Wisconsin Geological and Natural History Survey,
University of Wisconsin-Extension

Impacts of a rural subdivision on groundwater: results of a decade of monitoring

Final Report to the Wisconsin Department of Natural Resources

October, 2015

Kenneth R. Bradbury[1], Todd W. Rayne[2], Jacob J. Krause[1]

[1]Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, Madison, WI

[2]Hamilton College, Clinton, NY

Abstract

This report documents results of a groundwater study conducted at a rural subdivision in eastern Dane County, Wisconsin. The overall objective of the project is to update earlier studies at the site by reexamining the impacts of the unsewered subdivision on groundwater quality and quantity after more than a decade of existence. New rural subdivisions built on former agricultural land are common outside of rapidly growing cities. Typically, each home in the subdivision has an individual domestic well and onsite septic system. There is often concern that such subdivisions might contribute to groundwater contamination, but data to support or refute this idea are sparse. In this 78-acre rural subdivision, 18 homes were constructed starting in 2003. Prior to construction, the site was instrumented with monitoring wells, some completed in unlithified sediment and others in the underlying bedrock. Initial monitoring in the early 2000's showed that groundwater beneath the site had been impacted by previous agricultural use, with nitrate-N values as high as 30 mg/l and some detections of atrazine, an herbicide commonly used on corn.

Groundwater beneath the subdivision was monitored periodically from 2001 to 2012. The project reported here increased the scope of monitoring during 2013 and 2014, and collected and analyzed groundwater and soil water samples for emerging contaminants including human viruses, wastewater indicators, pesticides, and artificial sweeteners as well as major ions and environmental isotopes.

Over a decade of monitoring shows that the transition from agricultural to residential land use is changing groundwater quality in both negative and positive ways. The data reported here document long-term changes in groundwater quality, but no measurable change in groundwater levels or general flow directions. Chloride values have increased in many wells, possibly as a result of road salting or water softener discharge. Nitrate concentrations varied spatially and temporally over the past decade, with some concentrations substantially above the 10 mg/l-N drinking water standard. In some wells, nitrate-N and atrazine levels have declined substantially since agriculture ceased. However, atrazine, last used on the site prior to 2003, was still present in 2013 at trace concentrations throughout the site. Wastewater tracers show small but detectable impacts from septic effluent on groundwater quality, as human viruses, pharmaceutical compounds, and artificial sweeteners, all

indicators of domestic wastewater, were present in several wells. Particle traces based on a groundwater flow model are consistent with the hypothesis that septic leachate has impacted groundwater quality.

Table of Contents

List of Tables

List of Figures

List of Appendices

Introduction

History and background

The construction of new rural unsewered residential subdivisions in Wisconsin and elsewhere is an important land-use issue; one of the major concerns is that such subdivisions could contribute to groundwater contamination (Cieslewicz, 2002). Up to now, the data with which to either support or refute this argument are limited. Land-use disputes have been particularly acute in Dane County, Wisconsin, where communities bordering the greater Madison urban center are rapidly converting from long-time agricultural areas to residential housing. The fear of uncontrolled sprawl became so great that in the mid-1990's, former County Executive Rick Phelps ordered a moratorium on new unsewered subdivision plats throughout the county. To deescalate contentious land use decisions, in 1998 then Dane County Executive Kathleen Falk entered into a formal agreement with the Madison Area Builders Association (MABA) and the Realtors Association of Southern Wisconsin (RASCW). In the agreement, MABA and RASCW agreed to support a $30 million open space referendum to acquire parklands in Dane County while County Executive Falk agreed to work jointly with MABA and RASCW on an unsewered rural development pilot program that would allow construction of up to three clustered subdivisions and a combined total of 30 homes. It was specified that participants in the development program would utilize innovative septic technologies and be part of a 10-year groundwater monitoring project. Only one such site was established, and this report documents groundwater investigations at that site.

Site description

The study area is called Savannah Valley, a 78-acre unsewered subdivision located about 15 miles northeast of Madison, Wisconsin (Figure 1). The subdivision was originally planned for 30 homes, but as of 2013, only 16 homes had been built. Prior to being converted to residential lots, the area consisted of agricultural land, woods, and a wetland to the south. Immediately before being subdivided, the agricultural land was used for corn, soybean, and alfalfa production. Figure 2 shows aerial photographs of the site before and during development.

The topography of the area is rolling, with glacial drumlins on the east and west and a subtle valley in the area between where most of the houses are located. The general stratigraphy of the site is a thin (0-5 ft) silt loam soil overlying glacial deposits that in turn overlie Paleozoic bedrock. The glacial stratigraphy is complex and consists of Horicon Till in the upland areas and interbedded sand, gravel, and some silt in the valley (Figure 3). The glacial sediment ranges from 20 to 80 ft thick (Wilcox et al., 2005). The glacial sediments are underlain by the Ordovician St. Peter Formation (sandstone) on the west side of the subdivision. Elsewhere in the study area, the St. Peter is absent and the glacial sediments are underlain by the Ordovician Prairie du Chien Group, a sandy dolostone (Figure 4).

Regional groundwater flow is south to north, toward a stream on the north side of Highway 19. A tile drain that runs from the wetland on the south end of the subdivision empties into a drainage ditch in the stream valley north of Highway 19, along an environmental corridor (Figure 1). All homes built in the subdivision obtain water from individual wells completed in bedrock (two wells are shared between two of the homes) and use individual onsite septic systems. Several of these systems are conventional septic tanks and drain fields and others are either mound systems or "new-technology" systems with aerobic treatment, but all systems discharge to the unsaturated zone.

Results of previous studies

The original groundwater study began in 2001, with the objectives of establishing a groundwater monitoring system and protocol, monitoring groundwater quality and levels, determining baseline groundwater conditions, and drawing preliminary conclusions about subdivision impacts over a 2-year period. During the initial study (Bradbury and Wilcox, 2003) investigators installed four bedrock monitoring wells and 10 wells in the unlithified sediments (Figure 1), monitored these wells for both water levels and a host of geochemical parameters, and developed a conceptual hydrogeologic model of the site. Results of this work (Wilcox, 2003; Wilcox et al., 2005) showed that groundwater beneath the site had been impacted by previous agricultural use, with nitrate-N values as high as 30 mg/l, but that significant temporal and spatial variation in groundwater quality occurred across the site. Subsequent investigators (Bradbury et al., 2005; Wilcox, 2007) installed additional wells near two septic systems and examined potential contamination from six wastewater contaminants potentially released by septic systems. Although several compounds (caffeine, paraxanthine, acetaminophen) were detected in septic drainfield effluent, none of these compounds were detected in groundwater through 2005. Wilcox (2007) also developed a simple numerical model of the site and used this model to investigate the potential for domestic wells to capture wastewater from nearby septic systems (Wilcox et al., 2010).

Pharmaceuticals and other "emerging contaminants" can be effective tracers of septic waste (Hunt et al., 2010). Human viruses represent a new and potentially very powerful tracer of septic waste due to their small size, high mobility, and detectability at very low concentrations (Borchardt et al., 2007; Hunt et al., 2010). Recently, artificial sweeteners such as cyclamate have shown promise as potential tracers of septic waste (Van Stempvoort et al., 2011). The availability of an in-place monitoring network in the subdivision offered a rare opportunity to test these new techniques in Wisconsin.

Objectives

The overall objective of this project was to update the earlier studies by reexamining the impacts of an unsewered subdivision on groundwater quality and quantity after more than a decade of existence. By 2013, the subdivision had several more houses and the houses that were present during the earlier studies had been occupied for at least seven more years (i.e. the septic systems had that much more wastewater input). In addition, analytical methods for the detection of human tracers have been improved since the earlier studies. These new methods allowed analyses of groundwater for tracers that were previously undetectable.

The overall objective was divided into five components:

1. Update the site information by locating all new domestic wells and septic fields installed in the subdivision using GIS, and collect well construction reports for these wells.
2. Organize the existing database by compiling all the existing site data currently stored in various tables and spreadsheets and develop up-to-date relational database and GIS coverages for all parameters at the site.
3. Collect monthly water level measurements from all wells and piezometers at the site, and maintain continuously recording dataloggers in several key wells.
4. Sample water from all wells and lysimeters at the site and analyze the samples for field parameters (pH, electrical conductivity, dissolved oxygen, temperature), major inorganic ions, including nitrate and chloride), human enteric viruses and indicator bacteria, pesticides,

pharmaceutical and emerging compounds, including optical brighteners and artificial sweeteners, and stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H).

5. Develop a detailed numerical model based on new information from wells installed after the existing model (Wilcox et al., 2010) and based in large part on the new regional groundwater flow model developed for Dane County (Parsen et al., in press).

Acknowledgments

This work was funded by the Wisconsin Department of Natural Resources through the Groundwater Joint Solicitation Program and by the Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension. Dr. Jeff Wilcox, University of North Carolina Asheville, provided valuable advice and background information about the study site. Dr.Carol Ptacek, University of Waterloo, Ontario, graciously analyzed samples for artificial sweeteners. Laura Hubbard and Chuck Dunning at the USGS Wisconsin Water Science Center in Middleton, WI, facilitated the collection and analyses of wastewater indicators. Mr. Pete Chase, WGNHS, assisted with sample collection, and Hangjian Zhao assisted with data analyses. We thank the home owners in the Savannah Valley subdivision for providing access to their property.

Procedures and Methods

Major ion and isotope sampling and analysis

We collected samples from all monitoring and domestic wells in July 2013, August-September 2013, and April 2014. Before sampling, each well was purged using either a submersible pump or dedicated bailer. After purging, the wells were pumped or bailed as field parameters of temperature, electrical conductivity, and pH were monitored. When the parameters became stable, we collected acidified and unacidified samples for major ion and isotopic analyses. Major ion samples (Table 1) were analyzed at the Water and Environmental Analysis Lab, Center for Watershed Science & Education at the University of Wisconsin - Stevens Point.

Water samples collected at Savannah Valley were analyzed for deuterium (^{2}H) and oxygen-18 (^{18}O) at the Stable Isotope Laboratory at Iowa State University in Ames. Results are reported as permil (‰) deviation from the isotopic content of Standard Mean Ocean water (SMOW). Samples were measured via a Picarro L1102-i Isotopic Liquid Water Analyzer. The combined uncertainty (analytical uncertainty and average correction factor) for δ18O is ± 0.06‰ (VSMOW) and δD is ± 0.31‰ (VSMOW), respectively.

The Wisconsin Department of Agriculture, Trade, and Consumer Protection (DATCP) laboratory in Madison analyzed water samples for pesticides. During the sampling, field parameters of temperature, conductivity, pH, and dissolved oxygen were measured.

Virus and bacteria sampling and analysis

All monitoring and domestic wells were sampled for human enteric viruses in July 2013. Each monitoring well was pumped using a submersible pump until field parameters of temperature, electrical conductivity, and pH were stable. When parameters were stable, we followed the procedure described in Bradbury et al. (2013); we pumped 900 L through glass wool filters which were capped after pumping and stored at 4C. Domestic wells were sampled from an outside faucet using the same procedure except that the faucets were run for 15 minutes instead of being purged.

The glass wool filters and water samples collected for bacterial analysis were placed on ice and sent to the U.S. Department of Agriculture Agricultural Research Services Laboratory in Marshfield, Wisconsin. All samples were analyzed for viruses and bacteria by methods described in Bradbury et al. (2013).

Wastewater indicator sampling and analysis

We sampled all monitoring and domestic wells for a variety of wastewater indicator compounds listed in Appendix A. Samples were collected in November, 2013, using procedures outlined in Furlong et al. (2014). A peristaltic pump was used for sampling wells with water levels within the suction limit. Tubing dedicated to each well was cleaned before use using the method described by Furlong et al. (2014). In wells with water levels below the suction limit, we used a stainless steel bailer for purging and sampling. The bailer was cleaned in the field between wells using the same cleaning method. All samples were analyzed by the U.S. Geological Survey National Water Quality Laboratory in Denver, Colorado using liquid chromatography/tandem mass spectrometry published as USGS method number O–2440–14 (Furlong et al., 2014).

