Big Creek Research and Extension Team

University of Arkansas System Division of Agriculture

MONITORING THE SUSTAINABLE MANAGEMENT OF NUTRIENTS ON C&H FARM IN BIG CREEK WATERSHED

FINAL REPORT

BIG CREEK FINAL REPORT: OUTLINE

EXECUTIVE SUMMARY

The main results, conclusions, and interpretations of the Big Creek Research and Extension Team's monitoring of the impact of the C&H Farm's operation on soil and water resources of the Big Creek Watershed, within the Buffalo River Watershed, are summarized below. Monitoring started in September 2013 and finished July 2019 and focused on five main outcomes: the impact of slurry and field management on soil fertility; the slurry and field management on nutrient runoff; trends in the quality of water in well, interceptor trench, and ephemeral stream water; nutrient loads in Big Creek as a function of time, flow regime, and location; and trends in nutrient and bacteria concentrations up and downstream of the C&H Farm.

1. **SOILS AND LAND MANAGEMENT:** Soil survey and ground penetrating radar (GPR; conducted by NRCS) of Fields 1, 5a, and 12 showed soils varied in depth across and among fields. Field 1 had an overlying layer of soil that varied from zero (rock outcrops) to 50 cm (20 inches). Fields 5a and 12 adjacent to Big Creek had soils varying in depth from 80 to 150 cm deep (30 to 60 inches). The deeper soil profiles for Fields 5a and 12 were adjacent to Big Creek, with the thinner soils at a higher elevation on the side of a hill, on the field further from the Creek. This is typical of periodic flooding of Big Creek depositing alluvial material adjacent to the stream bank over the last century following land settlement creating thicker soils at lower elevations with soils thinning as you move away from flood plains and terraces and onto hillsides.
2. The nutrient distribution in soils of three fields (Fields 1, 5a, and 12) was determined by repeating soil sampling on a 0.25-acre grid in 2014, 2016, and 2018. Using GPS to locate the initial soil sample locations in 2014, subsequent sampling in 2016 and 2018 was made at the same point (with +/-1-m accuracy). Slurry was not applied to Field 5a, thus, data from this field provided a reference point for normal pasture management in the region.
3. On a whole-field basis (mathematical average of all grid samples) at the 0 to 4 inch depth, there was a statistically significant increase (at 0.05 level of probability) in Mehlich-3 P (59 – 91 mg/kg) for Field 1 between 2014 and 2018. For Field 5a, there was little change in Mehlich-3 P from 2014 to 2018 (45 – 47 mg/kg). Mehlich-3 P for Field 12 increased two-fold between 2014 and 2018 (63 to 122 mg/kg).
4. An accelerated accumulation of P occurred in Field 12 adjacent to the gate where cattle are consistently fed and thus, loaf, with levels as high as 275 mg/kg in the 0 to 4 inch depth. However, it should be noted that the accumulation of Mehlich-3 P in Field 12 was evident in the 2014 grid-soil sampling, conducted prior to the first application of swine slurry to Field 12.
5. Findings from the 2014 to 2018 grid-soil sampling reinforce the current nutrient management understanding, that the continued, long-term application of P (as fertilizer or manure) in amounts greater than pasture offtake (removal in cut hay), result in an accumulation of P at the soil surface and thus, potential for runoff. Where the accumulation rate, is largely determined by the magnitude of the P application above P removal. Increases in soil test P will eventually elevate the P-Index risk value to high and further limit P additions as fertilizer or manure in future iterations of nutrient management planning.

6. Future additions of any nutrients (i.e., as mineral fertilizer, swine slurry, or poultry litter) to fields, which received slurry from C&H Farms, should be carefully managed, so as not to lead further increases in soil test P. This can be achieved by application of nitrogen (N) fertilizer or slurry and poultry litter at P-based rates, where P applied is equivalent to expected forage uptake of P.
7. **MANURE MANAGEMENT AND NUTRIENT RUNOFF**: The annual loss of P and N in surface runoff from Field 1 for the five years of monitoring, averaged 0.8% and 1.8%, respectively, of that applied in slurry; for Field 12 losses were 2.2% and 4.5% of applied slurry P and N. For Field 5a, loss of P and N was an average 6.6 and 4.4%, respectively, of that applied annually in mineral fertilizer. The runoff collection station for Field 1 was located at the base of a hill. The existing nutrient management plan for this field restricted slurry application to the flat hilltop only and slurry was not directly applied to the slope. Effectively, the slope served as a vegetated buffer.
8. The greater nutrient runoff from Fields 5a and 12 and proportion of that applied in slurry or mineral fertilizer was dominated by major storm events in 2015, which resulted in more than twice the volume of runoff in 2015 (5.4 and 0.9 million gallons) than the other four years combined (1.3 and 0.4 million gallons). Additionally, Fields 5a and 12 are adjacent to Big Creek, which breached its banks and flooded these fields in May and December 2015. The higher percentage of nutrient loss from Field 5a relative to Field 12 may have been a combination of commercial mineral fertilizer P being more soluble than that in slurry and differences in surface hydrology. As these are permanent pastures, commercial fertilizer may settle at the soil surface and be unincorporated within the soil itself until rainfall occurs, while infiltration of slurry may help to rapidly incorporate the soluble portions of P into the soil.
9. Grazing, slurry, and fertilizer management of Fields 1, 5a, and 12 over the 5 years of monitoring, may have resulted in an increase in the potential loss of P and N to Big Creek. However, baseline data of P and N loss in runoff were not available for these fields prior to slurry application. Accurate historical nutrient management and nutrient applications were not available or were previous application rates known before the study.
10. **TRENDS IN WATER QUALITY ADJACENT TO C&H PRODUCTION FACILITY**: There was a statistically significant (probability <0.0001) increase in nitrate-N concentrations in ephemeral stream (annual mean of 0.760 to 1.152 mg/L for 2014 and 2019) and well samples (annual mean of 0.474 and 0.799 mg/L for 2014 and 2019) over the monitoring period (April 2014 to June 2019), as determined by the Seasonal Kendall's test for trends in nutrient concentrations, at sites adjacent to the swine production facility and holding ponds.
11. In contrast, chloride and electrical conductivity did not exhibit any statistically significant change over the monitoring period in well, ephemeral stream, and trench samples (April 2015 to June 2019), which suggests elevated nitrate-N concentrations in well and ephemeral stream samples may be influenced by sources other than the holding ponds (i.e., sources that have low chloride and electrical conductivity values).
12. Flow in the interceptor trenches (T1 and T2) was highly responsive to rainfall, indicating the trenches were mainly capturing shallow subsurface flows initiated by rainfall, indicating little to no mixing or contact with liquids in holding ponds.

13. **NUTRIENT LOADS**: The two largest storms occurring during each of the 5-year monitoring accounted for 44, 49, 37, and 42% of the total 5-year load of dissolved P, total P, nitrate-N, and total N, respectively, and 43% of discharge measured at BC7. Conservation measures that minimize the potential for loss during large storm events will need to focus on nutrient (i.e., rate, timing, source, and method of application) rather than transport management (i.e., runoff and erosion control).
14. **TRENDS IN WATER QUALITY IN BIG CREEK UPSTREAM AND DOWNSTREAM OF C&H**: Phosphorus and N concentrations in Big Creek were greater downstream than upstream of the C&H Farm. For example, the 5-year mean nitrate-N concentration was 0.13 mg/L at the upstream site and 0.29 mg/L at the downstream site. This difference was greater at low base flow conditions in Big Creek.
15. The was no consistent increase or decrease in P, N, and E. coli analyte concentrations between September 1 and December 31, 2013 when no slurry had been land applied, compared to the same four-month period for years following land application.
16. Use of WRTDS to estimate flow- adjusted concentrations of nutrients and E. coli over five water years (i.e., May 1, 2014 to April 30, 2019), removed the effect of inter- and intra-annual stream flow variability. This provided a more reliable representation of the effects of changes in source inputs, land use, and watershed response to management.
17. Based on WRTDS analysis, flow-adjusted N concentration increased slightly upstream and downstream (R^2 of 0.022 and 0.015 for 210 and 243 observations, respectively, not significant at 0.05 level of probability) of the C&H Farm between 2014 and 2019. In contrast, dissolved P (R^2 of 0.035 and 0.043, not significant at 0.05 level of probability) and total P concentrations decreased (R^2 of 0.170 and 0.154).
18. Differences in nitrate-N concentrations between down and upstream sites were strongly influenced by stream flow, where the difference (i.e., downstream was greater than upstream) is very large at low flow and small at high flow. This suggests that at low flows, base flow nitrate-N emerges into Big Creek between upstream and downstream sites and that this base flow has a higher nitrate-N concentration than in base flow above the upstream site. However, at high flows it appears that water entering Big Creek from both the subwatershed above the upstream site and the intervening subwatershed between the downstream site, is similar.
19. Despite higher nitrate-N concentrations at the down than upstream site on Big Creek, the relationship between upstream and downstream concentrations is unchanged over time, suggesting that over the 5 years of monitoring, the input of nitrate-N into Big Creek between up and downstream sites did not change (i.e., no increase or decrease).
20. **NUTRIENT CONTEXT**: Nutrient concentrations in streams draining the Boston and Ozark Mountains regions were related to the intensity of watershed land use, as represented by land in pasture and urban settings. Concentrations in Big Creek were similar to other watersheds in this region with similar land use, suggesting limited impact of the CAFO on Big Creek at the present time. However, this does not preclude future impacts of agricultural and urban operations in the watershed.

BIG CREEK SCIENCE TEAM

Andrew Sharpley, Ph.D., TEAM LEADER – Distinguished Professor. Soil science, water quality, soil phosphorus chemistry, agricultural management.

Kris Brye, Ph.D., Professor. Effects of land application of poultry litter on in-situ nutrient leaching, effects of land use and management practices on soil physical, chemical, and biological properties related to soil quality and sustainability.

Mike Daniels, Ph.D., Professor – Extension. Water quality and nutrient management specialist.

Edward Gbur, Ph.D., Professor and Director, Agricultural Statistics Laboratory. Experimental design, linear and generalized linear mixed models, regression, agricultural applications of statistics.

Brian Haggard, Ph.D., Professor. Ecological engineering, environmental soil and water sciences, water quality chemistry, water quality monitoring and modeling, algal nutrient limitation, pollutant transport in aquatic systems.

Phil Hays, Ph.D., Ground Water Specialist, U.S. Geological Survey and Research Professor with Geosciences Dept., University of Arkansas. Application of stable isotopes and other geochemical indicators in delineating movement and behavior of contaminants in ground-water systems.

Mary Savin, Ph.D., Professor. Structure and function of microbial communities in natural and managed ecosystems, microorganisms in nutrient cycling, contaminant degradation.

Karl VanDevender, Ph.D. and P.E., Professor, Extension Engineer. Livestock and poultry manure and mortality management, nutrient management planning.

Jun Zhu, PhD., Professor - Biological and Agricultural Engineering. Agricultural sustainability, manure treatment technologies.

Adam Willis, M.Sc., Newton County Extension Agent – Agriculture.

Field Technicians, The Big Creek Research and Extension Team are supported by several Program Technicians based in Fayetteville and Little Rock.

Table of Contents

List of Tables

List of Figures

Introduction

Nutrient impairment of surface waters continues despite widespread conservation efforts to reduce losses from urban, rural, and agricultural land uses (Scavia et al., 2014). Land use within watersheds influences the quality and quantity of water in streams draining the landscape. As land disturbance increases and use intensifies, an increase in stormwater runoff and nutrient inputs that lead to a greater potential for transport to receiving water is generally observed (Dubrovsky et al., 2010; Rebich et al., 2011). This has led to efforts to identify and quantify nutrient sources within watersheds, strategically target, and apportion nutrient loss reduction (Reckhow et al., 2011).

Numerous factors influence the relationship between land use in a given watershed and nutrient transport downstream from that watershed. With an increase in drainage area percentage in pasture, row crop, and/or urban use, a general trend of increasing nutrient concentrations in storm and base flows will be manifested (Buck et al., 2004; Giovannetti et al., 2013; Haggard et al., 2003; Migliaccio et al., 2007). Thus, nutrient concentrations in streams draining forested lands tend to be less than in watersheds with considerable anthropogenic land use.

For a range of reasons, great interest has been expressed in nutrient concentrations in several streams of the Boston and Ozark Mountains regions of northwest Arkansas, including the Buffalo National River and its tributaries. In particular, Big Creek has been the center of attention within the Buffalo National River Watershed because of a permitted concentrated animal feeding operation (CAFO).

Big Creek was monitored by the Big Creek Research and Extension Team (BCRET), a partnership between the University of Arkansas System's Division of Agriculture and USGS. Water samples were collected upstream and downstream of the swine CAFO on a near weekly basis since September 2013 (Figure 1).

The water samples were analyzed at an Arkansas Department of Environmental Quality certified water quality laboratory. The data collected is publicly available at https://bigcreekresearch.org/.

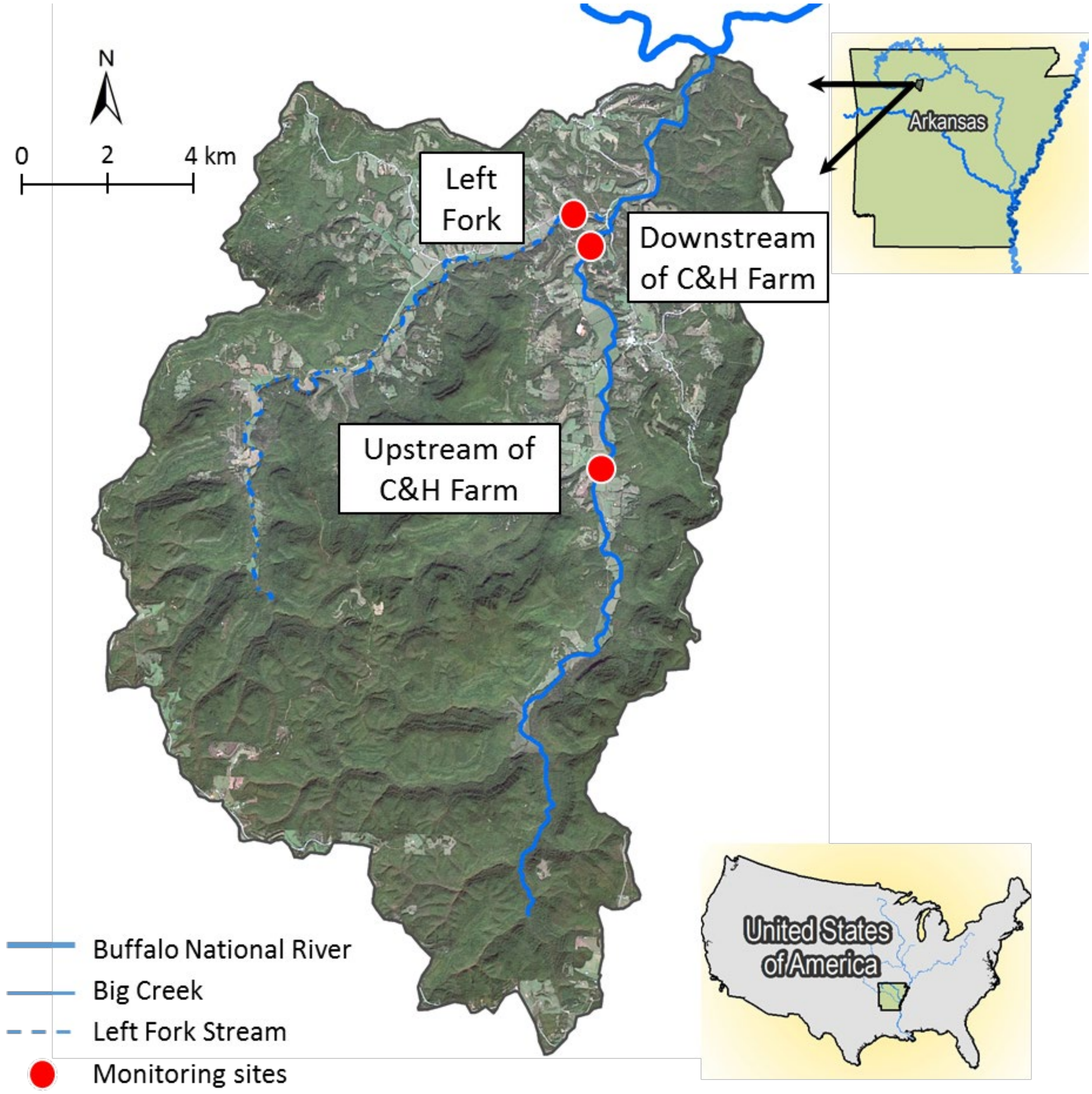


Figure 1. Map of Big Creek Watershed and its location. Watershed image credit: NASA and USGS Landsat 8 Image taken 10-20-2013.

Plan of Work

Summary

1. Collection of water samples for analysis was initiated in September 2013 and continued through June 2019 on a weekly basis for most sites (except when winter storms restricted access to sites and during extended periods of drought) and are included this final report at the following sites:
    a. base flow and periodic stormflow water samples from Big Creek above and below the C&H Farm;
    b. water from a spring (reflecting shallow aquifer flow);
    c. ephemeral stream (reflecting landscape drainage from the area of the holding ponds and operation facilities);
    d. surface runoff from Fields 1, 5a, and 12;
    e. two interceptor trenches below the slurry holding ponds (reflecting subsurface flow below the holding ponds); and
    f. house well (reflecting deeper ground water).
2. Grid-soil sampling (i.e., one-sample per 0.25 acre grid) of Fields 1, 5a, and 12 was conducted between December and February of 2014 prior to slurry application (i.e., Fields 1 and 12), in 2016 and in 2018.
3. Ground penetrating radar was completed in early 2014 on Fields 1, 5a, and 12 by NRCS to investigate below ground features that might accelerate water infiltration and flows. See Appendix C for details.
4. Due to difficulty in maintaining belowground piezometer stations on Fields 5a and 12 watertight, along with restricted access by the landowner to the stations during pasture growth (May through October), limited subsurface water depth information was obtained and thus, not included in this report.
5. Investigation of physical and chemical treatment of slurry from the holding ponds was conducted in 2013 and 2014 to explore potential long-term and economically viable options in order to modify to modify current manure management practices. Neither locally sourced limestone nor purchased slaked lime provided sufficient flocculation of slurry solids and precipitation of phosphorus (P), for on-site treatment of slurry to be an economically viable management option for the farm.
6. Vandalism was not a major problem during the project, except for:
    a. destruction of the sampler unit stand where Dry Creek enters Big Creek (November 2014) and was not replaced (a site recommended by initial Review Panel);
    b. solar panels from two sites were stolen for stream-side stations (October 2017); and
    c. animal carcasses dumped in the ephemeral stream upstream of our sampling unit (November 2017).

Overarching Goals

The overarching goal of the research and monitoring described in this Final Report was to understand if, how, and why stream nutrient concentrations change downstream at Big Creek and whether the permitted swine CAFO, C&H Farms has influenced water quality since extensive monitoring began in September 2013. See Appendix A for Memorandum of Agreement details.

This research and monitoring project evaluated the sustainable management of nutrients from the C&H Farm operation (subsequently referred to as C&H, to include animal facilities and fields permitted to receive land applications of slurry). The study included the following major tasks:

1. Monitor the fate and transport of nutrients and bacteria from land-applied swine effluent to pastures.
2. Assess the impact of farming operations (effluent holding ponds and land-application of effluent) on the quality of critical water features on and surrounding the farm including springs, ephemeral streams, creeks and ground water.
3. Determine the effectiveness and sustainability of alternative manure management techniques, including solid separation, which may enhance transport and export of nutrients out of the watershed.

To address the long-term sustainability of C&H, we grid-soil sampled every two years (2014, 2016 and 2018) to measure soil fertility levels of three fields (i.e., Fields 1, 5a, and 12), which we have a Memorandum of Understanding with landowners to access sampling sites (see Appendix A or details). This combined with nutrient levels in monitored wells will inform manure management decisions and ensure they remain environmentally sustainable. The project will assess the feasibility of manure treatment, which is regarded as addressing nutrient imbalance concerns and has the potential to provide the farm with cost-beneficial alternatives for the sustainable use and export of treated manures.

The plan of research meets the level of funding available. We deferred to Dr. Van Brahana on the use of dye-tracer tests to investigate the presence of possible rapid by-pass flow pathways common in karst-dominated areas. Dr. Brahana is an expert on dye-tracer studies and deferring to him avoided duplicative efforts and saved limited resources, which were used to pay for water sample analysis. A broad pool of expertise from the partner organizations will be brought together for work plan implementation and periodic review.

We believe the monitoring outlined in objectives I and 2 must continue for a minimum of five years, so that reliable conclusions and recommendations of the impact of operation of the C&H Farm on area soils and water quality can be made. This timeframe is recognized by NRCS, EPA, and general scientific community to be the minimum required to accurately assess any impacts and overcome annual weather fluctuations.

Field Evaluation - Land Application Sites

Assess water flow directions and risk of nutrient and bacteria losses from three fields (Fields 1, 5a, and 12) that will be used to land apply manure (Map 1 and Table 1). On each field;

1. Conduct a detailed topographic survey of the application fields to better understand surface water flow patterns and the most appropriate location for surface runoff collection and monitoring wells / piezometer devices.
2. Utilize GIS/GPS and grid soil sampling to develop initial soil nutrient maps for all application fields. Use results to develop strategic soil fertility sampling that will be repeated every two years to track changes in nutrient levels.
3. Conduct inventory of soil physical properties (surface infiltration, subsurface hydraulic conductivity, bulk density, P sorption isotherms, and particle size analysis) of the three application fields.
4. Install bermed surface runoff area (>2 acres) to collect and monitor surface runoff, with weather station.
5. Install two transects of monitoring wells / piezometers across the two stream-side fields (i.e., 5a and 12) to automatically and continuously determine if subsurface water is moving to or away from the adjacent river. Piezometers will be installed so that there is minimal piping or equipment above ground that could interfere or influence with day-to-day farm operations on that field.
6. Collect samples after each rainfall event from the surface runoff areas and monitoring wells, and from monitoring wells at monthly intervals, filter on site, store on ice and ship to the AWRC Laboratory for nitrogen (N), P, pH, sediment, and bacteria (E. coli) analysis for one year.
7. Annually measure soil nutrient fertility on every permitted field of C&H by state approved methods to assess the long-term sustainability of implemented measures.
8. Obtain nutrient application rates from farm records provided annually to the Arkansas Department of Environmental Quality (ADEQ), as part of the permitting requirements.

Water Quality Assessment of Springs, Ephemeral Streams, and Ephemeral Creeks in the Vicinity of the CAFO Production Facility

Measure nutrient, bacteria, and sediment concentrations in: a) an ephemeral stream that drains runoff from around the animal production facility and slurry holding ponds, b) springs connected to land-application fields, and c) Big Creek upstream and downstream of the C&H Farm.

1. Install two observation wells adjacent to the holding ponds and upslope of the holding ponds to determine any potential nutrient seepage.

3. Continuously monitor flow and automatically collect water samples at the road culvert draining the subwatershed containing the animal houses and manure holding ponds.

4. Install a calibrated stream gauge for continuous flow measurement and collect Big Creek water samples on a monthly basis.

5. Deploy sondes at the spring and Big Creek sampling locations to continuously determine dissolved oxygen (DO), excess partial pressure of carbon dioxide (EpCO_2), electrical conductivity (EC), and temperature of the water.

Manure Treatment via Solids and Chemical Separation: A Case Study to Evaluate Cost Benefits of Alternative Manure Management Options

Work with the owners of the C&H Farm to explore potential long-term, economically viable, options to modify current manure management practices in the general areas of:

1. Separating manure liquids and solids along with their differential management;
2. Retaining sufficient N to meet crop needs;
3. Exporting excess P off the farm;
4. Mitigating off site odor; and
5. Not exceeding the current economic, labor, and management resources of the farm.

The project will identify management options to meet the above objectives. It is anticipated that the options will include but not be limited to:

1. Mechanical separation of manure solids from liquids with or without chemicals as a precursor for off- farm transport of separated solids; and
2. Selective application of higher P content solids and lower P content liquids to different fields that minimizes any loss of nutrient loss.

For the management options identified, their initial and long-term costs will be estimated and an assessment of their implementation impacts made. Available literature and other information resources will be utilized in this process. However, there will be a need for laboratory and onsite tests/trials. This is especially true when evaluating manure solid-liquid separation and/or chemical use.

Land Use and Soils in the Big Creek Watershed and the Monitored Sub-Watershed

The Buffalo River Watershed is located in north central Arkansas (Figure 4). The location of the Big Creek watershed in the Buffalo River Watershed is depicted in Figure 5. Land use of the watershed drainage area was determined for several segments of the Big Creek Watershed (Table 1). This was accomplished using data from the USDA-NRCS Geospatial Data Gateway for Newton Co., AR http://datagateway.nrcs.usda.gov/; national land cover dataset by State for 2006; cropland data layer by State for 2006; and hydrography data layer for streams and HUC 12 watershed boundaries for 2007 to present. The following drainage areas were delineated; Big Creek (Figure 6), Big Creek upstream of the C&H (Figure 7), downstream of the C&H Farm to the Buffalo River (Figure 8), and the monitored land area encompassing fields permitted to receive manure slurry (Figure 9).

Overall, land use of the area of the monitored watershed encompassing the C&H Farm (18% pasture and 78% forest) was similar to the land area downstream of the C&H Farm to the Buffalo River (17% pasture and 80% forest) (Table 2). Upstream of the C&H Farm there was less pasture (8%) and more forest (90%; Table 2).

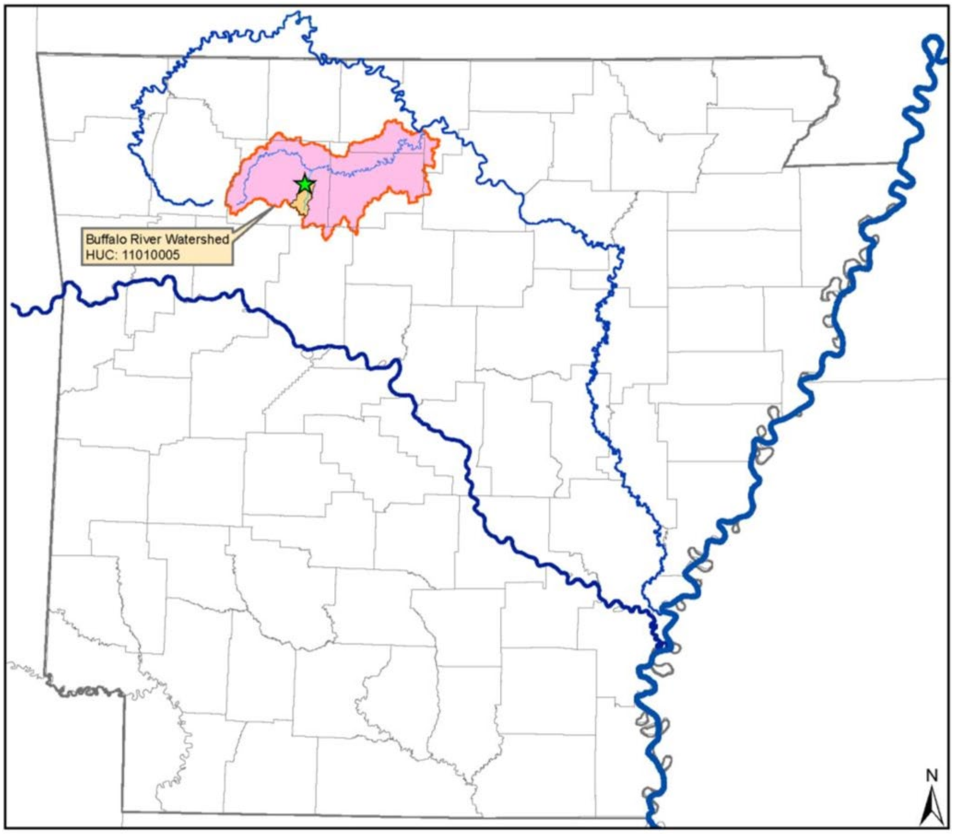


Figure 2. Location of the Buffalo River Watershed in Arkansas

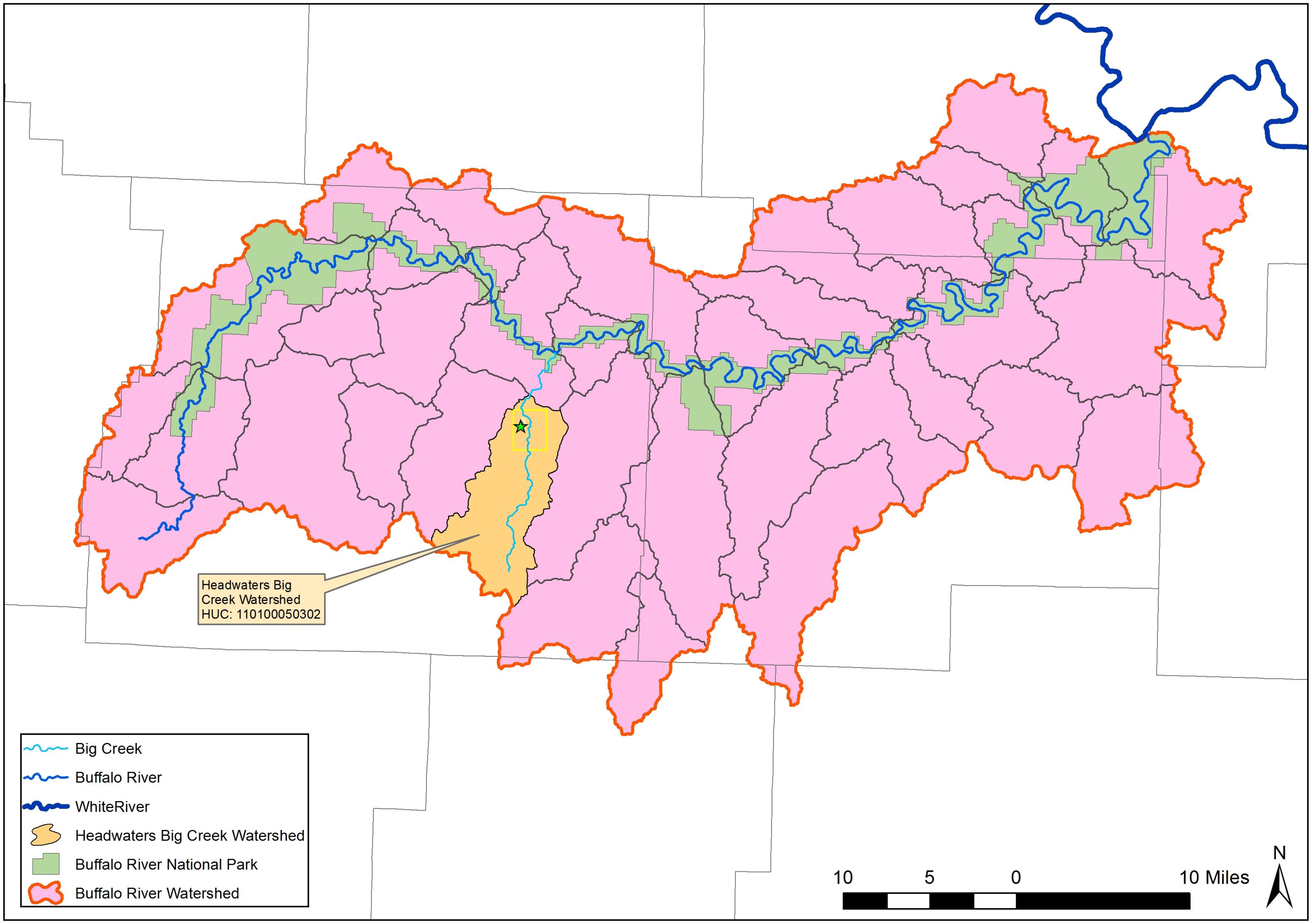


Figure 3. Location of Big Creek Watershed within the Buffalo River Watershed, Arkansas.

Table 1. Land use classification of the monitored watershed, upstream of C&H, downstream of C&H and Big Creek Watersheds. [1]

Land use/Land cover	Big Creek Watershed (Figure 4)		Upstream of C&H (Figure 5)		Downstream of C&H (Figure 6)		Monitored watershed (Figure 7)	
	Area (acres)	% of total area	Area (acres)	% of total area	Area (acres)	% of total area	Area (acres)	% of total area
Grassland/Pasture	8,381	14.4	1,389	8.0	5,431	17.0	1,561	17.8
Deciduous forest	45,977	79.0	15,110	86.5	24,297	75.9	6,570	75.1
Evergreen forest	1,858	3.2	514	2.9	1,094	3.4	250	2.9
Mixed forest	69	0.1	4	0.0	54	0.2	11	0.1
Shrubland	9	0.0	5	0.0	2	0.0	- - [2]	- -
Woody wetlands	2	0.0	0.4	0.0	0.7	0.00	0.7	0.0
Developed/Open space	1,800	3.1	435	2.5	1,038	3.2	327	3.7
Developed/Low intensity	113	0.2	13	0.1	77	0.2	23	0.3
Developed/Medium intensity	6	0.0	0.2	0.0	2	0.0	4	0.1
Developed/High intensity	1	0.0	- -	- -	- -	- -	1	0.1
Open water	1	0.0	- -	- -	0.9	0.0	- -	- -
TOTAL	**58,218**		**17,471**		**31,997**		**8,750**	

[1] Obtained the following data from the USDA:NRCS Geospatial Data Gateway for Newton Co., AR http://datagateway.nrcs.usda.gov/. National land cover dataset by State, 2006. Cropland data layer by State, 2006. Hydrography (streams and HUC 12 watershed boundaries), 2007-present.

[2] None measured.

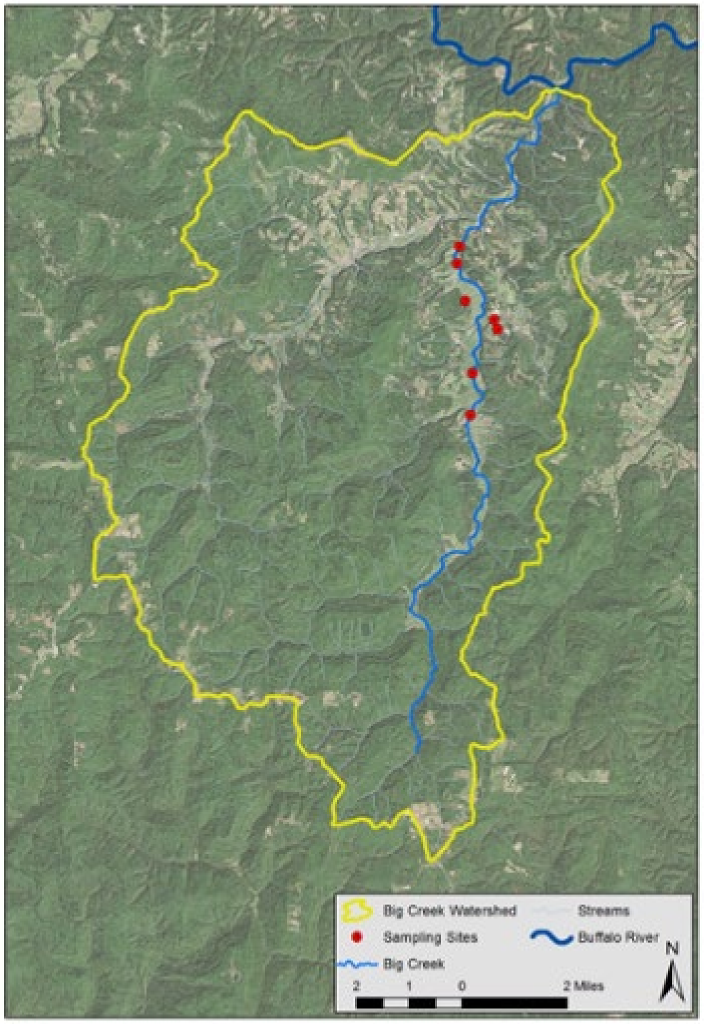


Figure 4. Big Creek Watershed with sampling sites.

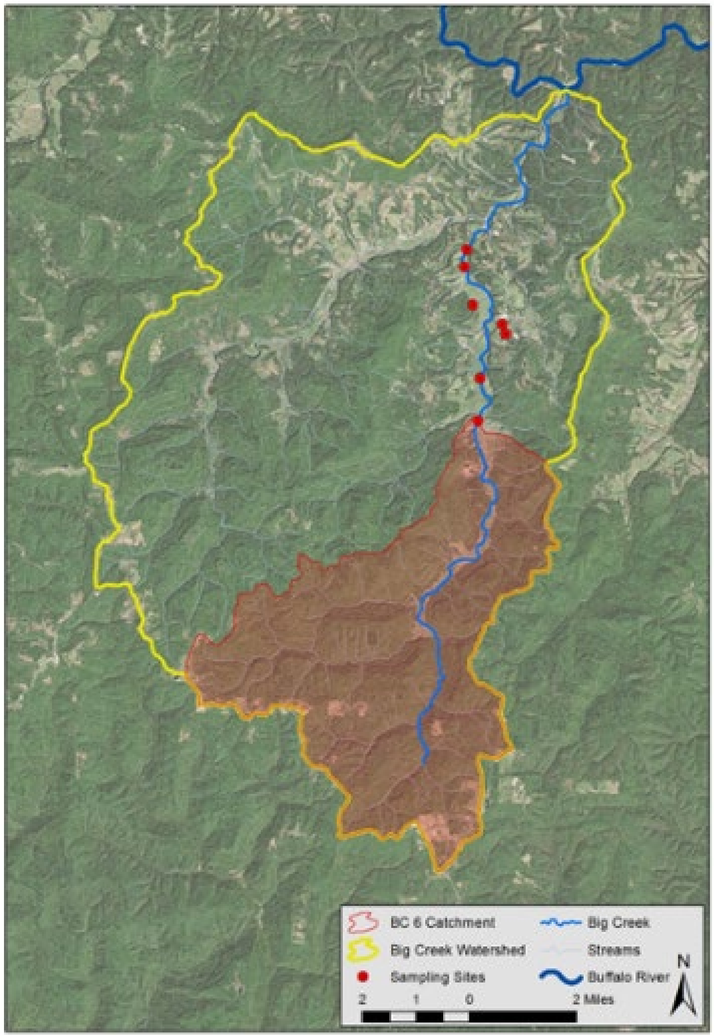


Figure 5. Watershed delineated by the sampling site upstream of the C&H farm.

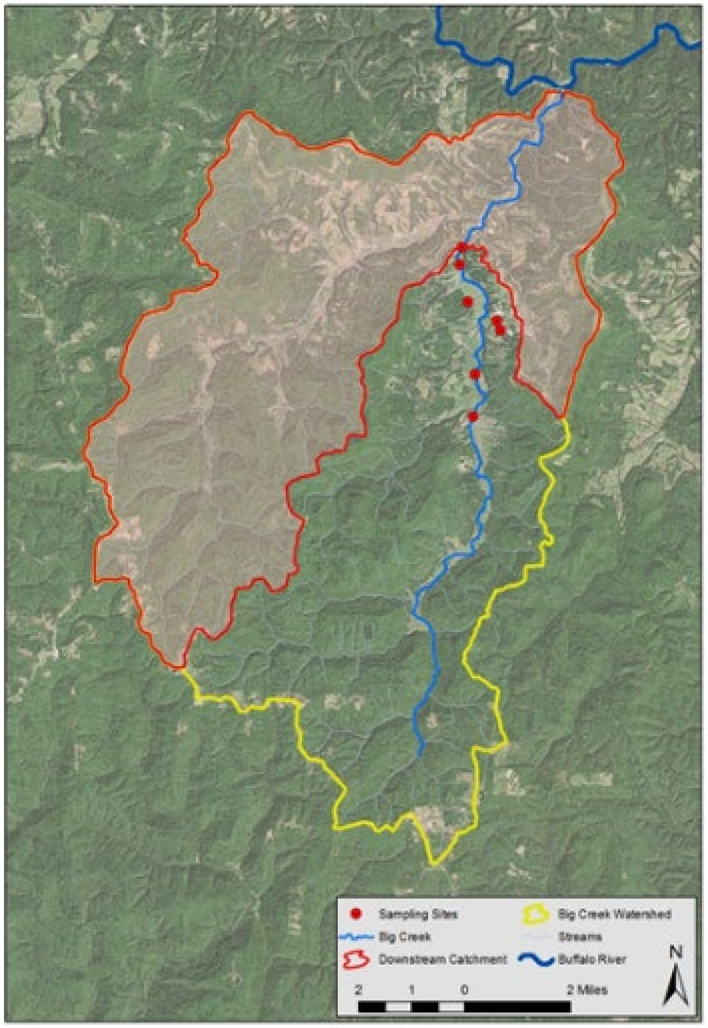


Figure 6. Watershed delineated by the sampling site downstream of the C&H farm to the Buffalo River.

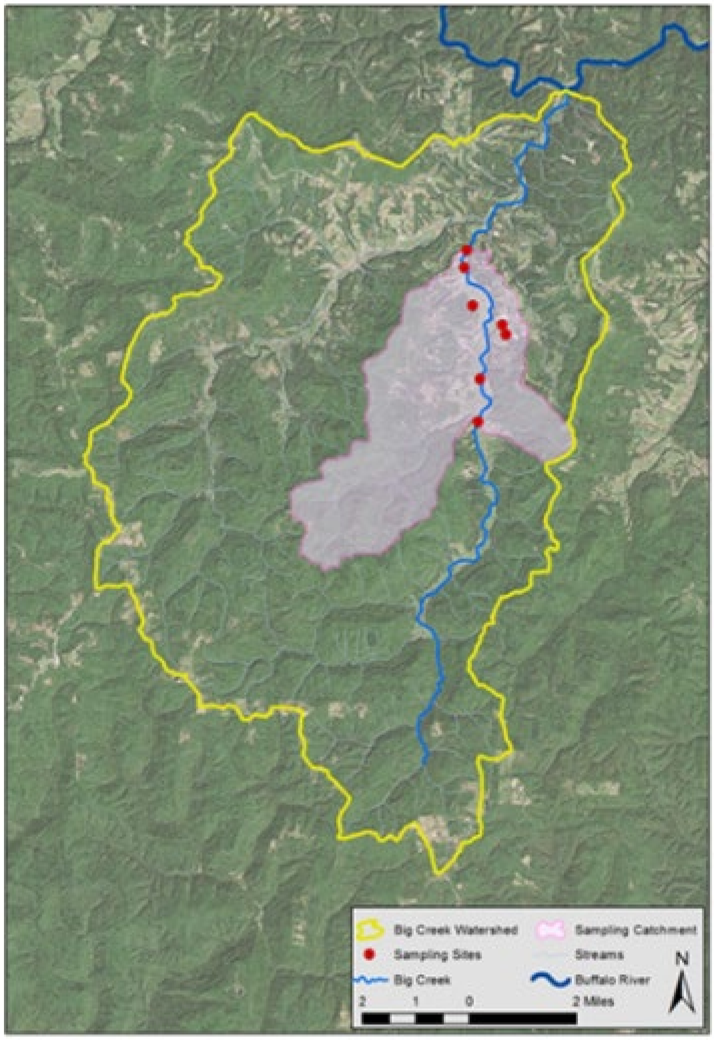


Figure 7. Watershed delineated by sampling sites upstream and downstream of the C&H Farm.

Table 2. Area as pasture, forest and urban for the monitored watershed, upstream of C&H, downstream of C&H and the Big Creek Watersheds.

Land use/Land cover	Big Creek Watershed		Upstream of C&H		Downstream of C&H		Monitored watershed	
	Area (acres)	% of total area	Area (acres)	% of total area	Area (acres)	% of total area	Area (acres)	% of total area
Pasture	8,381	14.4	1,389	8.0	5,431	17.0	1,561	17.8
Forest	47,915	82.3	15,633	89.5	25,448	79.5	6,834	78.1
Urban	1,920	3.3	448	2.6	1,117	3.5	355	4.1
Other	2	0.0	0	0.0	1	0.0	0	0.0

Sampling Locations

Water-quality monitoring sites detailed in Table 3 and Figure 10 are:

Site 1. Edge-of-field monitoring on Field 1 permitted to receive slurry.
Site 2. Edge-of-field monitoring on Field 5a excluded from receiving slurry.
Site 3. Edge-of-field monitoring on Field 12 permitted to receive slurry.
Site 4. Ephemeral stream flow draining a subwatershed containing the production facilities.
Site 5. Spring below Field 1.
Site 6. Big Creek upstream of the C&H Farm operation.
Site 7. Big Creak downstream of the C&H Farm operation.
Site 9. Left Fork downstream of the C&H Farm operation.
Site 10. North interceptor trench below the manure holding ponds.
Site 11. South interceptor trench below the manure holding ponds.
Site 12. House well at animal facility.

Table 3. Location of sampling sites on the Big Creek Research and Extension Team monitoring project.

Site description	Site	Latitude	Longitude	Elevation, ft
Field 1	BC1	35 55’ 06.42”	93 03’ 38.34”	984
Field 5a	BC2	35 56’03.01”	93 04’ 25.85”	778
Field 12	BC3	35 54’ 13.57”	93 04’ 04.76”	838

Site description	Site	Latitude	Longitude	Elevation, ft
Ephemeral stream	BC4	35 55’ 25.89”	93 04’ 14.94”	824
Spring	BC5	35 54’ 57.06”	93 03’ 34.64”	977
Big Creek upstream of farm	BC6	35 53’ 32.28”	93 04’ 06.38”	857
Big Creek downstream of farm	BC7	35 56’ 18.98”	93 04’ 21.81”	769
Left Fork	BC9	35 56’ 48.33”	93 04” 0.92”	760
Trench 1 (south)	T1	35 55’ 19.24”	93 04’ 23.04”	890
Trench 2 (north)	T2	35 55’ 21.39”	93 04’ 19.93”	882
House well	W1	35 55’ 27.02”	93 04’ 22.71”	915
Well water depth		35 55’ 27.02”	93 04’ 22.71”	590
Pond 1 base		35 55’ 20.36”	93 04’ 23.58”	900
Pond 2 base		35 55’ 22.27”	93 04’ 21.61”	892

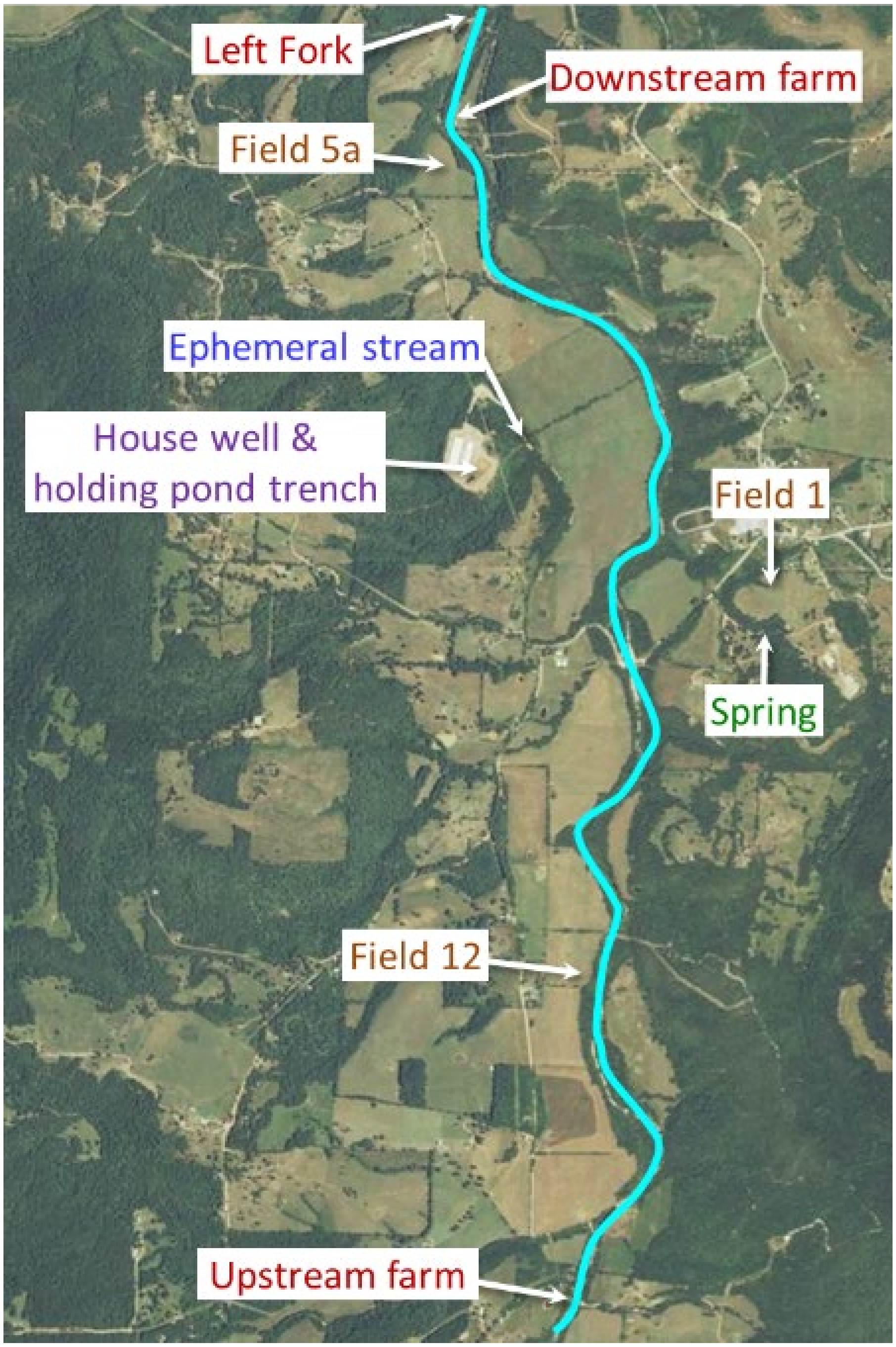


Figure 8. Location of sampling sites for the Big Creek Research and Extension Team project.

Soil Mapping Unit Description from NRCS, Newton Co., AR

For detailed soil survey information of the monitored portion of the Big Creek Watershed, see Appendix B.

Figure 9. Soil type distribution in the vicinity of the C&H Farm operation Mt. Judea, Newton Co., AR. Minor map unit components are excluded from this report.

Methods of Water Flow Measurement, Sample Collection, and Constituent Analysis

Sample Collection

Manual grab sample

The following protocols were used to collect, prepare, and analyze all water samples:

1. One-liter acid-washed bottles are used to collect grab stream samples for analysis.
2. Water is collected from just beneath the surface, where the stream was actively moving and well mixed.
3. The bottle is rinsed with stream water before collecting the sample.
4. Sterilized specimen cups are used to collect samples for bacterial evaluation.
5. Time of collection is noted, and samples placed in a cooler on ice to preserve them until processed and were submitted to the Arkansas Water Resources Center Water Quality Lab on the day of collection for analyses.

ISCO-autosampler collection

ISCO autosamplers collected storm flow samples at up and down stream of the C&H Farm (BC6 and BC7, respectively), ephemeral stream (BC4), Left Fork (BC9), trench (T1 and T2), and edge-of-field runoff sites (BC1, BC5a, and BC12). Each ISCO autosampler is programed to initiate sample collection when a critical stage height is exceeded (Tables 4 and 5). Pacing of sample collection is subsequently programmed to a specific volume of flow, as detailed in Tables 4 and 5.

Water samples during a storm event are composited in a 10 L bottle encased in the ISCO sampler, providing a flow-weighted composite sample for each event. Water collected in the sampler bottle is thoroughly agitated and transferred to a 1-L acid washed bottle. This rinsing process is repeated twice prior to final collection of a 1 L sample. Time of sample collection from the ISCO is noted, and samples placed in a cooler on ice to preserve them until processed. All samples are submitted to the Arkansas Water Resources Center Water Quality Lab on the day of collection for analysis.

Bacteria analysis is not conducted on ISCO collected samples as the tubing and other ISCO components contacting water (except for the acid-washed bottle) could not be isolated and thus, bacterial contamination during ISCO sample collection could not be guaranteed.

Table 4. Parameters used to enable ISCO auto-samplers at BCRET stream sites BC4, BC6, and BC7.

Site	Identifier	ISCO enabled when, over a 30-minute period, stage height (inches) increases	Volume pacing, 100 mL water collected per gallon of water		
			Rainfall, inches		
			<2.5	2.5 to 4	>4
Ephemeral stream	BC4	> 2.0 *	25,000	50,000	100,000
Upstream Big Creek	BC6	1.2	40,000,000	50,000,000	70,000,000
Downstream Big Creek	BC7	1.8	60,000,000	80,000,000	100,000,000

* For ephemeral stream stage height increases >2.0 inches over a 30-min period.

Table 5. Parameters used to enable ISCO auto-samplers at BCRET edge-of-field sites Field 1, 5a, and 12.

Site	Identifier	ISCO enabled when stage height (inches) above	Volume pacing, 100 mL water collected per gallon of water		
			Rainfall, inches		
			<2.5	2.5 to 4	>4
Field 1	BC1	> 0.75	500	1,000	5,000
Field 5a	BC2	> 0.75	5,000	10,000	50,000
Field 12	BC3	> 0.75	500	1,000	5,000

Discharge measurement at gaged sites

The rating curve providing discharge at the downstream site (BC7) is available from USGS via the BCRET website (see https://nwis.waterdata.usgs.gov/ar/nwis/uv/?cb_00065=on&cb_00045=on&cb_00010=on&format=gif_default&period=&begin_date=2014-04-16&end_date=2014-04-23&site_no=07055790) and provided here in Figure 10. USGS has not completed development of a rating curve for the Left Fork site and only concentrations will be given in this report.

Discharge at the ephemeral stream is calculated from water velocity and height of water in the culvert pipe where samples are collected, as measured by the velocity flow meter in the culvert opening and recovered by the ISCO sampler. This data along with diameter of the culver pipe is then used to determine discharge at this site.

Discharge at the edge-of-field sites, BC1, BC5a, and BC12, is calculated from water height in the flume's stilling well with a pressure transducer connected to the ISCO sampler. This recorded data along with dimensions of the 1.5 ft H flume at BC1 and 1.0 ft H flume at BC5a and 12 is used to determine discharge. The H flume at BC1 is larger than BC5a and 12, due to the larger drainage area and greater volume of surface runoff expected at BC1 than at 5a or 12.

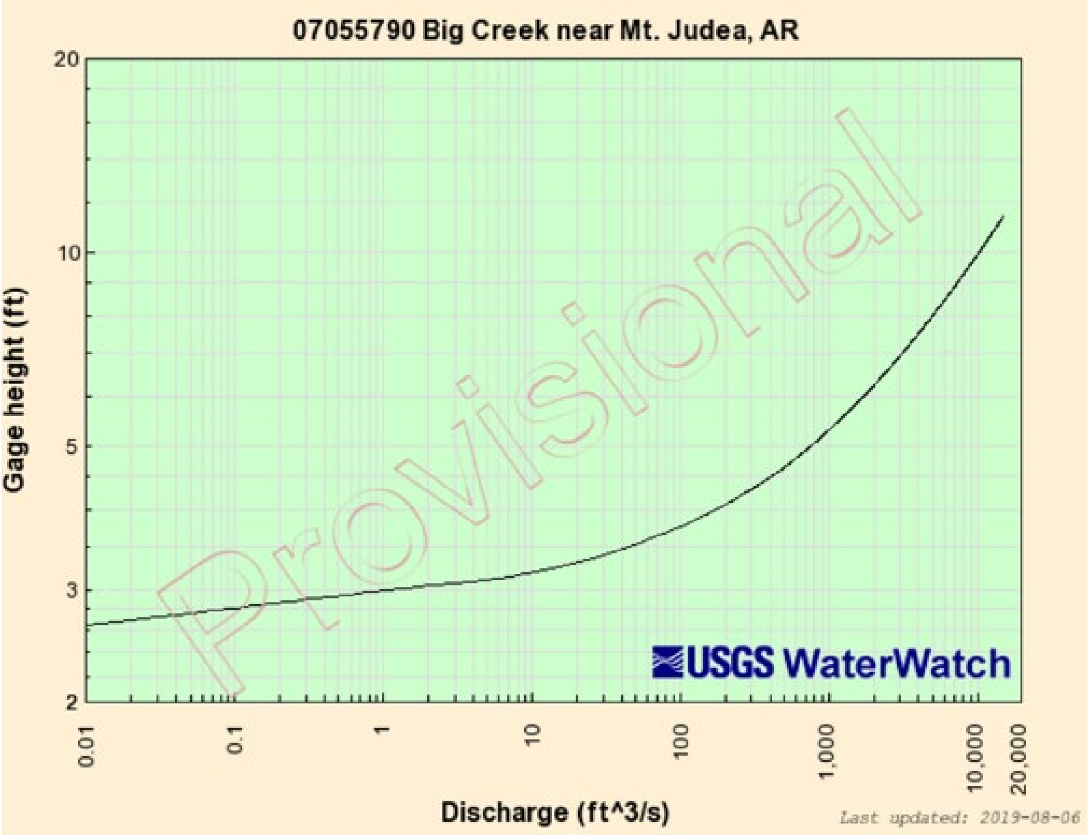


Figure 10. Rating curve developed by USGS for Big Creek downstream of the C&H Farm.

The ISCO area velocity flow module sensors use Doppler technology to directly measure average velocity in the flow stream. A pressure transducer measures liquid depth to determine flow area. The ISCO autosampler then calculates discharge by multiplying the area of the flow stream by its average velocity. For more detail, see https://www.teledyneisco.com/en-us/waterandwastewater/Sampler%20Documents/Datasheets/Isco%20750%20Area%20Velocity%20Flow%20Module%20Datasheet.pdf.

Note USGS states that Stage-discharge relations (ratings) are usually developed from a graphical analysis of numerous discharge measurements. Measurements are made on various schedules and sometimes for different purposes. All discharge measurements are compiled and maintained in a database. Each measurement is carefully made, and undergoes quality assurance review. Some measurements indicate a temporary change in the rating, often due to a change in the streambed (for example, erosion, or deposition) or growth of riparian vegetation. Such changes are called shifts; they may indicate a short- or long-term change in the rating for the gage. In normal usage, the measured shifts (or corrections) are applied mathematically to a defined rating.

Nutrient Load Estimation Using LOADEST

Nutrient loads in Big Creek were determined by the USGS tool LOAD ESTimator (LOADEST), which uses RStudio to estimate constituent loads in streams and rivers (https://water.usgs.gov/software/loadest/; Runkel, 2013; Runkel et al., 2004). LOADEST is based on two previously undocumented software programs known unofficially as LOADEST2 and ESTIMATOR [see Crawford (1996) and Cohn (1988) for relevant details]. Given a time series of streamflow, additional data variables, and constituent concentration, LOADEST assists the user in developing a regression model for the estimation of constituent load (calibration).

The calibration and estimation procedures within LOADEST are based on three statistical estimation methods. The first two methods, Adjusted Maximum Likelihood Estimation (AMLE) and Maximum Likelihood Estimation (MLE), are appropriate when the calibration model errors (residuals) are normally distributed (Runkel et al., 2004). Of the two, AMLE is the method of choice when the calibration data set (time series of streamflow, additional data variables, and concentration) contains censored data. The third method, Least Absolute Deviation (LAD), is an alternative to maximum likelihood estimation when the residuals are not normally distributed. LOADEST output includes diagnostic tests and warnings to assist the user in determining the appropriate estimation method and in interpreting the estimated loads. The LOADEST package tests many different regression models with different combinations of explanatory variables and selects the best model by minimization of the Akaike Information Criterion (AIC) (Runkel et al., 2004).

Explanatory variables within the regression model include various functions of streamflow, decimal time, and additional user-specified data variables. The formulated regression model is then used to estimate loads over a user-specified time interval (estimation) (Runkel et al., 2004). Mean load estimates, standard errors, and 95 percent confidence intervals are developed on a monthly and (or) seasonal basis.

We worked with USGS personnel in Little Rock, AR to develop and implement the R script used at the Carver site (USGS site 07055814 Big Creek at Carver, AR: https://waterdata.usgs.gov/ar/nwis/uv?site_no=07055814) for the BCRET downstream (BC7) site (i.e., USGS site 07055790 Big Creek near Mt. Judea, AR: https://waterdata.usgs.gov/ar/nwis/uv?site_no=07055790).

Acknowledgement

The Big Creek Research and Extension Team acknowledge and are extremely grateful to Brian Breaker (formerly U.S. Geological Survey) for advice and help in conducting, analyzing, and interpreting nutrient load estimations for Big Creek using LOADEST and Rscript. His vast experience informed and provided state of the science estimation of constituent loads.

Sample Analysis

1. Analyses included Alkalinity (APHA 2320-B), Chloride (EPA 300.0), Dissolved P (EPA 365.2), E. coli (APHA 9223-B), Electrical Conductivity (EPA 120.1), Nitrate-N (EPA 300.0), pH (EPA 150.1), Total N (APHA 4500-P J), and Total P (APHA 4500-P J) and are listed in Table 6. APHA is American Public Health Association from the Wadeable Streams Assessment, Water Chemistry Laboratory Manual http://www.epa.gov/owow/monitoring/wsa/WRS_lab_manual.pdf
2. Prior to collection of a house-well water sample, the well is purged and water temperature, pH, and electrical conductivity is measured on-site every 30 seconds until all values stabilize. At that point, a sample of water is collected in a 1-L acid-washed bottle. This method is taken from USGS and EPA well water sampling protocols. See USGS methods for sampling at https://water.usgs.gov/owq/FieldManual/chapter4/pdf/Chap4_v2.pdf. Specific and detailed guidance on the collected of water quality data can be found in the USGS National Field Manual at https://water.usgs.gov/owq/FieldManual/.

   The U.S. EPA also recommend that selected water quality parameters can be monitored during low-rate purging, with stabilization of these parameters indicating when the discharge water represents aquifer water or source well water. See: http://www.csus.edu/indiv/h/hornert/Geol_210_Summer_2012/Week%202%20readings/Puls%20and%20Barcelona%201996%20Low%20flow%20sampling.pdf and https://in-situ.com/wp-content/uploads/2015/01/Low-Flow-Groundwater-Sampling-Techniques-Improve-Sample-Quality-and-Reduce-Monitoring-Program-Costs-Case-Study.pdf
3. Minimum detection limits (MDLs) for each chemical and biological constituent are listed in Table 6. Some constituent concentrations were reported by the laboratory as less than the MDL but greater

than zero. Those values are given in subsequent tables but have less confidence in their accuracy than concentrations above the MDL.

Table 6. Minimum detection limits (MDLs) for each chemical and biological constituent.

Constituent	Method of analysis	Minimum detection limit [1]	Reporting limit [2]
Alkalinity, mg/L as $CaCO_3$	APHA 2320-B	2	- -
Chloride, mg/L	EPA 300.0	0.093	0.300
Dissolved P, mg/L	EPA 365.2	0.002	0.010
Conductivity, uS/cm	EPA 120.1	1	- -
Ammonia-N, mg/L	EPA 351.2	0.03	0.046
Dissolved organic carbon, mg/L	EPA 412.1	0.18	0.500
E. coli, MPN/100 mL	APHA 9223-B	1	<1
Nitrate-N, mg/L	EPA 300.0	0.004	0.050
pH	EPA 150.1	0.1	- -
Total coliform, MPN/100 mL	APHA 9223-B	1	<1
Total dissolved solids, mg/L	EPA 160.1	15.22	48.5
Total N, mg/L	APHA 4500-P J	0.006	0.050
Total P, mg/L	APHA 4500-P J	0.012	0.020
Total suspended solids, mg/L	EPA 160.2	6.58	10

[1] MDL the Minimum Detection Limit of an analyte that can be measured and reported with 99% confidence that the analyte concentration is greater than zero. Further information is available at http://water.usgs.gov/owq/OFR_99-193/detection.html

[2] The Reporting limit is the least (non-zero) calibrated standard used in analysis.

References

Buck, O., D.K. Niyogi, and C.R. Townsend. 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. Environ. Poll. 130(2):287-299.

Cohn, T.A. 1988. Adjusted maximum likelihood estimation of the moments of lognormal populations from type I censored samples. U.S. Geological Survey Open-File Report 88-350, 34 p.

Crawford, C.G. 1996. Estimating mean constituent loads in rivers by the rating-curve and flow-duration, rating-curve methods. Bloomington, Ind., Indiana University, Ph.D. dissertation, 245 p.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, and M.D. Munn. 2010. The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350. 174 pages. Available at: http://water.usgs.gov/nawqa/nutrients/pubs/circ1350

Giovannetti, J., L.B. Massey, B.E. Haggard, and R.A. Morgan. 2013. Land use effects on stream nutrients at Beaver Lake Watershed. J. Am. Water Works Assoc. 105:E1–E10. Available at: http://www.awwa.org/publications/journal-awwa/abstract/articleid/34406246.aspx

Haggard, B.E., P.A. Moore, Jr., I. Chaubey, and E.H. Stanley. 2003. Nitrogen and phosphorus concentrations and export from an Ozark Plateau Catchment in the United States. Biosys. Eng. 86(1):75-85.

Hays, P.D., Knierim, K.J., Breaker, Brian, Westerman, D.A., and Clark, B.R., 2016, Hydrogeology and hydrologic condi¬tions of the Ozark Plateaus aquifer system: U.S. Geological Survey 2016–5137, 61 p., http://dx.doi.org/10.3133/sir20165137.

Migliaccio, K.W., B.E. Haggard, I. Chaubey, and M.D. Matlock. 2007. Linking watershed subbasin characteristics to water quality parameters in War Eagle Creek Watershed. Trans. Am. Soc. Agric. Eng. 50(6):2007-2016.

Rebich, R.A., N.A. Houston, S.V. Mize, D.K. Pearson, P.B. Ging, and C.E. Hornig. 2011. Sources and delivery of nutrients to the northwestern Gulf of Mexico from streams in the south-central United States. J. Am. Water Res. Assoc. 47(5):1062-1086.

Reckhow, K.H., P.E. Norris, R.J. Budell, D.M. Di Toro, J.N. Galloway, H. Greening, A.N. Sharpley, A. Shirmhhammadi, and P.E. Stacey. 2011. Achieving nutrient and sediment reduction goals in the Chesapeake Bay: An evaluation of program strategies and implementation. The National Academies Press, Washington, DC. 258 pages.

Runkel, R.L., C.G. Crawford, and T.A. Cohn. 2004. Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. U.S. Geological Survey Techniques and Methods Book 4, Chapter A5, 69 p. Available at https://water.usgs.gov/software/loadest/doc/.

Runkel, R.L. 2013. Revisions to LOADEST. U.S. Geological Survey Techniques and Methods. 6 p. Available at https://water.usgs.gov/software/loadest/doc/.

Scavia, D., J.D. Allan, K.K. Arend, S. Bartell, D. Beletsky, N.S. Bosch, S.B. Brandt, R.D. Briland, I. Daloglu, J.V. DePinto, D.M. Dolan, M.A. Evans, T.M Farmer, D. Goto, H. Han, T.O. Hoeoek, R. Knight, S.A. Ludsin, D. Mason, A.M. Michalak, R.P. Richards, J.J. Roberts, D.K. Rucinski, E. Rutherford, D.J. Schwab, T.M. Sesterhenn, H. Zhang, and Y. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res. 40:226-246.

KARST GEOLOGY AND THE BIG CREEK WATERSHED

Contents

List of Tables

List of Figures

Background

The Big Creek Watershed below the C&H Farm and application field locations, lie within a karst hydrologic system of great complexity exhibiting intimate connection of surface-water and groundwater regimes. These characteristics endow the hydrologic system as an important recreational resource locally and regionally, but also render the system vulnerable to contamination. The complexity of karst prevents easy understanding of flow regimes, challenging effective protection and management. Karst hydrologic systems are defined by the heterogeneous distribution of high-permeability solution channels that have developed in soluble, carbonate rock and the connectivity of these channels with the land surface (Figure 2).

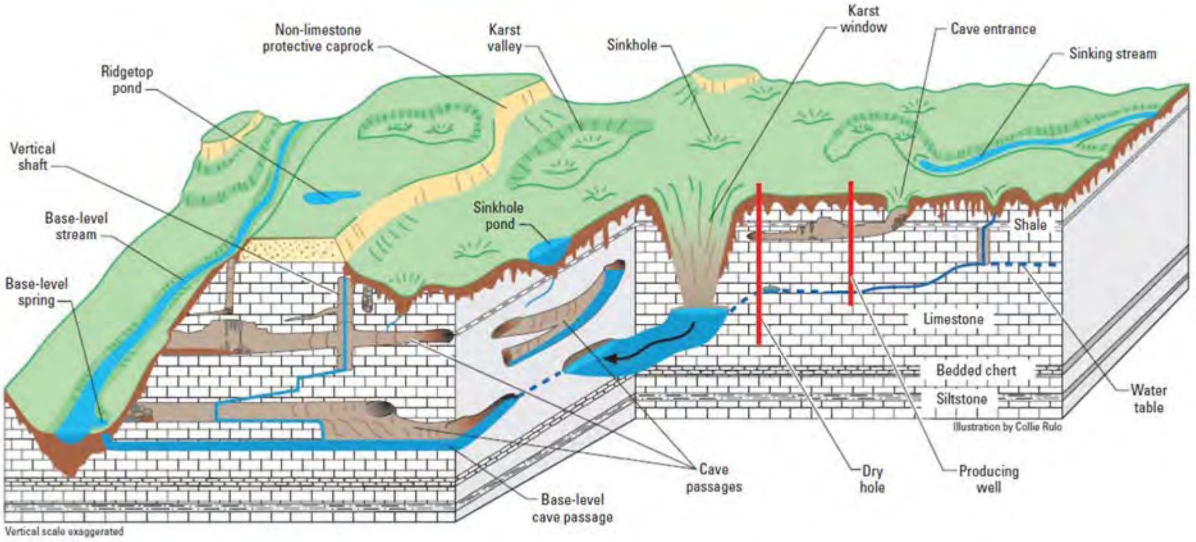


Figure 1. Schematic representation of karst features that influence the fate and transport of nutrients in the landscape; and which can increase the speed and unpredictability of nutrient flows (from Currens, 1995).

This connectivity results in rapid transport of surface water, as well as surface-derived contaminants, into the groundwater environment, bypassing soils, regolith, and granular rock strata, where any attenuation of contaminants may occur. Karst groundwater flow paths often cross surface topographic divides and are dynamic, frequently changing dominant conduits and flow direction, as well as changing recharge-area boundaries with changing hydrologic conditions. Karst terrane is often typified karst features representing locations on these solution-channel paths; e.g., sinkholes, springs, caves, and losing streams. In the Big Creek Watershed, these surface expressions of karst are often subdued or covered by a regolith mantle. Mantled karst is characteristic of the Springfield Plateau, the physiographic section in which the Big Creek Watershed is largely located.

Geologic Framework

The weathered regolith mantle overlying the karst bedrock of the Big Creek area is a key hydrogeologic framework component affecting hydrology in the Big Creek Watershed. The regolith varies greatly in thickness across short distances, from near zero (one example area is where bedrock is exposed at the surface, excluded from application of manure,) to 60 ft or more (as observed in the area of swine barns). The regolith tends to be thicker in more flat-lying valley floors, and thinner in steep areas.

The regolith is a clay-rich, typically low-permeability unit that contains variable amounts of chert; this material is derived from weathering of the original Mississippian and Pennsylvanian units. The regolith generally is present as a silt loam surface soil overlying a clay loam subsoil, which can vary from being well-drained and exhibiting moderate permeability, to very tight with low permeability. Chert constitutes up to 90% of the regolith in some areas, and is present from sand to boulder size, as well as being present as laterally continuous remnant layers that remain in autochthonous soils. These chert layers present permeability contrasts along which water flows, often acting as barriers to infiltration.

The variable thickness and composition of the regolith mantle, imparts heterogeneous and anisotropic hydraulic characteristics and resultant spatially variable flow rates through the unsaturated zone (Al-Qinna et al., 2014). Where present in considerable thickness, the regolith is a strong impediment to infiltration of precipitation and surface water, protecting the underlying karst aquifer from rapid input of surface-derived contaminants. However, the variable thickness of the regolith and the variable clay and chert distribution render the protective qualities of the regolith somewhat spatially sporadic. Big Creek valley is generally covered in alluvial sediments that range up to more than 20 ft in thickness.

Relatively horizontal sedimentary rocks of Ordovician through Pennsylvanian age are exposed and underlie the Big Creek watershed. Pennsylvanian clastics--sandstones, shale and siltstones—are present at the surface at higher elevations—ridges and plateaus. At lower elevations, in the foothills and valleys, the Mississippian Boone Formation, a cherty limestone, is exposed and is the predominant geological formation in the study area. The Ordovician Ferndale, Plattin, St. Peter Sandstone, and Everton Formations are exposed at low elevations in the Big Creek Watershed near the confluence with the Buffalo National River (Figure 3).

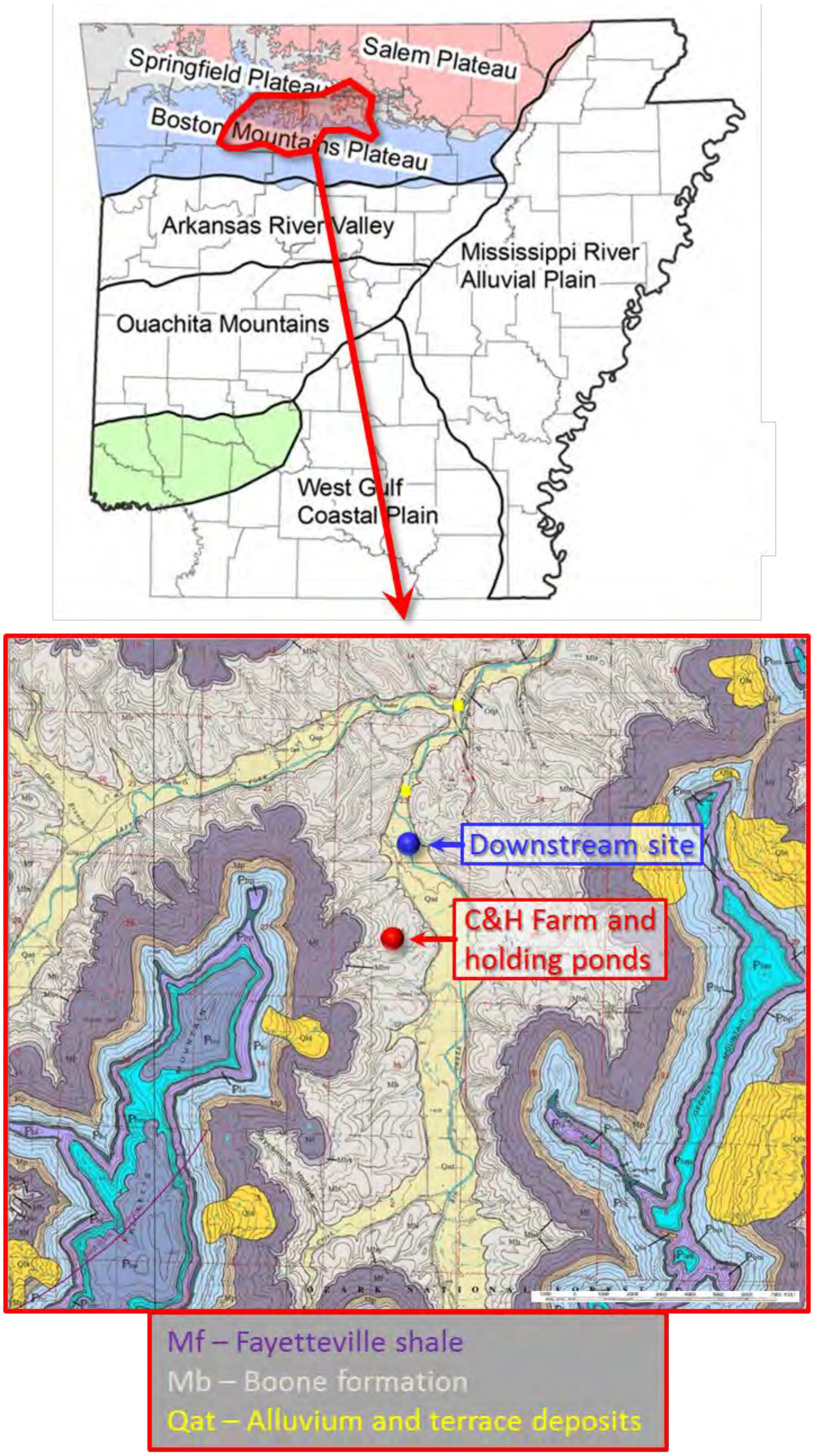


Figure 2. Physiographic map of Arkansas showing the areas containing rocks susceptible to karst formation with location of the Buffalo River Watershed (top map) and geology of the area encompassing the monitored Big Creek Watershed, C&H Farm, and BCRET sampling site on Big Creek downstream of the C&H Farm operation (bottom map adapted from Braden and Ausbrooks, 2003).

The Boone Formation is the main rock unit in the study area as it underlies C&H Farm and the application fields and is exposed at the surface or is present in the subsurface across most of the Big Creek Watershed. The Boone Formation consists of approximately 330 ft of interbedded limestone and chert. The basal St. Joe Member of the Boone Formation and the upper 20 ft of the Boone Formation, are generally represented by relatively pure limestone. Soluble limestone of the Boone contrasts with the highly insoluble, brittle chert, which constitutes 50 to 70% of the entire thickness of the Formation (Liner, 1979). Limestone layers form numerous couplets with the aerially extensive chert layers through much of the middle and lower sections of the Boone Formation (Hudson and Murray, 2003). Limestone layers are soluble and prone to karstification; the chert layers are relatively insoluble and present permeability contrasts, which separate and bound groundwater flow paths.

Karst Development and Hydrologic Characteristics

The highly soluble nature of the carbonate rocks of the Boone Formation has given rise to karst development resulting in conduits, springs, and other karst features in the Big Creek watershed. The older, deeper Ordovician carbonates—the Ferndale, Plattin, and Everton Formations—have also experienced karst development. Karst-development processes and history are important aspects of the geology controlling groundwater hydrology in the Big Creek Watershed and broader Ozark region. Multiple episodes of karst dissolution are evident in the carbonate strata, culminating in the karst development that is currently ongoing with exposure of these soluble carbonate strata to meteoric water and surface-weathering conditions. Paleokarst development occurred in Ordovician units at the Ordovician-Mississippian unconformity and in Mississippian units at the Mississippian-Pennsylvanian unconformity (Webb, 1994; Kresse et al., 2014). Additionally, hypogene karst development, predating recent epigenetic karst, occurred as lead and zinc ore-bearing fluids moved from the Arkoma Basin during Permian time and deposited the Mississippi Valley Type ores in northern Arkansas

In the Boone Formation, high hydraulic conductivity values (up to 3−10 ft/s; Stanton, 1993) are a result of development of secondary porosity through karst-forming diagenetic processes, particularly dissolution of bedrock along joints, fractures, and bedding planes, rather than from primary, matrix-type porosity. Enhancement or enlargements of fractures, bedding planes, and conduits by carbonate dissolution is an active, ongoing process. Hydraulic conductivity values of matrix porosity blocks are much lower, on the order of 10^{-12} ft/s or even less (Van den Heuvel, 1979; Peterson et al., 2002). Development of secondary porosity has produced anisotropic and heterogeneous hydraulic characteristics for the aquifer.

