter isotope and is preferred in terms of utilization both chemically and biologically as the bonds are easier to break. As a result of the utilization of  $^{14}\text{N}$  in the water, the remaining nitrogen is enriched in  $\delta^{15}\text{N}$ .

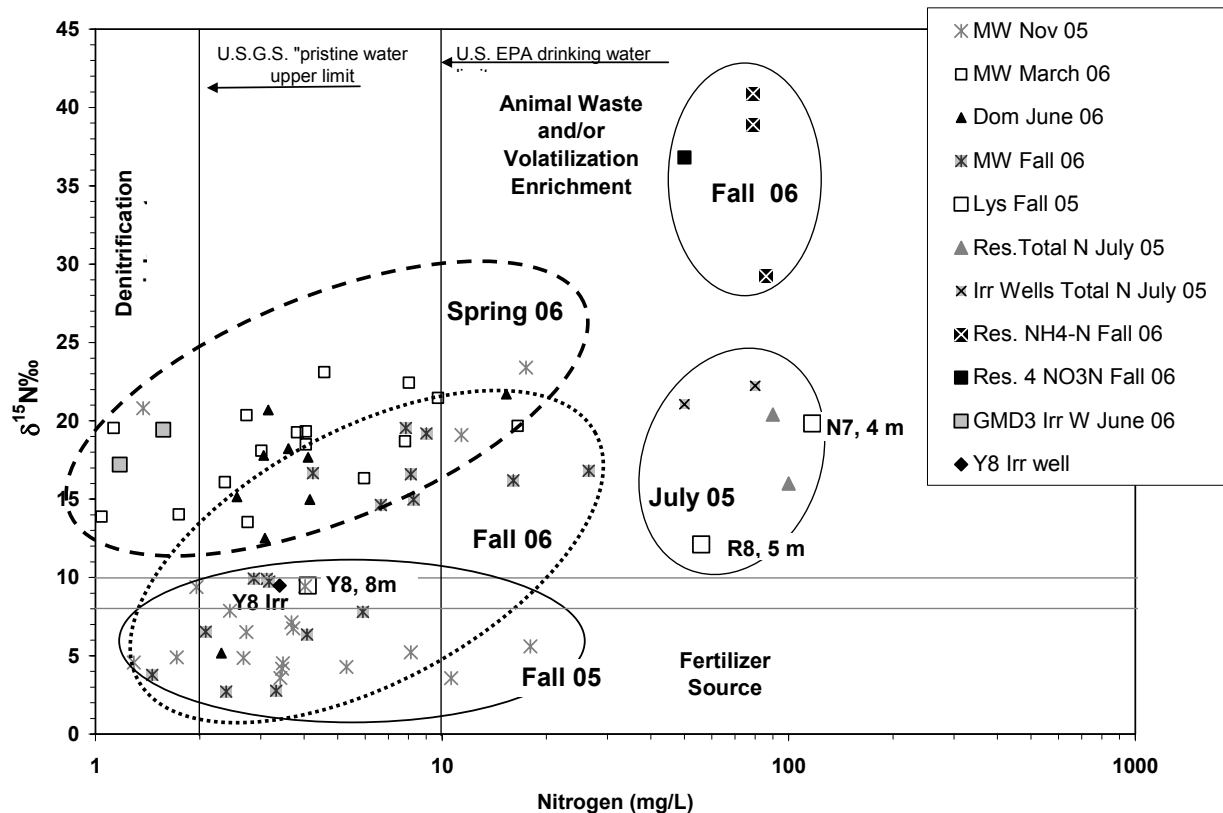


Figure 8. Figure shows variation between seasonal sampling of monitoring wells at Dodge City wastewater-irrigation site. Increased and decreased  $\delta^{15}\text{N}$  values are a reflection of the chemical and biological processes that have affected the wastewater applied and are related to season of water application, not sampling period.

The variation in the  $\delta^{15}\text{N}$  values are a reflection of the seasonal time period of application of the wastewater and are not related to the sampling time. As discussed in Sophocleous et al. (2007), recharge at the site is strongly impacted by macropore flow. The travel times of recharge to the ground water are also variable because of the presence of matrix flow (no macropores) and preferential flow via macropores. The presence of macropores as shown in the part A portion of this report indicates that rapid movement of wastewater can occur and can impact the vadose-zone water and ground water more rapidly than previously expected. If the plant uptake of wastewater is not sufficient to remove most of the nitrogen in the wastewater, then the remainder has a good chance of being converted to nitrate and moving to the ground water.

The higher  $\delta^{15}\text{N}$  values in the ground water from the spring of 2006 indicate that water was most likely applied late in the summer or in the fall after much volatilization enrichment and nitrification of the waste had occurred in the lagoons. Figure 8 shows that the wastewater from the fall 2006 is more highly enriched in  $\delta^{15}\text{N}$  than the samples collected in the summer of 2005. The starting enriched values moving through the vadose zone result in higher observed  $\delta^{15}\text{N}$  values in the sampled ground water.