Artificial sweetener sampling and analysis

We sampled all wells and lysimeters in April 2014 for the artificial sweeteners acesulfame, sucralose, saccharin, and cyclamate using methods modified slightly from those described in Liu et al. (2014). The main modifications were to purge the wells and then sample using a submersible (or peristaltic) pump before the filtration and acidification steps because we were sampling groundwater. The analyses were done at the University of Waterloo (Ontario). The samples were analyzed at the University of Waterloo (Ontario) using solid-phase extraction with liquid chromatography followed by tandem mass spectrometry. The method is described in Liu et al. (2014).

Hydraulic conductivity testing

Single well response tests (slug tests) were conducted in September 2013 on the following wells: MW-01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 20, 21, 22, and 23. All tests were monitored using a Solinst Levellogger, a real-time data cable and a laptop computer. Water in the well was displaced during the initial testing using a solid cylindrical PVC rod (slug) attached to a rope. Wells in which the water level response was too rapid to capture using the solid rod were re-tested using a pneumatic slug testing apparatus that uses air pressure to displace water in the well. For all wells where the solid rod was used to displace water, water level response was measured during a total of four tests per well: two positive displacement (slug in) tests and two negative displacement tests (slug out). The pneumatic test data were collected for positive water displacement only. Data from all tests were analyzed using the aquifer test software AQTESOLV (Duffield, 2007). Data from each test were analyzed using the (Hvorslev, 1951), (Bower and Rice, 1976), and Hyder et al. (1994) methods to compare estimates of hydraulic conductivity for the different solutions.

Water level monitoring

Depth to water was measured in each monitoring well when groundwater sampling occurred using an electric water-level tape. In addition, Solinst Leveloggers were deployed in wells MW-01, MW-04, MW-06, MW-09, MW-11, and MW-20 for the duration of the study to collect water level data at hourly intervals. Elevations of the measuring points of each well were previously reported by Wilcox (2003).

Unsaturated zone monitoring

Six suction cup lysimeters were installed into the down-gradient side of two mound septic systems during a previous study at the site (Wilcox, 2007). The lysimeters were used to sample unsaturated-zone soil pore water beneath domestic septic drain fields. The lysimeters nearest the center of the drain field at both of the instrumented septic systems (LS-2 and LS-5) were sampled during this project. Water samples from both lysimeters were analyzed for major ions, nitrate, oxygen and deuterium isotopes, pharmaceuticals, and artificial sweeteners. The lysimeters were purged one day before sampling; the following day, samples were extracted using a sterile syringe.

Groundwater flow modeling

In order to understand groundwater flow paths near septic fields, domestic wells, and monitoring points in the subdivision we utilized a refined version of a recently-developed groundwater flow model for Dane County, Wisconsin (Parsen et al., in press). The Dane County model uses the USGS MODFLOW code (Harbaugh, 2005). It is a three-dimensional finite-difference model representing the county geology as 12 hydrostratigraphic layers, and uses model cells 360 feet on a side. Parsen et al. (in press) describe the model construction and calibration. In order to apply this model to Savannah Valley we refined the spatial grid in the subdivision area to 50 feet on a side while keeping the rest of the Dane County model intact (Figure 5). No refinement of model layering or recalibration was done. The model simulates all domestic wells in the subdivision with an assumed steady-state pumping rate for each well of 26 ft^3/day (based on 60 gallons per day per person and 3 people per dwelling).

We used the MODPATH particle-tracking code (Pollock, 2012) to develop simulated pathlines away from each septic drain field. Particles were placed in model layer 1, representing the uppermost unlithified materials just below the locations of each septic drain field and traced forward for 10 years under steady-state conditions.

Results and Discussion

Characterization of the groundwater flow system

Field Observations

Based on our repeated water level measurements, the flow system at Savannah Valley has been consistent during the 11-year study period. Groundwater flow is generally from southwest to northeast and the configuration of the water table has been consistent from year to year. Fluctuations of water levels in the shallow monitoring wells are generally related to climate; high water levels correspond to wet years and vice versa (Figure 6). During most years the water table fluctuates approximately five feet, but during years of extreme precipitation, such as 2008, water levels in some wells fluctuated by over 10 feet. Most of the other monitoring wells showed the same pattern. Hydraulic conductivity values from slug tests range from about one foot per day (ft/d) in a monitoring well screened in silt to several hundred ft/d in several monitoring wells screened in gravel. Monitoring wells in sandstone bedrock had hydraulic conductivities around 8 ft/d (Table 2).

Vertical hydraulic gradients are generally downward at the site. Figure 7 is a long-term hydrograph from wells MW-9S and MW-9D, showing a consistent head drop of approximately 4.5 feet between the shallow and deep wells. These downward gradients are consistent with current understanding of the hydrogeology of Dane County, and are related in part to regional drawdown from deep high-capacity municipal wells operated by the City of Sun Prairie several miles to the west of the study site.

The conversion of land use from agricultural to residential in the subdivision has not significantly altered the direction and rate of regional or local groundwater flow. We observed no discernible drawdown from pumping in domestic wells in the subdivision. These minimal drawdowns were consistent with numerical modeling, described below In addition, although water levels rise and fall with climate, the overall configuration of the water table has remained fairly constant over the decade of monitoring.

Numerical modeling

The refined-grid numerical model of the site replicates the general configuration of the water table reasonably well, although the magnitude of the simulated horizontal hydraulic gradient is lower than was observed in the field (Figure 5). It is likely that local recalibration of the model would improve model fit, but recalibration was outside the scope of the present study. Simulated steady-state drawdown from the domestic wells was less than 0.1 ft, which is consistent with field observations of no perceptible drawdown near the wells. The results of the numerical modeling effort were primarily the paths of particles traced in the forward direction from septic drain fields. The paths are shown in figures associated with the following subsections.

Chemistry Results

Isotopes of hydrogen and oxygen

Naturally-occurring stable isotopes of hydrogen and oxygen in groundwater are often used in hydrogeologic studies to discriminate water sources and provide insights to recharge timing. Isotope samples were collected at the site three times: July 2013, September 2013, and late April/early May 2014. Two shallow suction lysimeters were also sampled once, in April 2014. Appendix B lists the isotope results.

The $^{18}O/^{2}H$ samples generally plot on or close to a meteoric water line developed by Swanson et al. (2006). Figure 8 shows plots for each of the sample events as well as the average of all three events. The trend along the meteoric water line shows that, as expected, groundwater at the Savannah Valley site originates as recharge from terrestrial precipitation. The isotope rations for bedrock wells cluster near the center of the plots and show little variation with time, which is consistent with our understanding of the bedrock water having longer travels times being less responsive to short-term climatic variables. Isotope ratios from the shallow wells show more variation, and this is expected because these wells sample water nearer the land surface that has had less time to mix and consequently carries the seasonal signatures of warmer (heavier isotopes) and colder (lighter isotopes) recharge water.

Several individual samples stand out as anomalies on these plots. For the July, 2013, sampling, well MW-11 falls on the MWL but contained significantly heavier isotopes, suggesting that water sampled from this well at that time originated during a warmer period (summer) than water in the other wells. Such an occurrence is quite possible given the topographic and material variation across the site. Variations away from the MWL seen in wells MW-5, MW-20, and lysimeter 5 in April/May 2014 are more difficult to explain. Deviation away from the MWL implies that fractionation or mixing with waters of other origin has altered the isotopic ratio in these samples. The reason for the fractionation of these samples remains unclear.

Major ion water chemistry

Concentrations major ions have fluctuated with time in groundwater beneath the subdivision, which significant changes occurring in chloride and nitrate concentrations. We analyzed groundwater from monitoring wells, domestic wells, and lysimeters in the subdivision to test for spatial and temporal variation of field parameters and major ions (Appendices C and D). Most naturally occurring major ions that are found in the groundwater due to its interaction with geological materials did not show substantial variation in space or time in the study area because those materials have not changed due to the transition from agricultural to residential land use. Dissolved chloride and nitrate are associated with human activities such as septic systems, fertilizers, and road deicing. These ions showed changes during the twelve-year study period.

Chloride concentrations increased from 2002 to the present in the twelve wells most frequently sampled, and in seven of these wells (58%) the increase, as shown by linear regression, was statistically significant (Figure 9). Significance is indicated by p-values on each plot. The regression slopes are deemed significant when $p<0.05$, interpreted as 95% probability that the slope of the regression line is not zero. For $p>0.05$ the regressions are not statistically significant, although a visual trend may be present. The increase in chloride is likely associated with the increased use of deicing salt on roads near and in the subdivision and from septic effluent that includes elevated chloride from water softener use.

Nitrate-N concentrations decreased with a statistically significant trend in 6 of 12 (50%) of the wells most frequently sampled between 2002 and 2013 (Figure 10). Nitrate levels increased in two wells: MW4 and MW9D. MW4 is located downgradient of two separate septic systems, and is likely showing the impacts of these systems. MW9D is not located near and septic systems and samples the deeper bedrock aquifer. It is possible that nitrate increases in this well are related to longer-term impacts of agricultural fertilizer use in the period prior to subdivision development. The remaining four frequently-sampled wells showed variation of nitrate with time, but no significant long-term trends (Figure 10). In 2002 seven wells exceeded the 10 mg/l (as N) nitrate standard; in 2013 only one well exceeded the standard (Figure 11). This pattern probably reflects the greatly decreased use of agricultural fertilizers and manure in farm fields within the study area. However, the use of nitrogen-based lawn fertilizer by homeowners is unevenly distributed and may be related to the wells in which nitrate concentrations showed an increase.

Pesticides

All wells contained atrazine at concentrations below the limit of detection (0.1 μg/l) from conventional laboratories. Most of the subdivision area was used for agriculture before 2001 and probably had atrazine applied in the past to any field planted with corn. Because of the normal rotation of crops, we assume that atrazine was applied to the entire area sometime during the years before 2001. In 2002, 9 of 13 wells contained atrazine with concentrations greater than 0.1 μg/l. With the change in land use from agriculture to residential since 2002, atrazine concentrations have declined markedly. In 2013, only 2 of 17 wells contained atrazine above 0.1 μg/l (Figure12), but *all wells* contained atrazine at trace levels (nanograms per liter). This is below the detection limit of 0.1 μg/l from typical regulatory analyses (i.e. analyses from DATCAP). Atrazine use is still allowed on neighboring farm fields, and it is possible that atrazine has been transported in groundwater from adjacent areas. However, the finding of trace amounts of atrazine in shallow wells in an area with downward hydraulic gradients suggests that atrazine has persisted in very low concentrations in the surficial and bedrock aquifers since its local use was discontinued over a decade ago.

Wastewater indicators and artificial sweeteners

With the exception of one lysimeter sample with xylocaine, we did not detect quantifiable amounts of wastewater indicators in the monitoring points. Most wastewater indicators are not conservative and will undergo retardation (adsorption) and degradation in the subsurface (Hunt et al., 2010) so our negative results were not unexpected.

The artificial sweeteners acesulfame potassium, sucralose, saccharine, and sodium cyclamate are used in many food products and have been shown to be persistent in surface water and groundwater (Liu et al., 2014). Artificial sweeteners were found in seven monitoring wells, two domestic wells, and one lysimeter installed under septic drain fields in Savannah Valley (Table 3). The highest concentrations were found adjacent to septic systems (Figure 13). The presence of acesulfame and sucralose in groundwater from monitoring wells in Savannah Valley indicates that septic effluent is impacting shallow groundwater.

Viruses and bacteria

We detected human enteric viruses in three of the ten monitoring wells that were screened in surficial materials (sand and gravel) and bacteria in one monitoring well (Table 4). These monitoring wells were adjacent to septic drainfields; particles traced forward from the drainfields intersected two of the wells (Figure 14). There were no detections of viruses or bacteria in monitoring or domestic wells in bedrock.