The presence of smaller-scale matrix, small-aperture fracture, and small-conduit porosity combined with the dissolution-enhanced conduits result in a bimodal permeability distribution and in water movement that may be described relative to two flow end members—diffuse flow and focused (conduit) flow. Because of the low rock-matrix hydraulic conductivity, a large fraction of groundwater transfer is through the focused-flow component, and rapid input of surface water, rapid flow velocities (often in the range of at velocities of 10s to 1,000s of ft/d; e.g., Hudson et al., 2007, 2011; Mott et al., 2000;

Funkhouser et al., 1999), rapid mass transfer, and minimal attenuation of contaminants are associated with this component of flow. More time-averaged flow, maintenance of stream flows during dry periods, low flow velocities, and effective attenuation of contaminants are behaviors associated with the diffuse component of flow.

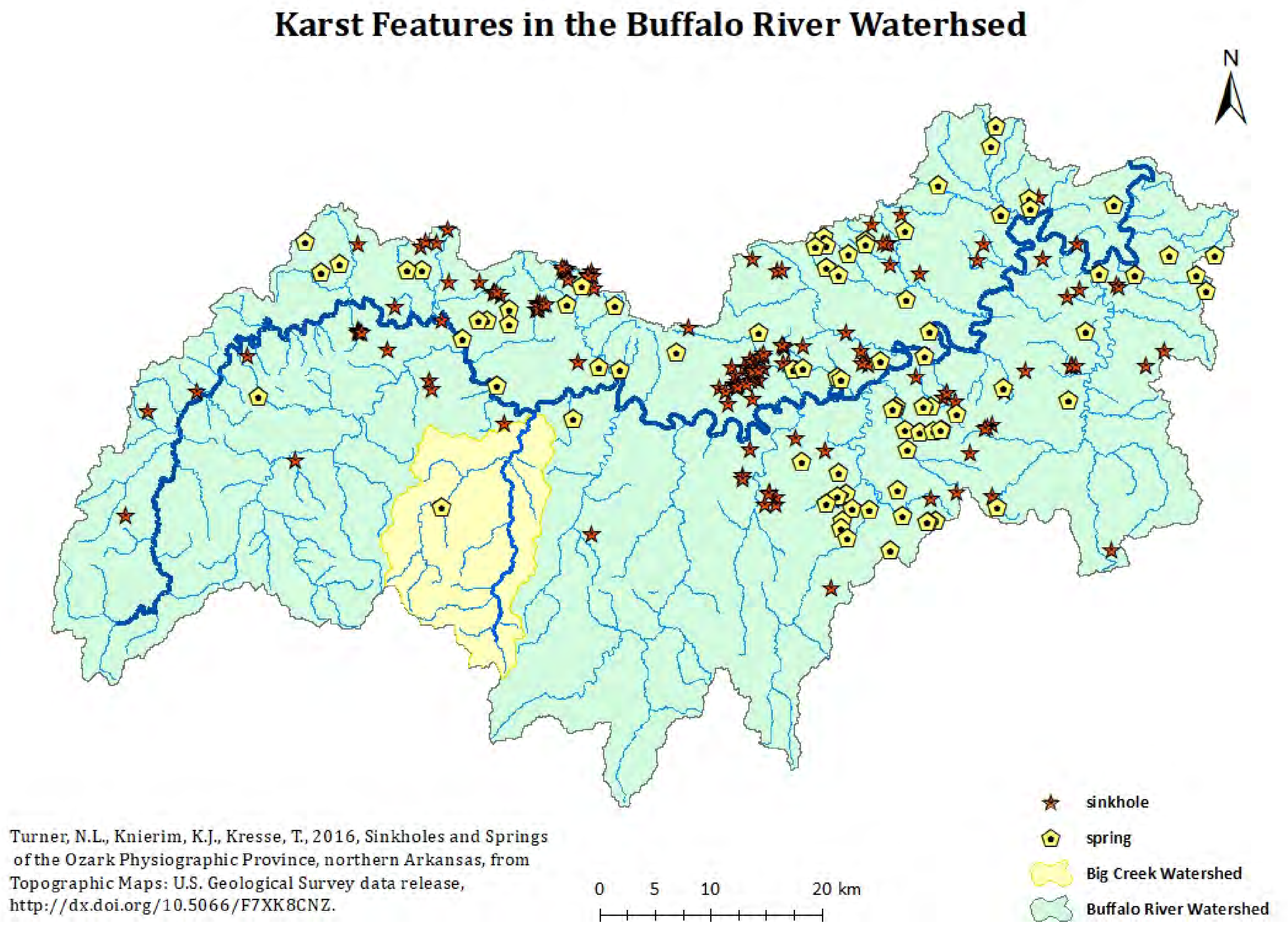
Wells yields in the study area reflect the porosity types: where wells intersect highly porous and permeable zones, yields of 10 gal/min and more are observed; where wells are completed in zones with little secondary development of porosity and permeability, well yields are typically less than 10 gal/min. An important phenomenon caused by karst development is inter-basin transfer of water. Dye-tracing studies and observations of drainage-area-discharge relations show the abundant occurrence of transfer of groundwater across surface-water drainage basin divides in subwatersheds along the Buffalo River (Brahana et al., 2016; Brahana, 1997; Sullivan, 1974; Mott et al., 2000). Consideration of inter-basin movement of water is an important point for protection and management of groundwater, because contributing zones are not apparent at the surface and contaminants can be introduced into groundwater from unexpected locations.

Groundwater recharge in the study area occurs through infiltration of precipitation and is strongly controlled by the karst development of the system. Recharge occurs as both diffuse and focused recharge. Diffuse recharge occurs by infiltration of precipitation through the overlying soils and regolith. Focused recharge occurs through karst features such as sinkholes, fractures and conduits, and losing stream reaches. Karst features and focused-flow avenues allow rapid recharge by precipitation falling on the surface, thus allowing influx of surface-derived contaminants into groundwater systems with little attenuation and results in higher susceptibility to surface-derived contamination.

Karst Features in the Buffalo River and Big Creek Watersheds

Turner et al. (2016) recently mapped karst features of the Ozark Physiographic Province, northern Arkansas. Those features mapped in the Buffalo River and Big Creek Watersheds are presented in Figure 3. The level of resolution of mapped features is too coarse to identify known observed surficial karst features on fields permitted to receive slurry from the C&H Farm.

Although on-farm nutrient management planning occurs at the field scale, there is a lack of consistent and well-maintained GIS databases of karst features and geologic mapping at this scale. As an example, in Arkansas, the AGS topographic-scale geologic mapping (which includes an inventory of karst features), usually maps 1- 3 quads a year; other states map at a similar rate. Thus, NMP development and risk assessment at a State level (where policy is made) would be greatly aided by consistent karst feature databases and geologic mapping.



Turner, N.L., Knierim, K.J., Kresse, T., 2016, Sinkholes and Springs of the Ozark Physiographic Province, northern Arkansas, from Topographic Maps: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7XK8CNZ.

Figure 3. Karst features in the Buffalo River Watershed, derived from Turner et al. (2016).

Implications of Karst on Nutrient Fate and Transport

The effective connection of surface with groundwater environments by high-permeability, dissolution-enhanced conduits, create rapid groundwater velocities and high volume and mass-transport capacities. This coupled with groundwater recharge bypassing the overlying soil and regolith, limit any filtration, and processing capacity within the karst framework, combine to render groundwater in karst hydrologic systems, very susceptible to contamination from various land uses. Studies of various agricultural land uses including CAFOs in karst terrain have shown that waste lagoons and manure application fields can be sources of groundwater contamination (Brahana et al., 2014, 2016; Chapman et al., 2015; Ham, 2002; Kelly et al., 2009; Hutchins et al., 2012). Contaminants include nutrients N and P, bacteria, steroid hormones, heavy metals, antibiotics, and pharmaceuticals (Hong et al., 2013; Mallin and Cahoon, 2003; Lapworth et al., 2012; Roland, 2016).

Dye-trace Studies Conducted in Big Creek Watershed

A series of dye-trace studies in the monitored Big Creek Watershed were conducted by Drs. Kosič and Brahana in 2014 after the C&H Farm became operational. As mentioned in our plan of work, in order to conserve resources, we chose not to conducted additional dye-trace studies and refer to Kosič (2019) and mimicked the surface application of slurry to our monitored, permitted fields. A general map of area geology and dye-trace studies conducted in the Big Creek Watershed is shown in Figure 3 (from Brahana et al., 2016). Additionally, we were not able to devise an appropriate dye-trace study that would simulate potential for movement with surface applied slurry.

Kosič (2019) used three dyes fluorescein, rhodamine, eosin and to trace groundwater flow paths in April and August 2014 at several sites in the Big Creek Watershed (Table 1). Dye injection points were chosen based on the hydrogeological setting of the area, direct accessibility to the aquifer, and proximity to the C&H Farm production area and its spray fields (Kosič, 2019 and Kosič et al., 2015). Dye receptors were placed at selected monitoring points in private or National Park Service springs, wells and caves. Several monitoring points were also located in the stream beds of Big Creek and Buffalo National River.

Sampling utilized active charcoal dye receptors which enabled the time-integrated monitoring of a large number of locations. For example, the eosin dye was injected in a field adjacent to Field 12 monitored by BCRET. Here 3 kg of eosin, previously diluted with 5 L of water, were injected on May 12, 2014 and flushed with 20 L of water. Two days later an 89 mm rainfall occurred.

Dye receptors were collected periodically over a period of four months, with a sample frequency of days to weeks depending on hydrological conditions. Receptors were cleaned, dried, and eluted with a mixture of 70 % of isopropanol and 5 % potassium hydroxide. The resulting eluent was analyzed after 5 hours, using a scanning Shimadzu spectrophotoflurimeter at the University of Arkansas. The resulting detects in springs, caves, and creeks in the Big Creek Watershed for fluorescein, rhodamine, and eosin are shown in Figures 4, 5, and 6, respectively. Arrows on these figures assume straight-line groundwater flow directions between injection and detection points.

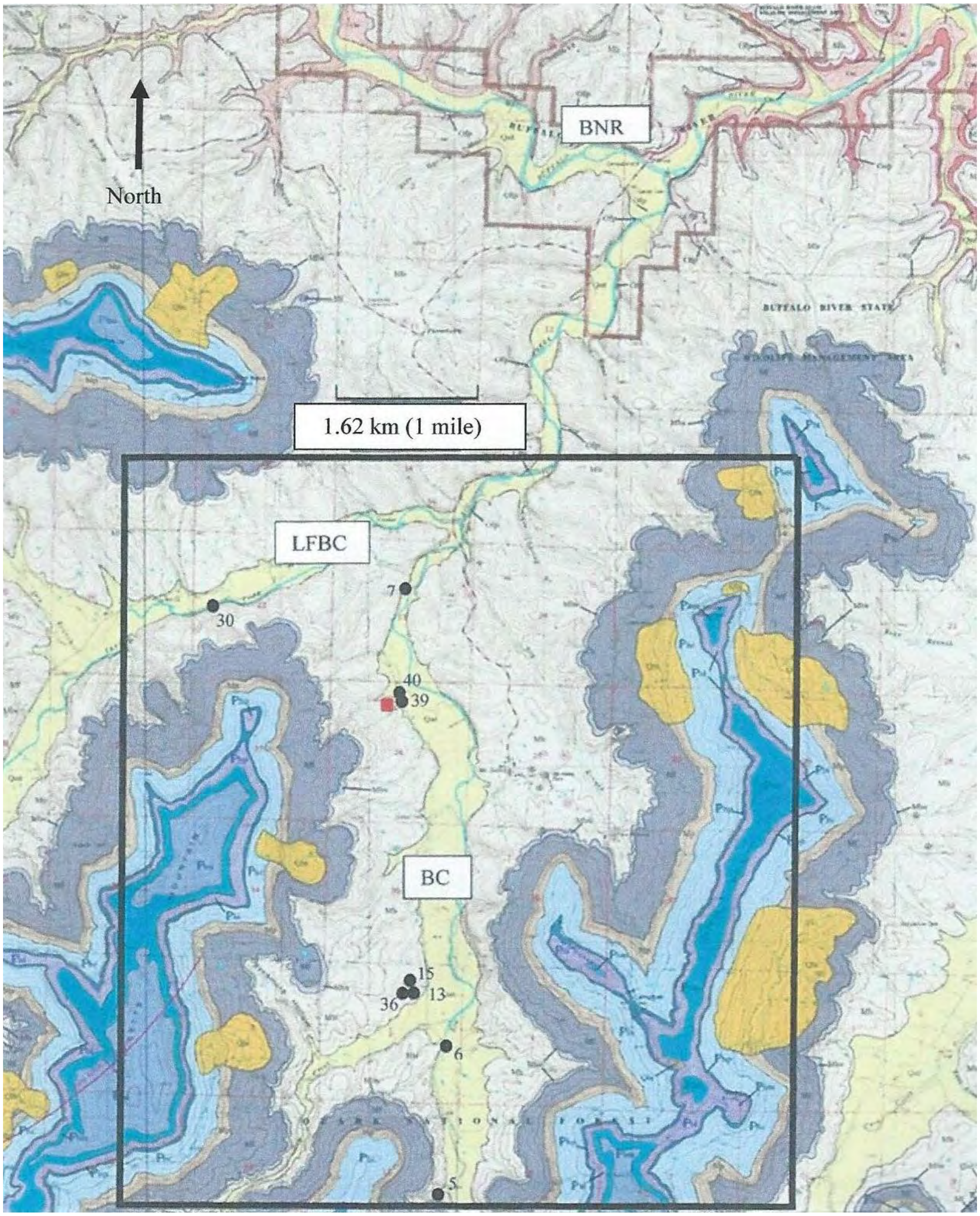


Figure 4. Geologic map of the study area, indicating the extent of karst where the Boone Formation (light grey color) occurs at land surface. BNR is Buffalo National River; BC is Big Creek and LFBC is Left Fork of Big Creek. The CAFO is shown by the red square, and the spreading fields for waste mostly lie between 7 & 6 on the west side of Big Creek. The study area is outlined by the black rectangle. Numbers 5 & 30 are the furthest extent of groundwater tracing in the study area from dye input at 36, which has an altitude greater than any of the dye-receiving sites. Map reproduced from Brahana et al. (2016) with the permission of Dr. Brahana.

Dye receptors were collected periodically over a period of four months, with a sample frequency of days to weeks depending on hydrological conditions. Receptors were cleaned, dried, and eluted with a mixture of 70 % of isopropanol and 5 % potassium hydroxide. The resulting eluent was analyzed after 5 hours, using a scanning Shimadzu spectrophotoflurimeter at the University of Arkansas. The resulting detects in springs, caves, and creeks in the Big Creek Watershed for fluorescein, rhodamine, and eosin are shown in Figures 4, 5, and 6, respectively. Arrows on these figures assume straight-line groundwater flow directions between injection and detection points.

The dye-trace studies of Kosič (2019) and Kosič et al. (2015) demonstrate the high velocity with which groundwater flows can occur in the Boone karst setting of Big Creek Watershed (Table 1 and Figures 4, 5, and 6). It was evident from the eosin-dye injection that subsurface flows traversed surface drainage basins, with detects from the field adjacent to BC12 occurring in Left Fork sub-watershed (Figure 6). The overall conclusions of the dye-trace studies of Kosič (2019) demonstrate the complexity of subsurface flows in the karst system in this area of the Boone formation.

Table 1 . Qualitative trace tests conducted in 2014 in Big Creek Watershed and adjacent watersheds using three fluorescent dyes; fluorescein (F), rhodamine (R), eosin (E). Information adapted from Kosič (2019) with permission from Dr. K. Kosič.

Injection date	Site	Injection point	Geology	Trace material	Groundwater flow	Detection comments
April 22	BS-39	Dug well, perched	Lower cherty Boone epikarst	F	Moderate: velocity about 600 m/day	Multiple visual and instrumental confirmation
April 27	BS-78	Sinking stream	Alluvial gravel over middle Boone	R	Low velocity, not calculated	No observable confirmation, likely perched
May 12	BS-36	Dug well, perched on chert	Middle cherty Boone	E	Very high velocity, about 800 m/day	Multiple instrumental confirmation; cross-basin and cross formation flow; radial flow
July 10	BS-71	Swallet, perched	Upper Boone	R	Moderate velocity, about 700 m/day	Visual and instrumental confirmation; surface flow part of the way
August 5	BS-36	Dug well, perched on chert	Middle cherty Boone	F	Very low, no velocity	No observable confirmation; dye sunk to lower reservoir, ,which was stagnant with no flow

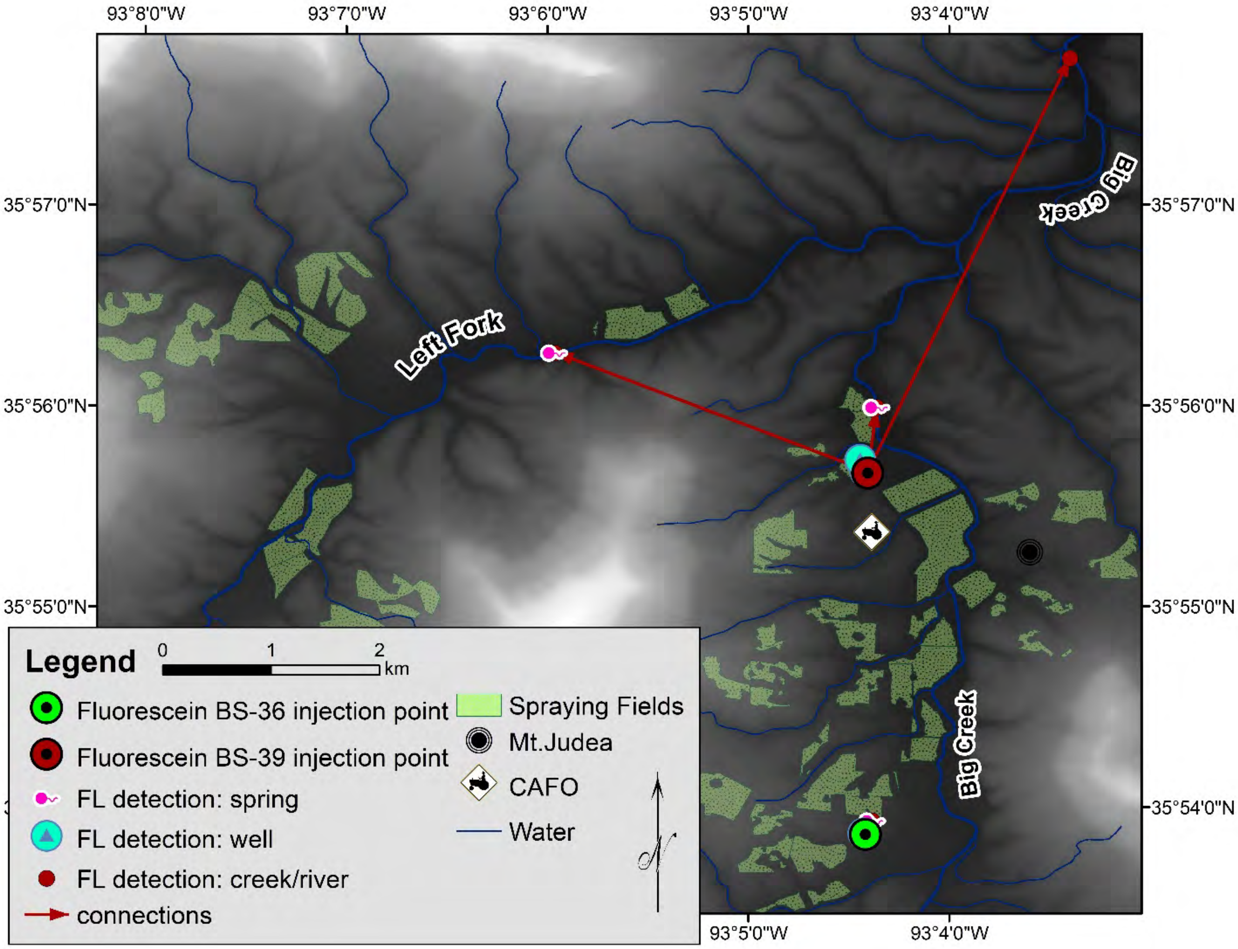


Figure 5. Map of dye-tracing results for fluorescein injections on April 22, 2014. No positive detects were obtained for tracing performed on August 5, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

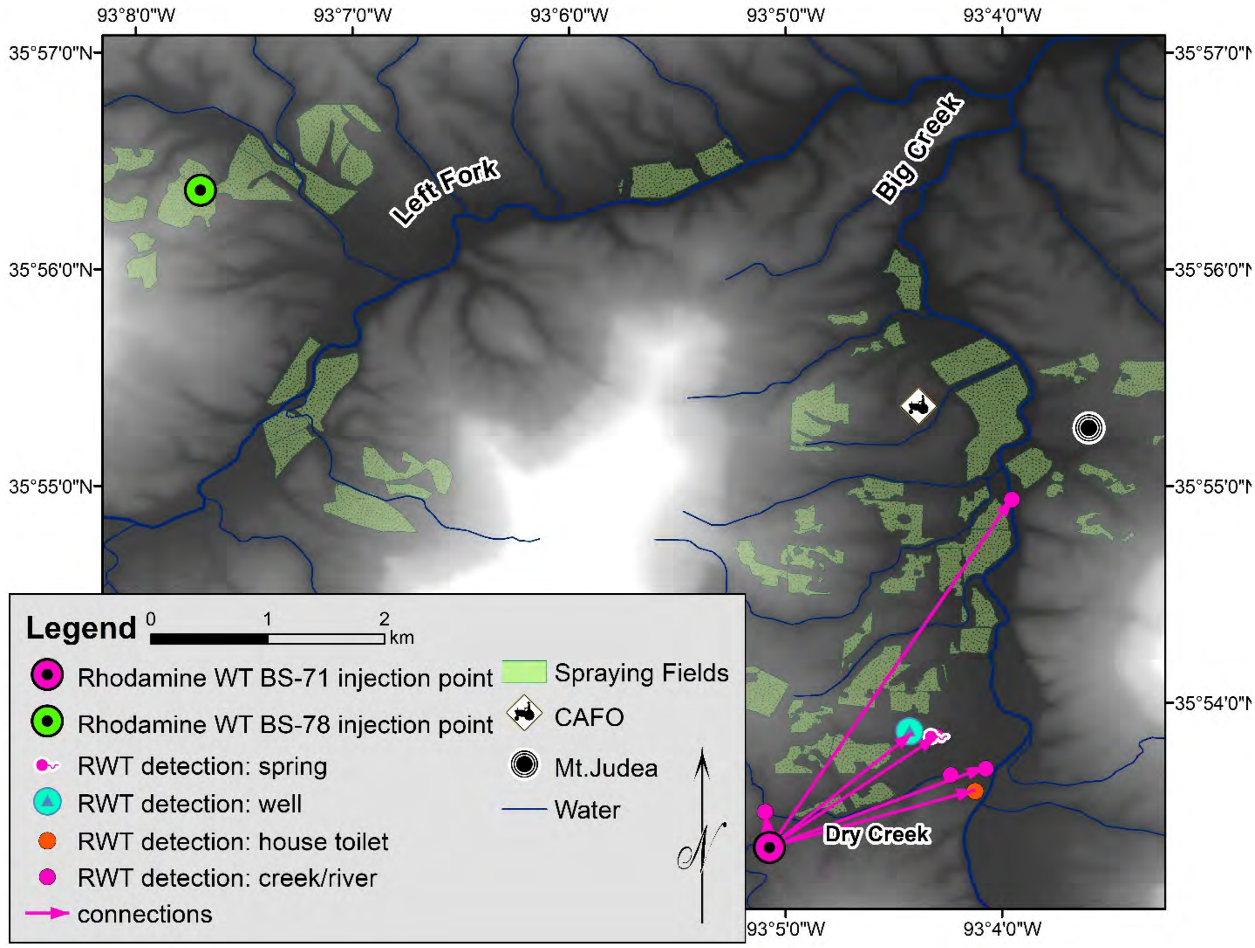


Figure 6. Map of dye-tracing results for rhodamine injections on July 10, 2014. No positive detects were obtained for tracing performed on April 27, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

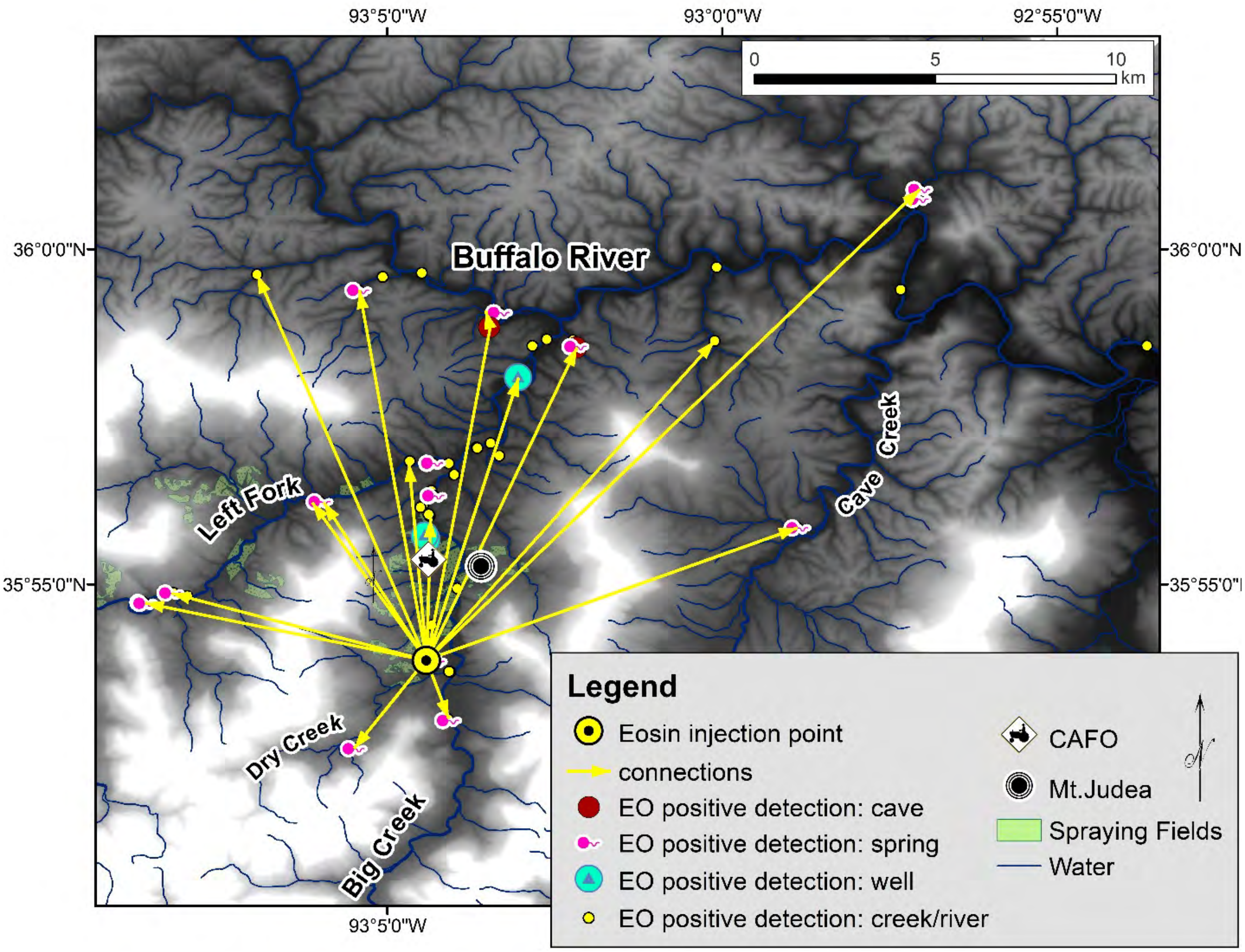


Figure 7. Map of dye-tracing results for eoscin injections on May 12, 2014. From Kosič (2019) reproduced with permission of Dr. K. Kosič.

Acknowledgement

The help of Drs. Katarina Kosič and Van Brahana in providing information on dye-trace studies they conducted in the Big Creek Watershed is gratefully acknowledged.

References

Al-Qinna, M., H.D. Scott, K.R. Brye, J.V. Brahana, T.J. Sauer, and A.N. Sharpley. 2014. Coarse fragments affect soil properties in a mantled-karst landscape of the Ozark Highlands. Soil Sci. 179:42-50.

Braden, A.K., and S.M. Ausbrooks. 2003. Geologic map of the Mt. Judea quadrangle. Arkansas Geological Commission, Newton County, AR, scale 1:24,000. 1 sheet.

Brahana, J.V. 1997. Rationale and methodology for approximating spring-basin boundaries in the mantled karst terrane of the Springfield Plateau, northwestern Arkansas *In* Beck, B.F. and B.J. Stephenson, Eds., Sixth Multidisciplinary Conference on Engineering Geology and Hydrogeology of Karst Terranes, A.A. Balkema, Rotterdam, The Netherlands. p. 77-82.

Brahana, V., J. Nix, C. Bitting, C. Bitting, R. Quick, J. Murdoch, V. Roland, A. West, S. Robertson, G. Scarsdale, and V. North. 2014. CAFOs on karst—Meaningful data collection to adequately define environmental risk, with specific application from the southern Ozarks of northern Arkansas. *In.* Currens, J.C. 1995. Generalized block diagram of the Western Pennyroyal Karst. Kentucky Geological Survey, Map, and Chart 16, Series XII, 2001. Publication number 1780. Available at https://kgs.uky.edu/kgsweb/main.asp.

Brahana, J.V., J. Nix, C. Kuyper, T. Turk, F. Usrey, S. Hodges, C. Bitting, K. Ficco, E. Pollock, R. Quick, B. Thompson, and J. Murdoch. 2016. Geochemical processes and controls affecting water quality of the karst area of Big Creek near Mt. Judea, Arkansas. J. Arkansas Acad. Sci. 70: 1-14.

Chapman, S., B. Parker, J. Cherry, J. Munn, A. Malencia, R. Ingleton, Y. Jiang, G. Padusenko, and J. Piersol. 2015. Hybrid multilevel system for monitoring groundwater flow and agricultural impacts in fractured sedimentary bedrock. groundwater monitoring and remediation. Natl. Ground Water Assoc. 35:55–67.

Funkhouser, J.E., P.R. Little, J.V. Brahana, T.M. Kresse, M. Anderson, S. Formica, and T. Huetter. 1999. Methodology to study the effects of animal production in mantled karst aquifers of the southern Ozarks. *In*. A.N. Palmer, M.V. Palmer and I.D. Sasowsky, Eds. Karst modeling: Special Publication 5, Karst Waters Institute, Charles Town (WV) p. 255-258.

Ham, J.M. 2002. Seepage losses from animal waste lagoons: A summary of a four/year investigation in Kansas. Am. Soc. Agric. Eng. 45(4):983–992.

Hays, P.D., K.J. Knierim, B. Breaker, D.A. Westerman, and B.R. Clark. 2016. Hydrogeology and hydrologic conditions of the Ozark Plateaus aquifer system: U.S. Geological Survey 2016–5137, 61 pages.

Hong, P., A. Yannarell, Q. Dai, M. Ekizoglu, and R. Mackie. 2013. Monitoring the perturbation of soil and groundwater microbial communities due to pig production activities. Appl. Environ. Microb. 79:2620–2629.

Hudson, M.R., and K.E. Murray. 2003. Geologic map of the Ponca Quadrangle, Newton, Boone, and Carroll Counties, Arkansas: U.S. Geological Survey Miscellaneous Field Studies Map 2412, 1:24,000 scale.

Hudson, M.R., K.J. Turner, and C. Bitting. 2011. Geology and karst landscapes of the Buffalo National River area, northern Arkansas. *In* Kuniansky, E.L., Ed., U.S. Geological Survey Karst Interest Group

Proceedings, Fayetteville, Arkansas, April 26-29, 2011. U.S. Geological Survey Scientific Investigations Report 2011-5031. p. 191-212.

Hutchins, S.R., M.V. White, and S.C. Mravik. 2012. Case studies on the impact of Concentrated Animal Feeding Operations (CAFOs) on groundwater quality. U.S Environmental Protection Policy. Nepis Epa QA ID #G-10033.

Kelly, W.R., S.V. Panno, K.C. Hackley, A.T. Martinsek, I.G. Krapac, C.P. Weibel, E.C. Storment. 2009. Bacteria contamination of groundwater in a mixed land-use karst region. Water Qual. Expo. Health 1(2):69–78.

Kosič, K. 2019. Evaluation of policy and technical factors for the protection of karst aquifers. Doctoral Thesis. University of Nova Gorica, Slovenia. 302 pages.

Kosič, K., C.L. Bitting, J.V. Brahana, and C.J. Bitting. 2015. Proposals for integrating karst aquifer evaluation methodologies into national environmental legislations. Sustain. Water Resour. Manag. 1:363–374. doi: 10.1007/s40899-015-0032-5

Kresse, T.M., P.D. Hays, K.R. Merriman, J.A. Gillip, D.T. Fugitt, J.L. Spellman, A.M. Nottmeier, D.A. Westerman, J.M. Blackstock, and J.L. Battreal. 2014. Aquifers of Arkansas—Protection, management, and hydrologic and geochemical characteristics of groundwater resources in Arkansas: U.S. Geological Survey Scientific Investigations Report 2014–5149, 334 p., http://dx.doi.org/10.3133/sir20145149.

Kuniansky, E.L., and L.E. Spangler, Eds. U.S. Geological Survey Karst-Interest Group Proceedings. U.S. Geological Survey Scientific Investigations Report 2014-5035:87-96.

Lapworth, D.J., N. Baran, M.E. Stuart, R. Ward. 2012. Emerging organic contaminants in groundwater: a review of sources, fate, and occurrence. Environ Pollut 163:287–303.

Liner, J.L. 1979. Lithostratigraphy of the Boone Limestone (Lower Mississippian), northwest Arkansas. University of Arkansas, unpublished M.S. thesis.

Mallin, M.A., and L.B. Cahoon. 2003. Industrialized animal production—a major source of nutrient and microbial pollution to aquatic ecosystems. Popul. Environ. 24:369–385.

Mott, D.N., M.R. Hudson, and T. Aley. 2000. Hydrologic investigations reveal interbasin recharge contributes significantly to detrimental nutrient loads at Buffalo National River, Arkansas. Proceedings of Arkansas Water Resources Center Annual Conference MSC-284, Fayetteville, AR. p. 13-20.

Peterson, E.W., R.K. Davis, J.V. Brahana, and H.O. Orndorff. 2002. Movement of nitrate through regolith covered karst terrane, northwest Arkansas. J. Hydrol. 256:35-47.

Roland, V. 2016. The role of organic matter in the fate and transport of antibiotic resistance, metals, and nutrients in the karst of Northern Arkansas, unpublished Ph.D. Dissertation, Univ of Arkansas, 96 p.

Stanton, G.P. 1993. Processes and Controls affecting anisotropic flow in the Boone-St. Joe aquifer in northwest Arkansas, unpublished M.S. thesis, University of Arkansas, Fayetteville, 217 pages.

Sullivan, J.N. 1974. Drainage areas of streams in Arkansas, White River Basin: U.S. Geological Survey Open-File Report, 123 pages.

Turner, K.J., M.R. Hudson, K.E. Murray, and D.N. Mott. 2007. Three-dimensional geologic framework model for a karst aquifer system, Hasty and Western Grove quadrangles, northern Arkansas. U.S. Geological Survey Scientific Investigations Report 2007-5095, 12 p. and CD digital archive.

Turner, N.L., Knierim, and T. Kresse. 2016. Sinkhole and springs of the Ozark Physiographic Province, northern Arkansas, from topographic maps. U.S. Geological Survey data release. Available at http://dx.doi.org/10.5066/F7XK8CNZ.

Van den Heuvel, P. 1979. Petrography of the Boone Formation, Northwest Arkansas. M.S. Thesis, University of Arkansas, Fayetteville, AR, 92 pages.

Webb, G. 1994. Paleokarst, paleosol, and rocky-shore deposits at the Mississippian-Pennsylvanian unconformity, northwestern Arkansas. Geol. Soc. Am. Bull. 106(5):634-648.

Methods of Water Flow Measurement, Sample Collection, and Constituent Analysis

Sample Collection

Manual grab sample

The following protocols were used to collect, prepare, and analyze all water samples:

1. One-liter acid-washed bottles are used to collect grab stream samples for analysis.
2. Water is collected from just beneath the surface, where the stream was actively moving and well mixed.
3. The bottle is rinsed with stream water before collecting the sample.
4. Sterilized specimen cups are used to collect samples for bacterial evaluation.
5. Time of collection is noted, and samples placed in a cooler on ice to preserve them until processed and were submitted to the Arkansas Water Resources Center Water Quality Lab on the day of collection for analyses.

ISCO-autosampler collection

ISCO autosamplers collected storm flow samples at up and down stream of the C&H Farm (BC6 and BC7, respectively), ephemeral stream (BC4), Left Fork (BC9), trench (T1 and T2), and edge-of-field runoff sites (BC1, BC5a, and BC12). Each ISCO autosampler is programed to initiate sample collection when a critical stage height is exceeded (Tables 4 and 5). Pacing of sample collection is subsequently programmed to a specific volume of flow, as detailed in Tables 4 and 5.

Water samples during a storm event are composited in a 10 L bottle encased in the ISCO sampler, providing a flow-weighted composite sample for each event. Water collected in the sampler bottle is thoroughly agitated and transferred to a 1-L acid washed bottle. This rinsing process is repeated twice prior to final collection of a 1 L sample. Time of sample collection from the ISCO is noted, and samples placed in a cooler on ice to preserve them until processed. All samples are submitted to the Arkansas Water Resources Center Water Quality Lab on the day of collection for analysis.

Bacteria analysis is not conducted on ISCO collected samples as the tubing and other ISCO components contacting water (except for the acid-washed bottle) could not be isolated and thus, bacterial contamination during ISCO sample collection could not be guaranteed.

Table 4. Parameters used to enable ISCO auto-samplers at BCRET stream sites BC4, BC6, and BC7.

Site	Identifier	ISCO enabled when, over a 30-minute period, stage height (inches) increases	Volume pacing, 100 mL water collected per gallon of water		
			Rainfall, inches		
			<2.5	2.5 to 4	>4
Ephemeral stream	BC4	> 2.0 *	25,000	50,000	100,000
Upstream Big Creek	BC6	1.2	40,000,000	50,000,000	70,000,000
Downstream Big Creek	BC7	1.8	60,000,000	80,000,000	100,000,000

* For ephemeral stream stage height increases >2.0 inches over a 30-min period.

Table 5. Parameters used to enable ISCO auto-samplers at BCRET edge-of-field sites Field 1, 5a, and 12.

Site	Identifier	ISCO enabled when stage height (inches) above	Volume pacing, 100 mL water collected per gallon of water		
			Rainfall, inches		
			<2.5	2.5 to 4	>4
Field 1	BC1	> 0.75	500	1,000	5,000
Field 5a	BC2	> 0.75	5,000	10,000	50,000
Field 12	BC3	> 0.75	500	1,000	5,000

Discharge measurement at gaged sites

The rating curve providing discharge at the downstream site (BC7) is available from USGS via the BCRET website (see https://nwis.waterdata.usgs.gov/ar/nwis/uv/?cb_00065=on&cb_00045=on&cb_00010=on&format=gif_default&period=&begin_date=2014-04-16&end_date=2014-04-23&site_no=07055790) and provided here in Figure 12. USGS has not completed development of a rating curve for the Left Fork site and only concentrations will be given in this report.

Discharge at the ephemeral stream is calculated from water velocity and height of water in the culvert pipe where samples are collected, as measured by the velocity flow meter in the culvert opening and recovered by the ISCO sampler. This data along with diameter of the culver pipe is then used to determine discharge at this site.

Discharge at the edge-of-field sites, BC1, BC5a, and BC12, is calculated from water height in the flume's stilling well with a pressure transducer connected to the ISCO sampler. This recorded data along with dimensions of the 1.5 ft H flume at BC1 and 1.0 ft H flume at BC5a and 12 is used to determine discharge. The H flume at BC1 is larger than BC5a and 12, due to the larger drainage area and greater volume of surface runoff expected at BC1 than at 5a or 12.

The ISCO area velocity flow module sensors use Doppler technology to directly measure average velocity in the flow stream. A pressure transducer measures liquid depth to determine flow area. The ISCO autosampler then calculates discharge by multiplying the area of the flow stream by its average velocity. For more detail, see https://www.teledyneisco.com/en-us/waterandwastewater/Sampler%20Documents/Datasheets/Isco%20750%20Area%20Velocity%20Flow%20Module%20Datasheet.pdf.

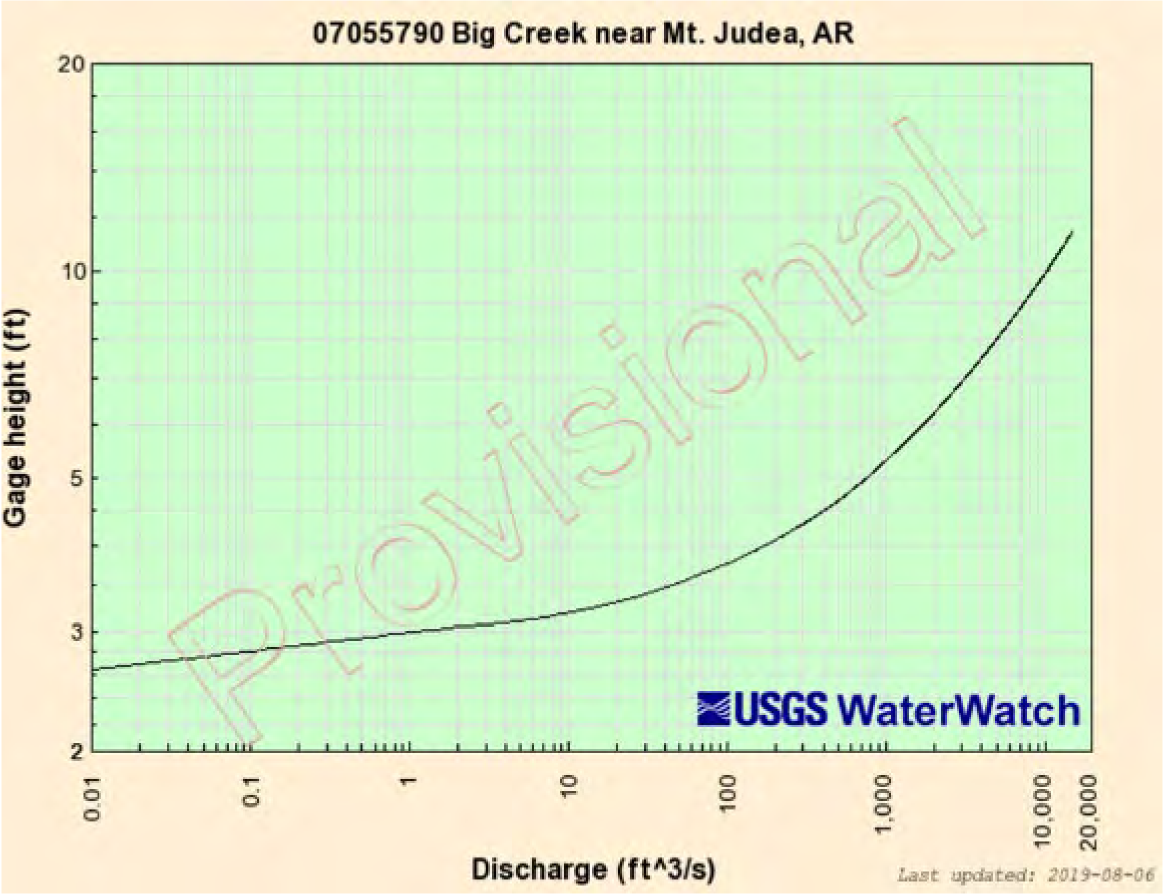


Figure 10. Rating curve developed by USGS for Big Creek downstream of the C&H Farm.

Note USGS states that Stage-discharge relations (ratings) are usually developed from a graphical analysis of numerous discharge measurements. Measurements are made on various schedules and sometimes for different purposes. All discharge measurements are compiled and maintained in a database. Each measurement is carefully made, and undergoes quality assurance review. Some measurements indicate a temporary change in the rating, often due to a change in the streambed (for example, erosion, or deposition) or growth of riparian vegetation. Such changes are called shifts; they may indicate a short- or long-term change in the rating for the gage. In normal usage, the measured shifts (or corrections) are applied mathematically to a defined rating.

Sample Analysis

1. Analyses included Alkalinity (APHA 2320-B), Chloride (EPA 300.0), Dissolved P (EPA 365.2), E. coli (APHA 9223-B), Electrical Conductivity (EPA 120.1), Nitrate-N (EPA 300.0), pH (EPA 150.1), Total N (APHA 4500-P J), and Total P (APHA 4500-P J) and are listed in Table 6. APHA is American Public Health Association from the Wadeable Streams Assessment, Water Chemistry Laboratory Manual http://www.epa.gov/owow/monitoring/wsa/WRS_lab_manual.pdf

2. Prior to collection of a house-well water sample, the well is purged and water temperature, pH, and electrical conductivity is measured on-site every 30 seconds until all values stabilize. At that point, a sample of water is collected in a 1-L acid-washed bottle. This method is taken from USGS and EPA well water sampling protocols. See USGS methods for sampling at https://water.usgs.gov/owq/FieldManual/chapter4/pdf/Chap4_v2.pdf. Specific and detailed guidance on the collected of water quality data can be found in the USGS National Field Manual at https://water.usgs.gov/owq/FieldManual/.

   The U.S. EPA also recommend that selected water quality parameters can be monitored during low-rate purging, with stabilization of these parameters indicating when the discharge water represents aquifer water or source well water. See: http://www.csus.edu/indiv/h/hornert/Geol_210_Summer_2012/Week%202%20readings/Puls%20and%20Barcelona%201996%20Low%20flow%20sampling.pdf and https://in-situ.com/wp-content/uploads/2015/01/Low-Flow-Groundwater-Sampling-Techniques-Improve-Sample-Quality-and-Reduce-Monitoring-Program-Costs-Case-Study.pdf

3. Minimum detection limits (MDLs) for each chemical and biological constituent are listed in Table 6. Some constituent concentrations were reported by the laboratory as less than the MDL but greater than zero. Those values are given in subsequent tables but have less confidence in their accuracy than concentrations above the MDL.

Table 6. Minimum detection limits (MDLs) for each chemical and biological constituent.

Constituent	Method of analysis	Minimum detection limit [1]	Reporting limit [2]
Alkalinity, mg/L as $CaCO_3$	APHA 2320-B	2	- -
Chloride, mg/L	EPA 300.0	0.093	0.300
Dissolved P, mg/L	EPA 365.2	0.002	0.010
Conductivity, uS/cm	EPA 120.1	1	- -
Ammonia-N, mg/L	EPA 351.2	0.03	0.046
Dissolved organic carbon, mg/L	EPA 412.1	0.18	0.500
E. coli, MPN/100 mL	APHA 9223-B	1	<1

Constituent	Method of analysis	Minimum detection limit [1]	Reporting limit [2]
Nitrate-N, mg/L	EPA 300.0	0.004	0.050
pH	EPA 150.1	0.1	- -
Total coliform, MPN/100 mL	APHA 9223-B	1	<1
Total dissolved solids, mg/L	EPA 160.1	15.22	48.5
Total N, mg/L	APHA 4500-P J	0.006	0.050
Total P, mg/L	APHA 4500-P J	0.012	0.020
Total suspended solids, mg/L	EPA 160.2	6.58	10

[1] MDL the Minimum Detection Limit of an analyte that can be measured and reported with 99% confidence that the analyte concentration is greater than zero. Further information is available at http://water.usgs.gov/owq/OFR_99-193/detection.html

[2] The Reporting limit is the least (non-zero) calibrated standard used in analysis.

References

Buck, O., D.K. Niyogi, and C.R. Townsend. 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. Environ. Poll. 130(2):287-299.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, and M.D. Munn. 2010. The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350. 174 pages. Available at: http://water.usgs.gov/nawqa/nutrients/pubs/circ1350

Giovannetti, J., L.B. Massey, B.E. Haggard, and R.A. Morgan. 2013. Land use effects on stream nutrients at Beaver Lake Watershed. J. Am. Water Works Assoc. 105:E1–E10. Available at: http://www.awwa.org/publications/journal-awwa/abstract/articleid/34406246.aspx

Haggard, B.E., P.A. Moore, Jr., I. Chaubey, and E.H. Stanley. 2003. Nitrogen and phosphorus concentrations and export from an Ozark Plateau Catchment in the United States. Biosys. Eng. 86(1):75-85.

Hays, P.D., Knierim, K.J., Breaker, Brian, Westerman, D.A., and Clark, B.R., 2016, Hydrogeology and hydrologic condi¬tions of the Ozark Plateaus aquifer system: U.S. Geological Survey 2016–5137, 61 p., http://dx.doi.org/10.3133/sir20165137.

Migliaccio, K.W., B.E. Haggard, I. Chaubey, and M.D. Matlock. 2007. Linking watershed subbasin characteristics to water quality parameters in War Eagle Creek Watershed. Trans. Am. Soc. Agric. Eng. 50(6):2007-2016.

Rebich, R.A., N.A. Houston, S.V. Mize, D.K. Pearson, P.B. Ging, and C.E. Hornig. 2011. Sources and delivery of nutrients to the northwestern Gulf of Mexico from streams in the south-central United States. J. Am. Water Res. Assoc. 47(5):1062-1086.

Reckhow, K.H., P.E. Norris, R.J. Budell, D.M. Di Toro, J.N. Galloway, H. Greening, A.N. Sharpley, A. Shirmhhammadi, and P.E. Stacey. 2011. Achieving nutrient and sediment reduction goals in the Chesapeake Bay: An evaluation of program strategies and implementation. The National Academies Press, Washington, DC. 258 pages.

Scavia, D., J.D. Allan, K.K. Arend, S. Bartell, D. Beletsky, N.S. Bosch, S.B. Brandt, R.D. Briland, I. Daloglu, J.V. DePinto, D.M. Dolan, M.A. Evans, T.M Farmer, D. Goto, H. Han, T.O. Hoeoek, R. Knight, S.A. Ludsin, D. Mason, A.M. Michalak, R.P. Richards, J.J. Roberts, D.K. Rucinski, E. Rutherford, D.J. Schwab, T.M. Sesterhenn, H. Zhang, and Y. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res. 40:226-246.

COMPOSITION AND LAND APPLICATION OF HOLDING POND SLURRY

Contents

List of Tables

List of Figures

List of Supplementary Tables

Sample Collection of Holding Pond Slurry

To help guide adaptive manure management decisions, samples of manure slurry from the C&H ponds were collected periodically over the 5-year monitoring for analysis. A foot valve liquid manure sampler was used to collect samples of slurry from the top 6 inches of slurry, pond bottom, and from the entire depth of pond profile (Figure 1). Additional information on manure sampling is described in the Extension Fact Sheet, given as supplementary information at the end of this section (Supplementary File 1). The distribution of chemical constituents with lagoon depth is given in Figure 2. This information was shared with C&H's owners as part of the adaptive manure management discussions.

Figure 1. Foot valve manure sampler as used to collect samples from the C&H ponds.

Collection and analysis of manure samples from the holding ponds, representing the top water, bottom slurry, and entire profile, generated chemical profiles typical of other holding ponds associated with hog production. That is, N and P concentrations of the manure increased with water depth (Figure 2). However, P concentrations increased at a greater rate than N. The result of the relatively greater increase in P than N with pond depth is that the N:P ratio is greater for surface liquid than bottom slurries. Consequently, the higher N:P ratio of the surface water is closer to the ratio of these nutrients required by pastures on the C&H Farm.

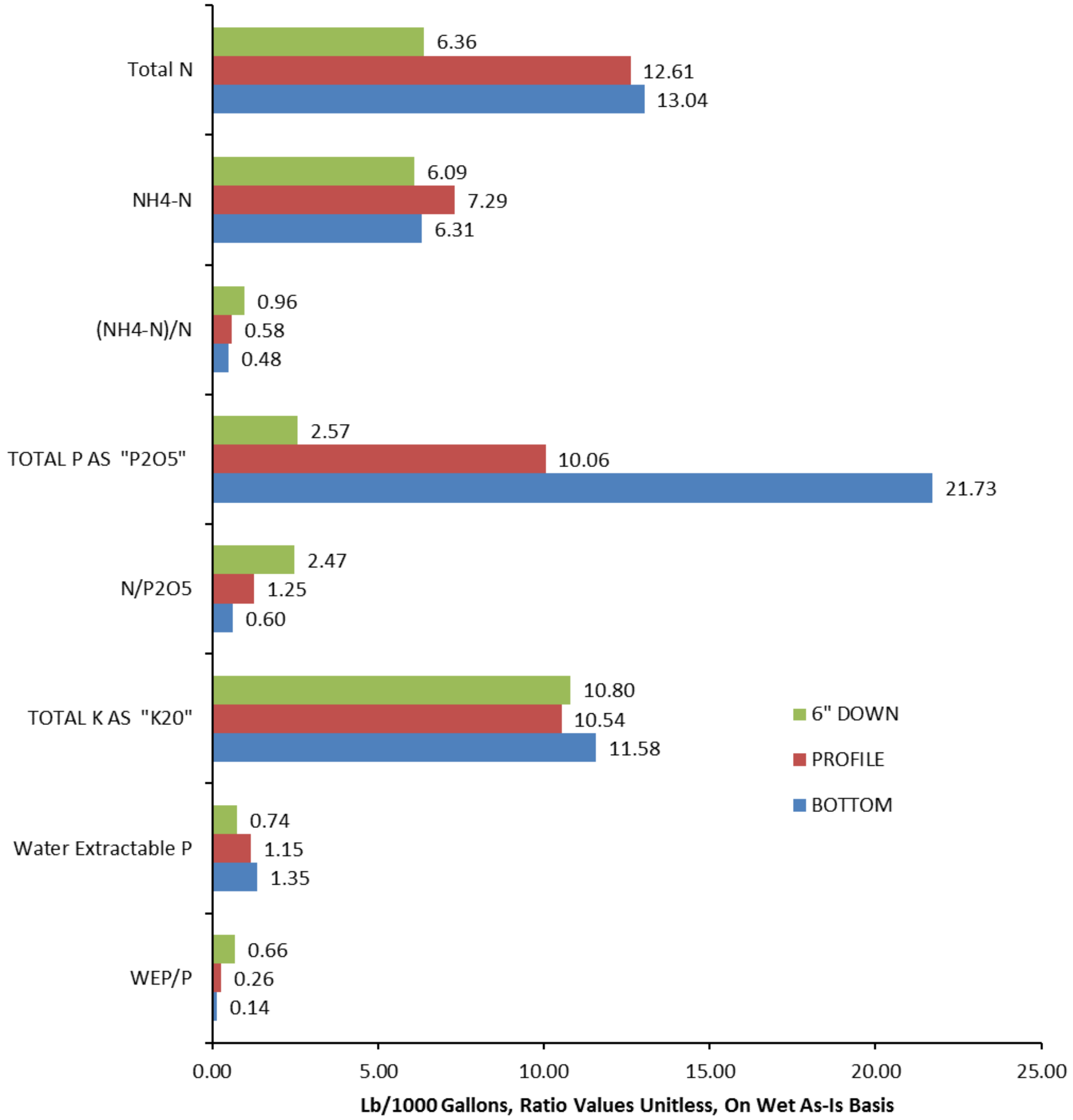


Figure 2. Distribution of N, P_2O_5, and K_2O with depth in the holding ponds, sampled on September 24, 2013

Land application of top water from the pond to farm pastures will more likely meet both the N and P needs of the pasture and avoid application of P surplus to plant needs. The higher concentration and lower N:P ratio of bottom slurries, will lend application of that slurry in a manure banking approach, where the slurry would be applied on alternate years to fields more distant from Big Creek. Even without the addition of mechanical and/or chemical separation approaches, the observed natural gravity separation of slurry and its constituents, provides opportunities for farm nutrient management to more closely match manure nutrients to crop nutrient needs.

Slurry Properties

Median values of physical and chemical properties of the manure slurry in the holding ponds determined at various times over the 5-year monitoring are presented in Table 1. These values represent samples collected September 24, 2013; April 10, 2014; October 28, 2014; April 16, 2015; January 15, May 27, and July 27, 2016; February 2, 2018; and February 8, February 20, and June 12, 2019.

An increasing linear relationship between total N, total P, total K, and water-extractable P concentrations and the increasing percent solids content of the slurry was observed (Figure 3). These nutrient concentrations are selected as they are required by plants for growth and are used to determine agronomic-based nutrient fertilizer applications. Water-extractable P is of interest due its key role in P Index calculations and determination of acceptable manure application rates. In addition, the ratio of total N:P_2O_5, total P_2O_5:Ca, and water extractable P and P_2O_5 concentration decreased exponentially with increasing percent solids content of slurry (Figure 4).

These trends reflect the variation in manure nutrient concentrations between ponds and depth within the ponds. C&H Farm management is aware of these variations and the nutrient management opportunities they present when making decisions regarding: which pond to pump from; whether the pond will be agitated; the depth at which to pump from; and which field to make the application. These factors coupled with the total number and size of application fields with the frequency in which each field receives a manure application, play a significant role in meeting the crop's nutrient fertility needs, while minimizing the potential for soil P accumulation and associated risk of P runoff.

Table 1. Median concentration of constituent property of manure sampled from the top 6 inches, bottom layer, and profile of holding ponds 1 and 2 on the C&H Farm between September 2013 and July 2019.

Property	Pond 1			Pond 2		
	Top 6 inches	**Bottom layer**	**Profile**	**Top 6 inches**	**Bottom layer**	**Profile**
pH	7.9	7.5	7.6	8.1	7.9	8.1
Electrical conductivity, µS/cm	13,905	10,710	12,780	10,275	10,475	8,371
Solids, %	0.8	11.9	3.62	0.5	4.3	2.2
Chloride, mg/L	360	409	467	338	409	483
Total N, mg/L	1,692	5,078	2,590	1,213	2,890	962
Ammonium-N, mg/L	1,323	1,437	1,146	859	938	536
Nitrate-N, mg/L	0.035	0.035	0.035	0.153	0.035	0.05
Total P, mg/L	180	5,070	1,492	114	458	216
Water-extractable P, mg/L	78	476	187	79	162	90
Total K, mg/L	1,383	1,593	1,408	1,109	1,180	1,123
Total Ca, mg/L	103	6,070	1,342	45	409	156
Total Mg, mg/L	30	2,368	365	6	177	67
Total S, mg/kg	60	1,076	169	23	133	87
Total Fe, mg/L	14	2,290	248	12	1,336	1,156
Total Mn, mg/L	0.6	102	11.5	0.0	9.8	4.6
Total Zn, mg/L	2.6	218	33.2	0.3	18.5	8.33

Property	Pond 1			Pond 2		
	Top 6 inches	**Bottom layer**	**Profile**	**Top 6 inches**	**Bottom layer**	**Profile**
Total Cu, mg/L	0.5	27.6	4.4	0.0	2.9	1.53
Total Na, mg/L	340	368	349	246	250	295

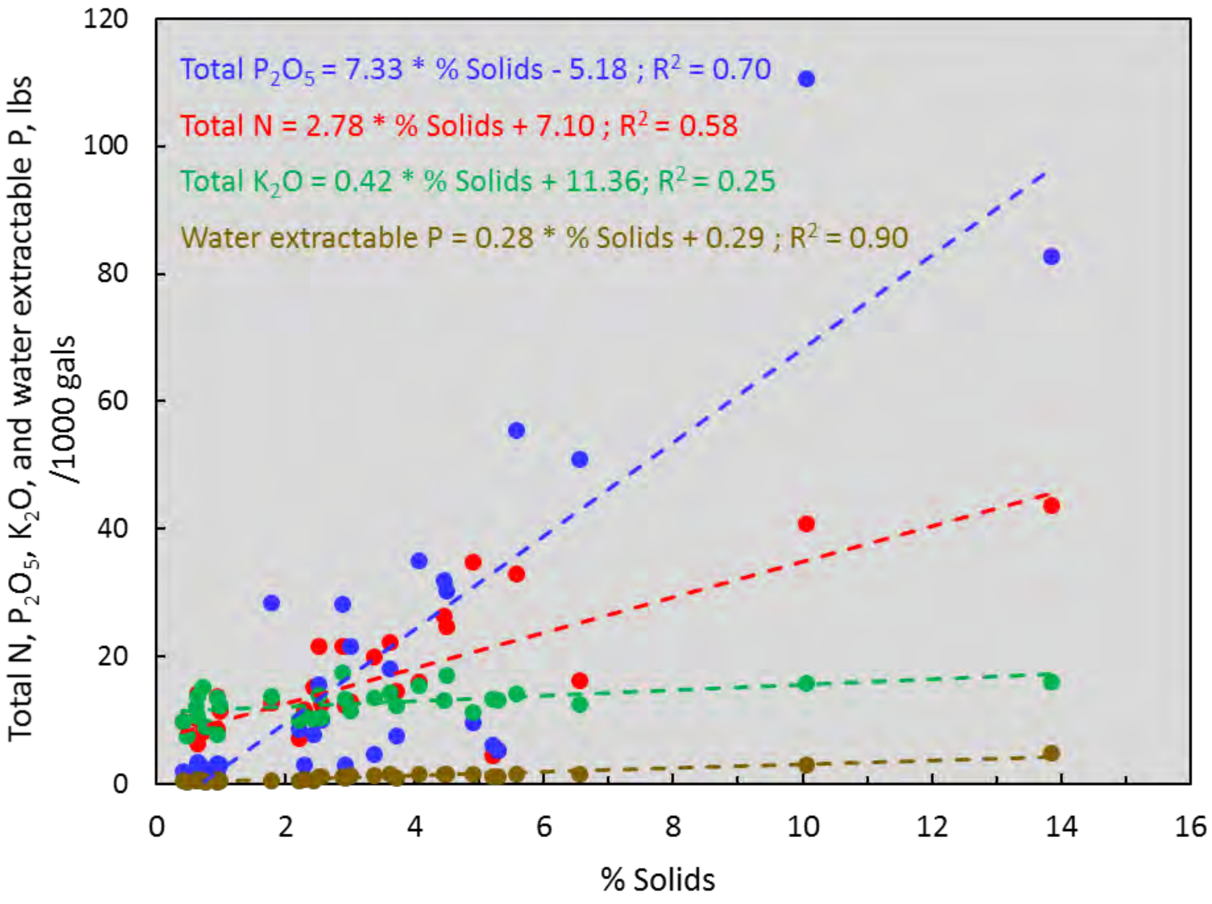


Figure 3. Relationship between total N, P, K and water-extractable P concentration and the percent solids content of swine slurry (all samples collected from ponds 1 and 2) from the C&H Farm operation.

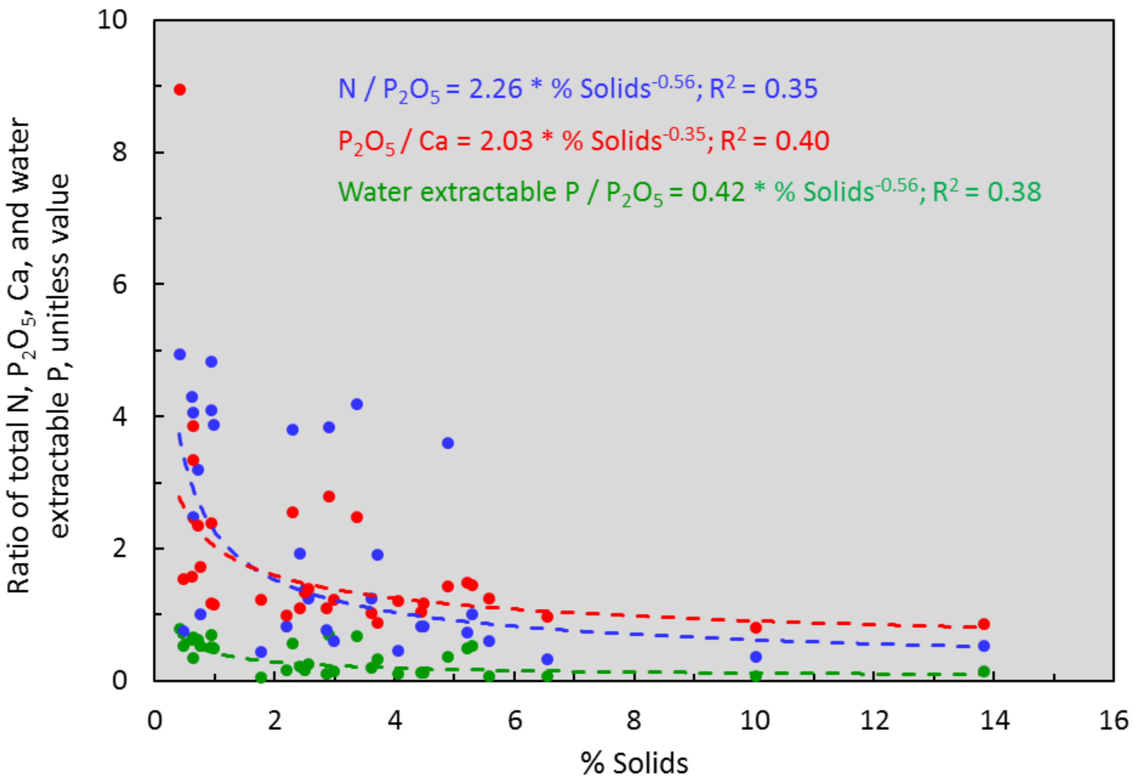


Figure 4. Relationship between the total N and P, total P and calcium, and total P and water extractable P concentration ratio and percent solids content of swine slurry (all samples collected from ponds 1 and 2) from the C&H Farm operation.

Land Application of Slurry

Fields permitted to receive manure slurry listed in the original approved Nutrient Management Plan for the C&H Farm, and are given in Table 2. Land application of slurry from holding ponds 1 and 2 of the C&H Farm are given in Supplementary Tables S1 to S7 for 2013 to 2018, respectively. These values are reported in the annual logs provided by C&H Farm owners to ADEQ each year. Annual land application of slurry to each field over the monitoring period was determined and presented in Table 3.

The average annual slurry application rate was consistent among years (2014 to 2018) ranging from 4,478 gals/ac in 2016 to 3,433 gals/ac in 2017 (Table 4). Thus, there was little change in land application and thereby, the amount of P and N applied in slurry to the monitored watershed between up and downstream sample collection sites.

The total application slurry, P, and N from the C&H Farm to permitted fields in the monitored watershed is given in Table 5. In terms of water volume, the amount of slurry applied in inches of liquid each year to each Feld was between 0.00 and 0.27 inches (Table 6).

Table 2. Fields permitted to receive manure slurry from the C&H operation. Fields bolded in red are monitored by BCRET.

Field	Area	Soil unit [†]	Field slope [‡]			Flood freq. [¶]
			Min.	Max.	Rep.	
	acres		- - - - - - - - - - - - - % - - - - - - - - - -			
1	**7.3**	**Noark very cherty silt loam**	**3**	**8**	**5**	**None**
2	6.0	Noark very cherty silt loam	8	20	14	None
3	13.6	Razort loam	0	3	2	Occasional
4	6.8	Noark very cherty silt loam	8	20	14	None
7	64.3	Razort loam	0	3	2	Occasional
8	8.6	Spadra loam	2	5	1.5	None
9	35.5	Spadra loam	0	3	2	Occasional
10	29.3	Spadra loam	2	5	2.5	None
11	14.2	Noark very cherty silt loam	8	20	14	None
12	**11.4**	**Spadra loam**	**0**	**3**	**2**	**Occasional**
13	50.9	Noark very cherty silt loam	8	20	14	None
14	8.1	Noark very cherty silt loam	8	20	14	None
15	37.5	Noark very cherty silt loam	8	20	14	None
16	15.2	Spadra loam	0	3	2	Occasional
17	31.9	Spadra loam	3	8	5	None

[†] NRCS soil mapped unit.

[‡] Minimum, maximum, and representative field slopes from NRCS soil survey.

[¶] NRCS flooding designation as none and occasional.

Table 3. Volume and nutrients applied in slurry from the C&H operation to permitted fields for 2014 to 2018. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Number apps	Average application rate †	Nutrients applied	
				P	N
	gallons		gals/acre	- - - - - - - - - - - - lbs	- - - - - - - - - - -
			2013		
15	36,000	1	3,000	30	38
			2014		
1	**46,000**	**2**	**3,538**	**221**	**925**
2	22,600	1	3,767	108	454
3	118,100	3	4,374	567	2,374
4	28,800	3	3,388	138	579
7	396,200	4	3,221	1,902	7,964
8	25,000	1	2,778	120	503
9	103,800	2	2,966	498	2,086
10	249,200	5	3,894	1,196	5,009
11	51,000	1	3,000	245	1,025
12	**48,000**	**1**	**4,848**	**230**	**965**
13	453,550	11	3,004	2,177	9,116
14	73,000	2	3,174	350	1,467
15	434,400	15	2,896	2,085	8,731
16	56,000	1	6,222	269	1,126
17	294,750	13	2,807	1,415	5,924
			2015		
1	**12,000**	**1**	**1,429**	**58**	**241**
2	39,000	1	6,500	187	784
3	0	0	0	0	0
4	18,000	1	2,500	86	362

Field	Slurry applied	Number apps	Average application rate †	Nutrients applied	
				P	N
	gallons		gals/acre	- - - - - - - - - - - - lbs - - - - - - - - - - -	
7	696,000	1	7,516	5,498	10,579
8	21,000	1	2,442	101	422
9	186,000	1	5,239	893	3,739
10	483,000	2	7,918	2,318	9,708
11	0	0	0	0	0
12	**93,000**	**2**	**4,079**	**446**	**1,869**
13	300,000	1	5,894	1,440	6,030
14	36,000	1	4,444	173	724
15	0	0	0	0	0
16	63,000	1	4,145	302	1,266
17	418,000	2	6,552	2,006	8,402
2016					
1	**78,000**	**2**	**4,643**	**641**	**1,143**
2	48,000	2	4,000	420	727
3	108,000	2	2,000	945	1,636
4	57,000	2	3,958	478	844
7	0	0	0	0	0
8	84,000	2	4,884	735	1,273
9	420,000	2	5,915	3,091	5,821
10	303,000	2	4,967	2,672	4,610
11	132,000	2	3,882	1,072	1,922
12	**156,000**	**2**	6,842	1,073	2,093
13	264,000	2	**2,593**	**3,311**	**4,928**
14	75,000	1	9,259	135	653
15	261,000	2	870	2,555	4,206

Field	Slurry applied	Number apps	Average application rate †	Nutrients applied	
				P	N
	gallons		gals/acre	- - - - - - - - - - - - lbs	- - - - - - - - - - -
16	93,000	1	6,118	1,460	2,009
17	462,000	2	7,241	2,583	5,645
2017					
1	**60,000**	**2**	**3,571**	**1,818**	**1,459**
2	48,000	2	4,000	1,447	1,133
3	105,000	2	1,944	3,170	2,496
4	54,000	2	3,750	1,634	1,303
7	756,000	3	2,721	22,892	18,317
8	57,000	2	3,314	1,733	1,414
9	346,000	3	3,249	10,468	8,341
10	243,000	3	2,656	7,326	5,731
11	63,000	1	3,706	1,915	1,562
12	**90,000**	**2**	**3,947**	**2,714**	**2,124**
13	281,000	3	1,840	8,472	6,630
14	60,000	2	3,704	1,812	1,430
15	318,000	2	1,060	9,592	7,526
16	90,000	1	5,921	2,691	2,016
17	390,000	2	6,113	11,733	9,082
2018					
1	**57,000**	**2**	**3,393**	**1,613**	**1,231**
2	51,000	2	4,250	1,443	1,102
3	108,000	2	2,000	3,056	2,333
4	57,000	2	3,958	1,613	1,231
7	639,000	2	3,450	18,084	13,802
8	78,000	2	4,535	2,207	1,685

Field	Slurry applied	Number apps	Average application rate †	Nutrients applied	
				P	N
	gallons		gals/acre	- - - - - - - - - - - - lbs	- - - - - - - - - - -
9	361,000	2	5,085	10,216	7,798
10	288,000	2	4,721	8,150	6,221
11	57,000	1	3,353	1,613	1,231
12	**105,000**	**2**	**4,605**	**2,972**	**2,268**
13	204,000	1	4,008	5,773	4,406
14	60,000	2	3,704	1,698	1,296
15	273,000	2	910	7,726	5,897
16	66,000	1	4,342	1,868	1,426
17	339,000	2	5,313	9,594	7,322

† Average slurry application rate is total applied / applied acres in a given field

Table 4. Average application rate of slurry from the C&H operation to permitted fields for each monitoring year. Fields bolded in red are monitored by BCRET.

Field	Average annual slurry application						
	2013	2014	2015	2016	2017	2018	Total
	----------------------------- gals/ac ------------------------------						
1		**3,538**	**1,429**	**4,643**	**3,571**	**3,393**	**19,889**
2		3,767	6,500	4,000	4,000	4,250	27,020
3		4,374	0	2,000	1,944	2,000	12,382
4		3,388	2,500	3,958	3,750	3,958	21,065
7		3,221	7,516	0	2,721	3,450	20,290
8		2,778	2,442	4,884	3,314	4,535	21,543
9		2,966	5,239	5,915	3,249	5,085	26,945
10		3,894	7,918	4,967	2,656	4,721	28,987
11		3,000	0	3,882	3,706	3,353	16,729
12		**4,848**	**4,079**	**6,842**	**3,947**	**4,605**	**29,185**
13		3,004	5,894	2,593	1,840	4,008	20,807
14		3,174	4,444	9,259	3,704	3,704	29,142
15	3,000	2,896	0	870	1,060	910	14,472
16		6,222	4,145	6,118	5,921	4,342	32,098
17		2,807	6,552	7,241	6,113	5,313	33,631
Average	3,000	3,592	3,911	4,478	3,433	3,482	354,185

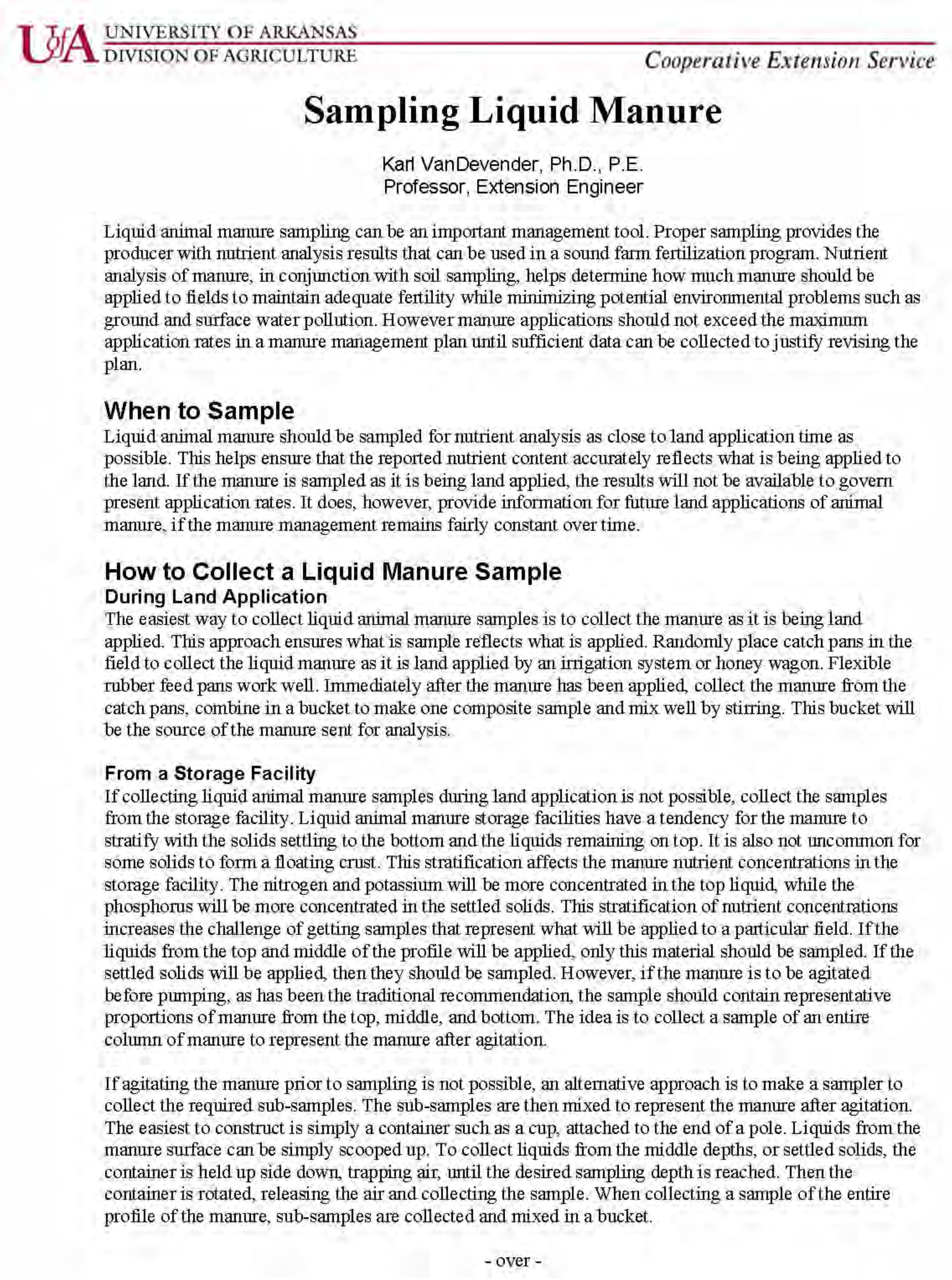
Table 5. Total volume and nutrients applied in slurry from the C&H operation to permitted fields from 2013 to 2018. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Number apps	Nutrients applied	
			P	N
	gallons		- - - - - - - - - - - - lbs	- - - - - - - - - - -
1	**253,000**	**9**	**4,350**	**4,999**
2	208,600	8	3,606	4,200
3	439,100	9	7,738	8,839
4	214,800	10	3,950	4,319
7	2,487,200	10	48,376	50,662
8	265,000	8	4,896	5,296
9	1,416,800	10	25,167	27,785
10	1,566,200	14	21,663	31,279
11	303,000	5	4,845	5,741
12	**492,000**	**9**	**7,435**	**9,319**
13	1,502,550	18	21,173	31,112
14	304,000	8	4,168	5,570
15	1,289,400	22	21,988	26,398
16	368,000	5	6,590	7,842
17	1,903,750	21	27,331	36,375

Table 6. Total volume as inches of slurry applied from the C&H operation to permitted fields for each monitoring year. Fields bolded in red are monitored by BCRET.