Although the  $\delta^{15}\text{N}$  values vary by sampling periods, the relative nitrate-N values from the ground-water monitoring wells and the three domestic wells in the irrigation area are relatively stable. No statistical difference is found in nitrate-N concentration between the three sampling periods. The statistical trend discussed previously is seen only with a long term record. This type of statistical difference between the lengths of sampling record is a good indication of the need for long-term ground-water monitoring.

Figure 8 also shows the variation in the  $\delta^{15}\text{N}$  values for the wastewater and lysimeter samples. Although the relative quantity of nitrogen remains relatively constant, the wastewater  $\delta^{15}\text{N}$  values for the summer of 2005 and the fall of 2006 show the impact of winter storage (lower values for summer of 2005 because of cold temperatures) and summer heat effects (fall 2006 with higher temperatures over the summer). The values for the lysimeter-water samples collected in the fall 2005 for sites N7 and R8 are close to the wastewater applied, indicating a rapid movement to 4- and 5-m depths.

Except for the fall 2005 samples, the other two sampling periods reflect an animal waste source. The fall 2005 samples appear to reflect the previous farming practices of fertilizer application with ground-water irrigation. The samples from the Y8 irrigation well and Y8 lysimeter are within the fertilizer range also. These values suggest that some volatilization or nitrification enrichment has occurred as the water moved through the vadose zone to the aquifer.

The two irrigation wells from GMD3 also reflect that denitrification may have occurred because of their low nitrate-N values but much enriched  $\delta^{15}\text{N}$  values.

The domestic wells sampled around the area showed a variety of nitrate-N and  $\delta^{15}\text{N}$  values indicating the likelihood of variable sources impacting the water quality. Some of the farmsteads had small feedlots nearby, and septic-tank sources are a possibility.



## Conclusions

Variability in water chemistry at the Dodge City wastewater treatment site is indicative of different processes occurring in the area due to soil differences, compositional differences in wastewater over the years, varying application rates, macropore versus matrix flow in the soil, temperature effects on the wastewater-treatment process due to seasonal variation, and the effects of bacteria and plant utilization of the wastewater. The chloride and nitrate-N sampling from monitoring wells indicates that certain areas of the wastewater-application site are being impacted by wastewater. The concentrations are increasing yearly at many, but not all, of the wells. A mixing effect with regional ground water is occurring at the edges of the site (wells #11, #12, #13, and #14, and in areas where wastewater application is not occurring, such as at Well #6 to the west of the lagoons but not surrounded by wastewater application fields.

The nitrogen-15 values are elevated at most of the wells, but there is a seasonal component to the values related to the original wastewater composition. Future work at the site should include sampling of the wastewater for nitrogen-15 isotopes on at least a quarterly basis to determine the range of variation that occurs within the lagoon waters.

Continued sampling of nitrate and chloride at the monitoring wells will assist in determining how quickly the nitrate and chloride concentrations are increasing. Use of these data will assist the farmer and consultants to determine the optimal land use and cropping patterns to utilize the wastewater and minimize leaching of future wastewater to the ground water.

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Appendix A. Monitoring and domestic wells at the Dodge City wastewater treatment site fall 2005.