The presence of human viruses in the monitoring wells is important because their presence is clearly a result of the conversion of the land from agricultural to residential and the construction of residential septic systems. Furthermore, the viruses were in groundwater, which indicates that they are being transported from the effluent drain fields in the unsaturated zone into the saturated zone. While human viruses have been detected in municipal wells impacted by municipal wastewater, this is one the few case where human viruses in groundwater are clearly linked to septic systems from individual houses.

The results of numerical modeling show that there are potential groundwater flow paths from septic drain fields to monitoring wells, which reinforces our conclusion that the septic drainfields are the sources of the viruses.

Conclusions

Groundwater quality in the study area has both improved and been impacted by the change in land use from agricultural to residential. Wilcox et al (2006) showed that the groundwater quality in the area prior to the construction of the subdivision had been negatively impacted by nitrate and atrazine from agricultural activities. With the cessation of agriculture, groundwater quality has improved relative to these constituents as concentrations of nitrate and atrazine have substantially decreased. However, our study shows that shallow groundwater quality has been negatively impacted by the subsequent construction of the subdivision, although, with the exception of nitrate-N in one well, no groundwater standards are currently being violated. The impacts are mainly from septic effluent, shown by the presence of septic tracers such as human viruses, bacteria, and artificial sweeteners. Additional impacts are likely from road deicing and the application of lawn fertilizer. Major conclusions are as follows:

- The removal of agricultural land use from the site has likely caused an overall decrease in nitrate concentrations, while the increases in two wells may be due to local effluent from nearby septic systems. Over the past decade, nitrate-N concentrations in groundwater beneath the site have generally decreased, although concentrations in two wells increased. In 2002 seven wells exceeded the 10 mg/l (as N) nitrate standard, while in 2013 only one well exceeded the standard.
- Chloride concentrations in groundwater beneath the site increased significantly at 58% of the monitoring points over the past decade, possibly due to the local application of road salt and the presence of nearby septic systems.
- The presence of septic effluent tracers (artificial sweeteners) in groundwater indicates that rural subdivisions can impact groundwater quality from runoff and effluent from properly constructed and operated, state-of-the-art onsite septic systems. Savannah Valley has a small number of houses, low housing density, and state-of-the-art septic systems. Despite these factors, the conversion of agricultural land to a subdivision has had a small but measurable impact on groundwater quality. Subdivisions with a higher housing density might have a more serious effect on groundwater quality
- Our numerical modeling supports this conclusion by showing that simulated flow paths extend from septic drainfields to domestic and monitoring wells.
- The presence of trace amounts of atrazine in all the monitoring and domestic wells is important because although the concentrations were below the level of detection for most labs, the compound was present even though it has not been used at the site for over a decade. This raises concerns about the source of the herbicide and whether atrazine is much more persistent in the subsurface than previously thought.

- With the exception of artificial sweeteners, trace organic compounds (wastewater indicators) are generally below detection in groundwater beneath the subdivision. We detected only one instance of a trace organic compound in groundwater in the subdivision. The general absence of trace organic compounds is reasonable; these compounds undergo adsorption and degradation and are considered non-conservative in the subsurface.
- Contaminants thought to originate in onsite septic systems took nearly ten years to reach shallow monitoring wells. These relatively long travel times are consistent with modeling results and demonstrate that short-term monitoring studies (1-2 years) may generally be too short to detect water quality changes. Long-term studies such as this one are necessary to determine the true impacts of subdivisions on groundwater quality and quantity.

References Cited

Borchardt, M. A., Bradbury, K. R., Gotkowitz, M. B., Cherry, J. A., and Parker, B. L., 2007, Human Enteric Viruses in Groundwater from a Confined Bedrock Aquifer: Environmental Science & Technology, v. 41, no. 18, p. 6606-6612.

Bower, H., and Rice, R. C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Waree Resources Research, v. 12, p. 423-428.

Bradbury, K. R., Bahr, J. M., and Wilcox, J. D., 2005, Monitoring and predictive modeling of subdivision impacts on groundwater in Wisconsin: Joint Solicitation Final Report, p. 17.

Bradbury, K. R., Borchardt, M. A., Gotkowitz, M., Spencer, S. K., Zhu, J., and Hunt, R. J., 2013, Source and Transport of Human Enteric Viruses in Deep Municipal Water Supply Wells: Environmental Science & Technology, v. 47, no. 9, p. 4096-4103.

Bradbury, K. R., and Wilcox, J. D., 2003, Impacts of privately sewered subdivisions on groundwater in Dane County, Wisconsin.

Cieslewicz, D. J., 2002, The environmental impacts of sprawl, *in* Squires, G. D., ed., Urban Sprawl: Causes Consequences, and Policy Responses: Washington, D.C., The Urban Institute Press, p. 33.

Duffield, G. M., 2007, AQTESOLV for Windows Version 4.5 User's Guide: Reston, VA.

Furlong, E. T., Noriega, M. C., Kanagy, C. J., Kanagy, L. K., Coffey, L. J., and Burkhardt, M. R., 2014, Determination of human-use pharmaceuticals in filtered water by direct aqueous injection—high-performance liquid chromatography/tandem mass spectrometry, U.S. Geological Survey Techniques and Methods, Book 5.

Harbaugh, A. W., 2005, MODFLOW-2005 : the U.S. Geological Survey modular ground-water model--the ground-water flow process, Reston, Va., U.S. Geological Survey, U S Geological Survey techniques and methods, v. 6-A16, 1 v. (various pagings) p.:

Hunt, R. J., Borchardt, M. A., Richards, K. D., and Spencer, S. K., 2010, Assessment of Sewer Source Contamination of Drinking Water Wells Using Tracers and Human Enteric Viruses: Environmental Science & Technology, v. 44, no. 20, p. 7956-7963.

Hvorslev, M. J., 1951, Time lag and soil permeability in ground water observations, Bulletin Army Corps of Engineers Waterways Experiment Station.

Hyder, Z., Butler, J. J. J., McElwee, C. D., and Liu, W., 1994, Slug tests in partially penetrating wells: Water Resources Research, v. 30, no. 11, p. 2945-2957.

Liu, Y., Blowes, D. W., Groza, L., Sabourin, M. J., and Ptacek, C. J., 2014, Acesulfame-K and pharmaceuticals as co-tracers of municipal wastewater in a receiving river: Environmental Science - Processes and Impacts, v. 16, no. 12, p. 2789-2795.

Parsen, M. J., Bradbury, K. R., Hunt, R. J., and Feinstein, D. T., in press, A new groundwater flow model for Dane County, Wisconsin: Wisconsin Geological and Natural History Survey.

Pollock, D. W., 2012, User guide for MODPATH version 6 - A particle-tracking model for MODFLOW, U.S. Geological Survey Techniques and Methods, book 6, Chapter A41.

Swanson, S. K., Bahr, J. M., and Potter, K. W., 2006, A local meteoric water line for Madison, Wisconsin: Wisconsin Geological and Natural history Survey.

Van Stempvoort, D. R., Roy, J. W., Brown, S. J., and Bickerton, G., 2011, Artificial sweeteners as potential tracers in groundwater in urban environments: Journal of Hydrology, v. 401, no. 1–2, p. 126-133.
Wilcox, J. D., 2003, Variability of groundwater chemistry in an agricultural setting an implications for assessing impacts of land use change [M.S.: University of Wisconsin-Madison, 121 p.
-, 2007, Transport and fate of organic wastewater contaminants beneath unsewered residential subdivisions [PhD: University of Wisconsin-Madison, 183 p.
Wilcox, J. D., Bradbury, K. R., Thomas, C. L., and Lahr, J. M., 2005, Assessing background ground water chemistry beneath a new unsewered subdivision: Ground Water, v. 43, no. 6, p. 787-795.
Wilcox, J. D., Gotkowitz, M. B., Bradbury, K. R., and Bahr, J. M., 2010, Using Groundwater Models to Evaluate Strategies for Drinking-Water Protection in Rural Subdivisions: Journal of the American Planning Association, v. 76, no. 3, p. 295-304.

Tables

Table 1. List of major ions analyzed in water samples. IC = ion chromatography; ICP = induction coupled plasma mass spectrometry.

Major ions	Analysis method	Limit of Detection (mg/l)
Nitrate (N)	IC	0.01
Chloride	Ferricyanide	0.5
Alkalinity	Titration	4.0
Arsenic	ICP	0.003
Calcium	ICP	0.006
Copper	ICP	0.0004
Iron	ICP	0.001
Potassium	ICP	0.05
Magnesium	ICP	0.001
Manganese	ICP	0.0004
Sodium	ICP	0.08
Phosphorus	Block Digester	0.006
Lead	ICP	0.002
Sulfate	IC	0.05
Zinc	ICP	0.002

Table 2. Average hydraulic conductivities (K, ft/d) from slug tests in monitoring wells.

Well Name	Average K (ft/day)
MW1	110
MW2	11
MW3	17
MW4	159
MW5	5
MW6	9
MW7	19
MW8	1
MW9	250
MW10	2
MW11	65
MW20	9
MW21	142
MW22	169
MW23	29

Table 3. Results of artificial sweetener analyses. Bold type indicates detections. MDL = method detection limit. Analytical method was liquid chromatography mass spectroscopy (LCMS).

Sweetener	Acesulfame	Sucralose	Saccharin	Cyclamate
Unit	(µg L-1)	(µg L-1)	(µg L-1)	(µg L-1)
MDL (µg L^{-1})	0.563	1.1	0.716	39
Sample Name				
LS-2	<0.563	<1.1	<0.716	<39
LS-5	**105.800**	**10.973**	<0.716	<39
WS-1	**2.300**	<1.1	<0.716	<39
WS-2	**2.599**	<1.1	<0.716	<39
WS-3	<0.563	<1.1	<0.716	<39
MW-1	**1.452**	<1.1	<0.716	<39
MW2	<0.563	<1.1	<0.716	<39
MW3	<0.563	<1.1	<0.716	<39
MW4	**7.635**	**3.007**	<0.716	<39
MW5	<0.563	<1.1	<0.716	<39
MW6	<0.563	<1.1	<0.716	<39
MW7	<0.563	<1.1	<0.716	<39
MW8	<0.563	<1.1	<0.716	<39
MW9	**2.763**	<1.1	<0.716	<39
MW10	<0.563	<1.1	<0.716	<39
MW11	<0.563	<1.1	<0.716	<39
MW20	**11.623**	**7.191**	<0.716	<39
MW21	**4.194**	<1.1	<0.716	<39
MW22	**3.397**	<1.1	<0.716	<39
MW23	**3.348**	<1.1	<0.716	<39
MW9D	<0.563	<1.1	<0.716	<39
MW12D	<0.563	<1.1	<0.716	<39

Table 4. Summary of virus and bacteria detections at Savannah Valley from sampling in July 2013.