Field	Slurry applied						
	2013	2014	2015	2016	2017	2018	Total
	- inches -						
1		**0.13**	**0.05**	**0.17**	**0.13**	**0.12**	**0.61**
2		0.14	0.05	0.15	0.15	0.16	0.64
3		0.16	0.00	0.07	0.07	0.07	0.38
4		0.12	0.05	0.15	0.14	0.15	0.61
7		0.12	0.05	0.00	0.10	0.13	0.40
8		0.10	0.05	0.18	0.12	0.17	0.62
9		0.11	0.05	0.22	0.12	0.19	0.69
10		0.14	0.24	0.18	0.10	0.17	0.84
11		0.11	0.00	0.14	0.14	0.12	0.51
12		**0.18**	**0.24**	**0.25**	**0.15**	**0.17**	**0.98**
13		0.11	0.05	0.10	0.07	0.15	0.47
14		0.12	0.05	0.34	0.14	0.14	0.78
15	0.01	0.11	0.00	0.03	0.04	0.03	0.22
16		0.23	0.05	0.23	0.22	0.16	0.89
17		0.10	0.24	0.27	0.23	0.20	1.03
Total		1.98	1.19	2.47	1.90	2.12	9.67
Rainfall		25.13	28.83	15.5	14.57	23.17	107.2

Supplementary File 1: Sampling Liquid Manure U of A Fact Sheet



UNIVERSITY OF ARKANSAS
DIVISION OF AGRICULTURE

Cooperative Extension Service

Sampling Liquid Manure

Karl VanDevender, Ph.D., P.E.
Professor, Extension Engineer

Liquid animal manure sampling can be an important management tool. Proper sampling provides the producer with nutrient analysis results that can be used in a sound farm fertilization program. Nutrient analysis of manure, in conjunction with soil sampling, helps determine how much manure should be applied to fields to maintain adequate fertility while minimizing potential environmental problems such as ground and surface water pollution. However manure applications should not exceed the maximum application rates in a manure management plan until sufficient data can be collected to justify revising the plan.

When to Sample

Liquid animal manure should be sampled for nutrient analysis as close to land application time as possible. This helps ensure that the reported nutrient content accurately reflects what is being applied to the land. If the manure is sampled as it is being land applied, the results will not be available to govern present application rates. It does, however, provide information for future land applications of animal manure, if the manure management remains fairly constant over time.

How to Collect a Liquid Manure Sample

During Land Application

The easiest way to collect liquid animal manure samples is to collect the manure as it is being land applied. This approach ensures what is sample reflects what is applied. Randomly place catch pans in the field to collect the liquid manure as it is land applied by an irrigation system or honey wagon. Flexible rubber feed pans work well. Immediately after the manure has been applied, collect the manure from the catch pans, combine in a bucket to make one composite sample and mix well by stirring. This bucket will be the source of the manure sent for analysis.

From a Storage Facility

If collecting liquid animal manure samples during land application is not possible, collect the samples from the storage facility. Liquid animal manure storage facilities have a tendency for the manure to stratify with the solids settling to the bottom and the liquids remaining on top. It is also not uncommon for some solids to form a floating crust. This stratification affects the manure nutrient concentrations in the storage facility. The nitrogen and potassium will be more concentrated in the top liquid, while the phosphorus will be more concentrated in the settled solids. This stratification of nutrient concentrations increases the challenge of getting samples that represent what will be applied to a particular field. If the liquids from the top and middle of the profile will be applied, only this material should be sampled. If the settled solids will be applied, then they should be sampled. However, if the manure is to be agitated before pumping, as has been the traditional recommendation, the sample should contain representative proportions of manure from the top, middle, and bottom. The idea is to collect a sample of an entire column of manure to represent the manure after agitation.

If agitating the manure prior to sampling is not possible, an alternative approach is to make a sampler to collect the required sub-samples. The sub-samples are then mixed to represent the manure after agitation. The easiest to construct is simply a container such as a cup, attached to the end of a pole. Liquids from the manure surface can be simply scooped up. To collect liquids from the middle depths, or settled solids, the container is held up side down, trapping air, until the desired sampling depth is reached. Then the container is rotated, releasing the air and collecting the sample. When collecting a sample of the entire profile of the manure, sub-samples are collected and mixed in a bucket.

- over -

A sampler design that automatically collects a sample of the entire profile uses 10 foot, 1 ½ inch PVC pipe with a PVC ball valve at the bottom. The handle of the ball valve is replaces with a lever arm about 2 feet long. The free end of the lever arm is attached to the end of a 10 foot, 1 inch PVC pipe. The lever arm and smaller pipe allow the ball valve to be operated while holding to top of the sampler. To use the sampler the valve is opened and the sampler is inserted (in a line, not and arc) into the manure. When the foot of the valve is at the bottom of the settled solids, it is closed. Then the sample of the entire manure profile can be removed from the manure and placed in a bucket.

Sketch of Cup Sampler

Sketch of Foot Valve Sampler

Whichever sampler is used, at least 8 locations around the manure storage unit should be sampled and mixed in a bucket to serve as a final composite sample. This bucket will be the source of the manure sent for analysis

Getting the Sample Analyzed

After thoroughly mixing the final composite sample, fill a one liter plastic bottle half full. These bottles may be obtained from your county Extension office. Never fill the bottle more than half full to allow for gas expansion of the sample and to prevent the bottle from exploding. Keep the samples as cool as possible until you can take them to your county Extensions office for shipping to the University of Arkansas lab for analysis. There you will get assistance in filling out an information sheet on your manure sample. There is a fee to have the sample analyzed. While the sample can be sent to a private lab, the fees are often higher. If you are required by the Arkansas Department of Environmental Equality (ADEQ) to sample your liquid animal manure as part of your Regulation No. 5 permit, make sure that you inform the individual helping you with the paperwork so the correct set of analyses can be performed. In addition to the analyses to determine the fertilizer value of manure, it is recommended to analyze for the amount of phosphorus in the manure that is water soluble. Water soluble phosphorus is needed to evaluate the potential environmental risk associated with phosphorus application rates specified in manure management plans. Having good farm based information should help planners develop plans tailored to and individual farm.

Key Points to Remember

The important things to remember in collecting a liquid animal manure sample are:

- Collect a sample that best represents the nutrient content of the manure in that storage facility and what will be applied. If only the top water is to be applied it should be sampled. If the storage unit will be agitated prior to application the sample should contain material from the entire depth profile.
- Only fill the sample bottle ½ full.
- Keep the sample cool prior to shipping.
- Ship the sample to the lab as soon as possible.

Handout, April 27, 2010

Supplementary Tables

Table S 1. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2013. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
15	3,000	12	250	30	38	2.5	3.2

Table S 2. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2014. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
1	**18,000**	**6**	**3,000**	**86**	**362**	**14.4**	**60.3**
1	**28,000**	**7**	**4,000**	**134**	**563**	**19.2**	**80.4**
2	22,600	6	3,767	108	454	18.1	75.7
3	18,000	6	3,000	86	362	14.4	60.3
3	38,500	6	6,417	185	774	30.8	129.0
3	61,600	15	4,107	296	1,238	19.7	82.5
4	3,000	1	3,000	14	60	14.4	60.3
4	12,000	4	3,000	58	241	14.4	60.3
4	13,800	3.5	3,943	66	277	18.9	79.3
7	133,000	29	4,586	638	2,673	22.0	92.2
7	67,200	15	4,480	323	1,351	21.5	90.0
7	87,000	19	4,579	418	1,749	22.0	92.0
7	109,000	60	1,817	523	2,191	8.7	36.5

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
8	25,000	9	2,778	120	503	13.3	55.8
9	72,800	25	2,912	349	1,463	14.0	58.5
9	31,000	10	3,100	149	623	14.9	62.3
10	60,000	15	4,000	288	1,206	19.2	80.4
10	18,000	6	3,000	86	362	14.4	60.3
10	51,000	14	3,643	245	1,025	17.5	73.2
10	67,200	15	4,480	323	1,351	21.5	90.0
10	53,000	14	3,786	254	1,065	18.2	76.1
11	51,000	17	3,000	245	1,025	14.4	60.3
12	**48,000**	**9.9**	**4,848**	**230**	**965**	**23.3**	**97.5**
13	33,000	11	3,000	158	663	14.4	60.3
13	57,500	19	3,026	276	1,156	14.5	60.8
13	87,000	29	3,000	418	1,749	14.4	60.3
13	44,800	14	3,200	215	900	15.4	64.3
13	58,000	19	3,053	278	1,166	14.7	61.4
13	27,500	9	3,056	132	553	14.7	61.4
13	28,750	9	3,194	138	578	15.3	64.2
13	12,000	4	3,000	58	241	14.4	60.3
13	14,200	5	2,840	68	285	13.6	57.1
13	62,800	22	2,855	301	1,262	13.7	57.4
13	28,000	10	2,800	134	563	13.4	56.3
14	45,000	15	3,000	216	905	14.4	60.3
14	28,000	8	3,500	134	563	16.8	70.4
15	3,000	1	3,000	14	60	14.4	60.3
15	6,000	2	3,000	29	121	14.4	60.3

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
15	24,000	9	2,667	115	482	12.8	53.6
15	18,000	7	2,571	86	362	12.3	51.7
15	36,000	13	2,769	173	724	13.3	55.7
15	42,000	14	3,000	202	844	14.4	60.3
15	45,000	15	3,000	216	905	14.4	60.3
15	25,400	9	2,822	122	511	13.5	56.7
15	16,800	6	2,800	81	338	13.4	56.3
15	16,800	6	2,800	81	338	13.4	56.3
15	11,200	4	2,800	54	225	13.4	56.3
15	8,200	3	2,733	39	165	13.1	54.9
15	90,000	29	3,103	432	1,809	14.9	62.4
15	57,500	20	2,875	276	1,156	13.8	57.8
15	34,500	12	2,875	166	693	13.8	57.8
16	56,000	9	6,222	269	1,126	29.9	125.1
17	6,000	2	3,000	29	121	14.4	60.3
17	30,000	10	3,000	144	603	14.4	60.3
17	3,000	10	300	14	60	1.4	6.0
17	30,000	5	6.000	144	603	28.8	120.6
17	21,000	7	3.000	101	422	14.4	60.3
17	36,000	12	3,000	173	724	14.4	60.3
17	25,000	9	2,778	120	503	13.3	55.8
17	22,400	8	2,800	108	450	13.4	56.3
17	16,800	6	2,800	81	338	13.4	56.3
17	11,800	4	2,950	57	237	14.2	59.3
17	18,000	6	3,000	86	362	14.4	60.3

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
17	46,000	16	2,875	221	925	13.8	57.8
17	28,750	10	2,875	138	578	13.8	57.8

Table S 3. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2015. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
1	**12,000**	**8.4**	**1,429**	**58**	**241**	**6.9**	**28.7**
2	39,000	6.0	6,500	187	784	31.2	130.7
4	18,000	7.2	2,500	86	362	12.0	50.3
7	696,000	92.6	7,516	5,498	10,579	59.4	114.2
8	21,000	8.6	2,442	101	422	11.7	49.1
9	186,000	35.5	5,239	893	3,739	25.1	105.3
10	174,000	30.5	5,705	835	3,497	27.4	114.7
10	309,000	30.5	10,131	1,483	6,211	48.6	203.6
12	**33,000**	**11.4**	**2,895**	**158**	**663**	**13.9**	**58.2**
12	**60,000**	**11.4**	**5,263**	**288**	**1,206**	**25.3**	**105.8**
13	300,000	50.9	5,894	1,440	6,030	28.3	118.5
14	36,000	8.1	4,444	173	724	21.3	89.3
16	63,000	15.2	4,145	302	1,266	19.9	83.3
17	178,000	31.9	5,580	854	3,578	26.8	112.2
17	240,000	31.9	7,524	1,152	4,824	36.1	151.2

Table S 4. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2016. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
1	**42,000**	**8.4**	**5,000**	**76**	**365**	**9.0**	**43.5**
1	**36,000**	**8.4**	**4,286**	**565**	**778**	**67.3**	**92.6**
2	24,000	6.0	4,000	43	209	7.2	34.8
2	24,000	6.0	4,000	377	518	62.8	86.4
3	54,000	27.0	2,000	97	470	3.6	17.4
3	54,000	27.0	2,000	848	1,166	31.4	43.2
4	30,000	7.2	4,167	54	261	7.5	36.3
4	27,000	7.2	3,750	424	583	58.9	81.0
8	42,000	8.6	4,884	76	365	8.8	42.5
8	42,000	8.6	4,884	659	907	76.7	105.5
9	252,000	35.5	7,099	454	2,192	12.8	61.8
9	168,000	35.5	4,732	2,638	3,629	74.3	102.2
10	150,000	30.5	4,918	270	1,305	8.9	42.8
10	153,000	30.5	5,016	2,402	3,305	78.8	108.4
11	72,000	17.0	4,235	130	626	7.6	36.8
11	60,000	17.0	3,529	942	1,296	55.4	76.2
12	**99,000**	**11.4**	**8,684**	**178**	**861**	**15.6**	**75.6**
12	**57,000**	**11.4**	**5,000**	**895**	**1,231**	**78.5**	**108.0**
13	60,000	50.9	1,179	108	522	2.1	10.3
13	204,000	50.9	4,008	3,203	4,406	62.9	86.6
14	75,000	8.1	9,259	135	653	16.7	80.6
15	111,000	150.0	740	200	966	1.3	6.4
15	150,000	150.0	1,000	2,355	3,240	15.7	21.6

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
16	93,000	15.2	6,118	1,460	2,009	96.1	132.2
17	336,000	31.9	10,533	605	2,923	19.0	91.6
17	126,000	31.9	3,950	1,978	2,722	62.0	85.3

Table S 5. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2017. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
1	**48,000**	**8.4**	**5,714**	**1,459**	**1,190**	**173.7**	**141.7**
1	**12,000**	**8.4**	**1,429**	**359**	**269**	**42.7**	**32.0**
2	24,000	6	4,000	730	595	121.6	99.2
2	24,000	6	4,000	718	538	119.6	89.6
3	60,000	27	2,222	1,824	1,488	67.6	55.1
3	45,000	27	1,667	1,346	1,008	49.8	37.3
4	39,000	7.2	5,417	1,186	967	164.7	134.3
4	15,000	7.2	2,083	449	336	62.3	46.7
7	255,000	92.6	2,754	7,752	6,324	83.7	68.3
7	321,000	92.6	3,467	9,758	7,961	105.4	86.0
7	180,000	92.6	1,944	5,382	4,032	58.1	43.5
8	30,000	8.6	3,488	912	744	106.0	86.5
8	27,000	8.6	3,140	821	670	95.4	77.9
9	216,000	35.5	6,085	6,566	5,357	185.0	150.9
9	30,000	35.5	845	912	744	25.7	21.0
9	100,000	35.5	2,817	2,990	2,240	84.2	63.1
10	66,000	30.5	2,164	2,006	1,637	65.8	53.7
10	54,000	30.5	1,770	1,642	1,339	53.8	43.9
10	123,000	30.5	4,033	3,678	2,755	120.6	90.3
11	63,000	17	3,706	1,915	1,562	112.7	91.9
12	**45,000**	**11.4**	**3,947**	**1,368**	**1,116**	**120.0**	**97.9**
12	**45,000**	**11.4**	**3,947**	**1,346**	**1,008**	**118.0**	**88.4**
13	80,000	50.9	1,572	2,432	1,984	47.8	39.0

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
13	60,000	50.9	1,179	1,824	1,488	35.8	29.2
13	141,000	50.9	2,770	4,216	3,158	82.8	62.1
14	36,000	8.1	4,444	1,094	893	135.1	110.2
14	24,000	8.1	2,963	718	538	88.6	66.4
15	168,000	150	1,120	5,107	4,166	34.0	27.8
15	150,000	150	1,000	4,485	3,360	29.9	22.4
16	90,000	15.2	5,921	2,691	2,016	177.0	132.6
17	144,000	31.9	4,514	4,378	3,571	137.2	111.9
17	246,000	31.9	7,712	7,355	5,510	230.6	172.7

Table S 6. Volume and nutrients applied in slurry from the C&H operation to permitted fields in 2018. Fields bolded in red are monitored by BCRET.

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
1	**30,000**	**8.4**	**849**	**648**	**101.1**	**77.1**	**1**
1	**27,000**	**8.4**	**764**	**583**	**91.0**	**69.4**	**1**
2	27,000	6	764	583	127.4	97.2	2
2	24,000	6	679	518	113.2	86.4	2
3	54,000	27	1,528	1,166	56.6	43.2	3
3	54,000	27	1,528	1,166	56.6	43.2	3
4	30,000	7.2	849	648	117.9	90.0	4
4	27,000	7.2	764	583	106.1	81.0	4
7	255,000	92.6	7,217	5,508	77.9	59.5	7
7	384,000	92.6	10,867	8,294	117.4	89.6	7
8	27,000	8.6	764	583	88.8	67.8	8
8	51,000	8.6	1,443	1,102	167.8	128.1	8
9	171,000	35.5	4,839	3,694	136.3	104.0	9
9	190,000	35.5	5,377	4,104	151.5	115.6	9
10	159,000	30.5	4,500	3,434	147.5	112.6	10
10	129,000	30.5	3,651	2,786	119.7	91.4	10
11	57,000	17	1,613	1,231	94.9	72.4	11
12	**48,000**	**11.4**	**1,358**	**1,037**	**119.2**	**90.9**	**12**
12	**57,000**	**11.4**	**1,613**	**1,231**	**141.5**	**108.0**	**12**
13	204,000	50.9	5,773	4,406	113.4	86.6	13
14	30,000	8.1	849	648	104.8	80.0	14
14	30,000	8.1	849	648	104.8	80.0	14
15	150,000	150	4,245	3,240	28.3	21.6	15

Field	Slurry applied	Area	Application rate	Nutrients applied		Application rate	
				P	N	P	N
	gallons	acres	gals/acre	- - - - - - - lbs - - - - - - -		- - - - - - lbs/ac - - - - - -	
15	123,000	150	3,481	2,657	23.2	17.7	15
16	66,000	15.2	1,868	1,426	122.9	93.8	16
17	147,000	31.9	4,160	3,175	130.4	99.5	17
17	192,000	31.9	5,434	4,147	170.3	130.0	17

EFFECT OF SLURRY AND FIELD MANAGEMENT ON SOIL NUTRIENTS

Contents

Summary

1. The nutrient distribution in soils of three fields (Fields 1, 5a, and 12) were determined by repeating soil sampling on a 0.25-acre grid in 2014, 2016, and 2018. Using GPS to locate the initial soil sample locations in 2014, subsequent sampling in 2016 and 2018 was made at the same point (with a 1-m accuracy). This provided data on soil nutrient status as a function of slurry application, along with grazing management on Fields 1 and 12. As slurry was not applied to Field 5a, data from this field provided a reference point for normal pasture management in the region, with mineral fertilizer applied annually. Furthermore, Fields 5a and 12 are adjacent to Big Creek while Field 1 is at a higher elevation, providing contrasting topographic positions common to the watershed.
2. Data from the grid sampling enables an assessment of the impact of field management on soil nutrient status and potential for nutrient accumulation or decline over time.
3. On a whole-field basis at the 0 to 4 inch depth, there was an increase (at 0.05 level of probability) in Mehlich-3 P (59 – 91 mg/kg), K (204 – 258 mg/kg), and Mg (113 – 143 mg/kg) in Field 1 between 2014 and 2018. For Field 5a, there was little change in Mehlich-3 P from 2014 to 2018 (45 – 47 mg/kg). Similar to Field 1, P, K, and Mg for Field 12 were greater in 2018 than 2014 and 2016 in 0 to 4 inch samples, with P increasing from 63 to 122 mg/kg.

4. An increase in Mehlich-3 P of the buffer zone of Field 12 (90 – 112 mg/kg) illustrates the complexity of cattle movement and preferential grazing areas, as an additional source of P. The accelerated accumulation of P occurs in Field 12 adjacent to the gate where cattle are consistently fed and thus, loaf. Additional areas of accumulation outside the slurry application zones of Fields 1 and 12 can be seen adjacent to shade trees.
5. Soil P sorption saturation, an estimate of soil P availability (i.e., Mehlich-3 P) as well as the capacity of that soil to bind further additions of P in fertilizer or manure, increased between the 2014 and 2018 grid-samplings for Fields 1 and 12 and showed a similar spatial distribution in these fields as to Mehlich-3 P.
6. It should be noted that the accumulation of Mehlich-3 P and increase in soil P sorption saturation in the southwest corner of Field 12 was evident in the 2014 grid soil sampling, which was completed January 31, 2014 prior to the first application of swine slurry to Field 12, which occurred April 22, 2014.
7. Findings from the 2014 to 2018 grid-soil sampling reinforce current nutrient management recommendations, that the continued, long-term application of P (as fertilizer or manure) in amounts greater than pasture offtake (removal in cut hay), result in a rapid accumulation of P at the soil surface and thus, potential for runoff. Increases in soil test P will eventually elevate the P-Index risk value to high and further limit P additions as fertilizer or manure in future iterations of nutrient management planning. Separation of solid and liquid slurry in adjacent holding ponds provides an opportunity for a farmer to more closely match the application of P in slurry to crop needs.
8. Future additions of any nutrients (i.e., as mineral fertilizer, swine slurry, or poultry litter) to fields, which received slurry from C&H Farms, should be carefully managed, so as not to lead further increases in soil test P. This can be achieved by application of nitrogen (N) fertilizer or slurry and poultry litter at P-based rates, where P applied is equivalent to expected forage uptake of P.

List of Tables

List of Figures

List of Supplemental Tables

Soil Sampling and Analysis

Grid-soil sampling

Grid-soil sampling of Fields 1, 5a and 12 was conducted in February 2014, January 2015, and February 2014, respectively. Note that in 2014 – 2015, Field 5a was sampled later than Fields 1 and 12 as Fields 5 and 5a were incorrectly located on the original C&H CNMP. In subsequent Tables and Figures, the Field 5a sampling is noted as 2014 for simplicity and comparison to 2014 sampling of Fields 1 and 12 data. Fields 1, 5a, and 12 were grid-sampled in February 2016 and March 2018. In each field, sampling points were geo-referenced so that bi-annually sampling could be collected at the same location in each field.

A grid network of approximately 0.25 acres was overlain on each field to determine the point of sampling, which were recorded with GPS. Each sample-hole remaining after the soil core was removed was carefully back-filled with commercial top soil. Where rock stopped the core penetrating below a specific layer, no sample was collected beyond that point. The 2018 sampling was a repeat of the 2014 and 2016 sampling and was conducted within a 5-foot radius of the original geo-referenced point in order to document any changes in soil composition with time and land management. In 2016 and 2018, Fields 1, 5a, and 12 soil were grid-sampled at 0 to 4 and 4 to 8 inch depths only. Due to rocks at or near the soil surface, only 0 to 4 inch samples were collected from Field 1 in 2018.

Maps of the grid sampling for each field are given in Figures 1, 2, and 3 for Fields 1, 5a, and 12, respectively, along with the buffers imposed by the C&H ADEQ permit for ponds, school, slope, and stream where no slurry can be applied. On field 12, the farm owners have implemented a 100 ft buffer along the south neighboring field. Based on these delineations, the area slurry can be applied to Fields 1 and 12 along with buffer areas of all three fields are given in Table 1.

Table 1. Whole field, slurry application, and buffer (no slurry application allowed) areas for Fields 1, 5a, and 12.

Site	Site ID	Field area		Slurry application zone		Buffer	
		acres	hectares	acres	hectares	acres	hectares

Field 1	BC 1	15.59	6.31	15.44	6.25	0.15	0.06
Field 5a [1]	BC 2	23.50	9.51	22.96	9.29	0.54	0.22
Field 12	BC 3	28.69	11.61	28.21	11.42	0.48	0.19

[1] Slurry has not been applied to Field 5a or the adjacent Field 5.

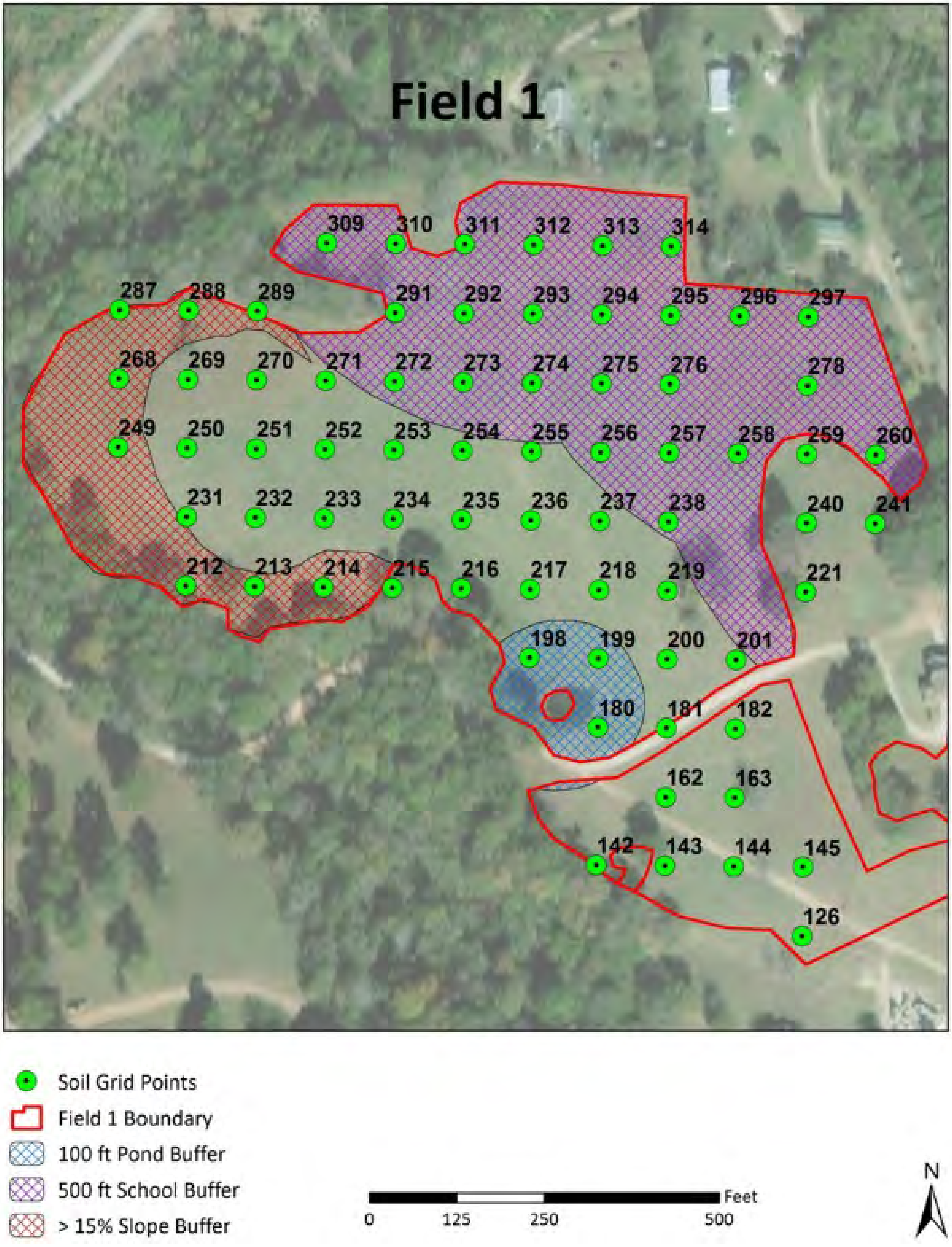


Figure 1. Grid-soil sampling locations for Field 1.

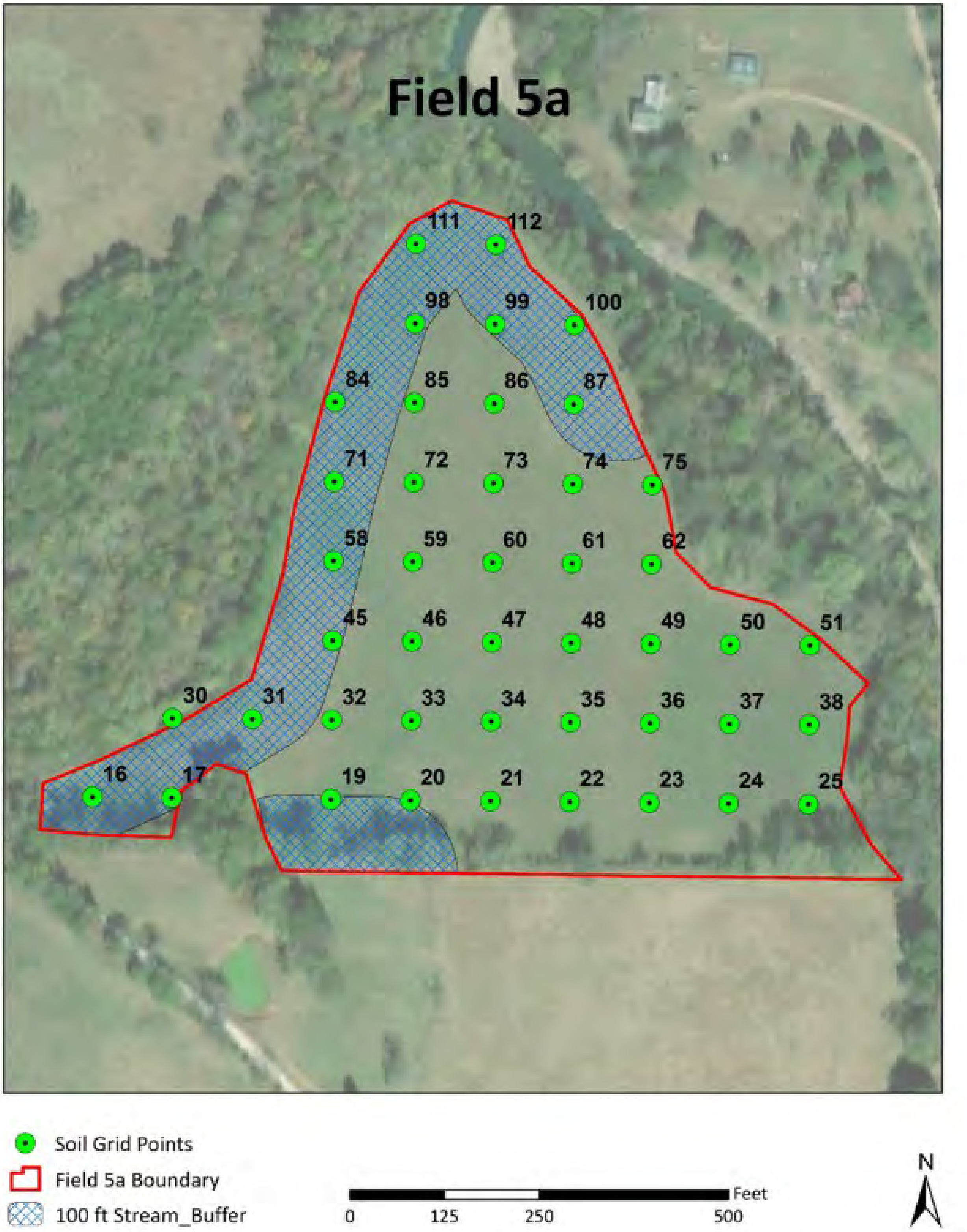


Figure 2. Grid-soil sampling locations for Field 5a.

Figure 3. Grid-soil sampling locations for Field 12.

Annual amounts and rates of commercial fertilizer (Field 5a) and slurry from the C&H operation (Fields 1 and 12) are given in Table 2. The slurry rates are obtained from ADEQ annual management reports for the farm and commercial fertilizer application from the landowner.

Table 2. Slurry (i.e., Fields 1 and 12) and fertilizer (i.e., Fields 5a) application to the monitored fields for 2014 to 2018.

Site	2014		2015		2016		2017		2018	
Slurry applied, gals										
Field 1	46,000		48,000		78,000		60,000		57,000	
Field 12	48,000		93,000		156,000		90,000		105,000	
Nutrients applied in slurry, lbs/1000 gallons										
	P	**N**	**P**	**N**	**P**	**N**	**P**	**N**		
Field 1	18.1	16.8	60.4	53.2	17.5	30.3	60.3	47.2	12.4	12.2
Field 12	18.1	16.8	4.8	20.1	17.5	30.3	60.3	47.2	12.4	12.2
Nutrients applied to field, lbs/acre										
Field 1	53	50	186	164	88	152	232	182	45	45
Field 5a [1]	25	57	25	57	25	57	25	57	25	57
Field 12	30	28	16	65	95	165	189	148	45	44
Nutrients applied to field, kg/ha										
Field 1	60	55	208	183	98	170	260	203	51	50
Field 5a [1]	28	64	28	64	28	64	28	64	28	64
Field 12	34	31	17	73	107	184	212	166	51	50

[1] Nutrient applied as 19-19-19 mineral fertilizer (i.e., 19% N, 19% P_2O_5, and 19% K_2O) in early spring at a rate of 300 lbs/acre.

Particle-size analysis

Soil samples were collected along a transect in Fields 1, 5a, and 12 in March 2014 for textural analysis by the hydrometer method (Huluka and Miller, 2014). Transect and sampling points are shown in Figures 4, 5, and 6, respectively. In each field, 10 sampling points were equidistant along a total transect length of approximately 457 ft (140 m).

Figure 4. Transect sampling points for soil texture analysis for Field 1.

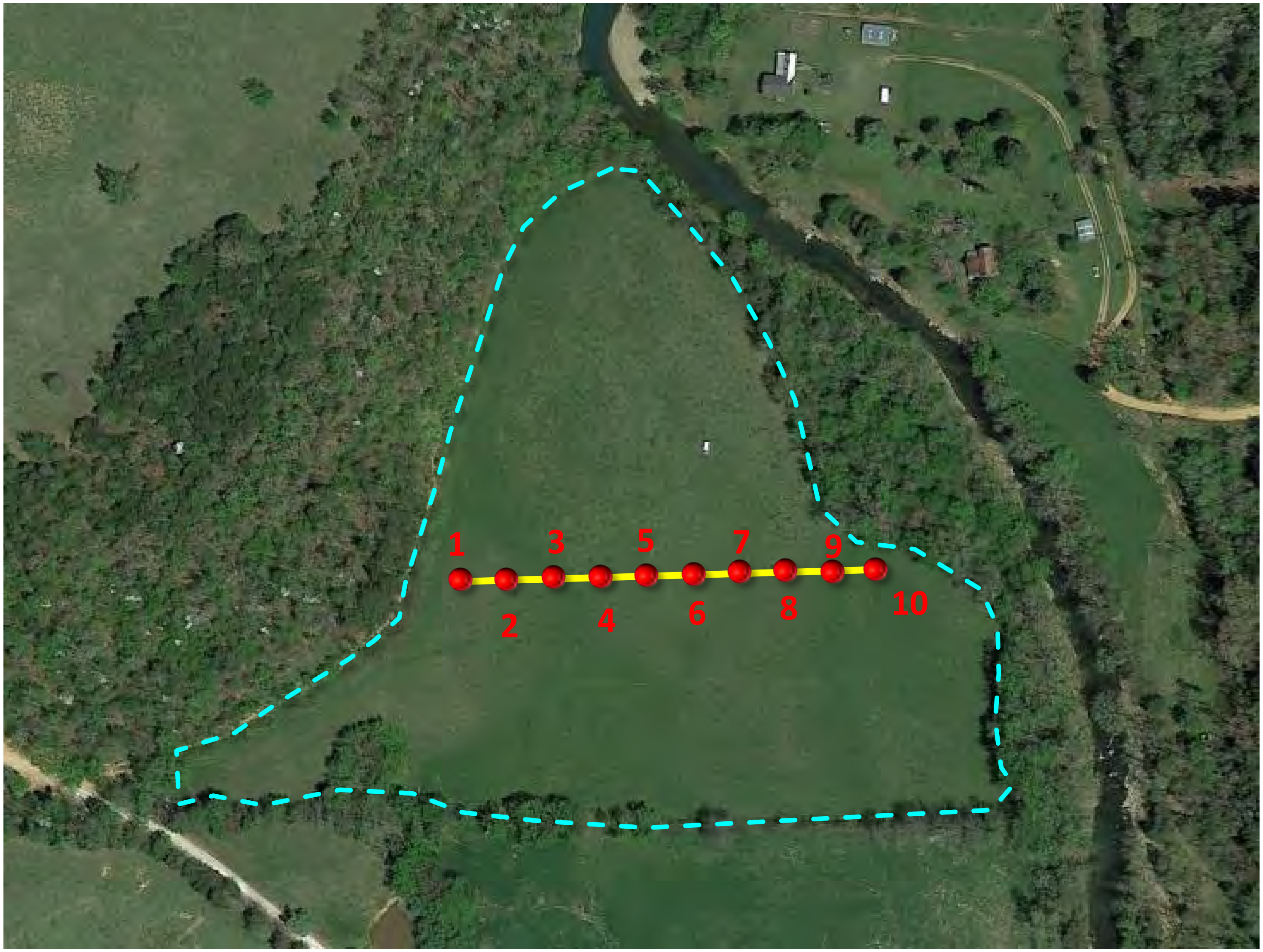


Figure 5. Transect sampling points for soil texture analysis for Field 5a.

Figure 6. Transect sampling points for soil texture analysis for Field 12.

Mehlich-3 soil extraction

Samples were sent to the University of Arkansas Soil Testing and Research Laboratory, Marianna, AR for analysis. All core samples were dried at 60 ^{o}C and ground to pass through a 2mm sieve. Any material that would not crush (mortar and pestle) to pass the 2mm screen was discarded. All analyses used subsamples from the ground material. Laboratory QA/QC includes among other standard protocols, that with every set of environmental samples digested, a blank, a duplicate, and a North American Proficiency Test Program certified soil sample (http://www.naptprogram.org/) are analyzed and compared. If the check is out of acceptable limits, more than 2.5 times the Mean Absolute Deviation value, the sample is digested again and rerun. The digest and duplicate for this set of core samples all met this analytical criterion.

Soil nutrients P, K, Ca, Mg, S, Na, Fe, Al, Mn, Zn, Cu, and B, were determined by Mehlich-3 extraction (Mehlich, 1984); and soil pH in a 1:2 soil:water mixture. Details of these methods are available at https://aaes.uark.edu/research-locations/soil-testing-and-research-laboratory/lab-analytical-services-and-methods/.

Degree of Soil Phosphorus Saturation

The degree of soil P sorption saturation (PSS) has been used as an environmental indicator for soil P, based on the observations that more P is released from soil to surface runoff or leaching water as PSS increases (Dari et al., 2018; Pote et al., 1996; Sibbesen and Sharpley, 1997; Vadas et al., 2005). The degree of soil P sorption saturation also provides an indication of the remaining potential of soil to adsorb and retain P that may be added in fertilizer, manure, or from grazing animals.

The degree of soil P sorption saturation was originally determined by Breeuwsma and Schoumans (1987) and Breeuwsma et al. (1995) as;

$$\text{PSS} = \frac{\text{Oxalate extractable soil P}}{\alpha\ (\text{Oxalate extractable soil Fe} + \text{Oxalate extractable soil Al})} \qquad \text{[Equation 1]}$$

A disadvantage of the definition of the PSS is that the parameter α, is a function of the phosphate sorption capacity of the soil representing the proportion of oxalate extractable Fe and Al dedicated to P sorption [Equation 1]. For the study of Breeuwsma and Schoumans (1987) for Dutch noncalcareous sandy soils used in the study was 0.5.

However, the function α varies among soil types and from layer to layer in a soil profile (Schoumans, 2009). Since the initial work of Breeuwsma and Schoumans (1987), the determination of PSS has been modified for wider use. Firstly, the acid ammonium oxalate extraction of soil was replaced by Mehlich-3 extraction, due to the instability of the oxalate solution under normal laboratory conditions (i.e., the oxalate solution has to kept in the dark), which required the extractant to be made fresh on a daily basis (Kleinman and Sharpley, 2002; Schoumans, 2009). The oxalate extraction cannot be applied to calcareous soils, where Ca dominates P sorption reactions, as oxalic acid precipitates Ca during oxalate extraction and reacts with carbonate to change the pH of the acid buffered extractant (Loeppert and Inskeep, 1996)

For this project, the PSS (% basis) of soils in Fields 1, 5a, and 12 was calculated from $P_{M\text{-}3}$, $Al_{M\text{-}3}$ and $Fe_{M\text{-}3}$ (in mmol/kg), as in Equation [2] below;

$$\mathrm{PSS} = \left(\frac{\mathrm{Mehlich{-}3\ extractable\ soilP}/31}{(\mathrm{Mehlich{-}3\ extractable\ soil\ Fe}/56)+(\mathrm{Mehlich{-}3\ extractable\ soilAl}/27)}\right) * 100 \qquad \text{[Equation 2]}$$

Kleinman and Sharpley found that PSS estimated from Mehich-3 P, Fe, and Al was highly correlated with PSS estimated from ammonium oxalate extraction (r of 0.94) as well as with a Langmuir P sorption maximum (r of 0.89; determined according to Syers et al., 1973) for 37 acidic and 25 alkaline soils from across the U.S. As most Land-Grant and private Soil Testing Laboratories currently conducting Mehlich-3 extraction employ Inductively-coupled plasma spectrometry (ICP), analytes required to estimate PSS in Equation [2] are measured simultaneously and routinely. Thus, this method has been widely adopted to estimate PSS for a wide range of soils and management practices (Dari et al., 2018; Schoumans, 2009).

Soil Particle Size and Texture

Soil distribution across Fields 1, 5a, and 12 are shown in Figures 7, 8, and 9, respectively. Field 1 was dominated by Noark very cherty silt loam, Field 5a by Razort loam, and Field 12 by Spadra loam.

Textural analysis for transects across Fields 1, 5a, and 12 is given in Table 3. On average, surface soil (0 – 4 inches) in Fields 5a and 12 had a higher clay content (28.2 and 29.8% clay, respectively) in than in Field 1 (20.6% clay), which is indicative of the dominant soils in those fields (Razort loam, Spadra loam, and Noark very cherty silt loam, respectively).

Table 3. Particle size analysis and texture of surface 0 – 4 inch samples collected March 2014 along a ~450 ft transect in Fields 1, 5a, and 12.

Location	Sand	Silt	Clay	Texture
	---------- % ---------			
Field 1				
1	11.0	67.7	21.3	Silt loam
2	19.9	58.8	21.3	Silt loam
3	18.7	58.4	22.9	Silt loam
4	21.5	63.6	14.9	Silt loam
5	16.9	62.0	21.1	Silt loam
6	16.2	64.9	18.9	Silt loam
7	15.6	61.5	22.9	Silt loam
8	15.5	65.7	18.8	Silt loam
9	9.0	69.9	21.1	Silt loam

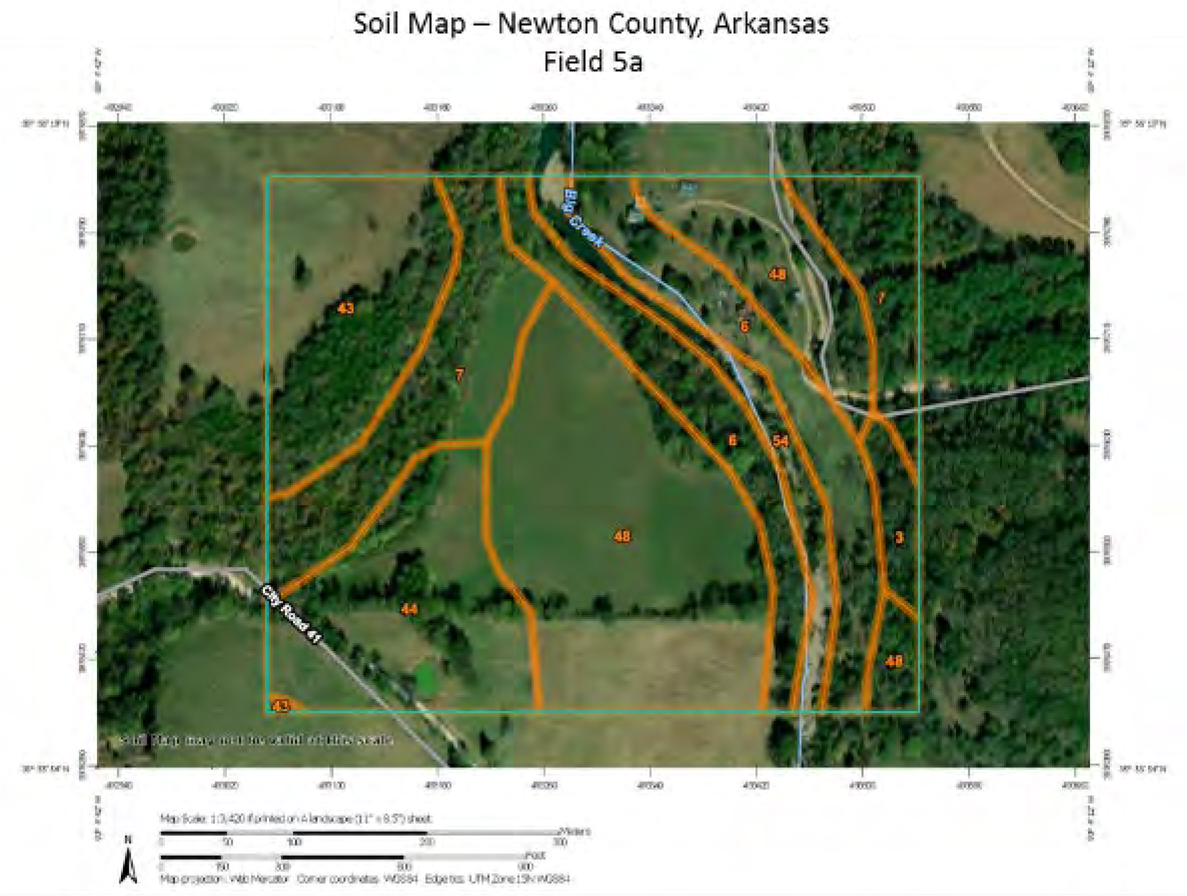
Location	Sand	Silt	Clay	Texture
10	14.1	62.8	23.1	Silt loam
Average	*15.8*	*63.5*	*20.6*	
Field 5a				
1	42.2	29.5	28.3	Sandy clay loam
2	46.8	25.9	27.2	Sandy clay loam
3	47.4	25.2	27.4	Sandy clay loam
4	41.0	22.0	37.0	Clay loam
5	48.2	24.8	27.0	Sandy clay loam
6	49.9	22.8	27.3	Sandy loam
7	48.4	23.6	28.0	Sandy clay loam
8	49.2	26.9	23.8	Sandy clay loam
9	43.9	24.0	32.1	Sandy clay loam
10	44.6	24.5	30.9	Sandy clay loam
Average	*43.4*	*28.4*	*28.2*	
Field 12				
1	38.3	32.8	28.9	Loam
2	39.7	26.2	34.2	Clay loam
3	38.8	33.2	28.0	Clay loam
4	38.7	31.6	29.7	Clay loam
5	43.0	27.3	29.7	Clay loam
6	44.8	27.2	28.0	Clay loam
7	39.5	27.3	33.2	Clay loam
8	52.8	20.8	26.4	Loam
9	44.0	26.8	29.2	Clay loam
10	41.7	30.2	28.1	Clay loam
11	31.0	36.7	32.4	Clay loam
Average	*41.1*	*29.1*	*29.8*	

Soil Map – Newton County, Arkansas
Field 1

Map unit symbol	Soil name	Acres in AOI [1]	Percent of AOI
42	Noark very cherty silt loam, 3 to 8% slopes	18.4	35%
43	Noark very cherty silt loam, 8 to 20% slopes	14.7	28%
44	Noark very cherty silt loam, 20 to 40% slopes	19.9	38%

[1] AOI is area of interest defined by the green rectangle

Figure 7. Soil map for Field 1.

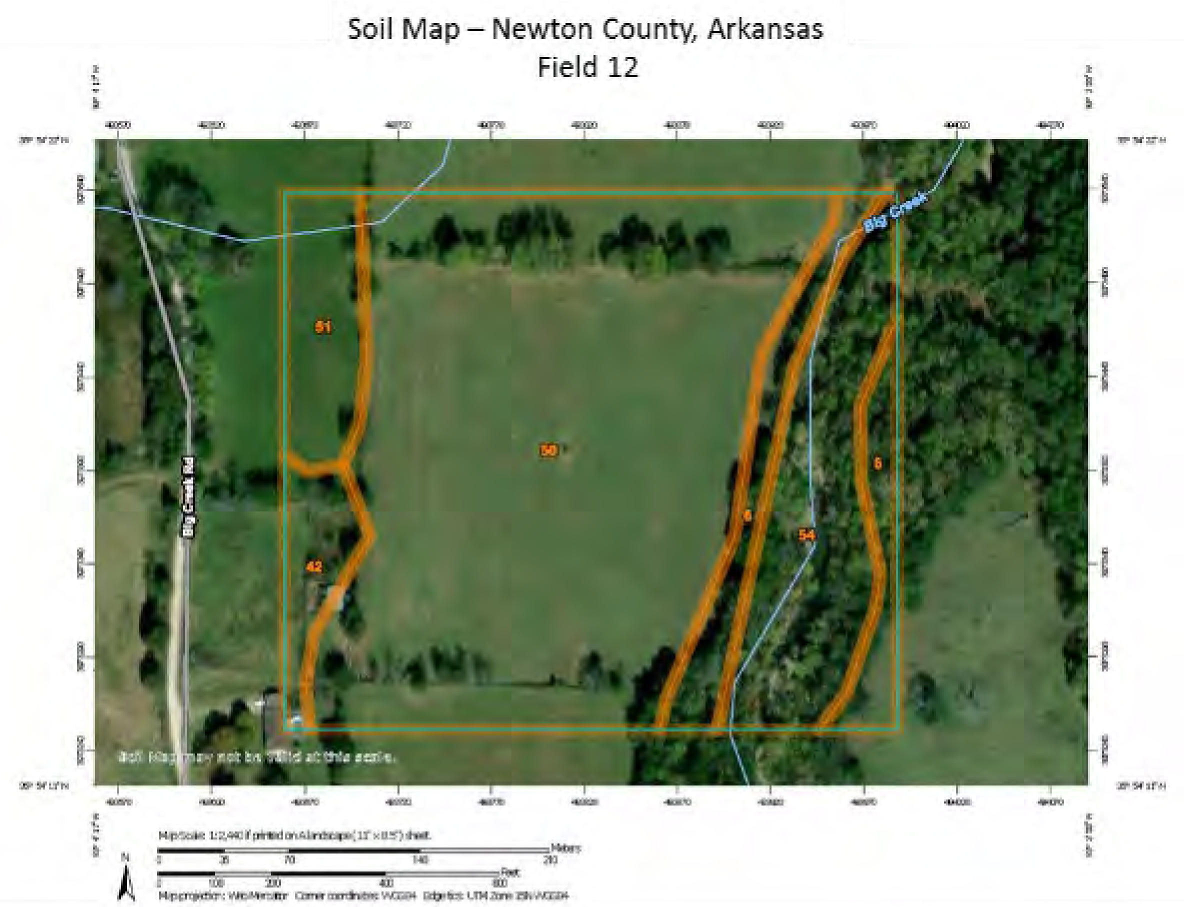


Map unit symbol	Soil name	Acres in AOI	Percent AOI
6	Ceda-Kenn complex, 0 to 3 percent slopes, frequently flooded	8.3	17%
7	Clarksville very cherty silt loam, 20 to 50 percent slopes	7.7	16%
43	Noark very cherty silt loam, 8 to 20% slopes	6.4	13%
44	Noark very cherty silt loam, 20 to 40% slopes	7.0	14%
48	Razort loam, occasionally flooded	16.2	33%

[1] AOI is area of interest defined by the green rectangle

Figure 8. Soil map for Field 5a.

Soil Map – Newton County, Arkansas
Field 12



Map unit symbol	Soil name	Acres in AOI	Percent AOI
6	Ceda-Kenn complex, 0 to 3% slopes, frequently flooded	2.3	10%
42	Noark very cherty silt loam, 3 to 8% slopes	0.9	4%
50	Spadra loam, occasionally flooded	15.2	65%
51	Spadra loam, 2 to 5 percent slopes	1.5	6%

[1] AOI is area of interest defined by the green rectangle

Figure 9. Soil map for Field 12.

In-Field Distribution of Soil Nutrients

The spatial distribution of Mehlich-3 extractable soil P (Mehlich-3 P) for Fields 1, 5a, and 12 are depicted in Figures 10 to 15 for both the 0 – 4 inch and 4 – 8 inch depths. Also, differences in Mehlich-3 P from the 2014 to 2018 samplings are depicted in Figures 16 and 17. Individual values at the grid points are noted on these Figures. The ranges in Mehlich-3 P concentrations depicted are <25, 25 to 50, 50 – 100, and >100 mg/L, which depict general soil fertility and plant response categories of deficiency levels, optimum levels for cool season grasses, little response to additional P expected for cool and warm season grasses, and no plant growth response expected to added P, respectively. Statistically significant differences of paired sampling points (<0.05 level of probability) between sampling dates for each field and Mehlich-3 analyte are listed in Supplemental Tables S1 to S5.

Mean values of Mehlich-3 extractable elements at a 0 – 4 inch soil depth for the whole field, slurry application zone, and buffer zone in 2014, 2016, and 2018, are given in Table 4. Individual analyses for each grid point, sample depth, and field are listed in Appendix C for whole field and application / buffer zones, respectively. Mean Mehlich-3 P values for Fields 1 and 5a decreased slightly from 2014 (59 and 45 mg/kg, respectively) to 2016 (57 and 39 mg/kg respectively). For Field 12, however, Mehlich-3 P increased from 63 mg/kg in 2014 to 122 mg/kg L in 2016 (Table 4).

It is evident from the Mehlich-3 P spatial distribution maps that accumulation of P occurs in some areas within the surface 0 – 4 inch depth of Fields 1 and 12 (Figures 10 to 15). These areas are generally located around areas of shade on Fields 1 and 12 (northern boundary of this field), where grazing cattle congregate to avoid the sun. On Field 12, the area of Mehlich-3 P greater than 100 mg/kg occurs on the southwest corner of the field and is located at the gated entrance to the field, where cattle are routinely fed hay. Further, individual points with elevated P levels on these fields may be due to cow pats that may no longer be visible at the surface.

It should be noted that the accumulation of Mehlich-3 P in the southwest corner of Field 12 was evident in the 2014 grid soil sampling (Figure 14), which was completed January 31, 2014 and that the first application of swine slurry to Field 12 did not occur until April 22, 2014. Thus, in-field spatial variations in Mehlich-3 P for Field 12 are likely a function of land use and management prior to any swine slurry application. Amounts of swine slurry applied to these fields in 2014, 2016, and 2018 are presented in Table 2.

We informed the owner of C&H, who discussed with the owner of Field 12, the use of alternative areas to feed cattle on Field 12, and the owners of C&H Farms have agreed to not spread slurry on this area of the field in order to not contribute to any further increase in surface soil Mehlich-3 P levels. While these areas are not adjacent to the Big Creek river channel, which minimizes the potential for this P to reach the river, management changes are in place to address the accumulation.

Table 4. Mean pH and concentrations of Mehlich-3 extractable elements for 0 to 4 inch soil samples collected in the 2014, 2016, and 2018 grid sampling of Fields 1, 5a, and 12, based on whole field, slurry application zone, and no application buffer zone samples. For a given field, zone, and element, means followed by the same letter are not significantly different as determined by unpaired *t* test with a <0.05 level of probability.

Year	No. samples	pH	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B
			- mg/kg -									
Field 1: Whole field												
2014	71	6.4 a	59 b	204 b	1936 a	113 b	18 a	109 a	262 a	0.6 b	4.3 b	0.4 b
2016	71	5.9 b	57 b	183 b	1845 a	110 b	15 b	118 a	209 b	1.4 a	5.1 b	0.5 a
2018	71	6.4 a	91 a	258 a	1909 a	143 a	19 a	106 a	213 b	1.3 a	7.1 a	0.4 b
Field 1: Application zone												
2014	39	6.5 a	65 b	266 ab	2046 a	118 b	19 b	116 a	256 a	0.6 c	4.7 b	0.5 a
2016	39	6.0 b	73 b	228 b	2106 a	125 b	15 c	125 a	213 b	1.7 a	6.5 b	0.5 a
2018	39	6.6 a	115 a	318 a	2205 a	164 a	21 a	118 a	213 b	1.3 b	8.8 a	0.5 a
Field 1: Buffer zone												
2014	32	6.2 a	52 ab	128 b	1803 a	106 a	18 a	101 a	269 a	0.6 c	3.9 a	0.3 ab
2016	32	5.6 b	38 b	127 b	1527 a	91 a	15 b	109 a	205 b	1.1 b	3.4 a	0.4 a
2018	32	6.3 a	62 a	185 a	1549 a	117 a	17 ab	92 a	214 b	1.3 a	5.1 a	0.3 b
Field 5a: Whole field												

Year	No. samples	pH	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B
			- mg/kg -									
2014	33	5.6 ab	45 a	59 a	1315 a	70 a	13 a	154 a	205 a	1.4 b	3.0 a	0.3 ab
2016	44	5.4 b	39 a	68 a	1258 a	73 a	13 a	148 a	171 b	1.5 b	2.8 a	0.4 a
2018	44	5.9 a	47 a	63 a	1341 a	72 a	13 a	128 b	166 b	2.1 a	3.4 a	0.3 b
Field 5a: Application zone												
2014	23	5.5 b	50 a	57 a	1076 a	69 b	12 a	163 a	220 a	1.3 b	2.7 b	0.2 b
2016	28	5.4 b	42 a	66 a	1198 a	78 a	12 a	157 a	175 b	1.6 b	3.0 ab	0.4 a
2018	28	5.8 a	45 a	60 a	1200 a	74 ab	12 a	134 b	169 b	2.2 a	3.5 a	0.2 b
Field 5a: Buffer zone												
2014	10	6.0 a	33 a	65 a	1864 a	71 a	13 a	131 a	171 a	1.4 b	3.6 a	0.4 a
2016	16	5.3 a	34 a	72 a	1364 a	63 a	15 a	132 a	163 a	1.5 b	2.5 a	0.4 a
2018	16	5.9 a	51 a	68 a	1588 a	69 a	16 a	116 a	162 a	2.0 a	3.2 a	0.3 a
Field 12: Whole field												
2014	40	5.9 b	63 b	92 b	1184 a	77 b	13 b	127 c	148 b	1.2 c	2.2 c	0.2 c
2016	45	5.5 c	104 a	129 ab	1301 a	118 a	16 a	182 a	177 a	1.7 b	4.9 b	0.5 a
2018	45	6.0 a	122 a	155 a	1205 a	125 a	14 b	154 b	164 ab	1.9 a	6.1 a	0.4 b
Field 12: Application zone												

Year	No. samples	pH	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B
			---------------------------------- mg/kg --------------------------------------									
2014	31	5.9 b	56 b	81 b	1210 a	75 b	13 b	121 c	144 b	1.2 b	2.1 c	0.2 c
2016	34	5.4 c	107 a	131 a	1364 a	124 a	17 a	177 a	173 a	1.8 a	5.1 b	0.5 a
2018	34	6.0 a	126 a	153 a	1239 a	131 a	14 b	149 b	162 ab	2.0 a	6.2 a	0.4 b
Field 12: Buffer zone												
2014	9	5.8 b	81 a	110 a	1062 a	80 a	14 a	146 b	161 a	1.0 b	2.9 b	0.2 b
2016	11	5.6 b	95 a	120 a	1105 a	101 a	14 a	200 a	187 a	1.5 a	4.4 ab	0.4 a
2018	11	6.1 a	112 a	161 a	1100 a	107 a	13 a	168 ab	173 a	1.7 a	5.6 a	0.4 a

Table 5. Mean pH and concentrations of Mehlich-3 extractable elements for 4 to 8 inch soil samples collected in the 2014, 2016, and 2018 grid sampling of Fields 5a and 12, based on whole field, slurry application zone, and no application buffer zone samples. For a given field, zone, and element, means followed by the same letter are not significantly different as determined by unpaired *t* test with a <0.05 level of probability.

Year	No. samples	pH	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B
			- - - - - - - - - - - - - - - - - -					mg/kg		- - - - - - - - - - - - - - - - - -		
						Field 5a: Whole field (4-8")						
2014	22	6.3 a	45 a	123 a	2307 a	88 a	8 b	107 b	104 b	1.9 a	4.7 a	0.0 c
2016	44	5.4 c	27 b	59 b	1183 b	47 b	10 b	136 a	157 a	1.6 a	2.0 b	0.3 b
2018	43	5.7 b	33 b	56 b	1210 b	43 b	12 a	134 a	171 a	1.5 a	1.9 b	0.6 a
						Field 5a: Application zone (4-8")						
2014	17	6.2 a	46 a	132 a	2321 a	90 a	8 b	114 b	104 b	1.9 a	5.3 a	0.1 c
2016	28	5.6 b	27 b	59 b	1241 b	48 b	9 b	141 a	151 a	1.7 a	2.0 b	0.3 b
2018	27	5.8 b	34 b	56 b	1214 b	44 b	10 a	142 a	171 a	1.7 a	2.0 b	0.6 a
						Field 5a: Buffer zone (4-8")						
2014	5	6.4 a	43 a	93 a	2260 a	83 a	7 b	86 b	106 a	1.9 a	2.8 a	0.0 c
2016	16	5.2 b	27 a	58 b	1082 a	47 b	12 ab	128 a	169 a	1.4 a	1.9 a	0.3 b
2018	16	5.5 b	31 a	56 b	1204 a	43 b	16 a	121 a	171 a	1.3 a	1.6 a	0.6 a
						Field 12: Whole field (4-8")						

Year	No. samples	pH	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B
			- mg/kg -									
2014	39	6.0 a	36 b	68 a	1235 a	54 b	11 a	104 b	97 b	1.2 b	1.4 b	0.1 c
2016	45	5.7 b	50 a	81 a	1332 a	72 a	12 a	134 a	128 a	1.7 a	2.0 a	0.4 b
2018	35	6.0 a	52 a	72 a	1296 a	74 a	10 a	134 a	123 a	1.6 a	2.5 a	0.6 a
Field 12: Application zone (4-8”)												
2014	31	6.0 a	33 b	67 a	1318 a	57 b	11 a	102 b	96 b	1.3 b	1.5 b	0.1 c
2016	34	5.7 b	47 a	78 a	1434 a	75 a	12 a	131 a	126 a	1.8 a	2.0 b	0.4 b
2018	28	6.1 a	55 a	78 a	1383 a	81 a	11 a	135 a	128 a	1.7 a	2.8 a	0.6 a
Field 12: Buffer zone (4-8”)												
2014	8	5.9 ab	49 a	74 a	915 a	46 a	11 a	110 b	102 a	0.9 b	1.3 b	0.1 b
2016	11	5.7 b	58 a	90 a	1019 a	63 a	10 a	141 a	136 a	1.5 a	2.2 a	0.3 a
2018	7	6.0 a	36 a	48 a	948 a	45 a	8 b	131 ab	104 a	1.2 ab	1.5 b	0.4 a

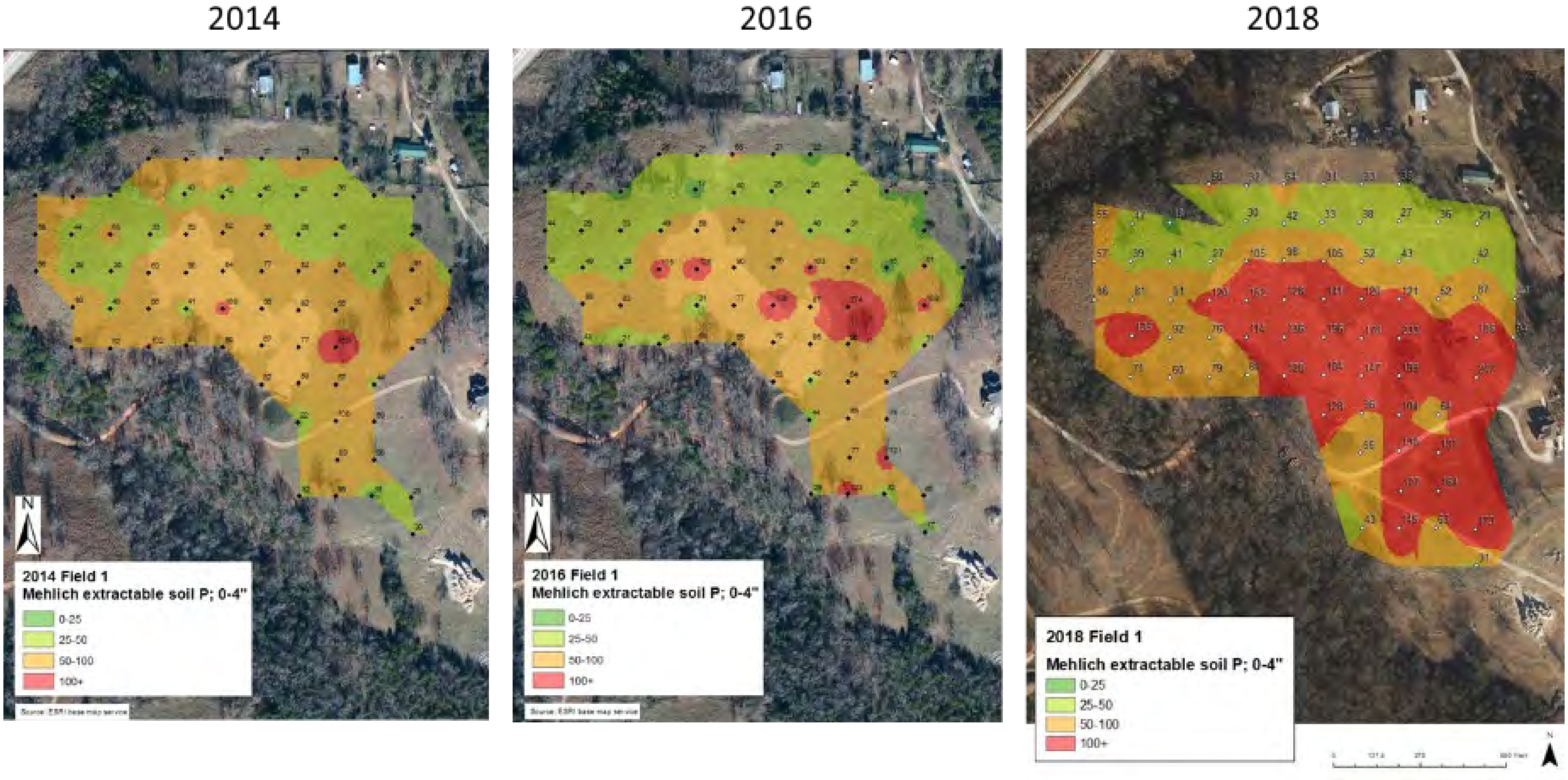
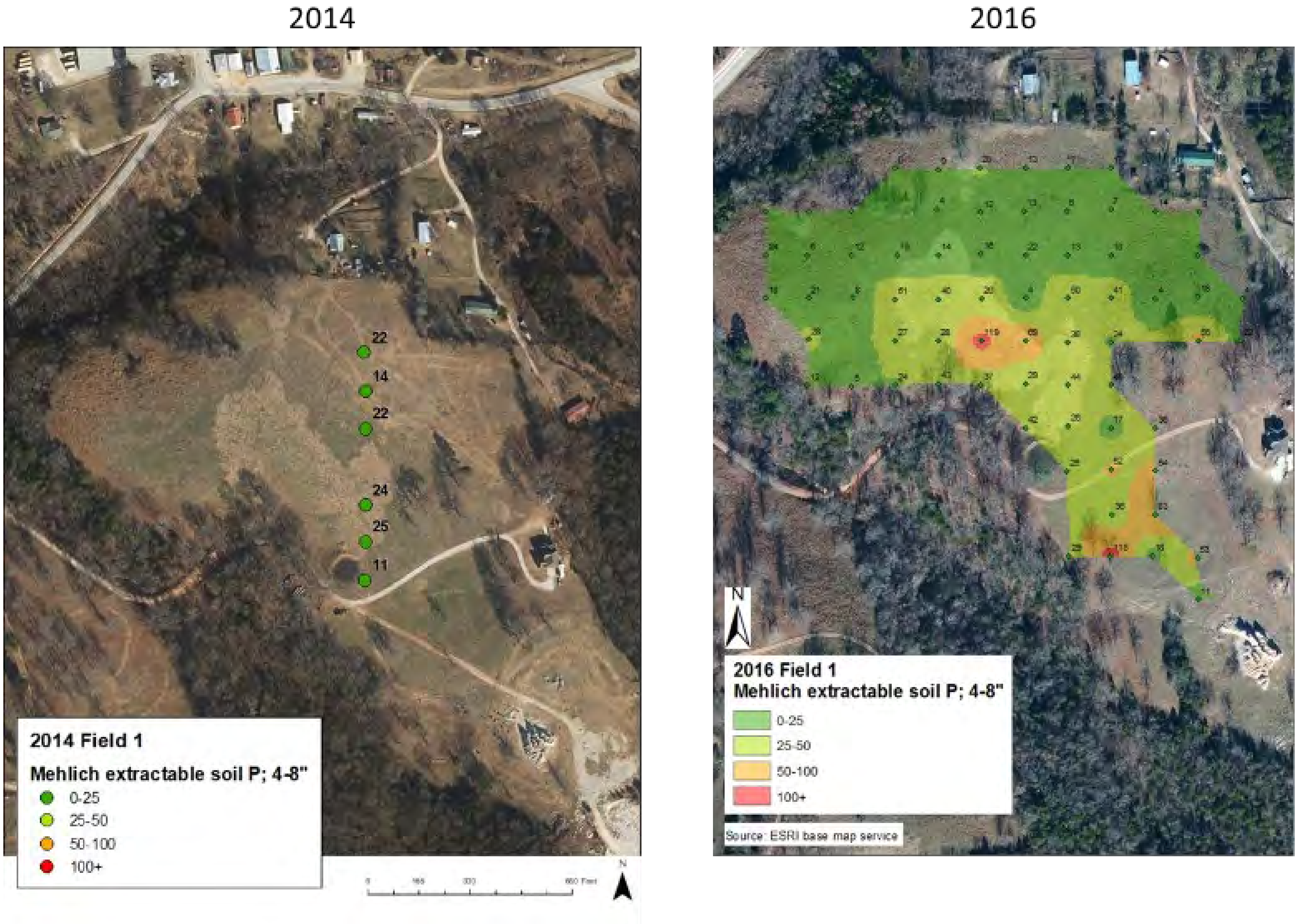


Figure 10. Mehlich-3 extractable soil P values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 1.



Source: ESRI base map service

Figure 11. Mehlich-3 extractable soil P values for 4 to 8 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 1.

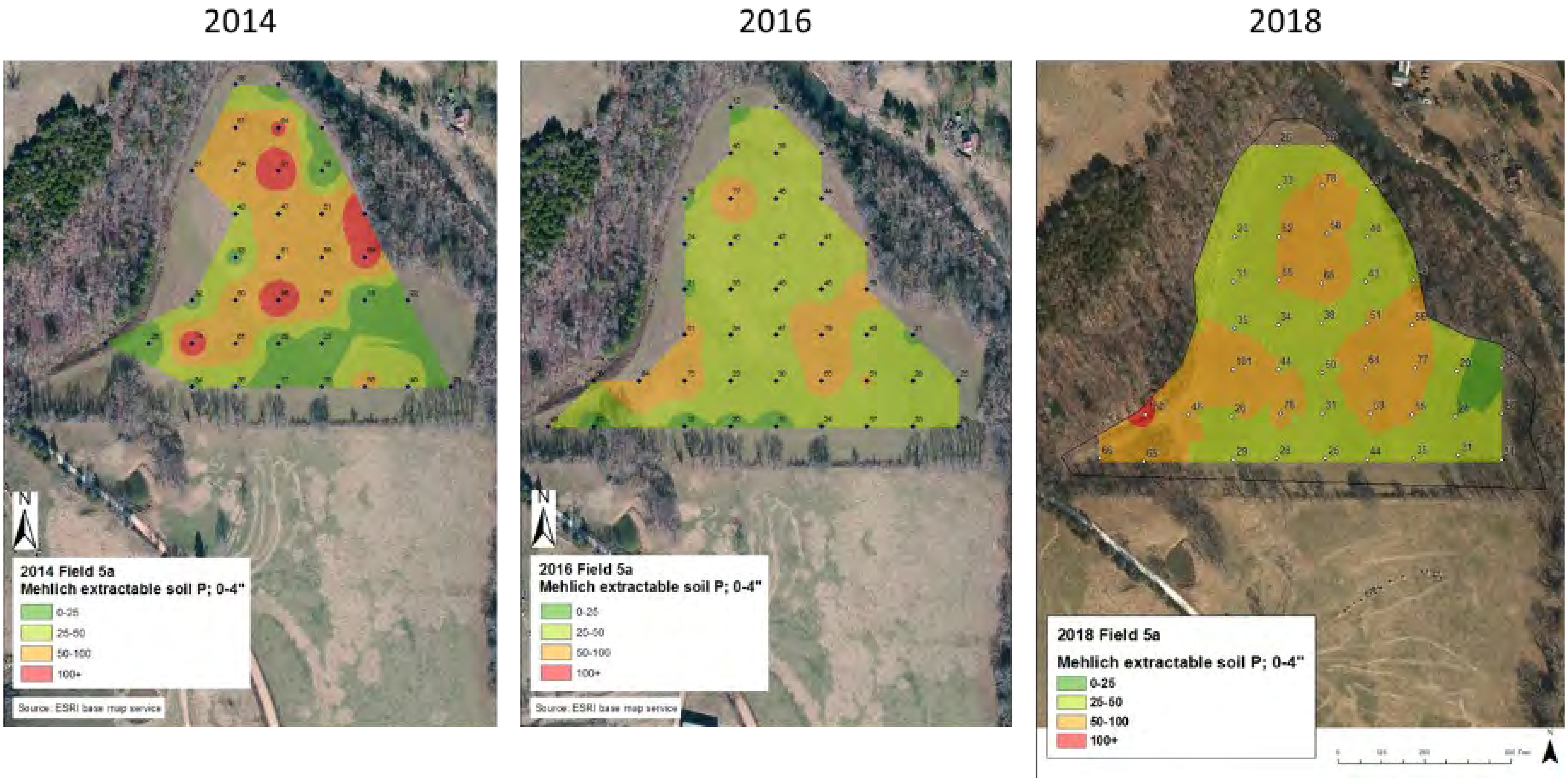


Figure 12. Mehlich-3 extractable soil P values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 5a.

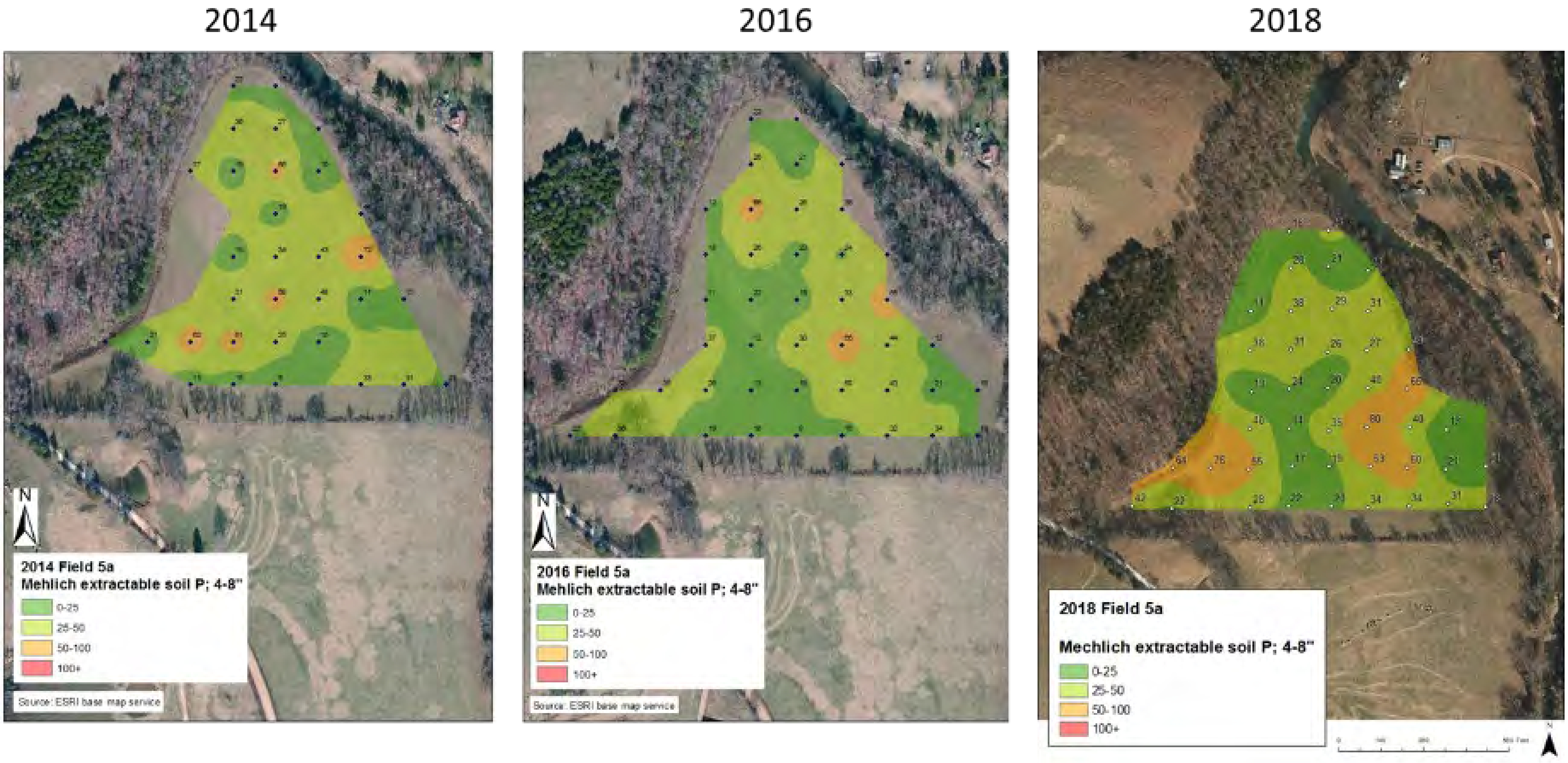


Figure 13. Mehlich-3 extractable soil P values for 4 to 8 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 5a.