ID	Date Sampled	Spec. Cond. (µmhos/cm)	pH	SiO <sub>2</sub>	Ca	Mg	Na	K	Sr	B	CO <sub>3</sub> <sup>-2</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-2</sup>	Cl <sup>-</sup>	F <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
MW #1	Fall 2005	1501	7.8	33.1	140.0	40.0	117.0	6.0	2.1	0.147		530	64.9	210.2	0.443	10.8
MW #2	Fall 2005															
MW #3	Fall 2005	522	7.5	16.8	81.0	9.2	3.2	3.1	0.4	0.080		169	9.3	44.5	0.01	79.7
MW #4	Fall 2005	774	8.0	30.6	65.0	21.6	5.3	3.5	1.2	0.045		295	9.4	5.0	0.426	36.0
MW #5	Fall 2005	415	8.3	30.8	52.6	15.7	14.3	4.1	1.0	0.047		207	23.3	10.5	0.609	8.7
MW #6	Fall 2005	484	8.1	31.2	59.9	17.8	13.6	4.3	1.1	0.049		260	20.2	10.4	0.525	12.1
MW #7	Fall 2005	771	8.1	17.5	80.2	21.8	36.7	3.9	1.1	0.223		201	39.5	122.6	0.114	15.4
MW #8	Fall 2005	595	8.0	38.1	66.8	23.9	13.8	4.0	1.4	0.073		248	13.0	35.3	0.702	47.1
MW #9	Fall 2005	587	8.3	44.8	139.0	28.1	12.9	5.2	1.6	0.064		238	18.2	48.6	0.926	23.5
MW #10	Fall 2005	238	8.0	11.9	26.2	9.4	5.7	2.3	0.6	0.029		111	7.2	11.3	0.506	16.3
MW #11	Fall 2005	398	8.3	65.8	43.4	16.0	25.3	4.6	1.1	0.109		210	24.8	6.2	1.49	5.7
MW #12	Fall 2005	414	8.1	42.4	52.0	18.3	9.5	3.7	1.1	0.046	10.13	232	14.3	7.4	0.864	7.6
MW #13	Fall 2005	474	8.2	58.0	48.4	17.5	22.1	4.1	1.0	0.115		262	23.2	5.0	0.107	6.1
MW #14	Fall 2005	233	9.6	24.4	32.1	1.9	9.0	3.1	0.5	0.060		42	43.2	7.1	0.647	8.3
East MW	Fall 2005	1022	8.0	35.4	128.0	33.6	37.5	5.6	2.1	0.088		380	53.7	118.0	0.307	16.5
South MW	Fall 2005	589	8.1	34.5	72.2	23.1	15.1	4.7	1.5	0.069		297	15.1	28.5	0.595	17.8
West MW	Fall 2005	989	8.1	35.1	110.0	38.3	42.2	6.6	2.1	0.142		355	28.0	112.1	0.782	50.4
Nicholson	Fall 2005	641	7.9	22.3	58.4	34.6	12.7	5.1	1.5	0.060		187	10.0	62.1	0.471	77.4
Gepford (N7)	Fall 2005	304	8.0	14.4	38.8	6.6	15.0	2.8	0.4	0.033		154	17.4	4.0	0.414	11.8
Kolbeck (R8)	Fall 2005	322	7.9	18.1	34.1	13.8	9.3	3.2	0.8	0.049		154	9.8	13.9	0.674	15.3
Y8 Irr	Fall 2005	421	8.0	25.6	58.0	9.2	18.7	3.5	0.5	0.062		173	31.6	14.5	0.338	15.1

Appendix A. Monitoring and domestic wells at the Dodge City wastewater treatment site fall 2005 (cont.).

ID	Date Sampled	NO <sub>3</sub> -N	PO <sub>4</sub> - <sup>2</sup>	Br <sup>-</sup>	Fe (ug/L)	Mn (ug/L)	δ <sup>13</sup> C ‰	δ <sup>15</sup> N ‰
MW #1	Fall 2005	2.4		0.034	421.9	5.7	-24.4	7.9
MW #2	Fall 2005							
MW #3	Fall 2005	18.0		0.131	0.2	1.8	-20.7	5.6
MW #4	Fall 2005	8.1		0.070	0.0	7.2	-21.6	5.2
MW #5	Fall 2005	2.0		0.089	2.2	0.8	-20.6	9.4
MW #6	Fall 2005	2.7		0.093	1.9	1.2	-21.9	6.5
MW #7	Fall 2005	3.5		0.339	0.3	0.1	-22.0	4.5
MW #8	Fall 2005	10.6		0.168	0.4	1.3	-20.7	3.6
MW #9	Fall 2005	5.3		0.233	48.1	0.0	-22.0	4.3
MW #10	Fall 2005	3.7		0.058	0.0	0.0	-21.1	7.1
MW #11	Fall 2005	1.3		0.069	568.5	26.7	-22.7	4.6
MW #12	Fall 2005	1.7		0.063	447.8	16.2	-21.4	4.9
MW #13	Fall 2005	1.4		0.064	4.7	1.2	-21.6	20.8
MW #14	Fall 2005	1.9		0.044	6.1	1.2		
East MW	Fall 2005	3.7		0.379	0.0	0.0	-22.0	6.8
South MW	Fall 2005	4.0		0.014	0.5	0.6	-20.4	9.4
West MW	Fall 2005	11.4		0.269	0.2	0.4	-21.4	19.1
Nicholson	Fall 2005	17.5		0.201	0.2	1.2	-20.7	23.4
Gepford (N7)	Fall 2005	2.7		0.056	0.0	18.9	-24.1	4.9
Kolbeck (R8)	Fall 2005	3.5		0.085	70.0	11.4	-20.8	4.2
Y8 Irr	Fall 2005	3.4		0.126	2.2	1.0	-23.2	3.6

Appendix A. Monitoring wells and domestic wells at the Dodge City wastewater treatment site spring 2006.