	Well	Constituent	Concentration	unit
Viruses				
	MW-01	Pepper Mild Mottle Virus	6.17	copies/L
	MW-04	HumanPolyomavirus	1.78	copies/L
	MW-22	Adenovirus A	3.58	copies/L
	MW-22	HumanPolyomavirus	4.63	copies/L
Bacteria				
	MW-04	Coliforms	12.2	CFU/L
	MW-09	Coliforms	4	
	MW-22	Coliforms	686.7	

Figures

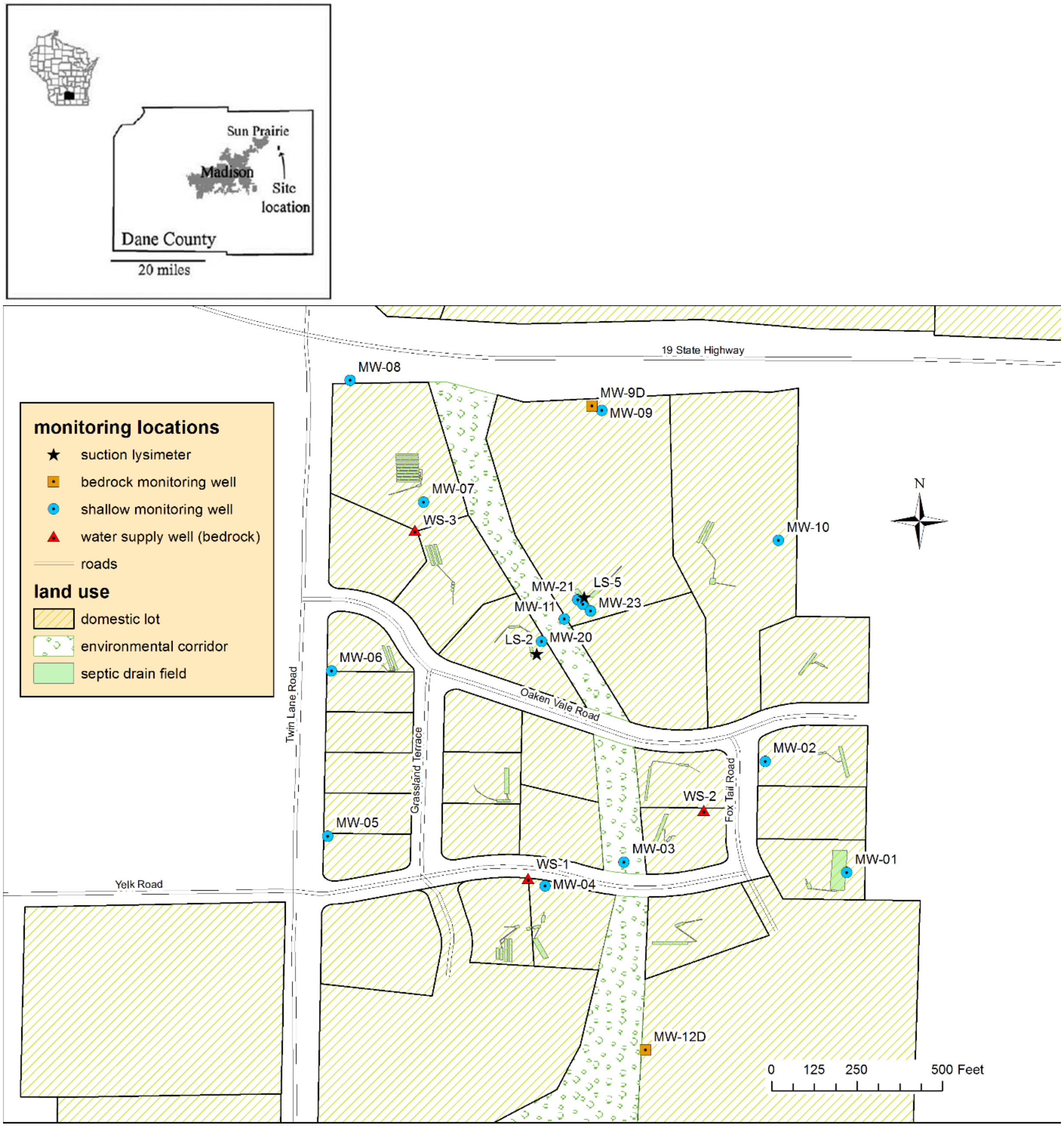


Figure 1. Location (upper left) and overview of the Sun Prairie subdivision site.

A. 2000 B. 2005

C. 2008 D. 2010

Figure 2. Time series of air photographs showing the conversion of land use from agricultural to residential at the Savannah Valley site.

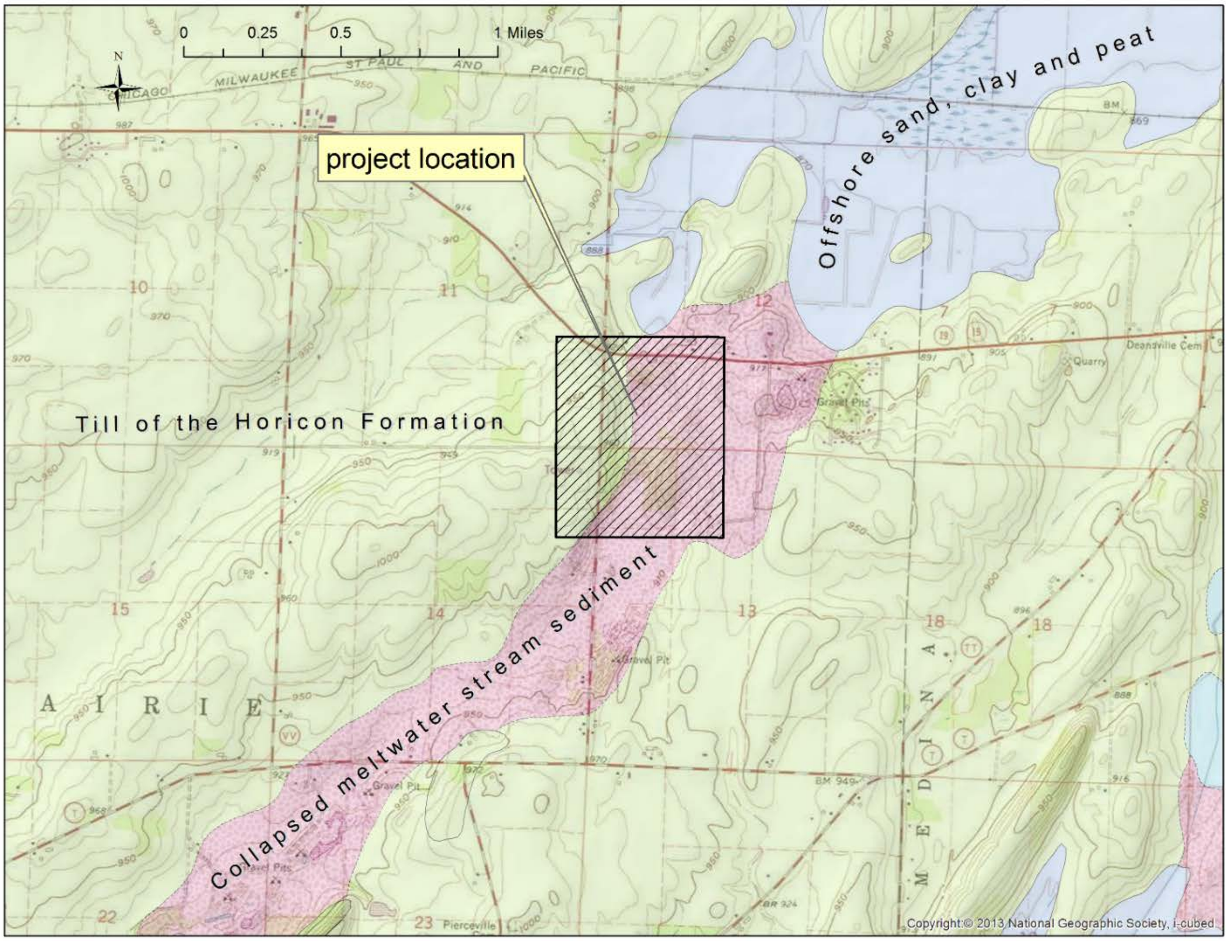
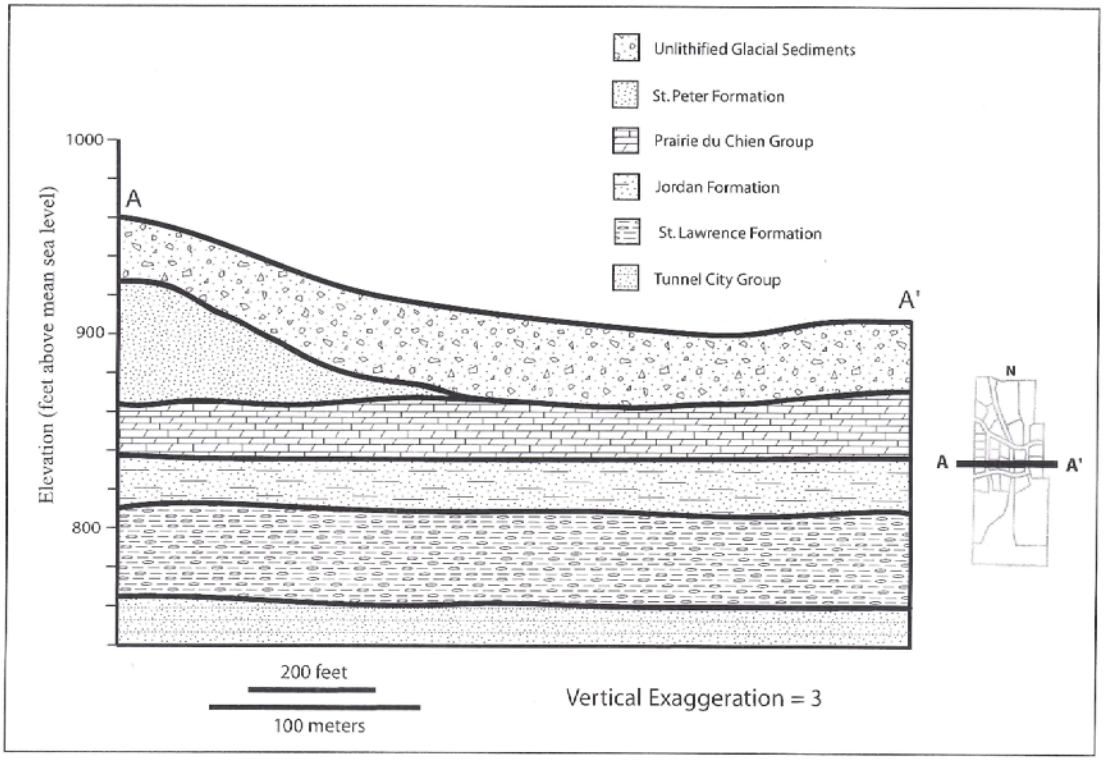


Figure 3. Generalized glacial geologic map of the Savannah Valley study area.



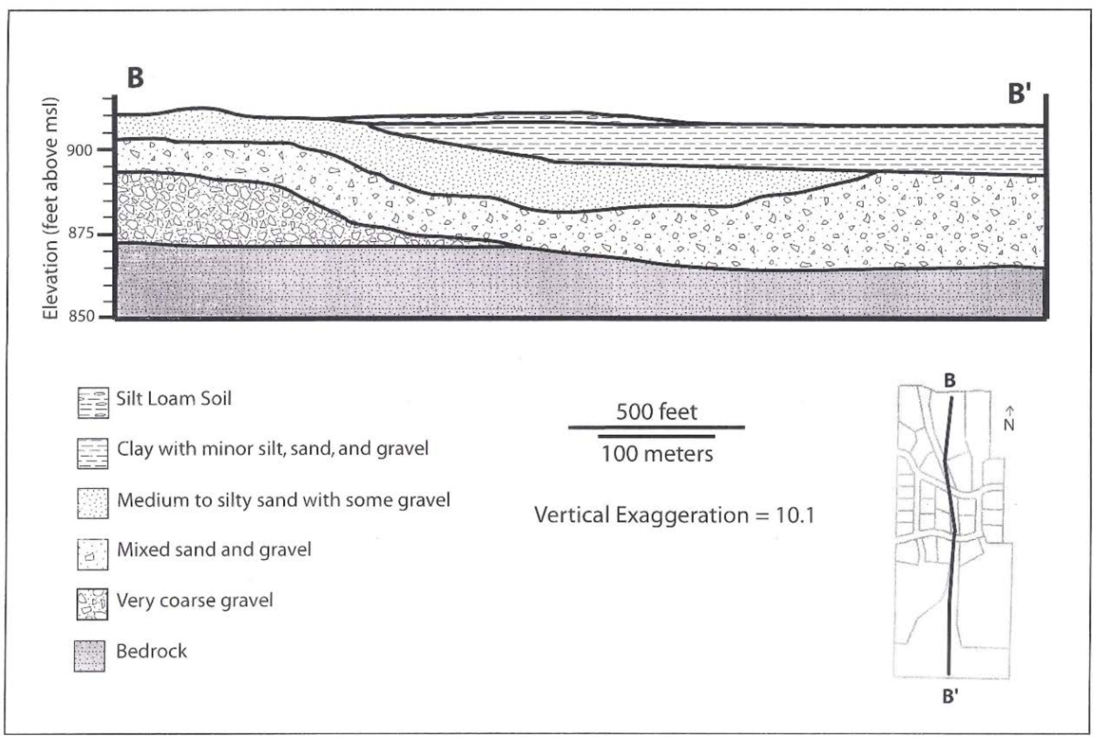


Figure 4. A. East-west schematic cross section through the Savannah Valley Subdivision. B. North-South schematic cross section modified from Wilcox (2003).