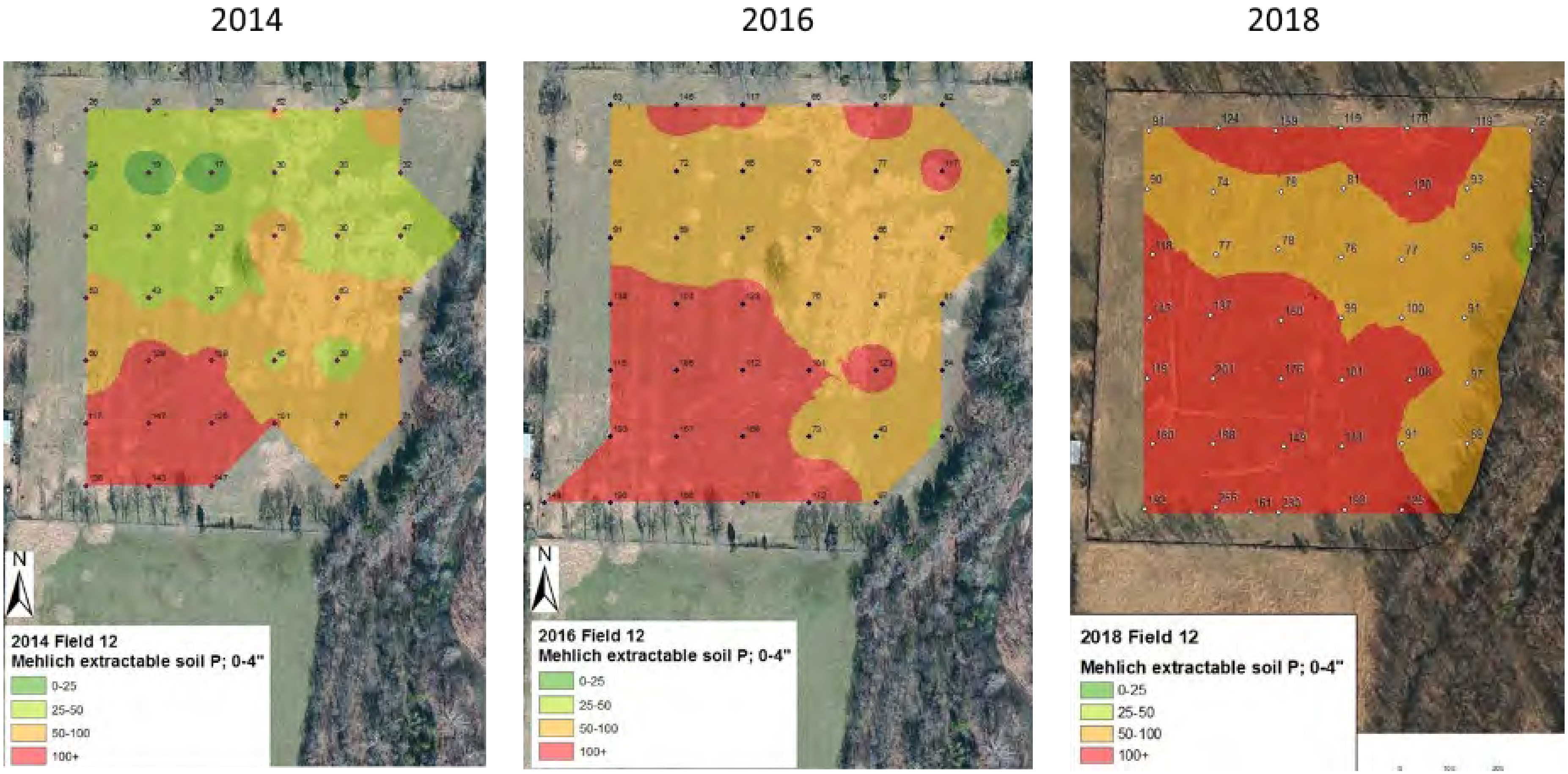


Figure 14. Mehlich-3 extractable soil P values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 12.

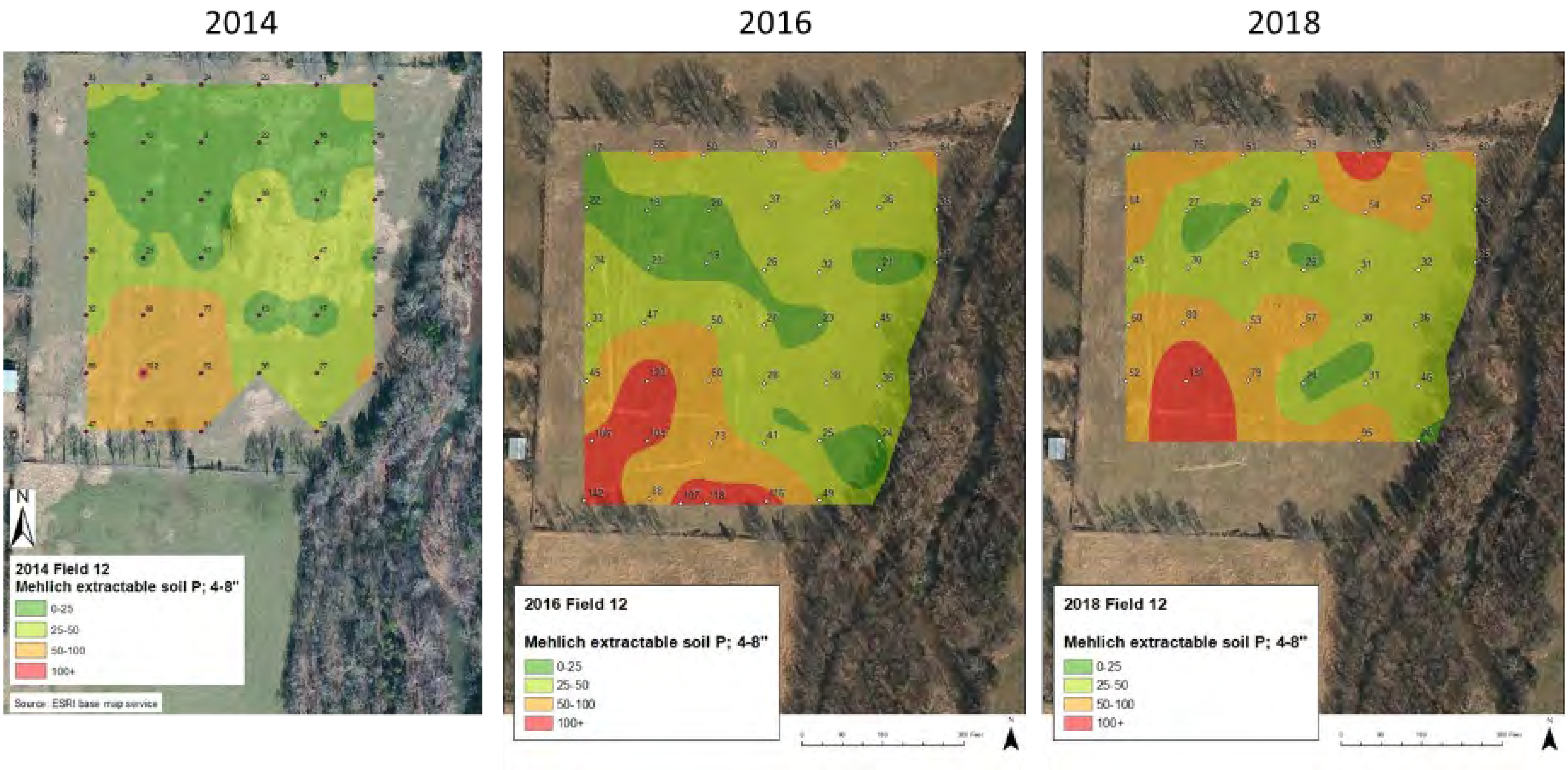


Figure 15. Mehlich-3 extractable soil P values for 4 to 8 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 12.


Field 1

Field 5a

Field 12

Figure 16. Difference in Mehlich-3 extractable soil P values between 2014 and 2018 grid-soil sampling of Fields 1, 5a, and 12.

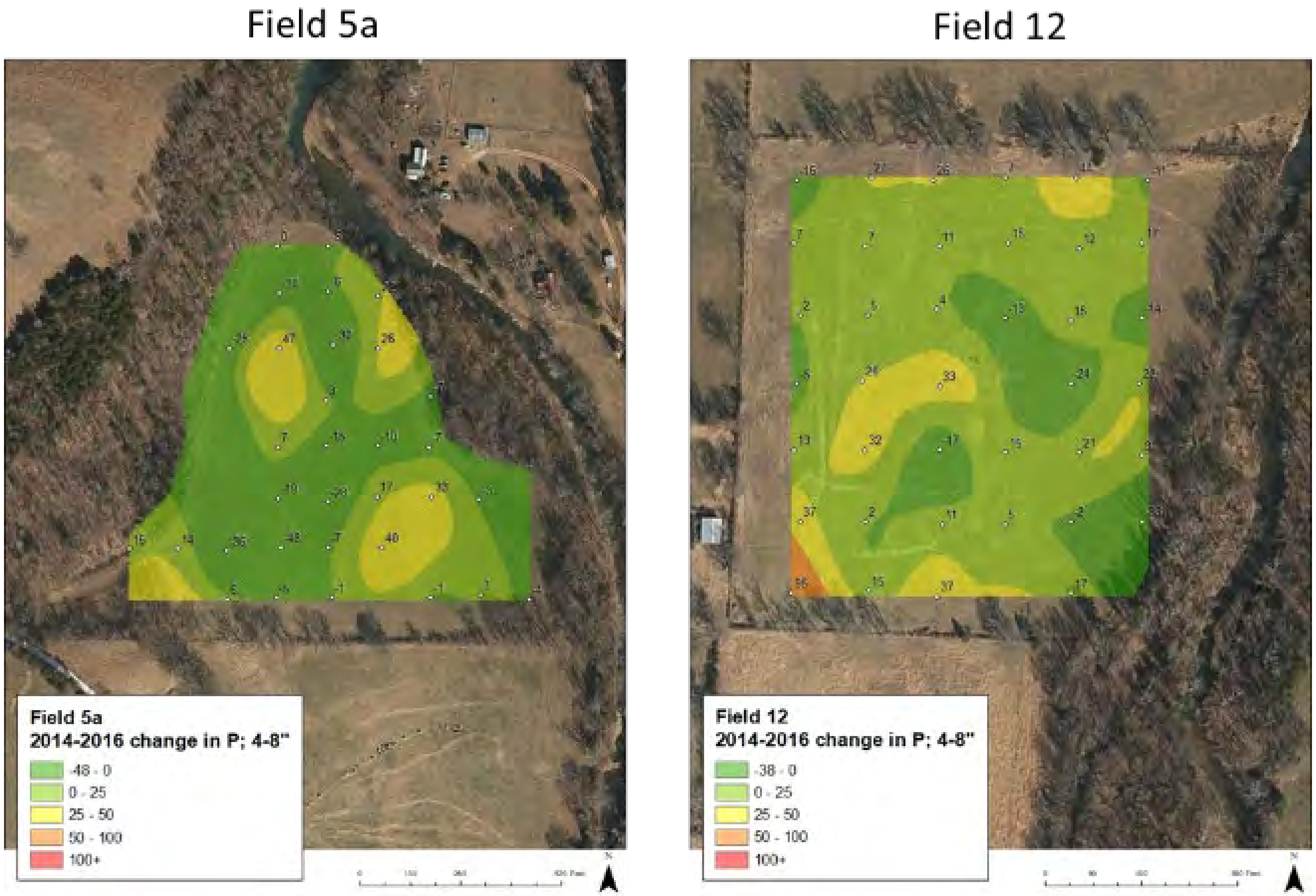


Figure 17. Difference in Mehlich-3 extractable soil P values between 2014 and 2016 grid-soil sampling of Fields 5a and 12.

Soil P sorption saturation

Soil P sorption saturation was calculated using Equation [2] and values given in Table 6 averaged on a whole field, slurry application zone, and buffer zone basis for Fields 1, 5a, and 12 for grid-soil sampling conducted in 2014, 2016, 2018. Differences among sampling dates are given in Table 7, with significantly different values (<0.05 level of probability) between years noted by different letters and bolded. Soil P sorption saturation values are also depicted on a grid-sampling basis in Figures 20 to 24 for Fields 1, 5a, and 12.

Table 6. Mean soil P sorption saturation and Mehlich-3 soil P for 0 to 4 inch grid-soil samples Fields 1, 5a, and 12 for 2014, 2016, and 2018 grid-soil sampling.

Field	Field position	Sampling depth	Mehlich-3 soil P			P sorption saturation		
			2014	2016	2018	2014	2016	2018
		inches	- - - - - mg/kg - - - - -			- - - - - - - % - - - - - - -		
Field 1	Whole field	0 to 4"	59	57	91	7.8	7.5	12.0
	Whole field	4 to 8"	20	27	--	2.3	3.1	--
	Application zone	0 to 4"	65	73	115	8.5	9.5	15.1
	Application zone	4 to 8"	20	35	--	2.3	4.0	--
	Buffer zone	0 to 4"	52	38	62	6.9	5.1	8.3
	Buffer zone	4 to 8"	19	17	--	2.3	1.9	--
Field 5a	Whole field	0 to 4"	45	39	47	4.4	3.7	4.6
	Whole field	4 to 8"	45	27	33	4.2	2.4	2.9
	Application zone	0 to 4"	50	42	45	4.9	3.8	4.3
	Application zone	4 to 8"	46	27	34	4.2	2.4	3.0
	Buffer zone	0 to 4"	33	34	51	3.3	3.6	5.0
	Buffer zone	4 to 8"	43	29	31	4.0	3.7	2.8
Field 12	Whole field	0 to 4"	63	104	122	6.0	9.2	11.0
	Whole field	4 to 8"	36	50	52	3.2	4.3	4.4
	Application zone	0 to 4"	56	107	126	5.3	9.5	11.3
	Application zone	4 to 8"	33	48	55	2.9	4.1	4.8

Field	Field position	Sampling depth	Mehlich-3 soil P			P sorption saturation		
			2014	2016	2018	2014	2016	2018
	Buffer zone	0 to 4"	90	95	112	8.4	8.3	10.0
	Buffer zone	4 to 8"	49	56	36	4.3	4.8	3.1

Soil P sorption saturation (PSS) reflects the degree to which potential P sorbing sites in a soil have P attached to them. As the degree (percent) of soil PSS increases, there are fewer sorption sites remaining. Soil PSS also provides an indication of the remaining potential of soil to adsorb and retain P that may be added in fertilizer, manure, or from grazing animals. The spatial distribution of PSS across fields and sampling dates is similar to that for Mehlich-3 P (Figures 20 to 24).

On a whole field basis, surface soil PSS (0 – 4 inch depth) increased from 7.8 to 12.0% for Field 1 and from 6.0 to 11% for Field 12 between 2014 and 2018 samplings (Table 6). A similar increase in PSS of the application zone of these Fields was observed (Table 12). These increases were significant at the <0.05 level of probability (Table 7). For Field 5a, PSS actually decreased between 2014 and 2018 samplings (Table 13). Increases in PSS were also apparent at the 4 – 8 inch soil depth in the slurry application zone Field 12, which translated to an increase in the whole field mean PSS (Table 7; at a <0.05 level of probability).

Table 7. Mean P sorption saturation (%) for Fields 1, 5a, and 12 for the 2014, 2016, and 2018 grid soil sampling at 0 – 4 inch and 4 – 8 inch depths (Field 1 is 0 – 4 inch sampled only). Parameters followed by the same letter for any given fields are not significantly different among 2014, 2016, and 2018 grid-soil samplings, as determined by paired *t* test with a <0.05 level of probability (bolded values are significantly greater).

	2014	2016	2016	2018	2014	2018
Field 1 (0-4 inch depth)						
Whole field	7.8 a	7.5 a	7.5 b	**12.0 a**	7.8 b	**12.0 a**
Application zone	8.5 a	9.5 a	9.5 b	**15.1 a**	8.5 b	**15.1 a**
Buffer zone	**6.9 a**	5.1 b	5.1 b	**8.3 a**	6.9 a	8.3 a
Field 5a (0-4 inch depth)						
Whole field	4.4 a	4.0 a	3.8 b	**4.6 a**	4.4 a	4.8 a
Application zone	4.8 a	4.0 a	4.0 a	4.3 a	4.9 a	4.5 a
Buffer zone	3.3 a	3.9 a	3.4 a	5.1 a	3.3 a	5.6 a

Field 5a (4-8 inch depth)								
Whole field	**4.2 a**	2.8 b		2.4 b	**2.9 a**		**4.2 a**	2.8 b
Application zone	**4.3 a**	2.8 b		2.4 b	**2.9 a**		4.4 a	3.2 a
Buffer zone	4.0 a	2.4 a		2.2 a	2.9 a		4.0 a	2.1 a
Field 12 (0-4 inch depth)								
Whole field	6.0 b	**9.1 a**		9.2 b	**11.0 a**		6.0 b	**11.0 a**
Application zone	5.3 b	**9.2 a**		9.5 b	**11.3 a**		5.3 b	**10.8 a**
Buffer zone	7.6 a	8.2 a		8.3 a	10.0 a		7.6 a	10.9 a
Field 12 (4-8 inch depth)								
Whole field	3.2 b	**4.1 a**		3.2 b	**4.4 a**		2.6 b	**4.5 a**
Application zone	2.9 b	**3.9 a**		3.3 b	**4.8 a**		2.5 b	**4.7 a**
Buffer zone	3.9 a	5.2 a		2.8 a	3.1 a		3.2 a	3.0 a

Further evaluation of PSS and Mehlich-3 P for soils from the three fields grid-sampled, shows a strong correlation between these two parameters describing soil P chemistry (Figure 18). The PSS – Mehlich-3 P relationship was similar for Fields 5a and 12, which had similar textures described as Razort and Spadra occasionally flooded loams, respectively (Figures 8 and 9). In contract, the PSS – Mehlich-3 P regression for Field 1 soils had a higher slope (0.137 compared to 0.097 and 0.091; Figure 18). The dominant soil type for Field 1 was the coarser Noark very cherty silt loam (Figure 7). The differing relationship between PSS and Mehlich-3 P among the three soils, reflects the added information on the dynamics of soil P availability provided by PSS compared to Mehlich-3 P. The greater regression slope for Noark than Razort and Spadra soils, reflects the lower clay content of the Noark soil than the other two soils, as clay-sized particles are the single most active and thus, dominant factor determining P sorption by soil. Although there are only three soil types in this comparison, there was a close relationship between soil clay content and the slope of the PSS – Mehlich-3 P regression shown in Figure 19.

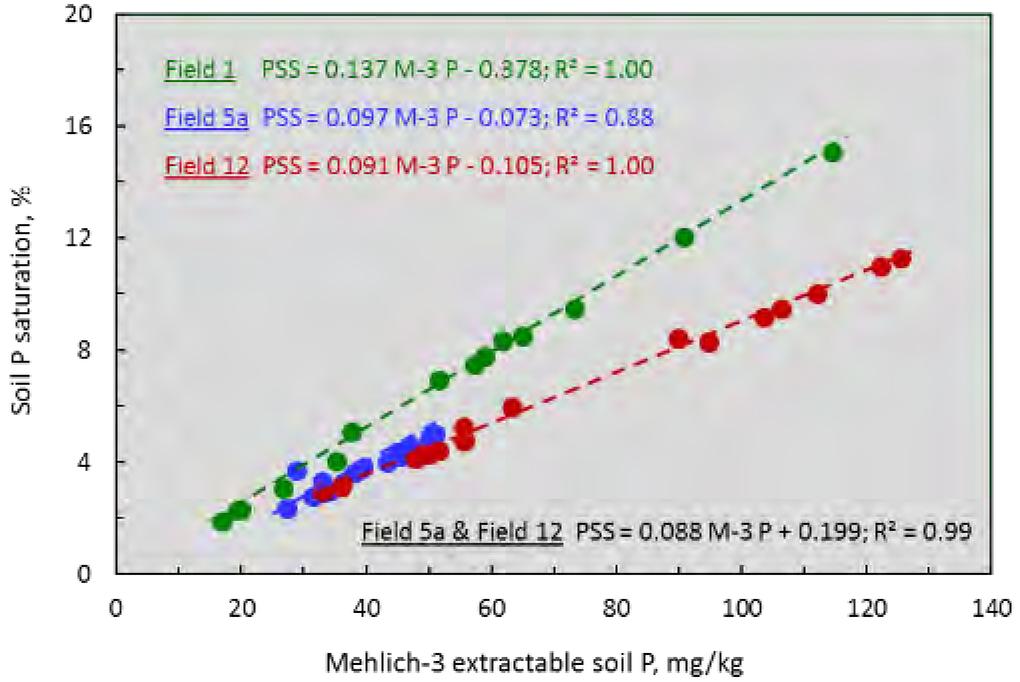


Figure 18. Relationship between Mehlich-3 extractable soil P and soil P sorption saturation for 0 to 4 and 4 to 8 inch sample depths; Fields 1, 5a, and 12; and 2014, 2016, and 2018 samplings.

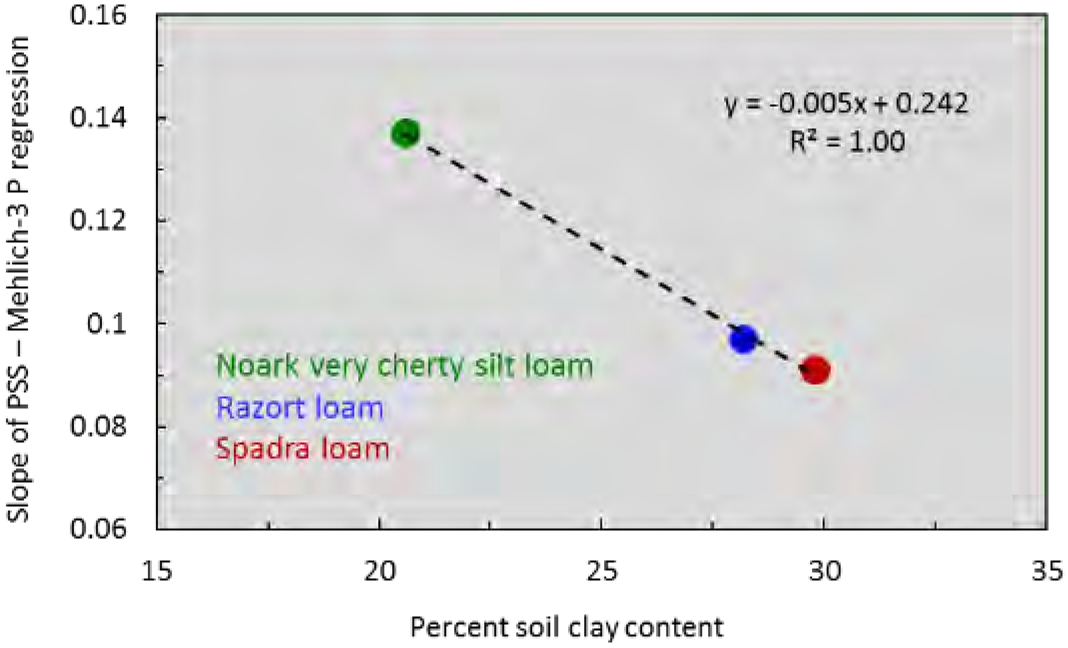


Figure 19. Relationship between the slope of the linear regression between soil P sorption saturation (PSS) and percent clay content of Noark (Field 1), Razort (Field 5a), and Spadra soils (Field 12).

Because of the Mehlich-3 P, PSS, and clay relationships; PSS reflects an estimate of soil P availability (i.e., Mehlich-3 P), as well as the capacity of that soil to bind further additions of P in fertilizer or manure. For example, assuming a Mehlich-3 P concentration of 100 mg/kg for all three fields using the regressions between PSS and Mehlich-3 P of Figure 18, a Noark soil would have a PSS value of 13.6% and the Razort and Spadra soils a value of 9.9 and 8.9%, respectively.

The capacity of the Noark soil of Field 1 to bind additional P is less than that for the Razort and Spadra soils of Field 5a and 12. Thus, the Mehlich-3 P concentration of Noark soil is likely to increase more quickly than that for Razort or Spadra soils, if the same amount of P was added to each soil. Hence PSS can provide additional information relevant to P management and fertility status of a soil.

Using the same method to estimate PSS as in the project (i.e., Equation 2), Pote at al. (1996) found PSS to range from 16 to 80% for a Captina silt loam in Arkansas. Using simulated rainfall and 54 small runoff plots (1.5 wide by 6 m long) under fescue, Pote et al. (1996) observed that PSS (r^2 of 0.77) was more closely related than Mehlich-3 P (r^2 of 0.72) to the concentration of dissolved P in runoff. Using a different method to estimate PSS (molar P, Fe and Al not used), Vadas et al. (2005) also showed PSS was more closely related to the concentration of dissolved P I runoff (r^2 of 0.83) than Mehish-3 or Bray-1 extractable soil P (r^2 of 0.77) for 31 soils ranging in clay content (6 to 24%) and PSS (1 to 82%). However, the limited in-field use of PSS to date and a variety of methods used to estimate PSS, there is limited information relating PSS to edge-of-field P runoff or the establishment of baseline values to enable valid quantitative comparisons at the present time.

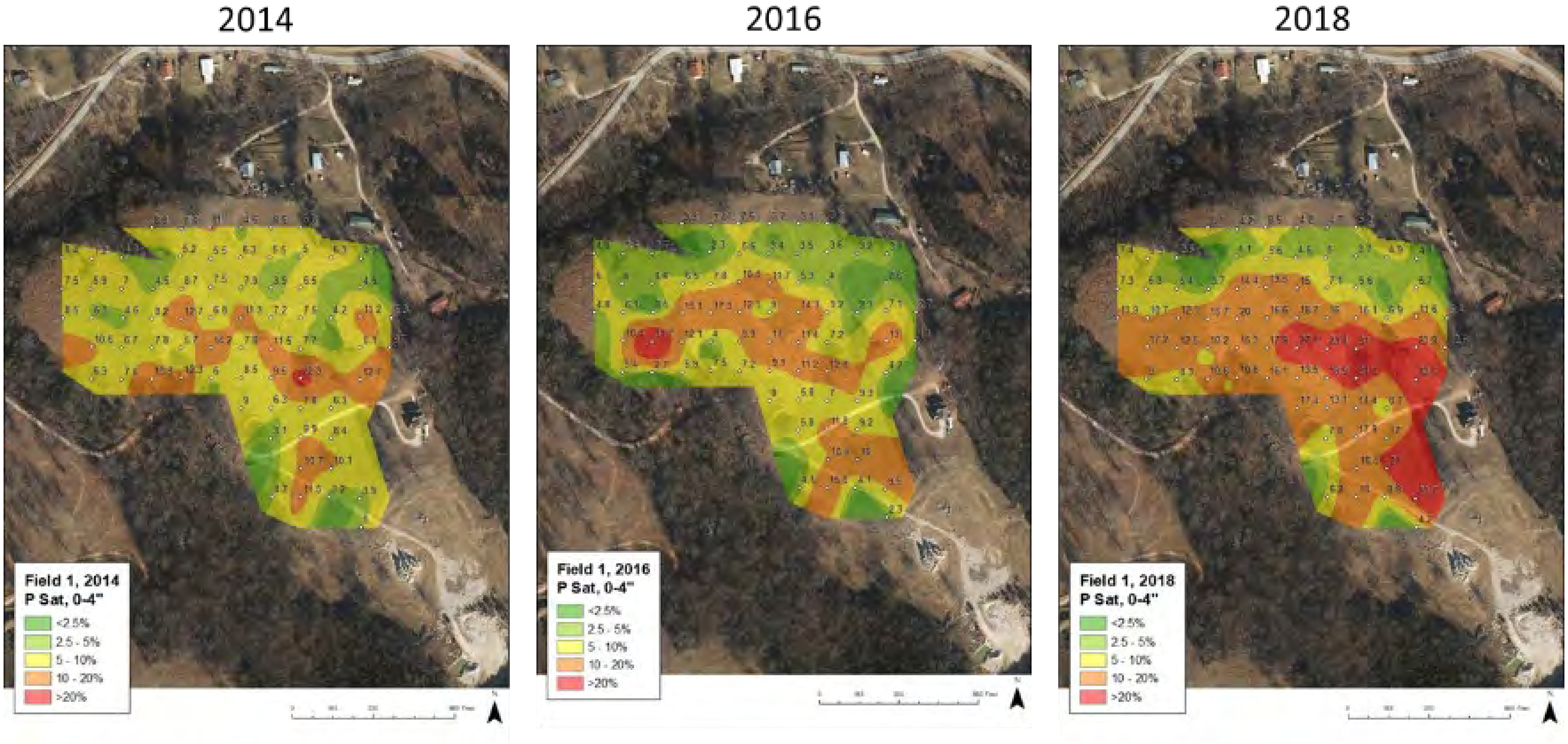
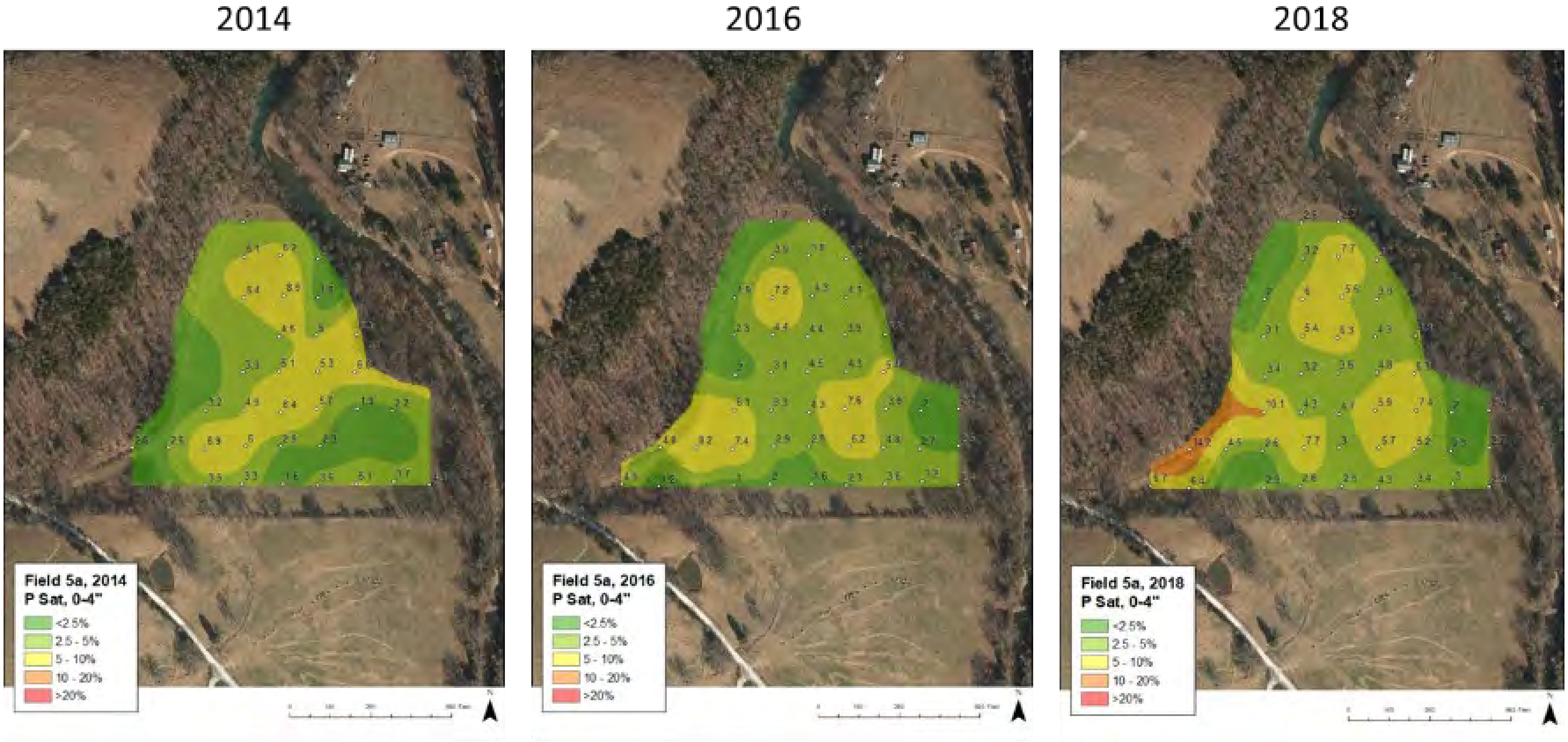


Figure 20. Soil P sorption saturation values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 1.


2014

2016

2018

Figure 21. Soil P sorption saturation values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 5a.

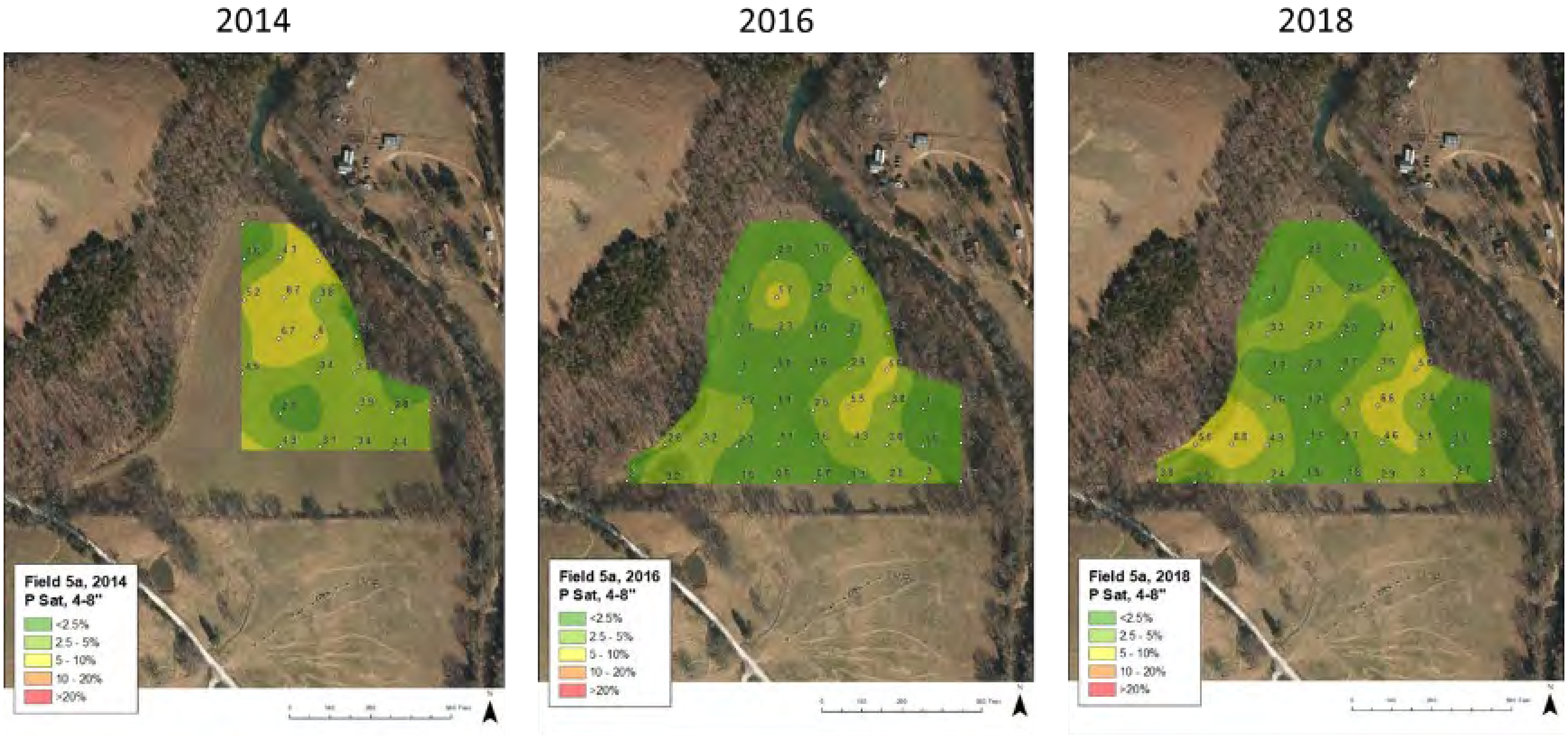


Figure 22. Soil P sorption saturation values for 4 to 8 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 5a.

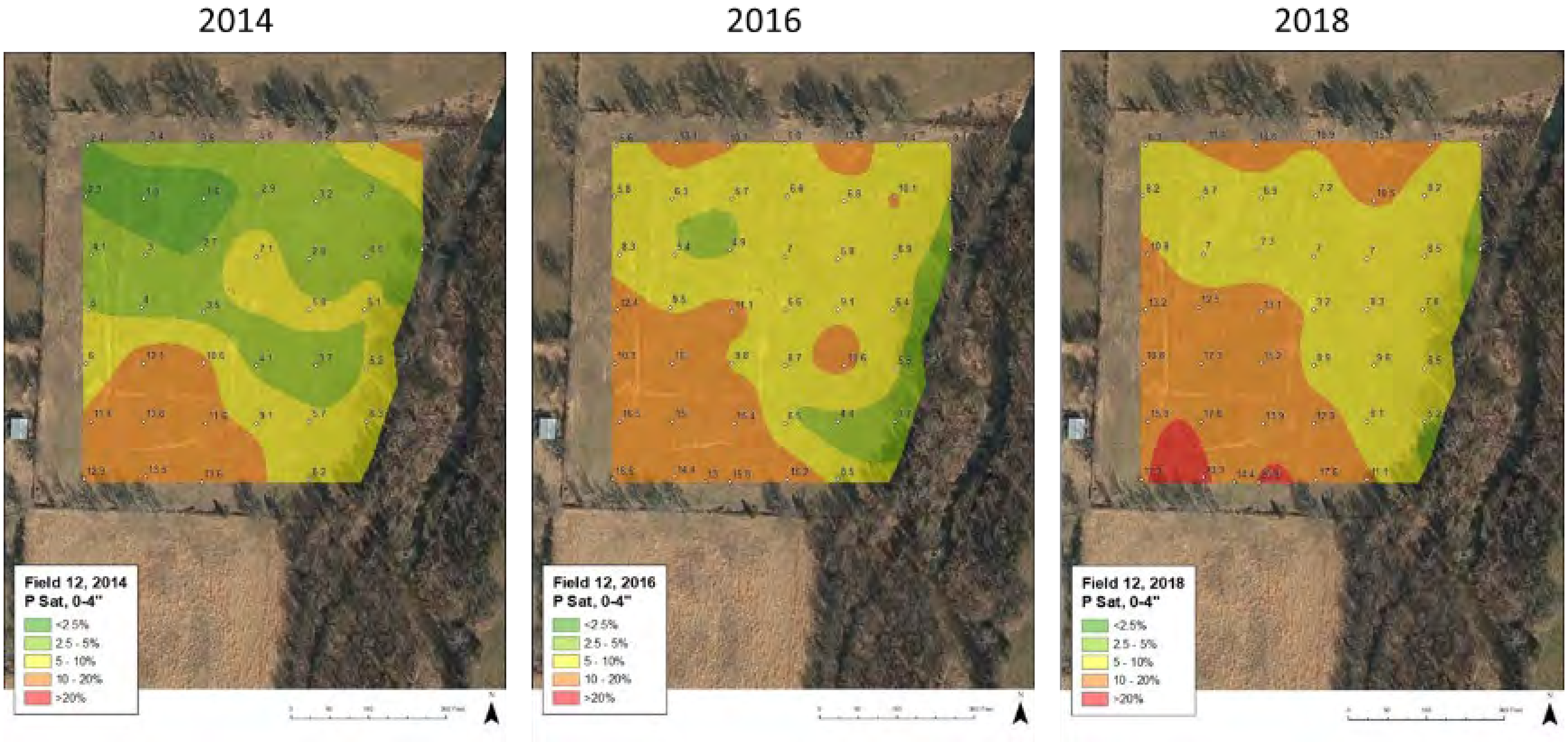
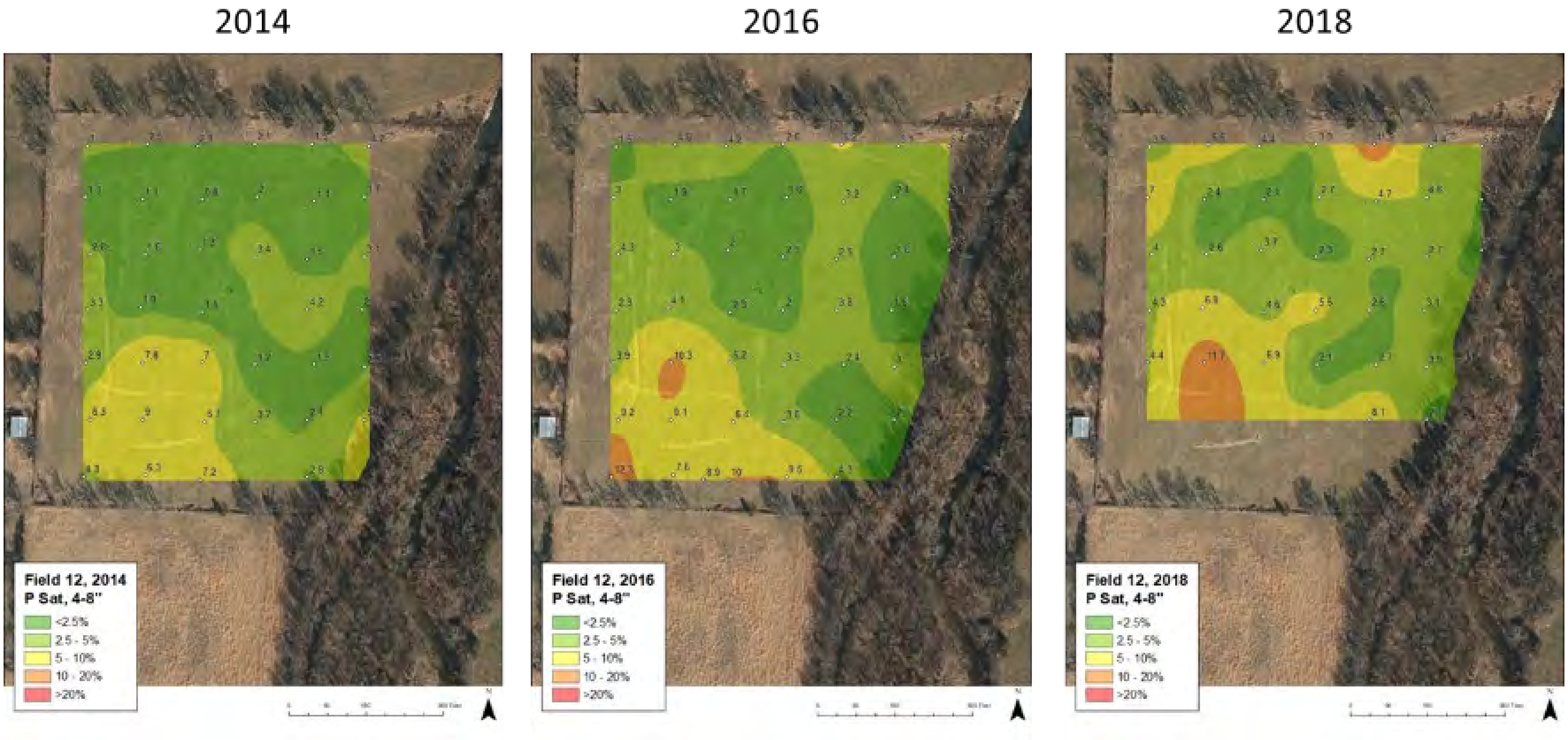


Figure 23. Soil P sorption saturation values for 0 to 4 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 12.


2014

2016

2018

Figure 24. Soil P sorption saturation values for 4 to 8 inch depth for 2014, 2016, and 2018 grid-soil sampling of Field 12.

References

Breeuwsma, A., and O.F. Schoumans. 1987. Forecasting phosphate leaching on a regional scale. p. 973-981. *In:* W. van Duijvenboode and H.G. van Waegeningh, Editors. Proceedings of the Int. Conf. on Vulnerability of soil and groundwater to pollutants on March 30 to April 3, 1987 at Noordwijk aan Zee. The Hague: TNO Committee on Hydrological Research, The Hague, Proceedings and Information No. 38.

Breeuwsma, A., J.G.A. Reijerink, and O.F. Schoumans. 1995. Impact of manure on accumulation and leaching of phosphate in areas of intensive livestock farming. p. 239–249. *In*: K. Steele, Editor. Animal Waste and the Land-Water Interface. Lewis Publication, NY.

Dari, B., V.D. Nair, A.N. Sharpley, P.J.A. Kleinman, D. Franklin, and W.G. Harris. 2018. Consistency of the threshold phosphorus saturation ratio across a wide geographic range of acid soils. Agrosyst. Geosci. Environ. 1:180028. Available at https://dl.sciencesocieties.org/publications/age/articles/1/1/180028.

Huluka, G., and R. Miller. 2014 Particle Size determination by hydrometer method. Chapter 6.3. p. 180-184. *In*: F.J. Sikora an K.P. Moore, Editors. Soil Test Methods from the Southeastern United States. Southern Cooperative Series Bulletin No. 419. Southern Extension and Research Activity Information Exchange Group - 6 (SERA-IEG-6). Available at http://aesl.ces.uga.edu/sera6/MethodsManualFinalSERA6.asp.

Kleinman, P.J.A., and A.N. Sharpley. 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data. Commun. Soil Sci. Plant Anal. 33:1825-1839.

Loeppert, R.H., and W.P. Inskeep. 1996. Iron. P. 639-664. *In:* D.L. Sparks, Editor. Methods of Soil Analysis. Part 3. Chemical Methods, Soil Science Society of America Book Series No. 5 Soil Science Society of America, Madison, WI.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, D.R. Edwards, D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

Schoumans, O.F. 2009. Determination of the degree of phosphate saturation in noncalcareous soils. *In*: J.L. Kovar and G.M. Pierzynski, Editors, Methods for phosphorus analysis for soils, sediments, residuals, and water. 2nd ed. SERA 17 Bull. 408. Virginia Tech, Blacksburg, VA. p. 29– 32.

Sibbesen, E. and A.N. Sharpley. 1997. Setting and justifying upper critical limits for phosphorus in soils. p. 151-176. *In:* H. Tunney, O. T. Carton, P. C. Brookes, and A. E.Johnston, Editors. Phosphorus loss from soil to water. CAB International Press, Cambridge, England.

Syers, J.K., M.G. Browman, G.W. Smillie, R.B. Corey. 1973. Phosphate sorption by soils evaluate by the Langmuir adsorption equation. Soil Sci. Soc. Am. Proc. 37:358-363.

Vadas, P.A., P.J.A. Kleinman, A.N. Sharpley, and B.L. Turner. 2005. Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. J. Environ. Qual. 34:572-580.

Supplemental Tables

Table S 1. Mean nutrient content of Field 1 for the 2014, 2016, and 2018 grid soil sampling at 0 – 4 inch and 4 – 8 inch depths. Parameters followed by the same letter for any given fields are not significantly different between 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	Field 1 (0-4 inch depth)					
	2014	2016	2016	2018	2014	2018
P	58.9 a	57.1 a	57.1 b	**90.7 a**	58.9 b	**90.7 a**
K	203.8 a	182.7 a	182.7 b	**258.1 a**	203.8 b	**258.1 a**
Ca	1936.3 a	1844.7 a	1844.7 a	1909.2 a	1936.3 a	1909.2 a
Mg	112.6 a	109.8 a	109.8 b	**142.5 a**	112.6 b	**142.5 a**
S	18.3 a	15.4 b	15.4 b	**19.0 a**	18.3 a	19.0 a
Fe	109.0 b	**118.0 a**	**118.0 a**	106.3 b	109.0 a	106.3 a
Mn	**261.7 a**	209.4 b	209.4 a	213.2 a	**261.7 a**	213.2 b
Cu	0.6 b	**1.4 a**	1.4 a	1.3 a	0.6 b	**1.3 a**
Zn	4.3 a	5.1 a	5.1 b	**7.1 a**	4.3 b	**7.1 a**
B	0.4 b	**0.5 a**	**0.5 a**	0.4 b	0.4 a	0.4 a

Nutrient	Field 1 (4-8 inch depth)	
	2014	2016
P	19.7 b	**26.7 a**
K	76.7 b	**120.9 a**
Ca	1234.3 b	**1758.8 a**
Mg	**74.7 a**	72.1 b
S	10.3 a	10.4 a
Fe	**101.7 a**	96.2 b
Mn	**287.7 a**	196.1 b
Cu	0.5 a	1.1 a
Zn	2.2 b	**2.7 a**
B	0.2 b	**0.4 a**

Table S 2. Mean nutrient content of Field 5a for the 2014, 2016, and 2018 grid soil sampling at 0 – 4 inch and 4 – 8 inch depths. Parameters followed by the same letter for any given fields are not significantly different between 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	Field 5a (0-4 inch depth)					
	2014	**2016**	**2016**	**2018**	**2014**	**2018**
P	45.0 a	39.0 a	39.0 a	47.1 a	45.0 a	47.1 a
K	59.4 a	68.5 a	**68.5 a**	63.0 b	**59.4 a**	63.0 b
Ca	1314.7 a	1258.3 a	1258.3 a	1341.3 a	1314.7 a	1341.3 a
Mg	70.6 a	72.9 a	72.9 a	72.2 a	70.6 a	72.2 a
S	12.8 a	13.3 a	13.3 b	**13.2 a**	12.8 a	13.2 a
Fe	153.7 a	148.2 a	**148.2 a**	127.6 b	**153.7 a**	127.6 b
Mn	**205.3 a**	170.7 b	**170.7 a**	166.3 b	205.3 a	166.3 a
Cu	1.4 a	1.5 a	1.5 a	2.1 a	1.4 a	2.1 a
Zn	3.0 a	2.8 a	2.8 a	3.4 a	3.0 a	3.4 a
B	0.3 a	0.4 a	**0.4 a**	0.3 b	0.3 a	0.3 a

Nutrient	Field 5a (4-8 inch depth)					
	2014	**2016**	**2016**	**2018**	**2014**	**2018**
P	**37.7 a**	27.3 b	27.3 b	**33.2 a**	37.7 a	33.2 a
K	**98.5 a**	58.5 b	58.5 b	**55.7 a**	98.5 a	55.7 a
Ca	**2256.3 a**	1182.8 b	1182.8 b	**1210.3 a**	2256.3 a	1210.3 a
Mg	**80.4 a**	47.5 b	47.5 a	43.5 a	**80.4 a**	43.5 b
S	8.3 a	9.9 a	9.9 a	12.4 a	8.3 a	12.4 a
Fe	107.8 b	**136.2 a**	136.2 a	134.0 a	107.8 b	**134.0 a**
Mn	105.0 b	**157.4 a**	157.4 a	170.9 a	105.0 b	**170.9 a**
Cu	1.8 a	1.6 a	1.6 a	1.5 a	1.8 a	1.5 a
Zn	**4.9 a**	2.0 b	2.0 a	1.9 a	4.9 a	1.9 a
B	0.2 b	**0.3 a**	0.3 a	0.6 a	0.2 b	0.6 a

Table S 3. Mean nutrient content of Field 12 for the 2014, 2016, and 2018 grid soil sampling at 0 – 4 inch and 4 – 8 inch depths. Parameters followed by the same letter for any given fields are not significantly different between 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	Field 12 (0-4 inch depth)					
	2014	**2016**	**2016**	**2018**	**2014**	**2018**
P	63.3 b	**103.6 a**	103.6 a	122.2 a	63.3 b	**122.2 a**
K	91.6 b	**128.5 a**	128.5 a	155.3 a	91.6 b	**155.3 a**
Ca	1183.9 a	1300.8 a	1300.8 a	1204.9 a	1183.9 a	1204.9 a
Mg	77.4 b	**118.5 a**	118.5 a	125.5 a	77.4 b	**125.5 a**
S	13.4 b	**16.1 a**	**16.1 a**	13.6 b	13.4 a	13.6 a
Fe	126.7 b	**182.4 a**	**182.4 a**	153.6 b	126.7 a	153.6 a
Mn	147.7 b	**176.6 a**	**176.6 a**	164.3 b	147.7 a	164.3 a
Cu	1.2 b	**1.7 a**	1.7 a	1.9 a	1.2 b	**1.9 a**
Zn	2.2 b	**4.9 a**	4.9 a	6.1 a	2.2 b	**6.1 a**
B	0.2 b	**0.5 a**	**0.5 a**	0.4 b	0.2 a	0.4 a

Nutrient	Field 12 (4-8 inch depth)					
	2014	**2016**	**2016**	**2018**	**2014**	**2018**
P	36.2 b	**49.7 a**	49.7 a	51.5 a	36.2 b	**51.5 a**
K	68.3 a	80.7 a	80.7 a	71.8 a	68.3 a	71.8 a
Ca	1235.5 a	1332.3 a	**1332.3 a**	1295.9 b	**1235.5 a**	1295.9 b
Mg	54.4 b	**71.8 a**	71.8 a	73.6 a	54.4 b	**73.6 a**
S	11.0 a	11.8 a	**11.8 a**	10.5 b	**11.0 a**	10.5 b
Fe	103.7 b	**133.1 a**	133.1 a	134.1 a	103.7 b	**134.1 a**
Mn	96.8 b	**128.0 a**	128.0 a	123.4 a	96.8 b	**123.4 a**
Cu	1.2 b	**1.7 a**	**1.7 a**	1.6 b	1.2 a	1.6 a
Zn	1.4 b	**2.0 a**	2.0 a	2.5 a	1.4 b	**2.5 a**
B	0.1 b	**0.4 a**	0.4 a	0.6 a	0.1 b	**0.6 a**

Table S 4. Differences in mean nutrient content of whole Fields 1, 5a, and 12 among the 2014, 2016, and 2018 grid soil sampling. Parameters followed by the same letter for any given fields are not significantly different among 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	Whole field differences		
	2014-2016	2016-2018	2014-2018
Field 1			
P	-1.8 b	**33.6 a**	**31.2 a**
K	-21.0 a	75.3 a	54.3 a
Ca	-91.6 a	64.5 a	-27.0 a
Mg	-2.8 b	32.7 a	29.9 a
S	-2.9 b	**3.6 a**	0.7 b
Fe	**9.0 a**	-11.7 b	**-2.7 a**
Mn	-52.3 b	**3.9 a**	-48.5 b
Cu	**0.8 a**	-0.2 b	**0.7 a**
Zn	0.8 a	2.0 a	2.8 a
B	**0.07 a**	-0.07 b	**0.01 a**
Field 5a			
P	-2.2 a	7.3 a	5.1 a
K	10.6 a	-4.0 a	6.6 a
Ca	-151.9 a	74.9 a	-77.0 a
Mg	4.2 a	0.9 a	5.2 a
S	**12.3 a**	**9.7 a**	0.4 b
Fe	0.6 a	-0.2 a	-23.3 a
Mn	-2.9 a	-20.3 a	-18.6 a
Cu	-17.6 a	-7.2 a	0.9 a
Zn	0.2 b	**0.7 a**	**0.5 a**
B	-0.1 a	0.6 a	-0.02 a
Field 12			
P	**39.7 a**	18.7 b	**59.8 a**

Nutrient	**Whole field differences**		
	2014-2016	2016-2018	2014-2018
K	33.7 a	16.6 a	50.3 a
Ca	**139.5 a**	-112.6 b	**26.9 a**
Mg	**42.6 a**	7.4 b	**49.9 a**
S	11.5 b	**23.6 a**	**0.2 a**
Fe	2.9 a	-2.7 b	26.5 a
Mn	**53.8 a**	-27.3 b	**14.2 a**
Cu	**26.2 a**	-12.0 b	**0.7 a**
Zn	**0.6 a**	0.2 b	**3.9 a**

Table S 5. Differences in mean nutrient content of slurry application zones for Fields 1, 5a, and 12 among the 2014, 2016, and 2018 grid soil sampling. Parameters followed by the same letter for any given fields are not significantly different among 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	**Slurry application zone differences**		
	2014-2016	2016-2018	2014-2018
Field 1			
P	8.3 b	**41.4 a**	**49.7 a**
K	-37.7 b	**89.6 a**	**51.9 a**
Ca	59.8 a	99.2 a	159.0 a
Mg	7.4 b	**38.5 a**	**45.9 a**
S	-4.8 b	**7.3 a**	2.4 b
Fe	9.2 a	-6.8 a	2.3 a
Mn	-43.1 b	**-0.5 a**	-43.6 b
Cu	**1.1 a**	-0.5 b	**0.6 a**
Zn	1.8 a	2.3 a	4.1 a
B	**0.1 a**	-0.02 b	**0.04 a**

Nutrient	Slurry application zone differences		
	2014-2016	2016-2018	2014-2018
Field 5a			
P	-7.1 a	3.0 a	-4.1 a
K	**12.6 a**	-6.2 b	**6.4 a**
Ca	94.7 a	19.5 a	114.2 a
Mg	9.9 a	-2.6 a	7.3 a
S	**12.3 a**	9.7 b	**-1.1 a**
Fe	-0.2 a	-1.0 a	-30.7 a
Mn	**-6.9 a**	**-23.9 a**	-53.5 b
Cu	-44.9 b	**-8.6 a**	**1.0 a**
Zn	0.3 a	0.7 a	0.8 a
B	0.2 a	0.6 a	0.01 a
Field 12			
P	**46.3 a**	18.2 b	**64.5 a**
K	49.9 a	20.2 a	70.1 a
Ca	**189.9 a**	-139.5 b	**50.4 a**
Mg	**52.0 a**	6.9 b	**58.8 a**
S	11.5 b	**23.6 a**	1.0 a
Fe	**4.2 a**	-3.1 b	**26.3 a**
Mn	**54.2 a**	-28.0 b	**18.2 a**
Cu	**25.2 a**	-7.0 b	**0.8 a**
Zn	**0.6 a**	0.2 b	**4.2 a**

Table S 6. Differences in mean nutrient content of buffer zones for Fields 1, 5a, and 12 among the 2014, 2016, and 2018 grid soil sampling. Parameters followed by the same letter for any given fields are not significantly different among 2014, 2016, and 2018 grid-soil samplings, as determined by paired t test with a <0.05 level of probability (bolded values are greater).

Nutrient	Buffer zone differences		
	2014-2016	2016-2018	2014-2018
Field 1			
P	-14.1 b	**24.1 a**	10.1 b
K	-0.7 b	**57.9 a**	**57.3 a**
Ca	-276.0 b	**22.3 a**	**-253.8 a**
Mg	-15.3 b	**25.8 a**	10.4 b
S	-2.7 b	**1.3 a**	-1.8 b
Fe	**8.7 a**	-17.6 b	**-8.9 a**
Mn	-63.7 b	**9.3 a**	-54.4 b
Cu	**0.5 a**	0.2 b	**0.7 a**
Zn	-0.5 b	**1.7 a**	**1.2 a**
B	**0.07 a**	-0.10 b	**-0.03 a**
Field 5a			
P	6.4 a	17.5 a	23.9 a
K	5.7 a	-2.7 a	3.0 a
Ca	-697.9 b	**171.3 a**	**-526.6 a**
Mg	-13.9 a	13.1 a	-0.8 a
S	1.6 a	1.6 a	3.2 a
Fe	4.1 a	-13.9 a	-9.8 a
Mn	4.4 a	-4.8 a	-0.4 a
Cu	0.1 a	0.6 a	0.7 a
Zn	-1.2 b	**0.8 a**	**-0.4 a**
B	-0.04 a	-0.08 a	-0.12 a
Field 12			
P	13.6 a	27.4 a	41.0 a

Nutrient	Buffer zone differences		
	2014-2016	2016-2018	2014-2018
K	-6.4 a	14.4 a	8.0 a
Ca	85.3 a	-38.7 a	46.6 a
Mg	16.3 a	9.6 a	25.9 a
S	-0.4 a	-1.4 a	-1.9 a
Fe	54.9 a	-27.3 a	27.6 a
Mn	24.6 a	-20.0 a	4.6 a
Cu	0.5 a	0.09 a	0.6 a
Zn	1.2 a	1.2 a	2.4 a

SURFACE RUNOFF FROM APPLICATION FIELDS AND RELATIONSHIP TO FIELD MANAGEMENT

Contents

Summary

1. Nutrient loss in surface runoff from Fields 1, 5a, and 12 are dominated by higher rainfall in 2015, than in other years of monitoring leading to large runoff volumes.
2. The annual loss of P and N in surface runoff from Field 1 for the five years of monitoring, averaged 0.8 and 1.8%, respectively, of that applied in slurry; for Field 12 losses were 2.2% P and 4.5% N. For Field 5a, loss of P and N was an average 6.6 and 4.4%, respectively, of that applied each year in mineral fertilizer.
3. The greater nutrient runoff from Fields 5a and 12 and proportion of that applied in slurry or mineral fertilizer was dominated by major storm events in 2015, which resulted in more than twice the volume of runoff in 2015 (5.4 and 0.9 million gallons) than the other four years combined (1.3 and 0.4 million gallons). Additionally, Fields 5a and 12 are adjacent to Big Creek, which breached its banks and flooded these fields in May and December 2015.

List of Tables

List of Figures

Supplemental Tables

Field Site Description

Surface runoff from Fields 1, 5a, and 12 has been collected after storm rainfall-induced runoff events. The catchment area for each flume located on Fields 1, 5a, and 12 is depicted in Figures 1, 2, and 3, respectively. The catchment area is that field area which contributes runoff water to our monitoring site. Due to natural slope and elevation changes in all fields, the flumes do not collect runoff water from the entire field. The catchment areas selected for instrumentation were the largest natural drainage areas with a surface discharge off the fields. Also depicted on Figures 1, 2, and 3, are buffers imposed by the C&H ADEQ permit for ponds, school, slope, and stream, where no slurry can be applied to Fields 1, 5a, and 12, respectively. On field 12, the farm owners have implemented a 100 ft buffer along the south neighboring field.

The field area, flume catchment area, and area to which slurry can be applied to Fields 1, 5a, and 12 is given in Table 1. Annual amounts and rates of commercial fertilizer (Field 5a) and slurry from the C&H operation (Fields 1 and 12) are given in Table 2. The slurry rates are obtained from ADEQ annual management reports for the farm and commercial fertilizer application from the landowner.

Surface Runoff of Nutrients and Sediment

All surface runoff samples are collected by ISCO autosamplers programed to initiate sample collection when a critical stage height is exceeded (Table 3). Pacing of sample collection is subsequently programmed to a specific volume of flow, as detailed in Table 3. This standard operating procedure for ISCO autosamplers results in the collection of one flow-weighted sample, which is subsequently analyzed. The flow-weighted event concentration of nutrients and sediment in surface runoff from each Field are detailed in Supplemental Table S1, along with runoff volume.

Based on flow-weighted concentration and total flow volume for each surface runoff event, the amount of nutrients and sediment based on flume catchment area are determined and presented in Table S2 in English units (i.e., lbs/acre) and in Table S3 in metric units (i.e., g/ha). There was no surface runoff measured at the flume for Field 12 in 2014 or 2018.

The annual flow and mean annual flow-weighted concentrations of P, N, and sediment in runoff for 2014 through 2018 are given in Table 4. The annual loss of P, N, and sediment in surface runoff from Fields 1, 5a, and 12 for 2014 through 2018 is given Table 5 in English and metric units.

Finally, the amount of P and N applied to the flume catchment area of Fields 1, 5a, and 12, loss in runoff, and percent of applied lost in runoff for 2014 through 2018 are given in Table 6. Losses are dominated by higher rainfall in 2015 than the other years of monitoring, which led to large runoff volumes (Table 6).

Mean annual nutrient loss was 0.78 lbs total P and 1.82 lbs total N/acre for BC1; 1.65 lbs total P and 2.49 lbs total N/acre for BC5a; and 1.67 lbs total P and 4.04 lbs total N/acre for BC12 (Table 7). These losses were similar to P losses reported elsewhere. For example, pastures in northwest Arkansas, also in the karst region of the Boston Mountains / Ozark Highlands, receiving poultry litter (1.5 – 2.0 tons/acre) had losses ranging from 0.94 – 1.45 lbs P/ acre (Table 7).

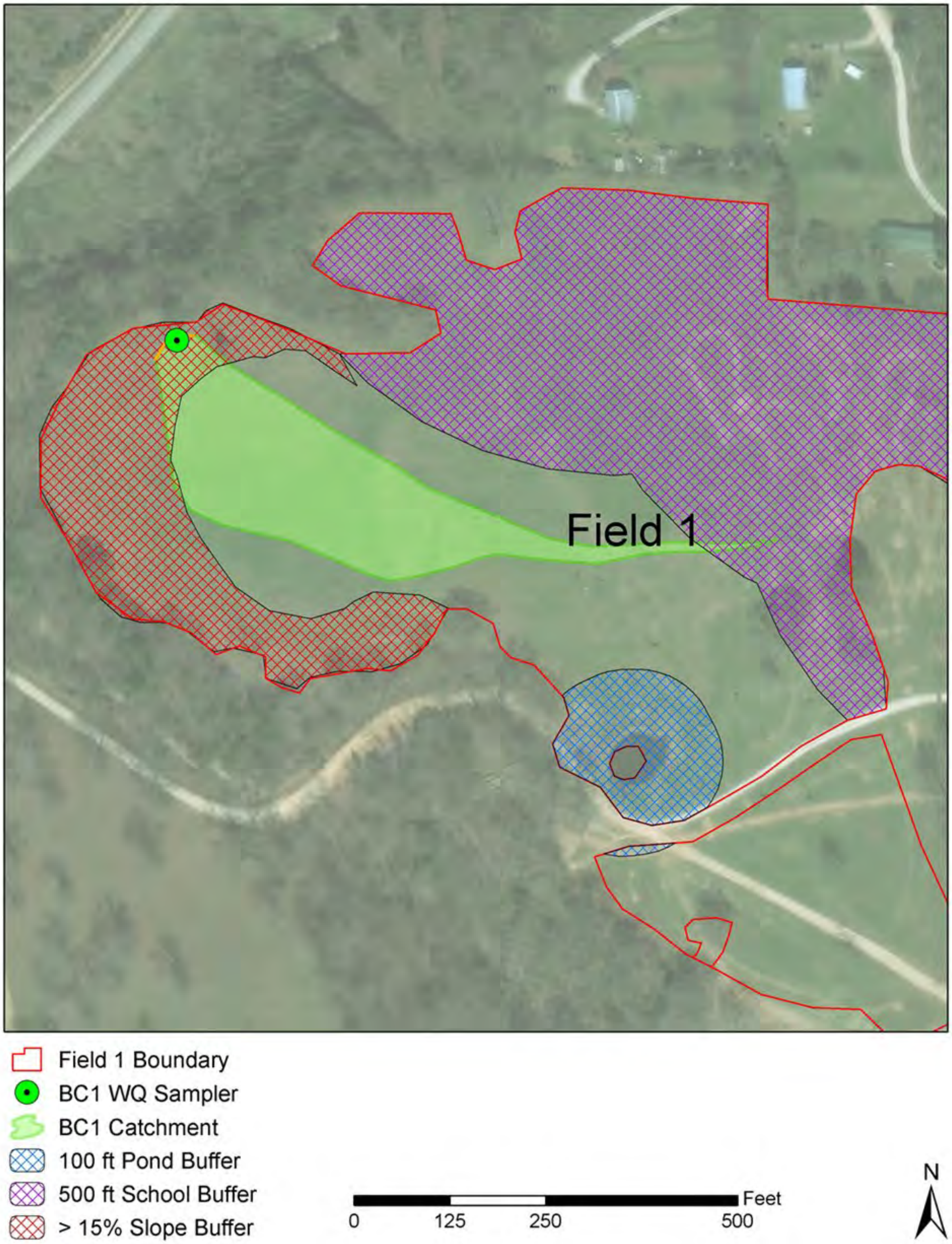


Figure 1. Map of Field 1 showing catchment area for surface runoff flume and buffers where no slurry can be applied.

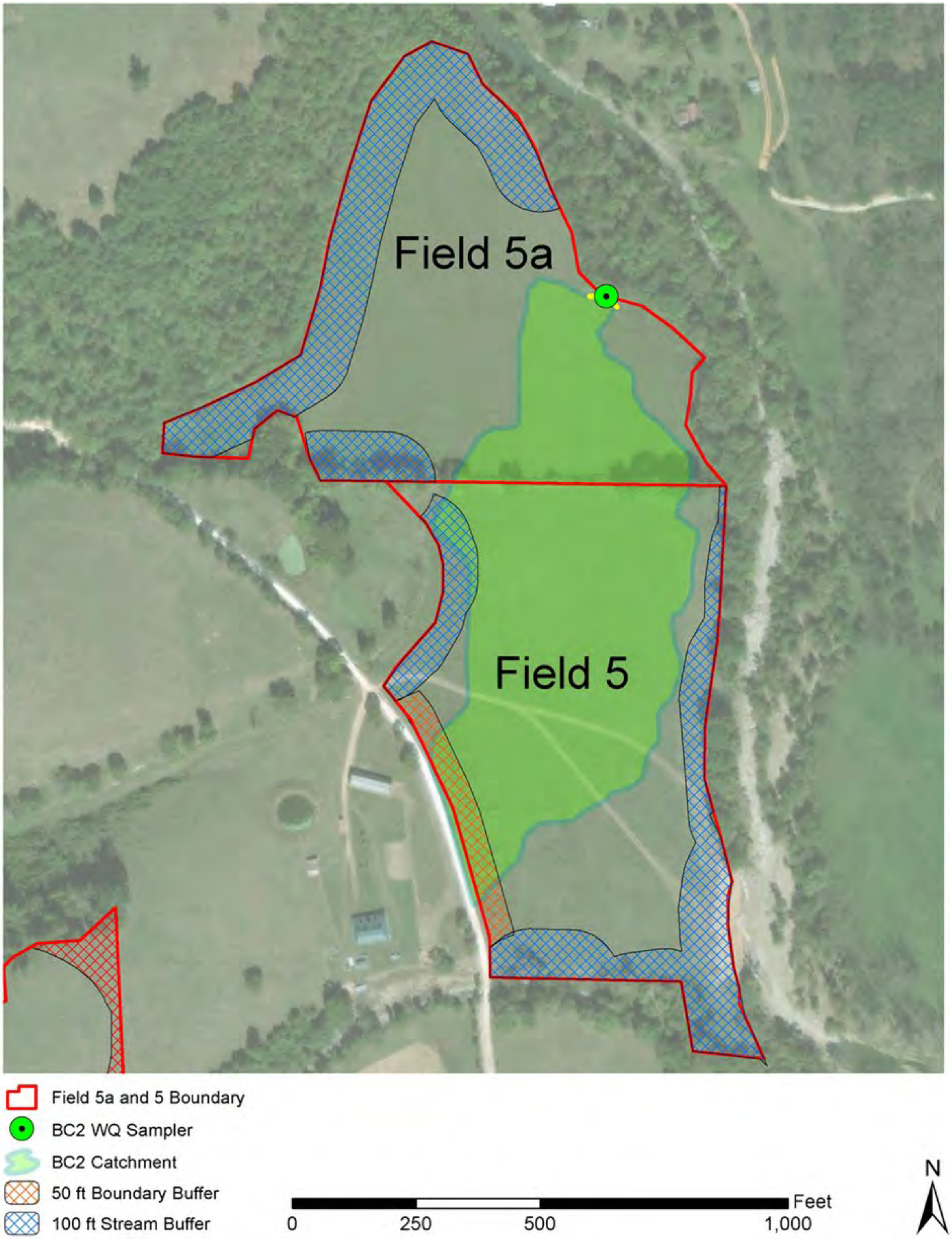


Figure 2. Map of Field 5a showing catchment area for surface runoff flume and buffers where no slurry can be applied.

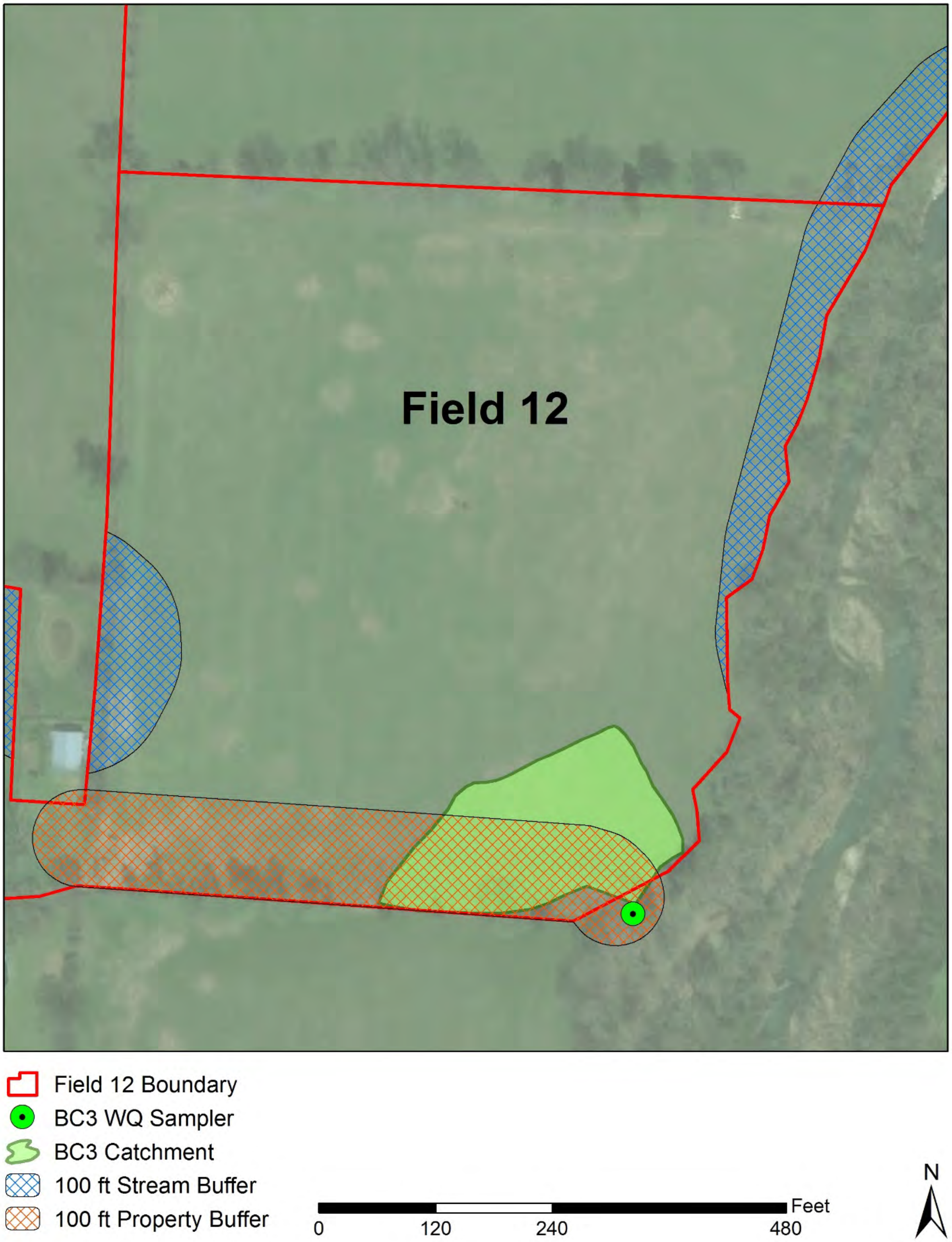


Figure 3. Map of Field 12 showing catchment area for surface runoff flume and buffers where no slurry can be applied.

Table 1. Area of Field 1, 5a, and 12 monitored for surface runoff, area of flume catchment, area of buffers where no slurry is applied, and area of flume receiving slurry.

Site	Site ID	Field area		Flume catchment area		Buffer		Flume catchment area minus buffer		Flume catchment receiving slurry	Area of flume catchment in designated field	
		acres	hectares	acres	hectares	acres	hectares	acres	hectares	%	acres	hectares
Field 1	BC 1	15.6	6.31	1.76	0.71	0.15	0.06	1.61	0.65	91.4	1.76	0.71
Field 5a	BC 2	23.5	9.51	9.58	3.88	0.54	0.22	9.04	3.66	0[1]	2.21	0.89
Field 12	BC 3	28.7	11.61	0.84	0.34	0.48	0.19	0.36	0.15	43	0.84	0.34

[1] Slurry has not been applied to Field 5a or the adjacent Field 5.

Table 2. Slurry (i.e., Fields 1 and 12) and fertilizer (i.e., Fields 5a) application to the monitored fields for 2014 to 2018.

Site	2014		2015		2016		2017		2018	
Slurry applied, gals										
Field 1	46,000		12,000		78,000		60,000		57,000	
Field 12	48,000		93,000		156,000		90,000		105,000	
Nutrients applied in slurry, lbs/1000 gallons										
	P	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Field 1	4.8	20.1	4.8	20.1	17.5	30.3	60.3	47.2	12.4	12.2
Field 12	4.8	20.1	4.8	20.1	17.5	30.3	60.3	47.2	12.4	12.2
Nutrients applied to field, lbs/acre										
Field 1	14	59	4	15	88	152	232	182	45	45
Field 5a [1]	25	57	25	57	25	57	25	57	25	57
Field 12	8	34	16	65	95	165	189	148	45	44
Nutrients applied to flume catchment, lbs										
Field 1	23	95	6	25	141	244	373	292	73	72
Field 5a [1]	55	126	55	126	55	126	55	126	55	126
Field 12	3	13	6	25	36	63	72	56	16	16
Nutrients applied to field, kg/ha										
Field 1	16	66	4	17	98	170	260	203	51	50
Field 5a [1]	28	64	28	64	28	64	28	64	28	64

Site	2014		2015		2016		2017		2018	
Field 12	9	38	17	73	107	184	212	166	51	50
Nutrients applied to flume catchment, kg										
Field 1	10	43	3	11	64	111	169	133	33	33
Field 5a [1]	25	57	25	57	25	57	25	57	25	57
Field 12	1	6	3	11	16	28	33	26	7	7

[1] Nutrient applied as 19-19-19 mineral fertilizer (i.e., 19% N, 19% P_2O_5, and 19% K_2O) in early spring at a rate of 300 lbs/acre.