ID	Date Sampled	Spec. Cond. (µmhos/cm)	pH	SiO <sub>2</sub>	Ca	Mg	Na	K	Sr	B	CO <sub>3</sub> <sup>-2</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-</sup>	Cl <sup>-</sup>	F <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
MW #1	Spring 2006	1473	7.1	32.1	138.6	39.6	114.6	6.8	2.1	0.087		512	66.1	188.4	0.425	12.1
MW #2	Spring 2006															
MW #3	Spring 2006	973	7.1	42.8	177.5	13.7	4.2	4.7	0.7	0.010		411	18.2	64.2	0.113	73.2
MW #4	Spring 2006	504	7.6	30.7	66.5	22.0	5.2	3.6	1.2	0.033		287	7.2	2.9	0.79	34.7
MW #5	Spring 2006	428	7.8	30.8	52.1	15.2	13.9	4.2	0.9	0.040		214	22.7	10.9	0.712	13.3
MW #6	Spring 2006	483	7.8	32.8	61.1	17.6	14.2	4.5	1.1	0.037		257	21.9	11.2	0.572	12.2
MW #7	Spring 2006	1418	7.2	34.8	171.3	39.7	66.8	7.2	2.2	0.056		424	60.4	192.4	0.304	17.9
MW #8	Spring 2006	571	7.5	40.9	66.5	23.2	13.6	4.5	1.3	0.056		240	14.0	34.8	0.782	35.5
MW #9	Spring 2006	643	7.7	39.1	76.2	28.0	13.3	5.1	1.6	0.055		230	17.8	62.4	1.01	26.4
MW #10	Spring 2006	491	7.7	42.2	56.8	20.7	11.8	4.4	1.3	0.054		233	15.4	25.5	0.858	17.9
MW #11	Spring 2006	434	7.8	67.5	44.0	16.1	25.4	4.6	1.1	0.107		234	25.2	6.6	1.82	5.0
MW #12	Spring 2006	414	7.7	40.7	49.0	17.4	9.1	3.7	1.1	0.040		233	15.0	7.7	0.996	7.7
MW #13	Spring 2006	460	7.8	63.2	58.0	17.7	22.0	4.4	1.0	0.115		265	24.0	5.1	1.3	4.6
MW #14	Spring 2006	339	8.6	33.1	44.1	11.0	10.3	3.8	0.9	0.050	6.59	158	25.5	8.0	0.704	10.5
East MW	Spring 2006	1101	7.1	35.5	135.0	35.4	43.6	6.5	2.1	0.047		399	54.2	126.8	0.348	16.9
South MW	Spring 2006	669	7.4	34.6	81.7	26.2	16.6	5.0	1.6	0.044		300	15.7	47.4	0.581	20.3
West MW	Spring 2006	1023	7.5	38.4	122.8	41.9	22.4	6.6	2.5	0.068		370	23.7	121.2	0.727	43.1
Nicholson	Spring 2006	725	7.6	39.5	83.9	31.9	13.2	4.9	1.9	0.065		268	11.3	58.5	0.515	67.9
Gepford (N7)	Spring 2006	399	8.0	24.9	54.7	8.9	19.1	3.0	0.5	0.047		213	23.6	5.1	0.444	11.3
Kolbeck (R8)	Spring 2006	473	7.7	39.6	55.1	20.3	12.8	4.4	1.2	0.068		234	14.3	21.4	0.73	16.0

Appendix A. Monitoring wells and domestic wells at the Dodge City wastewater treatment site spring 2006 (cont.).

ID	Date Sampled	NO <sub>3</sub> -N	PO <sub>4</sub> <sup>-2</sup>	Br <sup>-</sup>	Fe (ug/L)	Mn (ug/L)	δ <sup>13</sup> C ‰	δ <sup>15</sup> N ‰
MW #1	Spring 2006	2.7	0.028	0.446	0.0	0.0	-19.9	20.4
MW #2	Spring 2006							
MW #3	Spring 2006	16.5	0.165	0.167	0.0	0.0	-19.3	19.7
MW #4	Spring 2006	7.8	0.046	0.068	87.2	5.3	-23.5	18.7
MW #5	Spring 2006	3.0	0.017	0.085	186.9	0.0	-23.5	18.1
MW #6	Spring 2006	2.7	0.024	0.086	421.9	5.7	-15.3	13.5
MW #7	Spring 2006	4.0	0.030	1.646	0.0	18.9	-18.2	19.3
MW #8	Spring 2006	8.0	0.018	0.170	299.2	10.9	-19.6	22.4
MW #9	Spring 2006	6.0	0.018	0.256	447.8	16.2	-20.9	16.3
MW #10	Spring 2006	4.0	0.026	0.121	0.0	0.0	-19.2	18.5
MW #11	Spring 2006	1.1	0.029	0.059	0.0	0.0	-18.8	19.6
MW #12	Spring 2006	1.7	0.038	0.057	30.7	0.0	-20.1	14.0
MW #13	Spring 2006	1.0	0.024	0.055	568.5	26.7	-21.4	13.9
MW #14	Spring 2006	2.4	0.029	0.068	34.5	0.0	-23.4	16.1
East MW	Spring 2006	3.8	0.021	0.870	28.6	15.2	-19.8	19.3
South MW	Spring 2006	4.6	0.048	0.114	48.1	0.0	-20.2	23.1
West MW	Spring 2006	9.7	0.032	0.276	93.0	27.7	-19.1	21.5
Nicholson	Spring 2006	15.3	0.019	0.201	30.2		-20.2	21.7
Gepford (N7)	Spring 2006	2.6	0.059	0.061	9.7		-20.3	15.2
Kolbeck (R8)	Spring 2006	3.6	0.020	0.112	29.8		-20.6	18.2