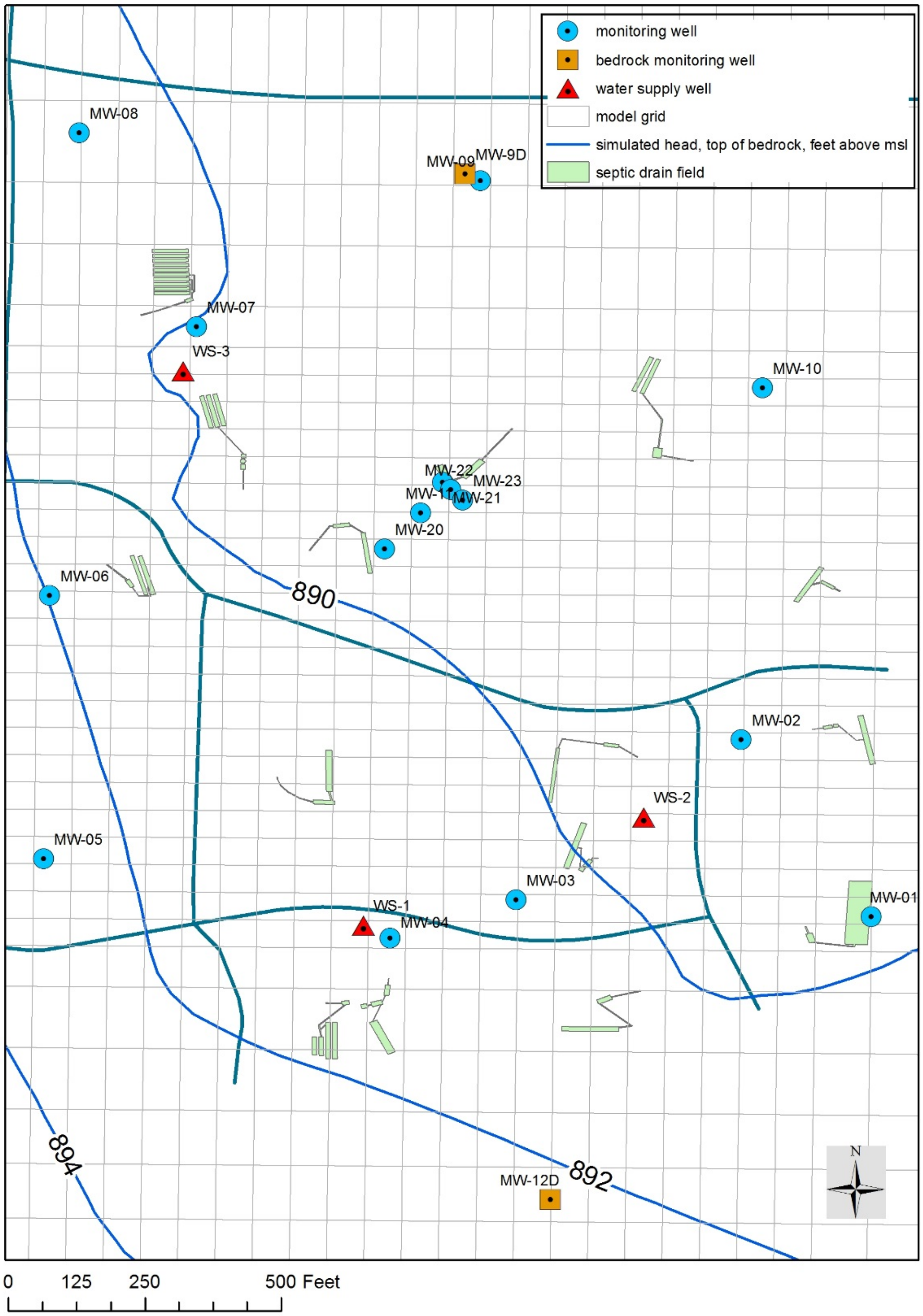


Figure 5. Model grid with simulated water table contours.

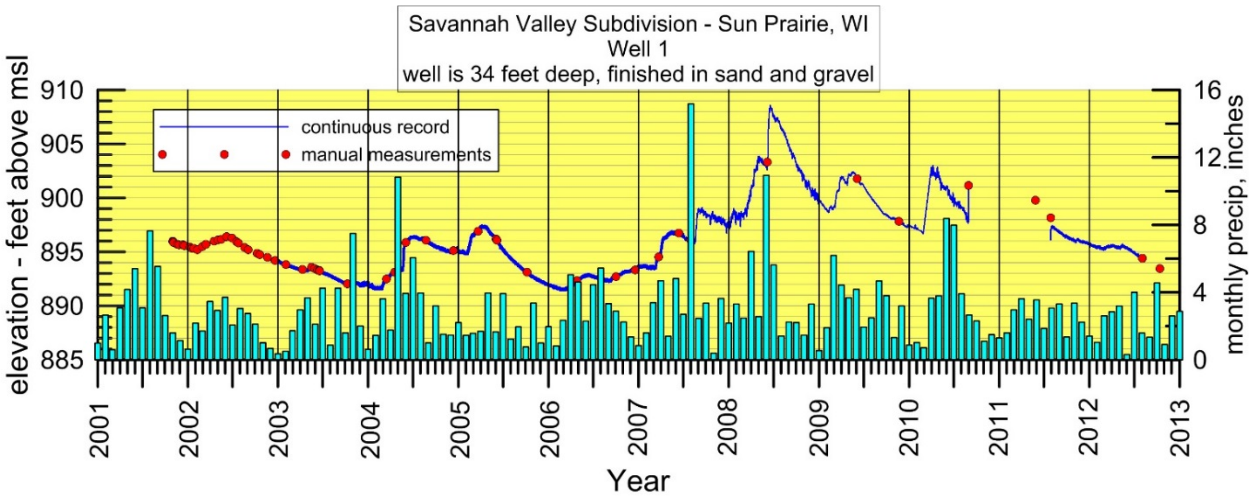


Figure 6. Long-term hydrograph and precipitation record for MW1 in Savannah Valley.