Table 3. Parameters used to enable ISCO auto-samplers at BCRET edge-of-field sites Field 1, 5a, and 12.

Site	Identifier	ISCO enabled when stage height (inches) above	Volume pacing, 100 mL water collected per gallon of water		
			Rainfall, inches		
			<2.5	2.5 to 4	>4
Field 1	BC1	> 0.75	500	1,000	5,000
Field 5a	BC2	> 0.75	5,000	10,000	50,000
Field 12	BC3	> 0.75	500	1,000	5,000

Table 4. Annual flow and flow-weighted concentrations of phosphorus, nitrogen, and sediment in runoff for 2014, 2015, 2016, 2017, and 2018.

	Flow				Dissolved P	TP	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- mg/L -					
Field 1										
2014	118,481	448,451	67,319	629,696	0.407	0.630	0.243	0.247	1.644	67.238
2015	103,754	392,708	58,951	551,425	0.302	0.480	0.286	0.272	1.989	33.457
2016	3,755	14,212	2,133	19,955	0.940	1.231	0.130	0.335	2.360	59.000
2017	682,789	2,584,356	387,948	3,628,845	0.529	0.761	0.296	0.220	1.846	62.480
2018	22,165	83,895	12,594	117,801	1.197	1.404	0.383	1.392	4.023	32.175
Field 5a										
2014	34,350	130,015	3,587	33,548	0.613	0.779	0.170	0.023	0.683	28.933
2015	5,357,063	20,276,483	559,335	5,231,990	0.385	0.915	0.260	0.175	1.700	217.900
2016	139,663	528,625	14,582	136,402	1.134	1.405	0.980	1.598	4.010	53.200
2017	1,039,108	3,933,024	108,494	1,014,848	0.845	1.101	0.115	0.632	1.583	11.525
2018	77,413	293,008	164,961	1,543,036	1.433	1.940	0.103	0.230	2.340	89.833

	Flow				Dissolved P	TP	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- mg/L -					
Field 12										
2014	N.R.[1]	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
2015	874,765	3,310,986	1,041,387	9,741,071	0.459	0.680	0.100	0.272	1.314	35.740
2016	2,888	10,931	3,438	32,159	0.387	0.596	0.463	0.336	2.263	346.400
2017	403,100	1,525,734	479,881	4,488,778	0.289	0.463	0.027	0.146	1.143	141.233
2018	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.

[1] N.R. is no runoff occurred from Field 12, while the site was operational in 2014.

Table 5. Annual loss of phosphorus and nitrogen in surface runoff from Fields 1, 5a, and 12 for 2014, 2015, 2016, 2017, and 2018.

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- lbs/ac -					
Field 1						
2014	0.30	0.43	0.07	0.11	0.72	41
2015	0.15	0.22	0.08	0.09	0.64	16
2016	0.02	0.02	0.00	0.01	0.04	1
2017	2.27	3.07	1.49	1.28	7.25	181
2018	0.13	0.15	0.03	0.18	0.44	2
Mean annual	**0.57**	**0.78**	**0.33**	**0.33**	**1.82**	**48**
Field 5a						
2014	0.02	0.02	0.00	0.00	0.02	1
2015	1.16	4.46	1.20	0.60	6.97	1,476
2016	0.14	0.16	0.03	0.04	0.20	3
2017	0.75	0.99	0.11	0.70	1.51	10
2018	1.78	2.63	0.18	0.33	3.76	134
Mean annual	**0.77**	**1.65**	**0.31**	**0.33**	**2.49**	**325**
Field 12						
2014	N.R. [1]	N.R.	N.R.	N.R.	N.R.	N.R.
2015	1.79	3.28	0.79	1.23	7.40	321
2016	0.01	0.02	0.03	0.02	0.12	16
2017	1.07	1.72	0.11	0.62	4.60	453
2018	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
Mean annual	**0.96**	**1.67**	**0.31**	**0.62**	**4.04**	**263**
	- g/ha -					

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
Field 1						
2014	342.1	486.6	82.8	127.6	813.0	45,620
2015	171.4	246.5	92.0	104.3	719.4	17,712
2016	18.8	24.6	2.6	6.7	47.1	1,177
2017	2,546.4	3,441.5	1,676.5	1,431.2	8,132.1	203,052
2018	148.1	170.2	36.6	197.6	496.9	2,751.1
Mean annual	**645**	**874**	**378**	**373**	**2,042**	**54,062**
Field 5a						
2014	19.5	25.3	5.5	0.8	22.3	1,254
2015	1,297.7	5,000.6	1,346.0	675.4	7,819.0	1,655,477
2016	157.4	184.4	37.0	41.6	228.5	3,623
2017	836.8	1,106.4	122.2	788.2	1,697.8	11,700
2018	1,991.0	2,948.7	202.0	372.4	4,221.5	150,783
Mean annual	**860**	**1,853**	**343**	**376**	**2,798**	**364,567**
Field 12						
2014	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
2015	2,010.8	3,680.0	887.1	1,374.4	8,296.2	359,901
2016	13.1	17.3	33.0	24.0	129.8	18,215
2017	1,194.9	1,928.8	126.4	694.9	5,158.1	508,434
2018	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
Mean annual	**1,073**	**1,875**	**349**	**698**	**4,528**	**295,517**

[2] N.R. is no runoff occurred from Field 12, while the site was operational in 2014.

Table 6. Amount of phosphorus and nitrogen applied to the flume catchment area of Fields 1, 5a, and 12, loss in runoff, and percent of applied lost in runoff for 2014, 2015, 2016, 2017, and 2018.

Date	Rain	Phosphorus			Nitrogen		
		Applied	Loss in runoff	Percent applied lost in runoff	Applied	Loss in runoff	Percent applied lost in runoff
	inches	lbs		%	lbs		%
Field 1							
2014	43.39	23	0.76	3.3	95	1.28	1.3
2015	61.42	6	0.39	6.5	25	1.13	4.5
2016	41.27	141	0.04	0.0	244	0.07	0.0
2017	47.04	373	5.40	1.4	292	12.76	4.4
2018	53.84	73	0.27	0.4	72	0.78	1.1
Field 5a							
2014	43.39	55	0.22	0.4	126	0.19	0.2
2015	61.42	55	42.70	77.6	126	66.77	53.0
2016	41.27	55	1.57	2.9	126	1.95	1.5
2017	47.044	55	9.45	17.2	126	14.50	11.5
2018	53.84	55	25.18	45.8	126	36.05	28.6
Field 12							
2014	43.39	N.R.[1]	N.R.	N.R.	N.R.	N.R.	N.R.
2015	61.42	6	2.76	46.0	25	6.21	24.8
2016	41.27	36	0.01	0.0	63	0.10	0.2
2017	47.04	72	1.44	2.0	56	3.86	6.9

[3] N.R. is no runoff occurred from Field 12, while the site was operational in 2014.

Table 7. Loss of P and N in runoff from fields in northwest AR and eastern OK and losses from Big Creek Fields BC1, BC5a, and BC12.

Site	Site years	Management	P applied	P runoff	% applied in runoff	N applied	N runoff	% applied in runoff	Reference
			lbs/ac/yr			lbs/ac/yr			
BC1	5	Grazed pasture with swine slurry	94	0.78	0.8	100	1.82	1.8	BCRET
BC5a	5	Fertilizer grazed and hayed pasture	25	1.65	6.6	57	2.49	4.4	BCRET
BC12	5	Grazed and hayed pasture with swine slurry	75	1.67	2.2	90	4.04	4.5	BCRET
Dumas, AR	15	Cotton – corn rotation	24	1.06	3.1	91	3.75	2.8	Daniels et al., 2019
El Reno, OK	32	Native grass	0	0.87	- -	0	0.10	- -	Sharpley and Smith, 1994
	29	Wheat	12	1.46	12.2	63	8.22	13.1	
Washington Co., AR	4	Grazed pasture with poultry litter	60	0.94	1.6	120	0.31	0.3	Bolster et al., 2019
	4	Grazed pasture with poultry litter	80	1.45	1.8	160	0.66	0.4	
	4	Hayed pasture with poultry litter	60	1.37	2.3	120	1.26	1.1	
	7	Hayed pasture	0	0.06	- -	0	0.29	- -	
Woodward, OK	14	Native grass	0	0.02	- -	0	0.18	- -	Sharpley and Smith, 1994
	8	Native grass	23	0.30	1.3	90	1.47	1.6	
	8	Wheat	23	1.71	7.4	92	6.47	7.0	

References

Bolster, C.H., C. Baffaut, N.O. Nelson, D.L. Osmond, M.L. Cabrera, J.J. Ramirez-Avila, A.N. Sharpley, T.L. Veith, A.M. S. McFarland, A.G. M. M. M. Senaviratne, G.M. Pierzynski, and R.P. Udawatta. 2019. Development of PLEAD: A database containing event-based runoff phosphorus loadings from agricultural fields. Journal of Environmental Quality 48:510-517.

Daniels, M.D., A.N Sharpley, B. Robertson, E. Gbur, L. Riley, P. Webb, B.L. Singleton, A. Free, C. Hallmark, and T. Nehls. 2019. Nutrients in runoff from cotton production in the Lower Mississippi River Basin: A case study. Cotton Research Report. / Agriculture Geosciences and Environment

Sharpley, A.N. and S.J. Smith. 1994. Wheat tillage and water quality in the Southern Plains. Soil and Tillage Research. 30:33-48.

Supplemental Tables and Figures

Table S 1. Flow and flow-weighted concentration of phosphorus and nitrogen in each runoff event for Fields 1, 5a, and 12 in 2014, 2015, 2016, 2017, and 2018.

Date	Flow	Flow	Flow	Flow	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- -		mg/L		- -	
Field 1										
4/4/2014	20,795	78,709	11,815	110,520	0.181	0.638	0.250	0.106	2.080	207.0
5/9/2014	15,956	60,393	9,066	84,802	0.079	0.312	0.170	0.209	1.630	125.9
5/13/2014	15,420	58,365	8,761	81,953	0.190	0.366	0.100	0.126	1.330	42.1
5/28/2014	17,600	66,616	10,000	93,539	0.235	0.310	0.000	0.000	0.000	56.1
6/24/2014	1,440	5,450	818	7,653	0.228	0.498	0.180	0.114	2.390	23.2
6/27/2014	41,380	156,623	23,511	219,924	1.166	1.374	0.100	0.333	1.180	12.3
7/25/2014	4,920	18,622	2,795	26,149	0.648	0.794	0.160	0.388	1.650	5.6
10/14/2014	970	3,671	551	5,155	0.529	0.746	0.980	0.698	2.890	65.7
3/25/2015	4,642	17,570	2,638	24,671	0.143	0.346	0.410	0.216	2.680	65.5
5/8/2015	12,510	47,350	7,108	66,487	0.525	0.714	0.160	0.475	2.190	16.9
5/11/2015	53,439	202,265	30,363	284,013	0.251	0.386	0.090	0.055	0.860	44.4

Date	Flow	Flow	Flow	Flow	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- mg/L -					
5/18/2015	960	3,634	545	5,102	0.208	0.512	0.540	0.410	3.590	53.7
5/26/2015	6,010	22,748	3,415	31,942	0.245	0.432	0.200	0.174	1.660	37.8
6/29/2015	6,133	23,214	3,485	32,596	0.354	0.524	0.370	0.226	1.640	11.0
7/7/2015	20,060	75,927	11,398	106,614	0.387	0.444	0.230	0.345	1.300	4.9
10/13/2016	3,755	14,212	2,133	19,955	0.940	1.231	0.130	0.335	2.360	59.0
3/27/2017	19,430	73,543	11,040	103,265	0.420	0.670	0.430	0.090	1.870	124.4
4/24/2017	21,120	79,939	12,000	112,247	0.395	0.592	0.130	0.143	1.500	43.1
4/27/2017	33,110	125,321	18,813	175,971	0.550	0.784	0.080	0.107	1.320	52.2
5/1/2017	49,820	188,569	28,307	264,780	0.534	0.760	0.330	0.321	2.200	36.7
6/6/2017	559,309	2,116,985	317,789	2,972,581	0.747	0.998	0.510	0.438	2.340	56.0
5/3/2018	8,412	31,839	4,780	44,708	0.273	0.467	0.060	0.037	1.750	27.500
8/30/2018	3,030	11,469	1,722	16,104	1.617	1.875	0.690	1.869	5.510	49.600

Date	Flow	Flow	Flow	Flow	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- mg/L	- -				
10/11/2018	10,570	40,007	6,006	56,177	1.941	2.103	0.400	2.492	5.830	12.300
11/1/2018	153	579	87	813	0.955	1.171	0.380	0.719	3.000	39.300
Field 5a										
6/27/2014	20,630	78,085	2,154	20,148	0.506	0.656	0.060	0.000	0.530	39.7
7/25/2014	2,000	7,570	209	1,953	0.625	0.754	0.090	0.000	0.610	9.0
10/13/2014	11,720	44,360	1,224	11,446	0.707	0.926	0.360	0.068	0.910	38.1
3/26/2015	42,743	161,782	4,463	41,745	0.813	1.330	0.390	0.225	2.590	72.3
5/11/2015	5,158,670 [1]	19,525,566	538,621	5,038,229	0.248	0.968	0.260	0.127	1.500	320.1
7/7/2015	155,650	589,135	16,252	152,016	0.094	0.448	0.130	0.172	1.010	261.3
3/31/2016	139,510	528,045	14,566	136,253	1.154	1.352	0.270	0.302	1.670	26.5
5/10/2016	153	580	16	150	1.114	1.458	1.690	2.894	6.350	79.9
4/24/2017	46,638	176,525	4,870	45,549	0.961	1.212	0.120	0.321	1.530	11.7

Date	Flow	Flow	Flow	Flow	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- mg/L -					
4/27/2017	251,410	951,587	26,250	245,540	0.686	0.846	0.070	0.063	0.860	11.3
5/1/2017	381,570	1,444,242	39,840	372,661	0.734	0.916	0.220	0.281	1.560	13.1
6/6/2017	359,490	1,360,670	37,535	351,097	1.000	1.430	0.050	1.861	2.380	10.0
2/21/2018	52,210	197,615	5,450	1,031,161	1.496	2.078	0.140	0.307	2.990	66.900
2/26/2018	22,598	197,615	110,238	457,726	0.735	1.495	0.120	0.087	2.280	175.500
3/29/2018	2,605	85,533	48,934	54,149	2.067	2.247	0.050	0.296	1.750	27.100
Field 12										
5/8/2015	13,630	51,590	16,226	151,779	0.675	0.956	0.140	0.303	1.820	57.0
5/11/2015	853,555	3,230,706	1,016,137	9,504,884	0.194	0.364	0.090	0.135	0.830	36.7
6/1/2015	110	416	131	1,225	0.235	0.482	0.120	0.210	1.110	33.2
6/29/2015	470	1,779	560	5,234	0.396	0.687	0.020	0.143	1.230	22.8
7/6/15	7,000	26,495	8,333	77,950	0.796	0.910	0.130	0.567	1.580	29.0
3/10/2016	2,496	9,445	2,971	27,789	0.411	0.522	1.170	0.852	4.490	621.5

Date	Flow	Flow	Flow	Flow	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	gal	L	gal/acre	L/ha	- -	mg/L	- -			
5/2/2016	209	791	249	2,327	0.381	0.600	0.100	0.093	1.268	321.0
5/10/2016	183	694	218	2,042	0.370	0.666	0.120	0.062	1.030	96.7
4/27/2017	73,890	279,674	87,964	822,813	0.326	0.544	0.020	0.105	0.710	102.3
5/1/2017	226,240	856,318	269,333	2,519,328	0.224	0.374	0.030	0.166	1.060	40.6
6/6/2017	102,970	389,741	122,583	1,146,637	0.316	0.470	0.030	0.166	1.660	280.8

[1] Flow measurement by the flume on Field 5a was affected by Big Creek breeching its banks during the 5-11-2015 rainfall – runoff event.

Table S 2. Loss of phosphorus and nitrogen in each runoff event as pounds per acre for Fields 1, 5a, and 12 in 2014, 2015, 2016, 2017, and 2018.

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- lbs/ac -					
Field 1						
4/4/2014	0.018	0.063	0.025	0.010	0.205	20.393
5/9/2014	0.006	0.024	0.013	0.016	0.123	9.517
5/13/2014	0.014	0.027	0.007	0.009	0.097	3.075
5/28/2014	0.020	0.026	0.000	0.000	0.000	4.678
6/24/2014	0.002	0.003	0.001	0.001	0.016	0.158
6/27/2014	0.229	0.269	0.020	0.065	0.231	2.411
7/25/2014	0.015	0.019	0.004	0.009	0.038	0.131
10/14/2014	0.002	0.003	0.005	0.003	0.013	0.302
3/25/2015	0.003	0.008	0.009	0.005	0.059	1.440
5/8/2015	0.031	0.042	0.009	0.028	0.130	1.002
5/11/2015	0.064	0.098	0.023	0.014	0.218	11.240
5/18/2015	0.001	0.002	0.002	0.002	0.016	0.244
5/26/2015	0.007	0.012	0.006	0.005	0.047	1.076
6/29/2015	0.010	0.015	0.011	0.007	0.048	0.320
7/7/2015	0.037	0.042	0.022	0.033	0.124	0.466
10/13/2016	0.017	0.022	0.002	0.006	0.042	1.049

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- lbs/ac -					
3/27/2017	0.039	0.062	0.040	0.008	0.172	11.451
4/24/2017	0.040	0.059	0.013	0.014	0.150	4.312
4/27/2017	0.086	0.123	0.013	0.017	0.207	8.188
5/1/2017	0.126	0.179	0.078	0.076	0.519	8.662
6/6/2017	1.979	2.644	1.351	1.161	6.200	148.383
5/3/2018	0.011	0.019	0.002	0.001	0.070	1.096
8/30/2018	0.023	0.027	0.010	0.027	0.079	0.712
10/11/2018	0.097	0.105	0.020	0.147	0.292	0.616
11/1/2018	0.001	0.001	0.000	0.001	0.002	0.028
Field 5a						
6/27/2014	0.009	0.012	0.001	0.000	0.010	0.713
7/25/2014	0.001	0.001	0.000	0.000	0.001	0.016
10/13/2014	0.007	0.009	0.004	0.001	0.009	0.389
3/26/2015	0.030	0.049	0.015	0.008	0.096	2.690
5/11/2015	1.114	4.347	1.168	0.570	6.736	1437.560
7/7/2015	0.013	0.061	0.018	0.023	0.137	35.407
3/31/2016	0.140	0.164	0.033	0.037	0.203	3.219
5/10/2016	0.000	0.000	0.000	0.000	0.001	0.011
4/24/2017	0.039	0.049	0.005	0.013	0.062	0.475

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- lbs/ac -					
4/27/2017	0.150	0.185	0.015	0.014	0.188	2.473
5/1/2017	0.244	0.304	0.073	0.093	0.518	4.352
6/6/2017	0.313	0.448	0.016	0.582	0.745	3.130
2/21/2018	1.375	1.910	0.129	0.282	2.748	61.491
2/26/2018	0.300	0.610	0.049	0.035	0.930	71.605
3/29/2018	0.100	0.108	0.002	0.014	0.084	1.308
Field 12						
5/8/2015	0.091	0.129	0.019	0.041	0.246	7.712
5/11/2015	1.644	3.084	0.763	1.144	7.032	310.939
6/1/2015	0.000	0.001	0.000	0.000	0.001	0.036
6/29/2015	0.002	0.003	0.000	0.001	0.006	0.106
7/6/15	0.055	0.063	0.009	0.039	0.110	2.015
3/10/2016	0.010	0.013	0.029	0.021	0.111	15.395
5/2/2016	0.001	0.001	0.000	0.000	0.003	0.666
5/10/2016	0.001	0.001	0.000	0.000	0.002	0.176
4/27/2017	0.239	0.399	0.015	0.077	0.521	75.031
5/1/2017	0.503	0.840	0.067	0.373	2.380	91.174
6/6/2017	0.323	0.480	0.031	0.170	1.697	287.002

Table S 3. Loss of phosphorus and nitrogen in each runoff event as grams per hectare for Fields 1, 5a, and 12 in 2014, 2015, 2016, 2017, and 2018.

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- g/ha -					
Field 1						
4/4/2014	20.0	70.5	27.6	11.7	229.9	22,877.6
5/9/2014	6.7	26.5	14.4	17.7	138.2	10,676.6
5/13/2014	15.6	30.0	8.2	10.3	109.0	3,450.2
5/28/2014	22.0	29.0	0.0	0.0	0.0	5,247.6
6/24/2014	1.7	3.8	1.4	0.9	18.3	177.6
6/27/2014	256.4	302.2	22.0	73.2	259.5	2,705.1
7/25/2014	16.9	20.8	4.2	10.1	43.1	146.4
10/14/2014	2.7	3.8	5.1	3.6	14.9	338.7
3/25/2015	3.5	8.5	10.1	5.3	66.1	1,616.0
5/8/2015	34.9	47.5	10.6	31.6	145.6	1,123.6
5/11/2015	71.3	109.6	25.6	15.6	244.3	12,610.2
5/18/2015	1.1	2.6	2.8	2.1	18.3	274.0
5/26/2015	7.8	13.8	6.4	5.6	53.0	1,207.4
6/29/2015	11.5	17.1	12.1	7.4	53.5	358.6
7/7/2015	41.3	47.3	24.5	36.8	138.6	522.4
10/13/2016	18.8	24.6	2.6	6.7	47.1	1,177.4

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	- g/ha -					
3/27/2017	43.4	69.2	44.4	9.3	193.1	12,846.2
4/24/2017	44.3	66.5	14.6	16.1	168.4	4,837.9
4/27/2017	96.8	138.0	14.1	18.8	232.3	9,185.7
5/1/2017	141.4	201.2	87.4	85.0	582.5	9,717.4
6/6/2017	2,220.5	2,966.6	1,516.0	1,302.0	6,955.8	166,464.5
5/3/2018	12.2	20.9	2.7	1.7	78.2	1,229.5
8/30/2018	26.0	30.2	11.1	30.1	88.7	798.7
10/11/2018	109.0	118.1	22.5	165.3	327.5	691.0
11/1/2018	0.8	1.0	0.3	0.6	2.4	32.0
Field 5a						
6/27/2014	10.2	13.2	1.2	0.0	10.7	799.9
7/25/2014	1.2	1.5	0.2	0.0	1.2	17.6
10/13/2014	8.1	10.6	4.1	0.8	10.4	436.1
3/26/2015	33.9	55.5	16.3	9.4	108.1	3,018.2
5/11/2015	1,249.5	4,877.0	1,309.9	639.9	7,557.3	1,612,737.1
7/7/2015	14.3	68.1	19.8	26.1	153.5	39,721.8
3/31/2016	157.2	184.2	36.8	41.1	227.5	3,610.7
5/10/2016	0.2	0.2	0.3	0.4	1.0	12.0

Date	Dissolved P	Total P	Ammonia-N	Nitrate-N	Total N	Solids
	g/ha					
4/24/2017	43.8	55.2	5.5	14.6	69.7	532.9
4/27/2017	168.4	207.7	17.2	15.5	211.2	2,774.6
5/1/2017	273.5	341.4	82.0	104.7	581.4	4,881.9
6/6/2017	351.1	502.1	17.6	653.4	835.6	3,511.0
2/21/2018	1,542.6	2,142.8	144.4	316.6	3,083.2	68,984.7
2/26/2018	336.4	684.3	54.9	39.8	1,043.6	80,330.9
3/29/2018	111.9	121.7	2.7	16.0	94.8	1,467.4
Field 12						
5/8/2015	102.5	145.1	21.2	46.0	276.2	8,651.4
5/11/2015	1,843.9	3,459.8	855.4	1,283.2	7,889.1	348,829.2
6/1/2015	0.3	0.6	0.1	0.3	1.4	40.7
6/29/2015	2.1	3.6	0.1	0.7	6.4	119.3
7/6/15	62.0	70.9	10.1	44.2	123.2	2,260.5
3/10/2016	11.4	14.5	32.5	23.7	124.8	17,270.9
5/2/2016	0.9	1.4	0.2	0.2	3.0	747.1
5/10/2016	0.8	1.4	0.2	0.1	2.1	197.5
4/27/2017	268.2	447.6	16.5	86.4	584.2	84,173.7
5/1/2017	564.3	942.2	75.6	418.2	2,670.5	102,284.7
6/6/2017	362.3	538.9	34.4	190.3	1,903.4	321,975.7

NUTRIENT AND BACTERIA TRENDS IN TRENCH, WELL, EPHEMERAL STREAM AND LEFT FORK WATER

Contents

Summary

1. There was a statistically significant (probability <0.0001) increase in nitrate-N concentrations in ephemeral stream and well samples over the monitoring period (April 2014 to June 2019), as determined by the Seasonal Kendall's test for trends in nutrient concentrations at sites adjacent to the swine production facility and holding ponds.
2. In contrast, chloride, which is a conservative element that can move freely through the soil without chemical, physical, or biological modification, and electrical conductivity did not exhibit any

statistically significant change over the monitoring period in well (W1), ephemeral stream (BC4), and trench (T1 and T2) samples (April 2015 to June 2019).

3. Flow in the interceptor trenches (T1 and T2) was highly responsive to rainfall, indicating the trenches were mainly capturing shallow subsurface flows initiated by rainfall.
4. The lack of any increasing trend in chloride and electrical conductivity for ephemeral stream (BC4), well (W1), or trench (T1 and T2) samples, suggests elevated nitrate-N concentrations in well and ephemeral stream samples may be influenced by sources other than the holding ponds (i.e., sources that have low chloride and electrical conductivity values).

List of Tables

List of Figures

List of Supplemental Tables and Figures

Background

Trends in water analytes measured at the ephemeral stream (BC4), house well (W1), trenches (T1 and T2), and Left Fork (BC9) sites were determined over the period of monitoring for each site, covering five years of operation and land application of slurry from the C&H Farm. In this trend assessment, we focus on dissolved P, total P, nitrate-N, total N, E, coli, chloride, and electrical conductivity to determine if any operational impacts were evident. Trends in analyte levels over time were determined by the established and widely used (i.e., USGS national water quality trend analysis) Seasonal Kendall's test for trends in measured analytes over the period of monitoring (Helsel and Hirsch, 2002).

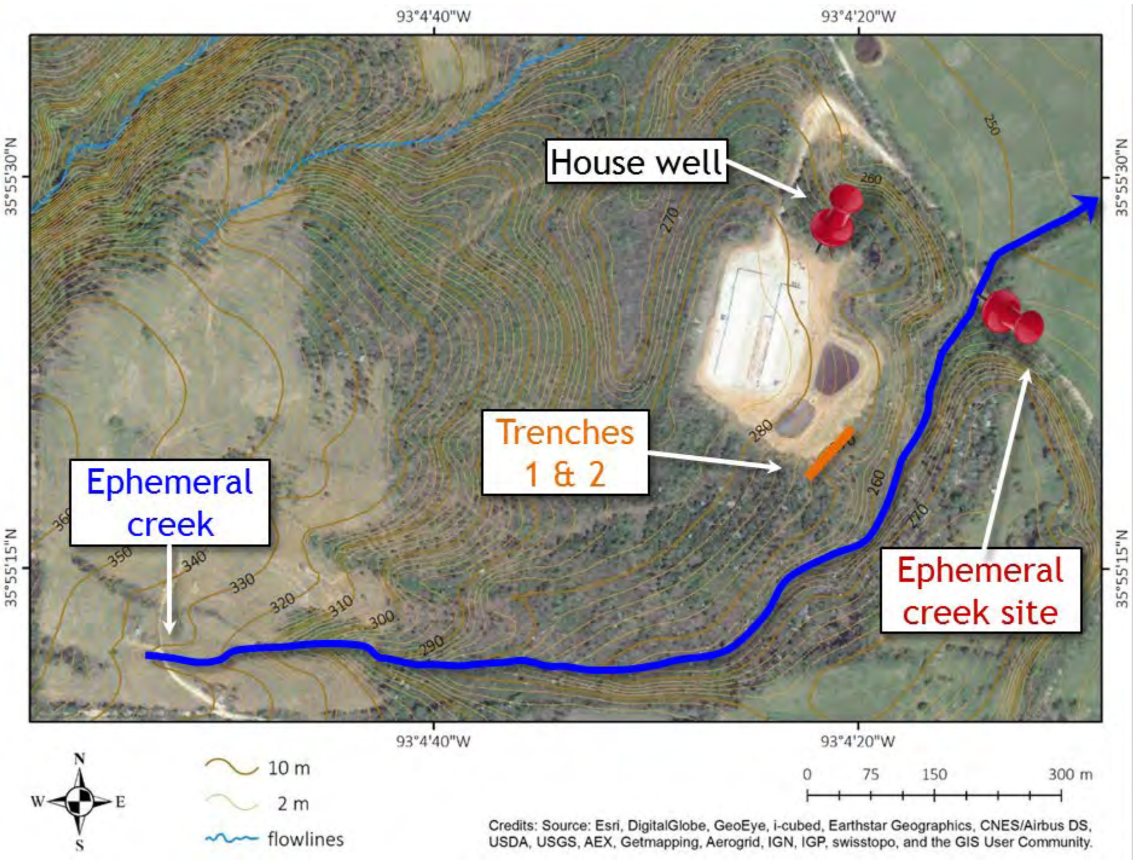
This trend analysis focuses on the area of the C&H Farm operation around the holding ponds, in an effort to discern if the integrity of the holding ponds was breached and slurry leached to shallow and deeper aquifer and ground waters. Nitrate-N, chloride, and electrical conductivity were primary constituents of interest in this regard for several reasons. The concentration of nitrate-N and chloride, along with electrical conductivity of swine slurry is appreciably higher than that found in ground and flowing surface waters. In particular, chloride and electrical conductivity can be used as "conservative tracers" (i.e., the analytes are not chemically transformed during movement through soil as nitrate-N or E. coli can be) of subsurface flows. Thus given their high concentrations in swine slurry, chloride and electrical conductivity can and have been widely used a potential tracers of slurry movement below holding ponds. The well adjacent to the C&H animal barns and holding ponds was sampled to reflect the chemistry of deep ground water below the C&H operation area.

Additionally, longitudinal trenches were installed downslope of the holding ponds to collect water that reflected a shallower aquifer source than the well. The trench approach was selected to represent a wider sphere of water collection than shallow wells, which would reflect one point on the landscape and has been used by others to monitor shallow aquifer flow and chemical composition. Neither the well nor the trench will provide a quantitative determination of slurry movement below the ponds; however, they have a greater potential to capture any subsurface seepage downslope of the ponds. Details of trench installation and monitoring is given below.

Direct Measurements as Indicators of Potential Holding Pond Leakage

Three direct measurements to monitor possible leakage of manure from the holding ponds are; (a) the interceptor trenches down slope of the ponds, (b) the house well, and (c) the ephemeral stream capturing surface runoff and shallow seepage water from the area around the animal houses and holding ponds. These sites are located on Figure 1.

We are confident that at least one of these direct measurements will capture any potential leakage from the holding ponds. While these direct measurements are not designed to quantify leakage, they will indicate by increases in indicator constituents any leakage of manure from the storage ponds. This is particularly the case for conservative tracers, such as chloride and electrical conductivity. Chloride is not commonly involved in geochemical reactions nor is it affected by pH and changes in redox reactions and, thus, behaves as a conservative tracer (see http://www.gwadi.org/tools/tracers/chloride).



Credits: Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Figure 1. Location of direct measurement sites in the vicinity of the manure holding ponds; the interceptor trenches, house well, and ephemeral stream.

Nitrate is an additional useful tracer, although it can be affected by changes in redox conditions and subject to denitrification. Together, these and other constituents aid in identifying potential leakage from the manure storage ponds.

Manure Holding Pond Interceptor Trench Installation and Sampling

To determine potential leaching of liquid from the manure holding ponds, an interceptor trench 200 feet in length was constructed approximately 150 feet downslope of the holding ponds (Figure 1). Any leakage from the ponds would initially move vertically, but horizontal flow will be induced at any permeability contrast in the subsurface. The trench was designed to intercept horizontal flow that would be induced over a low-permeability restricting layer existing at a soil depth of 2 to 3 feet that was identified during site evaluation. Soil profile description for the trench site is detailed in Figure S1 and Table S1. The trench was excavated to about 10 feet below the base of the holding ponds. The trench was designed to drain to outlets at both ends, with a minimum design gradient of 0.25 inch/foot maintained from the high midpoint of the trench to each of the two outlets to ensure unimpeded flow.

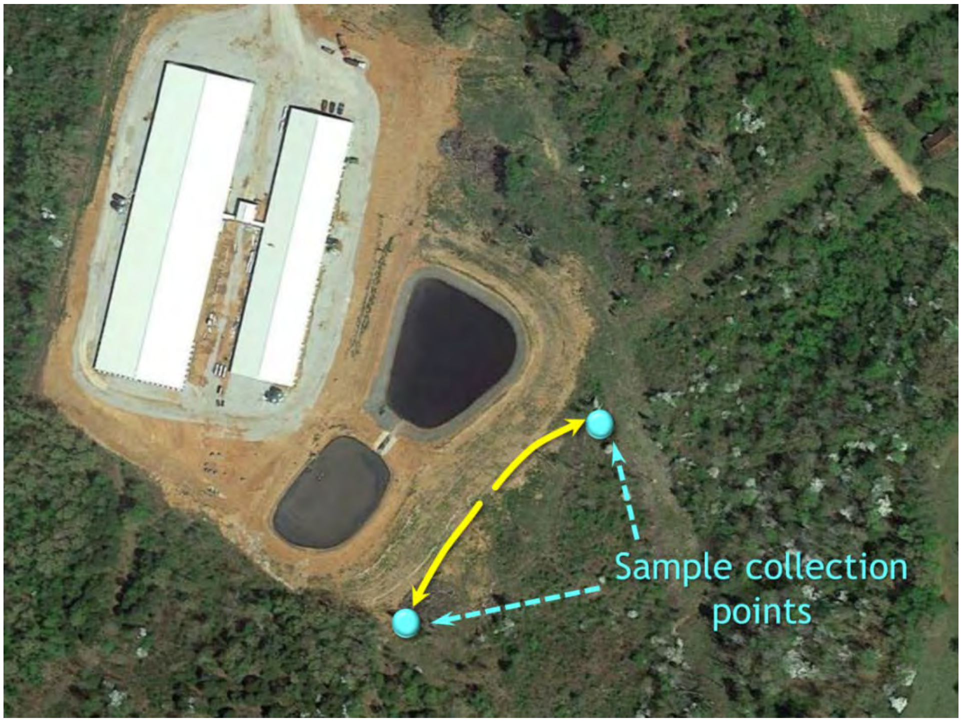


Figure 2. Trench location adjacent to the manure holding ponds at the C&H Farm.

The base of the interceptor trench was lined with impermeable plastic sheeting to capture all flow moving through trench walls into the trench. A 4-inch perforated pipe was laid on top of the plastic sheet and the trench filled with washed gravel to a depth of 2-3 feet below the soil surface. The remaining trench was then backfilled with compacted soil and seed and hay placed on the surface to encourage surface vegetation regrowth. The design will capture any flow moving horizontally into the trench, and direct flow for collection and transmittal to the outlets where flow rate can be measured and samples can be collected for water-quality analyses.

The trench approach was selected over a three-dimensional network of shallow observation and sampling wells located below the holding ponds due to the greater probability of the trench intercepting any seepage from the ponds. The continuous interception provided by the trench offers a greater probability of capturing any subsurface seepage as compared to a three dimensional grid of discontinuous point observations. Thus, the trench reduces the probability of by-pass flow of any seepage down slope of the ponds. Water exiting the interceptor trench pipe outlets is currently sampled by hand. We plan to instrument both pipes with flow monitoring and sonde to collect continuous flow and water-quality data.

Interceptor trenches have been widely used in the Ozark Mountains region to assess if manure holding ponds were leaking and worldwide as a preferred method to determine subsurface lateral flows in hillslopes along areas of differing or contrasting permeabilities. References to some of the relevant studies are; Hobza (2006), Pilgrim and Huff (1978a, b), Smettem, et al. (1991), Trudgill et al. (1983), Wagner (2005), Weyman (1974).

Flow Measurement and Auto-sampling of Interceptor Trenches Drainage

In mid-July 2016, installation of a 0.5-foot H flume, tipping bucket water meter, and ISCO automated water sampler was installed at the end of each interceptor trench pipe, below the slurry holding ponds. This equipment was encased in a locked shed. This equipment design allows interceptor trench flow to be recorded and samples of high trench flow collected, in addition to the routine weekly grab samples when flow was present. This also ensured that samples collected were not contaminated by external sources, such as wildlife. Figures 3, 4, and 5 show site configuration.

Flow from the trench pipe was directed into the 0.5’ H-flume, which was able to measure flows in excess of 10 mL/second. For smaller flows trench-water exited the flume into a tipping bucket rain gauge, which was able to accurately measure low interceptor trench flow (i.e., <~12 mL/second). The ISCO automated water sampler was powered by a solar battery and a deep-cycle marine battery. This secure location allowed collection of samples of water from the interceptor trenches, which had not been affected by external sources, such as wildlife.

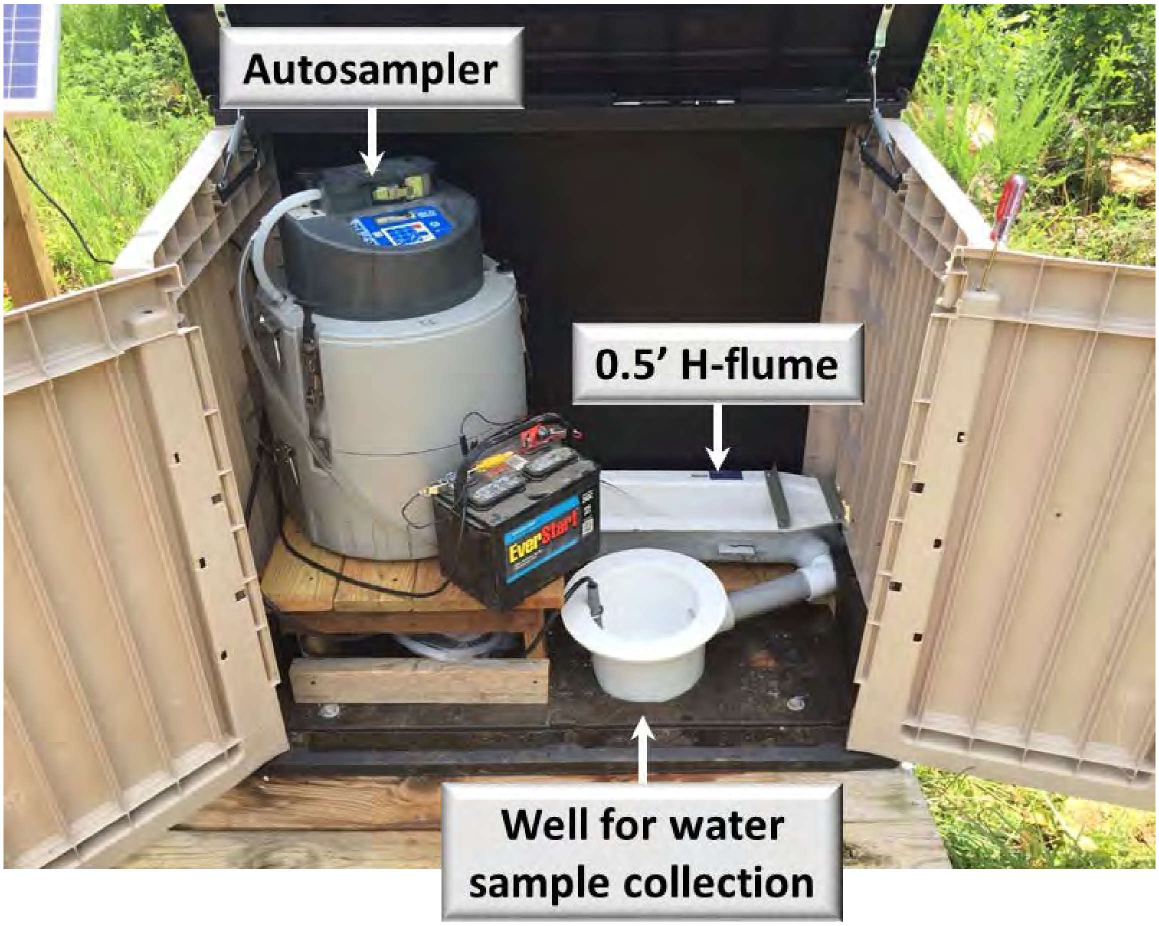


Figure 3. Sampling equipment installed on interceptor trenches.

Figure 4. Tipping bucket rain gage to measure low interceptor trench flow (i.e., <~12 mL/second).

Figure 5. External view of interceptor trench flow monitoring equipment.

House Well Configuration and Sample Collection

The sample collection point for the house well adjacent to the animal house facilities and slurry holding ponds was reconfigured during August 2015 to exclude any potential sources of sample contamination. It was determined that the risk of contamination was a result of factors such as well-head pump and in-house maintenance. In addition to installing a new well-water sampling site, USGS water quality sampling guidelines were used, which involved collection of a well sample when in-situ field measurement of well water temperature, pH, and electrical conductivity had stabilized. This was initiated September 10, 2015. The house well collects water from 265 to 285 feet (Supplemental Table S1) and serves to track any potential water-quality changes in the deeper groundwater table.

Prior to collection of a house-well water sample, the well is purged and water temperature, pH, and electrical conductivity measured on-site every 30 seconds until all values stabilize. At that point, a sample of water is collected in a 1-L acid-washed bottle. This method is taken from USGS and EPA well water sampling protocols. See USGS methods for sampling at https://water.usgs.gov/owq/FieldManual/chapter4/pdf/Chap4_v2.pdf. Specific and detailed guidance on the collected of water quality data can be found in the USGS National Field Manual at https://water.usgs.gov/owq/FieldManual/.

The U.S. EPA also recommend that selected water quality parameters can be monitored during low-rate purging, with stabilization of these parameters indicating when the discharge water represents aquifer water or source well water. See: http://www.csus.edu/indiv/h/hornert/Geol_210_Summer_2012/Week%202%20readings/Puls%20and%20Barcelona%201996%20Low%20flow%20sampling.pdf and https://in-situ.com/wp-content/uploads/2015/01/Low-Flow-Groundwater-Sampling-Techniques-Improve-Sample-Quality-and-Reduce-Monitoring-Program-Costs-Case-Study.pdf

Ephemeral Stream

The ephemeral stream site, where monitoring was initiated in March, 2014, drains a small sub-watershed containing the house barns, manure holding ponds, and interflow partially captured by the interceptor trenches (Figure 1). The stream will capture surface runoff and shallow interflow, seepage, and spring water from areas adjacent to and encompassing the animal house barns and holding ponds.

Trend Analysis by Seasonal Kendall's Test

Seasonal Kendall's test for monotonic trends in chemical constituents monitored, were determined for the ephemeral stream (site BC4), house well (site W1), trenches (sites T1 and T2), and Left Fork (site BC9). The Seasonal Kendall Tau (i.e., T) test is used to test for a monotonic increasing or decreasing trend of a chemical constituent, when data was collected over time (Helsel and Hirsch, 2002). The Seasonal Kendall test results in two values, the tau value, and a probability value. The tau value (T) has a possible range from -1.0 (perfect inverse correlation), 0.0 (no correlation), to +1.0 (perfect positive correlation). Probability values below the threshold value (typically 0.05) indicate that any observed trend is statistically unlikely to occur by chance and therefore the observed trend is statistically significant.

The following assumptions are made in the Seasonal Kendall's test:

1. Water samples collected over time are representative of the true conditions at the time of sampling.
2. Sample collection, handling, and measurement methods provide unbiased and representative observations of concentrations over time.
3. Any monotonic trends present are all in the same direction (increase or decrease). If there is an increasing trend in some seasons and a decreasing trend in other seasons, the Seasonal Kendall's test may be misleading.

Findings

Analyte Concentrations over Time

The concentration of dissolved P, total P, nitrate-N, total N, E. coli, chloride, and electrical conductivity from the ephemeral stream, well, trenches, and Left Fork sites with time since sampling began, are presented in Supplemental Figures S1 to S18, respectively.

The main findings of this analysis indicate a statistically significant increase in nitrate-N and total N (as nitrate-N comprises a respective 77, 91 and 58% of total N) in ephemeral stream, house well, and Left Fork samples over the monitoring period (Table 1 and Figures S2, S8, and S17). At the same time, however, there were statistically significant decreases in dissolved P, total P, E. coli, chloride, and electrical conductivity of well water, chloride of trench 1 water, and total P of Left Fork water samples with time (Table 1).

Table 1. Multivariate correlations for Seasonal Kendall's Test for ephemeral stream (BC4), spring (BC5), Well (W1), Trench 1 (T1), Trench 2 (T2), and Left Fork (BC9) for monitoring period.

	Dissolved P	Total P	Nitrate-N	Total N	E. coli	Chloride	Electrical conductivity
	- - - - - - - - - - - - - - - - mg/L - - - - - - - - - - - - - - - -				MPN/100mL	mg/L	µS/cm
Ephemeral stream, BC4							
Samples	136	136	136	136	108	78	77
Probability	0.5308	0.0012*	<0.0001*	<0.0001*	0.2979	0.3403	0.1009
Kendall **T**	0.0374	-0.1897	0.3738	0.3144	0.0681	-0.0737	0.1277
Spring, BC5							

	Dissolved P	Total P	Nitrate-N	Total N	E. coli	Chloride	Electrical conductivity
Samples	234	234	234	234	214	168	166
Probability	0.6056	0.0648	0.0638	0.0327*	0.6101	<0.0001*	0.8179
Kendall **T**	-0.0237	-0.0819	0.0815	0.0943	-0.0235	0.219	-0.0121
Well, W1							
Samples	198	198	198	198	160	170	167
Probability	0.0023*	<.0001*	<.0001*	<.0001*	<.0001*	0.0003*	0.1364
Kendall **T**	-0.1535	-0.3562	0.6253	0.5794	-0.302	-0.1891	-0.0781
Trench, T1							
Samples	65	65	65	65	47	59	57
Probability	0.3051	0.5823	<.0001*	0.0151*	0.1092	<.0001*	0.4530
Kendall **T**	-0.0919	0.0474	-0.3619	-0.2072	0.1638	-0.532	-0.0684
Trench, T2							
Samples	40	40	40	40	33	37	37
Probability	0.8943	0.4638	0.0010*	0.0025*	0.2058	0.2241	0.6971
Kendall **T**	0.0161	-0.0843	-0.3772	-0.3476	0.1576	-0.1463	0.0485
Left Fork, BC9							
Samples	176	176	176	176	171	176	173
Probability	0.1545	<0.0001*	0.0046*	0.0002*	0.9489	0.1698	0.0022*
Kendall **T**	-0.0748	-0.2548	0.1441	0.1917	0.0033	-0.0697	-0.1570

***** Values followed by '*' are significant and the level of probability stated.

Trench Flow and Rainfall

Installation of flow monitoring equipment, associated with an ISCO automated water sampler on the trenches (T1 and T2) in June 2016, allowed us to secure the integrity of sample collection (Figure 3). Based on 15-minute trench flow measurements and rainfall at the Big Creek downstream site operated by USGS, we were able to investigate trench flow as a function of weather and landscape setting (Supplemental Table S2). Trench flow was highly responsive to rainfall (Figure 6).

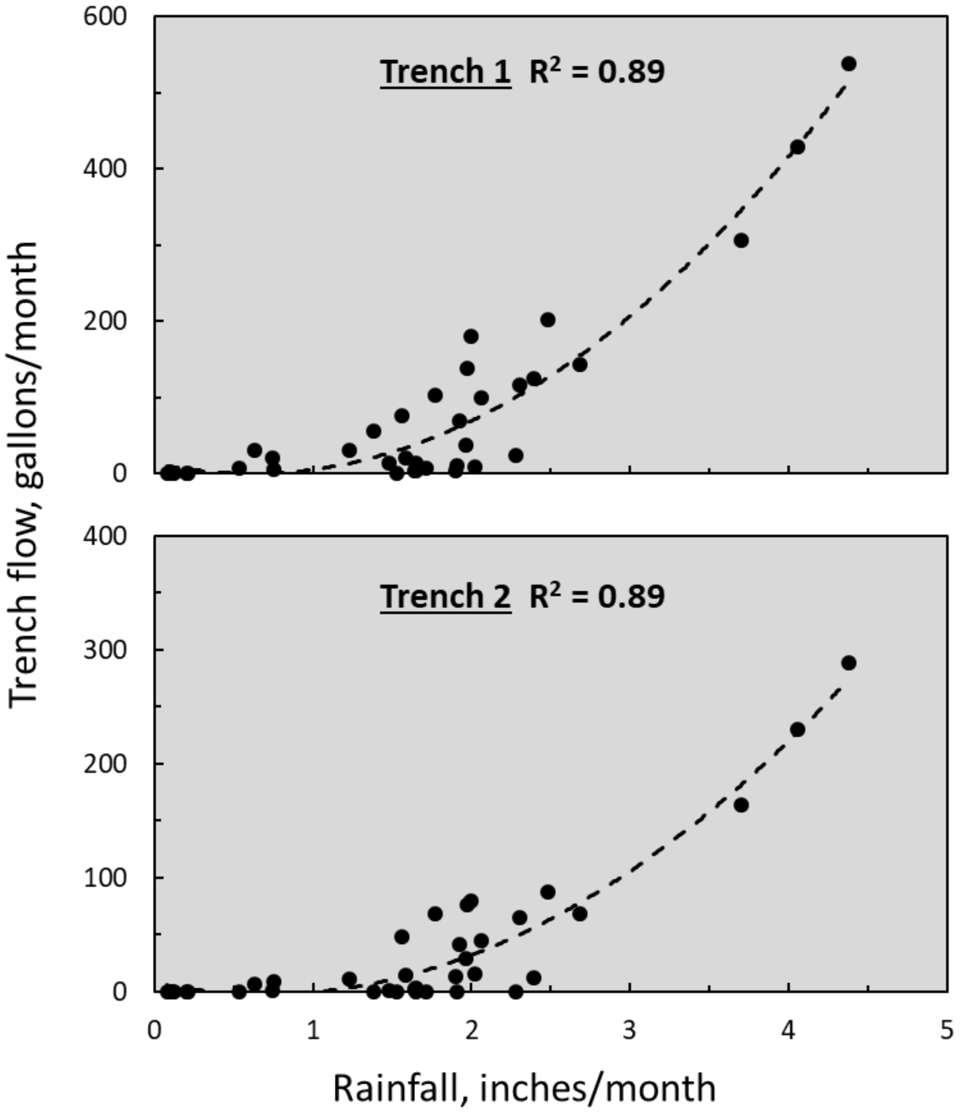


Figure 6. Relationship between monthly rainfall amounts and trench flow (T1 and T2) over the flow-monitoring period of July 2016 to June 2019

There was approximately 50% more flow from trench 1 than 2, despite the fact that they were located adjacent to each other (Figure 7). This spatial heterogeneity of water flow pathways is not surprising in karst or non-karst landscapes, and indicates the need for long-term monitoring to reliably estimate nutrient fluxes, in the absence of being able to install and implement several replicates.

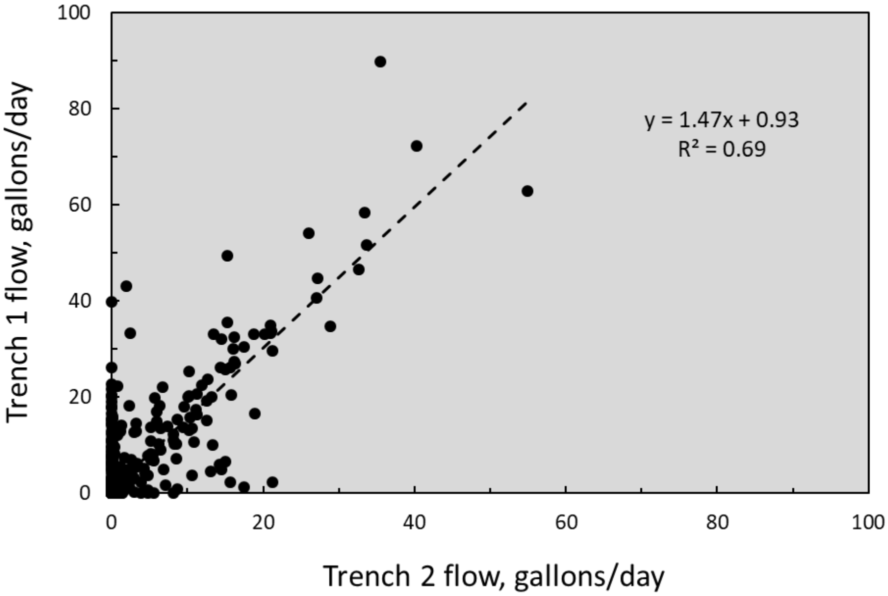


Figure 7. Relationship between daily flows measured in trench T1 and T2 over the flow-monitoring period of July 2016 to June 2019.

Conclusions

There has been a gradual increase in geomean nitrate concentrations of well samples each water year of site monitoring (i.e., May 1 to June 30; Figure 8). In contrast, concentrations of chloride, a conservative element that can move freely through the soil without chemical, physical, or biological modification, did not exhibit any statistically significant change over the monitoring period in ephemeral stream and well samples (Figure 8).

The chloride concentration and electrical conductivity of slurry in holding ponds 1 and 2 is appreciably greater than that measured upstream of the C&H Farm in Big Creek (i.e., BC6), which represents background concentrations not impacted by farm operations (see Table 4). Given chloride and electrical conductivity can be considered as conservative tracers of water flow, the lack of any increasing trend in these analytes for well (W1), trench (T1 and T2), or ephemeral stream (BC4) samples, suggests that elevated nitrate-N concentrations in well and ephemeral stream samples may be influenced by sources other than the holding ponds (i.e., sources that have low chloride and electrical conductivity values).

The mean concentration of nutrients, coliform, chloride, and electrical conductivity are provided in Table 4, along with respective concentrations for manure slurry collected from holding ponds 1 and 2 over the last two years, in addition to concentrations reported in published data for other swine manure holding ponds in Kansas and Manitoba. While there is a wide range in concentrations reported in the literature, the mean values are similar to those of manure collected from holding pond 1 (Table 4). Holding pond 2 has lower nutrient and conductivity values that reflect the accumulation of slurry from which solids of higher nutrient content have settled out in holding pond 1. The mean concentration of dissolved P, total P, total N, chloride, and electrical conductivity are appreciably lower than values measured in manure from holding pond 1 (Table 4).

These findings indicate that there is no evidence of major leakage of manure from holding ponds 1 or 2, at the present time.

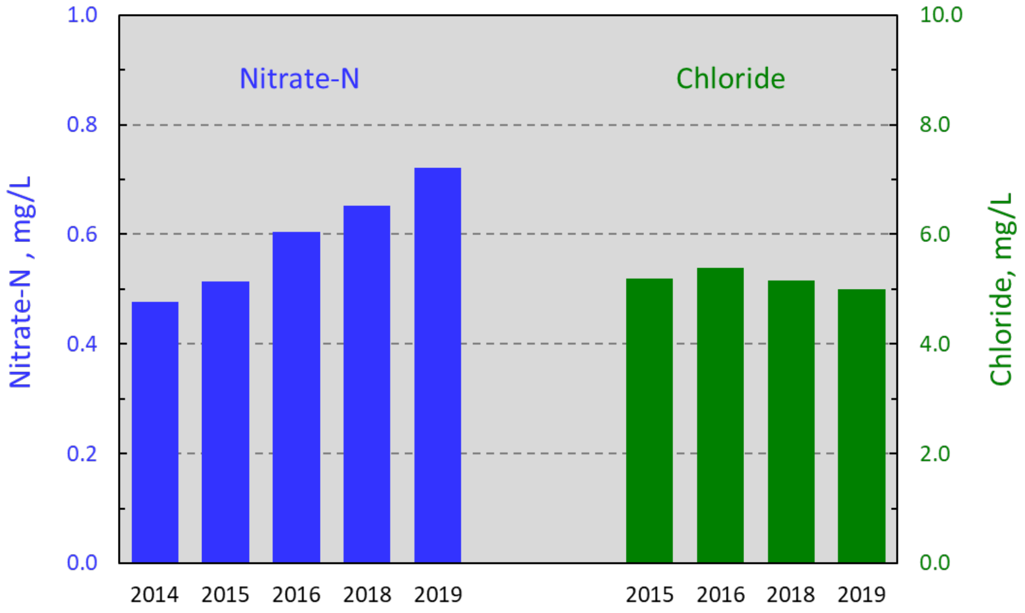


Figure 8. Geomean annual nitrate-N and chloride concentrations in the house well, based on water sampling year, which is May 1 to April 30 for 2014, 2015, 2016, 2017, and 2018 for nitrate-N and 2015, 2016, 2017, and 2018 for chloride. Vertical bars represent concentration range from minimum and maximum values. There were 31, 43, 32, 43, and 38 samples collected in 2014, 2015, 2016, 2017, and 2018 water years, respectively.

Table 2. Mean concentrations of water quality analyses for samples collected from the manure holding ponds, interceptor trenches, house well, ephemeral creek, upstream of farm and downstream of farm.

Source	#	Diss. P	Total P	Ammonia-N	Nitrate-N	Total N	Chloride	E. coli	Conductivity
		- - - - - - - - - - - - - - mg/L - - - - - - - - - - - - - - -						MPN/100 mL	µS/cm
Holding pond 1	7	176.5	1,284.8	1,146.7	0.058	2,614	467.5	N.D.	12,413
Holding pond 2	7	99.5	270.4	589.4	0.088	1,101.4	483.3	N.D.	8,159
Trench 1[¶]	65	0.004	0.023	0.02	0.57	0.75	1.51	433.3	220
Trench 2[¶]	40	0.014	0.075	0.07	1.35	2.06	0.83	921.0	172
House well[§]	197	0.009	0.021	0.02	0.62	0.70	5.27	12.1	435
Ephemeral creek[†]	135	0.016	0.092	0.07	0.92	1.36	2.86	1096.5	314
Manure from literature - mean *	162	363	579	1,445	N.D.	2,460	390	N.D.	N.D.
Manure from literature – range *	162	50 – 3,810	60 – 1,209	560 – 5,540	N.D.	610 – 10,140	73 – 1,149	N.D.	N.D.

N.D. Not determined.
¶ Samples collected August25, 2014 to June 26, 2019.
§ Samples collected April 2, 2014 to June 26, 2019.
† Samples collected March 18, 2014 to June 26, 2019.
* Values from published data; DeRouchey et al., 2002 and Malley et al., 2001.

References

DeRouchey, J.D., G. L. Keeler, R. D. Goodband, J. L. Nelssen, M. D. Tokach, and S. S. Dritz. 2002. Manure composition from Kansas swine lagoons and hoop barn manure. Journal of Animal Science 80(8):2051-2061.

Helsel, D.R., and R.M. Hirsch. 2002. Statistical methods in water resources. Chapter A3. *In* Techniques of Water-Resources Investigations of the United States Geological Survey. Book 4, Hydrologic Analysis and Interpretation. U.S. Geological Survey. Available at https://pubs.usgs.gov/twri/twri4a3/pdf/twri4a3-new.pdf. 524 pages.

Hobza, C.M. 2006. ground-water quality near a swine waste lagoon in a mantled karst terrane in Northwestern Arkansas. Master's Thesis. Geology, University of Arkansas, Fayetteville, AR. 81 pages.

Malley, D.F., P.D. Martin, and S.E. Woods. 2001. Analysis of nutrients in hog manure by field-portable near-infrared spectroscopy: Development of a mobile laboratory and results for Foss NIRSystem Inc. Model 6500 Spectrophotometer in the laboratory. Final Report 1 of 3 to CETAC-West on Manure Demo Project. Winnipeg, Manitoba, Canada. 33 pages. Available at http://www.pdkprojects.com/pdf/cetacfinalreport1manurenutrients6500reviseds.pdf.

Pilgrim, D.H., and D.D. Huff. 1978a. A field evaluation of subsurface and surface runoff: I. Tracer studies. Journal of Hydrology, 38:29-318.

Pilgrim, D.H., and D.D. Huff. 1978b. A field evaluation of subsurface and surface runoff: II. Runoff processes. Journal of Hydrology, 38:319-341.

Smettem, K.R.J., D.J. Chittleborough, B.G. Rishards, and F.W. Leaney. 1991. The influence of macropores on runoff generation from a hillslope soil with a contrasting textural class. Journal of Hydrology, 122:235-252.

Trudgill, S.T., A.M. Pickles, K.R.J. Smettem, and R.W. Crabtree. 1983. Soil water residence time and solute uptake: I. Dye tracing and rainfall events. Journal of Hydrology, 60:257-279.

Wagner, D. 2005. Applications of δ15N, δ18O of nitrate to waste storage effectiveness in mantled karst terrain, Northwestern Arkansas. Master's Thesis. Geology, University of Arkansas, Fayetteville, AR. 109 pages.

Weyman, D.R. 1974. Runoff processes, contributing area and streamflow in a small upland catchment. *In*: K.J. Gregory and D.E. Walling (Editors), Fluvial Processes in Instrumented Watersheds. British Institute of Geography, London, Spec. Publ., 6:33-43. London, United Kingdom.

Supplemental Information, Tables, and Figures

Soil Description Adjacent to Animal Barns and Slurry Holding Ponds

Soils adjacent to the animal barns and slurry holding ponds on the C&H Farm are classified as Noark very cherty silt loams, ranging from 3 to 40% slopes (Figure S1 and Table S1). The area south of the slurry holding ponds, where the inceptor trenches are (T1 and T2) located, borders between soil map units 42 and 43, which have 3 to 8% slopes identified during trench installation. Pipe was installed in the inceptor trench (i.e., French drain) located just below the BE horizon, a depth of 20 to 30 inches below the soil surface (Table S2). This is the 2Bt1 horizon. From Table S2 it can be seen that the 2Bt1 (i.e., very gravelling clay) horizon has a markedly greater fine clay-sized particles compared to the above BE horizon (i.e., very gravelling silty clay loam). This increase in clay imparts a zone of reduced permeability, such a portion of any seepage from the base of the ponds would move laterally above this transition to the inceptor trench.

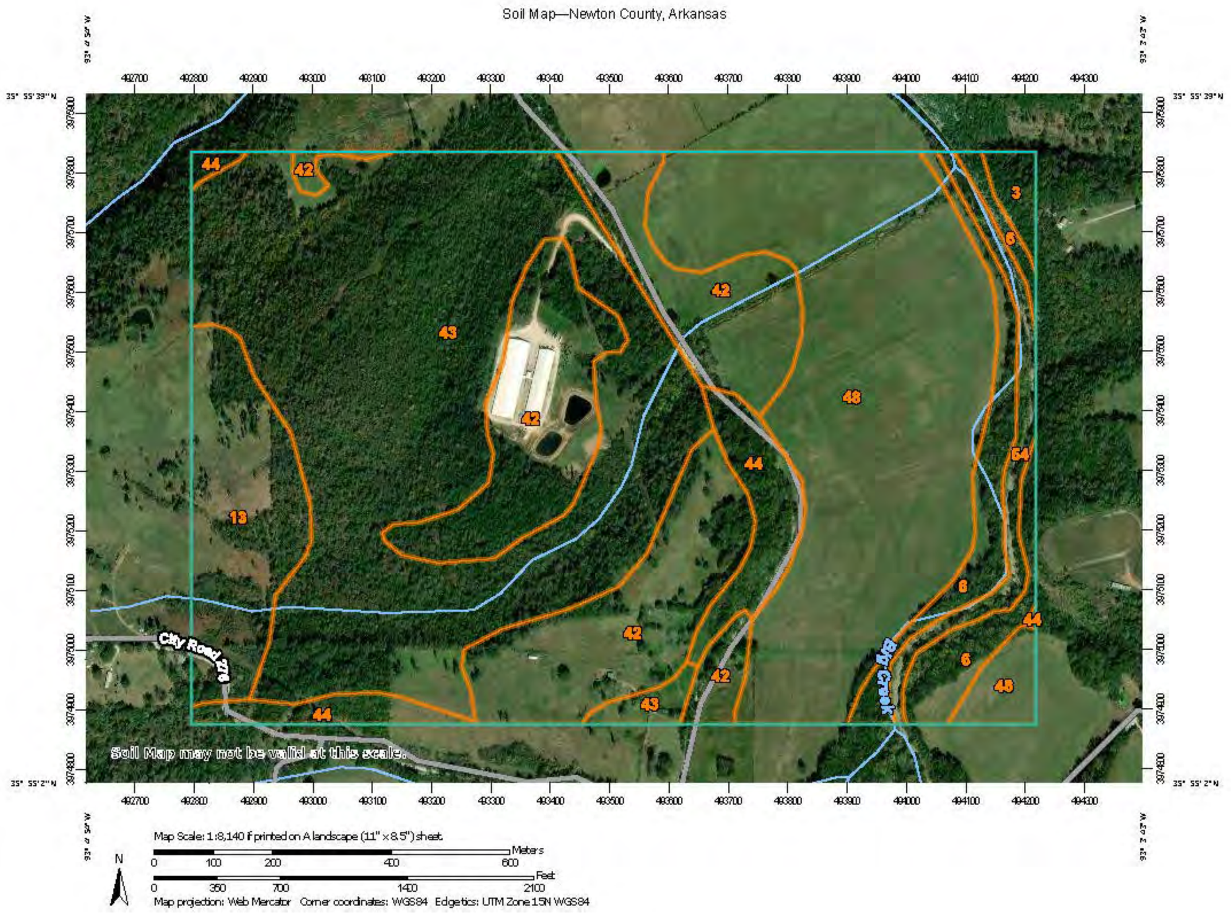


Figure S 1. Soils adjacent to the animal barns and slurry holding ponds at the C&H Farm.

Table S 1. Soil map unit descriptions in the area adjacent to the animal barns and slurry holding ponds at the C&H Farm.

Map unit legend	Map unit name	Acres in area of interest	Percent area of interest
3	Arkana-Moko complex, 20 to 40 percent slopes	2.5	0.7
6	Ceda-Kenn complex, 0 to 3 percent slopes, frequently flooded	18.3	5.4
13	Enders stony loam, 3 to 15 percent slopes	23.1	6.8
42	Noark very cherty silt loam, 3 to 8 percent slopes	68.1	20.1
43	Noark very cherty silt loam, 8 to 20 percent slopes	120.8	36.8
44	Noark very cherty silt loam, 20 to 40 percent slopes	14.2	4.2
48	Razort loam, occasionally flooded	84.0	24.8
54	Water	7.9	2.3

Noark Soil Series Profile Description

The Noark series consists of very deep, well drained, moderately permeable soils that formed in colluvium and clayey residuum from cherty limestones. These soils are on nearly level to very steep uplands of the Ozarks. Slopes range from 1 to 45%. The mean annual temperature is about 56 ^{o}F, and the mean annual precipitation is about 42 inches.

TAXONOMIC CLASS: Clayey-skeletal, mixed, semiactive, mesic Typic Paleudults

TYPICAL PEDON: Noark very gravelly silt loam, forested. (Colors are for moist soil unless otherwise stated.)

A--0 to 3 inches; dark grayish brown (10YR 4/2) very gravelly silt loam; moderate medium granular structure; friable; many medium roots; about 40% by volume angular chert fragments less than 3 inches in diameter; very strongly acid; abrupt smooth boundary. (1 to 7 inches thick)

E--3 to 12 inches; brown (10YR 5/3) very gravelly silt loam; weak medium subangular blocky structure; friable; many fine roots; about 40% by volume angular chert fragments less than 3 inches in diameter; extremely acid; clear wavy boundary. (6 to 14 inches thick)

BE--12 to 19 inches; yellowish red (5YR 4/6) very gravelly silty clay loam; pockets and streaks of brown (10YR 5/3) silt loam; moderate medium subangular blocky structure; firm; many fine roots; about 40%

by volume angular chert fragments less than 3 inches in diameter; very strongly acid; clear wavy boundary. (0 to 11 inches thick)

2Bt1--19 to 26 inches; red (2.5YR 4/6) very gravelly clay; strong medium blocky structure; very firm; common fine roots; common fine pores; many thin patchy clay films on ped faces and chert fragments; about 40% by volume angular chert fragments less than 3 inches in diameter; extremely acid; gradual wavy boundary.

2Bt2--26 to 37 inches; dark red (2.5YR 3/6) very gravelly clay; strong medium blocky structure; very firm; few fine roots; common fine pores; thick continuous clay films on ped faces and chert fragments; about 50% by volume chert fragments less than 3 inches in diameter; extremely acid; gradual wavy boundary.

2Bt3--37 to 80 inches; dark red (2.5YR 3/6) extremely gravelly clay; strong medium blocky structure; very firm; thick continuous clay films on ped faces and chert fragments; about 70% by volume angular chert fragments less than 3 inches in diameter; extremely acid. (Combined thickness of the 2Bt horizon ranges from 31 to 73 inches or more.)

Geologic Description

Below is a summary of the Harbor Environmental and Safety Drilling Study Report submitted to the Arkansas Department of Environmental Quality, December 2016 (available at https://www.adeq.state.ar.us/water/bbri/c-and-h/drilling.aspx#collapseResults). The drilling was conducted adjacent to the C&H animal houses and slurry holding ponds, which was approximately 20 m from the BCRET interceptor trenches.

The uppermost geologic formation below the site is the Mississippian-age Boone Formation, a fossiliferous limestone interbedded with abundant chert, which varies considerably in abundance vertically and horizontally. The chert-free St. Joe Member is observed at the base of the Boone Formation. The Boone Formation is well known for dissolutional features, such as sinkholes, caves, and enlarged fissures. Thickness of the Boone Formation ranges from approximately 90 to 107 m (300 to 350 ft) in most of northern Arkansas. Groundwater below the site is contained within the Springfield Plateau aquifer, comprising the Boone Formation and the St. Joe Member of the Boone Formation.

The ADEQ test boring encountered yellowish red silty clay (CL) with chert and limestone fragments from the surface to a depth of 2.5 m (8 ft) below ground surface. All subsequent depths are stated as below ground surface. This material appeared to be fill soil placed during construction of the hog farm and adjacent waste ponds. Yellowish red fat clay (CH) was encountered from 2.5 to 4 m (8 to 13.5 ft). Fine-grained, fossiliferous, gray limestone was encountered from 13.5 feet to 20 feet with a six-inch seam of fat clay as above occurring from approximately 5.5 to 5.6 m (18 to 18.5 ft). Weathered and fractured, fossiliferous gray to buff limestone was encountered from 6.0 to 8.7 m (20 to 28.5 ft). The driller reported drilling water loss in this zone.

Competent, fossiliferous gray limestone (consistent with the Boone Formation), with some minor fracturing and bedding planes was encountered at 8.7 m (28.5 ft), which generally extended to 37 m (120 ft). Zones of increased fracturing were encountered around 21 and 27 m (70 and 90 ft); however, no karst features such as dissolution features were encountered. Natural gamma logging correlated with the boring log with counts ranging 60 to 100 counts/sec in the upper 4.6 m (15 ft) as would be expected in a clay, but decreasing from 4.6 to 6.1 m (15 to 20 ft; as would be expected in a limestone.

From 6.1 to 36.6 m (20 to 120 ft), natural gamma counts range from approximately 20 to 40 counts/sec, but are typically in the 20 to 30 counts/sec range. Minor spikes of increased counts, which might suggest weathered zones, occur at 20, 24, and 30 m (64, 78, and 115 ft). Neutron logging also correlated well with the boring log. Neutron counts range from approximately 750 to 1,750 counts/sec in the upper 4.6 m (15 ft), as would be expected in a high moisture clay and increased 4.6 to 6.1 m (15 to 20 ft) as the subsurface material becomes more dense (as would be expected in a less porous limestone). From 6.7 to 30.2 m (22 to 99 ft), neutron counts range from approximately 1,750 to 3,000 counts/sec. At 30.2 m (99 ft), a sharp drop in neutron counts occurs. From 30.5 to 36.6 m (100 to 120 ft, neutron counts range from approximately 600 to 1,500 counts/sec, suggesting a porous zone.

Core analysis from 8.5 m to a total depth of 36.6 m (28 to 120 ft), confirmed the Boone Formation, and basal St. Joe Limestone member. Zones of thin bedding that appeared to be mechanically broken by the drilling process were observed, but no significant karst voids were identified in core recovery or by driller observation. The primary karst feature identified was the epikarst zone noted between 4.2 and 8.5 m (13.8 and 28.0 ft).

Table S 2. Drilling log for water well on the C&H Farm.

A

1. Contractor Name & Number: 1077 ARNOLD WELL DRILLING & PUMP SE
2. Driller Name & Number: 2819 JOSHUA ARNOLD
3. Pump Installer Name & Number:
4. Date Well Completed: 02/15/2013 New Well

5. COUNTY : NEWTON (101)

6 FRACTION ¼ of ¼

7 SECTION:

8 TOWNSHIP

9 RANGE

11. LONGITUDE 93-04-23 12. LATITUDE 35-55-27

FT TO: FT

B

DESCRIPTION OF FORMATION	DEPTHS IN FEET		WATER BEARING	IF YES.. DEPTH
	FROM	TO		
Red Clay	0	54	No	
Gray Limestone	54	310	Yes	145
White Limestone	310	320	No	
Gray Limestone	320	325	No	
			Yes	285
			No	
			Yes	265
			No	

2. TOTAL DEPTH OF WELL 325

3. STATIC WATER LEVEL 138 Ft. below land surface

4. YIELD 30 gallons per

5. DIAMETER OF BORE HOLE 6.06 IN

C PUMP REPORT

1 TYPE PUMP

2 SETTING DEPTH FEET

3 BRAND NAME AND SERIAL NUMBERS:

4 RATED CAPACITY gallons per minute

5 TYPE LUBRICATION

6 DROP PIPE OR COLUMN PIPE SIZE

7 WIRE SIZE

8 PRESSURE TANK:
SIZE: MAKE: MODEL:

9 DATE OF INSTALLATION OR REPAIR

10 Is there an abandoned water well on the property?

D 1 LAND OWNER OR OTHER CONTACT PERSON

NAME JASON HENSON (C & H FARM)

STREET ADDRESS HC 72 BOX 10

CITY MT JUDEA

CASING FROM 0 TO 74 W/ 6.25 Inner Diameter

CASING FROM TO W/ Inner Diameter

TYPE CASING STEEL

3. SCREEN

TYPE: DIA SLOT/GA

SET FROM FT TO FT

TYPE: DIA SLOT/GA

SET FROM FT TO FT

4. GRAVEL PACK FROM: FT TO: FT

5. BACK FILLED WITH: CUTTINGS

FROM: 0 FT TO: 69 FT

6. SEALED WITH: BENTONITE

FROM: 69 FT TO: 74 FT

FROM: FT TO: FT

7. DISINFECTED WITH: CHLORINE

8. USE OF WELL:

COMMERCIAL

OTHER

A/C HEATPUMP TYPE WELLS

(For A/C only)Will system also be used for purposes other than Heating and Air Conditioning?

If yes, name use:

(For A/C open-loop only) Into what medium is water returned?

11. REMARKS

12. SIGNED DATE

Table S 3. Rainfall and flow from trench 1 and 2 (T1 and T2) following installation of flumes in June, 2016.