Appendix A. Domestic wells and irrigation wells surrounding the Dodge City wastewater treatment site summer 2006.

ID	Date Sampled	Spec. Cond. (µmhos/cm)	pH	SiO <sub>2</sub>	Ca	Mg	Na	K	Sr	B	CO <sub>3</sub> <sup>-2</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-2</sup>	Cl <sup>-</sup>	F <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
Dodge City COOP	Summer 2006	664	8.2	9.2	3.2	1.7	151.1	3.3	0.1	0.502	0.50	263	97.0	9.9	3.570	0.1
Gary Bell	Summer 2006	630	7.9	10.8	10.3	2.6	133.8	3.0	0.1	0.488	0.49	248	96.8	9.3	2.820	1.0
C. Nicholson	Summer 2006	394	7.7	24.6	52.8	8.7	19.0	3.5	0.5	0.044	0.04	208	24.8	4.9	0.374	10.2
Dowling	Summer 2006	405	7.8	24.5	55.9	9.0	18.7	3.5	0.5	0.043	0.04	214	21.3	5.9	0.356	13.7
Frink/Scoggings	Summer 2006	499	7.8	24.6	67.1	11.1	21.8	3.6	0.6	0.043	0.04	207	31.6	29.3	0.368	18.2
Roesener	Summer 2006	454	8.1	27.0	60.6	10.3	20.1	3.8	0.6	0.042	0.04	209	27.7	19.9	0.380	14.0
Kolbeck	Summer 2006	473	7.7	39.6	55.1	20.3	12.8	4.4	1.2	0.068	0.07	234	14.3	21.4	0.730	16.0
G. Harshberger	Summer 2006	475	7.7	32.7	58.5	20.0	10.0	3.4	1.2	0.052	0.05	228	14.2	24.1	0.689	18.4
Stewart	Summer 2006	436	7.8	41.0	52.1	17.4	13.7	4.3	1.1	0.057	0.06	218	22.5	14.3	0.987	13.5
M. Nicholson	Summer 2006	725	7.6	39.5	83.9	31.9	13.2	4.9	1.9	0.065	0.07	268	11.3	58.5	0.515	67.9
R. Harshberger Jr.	Summer 2006	816	7.5	32.2	102.5	37.3	17.2	4.5	2.1	0.068	0.07	409	5.8	67.7	0.422	1.6
Gepford	Summer 2006	399	8.0	24.9	54.7	8.9	19.1	3.0	0.5	0.047	0.05	213	23.6	5.1	0.444	11.3
GMD3 Well F029	Summer 2006															30.8
GMD3 Well F035	Summer 2006															23.1
Dodge City COOP	Summer 2006	664	8.2	9.2	3.2	1.7	151.1	3.3	0.1	0.502	0.50	263	97.0	9.9	3.570	0.1
Gary Bell	Summer 2006	630	7.9	10.8	10.3	2.6	133.8	3.0	0.1	0.488	0.49	248	96.8	9.3	2.820	1.0
C. Nicholson	Summer 2006	394	7.7	24.6	52.8	8.7	19.0	3.5	0.5	0.044	0.04	208	24.8	4.9	0.374	10.2
Dowling	Summer 2006	405	7.8	24.5	55.9	9.0	18.7	3.5	0.5	0.043	0.04	214	21.3	5.9	0.356	13.7
Frink/Scoggings	Summer 2006	499	7.8	24.6	67.1	11.1	21.8	3.6	0.6	0.043	0.04	207	31.6	29.3	0.368	18.2
Roesener	Summer 2006	454	8.1	27.0	60.6	10.3	20.1	3.8	0.6	0.042	0.04	209	27.7	19.9	0.380	14.0

Appendix A. Domestic wells and irrigation wells surrounding the Dodge City wastewater treatment site summer 2006 (cont.).