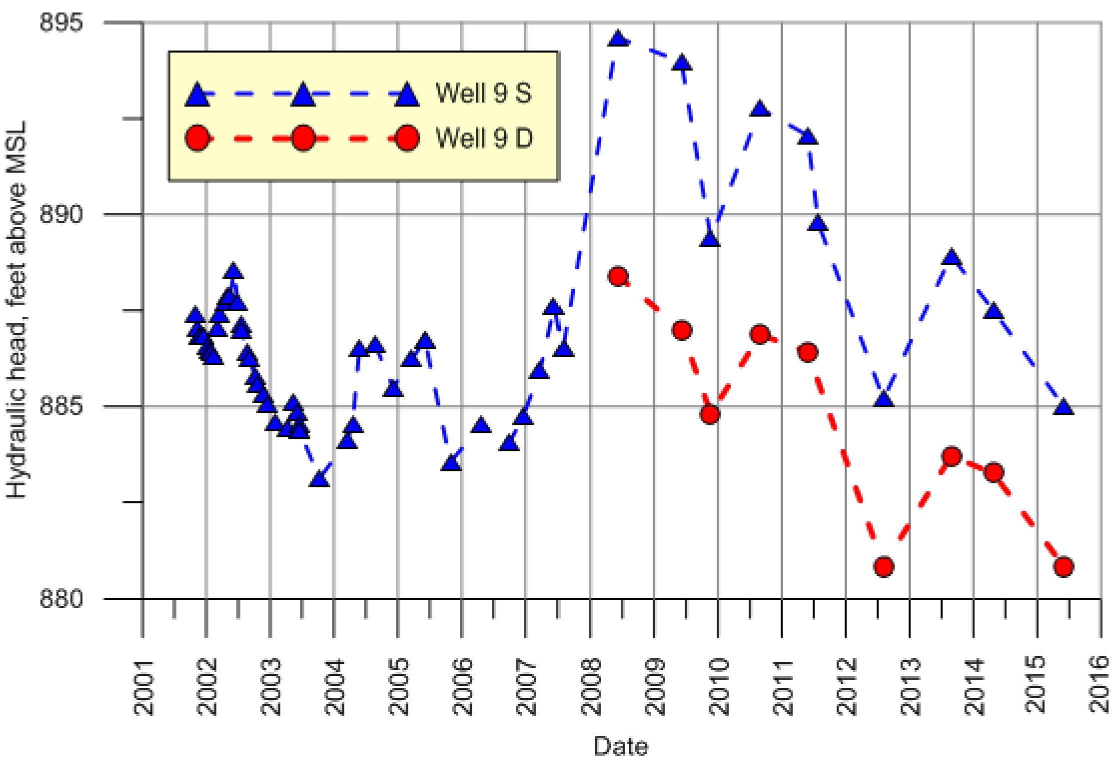


Figure 7. Hydrographs of wells MW9 shallow and MW deep

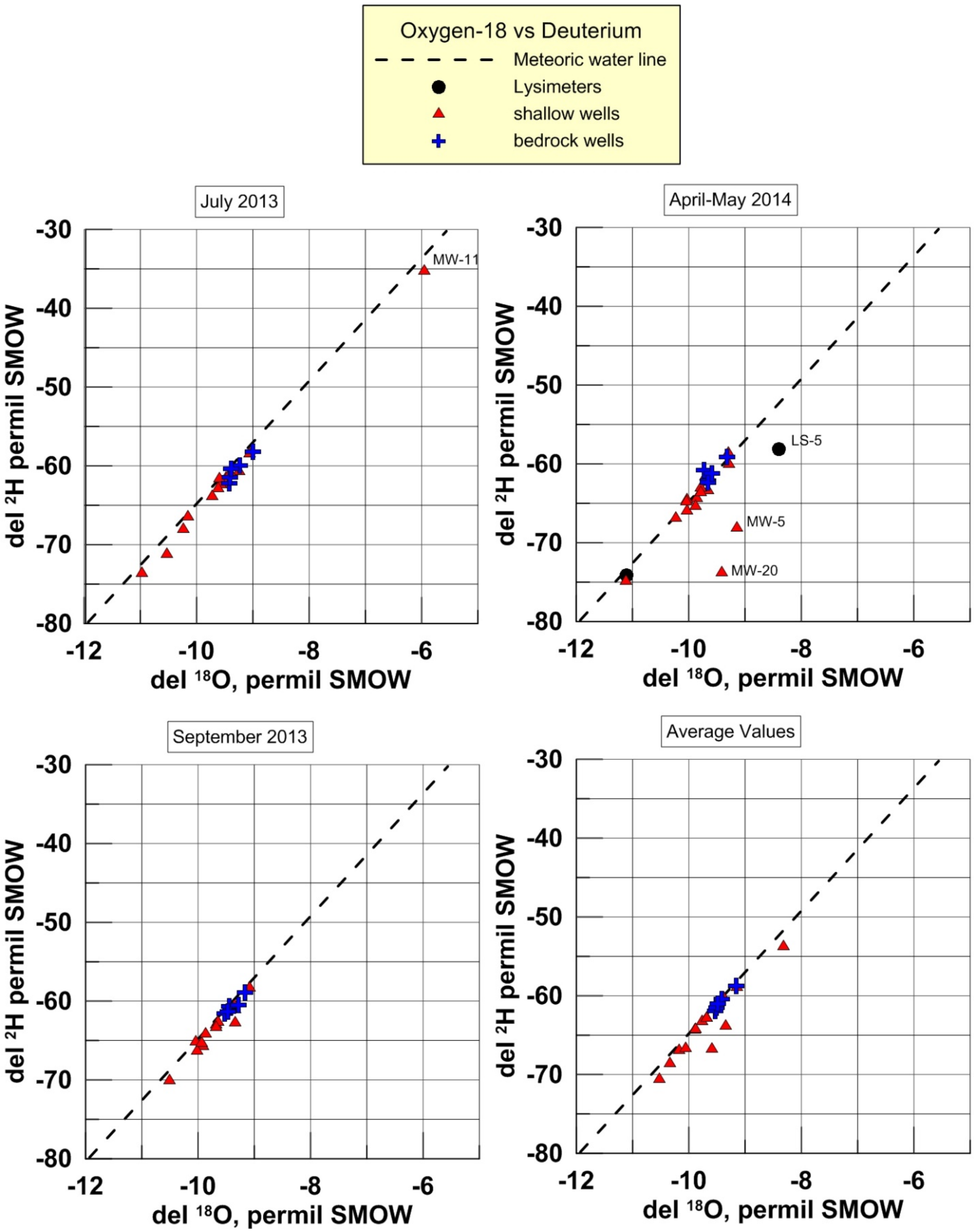


Figure 8. del ^{18}O versus del deuterium plots for each of the three sampling events and the average of all events. Dashed line shows local meteoric water line from Swanson et al. (2006).

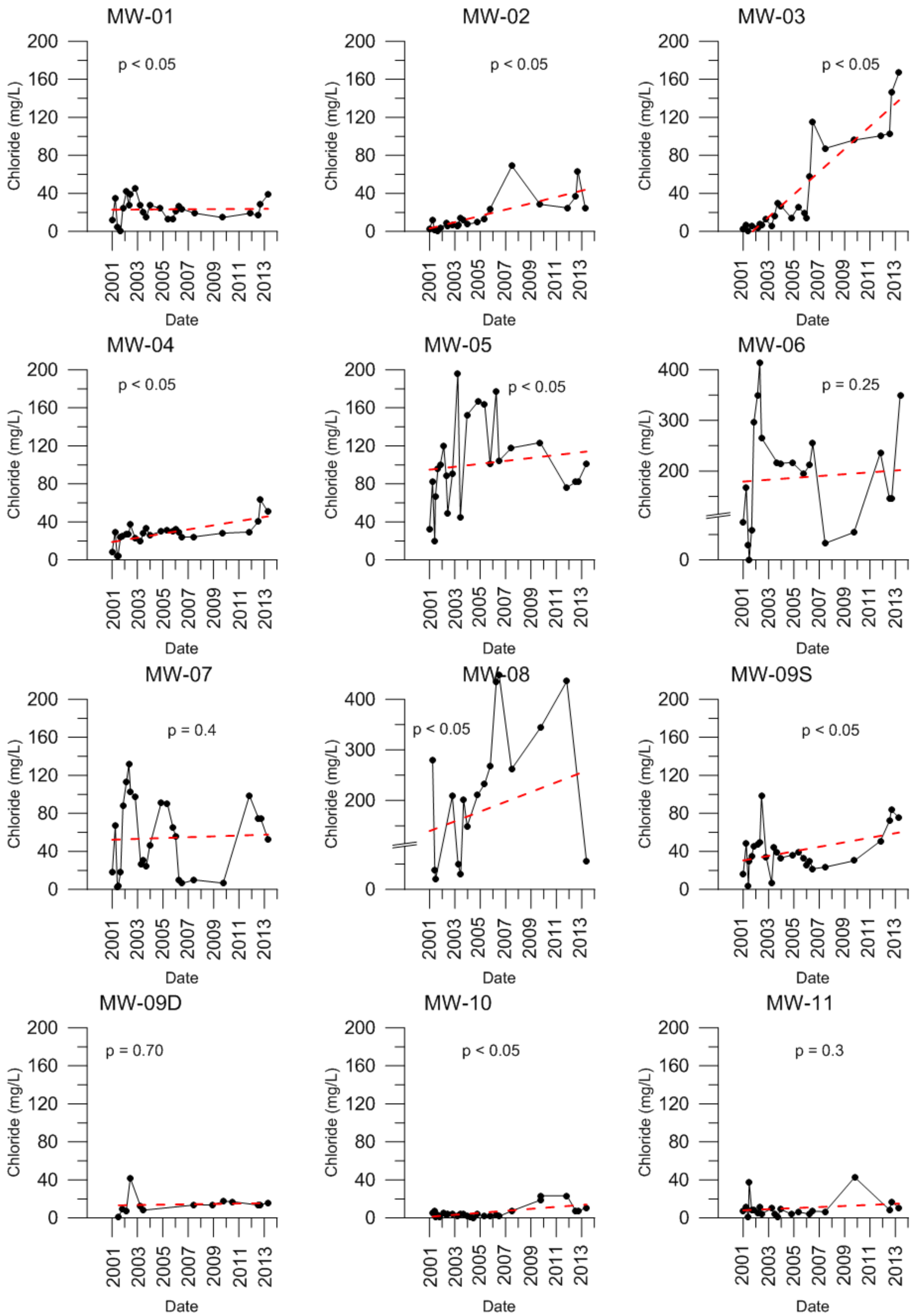


Figure 9. Concentrations of dissolved chloride through time at 12 selected wells. Dashed lines indicate linear regression fit, and p-values indicate significance of the regression slope.

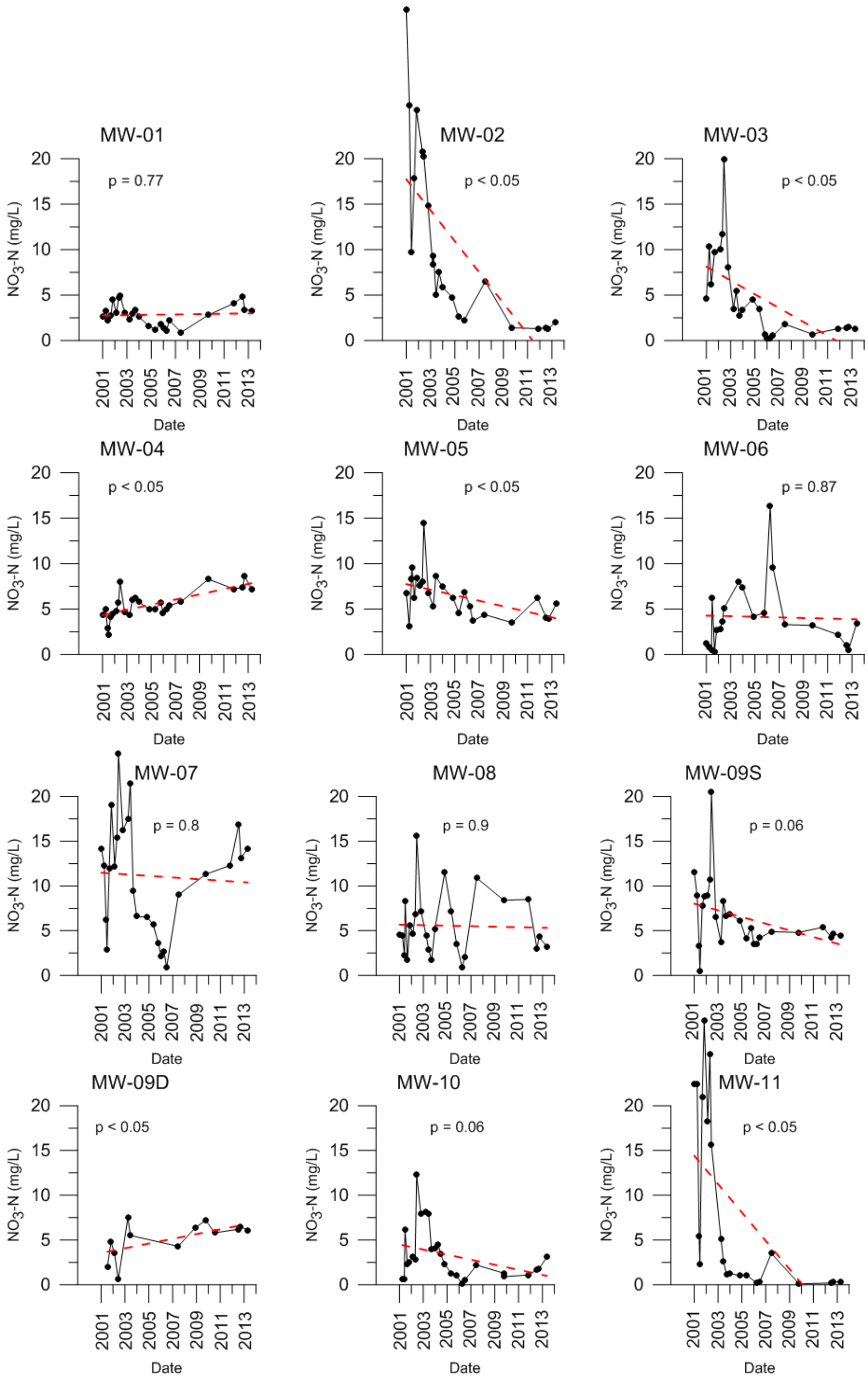


Figure 10. Concentrations of dissolved nitrate (as N) through time at 12 selected wells. Dashed lines indicate linear regression fit, and p-values indicate significance of the regression slope.