	Rainfall	Trench 1	Trench 2
	inches	gallons	
July-16	2.28	22.81	0.09
August-16	2.48	201.78	87.68
September-16	1.65	14.01	0.38
October-16	1.91	10.88	0.25
November-16	0.75	5.21	8.99
December-16	0.10	0.01	0.00
January-17	0.21	0.00	0.00
February-17	0.20	0.00	0.00
March-17	1.56	74.95	48.33
April-17	4.38	538.36	288.46
May-17	2.00	180.71	79.89
June-17	1.64	3.60	1.89
Annual total	***19.16***	***1052.3***	***516.0***
July-17	1.48	14.35	1.54
August-17	1.53	0.44	0.00
September-17	0.08	0.00	0.00
October-17	0.63	29.92	6.30
November-17	0.12	0.29	0.39
December-17	0.74	20.48	0.62
January-18	0.53	6.48	0.36
February-18	2.30	115.57	65.48
March-18	1.77	103.36	68.84
April-18	1.97	138.80	76.64
May-18	1.96	37.07	28.71
June-18	1.71	5.97	0.34
Annual total	***14.82***	***472.7***	***249.2***

July-18	1.58	20.75	14.57
August-18	4.06	429.06	230.64
September-18	1.23	29.74	11.37
October-18	2.02	7.89	16.15
November-18	1.65	3.95	3.61
December-18	2.39	124.36	12.86
January-19	1.90	3.44	13.37
February-19	2.68	143.01	68.38
March-19	1.38	55.21	0.24
April-19	2.06	99.84	45.39
May-19	3.70	306.61	164.12
June-19	1.92	69.77	41.44
Annual total	***26.57***	***1293.6***	***622.1***
TOTAL	***60.55***	***2818.7***	***1387.3***

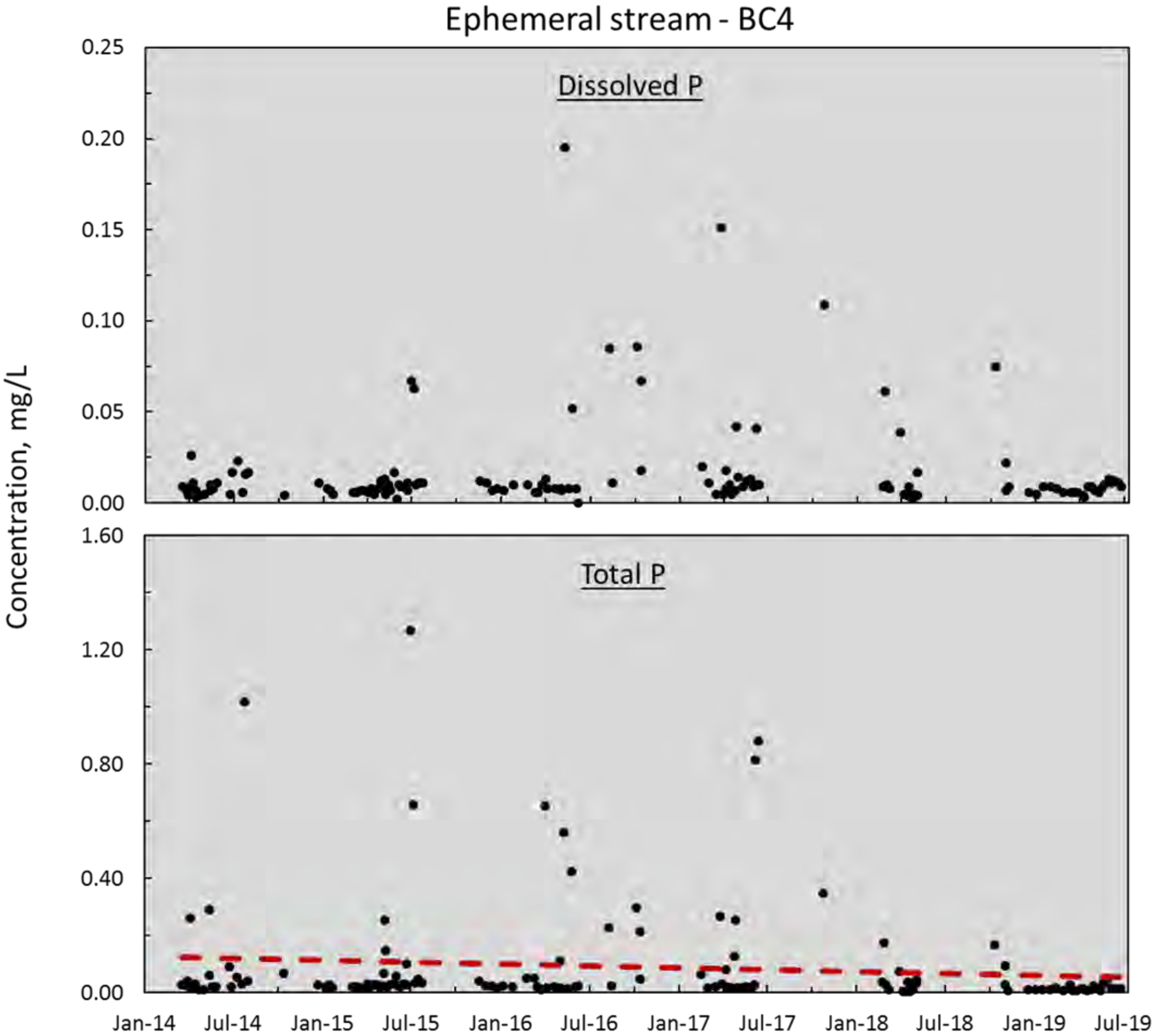


Figure S 2. Dissolved and total P concentration measured in the ephemeral stream (BC4) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

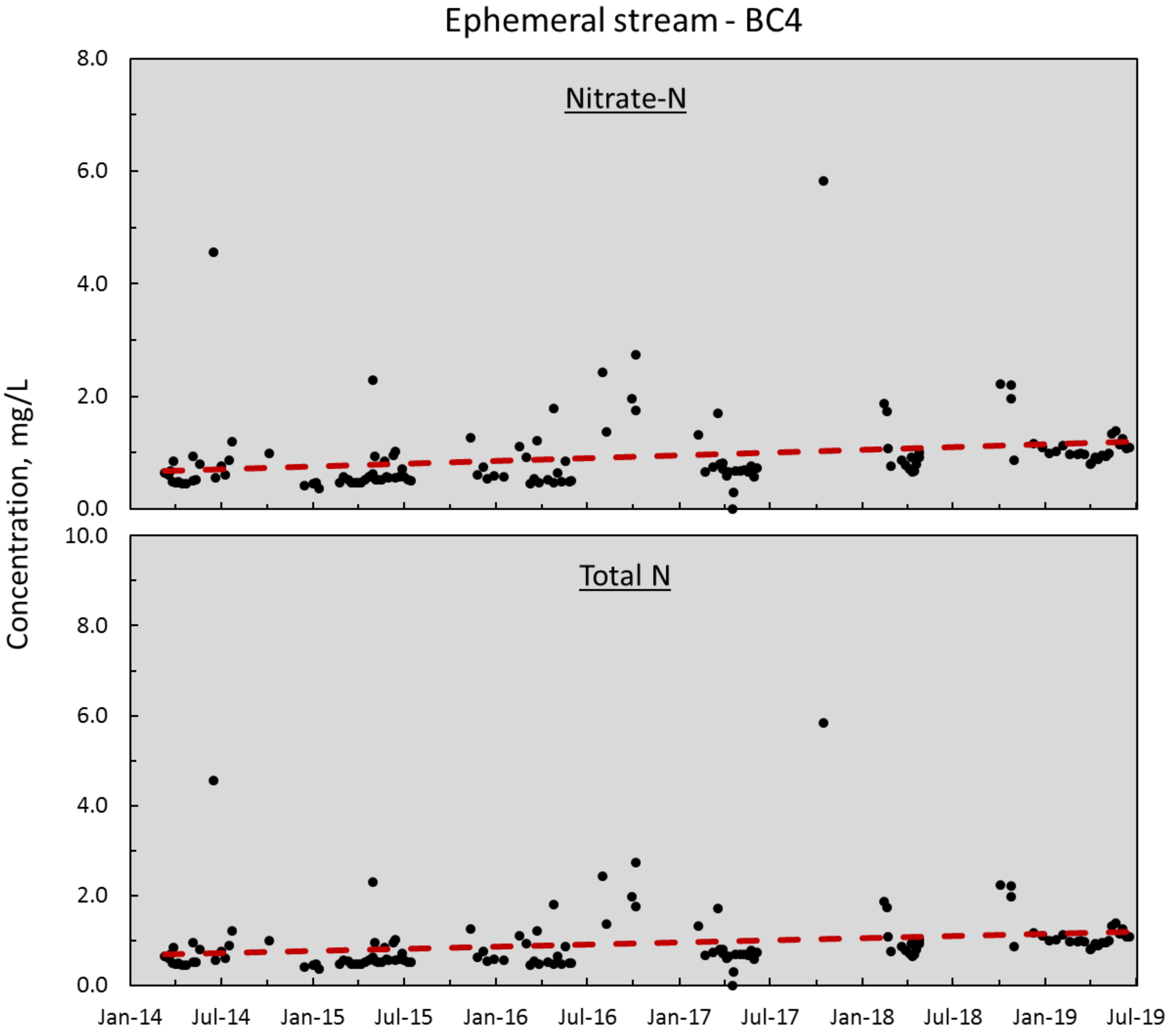


Figure S 3. Nitrate-N and total N concentration measured in the ephemeral stream (BC4) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

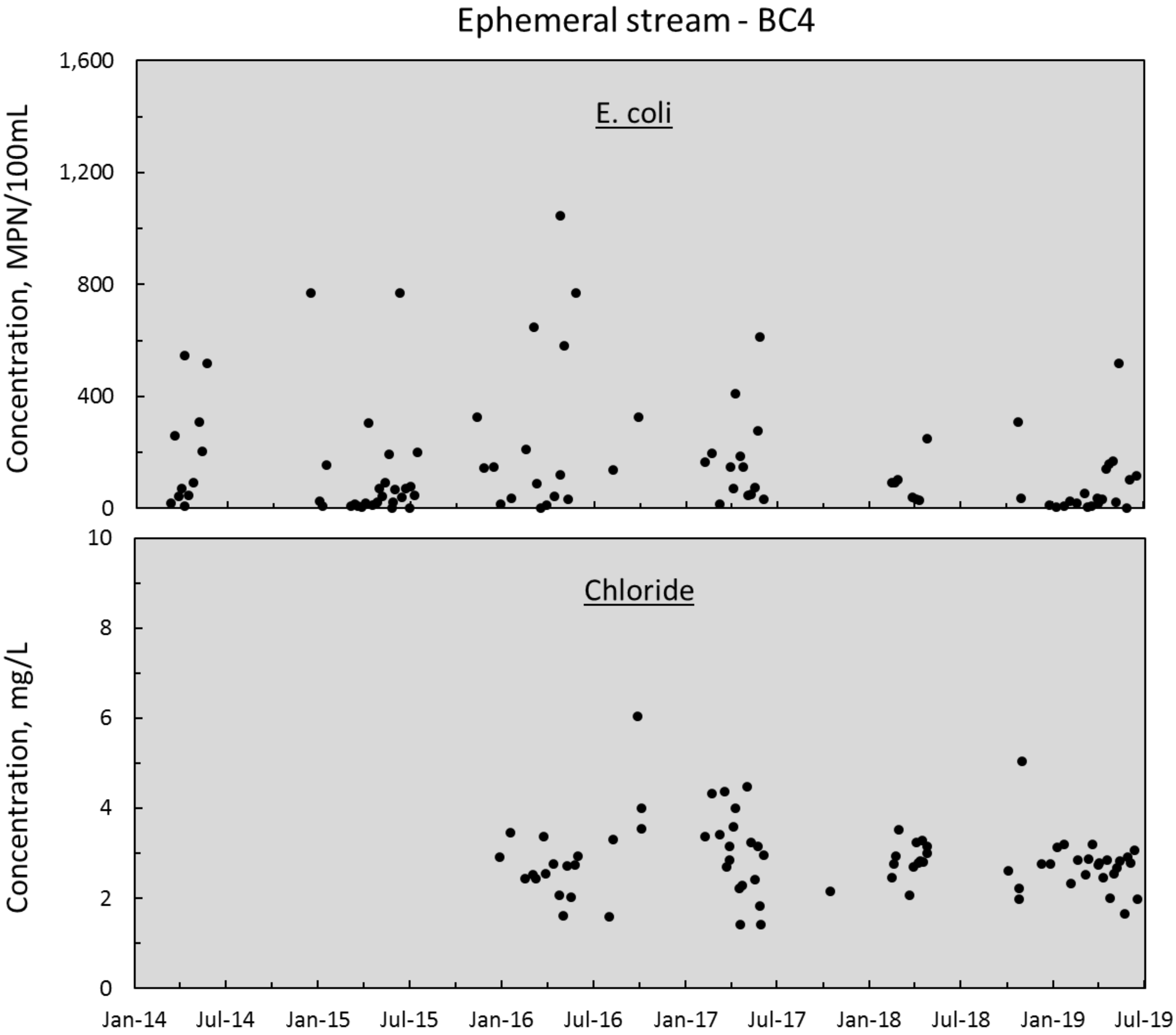


Figure S 4. E. coli and chloride concentration measured in the ephemeral stream (BC4) over the period of monitoring.

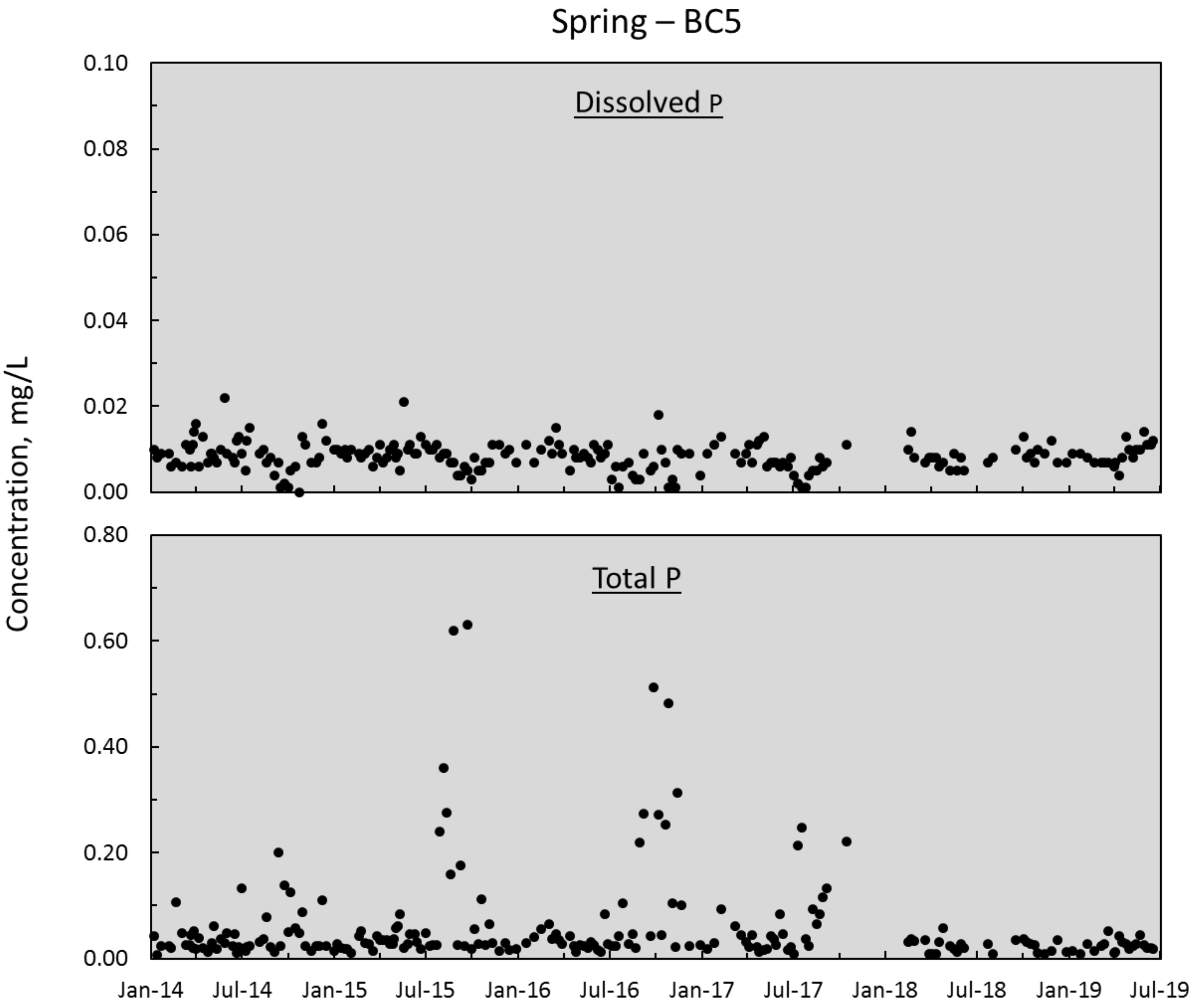


Figure S 5. Dissolved and total P concentration measured in the spring (BC5) over the period of monitoring.

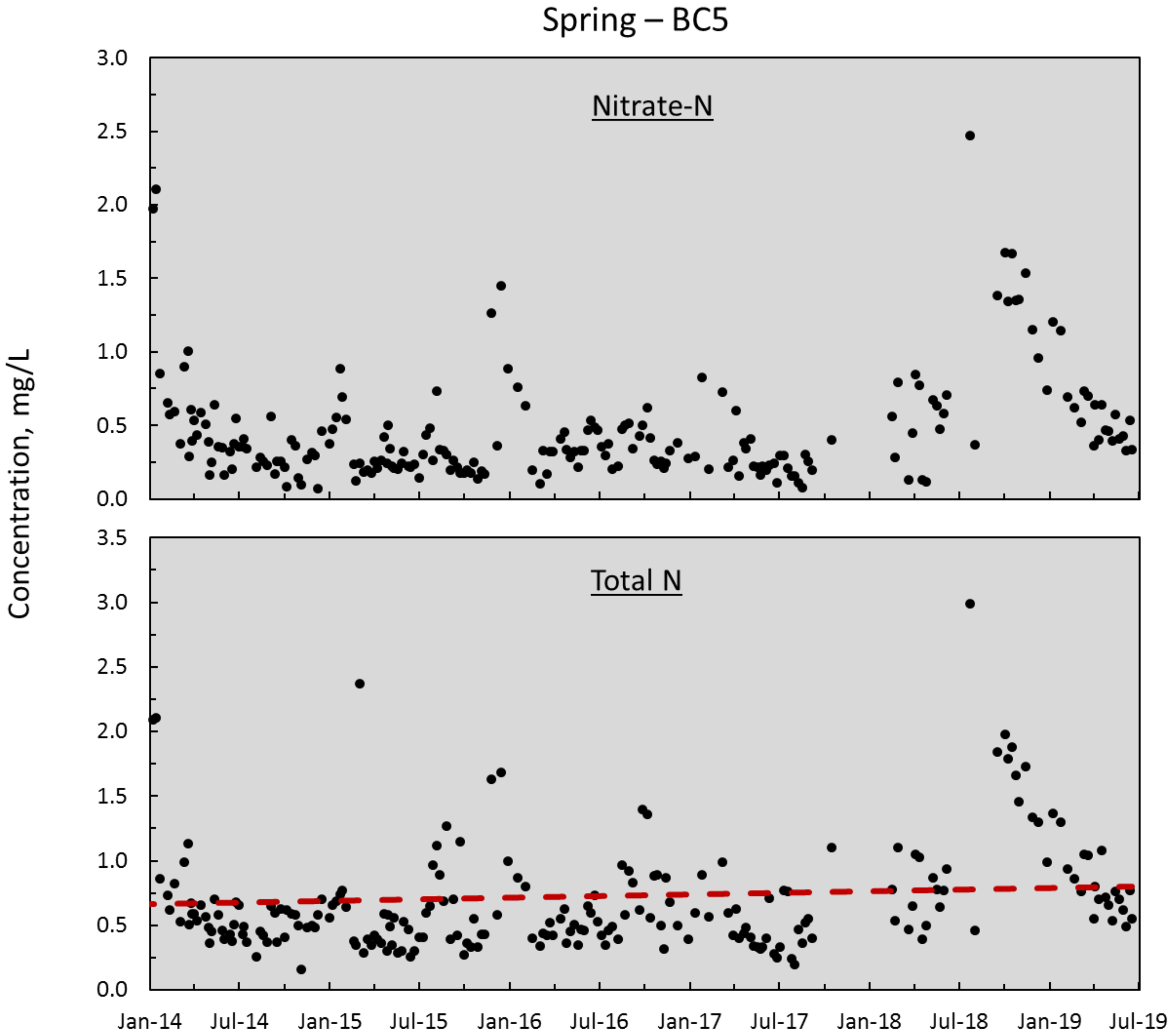


Figure S 6. Nitrate-N and total N concentration measured in the spring (BC5) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

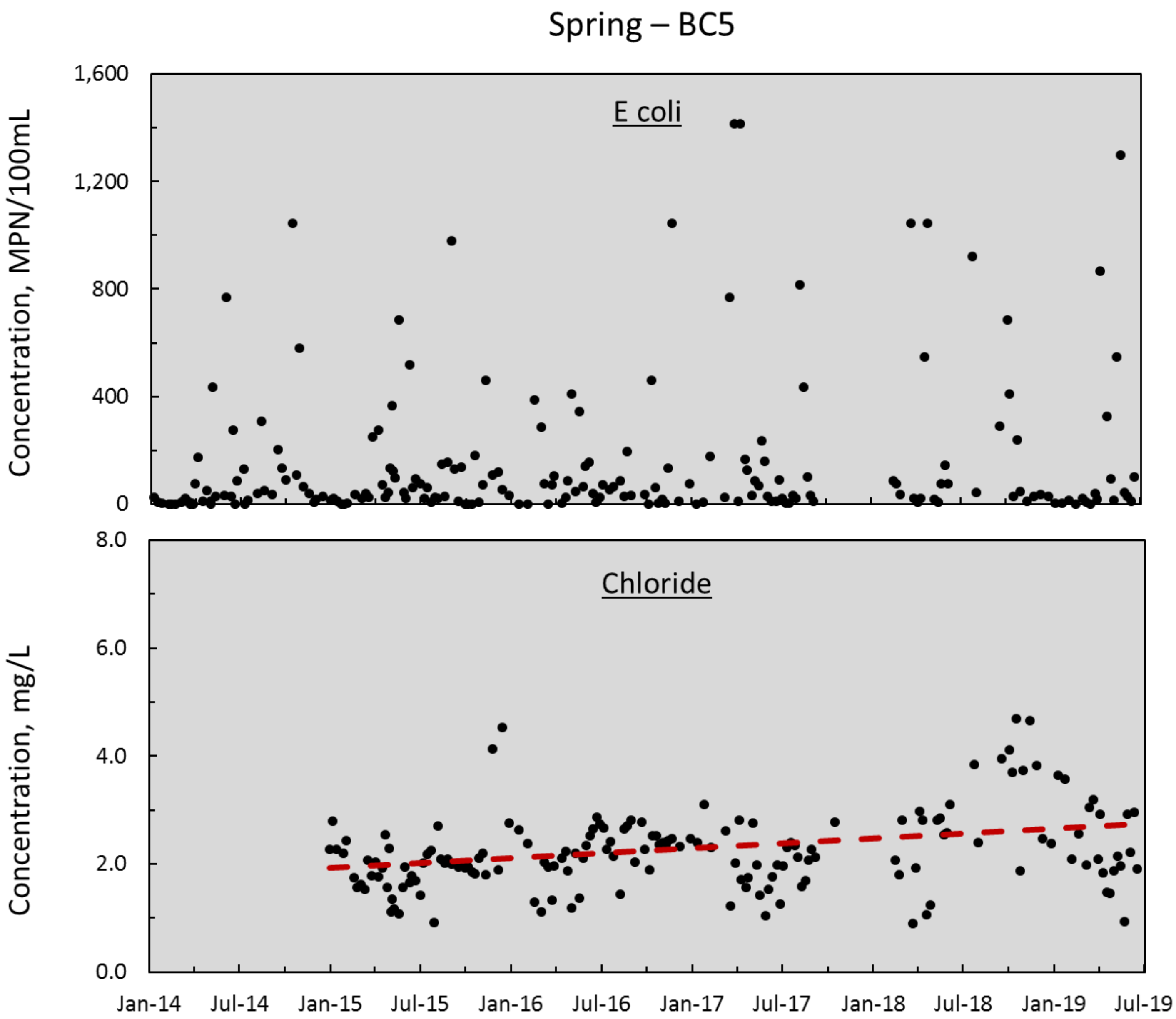


Figure S 7. E. coli and chloride concentration measured in the spring (BC5) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

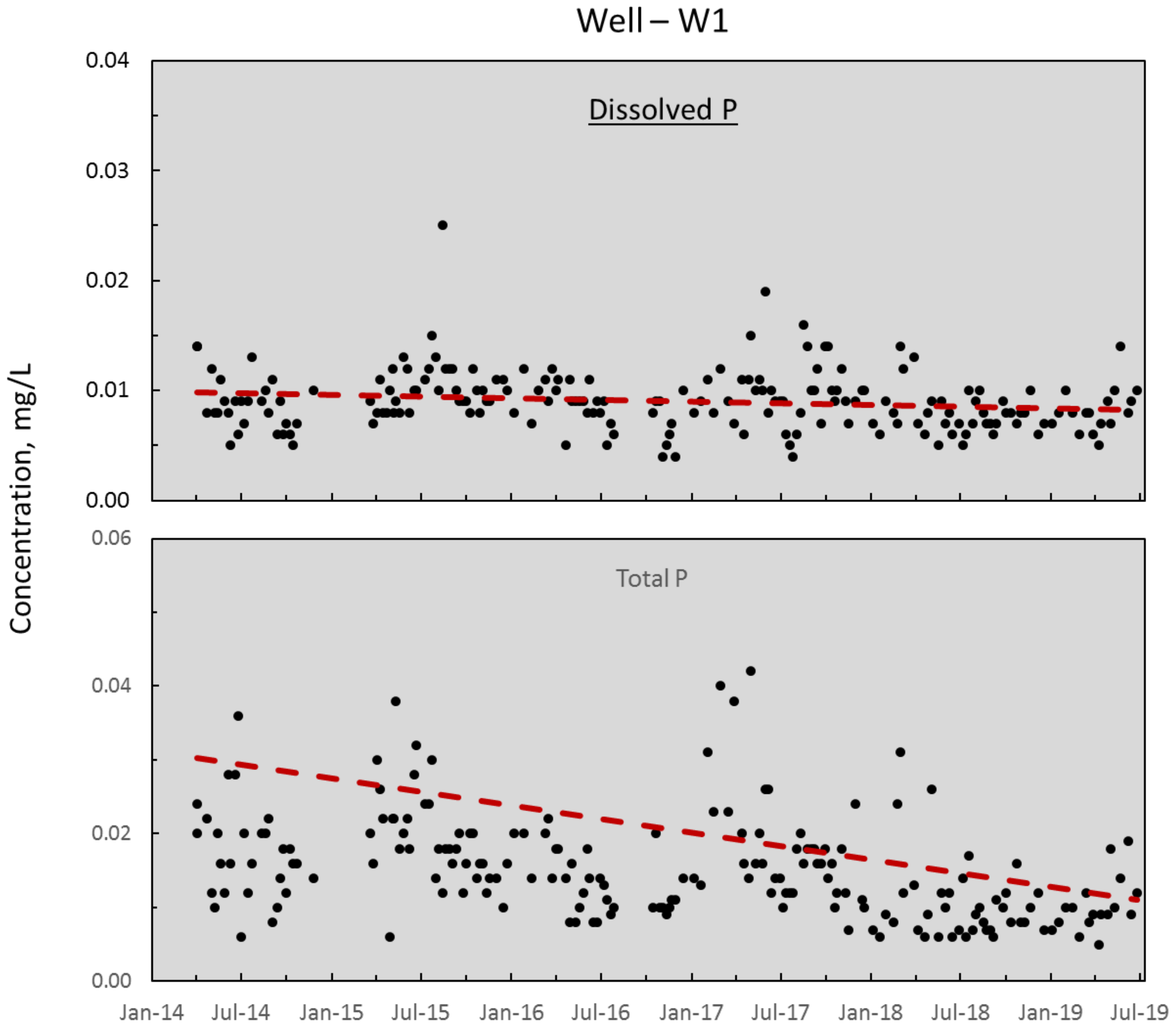


Figure S 8. Dissolved and total P concentration measured in the well (W1) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

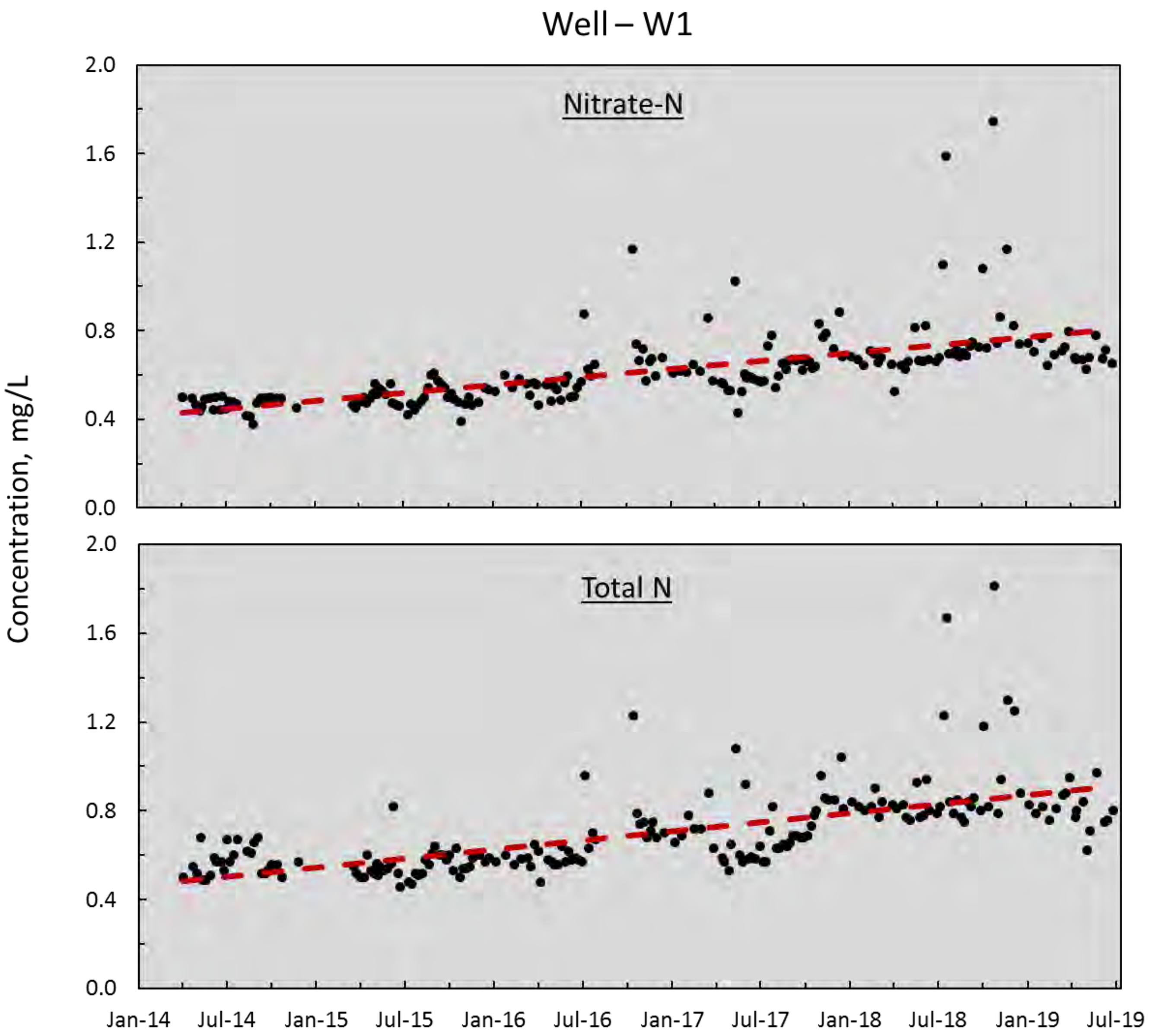


Figure S 9. Nitrate-N and total N concentration measured in the well (W1) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

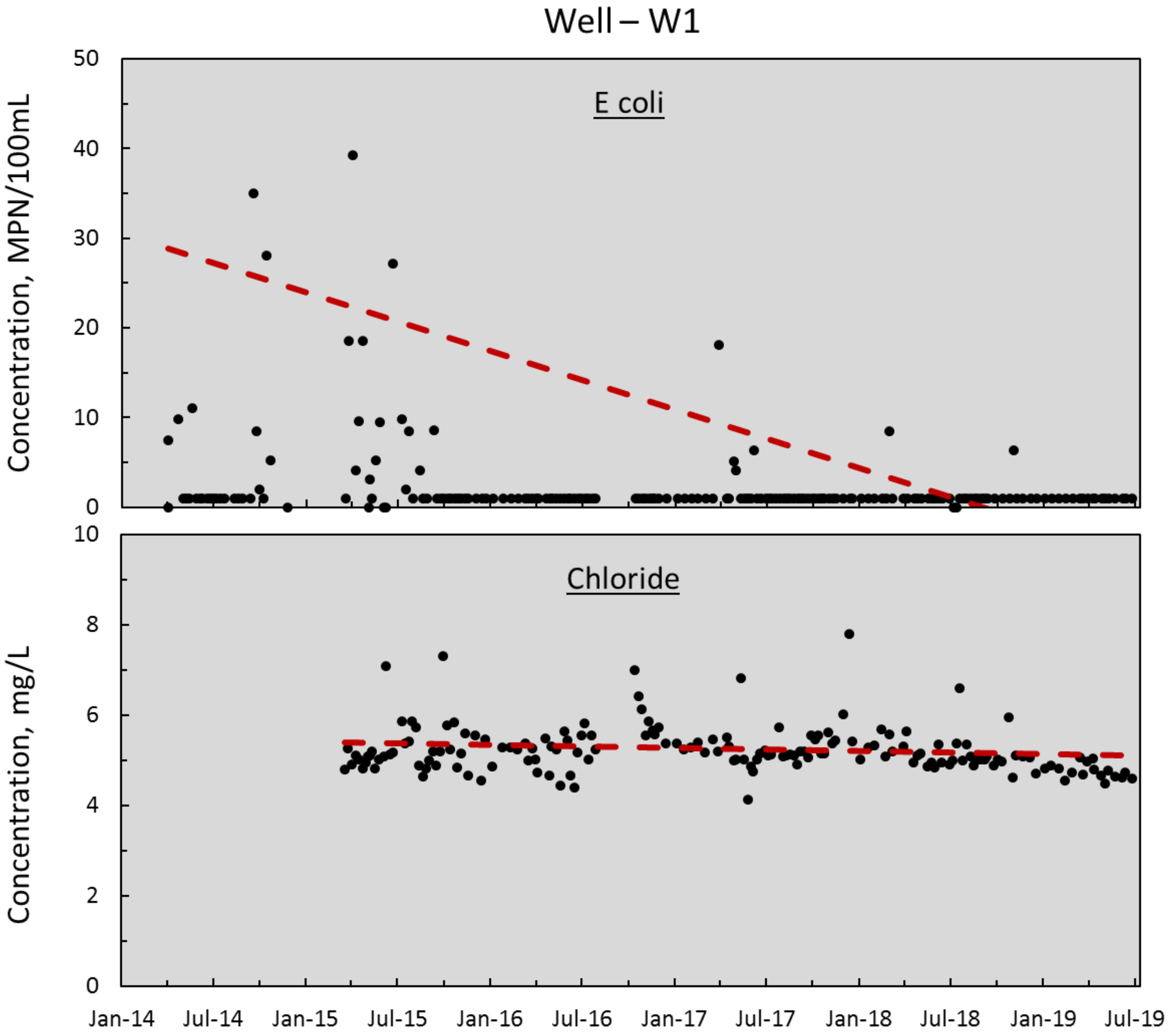


Figure S 10. E. coli and chloride concentration measured in the well (W1) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

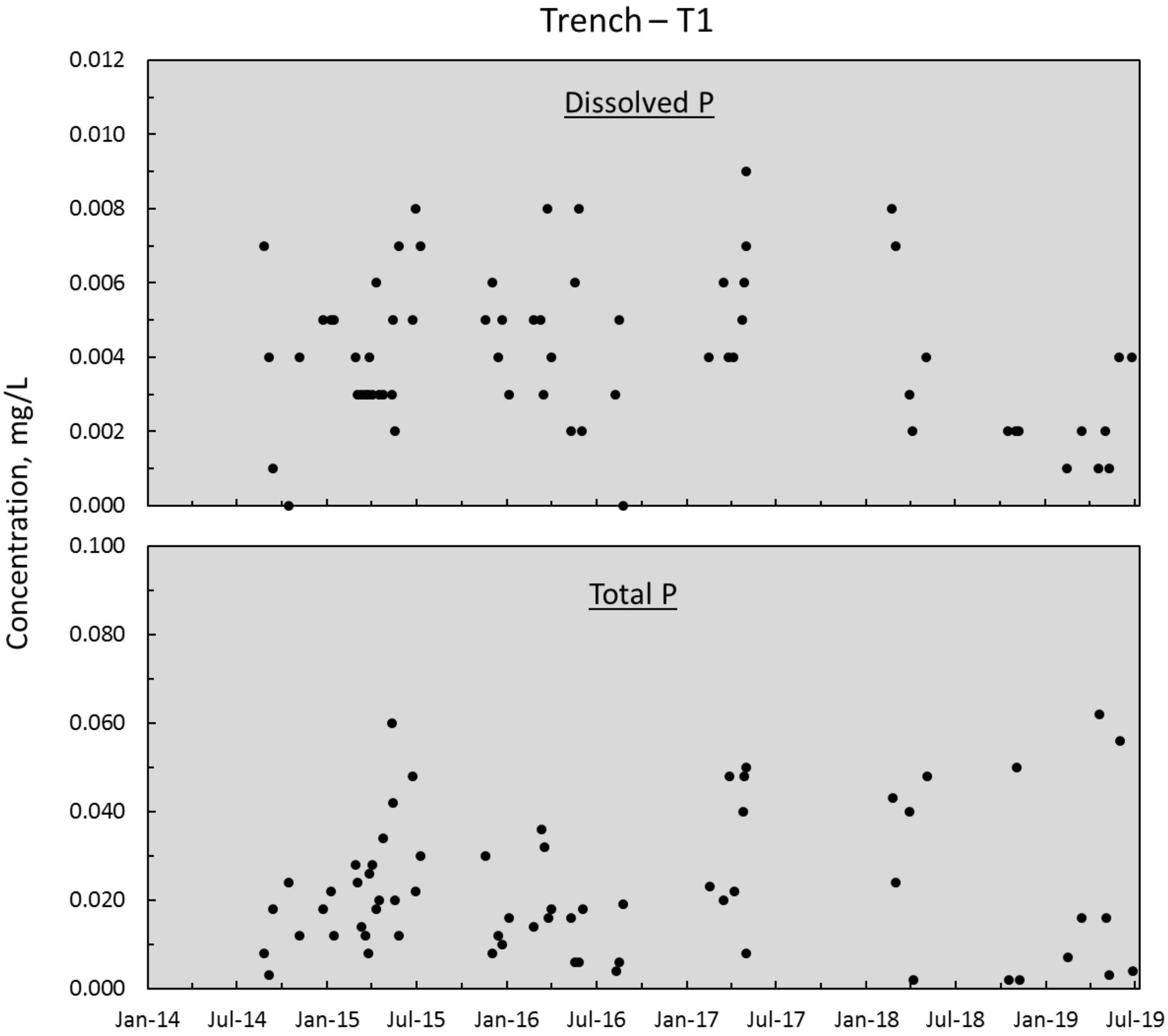


Figure S 11. Dissolved and total P concentration measured in the trench (T1) over the period of monitoring.

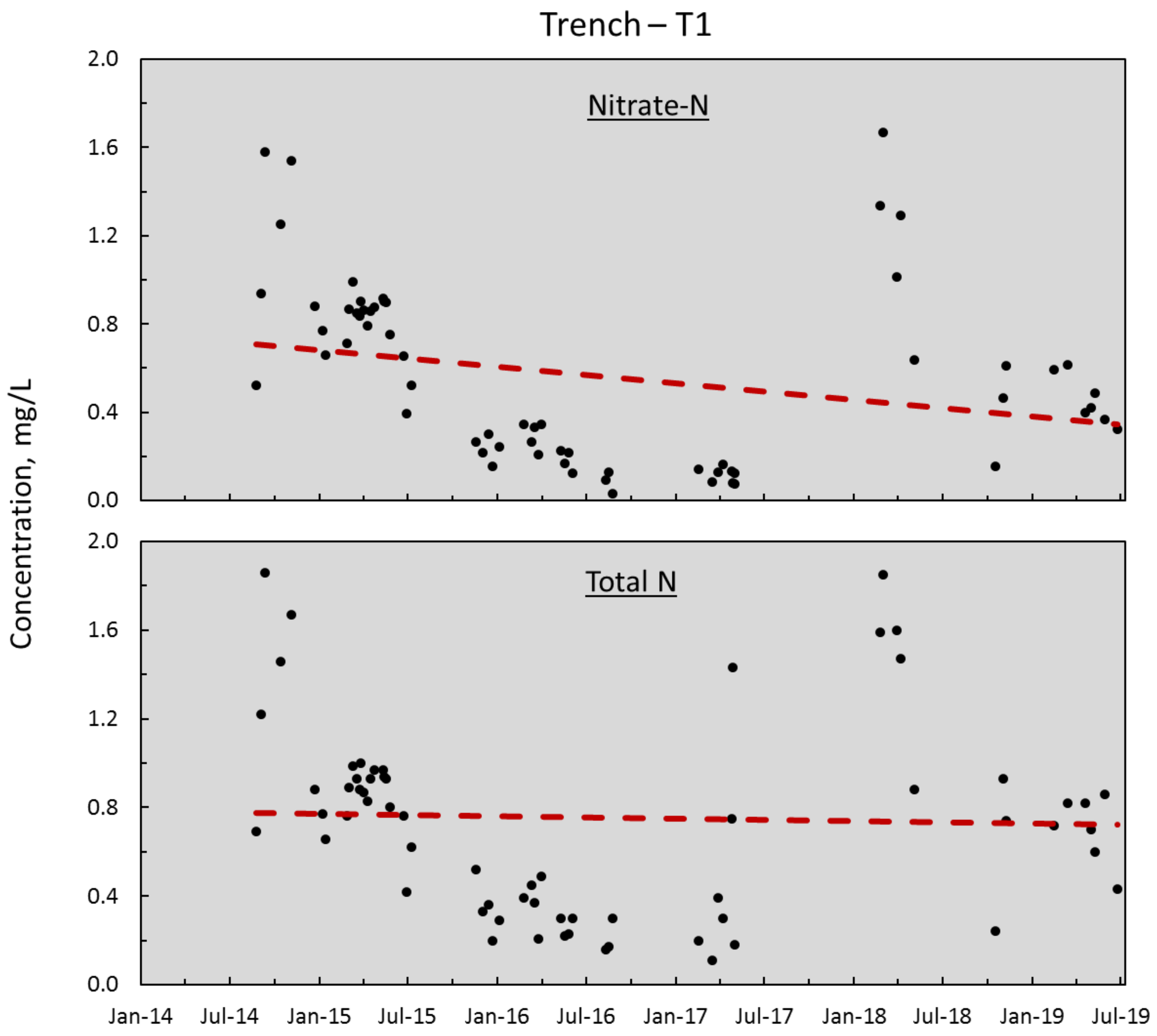


Figure S 12. Nitrate-N and total N concentration measured in the trench (T1) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

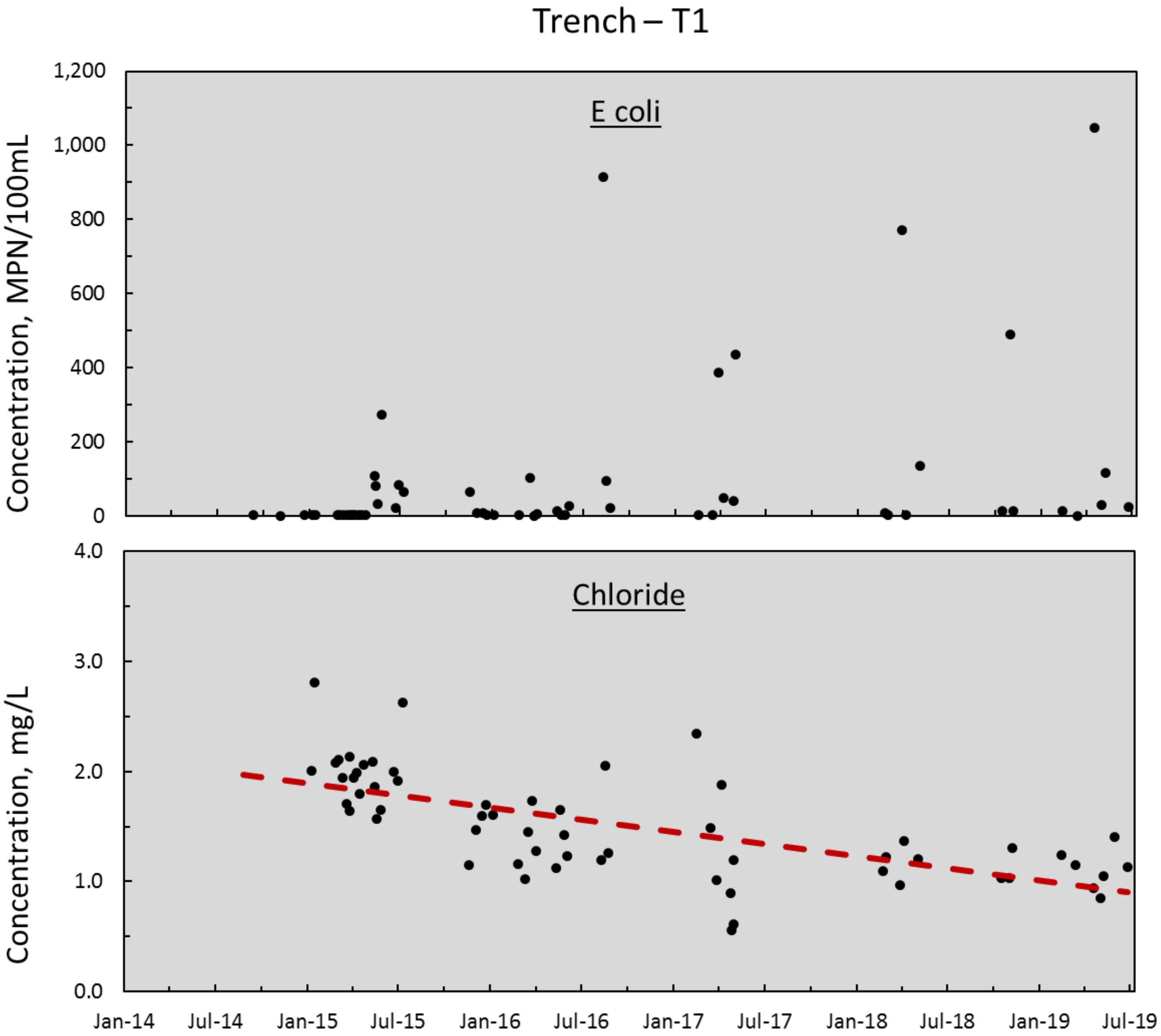


Figure S 13. E. coli and chloride concentration measured in the trench (T1) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

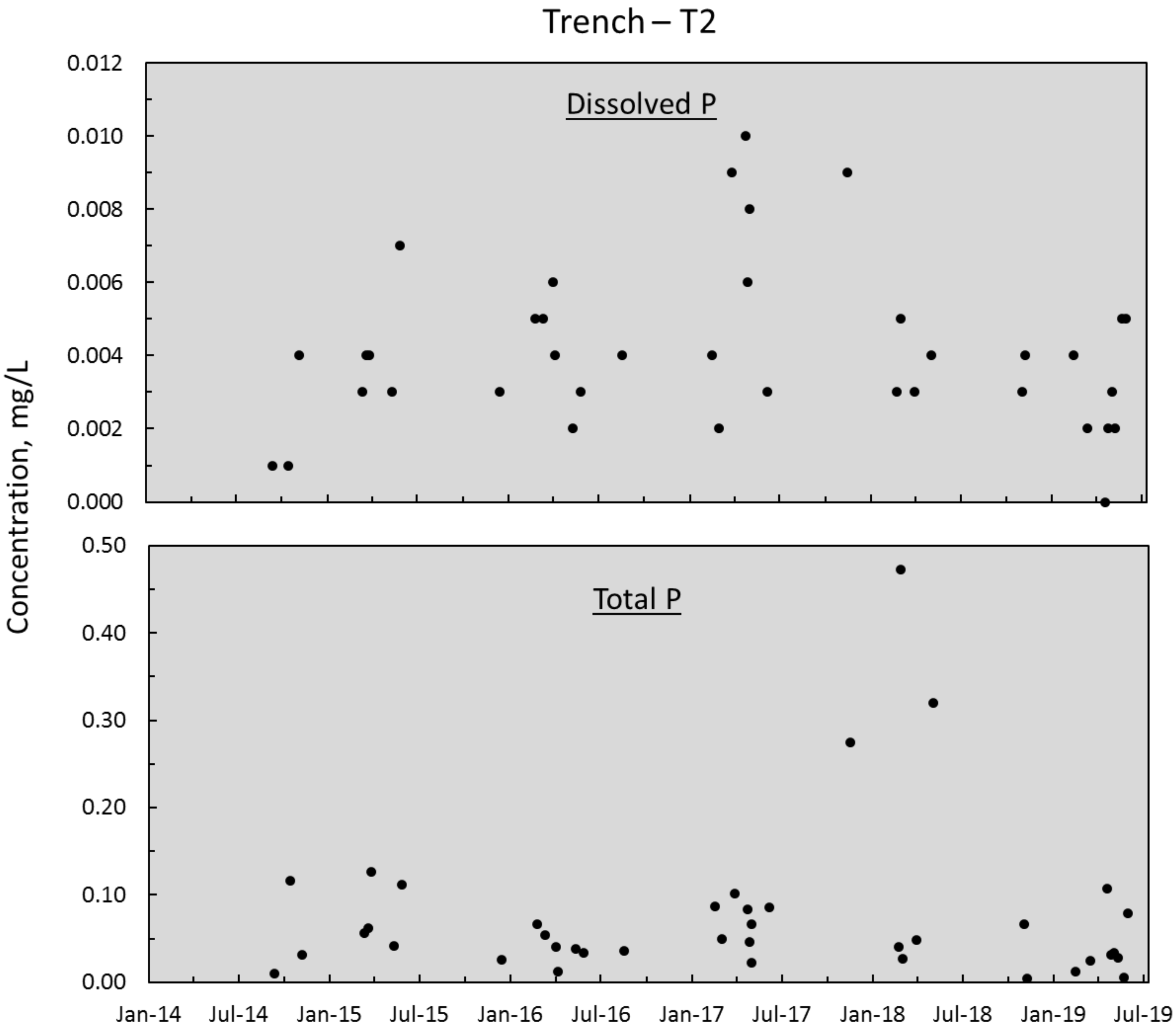


Figure S 14. Dissolved and total P concentration measured in the trench (T2) over the period of monitoring.

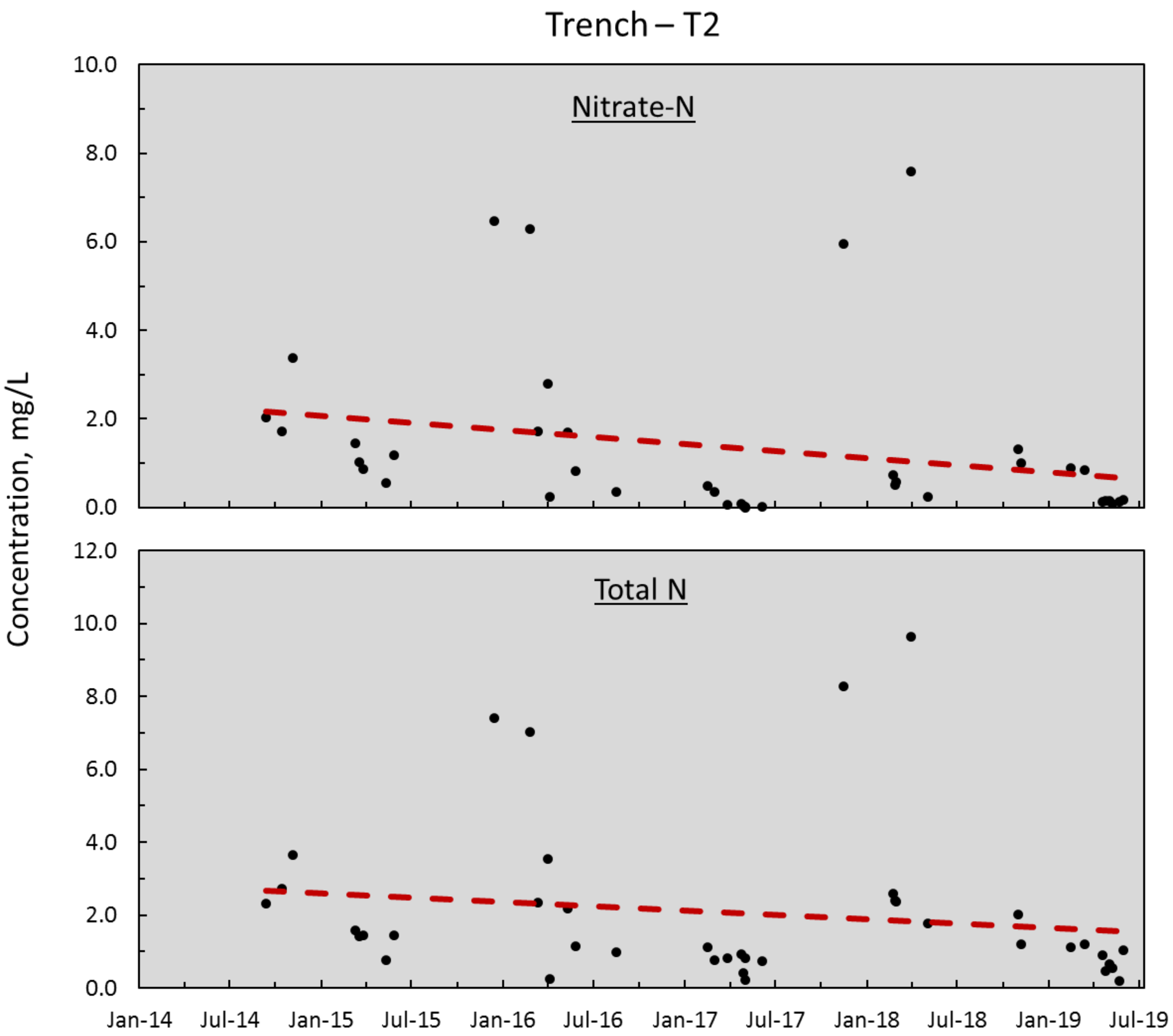


Figure S 15. Nitrate-N and total N concentration measured in the trench (T2) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

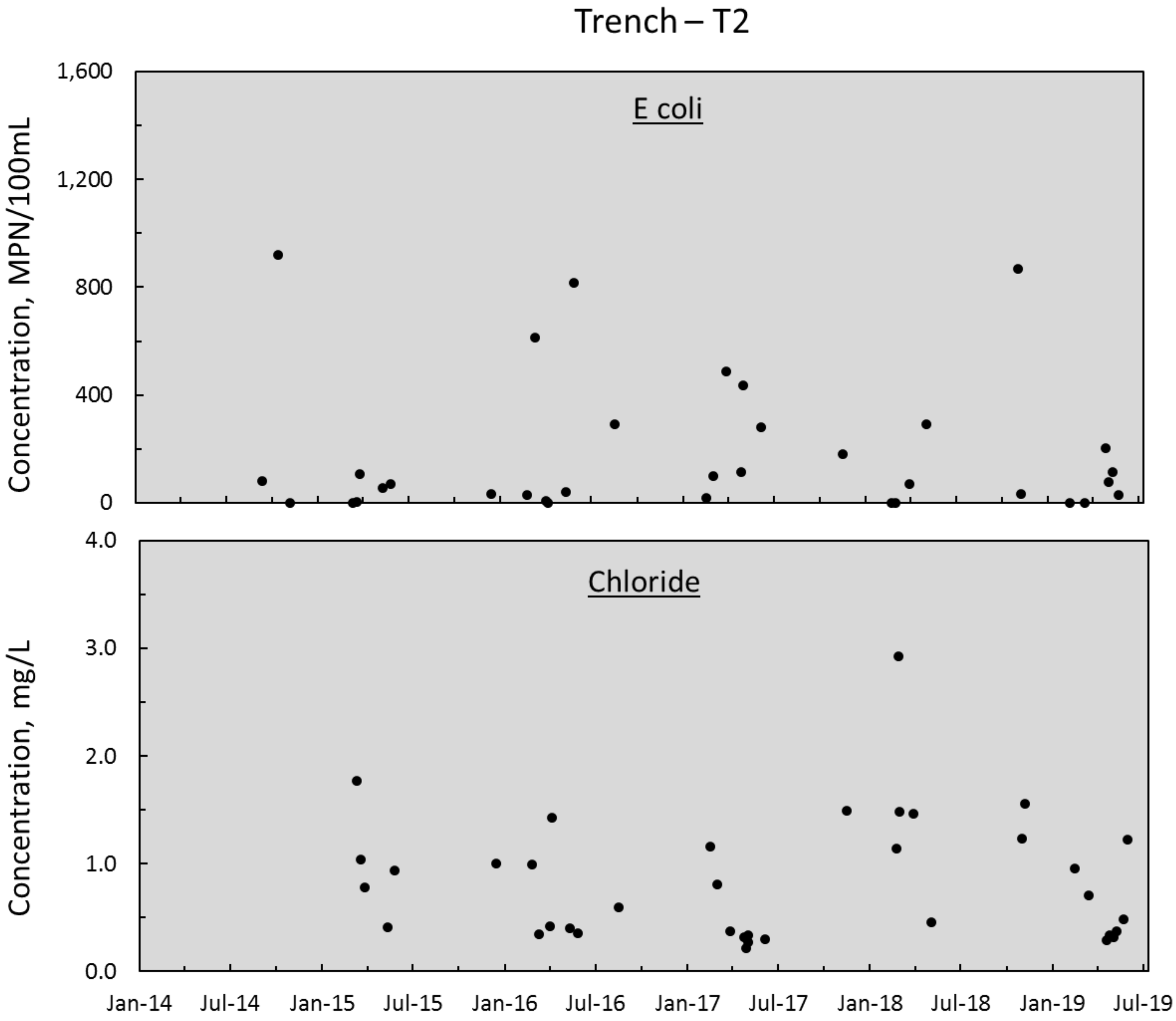


Figure S 16. E. coli and chloride concentration measured in the trench (T2) over the period of monitoring.

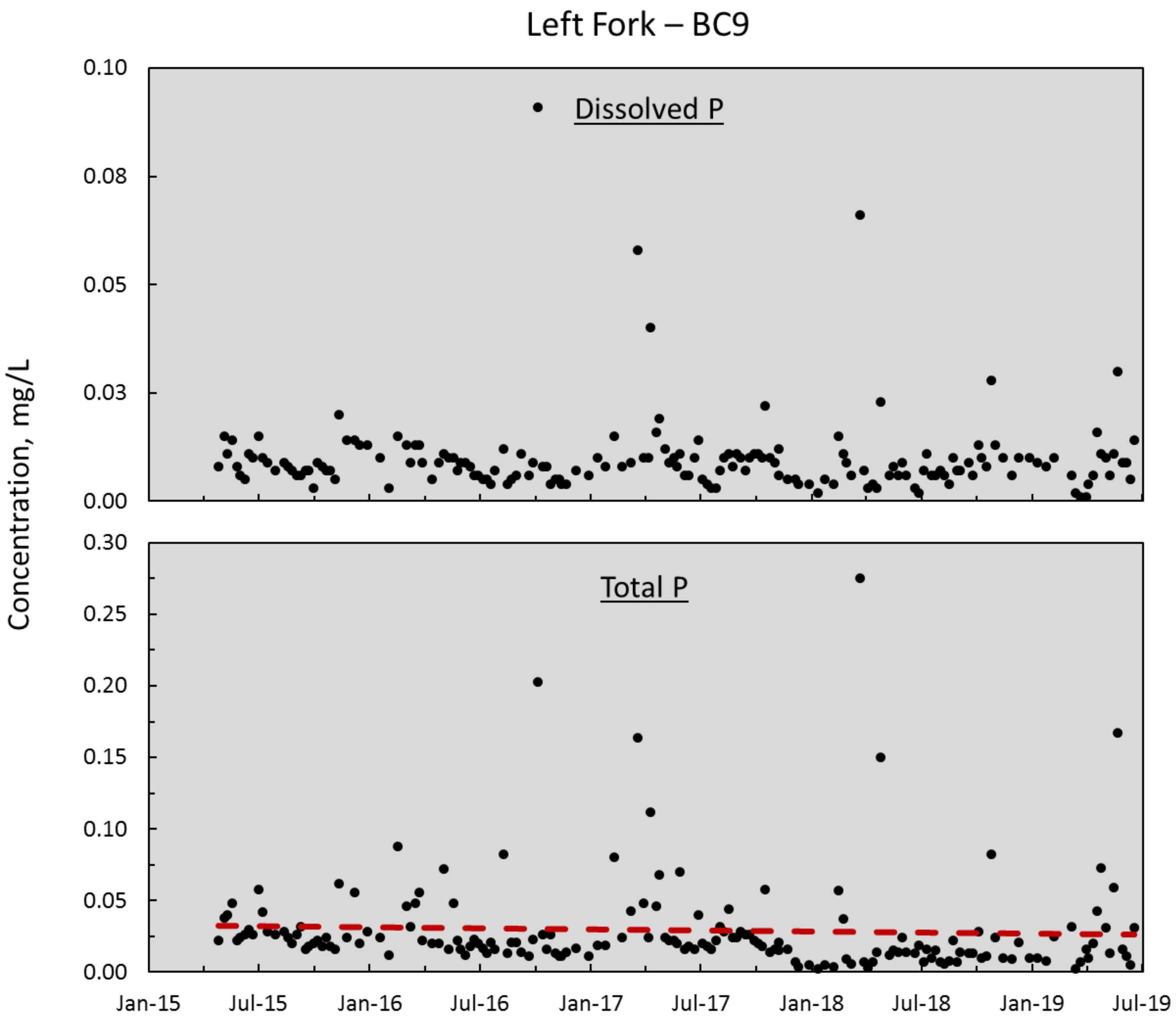


Figure S 17. Dissolved and total P concentration measured in the trench (T2) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

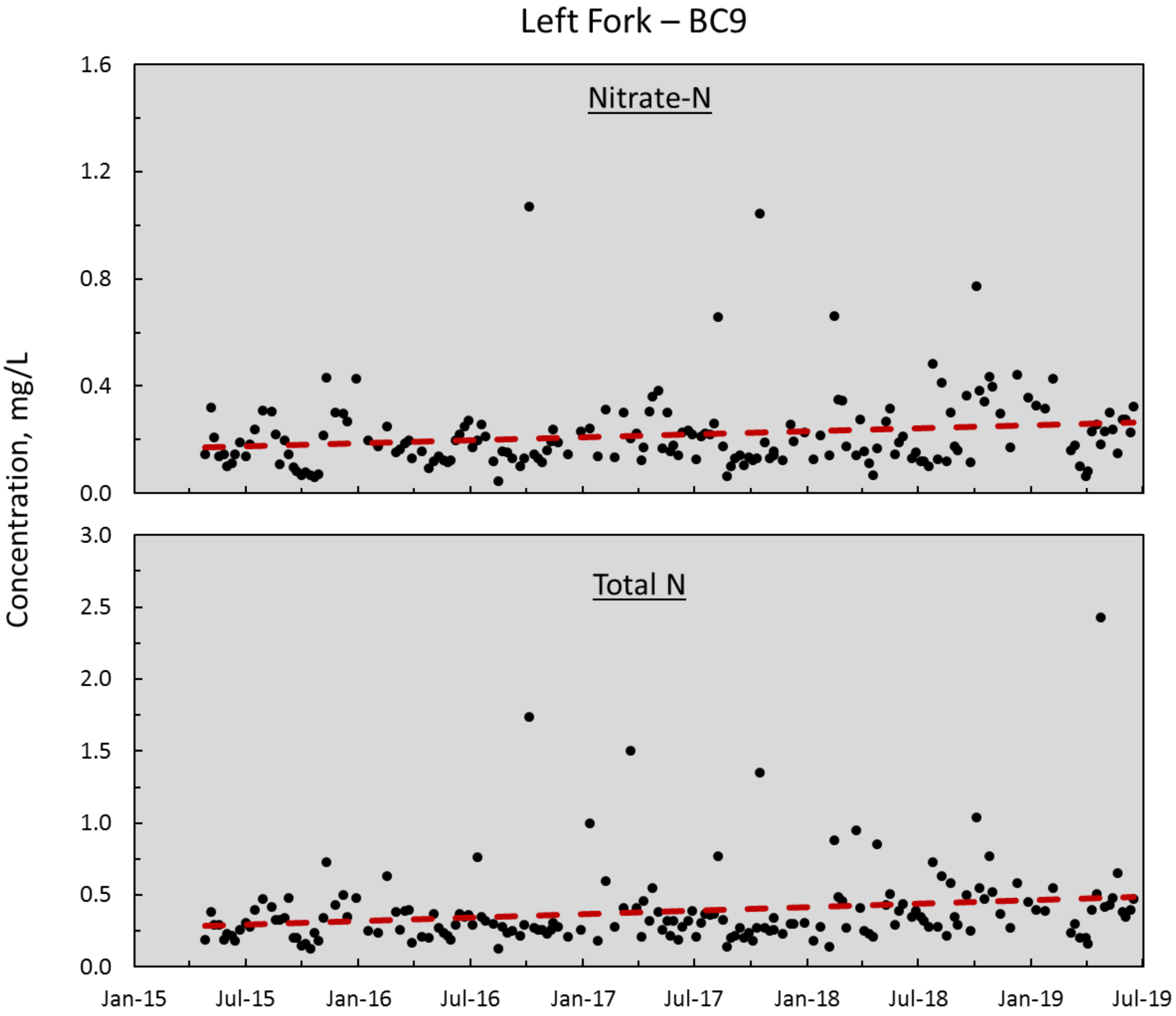


Figure S 18. Nitrate-N and total N concentration measured in Left Fork (BC9) over the period of monitoring. Dashed line is statistically significant change in concentration as determined by Kendall's Seasonal Test.

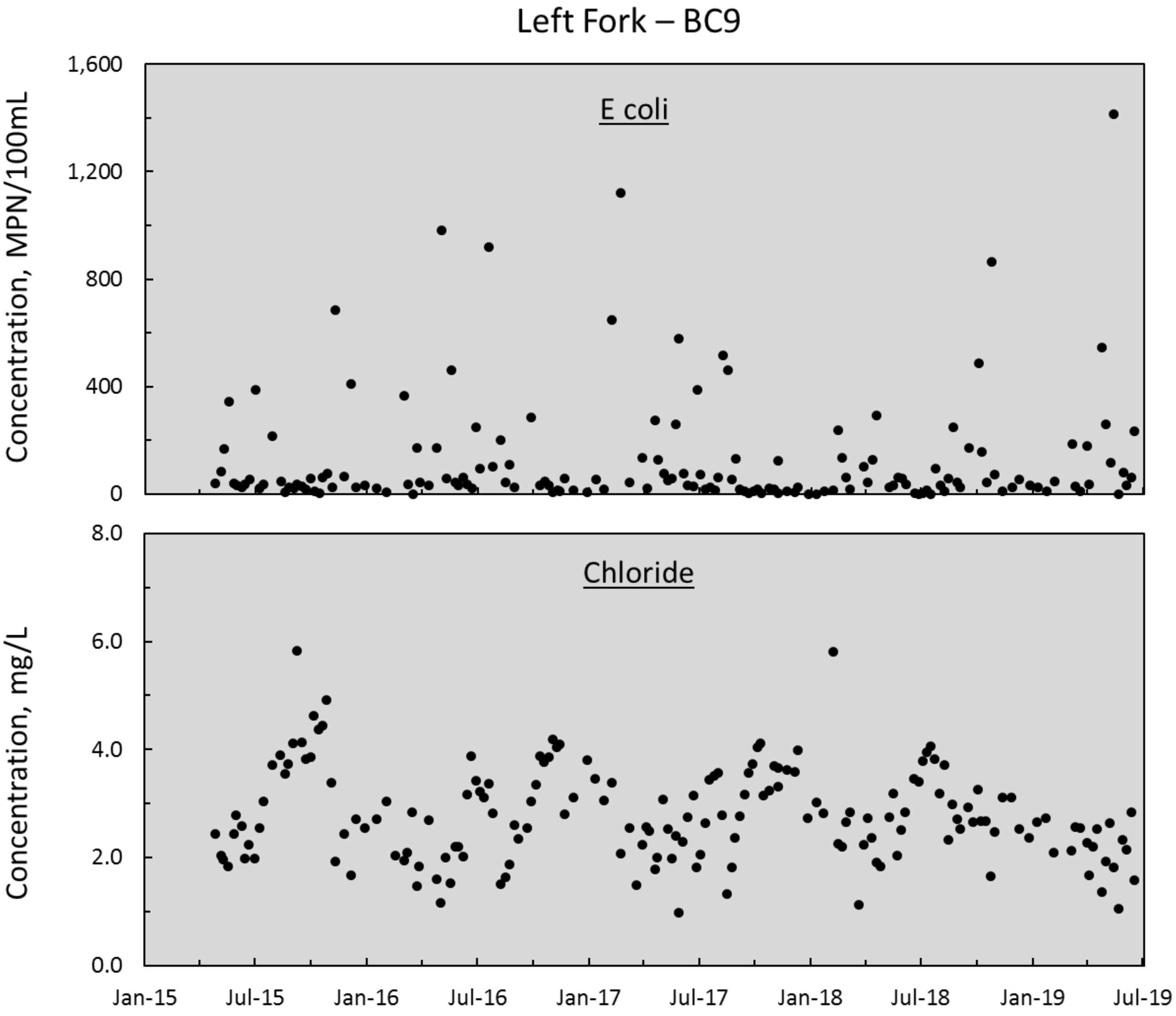


Figure S 19. E. coli and chloride concentration measured in the Left Fork (BC9) over the period of monitoring.

NUTRIENT LOADS IN BIG CREEK UP AND DOWNSTREAM OF C&H FARM

Contents

Summary

1. Water discharge and nutrient load in Big Creek was monitored starting in May 2014, when USGS installed a gaging station at BC7 (USGS 07055790 Big Creek near Mt. Judea, AR). Discharge and loads are determined on a climate year basis of May 1 to April 30.

2. The two largest storms occurring during each of the 5-year monitoring accounted for 44, 49, 37, and 42% of the total 5-year load of dissolved P, total P, nitrate-N, and total N, respectively, and 43% of discharge measured at BC7. At the upstream site (BC6), these same storms comprised 45, 47, 42, and 44% of dissolved P, total P, nitrate-N, and total N load, respectively, and 43% of total discharge.

3. During these large storm events, the monitored application fields BC5a and BC12 were mostly flooded as Big Creek breached its banks. Thus, the effectiveness of conservation practices, such as buffer strips or no-application zones for slurry would have little impact on the conservation of nutrients or limiting their movement to Big Creek, under such extreme flow events.

List of Tables

List of Figures

List of Supplementary Tables and Figures

Discharge Determination

Water discharge was measured at 15 minute intervals at the downstream site (BC7) on Big Creek, starting in May, 2014, when USGS installed a gaging station at BC7; USGS 07055790 Big Creek near Mt. Judea, AR (see https://nwis.waterdata.usgs.gov/ar/nwis/uv/?cb_00065=on&cb_00045=on&cb_00010=on&format=gif_default&period=&begin_date=2014-04-16&end_date=2014-04-23&site_no=07055790). As detailed earlier in this Final Report, gaging of the upstream site was not possible and USGS used a watershed area ratio for BC6 to BC7 of 0.66 to estimate upstream discharge (i.e., the upstream drainage area of 27.1 sq. mi divided by the downstream drainage area of 40.8 sq. mi). While not ideal, it proved to be the sole option available.

Storm flow samples were collected by ISCO autosamplers and base flow samples collected manually at weekly to biweekly intervals at up and downstream sites (BC6 and BC7). More information on sample collection and analysis is available in the first section (see “Method of Water Flow Measurement, Sample Collection, and Constituent Analysis”) of this final report. Discharge and loads are determined on a climate year basis of May 1 to April 30.

Nutrient Load Estimation Using LOADEST

Nutrient loads in Big Creek were determined by the USGS tool LOAD ESTimator (LOADEST), which uses RStudio to estimate constituent loads in streams and rivers (https://water.usgs.gov/software/loadest/; Runkel, 2013; Runkel et al., 2004). LOADEST is based on two previously undocumented software programs known unofficially as LOADEST2 and ESTIMATOR [see Crawford (1996) and Cohn (1988) for relevant details]. Given a time series of streamflow, additional data variables, and constituent concentration, LOADEST assists the user in developing a regression model for the estimation of constituent load (calibration).

The calibration and estimation procedures within LOADEST are based on three statistical estimation methods. The first two methods, Adjusted Maximum Likelihood Estimation (AMLE) and Maximum Likelihood Estimation (MLE), are appropriate when the calibration model errors (residuals) are normally distributed (Runkel et al., 2004). Of the two, AMLE is the method of choice when the calibration data set (time series of streamflow, additional data variables, and concentration) contains censored data. The third method, Least Absolute Deviation (LAD), is an alternative to maximum likelihood estimation when the residuals are not normally distributed. LOADEST output includes diagnostic tests and warnings to assist the user in determining the appropriate estimation method and in interpreting the estimated loads. The LOADEST package tests many different regression models with different combinations of explanatory variables and selects the best model by minimization of the Akaike Information Criterion (AIC) (Runkel et al., 2004).

We selected Model 3 based on the lowest AIC value for Total P and N estimates for climate year 2015 (Table 1). We eliminated Models 2 and 9 from consideration as they had abnormally high load estimates due to the quadratic equation applied to flow used in these two models (see annual load estimates for each model in Table 1). Model 3 was selected over Model 4, which had similar AIC and

AMLE metric values (Table 1), as Model 3 was simpler than Model 4 and it includes a seasonality / time variable, which was highly significant (*p*-value for the time coefficient was 0.0001).

Explanatory variables within the regression model include various functions of streamflow, decimal time, and additional user-specified data variables. The formulated regression model is then used to estimate loads over a user-specified time interval (estimation) (Runkel et al., 2004). Mean load estimates, standard errors, and 95 percent confidence intervals are developed on a monthly and (or) seasonal basis.

We worked with USGS personnel in Little Rock, AR to develop and implement the R script used at the Carver site (USGS site 07055814 Big Creek at Carver, AR: https://waterdata.usgs.gov/ar/nwis/uv?site_no=07055814) for the BCRET downstream (BC7) site (i.e., USGS site 07055790 Big Creek near Mt. Judea, AR: https://waterdata.usgs.gov/ar/nwis/uv?site_no=07055790).

Nutrient Loading of Big Creek

Monthly discharge and nutrient flux varied dramatically over the 5-year monitoring period but the dominance of the large storm events on May 11 and December 26, 2005 is clear (Table 2). Discharge during these two large storms (Figure 1) contributed to in the two highest monthly discharge at the monitored sites on Big Creek (978 and 845 cubic feet/second for May and December 2015, respectively, at BC7). On a climate year basis (i.e., May 1 to April 30), the variance in rainfall and Big Creek flow led to a wide variation in annual dissolved P, total P, nitrate-N, and total N flux at both the up and downstream sites BC6 and BC7 (Figure 2).

The two largest storms occurring during each of the 5-year monitoring accounted for 44, 49, 37, and 42% of the total 5-year load of dissolved P, total P, nitrate-N, and total N, respectively, and 43% of discharge measured at BC7. At the upstream site (BC6), these same storms comprised 45, 47, 42, and 44% of dissolved P, total P, nitrate-N, and total N load, respectively, and 43% of total discharge.

The dominance of a few large rainfall and thus, flow events over extended periods of monitoring is found in many watersheds across the U.S. and overseas (Haygarth et al., 1998; Ockenden et al., 2017; Pionke et al., 1996) and is certainly not unique to the Big Creek or Buffalo River Watershed. During these large storm events, the monitored application fields BC5a and BC12 were mostly flooded as Big Creek breached its banks. Thus, the effectiveness of conservation practices such as buffer strips or no-application zones for slurry would have little impact on the conservation of nutrients or limiting their movement to Big Creek, under such extreme flow events.

Supplementary Table S1 gives monthly discharge and nutrient loads at the up- (BC6) and downstream (BC7) sites. Supplementary Tables S2 and S4 present annual nutrient loss (tons) and loads (lbs/ac), respectively, and in Tables S2 and S4 as Mg (i.e., 1,000 kg) and g/ha, respectively. The difference in nutrient load between up (BC6) and downstream sites (BC7) is depicted in Supplementary Figures S 1 and 2 for P and N forms, respectively. A slight decrease in particulate P was observed between up and downstream sites (i.e., BC6 and BC7) in 2015, a year which had the lowest annual flow (1,528 cubic feet*10^6) compared with the other monitored years (1,908 to 3,344 cubic feet*10^6; Table 3).

The decrease particulate P is likely due to a greater in-channel deposition of sediment in 2015, which would probably be resuspended during subsequent high flow storm events. A similar decrease in particulate N was not observed, due to a greater proportion of organic N rather than sediment bound forms (as in the case of P). These lighter, less dense organic particles and colloids are less likely to be deposited in the stream channel, even under low flow conditions.

Stream discharge and percent water-year loss of P and N on a monthly basis are depicted in Supplementary Figures S3 and S4, respectively. Cumulative flows and P and N loads at the up and downstream sites are presented in Supplementary Figures S5, S6, and S7, respectively.

References

Cohn, T.A. 1988. Adjusted maximum likelihood estimation of the moments of lognormal populations from type I censored samples. U.S. Geological Survey Open-File Report 88-350, 34 p.

Crawford, C.G. 1996. Estimating mean constituent loads in rivers by the rating-curve and flow-duration, rating-curve methods. Bloomington, Ind., Indiana University, Ph.D. dissertation, 245 p.

Haygarth, P.M., L. Hepworth, and S.C. Jarvis. 1998. 72Forms of phosphorus transfer in hydrological pathways from soil under grazed grassland. European Journal of Soil Science 49:65-72.

Ockenden, M.C., M.J. Hollaway, K.J. Beven, A.L. Collins, R. Evans, P.D. Falloon, K.J. Forber, K.M. Hiscock, R. Kahana, C.J.A. Macleod, W. Tych, M.L. Villamizar, C. Wearing, P.J.A. Withers, J.G. Zhou, P.A. Barker, S. Burke, J.E. Freer, P.J. Johnes, M.A. Snell, B.W.J. Surridge, and P.M. Haygarth. 2017. Major agricultural changes required to mitigate phosphorus losses under climate change. Nature Communications 8:161. Available at https://www.nature.com/articles/s41467-017-00232-0.

Pionke, H.B., W.J. Gburek, A.N. Sharpley, and R.R. Schnabel. 1996. Flow and nutrient export patterns for an agricultural hill-land watershed. Water Resources Research 32(6):1795-1804.

Runkel, R.L., C.G. Crawford, and T.A. Cohn. 2004. Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. U.S. Geological Survey Techniques and Methods Book 4, Chapter A5, 69 p. Available at https://water.usgs.gov/software/loadest/doc/.

Runkel, R.L. 2013. Revisions to LOADEST. U.S. Geological Survey Techniques and Methods. 6 p. Available at https://water.usgs.gov/software/loadest/doc/.

Acknowledgement

The Big Creek Research and Extension Team acknowledge and are extremely grateful to Brian Breaker (formerly U.S. Geological Survey) for advice and help in conducting, analyzing, and interpreting nutrient load estimations for Big Creek using LOADEST. His vast experience informed and provided state of the science estimation of constituent loads.