ID	Date Sampled	NO <sub>3</sub> -N	PO <sub>4</sub> <sup>-2</sup>	Br <sup>-</sup>	Fe (ug/L)	Mn (ug/L)	δ <sup>13</sup> C ‰	δ <sup>15</sup> N ‰
Dodge City COOP	Summer 2006	3.6	0.020	0.112	29.8		-20.6	18.2
Gary Bell	Summer 2006	0.0	0.177	0.090	175.8	v	-21.00	8.73
C. Nicholson	Summer 2006	0.2	0.050	0.090	44.6	30.2	-21.30	2.79
Dowling	Summer 2006	2.3	0.042	0.060	< 43	< 43	-20.90	5.17
Frink/Scoggings	Summer 2006	3.1	0.037	0.055	< 43	< 43	-20.10	12.51
Roesener	Summer 2006	4.1	0.036	0.151	< 43	< 43	-19.80	17.66
Kolbeck	Summer 2006	3.2	0.039	0.111	77.6	< 43	-20.70	20.69
G. Harshberger	Summer 2006	3.6	0.020	0.112	< 43	< 43	-20.60	18.23
Stewart	Summer 2006	4.2	0.019	0.132	49.5	< 43	-20.30	14.98
M. Nicholson	Summer 2006	3.1	0.017	0.110	< 43	< 43	-21.40	17.79
R. Harshberger Jr.	Summer 2006	15.3	0.019	0.201	< 43	< 43	-20.20	21.70
Gepford	Summer 2006	0.4	0.029	0.367	151.5	86.0	-19.10	8.77
GMD3 Well F029	Summer 2006	2.6	0.059	0.061	< 43	< 43	-20.30	15.15
GMD3 Well F035	Summer 2006	7.0					-20.40	19.43
Dodge City COOP	Summer 2006	5.2					-20.20	17.20
Gary Bell	Summer 2006	3.6	0.020	0.112	29.8		-20.6	18.2
C. Nicholson	Summer 2006	0.0	0.177	0.090	175.8	v	-21.00	8.73
Dowling	Summer 2006	0.2	0.050	0.090	44.6	30.2	-21.30	2.79
Frink/Scoggings	Summer 2006	2.3	0.042	0.060	< 43	< 43	-20.90	5.17
Roesener	Summer 2006	3.1	0.037	0.055	< 43	< 43	-20.10	12.51



Appendix A. Monitoring and domestic ground-water samples fall 2006.

ID	Date Sampled	Spec. Cond. (µmhos/cm)	pH	SiO <sub>2</sub>	Ca	Mg	Na	K	Sr	B	CO <sub>3</sub> <sup>-2</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-2</sup>	Cl <sup>-</sup>	F <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
MW #1	Fall 2006	1469	7.2	32.1	136.4	40.6	115.7	6.3	2.0	0.100		486	68.1	192.3	0.372	13.8
MW #2	Fall 2006	737	7.4	39.4	132.1	9.6	3.9	4.1	0.5			344	8.5	28.2	0.127	71.2
MW #3	Fall 2006															117.4
MW #4	Fall 2006	490	7.5	30.5	61.0	21.1	5.7	5.2	1.2	0.032		273	9.1	4.9	0.643	34.8
MW #5	Fall 2006	427	7.7	29.9	50.8	15.3	14.7	4.5	0.9	0.045		216	23.5	11.4	0.613	14.0
MW #6	Fall 2006	473	7.8	30.8	58.1	17.1	14.0	4.5	1.0	0.044		252	21.3	10.0	0.515	12.7
MW #7	Fall 2006	1134	7.3	32.3	146.7	30.7	46.4	6.1	1.6	0.058		391	41.8	145.0	0.284	29.5
MW #8	Fall 2006	556	7.7	59.7	64.0	23.6	15.3	5.6	1.3	0.075		295	14.9	35.8	0.658	36.6
MW #9	Fall 2006	656	7.8	36.6	72.8	28.2	14.4	5.5	1.6	0.068		239	19.1	72.6	0.819	36.0
MW #10	Fall 2006	458	7.6	40.3	54.9	20.1	12.0	4.4	1.2	0.056		231	16.0	22.7	0.733	18.1
MW #11	Fall 2006	436	7.9	63.4	42.5	15.7	25.4	5.1	1.0	0.112		234	25.7	6.3	1.54	6.5
MW #12	Fall 2006	415	7.7	39.9	48.8	17.3	9.7	3.7	1.0	0.044		231	16.2	6.7	0.837	9.2
MW #13	Fall 2006	467	8.0	59.7	52.2	18.1	27.5	7.4	c	0.149		264	25.4	4.7	1.04	10.6
MW #14	Fall 2006	351	8.6	32.3	43.0	11.3	10.6	6.7	0.9	0.059	6.00	177	24.3	8.2	0.579	14.7
East MW	Fall 2006	937	7.6	32.9	110.3	29.2	40.4	6.9	1.7	0.062		370	48.6	93.1	0.331	18.8
South MW	Fall 2006	673	7.6	32.7	74.0	26.3	17.2	9.2	1.6	0.051		295	18.3	58.1	0.477	26.2
West MW	Fall 2006	979	7.7	36.8	120.1	39.6	21.7	6.7	2.3	0.075		364	25.1	113.4	0.528	39.9

Appendix A. Monitoring and domestic ground-water samples fall 2006 (cont.)