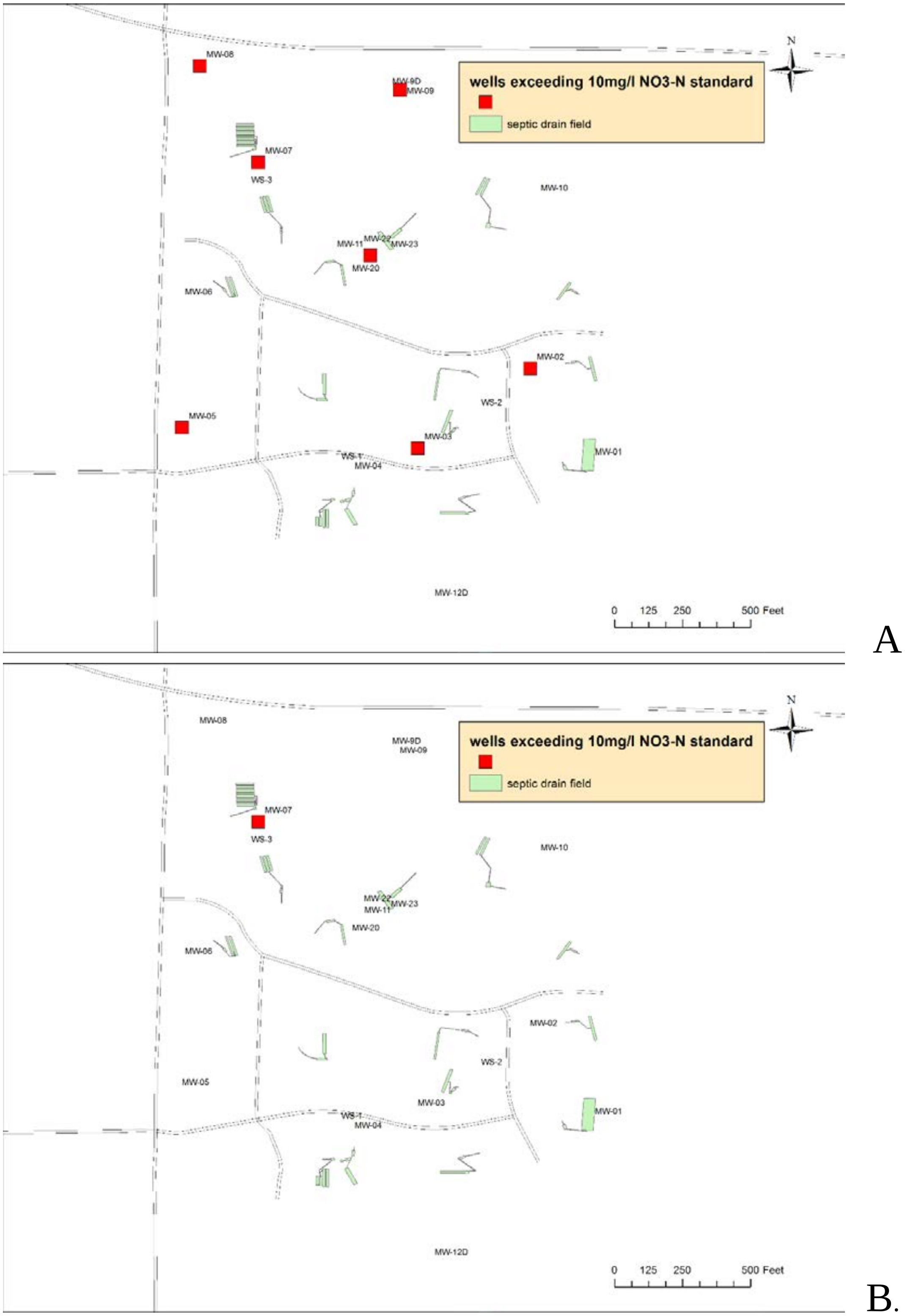


Figure 11. A. Wells exceeding drinking water standard for nitrate (10 mg/l NO_3-N) in 2002. B. Wells exceeding drinking water standard for nitrate in 2013. Septic systems are shown in green.

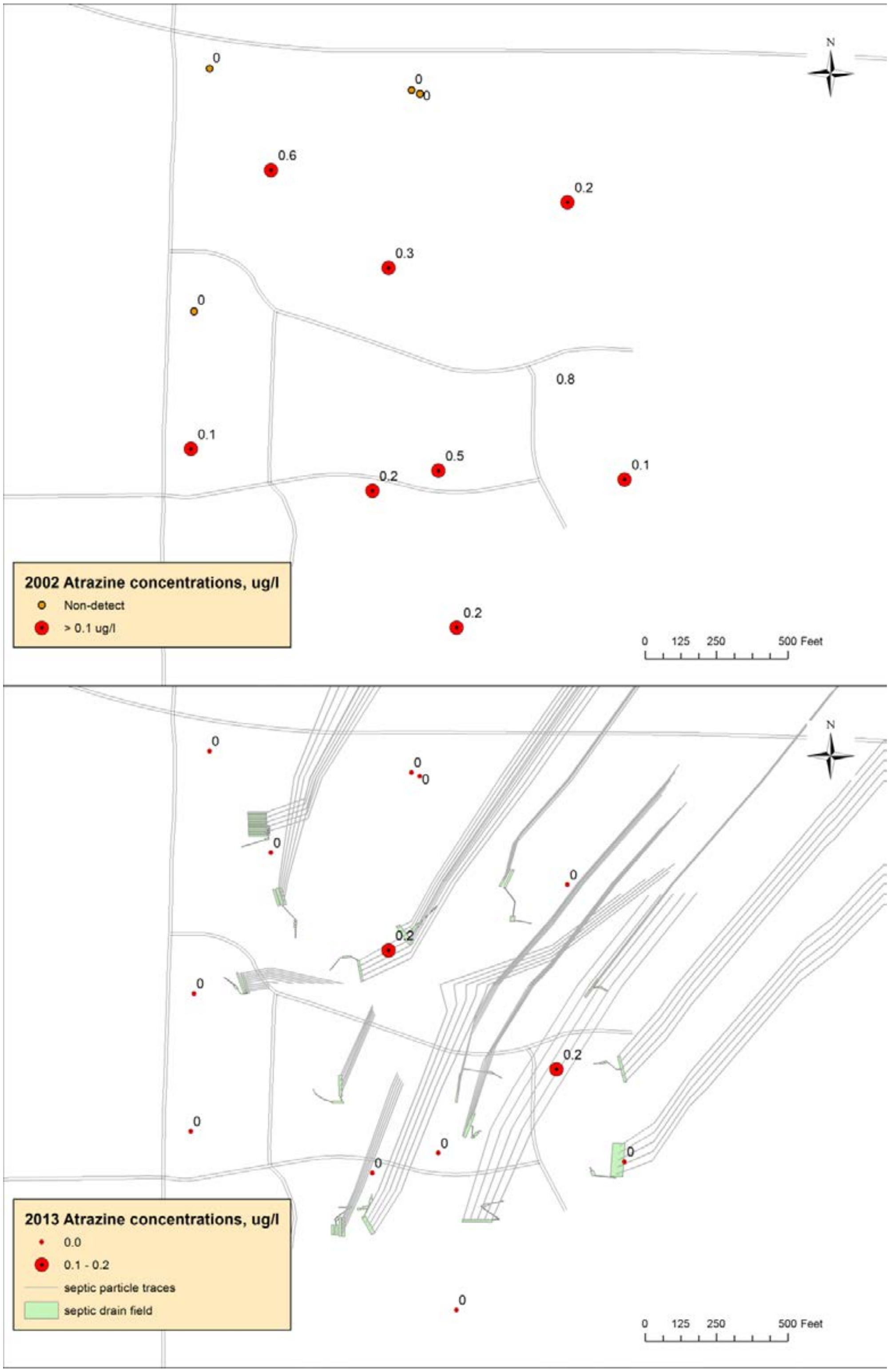


Figure 12. Top: Atrazine concentrations (μg/l) in 2002 (prior to development). Bottom: Atrazine concentrations (μg/l) in 2013. Gray lines represent forward particle paths from septic drainfields. Light green represents septic systems.

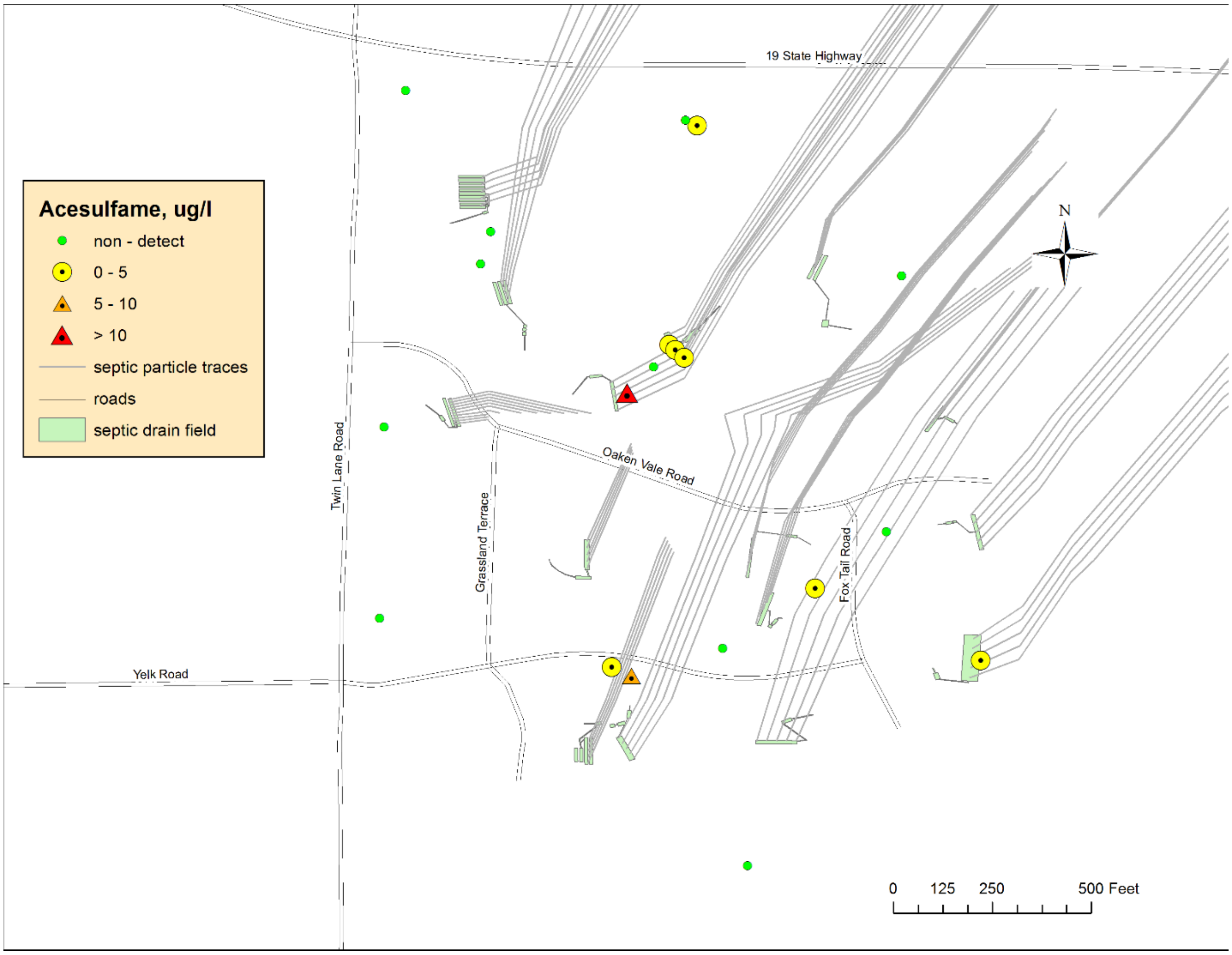


Figure 13. Distribution of artificial sweeteners from 2013 sampling. Gray lines show forward particle tracks from septic drain fields. Septic systems shown in light green.