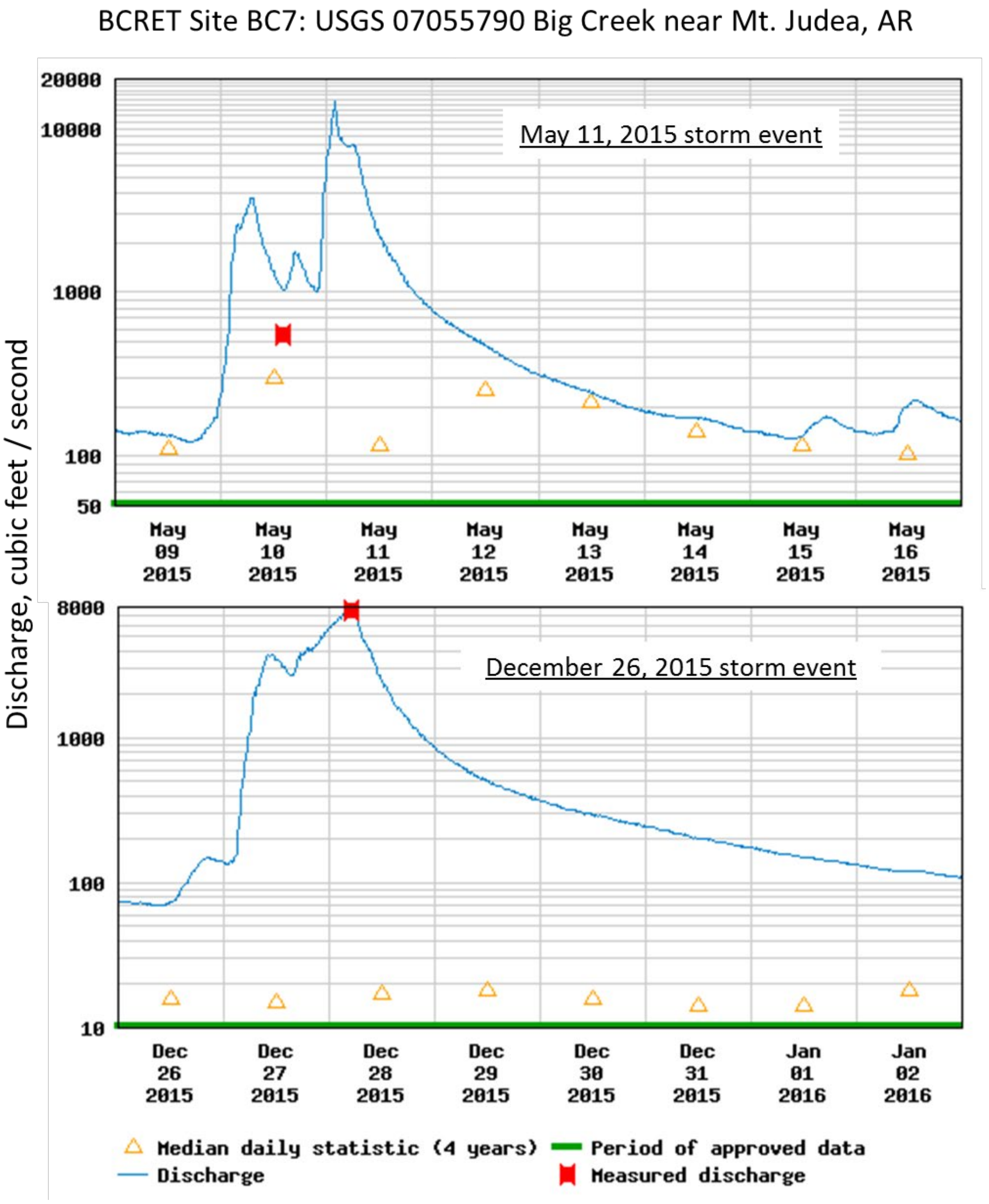


Figure 1. Discharge at BC7 (USGS 07055790 Big Creek near Mt. Judea, AR) downstream of the C&H Farm for the May 11 and December 26, 2015 storm events.

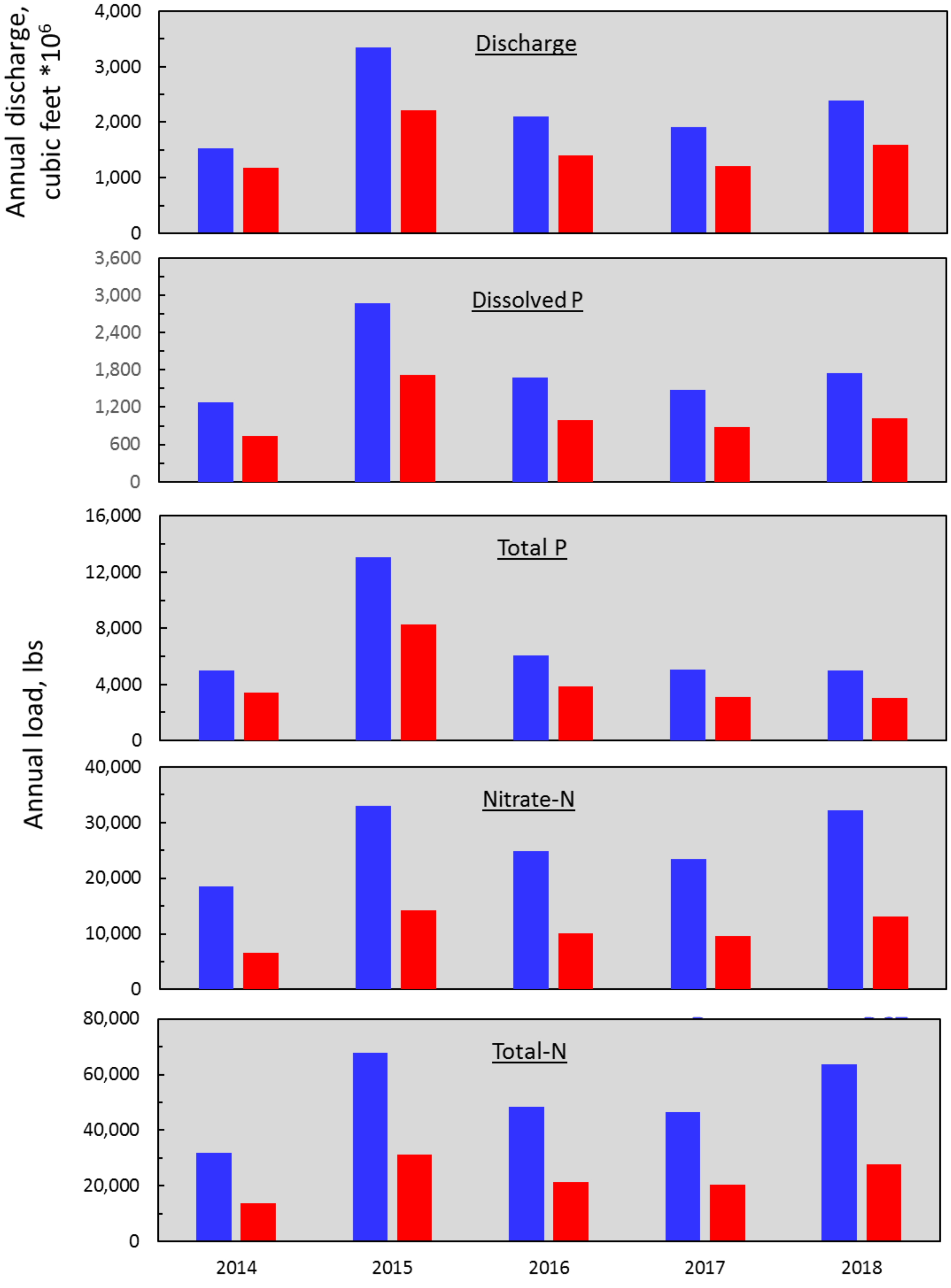


Figure 2. Annual discharge and load of phosphorus and nitrogen up- (BC6) and downstream (BC7) of the C&H Farm (water-year basis; May 1 to April 30).

Table 1. Akaike Information Criteria (AIC) and Adjusted Maximum Likelihood Estimation (AMLE) was used to select the most appropriate model to estimate chemical constituent loads at the site downstream of the C&H Farm (BC7) for climate year 2015 (i.e., May 1. 2015 to April 30, 2016).

Model	Total P and N load for climate year 2015	AIC	AMLE regression statistics	
			Residual variance	R^2
Regression model [†]				
1	$a_0 + a_1\ln Q$			
2	$a_0 + a_1\ln Q + a_2\ln Q^2$			
3	$a_0 + a_1\ln Q + a_2 dtime$			
4	$a_0 + a_1\ln Q + a_2\sin(2\pi dtime) + a_3\cos(2\pi dtime)$			
9	$a_0 + a_1\ln Q + a_2\ln Q^2 + a_3\sin(2\pi dtime) + a_4\cos(2\pi dtime) + a_5 dtime + a_6 dtime^2$			
Total P, lbs				
1	18,124,156	445.7	0.3475	91.79
2	68,639,195	391.4	0.2714	93.50
3	21,025,214	415.0	0.3053	92.83
4	23,311,620	422.3	0.3140	92.67
9	85,907,930	325.7	0.2044	95.20
Total N, lbs				
1	78,754,748	283.4	0.1858	93.76
2	235,549,647	204.3	0.1334	95.53
3	71,847,289	269.3	0.1745	94.16
4	101,492,646	249.1	0.1599	94.67
9	231,481,266	155.5	0.1073	96.47

† Equation parameters are; I, Integer; lnQ = ln(streamflow) - center of ln(streamflow); dtime = decimal time - center of decimal time; per = period, 1 or 0 depending on defined period. From Runkel et al. (2004).

Table 2. Monthly flow and nutrient loss for the downstream (BC7) sampling site and percent of annual value, based on a climate year (i.e., May 1 to April 30).

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Volume	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual
	ft^3 *10^6	%	lbs	%	lbs	%	lbs	%	lbs	%
Climate year 2014										
May, 2014	178	11.6	151	11.8	612	12.3	2,090	11.3	3,583	11.2
June, 2014	70	4.6	57	4.5	189	3.8	1,029	5.6	1,539	4.8
July, 2014	133	8.7	111	8.7	414	8.3	1,700	9.2	2,797	8.7
August, 2014	31	2.0	24	1.9	70	1.4	536	2.9	726	2.3
September, 2014	8	0.5	6	0.5	14	0.3	189	1.0	213	0.7
October, 2014	60	4.0	49	3.8	177	3.6	827	4.5	1,308	4.1
November, 2014	15	1.0	12	0.9	29	0.6	313	1.7	387	1.2
December, 2014	60	3.9	47	3.7	146	2.9	919	5.0	1,363	4.3
January, 2015	156	10.2	132	10.4	540	10.9	1,811	9.8	3,229	10.1
February, 2015	52	3.4	41	3.2	128	2.6	798	4.3	1,196	3.7
March, 2015	510	33.3	435	34.1	1,855	37.3	5,233	28.4	10,256	32.1
April, 2015	254	16.6	210	16.5	798	16.0	3,001	16.3	5,394	16.9
Sum	**1,528**		**1,275**		**4,972**		**18,446**		**31,991**	

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Volume	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual
	$ft^3 *10^6$	%	lbs	%	lbs	%	lbs	%	lbs	%
Climate year 2015										
May, 2015	978	29.2	874	30.5	4,551	34.8	8,102	24.6	18,321	27.1
June, 2015	220	6.6	181	6.3	685	5.2	2,625	8.0	4,723	7.0
July, 2015	330	9.9	280	9.8	1,190	9.1	3,416	10.4	6,747	10.0
August, 2015	9	0.0	6	0.2	13	0.1	208	0.6	242	0.4
September, 2015	7	0.0	5	0.2	10	0.1	175	0.5	198	0.3
October, 2015	4	0.0	3	0.1	5	0.0	111	0.3	118	0.2
November, 2015	161	4.8	134	4.7	527	4.0	1,793	5.4	3,444	5.1
December, 2015	845	25.3	746	26.0	3,809	29.1	6,922	21.0	16,238	24.0
January, 2016	140	4.2	110	3.8	350	2.7	1,955	5.9	3,275	4.8
February, 2016	68	2.0	52	1.8	155	1.2	1,041	3.2	1,641	2.4
March, 2016	438	13.1	361	12.6	1,418	10.8	4,702	14.3	9,401	13.9
April, 2016	143	4.3	113	3.9	372	2.8	1,923	5.8	3,339	4.9
Sum	**3,344**		**2,865**		**13,085**		**32,973**		**67,687**	
Climate year 2016										
May, 2016	328	15.6	265	15.8	964	16.0	3,828	15.4	7,323	15.1

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Volume	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual
	$ft^3 *10^6$	%	lbs	%	lbs	%	lbs	%	lbs	%
June, 2016	57	2.7	43	2.6	122	2.0	923	3.7	1,436	3.0
July, 2016	17	0.8	12	0.7	28	0.5	369	1.5	482	1.0
August, 2016	238	11.3	188	11.2	641	10.6	2,955	11.9	5,486	11.3
September, 2016	41	2.0	30	1.8	81	1.3	720	2.9	1,077	2.2
October, 2016	14	0.7	10	0.6	20	0.3	319	1.3	401	0.8
November, 2016	18	0.8	12	0.7	28	0.5	368	1.5	493	1.0
December, 2016	27	1.3	19	1.1	42	0.7	542	2.2	743	1.5
January, 2017	49	2.3	35	2.1	91	1.5	843	3.4	1,287	2.7
February, 2017	76	3.6	56	3.3	152	2.5	1,217	4.9	1,969	4.1
March, 2017	428	20.3	340	20.3	1,232	20.4	4,809	19.3	9,816	20.3
April, 2017	813	38.6	662	39.6	2,639	43.7	8,022	32.2	17,097	37.0
Sum	**2,106**		**1,672**		**6,040**		**24,915**		**48,420**	
Climate year 2017										
May, 2017	491	25.7	390	26.3	1,412	28.0	5,474	23.4	11,325	24.4
June, 2017	350	18.4	283	19.1	1,103	21.9	3,647	15.6	7,879	17.0
July, 2017	60	3.2	44	3.0	111	2.2	1,027	4.4	1,627	3.5

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Volume	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual	Loss	Percent of annual
	ft^3 *10^6	%	lbs	%	lbs	%	lbs	%	lbs	%
August, 2017	51	2.7	37	2.5	92	1.8	894	3.8	1,401	3.0
September, 2017	10	0.5	6	0.4	12	0.2	243	1.0	301	0.6
October, 2017	6	0.3	4	0.3	6	0.1	160	0.7	183	0.4
November, 2017	8	0.4	5	0.3	9	0.2	210	0.9	251	0.5
December, 2017	6	0.3	9	0.6	18	0.4	323	1.4	425	0.9
January, 2018	32	1.7	22	1.5	47	0.9	633	2.7	927	2.0
February, 2018	395	20.7	310	20.9	1,120	22.2	4,193	17.9	9,305	20.1
March, 2018	200	10.5	149	10.1	455	9.0	2,635	11.3	5,088	11.0
April, 2018	300	15.7	223	15.0	661	13.1	3,957	16.9	7,688	16.6
Sum	**1,908**		**1,482**		**5,046**		**23,396**		**46,400**	
Climate year 2018										
May, 2018	215	9.0	161	9.2	492	9.8	2,813	8.8	5,496	8.6
June, 2018	51	2.2	36	2.1	89	1.8	893	2.8	1,456	2.3
July, 2018	7	0.3	4	0.2	7	0.1	195	0.6	232	0.4
August, 2018	26	1.1	18	1.0	39	0.8	510	1.6	779	1.2
September, 2018	17	0.7	11	0.6	20	0.4	392	1.2	536	0.8

Month and year	**Flow**		**Dissolved P**		**Total P**		**Nitrate-N**		**Total N**	
	Volume	**Percent of annual**	**Loss**	**Percent of annual**	**Loss**	**Percent of annual**	**Loss**	**Percent of annual**	**Loss**	**Percent of annual**
	ft^3 *10^6	%	lbs	%	lbs	%	lbs	%	lbs	%
October, 2018	82	3.4	58	3.3	143	2.9	1,363	4.2	2,338	3.7
November, 2018	184	7.7	134	7.7	379	7.6	2,564	8.0	4,932	7.7
December, 2018	304	12.7	223	12.8	643	12.9	4,013	12.5	8,071	12.7
January, 2019	399	16.7	293	16.8	859	17.2	5,133	16.0	10,528	16.5
February, 2019	490	20.5	364	20.9	1,113	22.3	5,911	18.4	12,707	19.9
March, 2019	183	7.7	128	7.3	312	6.2	2,859	8.9	5,215	8.2
April, 2019	429	18.0	313	18.0	902	18.0	5,492	17.1	11,457	18.0
Sum	**2,388**		**1,743**		**4,998**		**32,138**		**63,747**	

Table 3. Annual flow (million cubic feet) and nutrient loss (lbs) for the upstream (BC6) and downstream (BC7) sampling sites and difference between these two sites, based on a climate year (i.e., May 1 to April 30).

Parameter	2014	2015	2016	2017	2018
Flow, cubic feet * 10^6					
Upstream	1,185	2,221	1,399	1,207	1,586
Downstream	1,528	3,344	2,106	1,908	2,388
Difference	344	1,123	707	702	802
Dissolved P, lbs					
Upstream	738	1,714	988	878	1,024
Downstream	1,275	2,865	1,672	1,482	1,743
Difference	537	1,151	684	604	719
Particulate P, lbs [1]					
Upstream	2,709	6,567	2,847	2,247	2,025
Downstream	3,697	10,220	4,368	3,564	3,255
Difference	988	3,653	1,521	1,317	1,230
Total P, lbs					
Upstream	3,447	8,281	3,835	3,125	3,049
Downstream	4,972	13,085	6,040	5,046	4,998
Difference	1,525	4,084	2,205	1,921	1,949
Nitrate-N, lbs					
Upstream	6,552	14,218	10,041	9,627	13,152
Downstream	18,446	32,973	24,915	23,396	32,138
Difference	11,894	18,755	14,874	13,769	18,986
Particulate N, lbs [2]					
Upstream	7,035	17,059	11,340	10,875	14,452
Downstream	13,545	34,714	23,505	23,004	31,609
Difference	6,510	17,655	12,165	12,129	17,157

Parameter	2014	2015	2016	2017	2018
Total N, lbs					
Upstream	13,587	31,277	21,381	20,502	27,604
Downstream	31,991	67,687	48,420	46,400	63,747
Difference	18,404	36,410	27,039	25,898	36,143

[1] Particulate P is estimated as the difference between dissolved P and total P.

[2] Particulate N is estimated as the difference between nitrate-N and total N. Monitoring shows ammonium-N to be negligible in Big Creek.

Supplementary Tables and Figures

Table S 1. Monthly and annual flow (million cubic feet) and nutrient loss (lbs) for the upstream (BC6) and downstream (BC7) sampling sites, based on a climate year (i.e., May 1 to April 30).

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
	ft^3 *10^6		- lbs -							
Climate year 2014										
May, 2014	118	178	87	151	434	612	733	2,090	1,517	3,583
June, 2014	47	70	32	57	141	189	308	1,029	604	1,539
July, 2014	89	133	64	111	298	414	568	1,700	1,154	2,797
August, 2014	21	31	13	24	54	70	143	536	270	726
September, 2014	5	8	3	6	11	14	41	189	72	213
October, 2014	40	60	28	49	127	177	264	827	531	1,308
November, 2014	10	15	6	12	23	29	75	313	137	387
December, 2014	40	60	26	47	108	146	272	919	530	1,363
January, 2015	104	156	77	132	367	540	664	1,811	1,394	3,229
February, 2015	35	52	23	41	94	128	239	798	468	1,196
March, 2015	338	510	257	435	1,240	1,855	2,137	5,233	4,600	10,256
April, 2015	169	254	122	210	550	798	1,108	3,001	2,310	5,394
Sum	**1,185**	**1,528**	**738**	**1,275**	**3,447**	**4,972**	**6,552**	**18,446**	**13,587**	**31,991**

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
	ft^3 $*10^6$		- lbs -							
Climate year 2015										
May, 2015	650	978	530	874	2,831	4,551	3,907	8,102	8,899	18,321
June, 2015	146	220	106	181	468	685	970	2,625	2,024	4,723
July, 2015	219	330	166	280	782	1,190	1,408	3,416	3,041	6,747
August, 2015	6	9	3	6	11	13	46	208	82	242
September, 2015	5	7	3	5	8	10	38	175	66	198
October, 2015	3	4	1	3	4	5	22	111	38	118
November, 2015	107	161	79	134	347	527	715	1,793	1,525	3,444
December, 2015	561	845	455	746	2,305	3,809	3,478	6,922	8,002	16,238
January, 2016	93	140	63	110	244	350	664	1,955	1,339	3,275
February, 2016	45	68	30	52	109	155	329	1,041	651	1,641
March, 2016	291	438	213	361	919	1,418	1,960	4,702	4,219	9,401
April, 2016	95	143	65	113	253	372	681	1,923	1,391	3,339
Sum	**2,221**	**3,344**	**1,714**	**2,865**	**8,281**	**13,085**	**14,218**	**32,973**	**31,277**	**67,687**
Climate year 2016										
May, 2016	218	328	155	265	634	964	1,515	3,828	3,202	7,323
June, 2016	38	57	25	43	86	122	287	923	563	1,436

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
	ft^3 *10^6		- - - - - - - - - - - - - - - - - - lbs - - - - - - - - - - - - - - - - - -							
July, 2016	12	17	7	12	21	28	94	369	172	482
August, 2016	158	238	110	188	424	641	1,129	2,955	2,355	5,486
September, 2016	28	41	17	30	57	81	214	720	414	1,077
October, 2016	9	14	5	10	15	20	77	319	140	401
November, 2016	12	18	7	12	20	28	96	368	178	493
December, 2016	18	27	10	19	31	42	145	542	270	743
January, 2017	32	49	20	35	64	91	256	843	496	1,287
February, 2017	51	76	32	56	105	152	395	1,217	780	1,969
March, 2017	284	428	202	340	774	1,232	2,047	4,809	4,405	9.816
April, 2017	540	813	398	662	1,604	2,639	3,786	8,022	8,406	17,907
Sum	**1,399**	**2,106**	**988**	**1,672**	**3,835**	**6,040**	**10,041**	**24,915**	**21,381**	**48,420**
Climate year 2017										
May, 2017	326	491	232	390	880	1,412	2,365	5,474	5,107	11,325
June, 2017	233	350	170	283	669	1,103	1,659	3,647	3,654	7,879
July, 2017	40	60	25	44	76	111	325	1,027	636	1,627
August, 2017	34	51	21	37	63	92	280	894	544	1,401
September, 2017	6	10	3	6	9	12	58	243	103	301

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
	$ft^3 *10^6$		lbs							
October, 2017	4	6	2	4	5	6	35	160	60	183
November, 2017	5	8	3	5	6	9	48	210	84	251
December, 2017	9	6	5	9	13	18	82	323	150	425
January, 2018	21	32	12	22	33	47	183	633	345	927
February, 2018	262	395	186	310	670	1,120	1,960	4,193	4,318	9,305
March, 2018	133	200	88	149	285	455	1,048	2,635	2,194	5,088
April, 2018	199	300	131	223	416	661	1,584	3,957	3,307	7,688
Sum	**1,207**	**1,908**	**878**	**1,482**	**3,125**	**5,046**	**9,627**	**23,396**	**20,502**	**46,400**
Climate year 2018										
May, 2018	143	215	95	161	305	492	1,134	2,813	2,383	5,496
June, 2018	34	51	21	36	58	89	292	893	574	1,456
July, 2018	5	7	2	4	5	7	44	195	77	232
August, 2018	17	26	10	18	26	39	154	510	295	779
September, 2018	11	17	6	11	14	20	104	392	191	536
October, 2018	55	82	33	58	92	143	472	1,363	941	2,338
November, 2018	122	184	78	134	234	379	1,013	2,564	2,107	4,932
December, 2018	202	304	131	223	393	643	1,668	4,013	3,512	8,071

Month and year	Flow		Dissolved P		Total P		Nitrate-N		Total N	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
	ft^3 *10^6		- lbs -							
January, 2019	265	399	173	293	520	859	2,182	5,133	4,622	10.528
February, 2019	326	490	216	364	663	1,113	2,652	5,911	5,708	12,707
March, 2019	121	183	74	128	198	312	1,059	2,859	2,141	5,215
April, 2019	285	429	185	313	541	902	2,378	5,492	5,053	11,457
Sum	**1,586**	**2,388**	**1,024**	**1,743**	**3,049**	**4,998**	**13,152**	**32,138**	**27,604**	**63,747**

Table S 2. Annual flow and nutrient loss (tons) for the upstream (BC6), downstream (BC7) sampling sites, and difference between these two sites, based on a climate year (i.e., May 1 to April 30).

Parameter	2014	2015	2016	2017	2018
Flow, cubic feet * 10^6					
Upstream	1,185	2,221	1,399	1,207	1,586
Downstream	1,528	3,344	2,106	1,908	2,388
Difference	344	1,123	707	702	802
Dissolved P, tons					
Upstream	0.37	0.86	0.49	0.44	0.51
Downstream	0.64	1.43	0.84	0.74	0.87
Difference	0.27	0.58	0.34	0.30	0.36
Particulate P, tons [1]					
Upstream	1.35	3.28	1.42	1.12	1.01
Downstream	1.85	5.11	2.18	1.78	1.63
Difference	0.49	1.83	0.76	0.66	0.62
Total P, tons					
Upstream	1.72	4.14	1.92	1.56	1.52
Downstream	2.49	6.54	3.02	2.52	2.50
Difference	0.76	2.04	1.10	0.96	0.97
Nitrate-N, tons					
Upstream	3.28	7.11	5.02	4.81	6.58
Downstream	9.22	16.49	12.46	11.70	16.07
Difference	5.95	9.38	7.44	6.88	9.49
Particulate N, tons [2]					
Upstream	3.52	8.53	5.67	5.44	7.23
Downstream	6.77	17.36	11.75	11.50	15.80
Difference	3.26	8.83	6.08	6.06	8.58
Total N, tons					
Upstream	6.79	15.64	10.69	10.25	13.80
Downstream	16.00	33.84	24.21	23.20	31.87
Difference	9.20	18.21	13.52	12.95	18.07

[1] Particulate P is estimated as the difference between dissolved P and total P.

[2] Particulate N is estimated as the difference between nitrate-N and total N. Monitoring shows ammonium-N to be negligible in Big Creek.

Table S 3. Annual nutrient load (lbs/acre/year) for the upstream (BC6), downstream (BC7) sampling sites, and difference between these two sites, based on a climate year (i.e., May 1 to April 30).

Parameter	2014	2015	2016	2017	2018
Dissolved P, lbs/acre/year					
Upstream	0.042	0.098	0.057	0.050	0.059
Downstream	0.049	0.109	0.064	0.057	0.066
Difference	0.006	0.011	0.007	0.006	0.008
Particulate P, lbs/acre/year [1]					
Upstream	0.155	0.376	0.163	0.129	0.116
Downstream	0.141	0.390	0.167	0.136	0.124
Difference	-0.014	0.014	0.004	0.007	0.008
Total P, lbs/acre/year					
Upstream	0.197	0.474	0.220	0.179	0.175
Downstream	0.190	0.499	0.230	0.192	0.191
Difference	-0.008	0.025	0.011	0.014	0.016
Nitrate-N, lbs/acre/year					
Upstream	0.375	0.814	0.575	0.551	0.753
Downstream	0.703	1.258	0.950	0.892	1.226
Difference	0.328	0.444	0.375	0.341	0.473
Particulate N, lbs/acre/year [2]					
Upstream	0.403	0.976	0.649	0.622	0.827
Downstream	0.517	1.324	0.896	0.877	1.205
Difference	0.114	0.347	0.247	0.255	0.378
Total N, lbs/acre/year					
Upstream	0.778	1.790	1.224	1.173	1.580
Downstream	1.220	2.581	1.847	1.770	2.431
Difference	0.442	0.791	0.623	0.596	0.851

[1] Particulate P is estimated as the difference between dissolved P and total P.

[2] Particulate N is estimated as the difference between nitrate-N and total N. Monitoring shows ammonium-N to be negligible in Big Creek.

Table S 4. Annual flow (million cubic feet) and nutrient loss (Mg) for the upstream (BC6), downstream (BC7) sampling sites, and difference between these two sites, based on a climate year of May 1 to April 31 (i.e., May 1 to April 30).

Parameter	2014	2015	2016	2017	2018
Flow, cubic meter * 10^6					
Upstream	33.6	62.9	39.6	34.2	44.9
Downstream	43.3	94.7	59.6	54.0	67.6
Difference	9.7	31.8	20.0	19.9	22.7
Dissolved P, Mg					
Upstream	0.3	0.8	0.4	0.4	0.5
Downstream	0.6	1.3	0.8	0.7	0.8
Difference	0.2	0.5	0.3	0.3	0.3
Particulate P, Mg [1]					
Upstream	1.2	3.0	1.3	1.0	0.9
Downstream	1.7	4.6	2.0	1.6	1.5
Difference	0.4	1.7	0.7	0.6	0.6
Total P, Mg					
Upstream	1.6	3.8	1.7	1.4	1.4
Downstream	2.3	5.9	2.7	2.3	2.3
Difference	0.7	2.2	1.0	0.9	0.9
Nitrate-N, Mg					
Upstream	3.0	6.4	4.6	4.4	6.0
Downstream	8.4	15.0	11.3	10.6	14.6
Difference	5.4	8.5	6.7	6.2	8.6
Particulate N, Mg [2]					
Upstream	3.2	7.7	5.1	4.9	6.6
Downstream	6.1	15.7	10.7	10.4	14.3
Difference	3.0	8.0	5.5	5.5	7.8
Total N, Mg					
Upstream	6.2	14.2	9.7	9.3	12.5
Downstream	14.5	30.7	22.0	21.0	28.9
Difference	8.3	16.5	12.3	11.7	16.4

[1] Particulate P is estimated as the difference between dissolved P and total P.

[2] Particulate N is estimated as the difference between nitrate-N and total N. Monitoring shows ammonium-N to be negligible in Big Creek.

Table S 5. Annual nutrient load (g/hectare/year) for the upstream (BC6), downstream (BC7) sampling sites and difference between these two sites, based on a climate year of May 1 to April 31 (i.e., May 1 to April 30).

Parameter	2014	2015	2016	2017	2018
Dissolved P, g/ha/yr					
Upstream	38	88	50	45	52
Downstream	43	98	57	50	59
Difference	6	10	6	6	7
Particulate P, g/ha/yr [1]					
Upstream	138	336	146	115	104
Downstream	126	348	149	121	111
Difference	-13	12	3	7	7
Total P, g/ha/yr					
Upstream	176	423	196	160	156
Downstream	169	446	206	172	170
Difference	-7	22	10	12	14
Nitrate-N, g/ha/yr					
Upstream	335	727	513	492	672
Downstream	628	1,123	849	797	1,095
Difference	293	396	335	305	422
Particulate N, g/ha/yr [2]					
Upstream	360	872	580	556	739
Downstream	461	1,182	801	783	1,076
Difference	102	310	221	228	338
Total N, g/ha/yr					
Upstream	694	1,599	1,093	1,048	1,411
Downstream	1,090	2,305	1,649	1,580	2,171
Difference	395	707	556	532	760

[1] Particulate P is estimated as the difference between dissolved P and total P.

[2] Particulate N is estimated as the difference between nitrate-N and total N. Monitoring shows ammonium-N to be negligible in Big Creek.

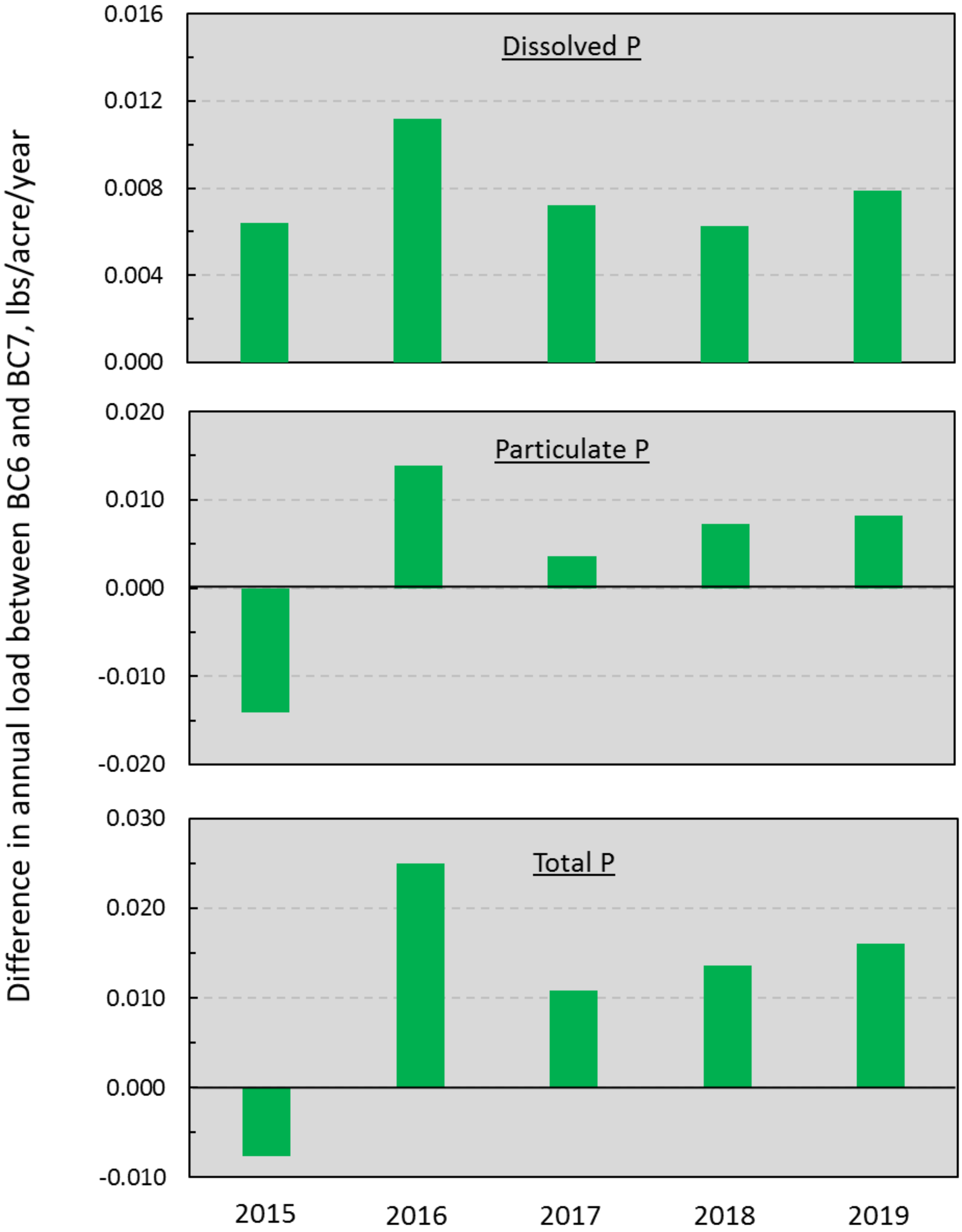


Figure S 1. Difference in P load between BC7 and BC6 for each monitored climate year (May 1, 2014 to April 30).

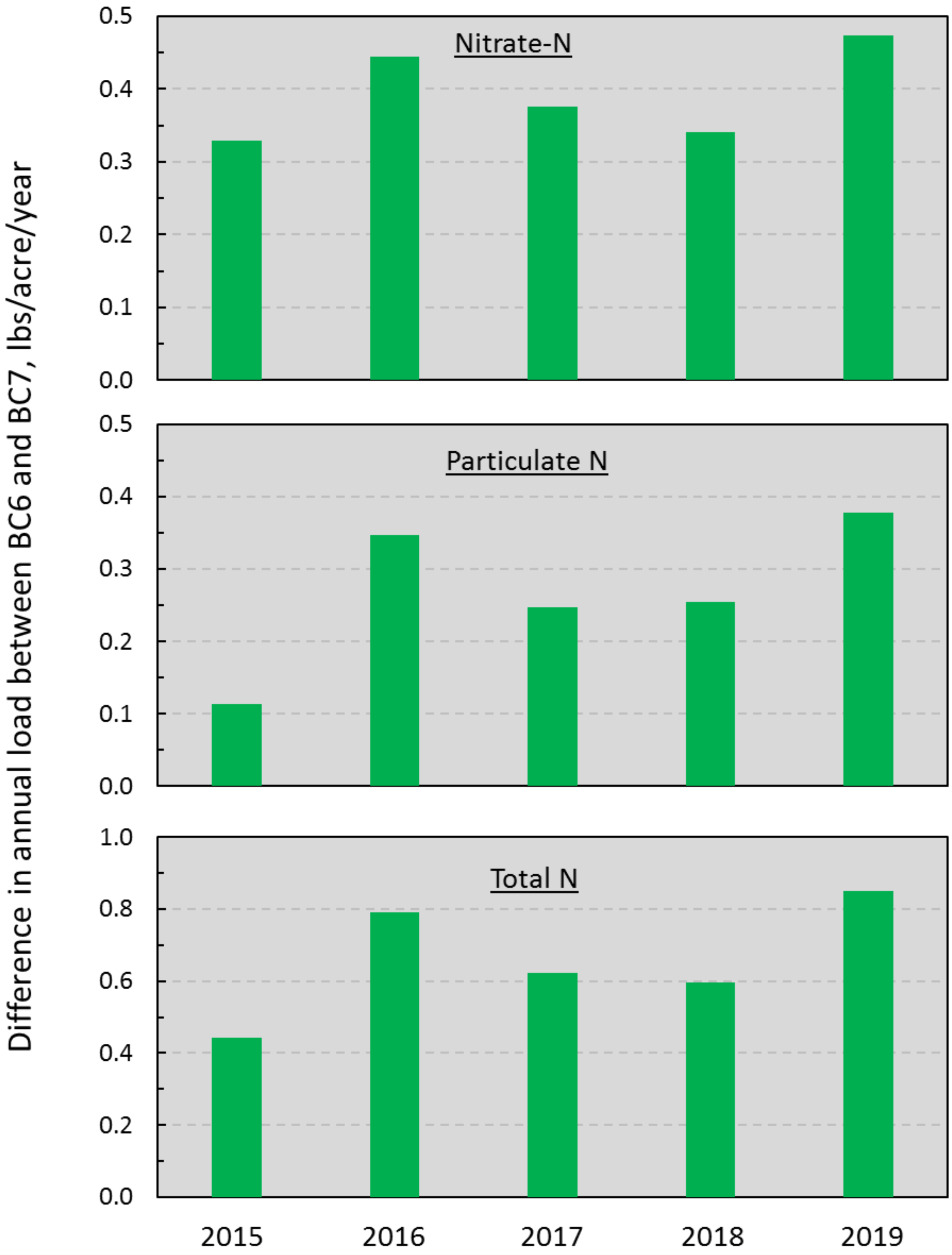


Figure S 2. Difference in N load between BC7 and BC6 for each monitored climate year (May 1, 2014 to April 30).

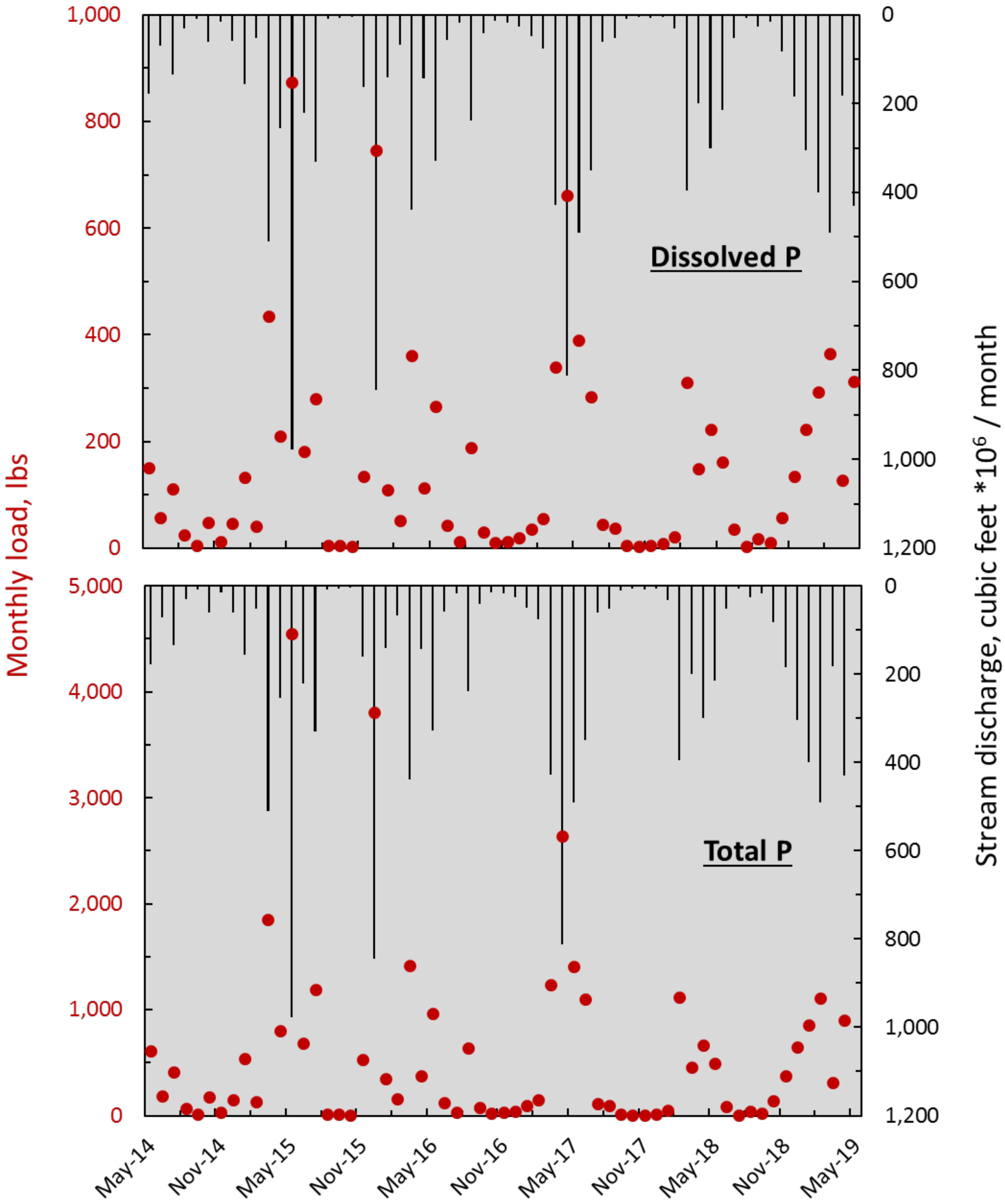


Figure S 3. Monthly dissolved and total P load for climate year (May 1, 2014 to April 30) and discharge at BC7 downstream of the C&H Farm.

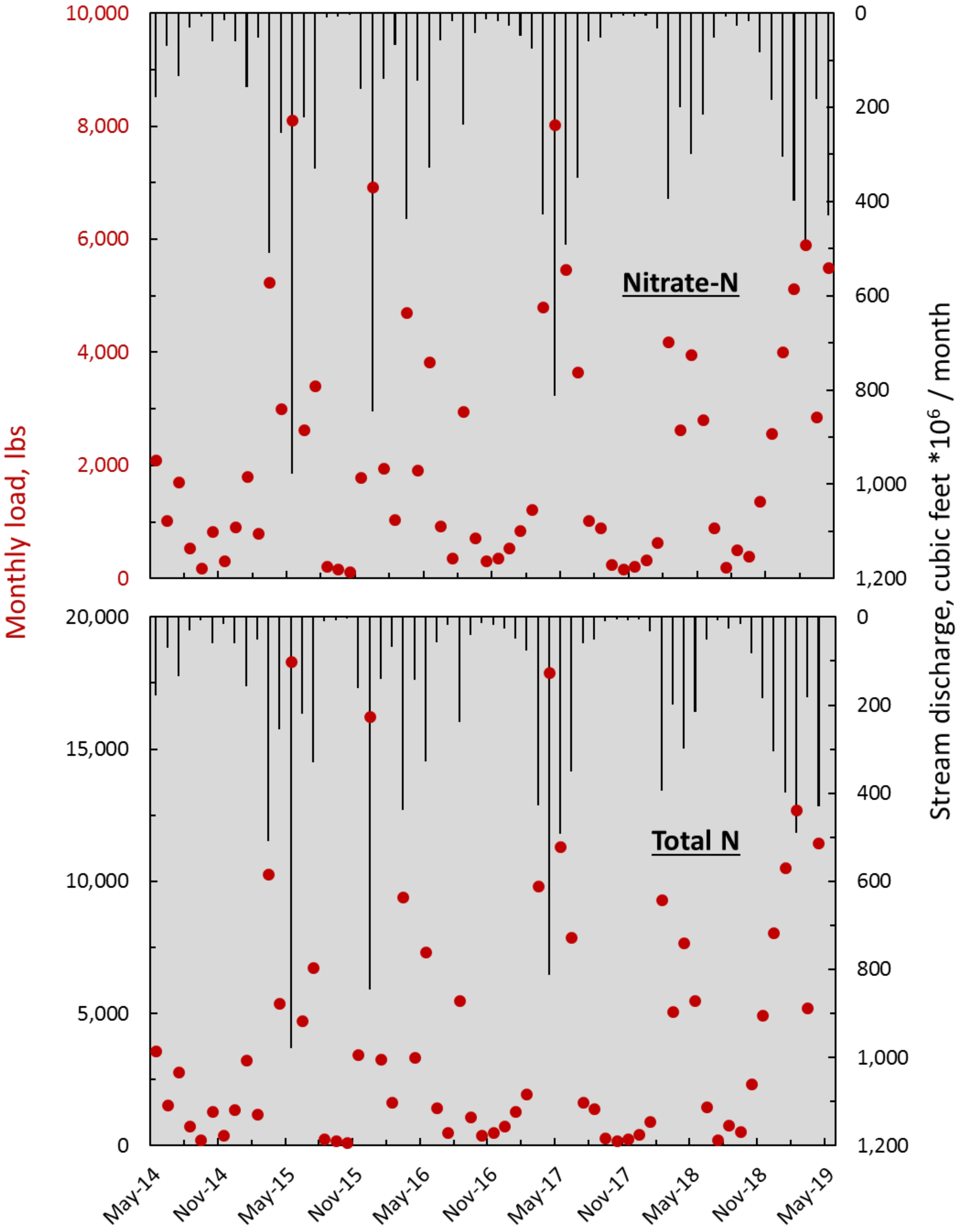


Figure S 4. Monthly nitrate-N and total N load a climate year (May 1, 2014 to April 30) and discharge at BC7 downstream of the C&H Farm.

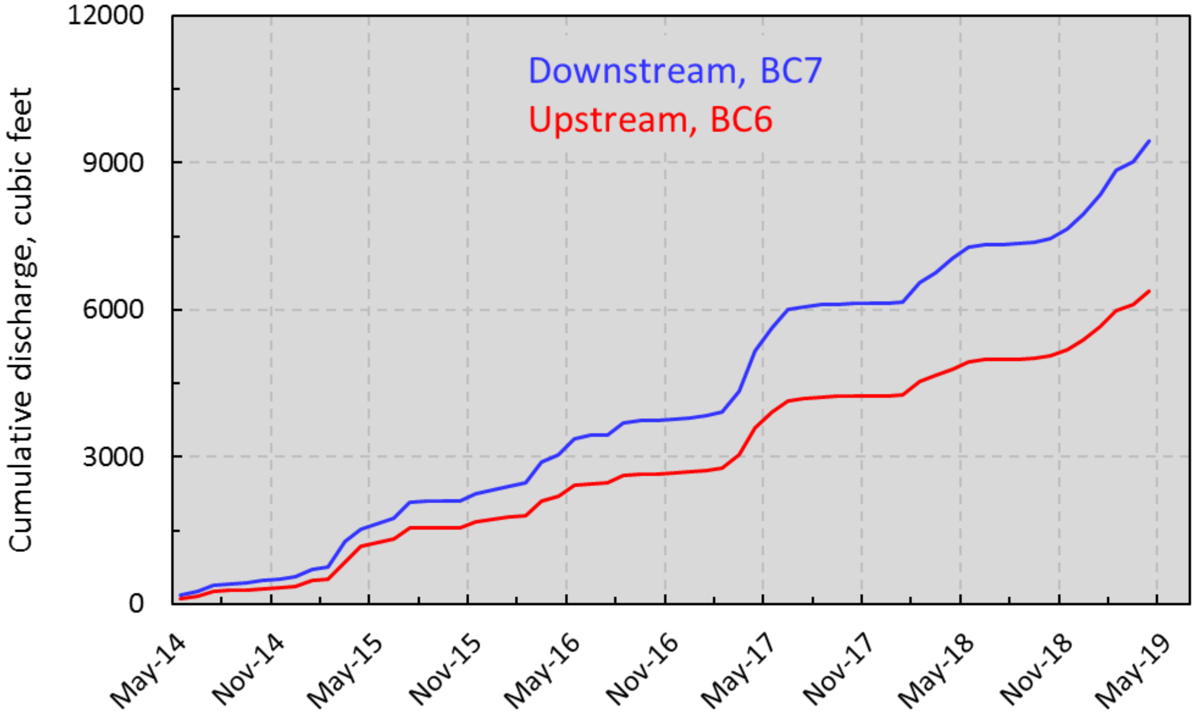


Figure S 5. Cumulative discharge up- (BC6) and down-stream (BC7) of the C&H Farm on Big Creek.

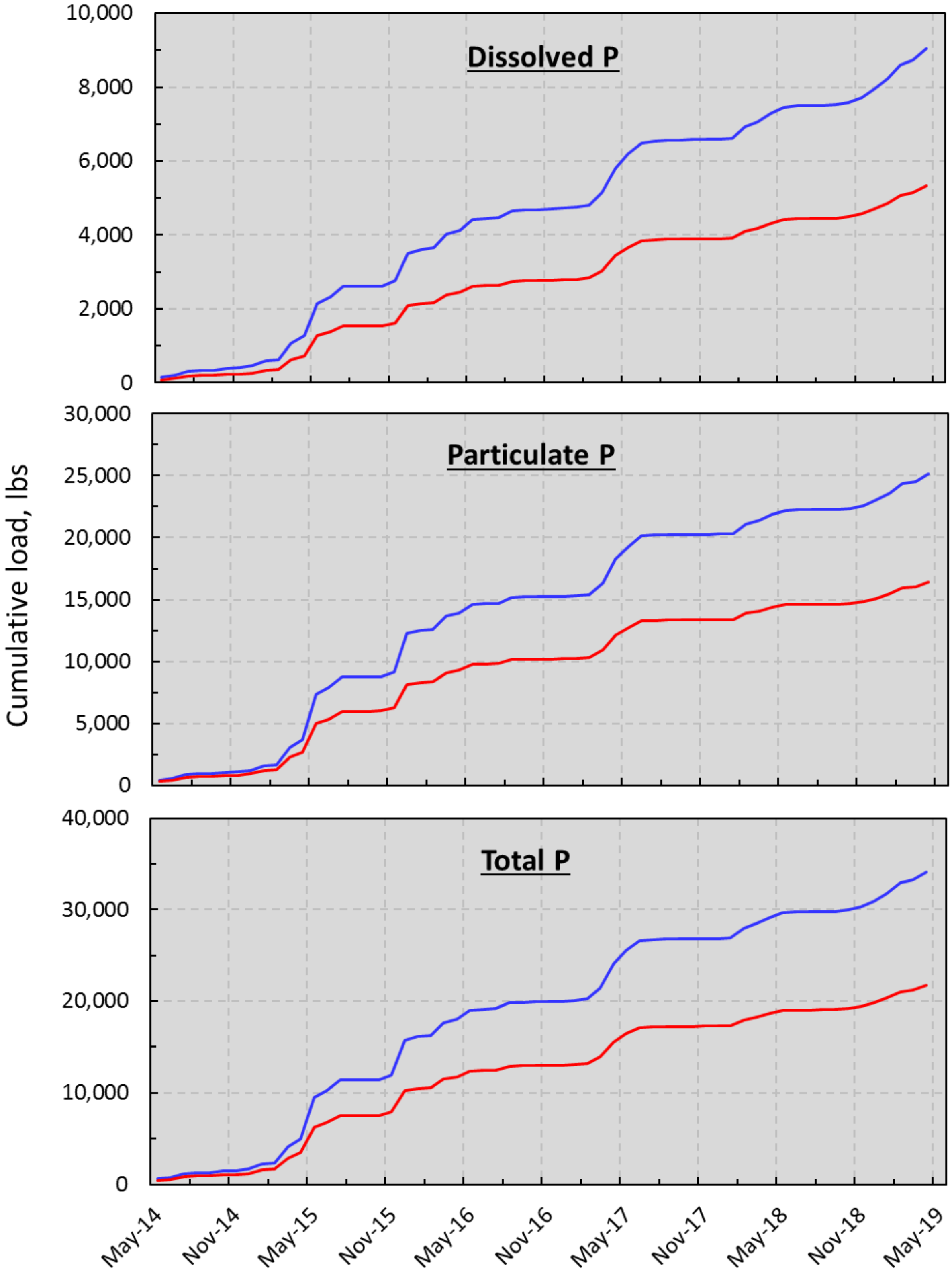


Figure S 6. Cumulative dissolved and total P load up- (BC6) and down-stream (BC7) of the C&H Farm on Big Creek.

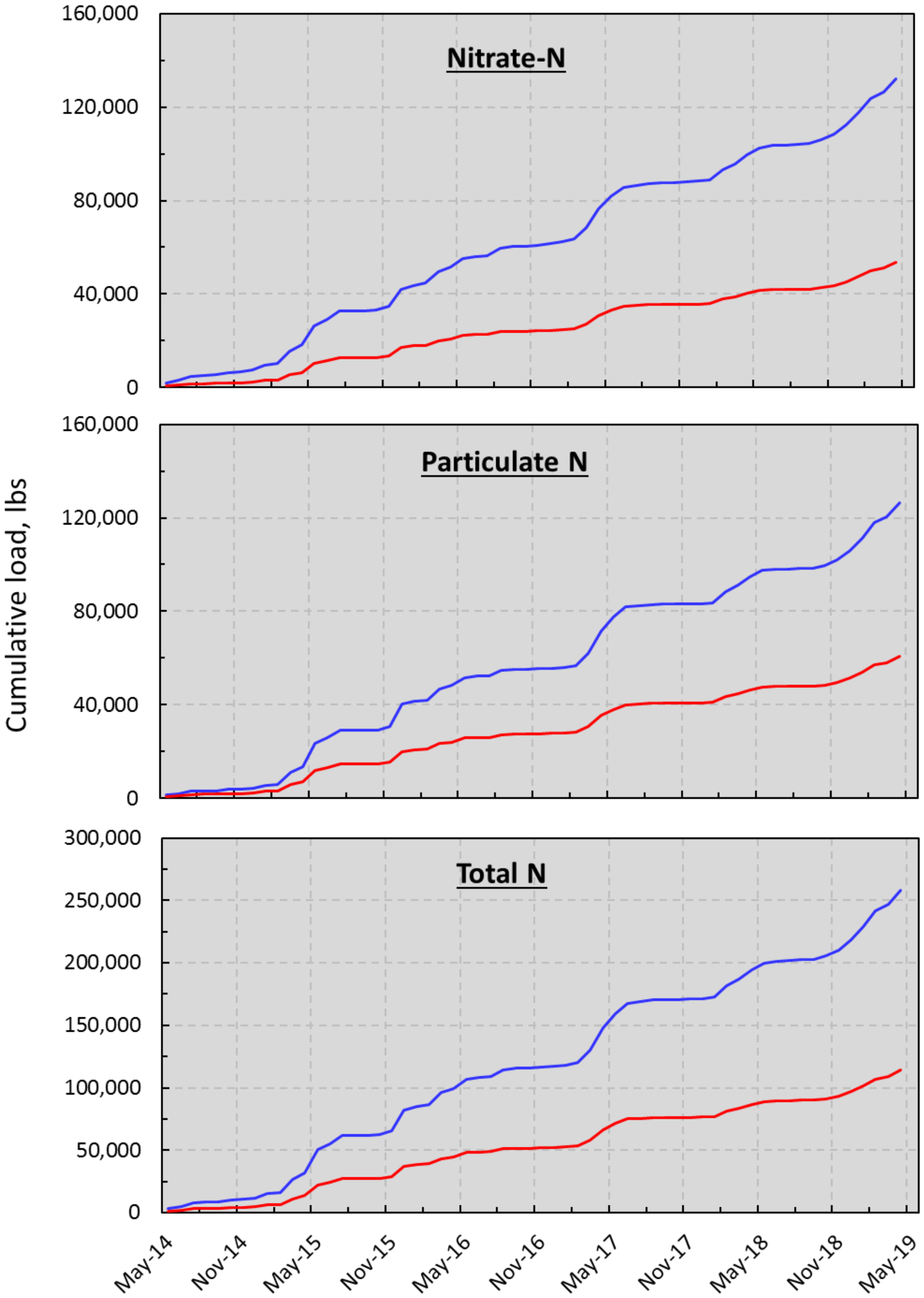


Figure S 7. Cumulative nitrate-N and total N load up- (BC6) and down-stream (BC7) of the C&H Farm on Big Creek.

NUTRIENT AND BACTERIA TRENDS IN BIG CREEK UP AND DOWN STREAM OF THE C&H FARM

Contents

Summary

1. Phosphorus and nitrogen (N) concentrations in Big Creek were greater downstream than upstream of the C&H Farm. For example, the 5-year mean nitrate-N concentration was 0.13 mg/L at the

upstream site (BC6) and 0.29 mg/L at the downstream site (BC7). This difference was greater at low base flow conditions in Big Creek.

2. This difference is due to a number of factors, such as a change in land use between upstream and downstream sites, which can influence both the amounts of nutrients available to be transported, as well as the propensity and speed by which nutrients move to a stream.
3. Using WRTDS to estimate flow-normalized concentrations of nutrients and E. coli over five water years (i.e., May 1, 2014 to April 30, 2019), we are able to remove the effect of inter- and intra-annual stream flow variability, for both up and down stream of the C&H Farm. Thus, providing a more reliable representation of the effects of changes in source inputs, land use, and watershed response to management, than simple concentrations or fluxes.
4. Based on WRTDS analysis, it is evident that flow-adjusted P concentrations decreased, while flow-adjusted N concentrations increased, both upstream and downstream of the C&H Farm during the monitoring period.
5. The was no consistent increase or decrease in P, N, E. coli analyte concentrations between September 1 and December 31, 2013 when no slurry had been land applied and in subsequent years following land application for the same four-month period.
6. Differences in nitrate-N concentrations between down and upstream sites were strongly influenced by stream flow, where the difference (i.e., downstream was greater than upstream) is very large at low flow and small at high flow. This suggests that at low flows, base flow nitrate-N emerges into Big Creek between upstream and downstream sites and that this base flow has a higher nitrate-N concentration than in base flow above the upstream site. However, at high flows it appears that water entering Big Creek from both the subwatershed above the upstream site and the intervening subwatershed between the downstream site is similar.
7. Despite higher nitrate-N concentrations at the down than upstream site on Big Creek, the relationship between upstream and downstream concentrations is unchanged over time, suggesting that over the 5 years of monitoring, the input of nitrate-N into Big Creek between up and downstream sites has not changed (i.e., no increase or decrease).

List of Tables

List of Figures

List of Supplementary Figures

Background

The Memorandum of Understanding with ADEQ states that BCRET will “Undertake and complete a study of the potential for water quality impacts within the Buffalo River Watershed from animal wastes produced by the permitted CAFO, C&H Farm, and its operation within the watershed.” Installation of the USGS-gaged site on Big Creek downstream of the watershed impacted by CAFO-generated slurry application to permitted fields (BC7) and the site upstream of permitted fields (BC6) provides locales to assess the impact of C&H operation on Big Creek.

As detailed earlier in this Final Report, gaging of the upstream site was not possible and USGS used a watershed area ratio for BC6 to BC7 of 0.66 to estimate upstream discharge (i.e., the upstream drainage area of 27.1 sq. mi divided by the downstream drainage area of 40.8 sq. mi). While not ideal, it proved to be the sole option available. Discharge measurements at BC7 started May 1, 2014. Thus, spatial and temporal trend analysis Big Creek water quality was conducted on a water year basis of May 1 to April 30 for 2015, 2016, 2017, 2018, and 2019.

Methods of Trend Analysis

Locally estimated scatterplot smoothing – LOESS Analysis

Simple trend analysis of in-stream nutrient concentrations was completed using three steps (see White et al., 2004). Briefly, the steps include:

i. Daily mean discharge and nutrient concentrations were log transformed to account for typical log-normal distribution of water quality data and to minimize the effects of outliers within the data (Hirsch et al., 1991; Lettenmaier et al., 1991);
ii. Log-transformed TP concentrations were adjusted against log-transformed daily mean discharge using the LOESS two-dimensional smoothing technique (Richards and Baker, 2002; Hirsch et al., 1991); and
iii. Flow-adjusted TP concentrations (derived from residuals of the LOESS regression of discharge versus concentration) were analyzed for temporal trends using regression tree analysis and LOESS.

The relationship between log-transformed stream discharge and log-transformed TP concentrations were quantified using LOESS two-dimensional smoothing, with a sampling proportion of 0.5 and a first order polynomial function (Systat Software, Inc., San Jose, CA). Bekele and McFarland (2004) observed that a sampling proportion of 0.5 was adequate to reduce variability in concentrations with stream discharge. The LOESS smoothing uses locally weighted regression algorithms and overcomes limitations often associated with parametric techniques that are more sensitive to outliers in the data (Lettenmaier et al., 1991). The residuals from this LOESS smoothing of log-transformed discharge and concentration represent the flow-adjusted concentrations.

Data from Big Creek were paired with discharge available from a gaging station just downstream from the swine CAFO, where the USGS developed the rating curve; discharge information was only available from May 2014 through June 2019. The data were then used in a simple three-step process (White et al., 2004) to look at monotonic changes in the nutrients at Big Creek:

i. Log-transform concentration (mg/L) and associated instantaneous discharge (ft^3/s);
ii. Use locally weighted regression (LOESS) to smooth the data with a sampling proportion (n) of 0.5; and
iii. Plot the residuals from LOESS (i.e., the flow-adjusted concentrations) over time and use linear regression to evaluate monotonic trends.

Weighted Regressions on Time, Discharge, and Season – WRTDS Analysis

Weighted Regressions on Time, Discharge, and Season (WRTDS), developed by USGS personnel, is a relatively new approach to the analysis of long-term (a minimum of a 5-year record of data) surface water-quality data (Hirsch et al., 2010). This statistical approach increases the amount of information that can be gleaned from water-quality monitoring data, such as that obtained by BCRET, eliminating the influence of year-to-year variations in streamflow to provide concentration and flux estimates. It has been shown to be a useful diagnostic tool to evaluate changes in watershed land use; in this case, the Big Creek watershed defined by our stream sampling sites (i.e., BC6 and BC7) related to surface- and ground-water flows and nutrient fluxes (Hirsch et al., 2010). Ideally, long-term, water-quality trend analysis by WRTDS should include more than 200 water samples collected over 20 years.

In general, WRTDS can produce two types of concentration and loading estimates, which are called "true-condition" and "flow-normalized" estimates, respectively. True-condition estimates are model-based approximations of the real history of riverine concentration or loading and are relevant to understanding actual downstream impacts (Moyer et al., 2012). By contrast, the flow-normalization method uses the full history of flows on the given calendar date to effectively remove the effects of inter-annual streamflow variability. It should therefore better reflect the effects of changes in source inputs and watershed system response (Chanat et al., 2016; Hirsch and De Cicco, 2015).

Nutrient Concentrations over Time

Nutrient concentrations for the monitoring period upstream and downstream of the C&H Farm are given in Supplemental Figures S1 to S6 for dissolved P, total P, nitrate-N, total N, E.coli, and chloride, respectively. A seasonal fluctuation in nitrate-N (Figure S3) and chloride (Figure S6) reflects a varying contribution of surface and subsurface flow to Big Creek. During the generally drier summer months, Big Creek base flow originates predominantly from the influx of ground water. During spring and fall rains, "flashy" storms are dominated by water originating from surface or near surface water flows in the Big Creek Watershed (Figure 1). As nitrate-N and chloride are soluble constituents, they can move preferentially with ground water, rather than in surface runoff, which a more important transporter of P from fields to streams.

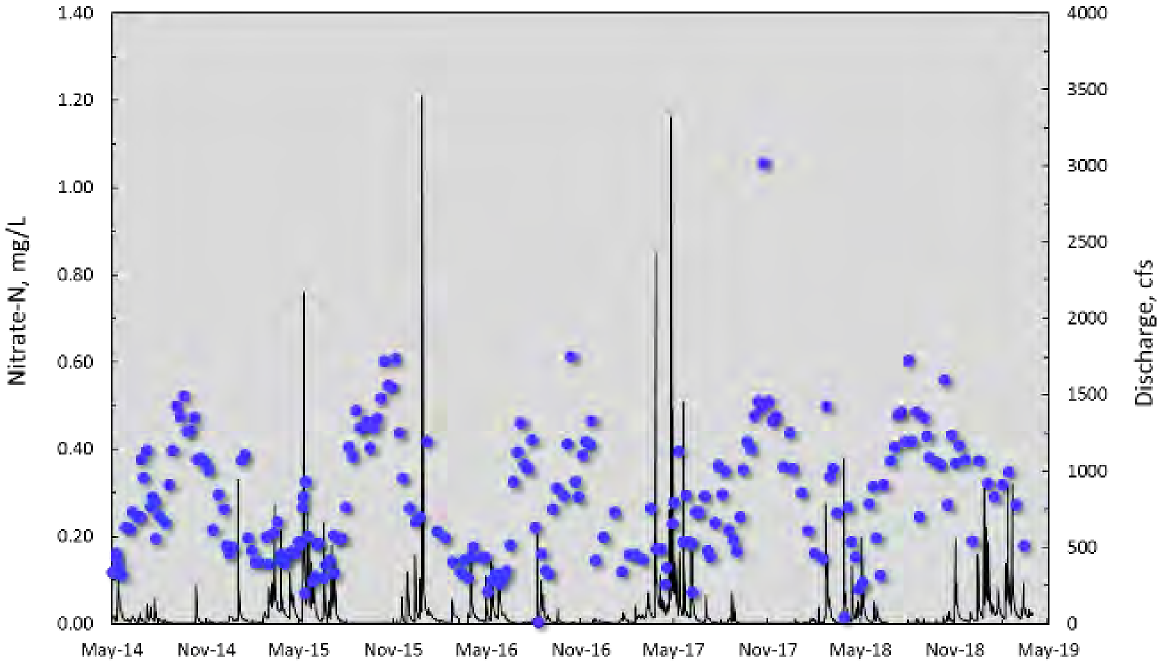


Figure 1. Nitrate-N concentration and discharge at the downstream site (BC7) over the sampling period.

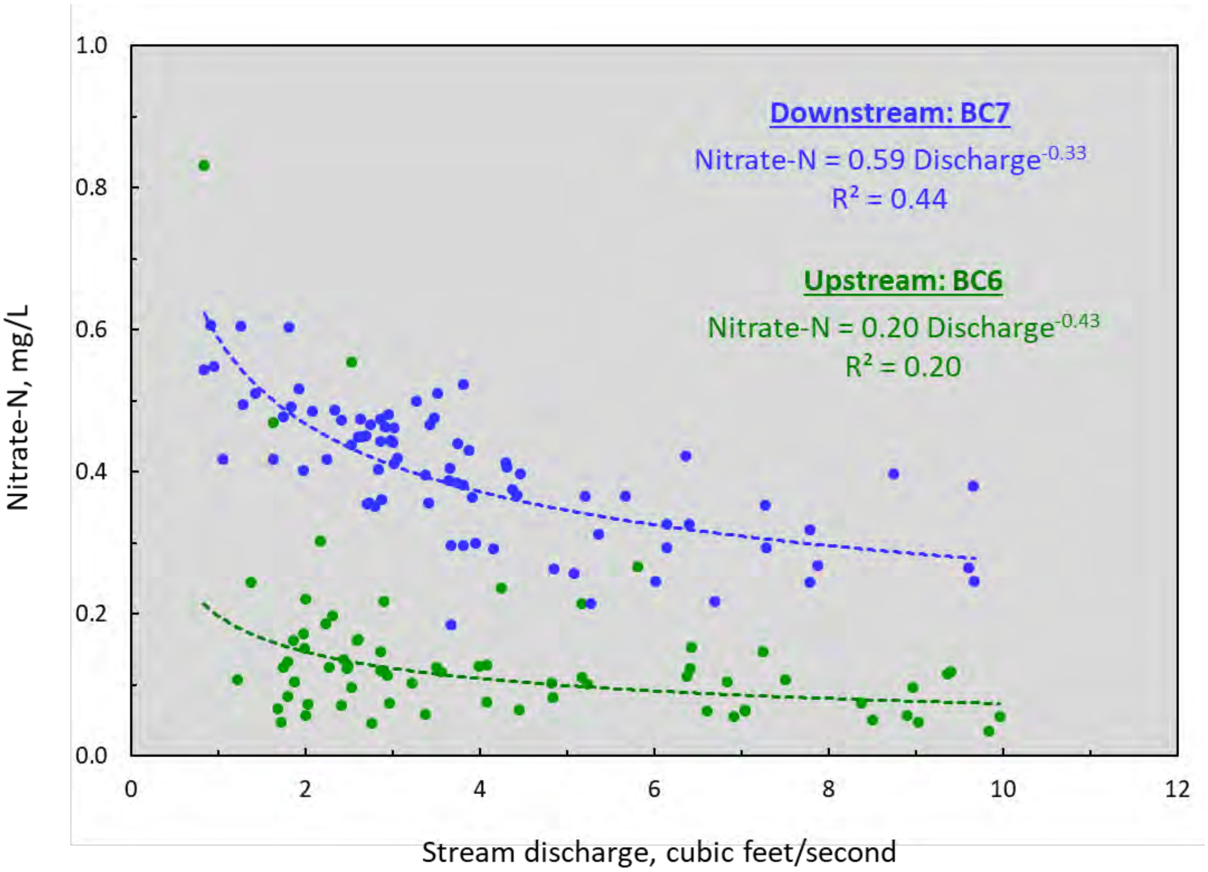


Figure 2. Nitrate-N concentration as a function of discharge for the upstream (BC6) and downstream sites (BC7) for stream discharge below 10 cubic feet/second, between May 1, 2014 and April 30, 2019.

Nitrate concentrations in Big Creek tend to be greater at the downstream site than at the upstream site. For example, mean nitrate-N concentration for the 5-year monitoring period was 0.133 mg/L at the upstream site (BC6) and 0.286 mg/L at the downstream site (BC7). This difference was greater at low base flow conditions in Big Creek, as shown in Figure 2. Other nutrients, dissolved P, total P, and total N were also greater at down than at the upstream sites. This difference is due to a number of factors, such as a change in land use between upstream and downstream sites, which can influence both the amounts of nutrients available to be transported, as well as the propensity and speed by which nutrients move to a stream. Also, ground water is the main contributor of flow and thereby nitrate-N, during base flow conditions in Big Creek. Thus, nitrate-N concentrations in Big Creek under low flow conditions tend to gravitate towards ground water nitrate-N, which we can best measure at the well adjacent to the animal barns (collects water from 265 to 285 feet deep). Over the well-sampling period (April 2014 to July 2019), nitrate-N had a mean of 0.62 mg/L, median of 0.59 mg/L, and geomean of 0.60 mg/L (see section titled "Nutrient and E. coli Trends: Trench, Well, Ephemeral Stream and Left Fork).

The effect of land use on nutrient flux in and from watersheds in the karst region of the Boston Mountains and Ozark Highlands has been demonstrated by McCarty and Haggard (2016), Giovannetti et al. (2013), and Sharpley et al. (2017). Big Creek monitoring did not provide sufficient information to distinguish the relative roles of changing land use along Big Creek and the operation of C&H as a source of nutrients to Big Creek.

Comparison of Time Period Trends With and Without Slurry Applications

Collection of water quality samples from Big Creek upstream and downstream of the C&H Farm was initiated in the beginning of September 2013. As no slurry generated on the Farm was applied to any of the permitted fields prior to December 31, 2013, we compared nutrient and E. coli concentrations measured between September 1 and December 31 each year of our monitoring. The comparison is depicted as box plots, in Figures 3 through 5. Median, first (25th), and third (75th) quantile values from this analysis are given in Table 1.

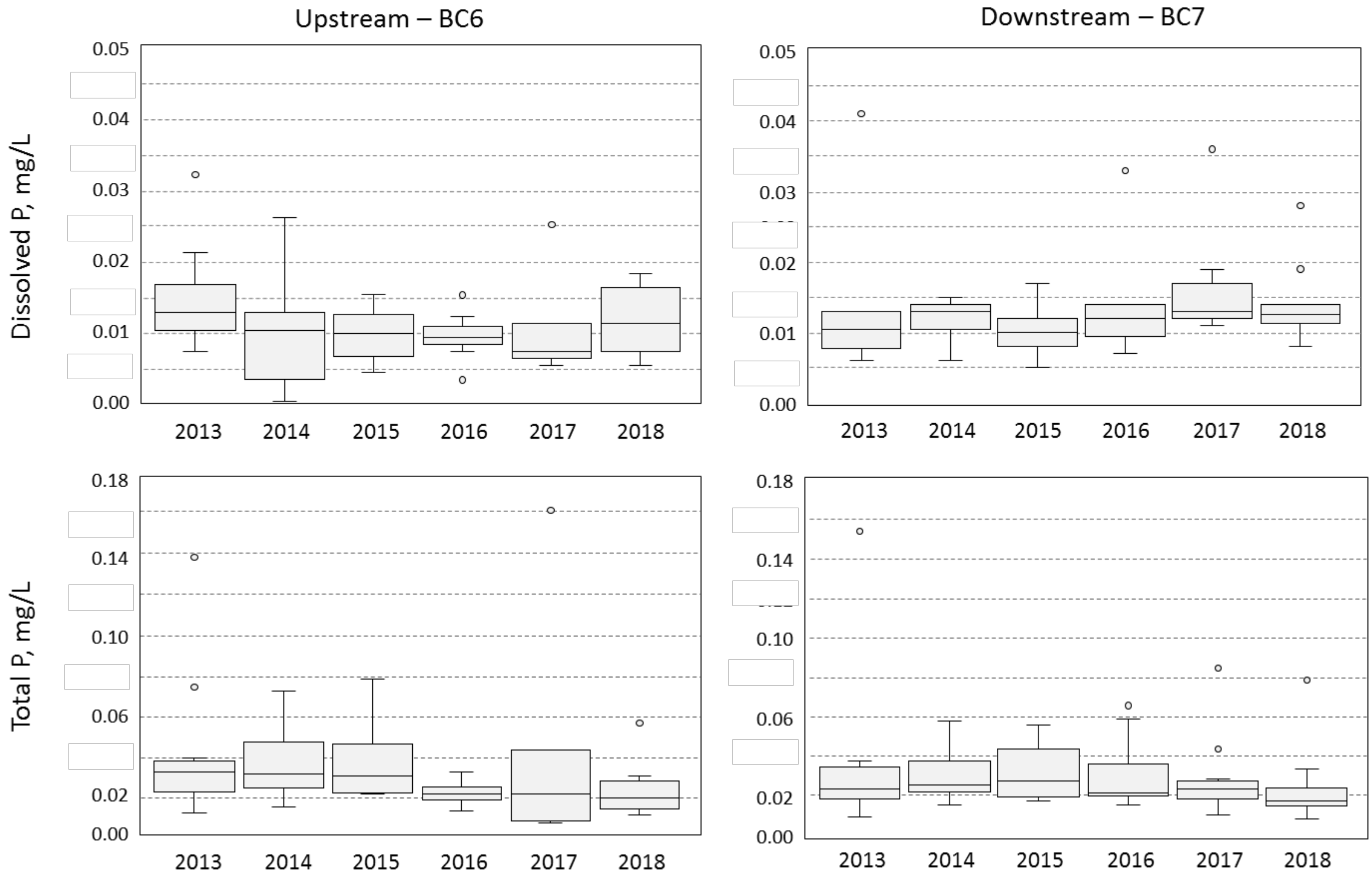


Figure 3. Comparison of dissolved and total P concentrations measured up and downstream of the C&H Farm between September 1 and December 31 for 2013 to 2018.

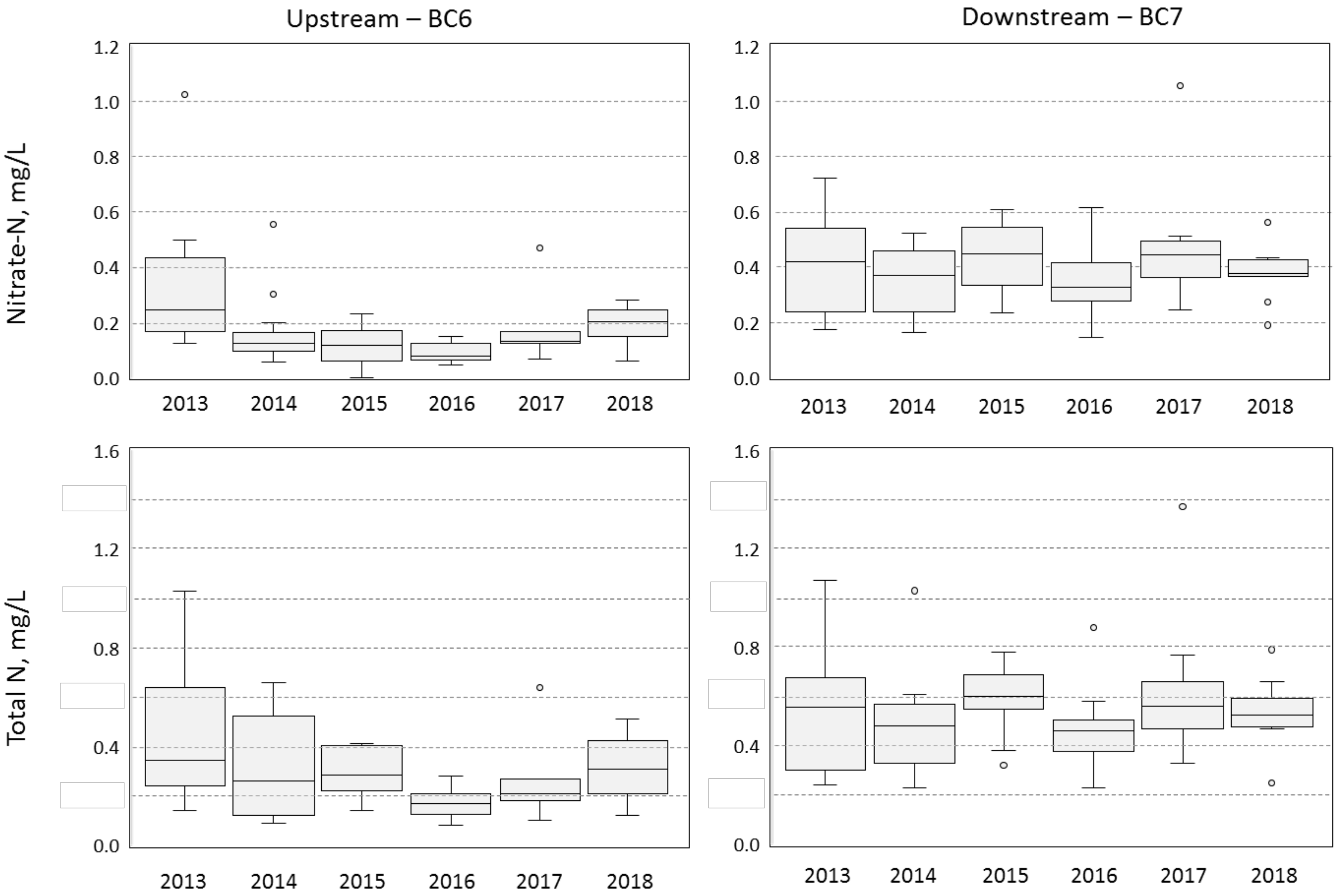


Figure 4. Comparison of nitrate-N and total N concentrations measured up and downstream of the C&H Farm between September 1 and December 31 for 2013 to 2018.