ID	Date Sampled	NO <sub>3</sub> -N	PO <sub>4</sub> <sup>-2</sup>	Br <sup>-</sup>	Fe (ug/L)	Mn (ug/L)	δ <sup>13</sup> C ‰	δ <sup>15</sup> N ‰
MW #1	Fall 2006	3.1	0.064	0.517			-26.3	9.9
MW #2	Fall 2006	16.1	0.586	0.128			-24.6	16.2
MW #3	Fall 2006	26.5	0.140				-27.5	16.8
MW #4	Fall 2006	7.9	0.074	0.051			-27.4	19.5
MW #5	Fall 2006	3.2	0.151	0.126			-26.0	9.7
MW #6	Fall 2006	2.9	0.183	0.124			-27.9	9.9
MW #7	Fall 2006	6.7	0.029	1.056			-25.9	14.6
MW #8	Fall 2006	8.3	1.276	0.164			-26.9	15.0
MW #9	Fall 2006	8.1	0.219	0.294	276.3		-25.0	16.6
MW #10	Fall 2006	4.1	0.114	0.152			-29.3	6.4
MW #11	Fall 2006	1.5	0.017	0.064		13.6	-29.9	3.8
MW #12	Fall 2006	2.1	0.139	0.058			-27.9	6.5
MW #13	Fall 2006	2.4	0.037	0.049			-26.7	2.7
MW #14	Fall 2006	3.3	0.080	0.056			-29.6	2.8
East MW	Fall 2006	4.2	0.024	0.625			-28.0	16.7
South MW	Fall 2006	5.9	0.035	0.173			-24.1	7.8
West MW	Fall 2006	9.0	0.053	0.299	86.5		-24.1	19.2

Appendix A. Wastewater samples from Dodge City wastewater treatment site 2005-07.

ID	Date Sampled	Spec. Cond. (µmhos/cm)	pH	SiO <sub>2</sub>	Ca	Mg	Na	K	Sr	B	CO <sub>3</sub> <sup>-2</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-2</sup>	Cl <sup>-</sup>	F <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
<b>Wastewater samples</b>																
#1 Res. (North)	Summer 2005	2352			180.0	34.3	250.0	37.0		0.318		756	181.3	309.4		
#2 Res. (Middle)	Summer 2005	2475			164.8	32.0	237.1	36.7		0.352		739	175.0	303.7		
#3 Res. (South)	Summer 2005	2473			157.0	41.8	256.0	37.4		0.300		686	175.0	322.0		
#4 Res. (Final)	Summer 2005	2291			121.8	37.0	288.8	33.0		0.299		355	181.3	325.1		
Irr. Sta. #1	Summer 2005	2315			148.0	23.0	240.5	38.0		0.451		624	200.0	305.4		
Irr. Sta. #2	Summer 2005	2027			126.2	22.8	253.8	41.9		0.581		314	175.0	314.8		
N7 Medium	Summer 2005	3142			293.3	62.5	365.0	15.8		0.390		278	465.0	376.7		518.3
R8 MEDIUM	Summer 2005	2970			296.0	63.2	386.0	8.0		0.184		382	828.0	250.0		247.5
R8 SHALLOW	Summer 2005	6030			423.3	140.0	736.7	27.3		0.397		573	1070.0	793.3		655.6
Municipal Influent	Fall 2006	1491	8.0		110.0	29.0	130.0	15.0		0.290		390	186.8	180.0		
National Beef Influent	Fall 2006	4304	7.0		180.0	52.0	560.0	69.0		0.220		380	333.6	871.0		
#1 Res. (North)	Fall 2006	2714	8.3		82.0	35.0	290.0	33.0		0.430	46.00	540	226.0	434.3		
#2 Res. (Middle)	Fall 2006	2678	8.2		82.0	34.0	280.0	32.0		0.490	39.00	580	188.5	422.9		
#3 Res. (South)	Fall 2006	3046	8.3		110.0	36.0	310.0	37.0		0.380	68.00	670	160.5	483.7		
#4 Res. (Final)	Fall 2006	2688	7.9		110.0	42.0	350.0	40.0		0.370		290	172.6	519.2		

Appendix A. Wastewater samples from Dodge City wastewater treatment site 2005-07 (cont.).