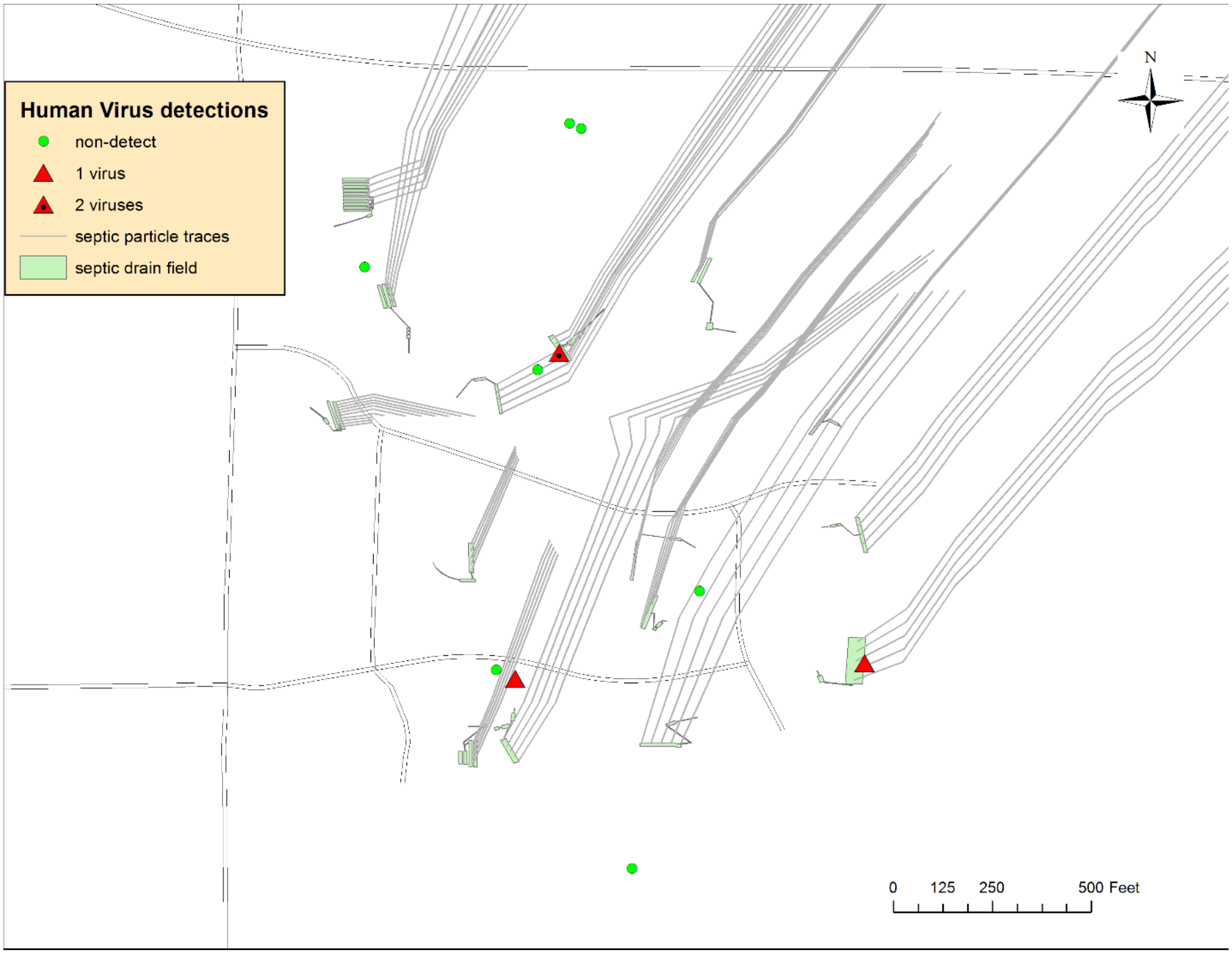


Figure 14. Human virus detections in sampling points in the Savanna Valley study area. Gray lines show forward particle tracks from septic drain fields. Septic systems shown in light green.

Name	LOD	Name	LOD	Name	LOD
Atrazine	18.4	Fexofenadine	19.9	Oxazepam	140.0
Thiabendazole	4.1	Fluconazole	71.0	Oxycodone	24.9
Dimethylxanthine	87.7	Fluoxetine	26.9	Paroxetine	20.6
10-Hydroxy-amitriptyline	8.3	Fluticasone	4.6	Penciclovir	40.2
Abacavir	8.2	Fluvoxamine	53.8	Pentoxifylline	9.35
Acetaminophen	20.0	Glipizide	80.0	Phenazopyridine	13.3
Acyclovir	22.2	Glyburide	4.0	Phendimetrazine	31.1
Albuterol	6.1	Hydrocodone	10.5	Phenytoin	188.0
Alprazolam	21.3	Hydrocortisone	147.0	Piperonyl butoxide	3.1
Amitriptyline	37.2	Hydroxyzine	7.4	Prednisolone	150.0
Amphetamine	8.1	Iminostilbene	145.0	Prednisone	168.0
Antipyrine	116.0	Ketoconazole	113.0	Promethazine	50.0
0Atenolol	13.3	Lamivudine	16.1	Propoxyphene	17.2
Benztropine	15.8	Lidocaine	24.9	Propranolol	26.3
Betamethasone	114.0	Loperamide	11.5	Pseudoephedrine	11.1
Bupropion	17.8	Loratadine	7.0	Quinine	79.9
Caffeine	90.7	Lorazepam	116.0	Raloxifene	9.7
Carbamazepine	4.2	Meprobamate	86.0	Ranitidine	192.0
Carisoprodol	12.5	Metaxalone	15.6	Sertraline	16.2
Chlorpheniramine	4.7	Metformin	80.0	Sitagliptin	97.3
Cimetidine	27.8	Methadone	7.6	Sulfadimethoxine	65.5
Citalopram	6.6	Methocarbamol	8.7	Sulfamethizole	104.0
Clonidine	60.8	Methotrexate	52.4	Sulfamethoxazole	26.1
Codeine	88.3	Methylbenzotriazole	141.0	Tamoxifen	52.4
Cotinine	6.4	Metoprolol	27.5	Temazepam	18.4
Dehydronifedipine	24.5	Morphine	40.0	Theophylline	41.5
Desmethyldiltiazem	12.4	Nadolol	80.8	Tiotropium	43.1
Desvenlafaxine	7.5	Nevirapine	15.1	Tramadol	15.1
Dextromethorphan	8.2	Nicotine	57.8	Triamterene	5.3
Diazepam	2.2	Nizatidine	20.0	Trimethoprim	19.0
Diltiazem	10.2	Nordiazepam	41.4	Valacyclovir	163.0
Diphenhydramine	5.8	Norethindrone	10.9	Venlafaxine	4.5
Duloxetine	36.6	Norfluoxetine	199.0	Verapamil	15.5
Erythromycin	53.1	Norsertraline	192.0	Warfarin	6.0
Ezetimibe	63.5	Norverapamil	8.6		
Fadrozole	7.3	Omeprazole	10.0		
Famotidine	10.7	Orlistat	200.0		
Fenofibrate	6.3	Oseltamivir	14.6		

Appendix A. List of wastewater indicator compounds analyzed by the U.S. Geological Survey (USGS) laboratory in Denver CO using USGS method number O–2440–14.This list is an expanded version of USGS National Water Quality Laboratory Schedule 4433: Waste Indicator Compounds, unfiltered water, by GC-MS. All LOD values are in ng/l (nanograms per liter).

Sample	δ18O (VSMOW)	δD (VSMOW)
MW01	-10.5	-71.2
MW02	-9.1	-58.5
MW03	-10.2	-66.5
MW04	-9.2	-60.7
MW05	-9.5	-62.4
MW06	-9.4	-61.0
MW07	-9.5	-61.6
MW08	-11.0	-73.6
MW09	-9.6	-62.4
MW09 deep	-9.2	-60.0
MW10	-10.2	-68.1
MW11	-6.0	-35.3
MW12 deep	-9.4	-60.4
MW20	-9.4	-61.1
MW21	-9.6	-62.9
MW22	-9.6	-61.6
MW23	-9.7	-63.9
WS01	-9.4	-62.2
WS02	-9.4	-61.5
WS03	-9.0	-58.2
RIO 73	-9.6	-63.6

Appendix B. Isotope values for Savannah Valley water samples. All values are per mil.

Well ID	Date/Time	Depth to Water (ft)	pH	Conductivity (uS/cm)	DO (mg/L)	Temp C
MW-01	7/2/2013 15:06	26.95	7.22	868	3.78	9.0
MW-02	7/2/2013 14:31	9.96	6.92	1217	1.44	9.7
MW-03	7/3/2013 10:46	11.63	7.45	1030	7.00	9.0
MW-04	7/3/2013 10:24	20.25	7.07	1106	4.39	9.5
MW-05	7/3/2013 14:05	48.24	7.18	1761	11.50	7.9
MW-06	7/3/2013 14:32	46.56	7.17	1481	7.80	11.4
MW-07	7/2/2013 11:35	24.40	7.13	978	8.58	9.9
MW-08	7/2/2013 9:30	8.63	7.28	1388	9.38	11.4
MW-09	7/2/2013 10:11	23.11	7.32	1021	7.72	9.4
MW-09D	7/2/2013 11:05	27.25	7.34	736	8.70	9.4
MW-10	7/3/2013 11:55	10.96	7.33	699	5.39	11.7
MW-11	7/2/2013 13:05	11.20	7.44	501	5.67	12.6
MW-12D	7/3/2013 11:12	27.08	7.35	834	3.31	9.7
MW-20	7/2/2013 14:31	11.59	7.20	1217	6.86	14.8
MW-21	7/3/2013 13:21	11.13	7.20	1159	7.09	9.2
MW-22	7/3/2013 13:08	10.65	7.17	1090	6.69	8.9
MW-23	7/3/2013 12:45	11.57	7.15	1066	6.51	9.1
WS-1	7/2/2013 15:45	N/A	7.18	924	5.79	10.7
WS-2	7/2/13 14:50	N/A	7.15	951	3.47	11.1
WS-3	7/2/2013 12:20	N/A	7.20	989	8.32	11.9

Appendix C. Field parameters for groundwater samples from Savannah Valley, July, 2013.

Well	NO3 (N)	Cl	Alkalinity	As	Ca	Cu	Fe	K	Mg	Mn	Na	PO_4	Pb	SO_4	Zn
WS-01	6.6	50.7	344	<0.003	92.9	0.014	0.007	1.5	47.1	<0.0004	23.83	0.028	<0.002	24.6	0.002
MW-04	7.4	84.0	396	0.006	112.9	0.001	0.006	1.6	58.7	<0.0004	25.10	0.044	<0.002	29.8	<0.002
MW-03	1.4	146.0	256	<0.003	78.3	0.001	0.005	1.0	37.2	<0.0004	61.49	0.041	<0.002	15.1	<0.002
MW-12D	5.7	27.5	336	<0.003	92.4	0.001	0.267	1.5	44.6	0.010	7.93	0.006	<0.002	32.6	<0.002
MW-10	1.7	7.4	840	<0.003	74.4	0.001	0.007	2.0	38.9	0.101	9.94	0.083	0.003	20.2	<0.002
MW-23	5.4	83.0	360	0.005	100.5	0.002	0.013	1.3	51.6	0.001	31.81	0.039	<0.002	20.3	<0.002
MW-22	5.1	89.4	384	<0.003	101.8	0.002	0.011	1.2	52.5	0.001	34.79	0.033	<0.002	19.8	<0.002
MW-21	5.4	118.0	364	<0.003	105.0	0.002	0.008	0.8	54.2	<0.0004	38.60	0.028	<0.002	17.7	<0.002
MW-05	4.1	338.0	372	0.004	125.1	0.002	0.011	0.5	62.9	0.001	125.10	0.009	<0.002	20.2	<0.002
MW-06	1.0	265.0	364	<0.003	102.2	0.002	0.016	0.4	52.7	0.001	113.84	0.007	<0.002	17.8	<0.002
MW-08	3.0	258.0	304	<0.003	106.4	0.001	0.009	0.6	50.0	0.001	87.47	0.006	<0.002	13.5	<0.002
MW-09	4.2	73.2	724	<0.003	95.6	0.010	0.013	1.5	49.5	0.001	29.26	0.042	<0.002	19.2	<0.002
MW-09D	6.2	13.6	312	<0.003	81.0	<0.0004	0.070	0.6	40.4	0.010	3.84	0.009	<0.002	18.8	<0.002
MW-07	16.9	48.8	332	<0.003	96.2	0.002	0.007	0.6	49.0	<0.0004	23.41	0.015	<0.002	21.5	<0.002
WS-03	12.8	67.6	328	<0.003	94.7	0.008	0.005	0.6	47.6	<0.0004	29.08	0.011	<0.002	20.1	<0.002
MW-11	0.2	10.8	224	0.004	57.2	0.004	0.006	3.7	22.2	<0.0004	7.36	0.081	<0.002	14.9	<0.002
MW-20	16.3	193.0	484	0.004	117.5	0.003	0.006	1.0	60.3	0.004	85.50	0.034	<0.002	21.1	<0.002
MW-02	1.4	93.7	468	0.004	121.8	0.001	0.009	2.0	62.4	0.001	29.40	0.15	<0.002	19.7	<0.002
WS-02	4.9	49.5	328	<0.003	100.9	0.004	0.006	1.5	50.4	<0.0004	15.47	0.031	<0.002	29.0	0.002
MW-01	4.8	50.2	304	<0.003	87.9	0.001	0.005	3.1	43.7	<0.0004	15.43	0.096	<0.002	31.8	<0.002

Appendix D. Results of major ion analyses from July 2013 water samples. MW = monitoring well; WS = domestic water supply well.