ID	Date Sampled	NO <sub>3</sub> -N	PO <sub>4</sub> <sup>-2</sup>	Br <sup>-</sup>	Fe (ug/L)	Mn (ug/L)	δ <sup>13</sup> C ‰	δ <sup>15</sup> N ‰	Organic N (mg/L)	Total Kjeldahl N (mg/L)	NH <sub>4</sub> -N (mg/L)
<b>Wastewater samples</b>											
#1 Res. (North)	Summer 2005	3.4									93.2
#2 Res. (Middle)	Summer 2005	2.5					-19.89	16			94.6
#3 Res. (South)	Summer 2005	5.1					-15.40	20.4			67.1
#4 Res. (Final)	Summer 2005	22.9									20.1
Irr. Sta. #1	Summer 2005	33.1					-16.41	22.24			63.6
Irr. Sta. #2	Summer 2005	72.8					-15.23	21.06			16.5
N7 Medium	Summer 2005	117.0			465.0	278.3	-19.26	19.82			376.7
R8 MEDIUM	Summer 2005	55.9			828.0	382.0	-19.86	12.11			250.0
R8 SHALLOW	Summer 2005	148.0			1070.0	573.3	-20.27	9.48			793.3
Municipal Influent	Fall 2006	1.3	0.013	0.183					12	36	24
National Beef Influent	Fall 2006		0.089	2.014	5200.0	690.0			200	230	30
#1 Res. (North)	Fall 2006	16.9	0.013	0.525	350.0	340.0			16	95	79
#2 Res. (Middle)	Fall 2006	16.7	0.012	0.436	450.0	350.0			17	96	79
#3 Res. (South)	Fall 2006	12.4	0.032	0.409	300.0	360.0			14	100	86
#4 Res. (Final)	Fall 2006	55.6	0.023	0.399	350.0	240.0	-12.60	21.78	20	22	

Appendix B. Shapiro-Wilk  $W$  statistic and  $p$  value. Parameter is non-normal in distribution if  $p < \alpha = 0.10$ .

Samples	NO3-N	CL	SPCD	HCO3	SO4	Ca	Mg	Na	B	N15
All Wells	0.781 $p < 0.0001$	0.765 $p < 0.0001$	0.846 $p < 0.0001$	0.961 $p = 0.072$	0.836 $p < 0.0001$	0.859 $p < 0.0001$	0.954 $p = 0.0377$	0.621 $p < 0.0001$	0.830 $p < 0.0001$	0.908 $p = 0.0005$
Fall 2005	0.74 $p = 0.0001$	0.734 $p = 0.0001$	0.866 $p = 0.010$	0.938 $p = 0.225$	0.865 $p = 0.0096$	0.877 $p = 0.016$	0.961 $p = 0.5688$	0.612 $p < 0.0001$	0.827 $p = 0.0023$	0.708 $p < 0.0001$
Spring 2006	0.845 $p = 0.0056$	0.753 $p = 0.0003$	0.815 $p = 0.0019$	0.934 $p = 0.213$	0.800 $p = 0.0012$	0.807 $p = 0.0015$	0.929 $p = 0.1667$	0.629 $p < 0.0001$	0.923 $p = 0.1276$	0.952 $p = 0.4347$
Fall 2006	0.733 $p = 0.0003$	0.805 $p = 0.0032$	0.836 $p = 0.0088$	0.922 $p = 0.187$	0.820 $p = 0.0052$	0.831 $p = 0.0074$	0.941 $p = 0.3655$	0.647 $p < 0.0001$	0.861 $p = 0.0248$	0.915 $p = 0.1195$

Appendix C. Kruskal-Wallis  $p$  values for tests of seasonal (fall 2005 and spring and fall 2006) and spatial variation among samples from monitoring wells.

	NO3N	CL	SPCD	<sup>15</sup> N	SO4	<sup>13</sup> C	B	Ca	Mg	Na	K	HCO3	F	Br
Spatial (21 groups)	0.0037	0.0015	0.0003	0.4163	0.0007	0.9909	0.0071	0.0009	0.0003	0.0002	0.0229	0.0013	0.0074	0.0451
Seasonal (3 groups)	0.2313	0.8337	0.5551	<.0001	0.7749	<.0001	0.1968	0.4989	0.5748	0.7945	0.0043	0.1632	0.0474	0.1671

\* Seasonal groups are fall 2005, spring 2005, and fall 2006.

# **Information Transfer Program**

## Student Support

<b>Student Support</b>					
<b>Category</b>	<b>Section 104 Base Grant</b>	<b>Section 104 NCGP Award</b>	<b>NIWR-USGS Internship</b>	<b>Supplemental Awards</b>	<b>Total</b>
<b>Undergraduate</b>	1	0	0	0	1
<b>Masters</b>	2	0	0	0	2
<b>Ph.D.</b>	0	0	0	0	0
<b>Post-Doc.</b>	0	0	0	0	0
<b>Total</b>	3	0	0	0	3

## Notable Awards and Achievements

## Publications from Prior Projects