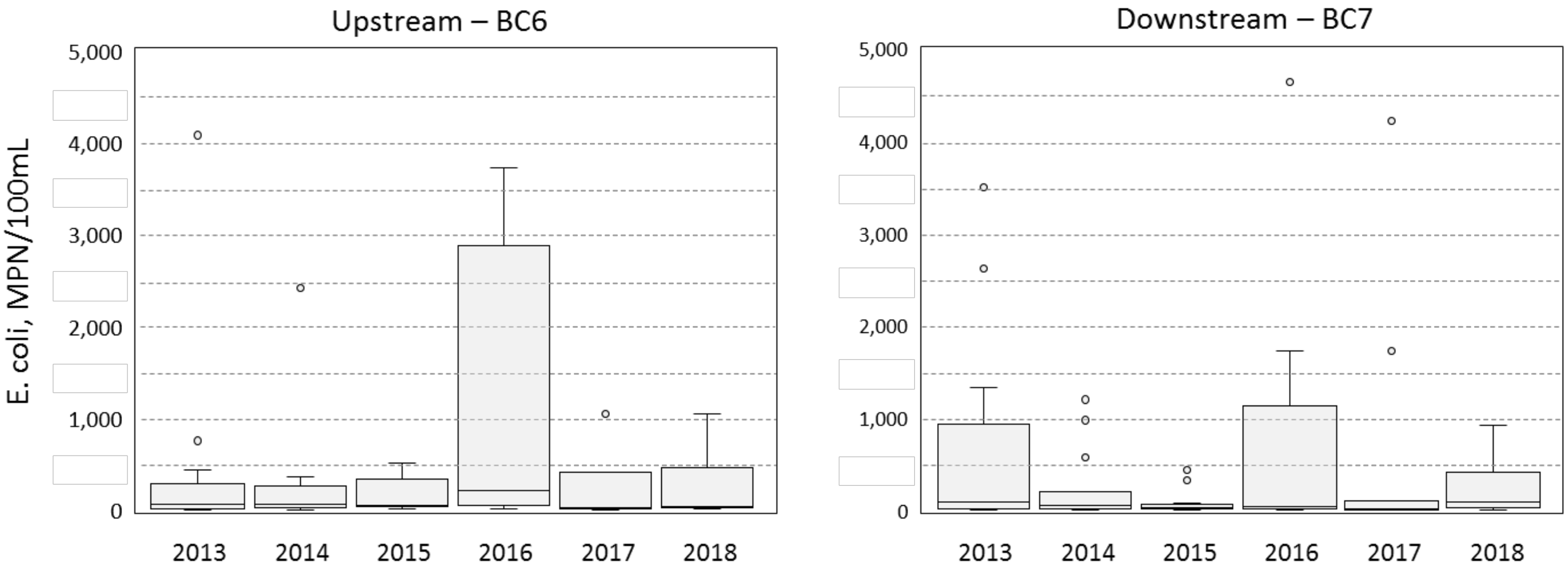


Figure 5. Comparison of E. coli concentrations measured up and downstream of the C&H Farm between September 1 and December 31 for 2013 to 2018.

Median nitrate-N and total N concentrations, and 25th and 27th quantiles for Big Creek were greater downstream than upstream of the C&H Farm, as noted previously. However, the analysis showed there was no consistent increase or decrease in these values between 2013 when no slurry had been land applied and in subsequent years following land application, for this specific four-month period.

Table 1. Median, 25th quantile, and 75th quantile concentrations for P, N, and E.coli upstream (BC6) and downstream (BC7) of the C&H Farm for the period September 1 and December 31 for 2013 through 2018.

	2013	2014	2015	2016	2017	2018
Median concentration, mg/L						
Upstream, BC6						
Dissolved P	0.013	0.010	0.010	0.009	0.010	0.011
Total P	0.031	0.029	0.029	0.020	0.032	0.018
Nitrate-N	0.25	0.12	0.12	0.08	0.13	0.20
Total N	0.34	0.22	0.29	0.71	0.20	0.31
E. coli †	71	68	53	216	238	42
Downstream, BC7						
Dissolved P	0.011	0.013	0.010	0.010	0.012	0.013
Total P	0.024	0.026	0.028	0.022	0.023	0.018
Nitrate-N	0.42	0.37	0.45	0.33	0.45	0.38
Total N	0.56	0.48	0.60	0.46	0.54	0.53
E. coli †	87	56	32	216	19	86
25th quantile concentration, mg/L						
Upstream, BC6						
Dissolved P	0.010	0.004	0.006	0.008	0.007	0.007
Total P	0.020	0.023	0.021	0.017	0.020	0.012
Nitrate-N	0.17	0.10	0.06	0.06	0.08	0.15
Total N	0.24	0.12	0.22	0.13	0.12	0.21
E. coli †	23	32	47	60	25	34
Downstream, BC7						
Dissolved P	0.008	0.010	0.008	0.010	0.012	0.011
Total P	0.019	0.022	0.020	0.021	0.019	0.015
Nitrate-N	0.24	0.23	0.33	0.28	0.36	0.37

	2013	2014	2015	2016	2017	2018
Total N	0.30	0.33	0.55	0.38	0.47	0.48
E. coli †	20	20	20	24	7	36
75th quantile concentration, mg/L						
Upstream, BC6						
Dissolved P	0.017	0.013	0.012	0.011	0.022	0.016
Total P	0.037	0.039	0.045	0.024	0.013	0.027
Nitrate-N	0.44	0.17	0.07	0.02	0.38	0.25
Total N	0.64	0.53	0.41	0.21	0.53	0.43
E. coli †	295	270	337	2885	887	461
Downstream, BC7						
Dissolved P	0.010	0.014	0.012	0.014	0016	0.014
Total P	0.034	0.031	0.044	0.037	0.027	0.025
Nitrate-N	0.54	0.47	0.54	0.42	0.50	0.43
Total N	0.68	0.56	0.69	0.51	0.65	0.59
E. coli †	941	200	66	1436	79	411

† E. coli concentration is MPN/100mL.

Trends Determined by WRTDS

Flow-Adjusted Concentrations

Using WRTDS to estimate flow-normalized concentrations of nutrients and E. coli over five water years (i.e., May 1, 2014 to April 30, 2019), we are able to remove the effect of inter- and intra-annual stream flow variability for both up and down stream of the C&H Farm (i.e., BC6 and BC7). These flow-adjusted or normalized concentrations provide a more reliable representation of the effects of changes in source inputs, land use, and watershed response to management, than simple concentrations or fluxes.

Flow-adjusted concentrations for up and downstream sites for dissolved P, total P, nitrate-N, total N, and E. coli are presented in Figures 6 to 10. It is evident from these relationships that dissolved and total P decreased during the monitoring period (Figures 6 and 7) and based on the slope of that relationship the decrease was slightly greater for total P at the upstream than downstream site (Figure 7). In contrast to P, nitrate-N and total N increased over the five-year monitoring (Figures 8 and 9, respectively), although this relationship showed similar increases up and downstream, based on slope values.

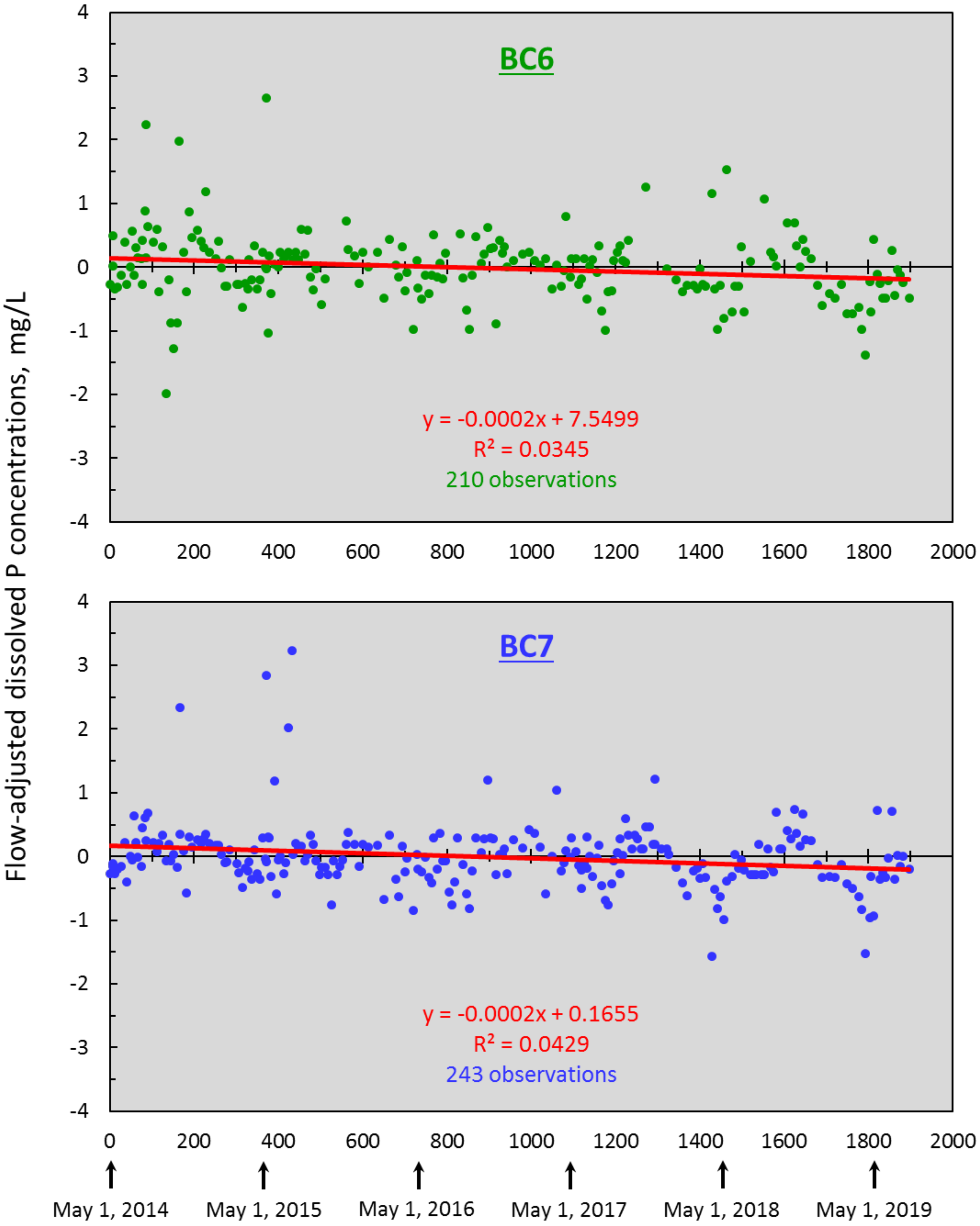


Figure 6. Flow-adjusted dissolved P concentrations upstream (BC6) and downstream sites (BC7) of the C&H Farm over time since May 1, 2014, when discharge measurements started.

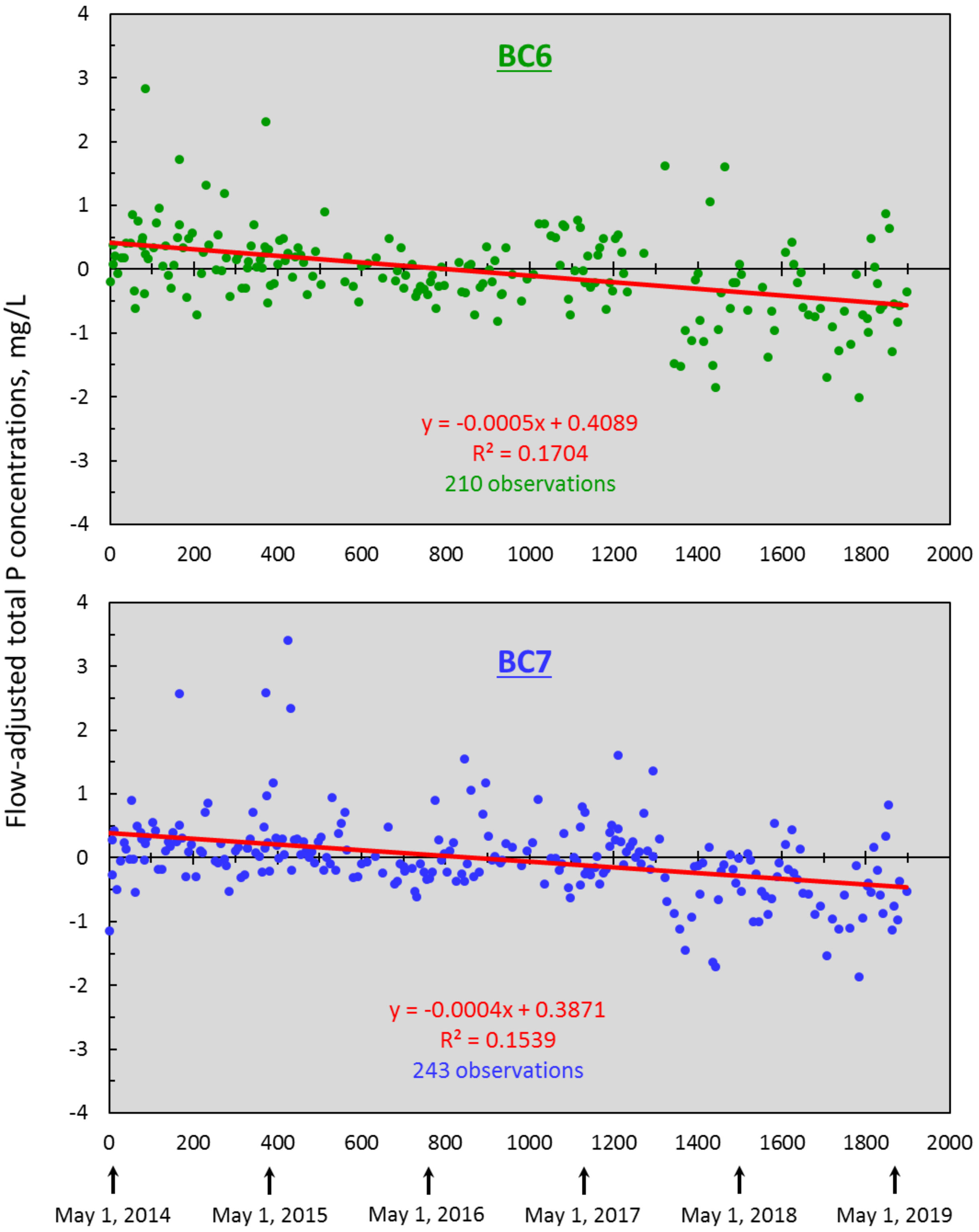


Figure 7. Flow-adjusted total P concentrations upstream (BC6) and downstream sites (BC7) of the C&H Farm over time since May 1, 2014, when discharge measurements started.

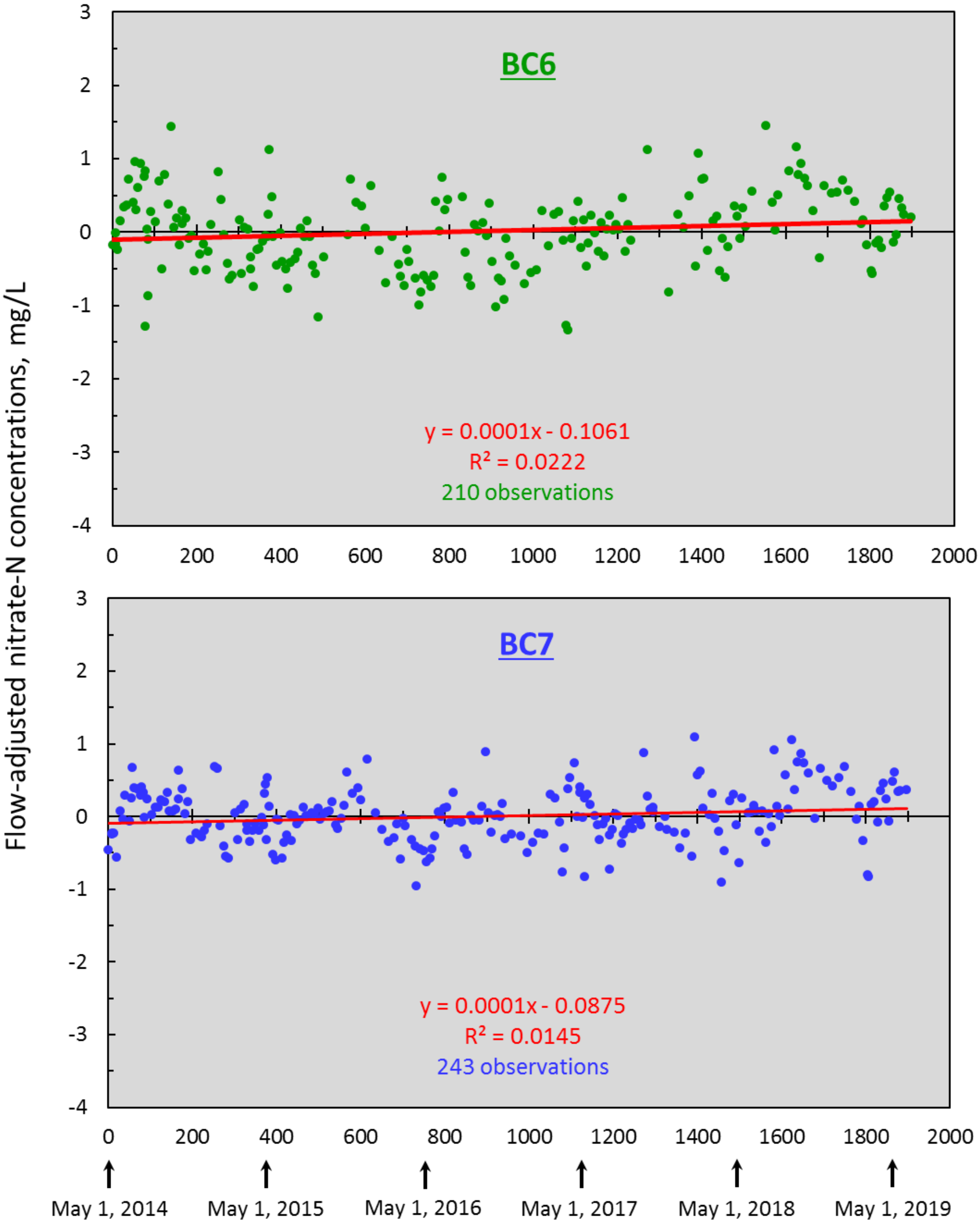


Figure 8. Flow-adjusted nitrate-N concentrations upstream (BC6) and downstream sites (BC7) of the C&H Farm over time since May 1, 2014, when discharge measurements started.

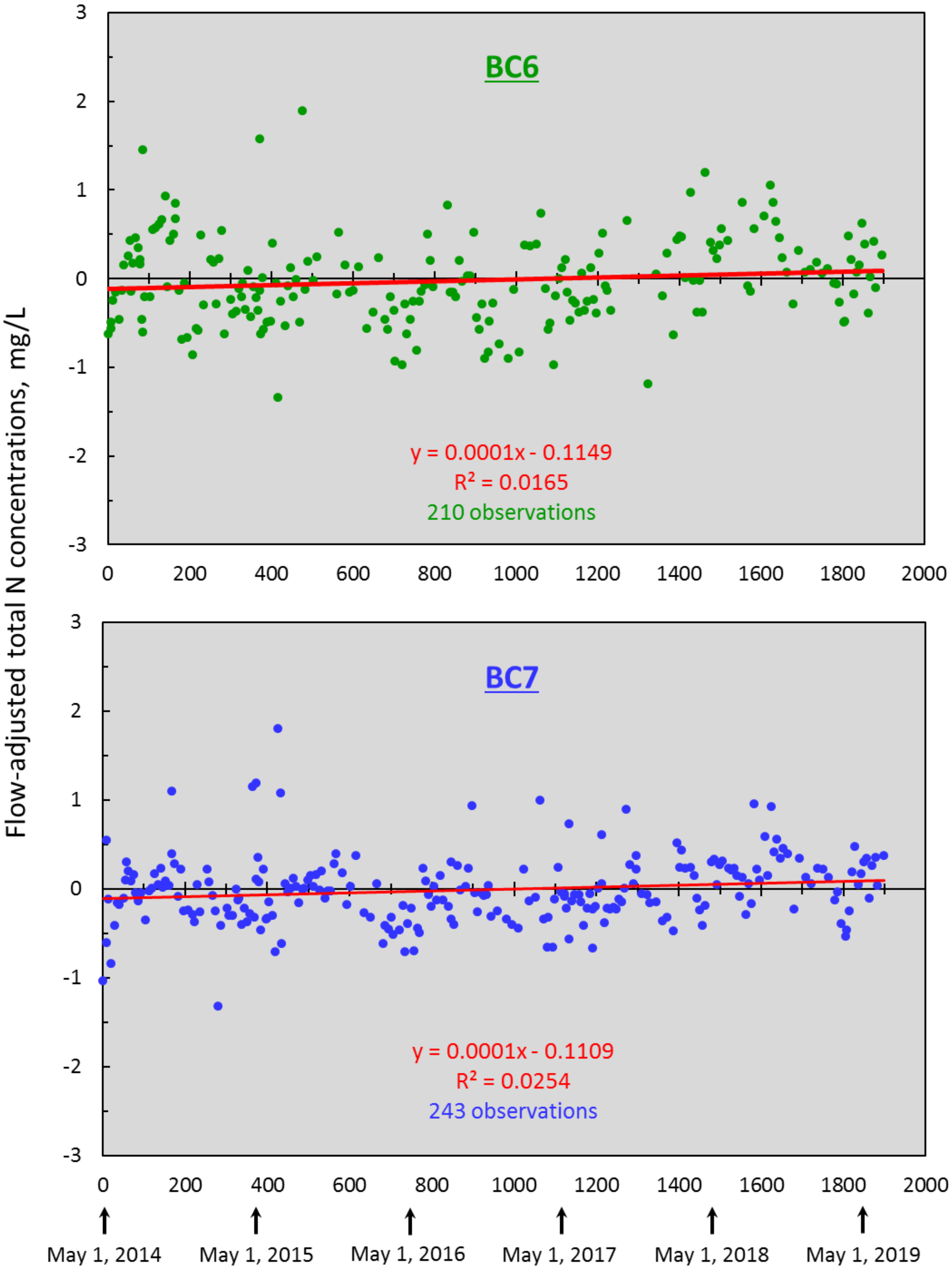


Figure 9. Flow-adjusted total N concentrations upstream (BC6) and downstream sites (BC7) of the C&H Farm over time since May 1, 2014, when discharge measurements started.

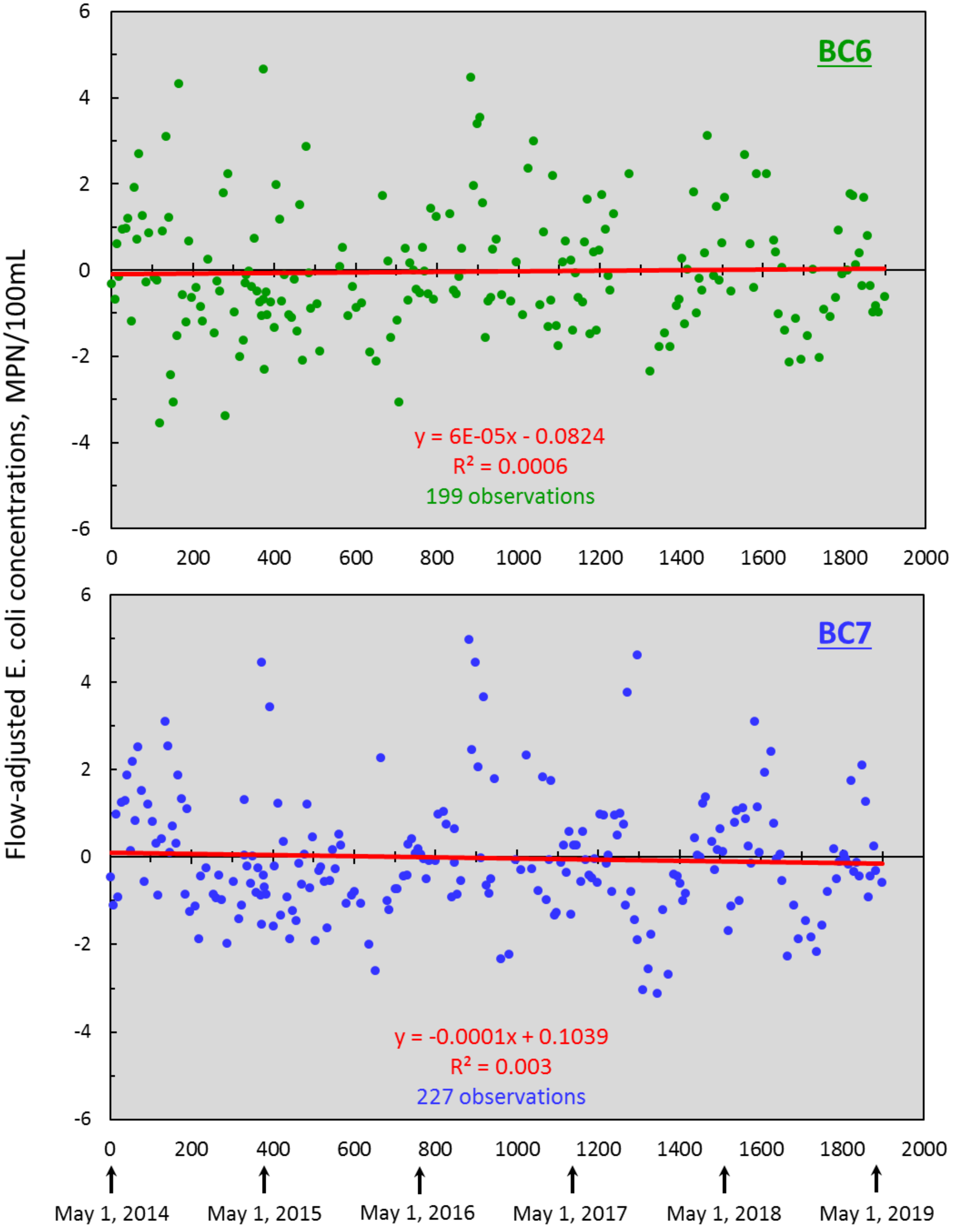


Figure 10. Flow-adjusted E. coli concentrations upstream (BC6) and downstream sites (BC7) of the C&H Farm over time since May 1, 2014, when discharge measurements started.

Trends as a function of Flow Regime

Big Creek flows were classified as base, intermediate or storm flows using hydrographs provided by the United States Geological Survey (USGS – see https://nwis.waterdata.usgs.gov/ar/nwis/uv?cb_00060=on&format=gif_default&site_no=07055790&period=&begin_date=2014-04-16&end_date=2017-04-10). Base flows were assessed by lower, level plateaus of the hydrograph curve, while storm flows were determined by sharp, elevated peaks within the hydrograph. Intermediate flows were determined as being between base and storm and located mid-slope as storm flows descended to base flows on the curve. If the hydrograph for a certain sampling event had pronounced peaks, but did not vary significantly in discharge, the resulting flow was characterized as base flow.

The mean concentrations of analytes measured under each flow condition between April 2014 and June 2019 are presented for Big Creek sites upstream and downstream of the C&H Farm operation in Table 2, along with differences determined by paired "t". In addition, trends over time were assessed by the Seasonal Kendall's Tau Test, where negative tau (τ) values represent a decreasing concentration trend over time and a positive τ, an increasing trend at a given probability (Table 2). These relationships provide insight into the dominant flow pathways for P, N, sediment, and bacteria transport in this watershed.

Table 2. Mean concentration and differences as determined by paired "t" test of analytes in Big Creek at upstream (BC6) and downstream (BC7) sites, and multivariate correlations for Seasonal Kendall's Test, as a function of flow regime.

Flow regime	Upstream - BC6			Downstream - BC7		
	Mean †	Kendall τ	Probability ‡	Mean †	Kendall τ	Probability ‡
Dissolved P, mg/L						
Base [#]	0.009 b	-0.0789	0.2022	0.011 b	0.0141	0.8033
Intermediate [¶]	0.008 b	-0.2280	0.0301*	0.009 b	-0.3309	0.0009*
Storm [††]	0.018 a	-0.0048	0.9653	0.026 a	-0.0308	0.7681
Total P, mg/L						
Base	0.034 b	-0.2558	<.0001*	0.027 b	-0.2207	<.0001*
Intermediate	0.019 b	-0.3720	0.0003*	0.021 b	-0.4148	<.0001*
Storm	0.145 a	0.0106	0.9222	0.108 a	0.0233	0.8301
Nitrate-N, mg/L						

Flow regime	Upstream - BC6				Downstream - BC7		
	Mean †	Kendall τ	Probability ‡		Mean †	Kendall τ	Probability ‡
Base	0.119 a	0.0067	0.9108		0.308 a	0.1584	0.0043*
Intermediate	0.119 a	0.1374	0.1746		0.260 b	0.0126	0.8966
Storm	0.126 a	0.1794	0.095		0.212 b	0.0135	0.8945
Total N, mg/L							
Base	0.217 b	0.0705	0.2443		0.420 b	0.2084	0.0001*
Intermediate	0.198 b	0.1296	0.2076		0.359 b	0.1075	0.2719
Storm	0.400 a	0.2312	0.0318*		0.536 a	0.1595	0.1202
E. coli, MPN/100 mL							
Base	633 b	0.0395	0.5102		271 b	-0.0815	0.1405
Intermediate	182 b	-0.0730	0.4852		145 b	-0.0704	0.4858
Storm	2577 a	0.1128	0.3413		2297 a	0.0947	0.4099
Chloride, mg/L							
Base	1.748 a	0.0000	1.0000		2.481 a	0.1743	0.0034*
Intermediate	1.482 b	-0.1416	0.1708		1.863 b	-0.0742	0.4832
Storm	1.340 b	-0.2857	0.0296*		1.538 c	-0.0648	0.5614
Electrical conductivity, µS/cm							
Base	150 a	0.2388	0.0004*		227 a	0.2230	0.0002*
Intermediate	117 b	-0.1835	0.0765		170 b	-0.0067	0.9499
Storm	96 b	-0.2469	0.0606		144 b	-0.1580	0.1696

† Mean concentrations within columns (i.e., flow regime, upstream, and downstream) with different letters are significantly different as determined by paired "t" test at a 5% level of significance.

‡ Probability values with * designate a significant trend with time.

Upstream (BC6) had 129 and downstream (BC7) 155 observations for base flow.

¶ Upstream (BC6) had 47 and downstream (BC7) 51 observations for intermediate flow.

†† Upstream (BC6) had 42 and downstream (BC7) 46 observations for storm flow.

Conclusions where trends are significant:

1. Dissolved and total P concentrations in storm flow were greater than in base and intermediate flows at sites up (BC6) and downstream (BC7) of the Big Creek farm.
2. Nitrate-N concentrations were greater for base flow than the other flow types at the downstream site only (BC7). The greater concentration of total N in storm than base and intermediate flows, likely reflects an increased transport of particulate N during higher energy, storm flow events.
3. E. coli concentrations were appreciably greater in storm than base and intermediate flows.
4. There was a greater decrease in dissolved and total P concentrations at the downstream site (BC7) during the monitoring period (2013 to 2019) compared to the upstream site (BC6), as represented by Kendall's Tau.
5. There was a greater increase in nitrate-N and total N concentrations at the downstream site (BC7) than at the upstream site (BC6) with time during base flow conditions, as represented by Kendall's Tau. Chloride concentrations and electrical conductivity showed the same trend.
6. A better understanding these flow – concentration relationships in Big Creek, will help identify and target effective conservation measures aimed at minimizing P, N, sediment, and bacterial transport and input to Big Creek.

Table 3. Statistically different mean concentrations in Big Creek upstream (BC6) and downstream (BC7) of C&H determined by paired "t" test of analytes for paired samplings as a function of flow regime; with and without two outlier samples.

Flow regime	All data			Two outliers excluded		
	# Obs.	Upstream	Downstream	# Obs.	Upstream	Downstream
Dissolved P, mg/L						
Base	123	0.009 b[†]	0.011 a	123	0.009 b[†]	0.011 a
Intermediate	50	0.008 b	0.009 a	50	0.008 b	0.009 a
Storm	38	0.015 a	0.020 a	38	0.015 a	0.020 a
Total P, mg/L						
Base	123	0.034 a	0.027 a	122[‡]	0.027 a	0.027 a
Intermediate	50	0.020 a	0.020 a	50	0.020 a	0.020 a
Storm	38	0.014 a	0.010 a	37[#]	0.063 a	0.098 a
Nitrate-N, mg/L						

Flow regime	All data				Two outliers excluded		
	# Obs.	Upstream	Downstream		# Obs.	Upstream	Downstream
Base	123	0.119 b	0.276 a		123	0.119 b	0.276 a
Intermediate	50	0.116 b	0.253 a		50	0.116 b	0.253 a
Storm	38	0.134 b	0.226 a		38	0.134 b	0.226 a
Total N, mg/L							
Base	123	0.215 b	0.383 a		123	0.215 b	0.383 a
Intermediate	50	0.196 b	0.352 a		50	0.196 b	0.352 a
Storm	38	0.390 a	0.526 a		37 ¶	0.329 b	0.525 a
E. coli, MPN/100 mL							
Base	120	657 a	289 a		119 ††	404 a	282 b
Intermediate	46	173 a	121 a		46	173 a	121 a
Storm	34	1962 a	2469 a		34	1962 a	2469 a
Chloride, mg/L							
Base	97	1.780 b	2.307 a		97	1.780 b	2.307 a
Intermediate	44	1.475 b	1.852 a		44	1.475 b	1.852 a
Storm	30	1.317 b	1.605 a		30	1.317 b	1.605 a
Electrical conductivity, µS/cm							
Base	95	153 b	208 a		95	153 b	208 a
Intermediate	44	114 b	170 a		44	114 b	170 a
Storm	30	101 b	144 a		30	101 b	144 a

† Mean concentrations within rows (i.e., flow regime, upstream, and downstream) with different letters are significantly different as determined by paired “t” test at a 5% level of significance.

‡ Outlier for total P of 0.888 mg/L during base flow at BC6 on April 22, 2014 excluded due to sampling of stagnant water at BC6.

Outlier for total P of 2.956 mg/L during storm flow at BC6 on August 20, 2015 excluded due to sampling of stagnant water at BC6.

¶ Outlier for total N of 2.640 mg/L during storm flow at BC6 on August 20, 2015 excluded due to sampling of stagnant water at BC6.

†† Outlier for E. coli of 30,760 MPN/100ml during base flow on August 8, 2019 excluded due to sampling of stagnant water at BC6.

Conclusions where trends are significant:

1. When samples were collected at both up (BC6) and downstream sites (BC7) on the same day, dissolved P, total P, nitrate-N, total N, chloride, and electrical conductivity were greater downstream of the C&H Farm (0.05 % level of significance) for all three flow regimes (i.e., base, intermediate, and storm flows).
2. Excluding total P, total N, and E. coli outliers, all measured upstream of the C&H Farm, resulted in one change; E. coli was lower at the down than upstream site (0.05 % level of significance).

Trends as a function of Season

Table 4. Mean concentration and differences as determined by paired “t” test of analytes in Big Creek at upstream (BC6) and downstream (BC7) sites, and multivariate correlations for Seasonal Kendall’s Test, as a function of season March to June, July to October, and November to February.

Season [†]	Upstream - BC6			Downstream - BC7		
	Mean [‡]	Kendall τ	Probability [#]	Mean [‡]	Kendall τ	Probability [#]
Dissolved P, mg/L						
March - June [¶]	0.011 a	-0.1362	0.0606	0.012 a	-0.1063	0.1314
July - October [††]	0.011 a	0.0112	0.8930	0.015 a	-0.0714	0.3215
November – February [‡‡]	0.009 a	-0.4416	<.0001*	0.012 a	-0.2108	0.0284*
Total P, mg/L						
March - June	0.047 a	-0.1772	0.0114*	0.045 a	-0.1222	0.0732
July - October	0.077 a	-0.3122	0.0002*	0.043 a	-0.3027	<.0.0001*
November - February	0.026 a	-0.3459	0.0005*	0.026 a	-0.2606	0.0053*
Nitrate-N, mg/L						
March - June	0.102 b	0.1421	0.0408*	0.196 c	0.1288	0.0568
July - October	0.148 a	0.0404	0.6196	0.358 a	0.048	0.4914
November - February	0.117 b	0.1980	0.0455*	0.299 b	0.1131	0.2187
Total N, mg/L						
March - June	0.221 b	0.2499	0.0004*	0.363 b	0.2409	0.0004*
July - October	0.325 a	0.0332	0.6871	0.512 a	0.148	0.0351*

Season †	Upstream - BC6				Downstream - BC7		
	Mean ‡	Kendall τ	Probability #		Mean ‡	Kendall τ	Probability #
November - February	0.191 b	0.1604	0.1099		0.403 b	0.1542	0.0964
E. coli, MPN/100mL							
March - June	858 a	0.0953	0.1812		976 a	0.0618	0.3809
July - October	1372 a	0.0564	0.5077		333 a	-0.0079	0.9139
November - February	200 a	-0.1242	0.2133		250 a	-0.0379	0.6870
Chloride, mg/L							
March - June	1.393 b	-0.2054	0.0068*		1.716 b	-0.0620	0.3930
July – October	1.744 a	-0.0604	0.5405		2.521 a	-0.0422	0.5947
November - February	1.878 a	-0.1344	0.1932		2.486 a	-0.1659	0.0928
Electrical conductivity, µS/cm							
March - June	107 b	-0.1351	0.0753		155 c	-0.0137	0.8517
July - October	186 a	-0.1443	0.1450		258 a	-0.0855	0.2892
November - February	121 b	-0.0999	0.3461		192 b	-0.1161	0.2558

† Three seasons of equal length (i.e., 4 months) are designated according to runoff potential based on historical rainfall and stream flow data for the area. The potential for runoff increases in the periods July to October, to March to June, to November to February (see Sharpley et al., 2010). The Arkansas P Index assigns loss rating factors of 0.1, 0.25, and 0.60 for these periods, respectively.

‡ Mean concentrations within columns (i.e., season, upstream, and downstream) with different as determined by paired "t" test at a 5% level of significance.

Probability values with * designate a significant trend with time.

¶ Upstream (BC6) had 98 and downstream (BC7) 99 observations for base flow.

†† Upstream (BC6) had 71 and downstream (BC7) 95 observations for intermediate flow.

‡‡ Upstream (BC6) had 49 and downstream (BC7) 56 observations for storm flow.

Conclusions where trends are significant:

1. Nitrate-N and total N concentrations were greatest during the summer (July to October period), while there was no seasonal difference in dissolved or total P concentration.
2. There was no seasonal difference in E. coli concentrations at the up (BC6) and downstream sites (BC7).

Table 5. Statistically different mean concentrations in Big Creek upstream (BC6) and downstream (BC7) of C&H determined by paired "t" test of analytes for paired samplings as a function of flow regime; with and without two outlier samples.

Season [†]	# Obs.	Upstream [‡]	Downstream [‡]
Dissolved P, mg/L			
March - June	97	0.011 a	0.013 a
July - October	65	0.009 b	0.012 a
November - February	49	0.009 b	0.011 a
Total P, mg/L			
March - June	97	0.047 a	0.052 a
July – October [#]	64	0.026 a	0.027 a
November - February	49	0.026 a	0.025 a
Nitrate-N, mg/L			
March - June	97	0.101 b	0.197 a
July – October	65	0.154 b	0.348 a
November - February	49	0.117 b	0.276 a
Total N, mg/L			
March - June	97	0.221 b	0.377 a
July - October	65	0.312 b	0.460 a
November - February	49	0.191 b	0.371 a
E. coli, MPN/100 mL			
March - June	91	833 a	984 a
July – October [¶]	61	613 a	399 b
November - February	47	204 a	196 a
Chloride, mg/L			
March - June	82	1.395 b	1.739 a
July - October	47	1.767 b	2.384 a
November - February	42	1.896 b	2.350 a
Electrical conductivity, µS/cm			
March - June	82	107 b	155 a
July - October	47	189 b	246 a
November - February	40	123 b	183 a

† Three seasons of equal length (i.e., 4 months) are designated according to runoff potential based on historical rainfall and stream flow data for the area. The potential for runoff increases in the periods July to October, to March to June, to November to February (see Sharpley et al., 2010). The Arkansas P Index assigns loss rating factors of 0.1, 0.25, and 0.60 for these periods, respectively.

‡ Mean concentrations within columns (i.e., season, upstream, and downstream) with different as determined by paired "t" test at a 5% level of significance.

Outlier for total P of 0.888 mg/L at BC6 on August 20, 2015 excluded due to sampling of stagnant water at BC6.

¶ Outlier for E. coli of 30,760 MPN/100mL BC6 on August 8, 2019 excluded due to sampling of stagnant water at BC6.

Conclusions where trends are significant:

1. Removal of outliers basically eliminated any season differences in N, P, E. coli, chloride or conductivity differences.

Comparison of Upstream and Downstream Trends as a Function of Time and Discharge

Monthly mean nitrate-N and dissolved P concentration values for all 61 months of record (May 2014 through May 2019 inclusive) for up (BC6) and downstream Sites (BC7) were estimated using an autoregressive model in WRTDS, which enables interpolation between the measured days (i.e., when water quality sample was taken).

What this means is that for any given day when no sample was collected, three pieces of information are used: (a) the WRTDS estimate for that day – based on the discharge, time of year, and year; (b) the amount of error the WRTDS model had on the most recent sampled day; and (c) the amount of error the WRTDS model had on the next sampled day.

When the day being estimated is close to one of the sampled days, that sampled day value gets a large weighting. When there is a long time (e.g., two weeks) from the day being estimated to the nearest sampled day, the WRTDS model dominates the estimate. On sampled days, the sampled value for that day is used. From the time series of monthly mean concentrations at both sites, the difference between the concentration at the downstream site (BC7) and upstream site (BC6; always a positive number) is computed.

The difference in monthly mean nitrate-N and dissolved P concentrations over the 5-year monitoring period are presented in Figure 11. More emphasis will be given the discussion of nitrate-N due to downstream increases noted earlier in this section (see Figure 1). There is no apparent strong trend in this record, but there is a period of relatively high nitrate-N concentrations in 2015. These high values lie in the months of August, September, and October of 2015, which were months of very low flow but they lie between the two very high flow period in May and December of 2015. This suggests this time series of nitrate-N differences might be very strongly influenced by streamflow.

The difference in down and upstream nitrate-N concentrations is larger at low flows than at high flows. What that means is that at low flows, there is a source of higher nitrate-N concentration base flow that emerges into the stream between up and downstream sites than in baseflow above the upstream site.

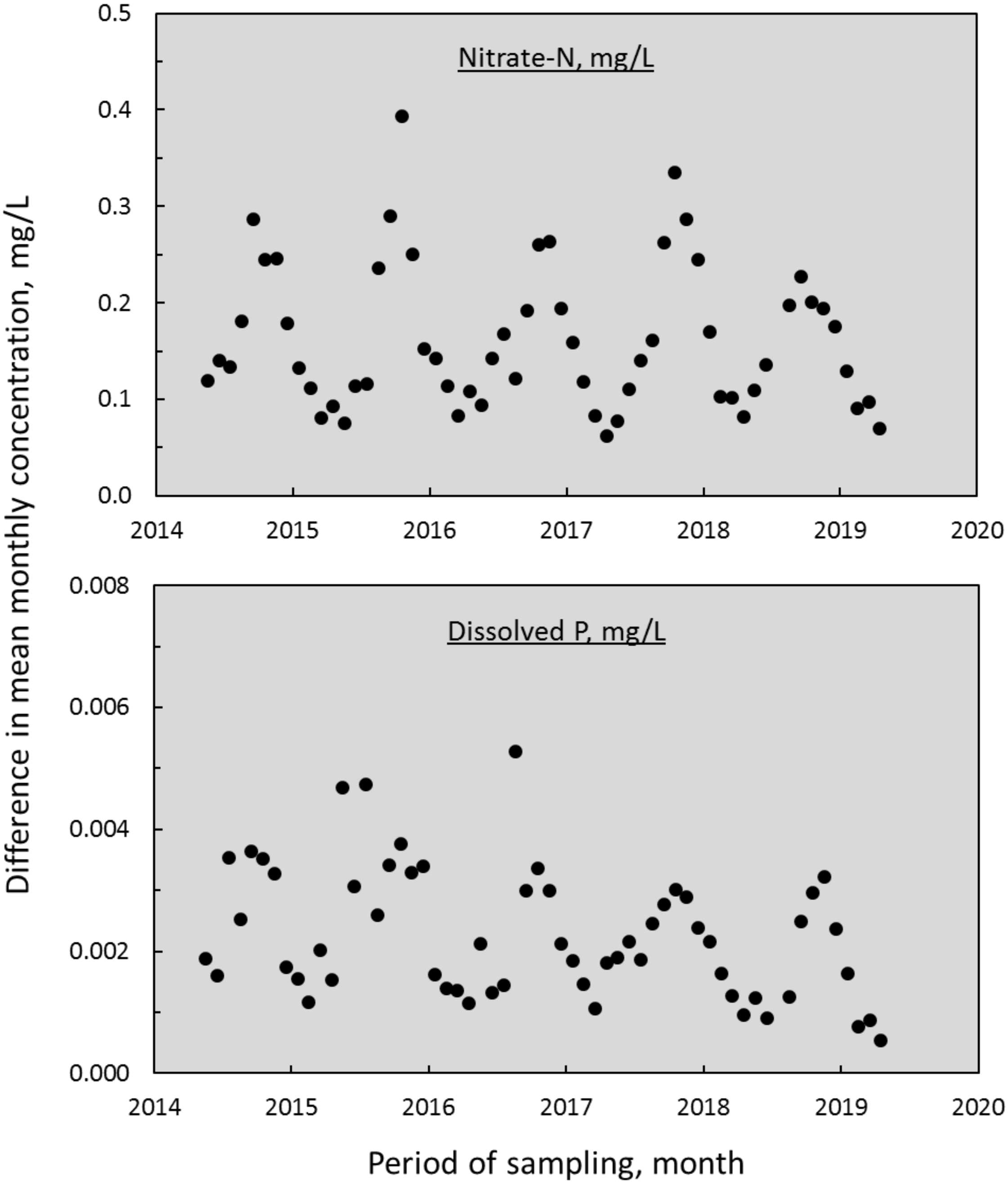


Figure 11. Difference in monthly mean nitrate-N and dissolved P concentrations between sites down (BC7) and upstream (BC6) of the C&H Farm as a function of time (May 1, 2014 to May 31, 2019).

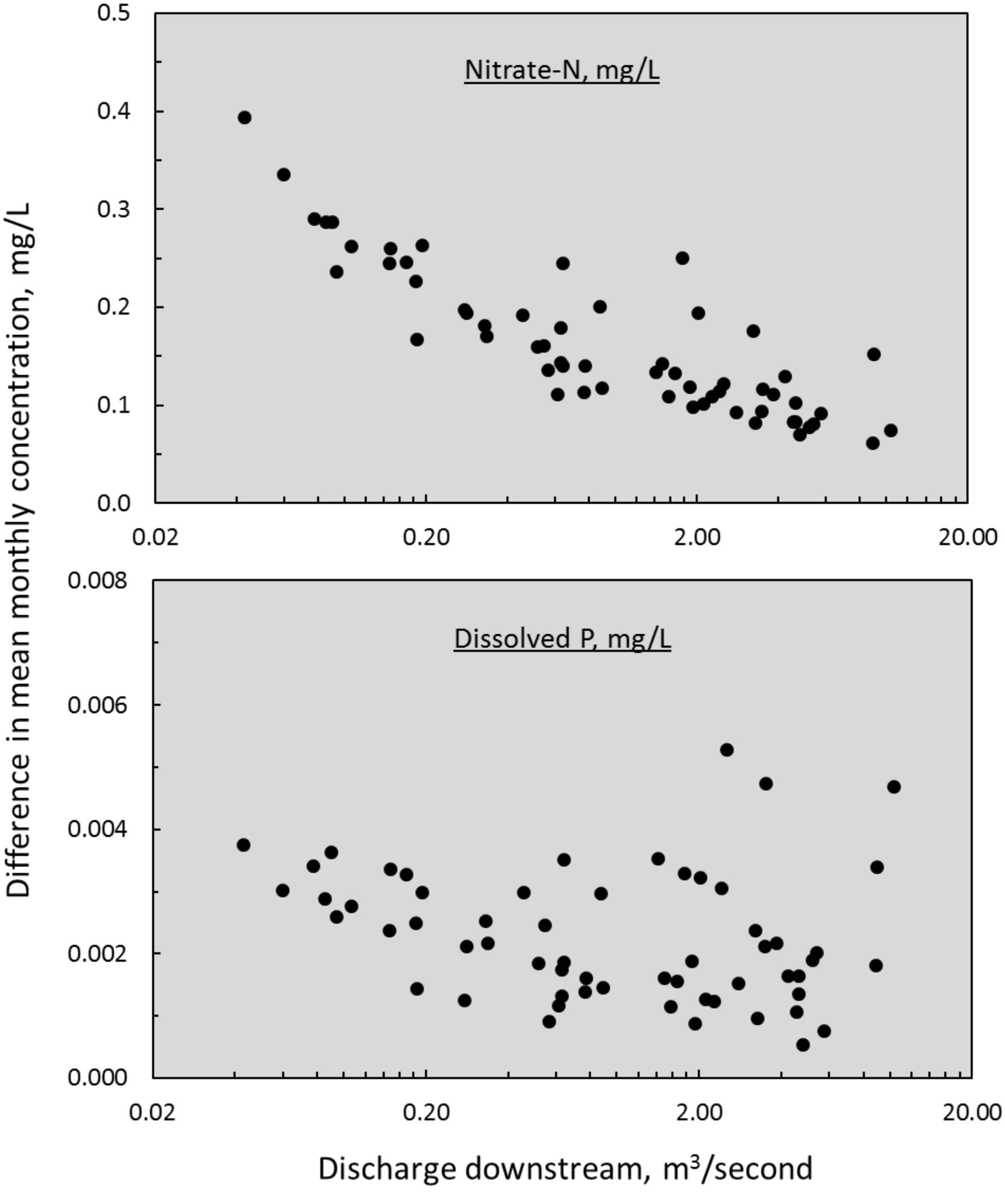


Figure 12. Difference in monthly mean nitrate-N and dissolved P concentrations between sites down (BC7) and upstream (BC6) of the C&H Farm as a function of downstream discharge (May 1, 2014 to May 31, 2019).

At high flows, it appears that the water coming from both the subwatershed above the upper site and the intervening subwatershed is closer, with nitrate-N concentrations slightly higher at BC7 than BC6.

As there is an influence of discharge on the difference in monthly nitrate-N concentrations between down and upstream sites, the following multiple regression was applied to nitrate-N concentration differences;

$D = b_0 + b_1 * \log(Q) + b_2 * (\log(Q))^2 + DecYear$ Regression Model [1]

Where Q is monthly mean discharge in m^3/sec and DecYear is decimal year. Output from this model is given in Table 6.

Table 6. Output of regression Model 1 for nitrate-N.

	Estimate	Standard error	t value	Probability (>t)
Intercept, b_0	1.43656	9.28658	0.155	0.878
DecYear	-0.00065	0.00460	-0.141	0.888
Log Q	-0.03032	0.00505	-6.005	1.41e-07 ***
Log Q2	0.01174	0.00330	3.561	0.00075 ***
Multiple R^2	0.5931			
Adjusted R^2	0.5717			

The multiple regression shows that the two flow terms are highly significant but the time trend term (DecYear) is not close to being significant (*p*-value is 0.88). This non-significant slope is negative, meaning slightly lower BC7 to BC6 differences in nitrate-N concentrations from one year to the next. However, decrease it is very small (i.e., -0.00065 mg/L/year). A plot of residuals and estimated concentration differences exhibits homoscedasticity, where model variable can be assumed to have the same finite variance, simplifying further statistical analysis (Figure 13).

Removing the two flow terms from the regression Model [1], the following Model focusing on time is applied to the nitrate-N concentration differences.

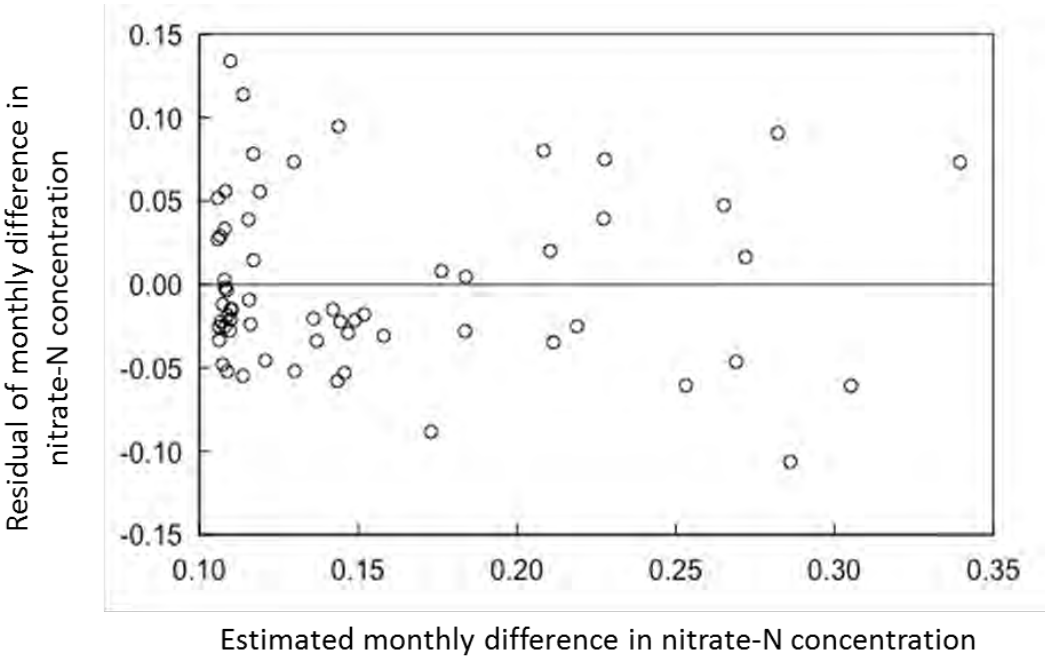


Figure 13. Relationship between the residuals and estimated mean monthly nitrate-N concentrations difference between BC7 and BC6 from regression Model [1].

1 month = Concentration~ Log Q + Log Q2 Regression Model [2]

Output from this model is given in Table 7. Note that the R^2 value from regression Model [1] of 0.5929 is very similar to that for Model [2] 0.5931; due to the fact that the DecYear time variable explained little of the variance. Plotting the residuals with time over the monitoring period shows little influence of time (Figure 14).

Applying the Kendall's Seasonal test to the residuals of regression Model [2] provided a slope of 0.0011 mg/L/year and probability values for this trend of 0.41, which is not significant.

Table 7. Output of regression Model 2 for nitrate-N.

	Estimate	Standard error	t value	Probability (>t)
Intercept, b_0	0.1266	0.0096	13.183	< 2e-16***
Log Q	-0.0304	0.0050	-6.127	8.42e-08 ***
Log Q2	0.0117	0.0033	3.594	0.00067
Multiple R^2	0.5929			
Adjusted R^2	0.5789			

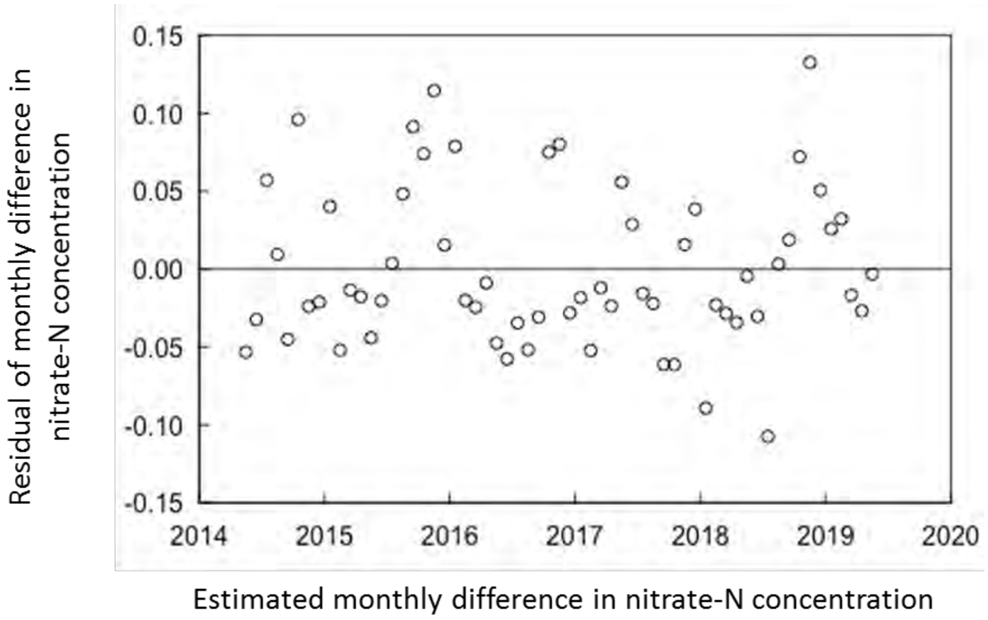


Figure 14. Relationship between the residuals and estimated mean monthly nitrate-N concentrations difference between BC7 and BC6 from regression Model [1].

Conclusion

The main conclusion from the above trend analysis of the difference between down (BC7) and upstream (BC6) nitrate-N concentrations, is the relationship between up and downstream concentrations is virtually unchanged over time. The two different trend analysis approaches give different signs to the relationship slope; but in either case, they are nowhere near being significantly different from zero and have very small magnitudes (i.e., -0.0006 mg/L/yr and 0.0011 mg/L/yr for regression Models [1] and [2] respectively). Thus, up to this point in time, the relationship between nitrate-N concentrations upstream and downstream of the farm are unchanged over the 5 years of data collection.

Acknowledgement

The Big Creek Research and Extension Team acknowledge and are extremely grateful to Dr. Robert Hirsch (retired U.S. Geological Survey) for advice and help in conducting, analyzing, and interpreting Weighted Regressions on Time, Discharge, and Season (WRTDS) analysis of discharge and nutrient data collected from Big Creek up and downstream of the C&H Farm. His vast experience informed and provided state of the science analysis of in-stream trends,

References

Bekele, A., and A. McFarland. 2004. Regression-based flow adjustment procedures for trend analysis of water quality data. Trans. ASAE 47:1093–1104.

Chanat, J.G., D.L. Moyer, J.D. Blomquist, K.E. Hyer, and M.J. Langland. 2016. Application of a weighted regression model for reporting nutrient and sediment concentrations, fluxes, and trends in concentration and flux for the Chesapeake Bay Nontidal Water-Quality Monitoring Network, results through water year 2012. U.S. Geological Survey, Reston, VA. 76 pages. Available at http://dx.doi.org/10.3133/sir20155133

Giovannetti, J., L.B. Massey, B.E. Haggard, and R.A. Morgan. 2013. Land use effects on stream nutrients at Beaver Lake watershed. J. Am. Water Works Assoc. 105:E1–E10.

Helsel, D.R., and R.M. Hirsch. 2002. Statistical methods in water resources. Chapter A3. *In* Techniques of Water-Resources Investigations of the United States Geological Survey. Book 4, Hydrologic Analysis and Interpretation. U.S. Geological Survey. Available at https://pubs.usgs.gov/twri/twri4a3/pdf/twri4a3-new.pdf. 524 pages.

Hirsch, R.M. 2012. Flux of nitrogen, phosphorus, and suspended sediment from the Susquehanna River basin to the Chesapeake Bay during tropical storm Lee, September2011, as an indicator of the effects of reservoir sedimentation on water quality. U.S. Geological Survey, Reston, VA. 17 pages. Available at http://pubs.usgs.gov/sir/2012/5185/

Hirsch, R.M., and L. De Cicco. 2015. User guide to exploration and graphics for RivEr Trends (EGRET) and Data Retrieval: R Packages for Hydrologic Data (Version 2.0, February2015). U.S. Geological Survey, Reston, VA. 93 pages. Available at http://dx.doi.org/10.3133/tm4A10.

Hirsch, R.M., R.B. Alexander, and R.A. Smith. 1991. Selection of methods for the detection and estimation of trends in water quality. Water Resour. Res. 27:803–813.doi:10.1029/91WR00259

Hirsch, R.M., D.L. Moyer, and A.S. Archfield. 2010. Weighted regressions on time, discharge, and season (WRTDS, with an application to Chesapeake Bay River inputs. J. Am. Water Resour. Assoc. 46(5):857-880. DOI: 10.1111 ⁄ j.1752-1688.2010.00482.x

Lettenmaier, D.P., E.R. Hooper, C. Wagner, and K.B. Faris. 1991. Trends in stream quality in the continental United States, 1978–1987. Water Resour. Res. 27:327–339.doi:10.1029/90WR02140

McCarty, J.A., and B.E. Haggard. 2016. Can we manage nonpoint-source pollution using nutrient concentrations during seasonal baseflow? Agric. Environ. Lett. 1:160015

Moyer, D.L., R.M. Hirsch, and K.E. Hyer. 2012. Comparison of two regression-based approaches for determining nutrient and sediment fluxes and trends in the Chesapeake Bay Watershed. U.S. Geological Survey, Reston, VA. 118 pages. Available at http://pubs.usgs.gov/sir/2012/5244/

Sharpley, A.N., B.E. Haggard, L. Berry, K. Brye, J. Burke, M.B. Daniels, E. Gbur, T. Glover, P. Hays, T. Kresse, and K.W. VanDevender. 2017. Nutrient concentrations in Big Creek correlate to regional watershed land use. Agric. Environ. Lett. 2017 2:170027.

Sharpley, A.N., P. Moore, K. VanDevender, M. Daniels, W. Delp, B. Haggard, T. Daniel, and A. Baber. 2010. Arkansas Phosphorus Index. Cooperative Extension Service, Division of Agriculture, University of Arkansas. Fact Sheet FSA 9531. 8 pages. Available at http://www.uaex.edu/Other_Areas/publications/PDF/FSA-9531.pdf.

White, K.L., B.E. Haggard, and I. Chaubey. 2004. Water quality at the Buffalo National River, Arkansas, 1991–2001. Trans. ASAE 47(2):407–417. doi:10.13031/2013.16042

Zhang, Q., D.C. Brady, and W.P. Ball. 2016. Decadal-scale export of nitrogen, phosphorus, and sediment from the Susquehanna River basin, USA: Analysis and synthesis of temporal and spatial patterns. Sci. Total Environ. 563-564:1016-1029.

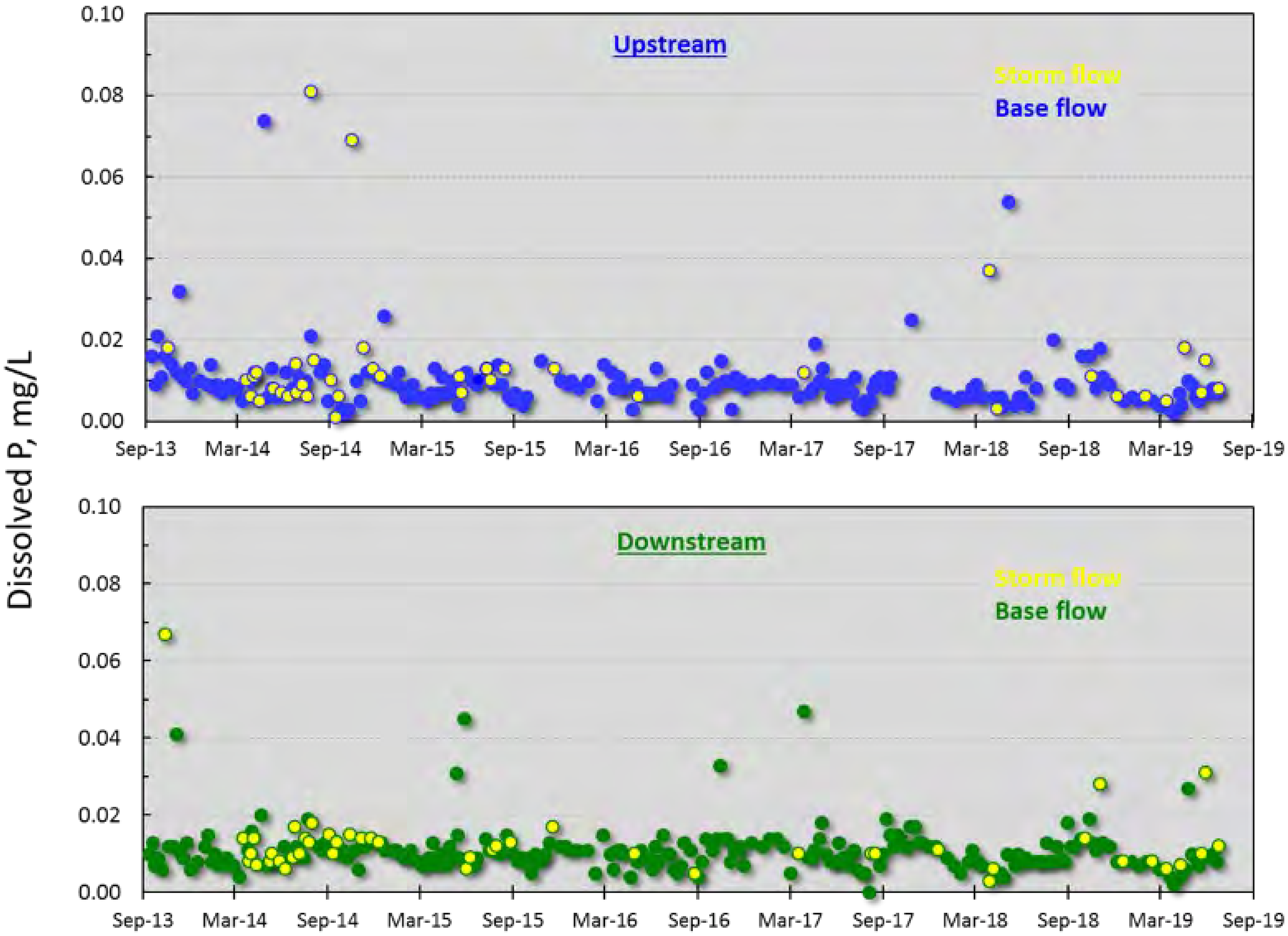


Figure S 1. Dissolved P concentration at the Big Creek monitoring site up- and downstream of the C&H Farm.

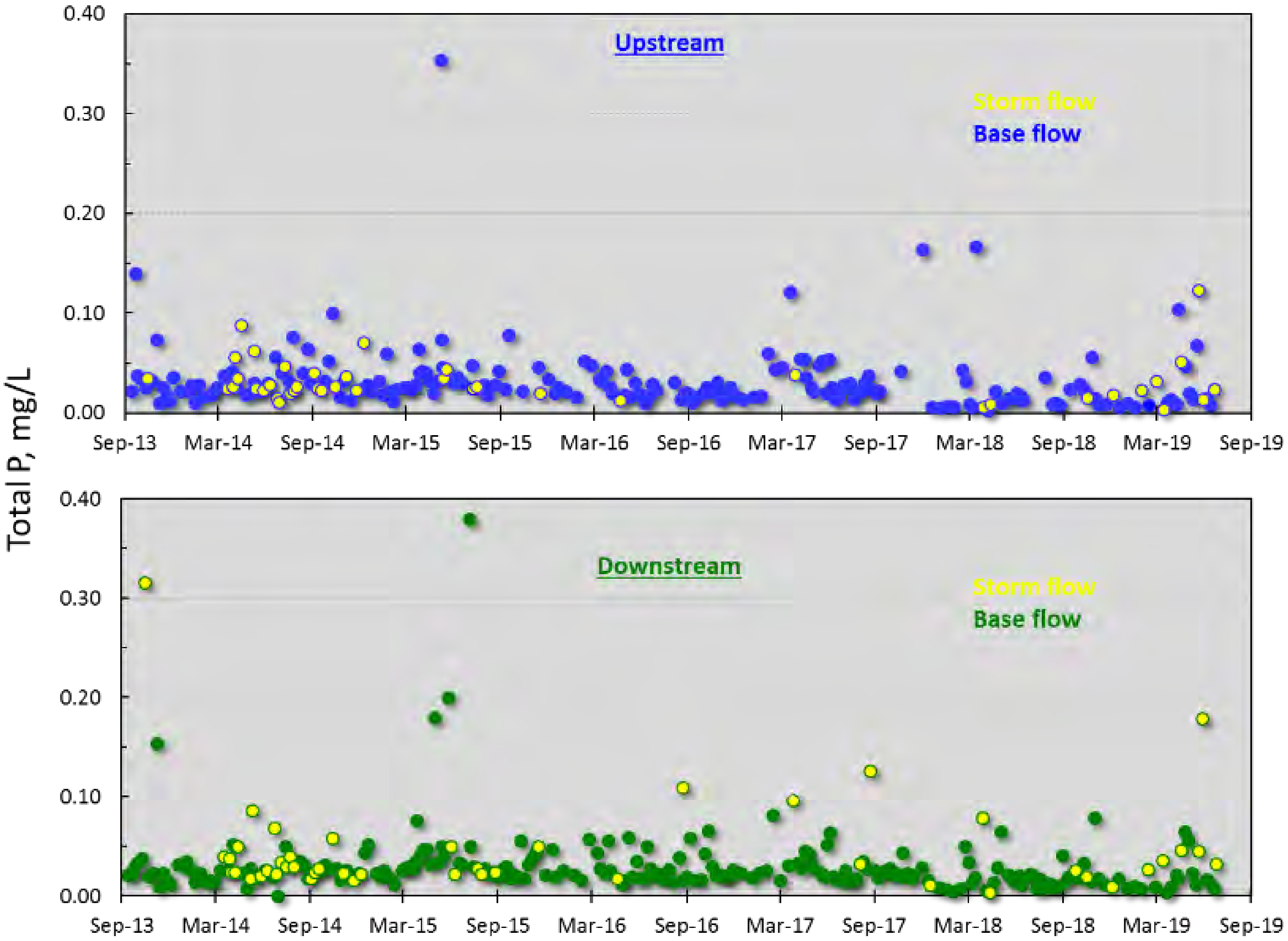


Figure S 2. Total P concentration at the Big Creek monitoring site up- and downstream of the C&H Farm.

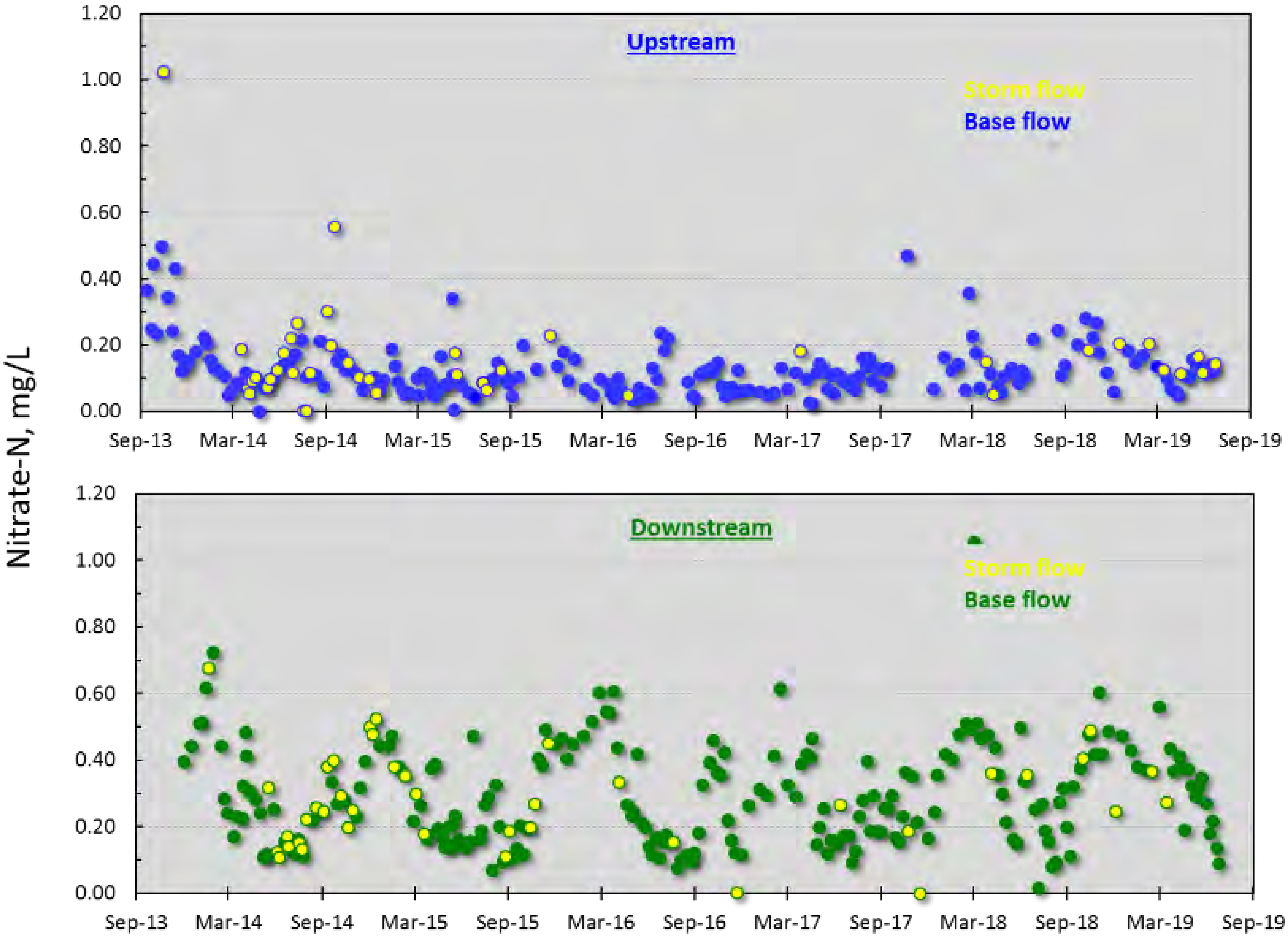


Figure S 3. Nitrate-N concentration at the Big Creek monitoring site up- and downstream of the C&H Farm.

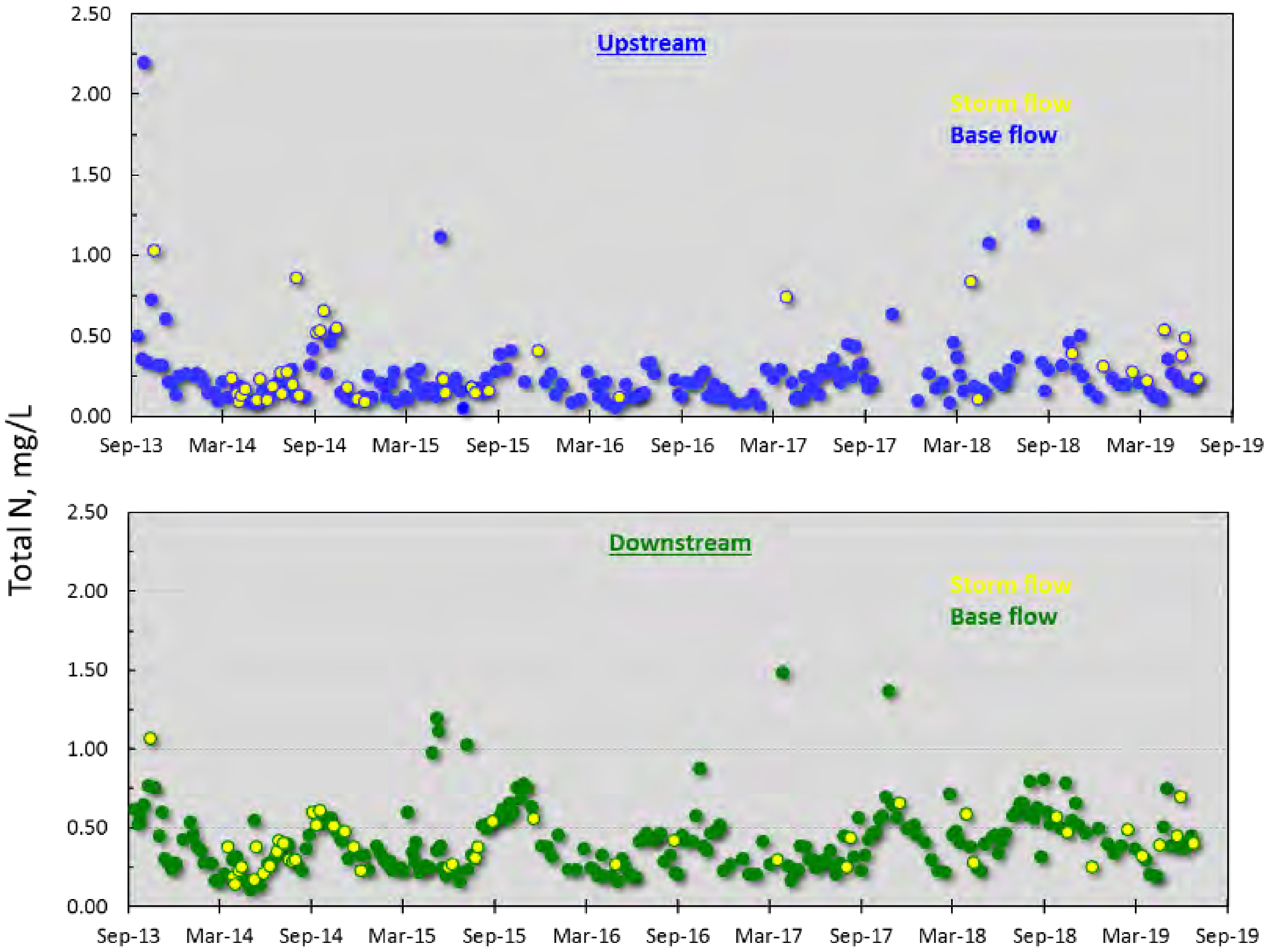


Figure S 4. Total N concentration at the Big Creek monitoring site up- and downstream of the C&H Farm.

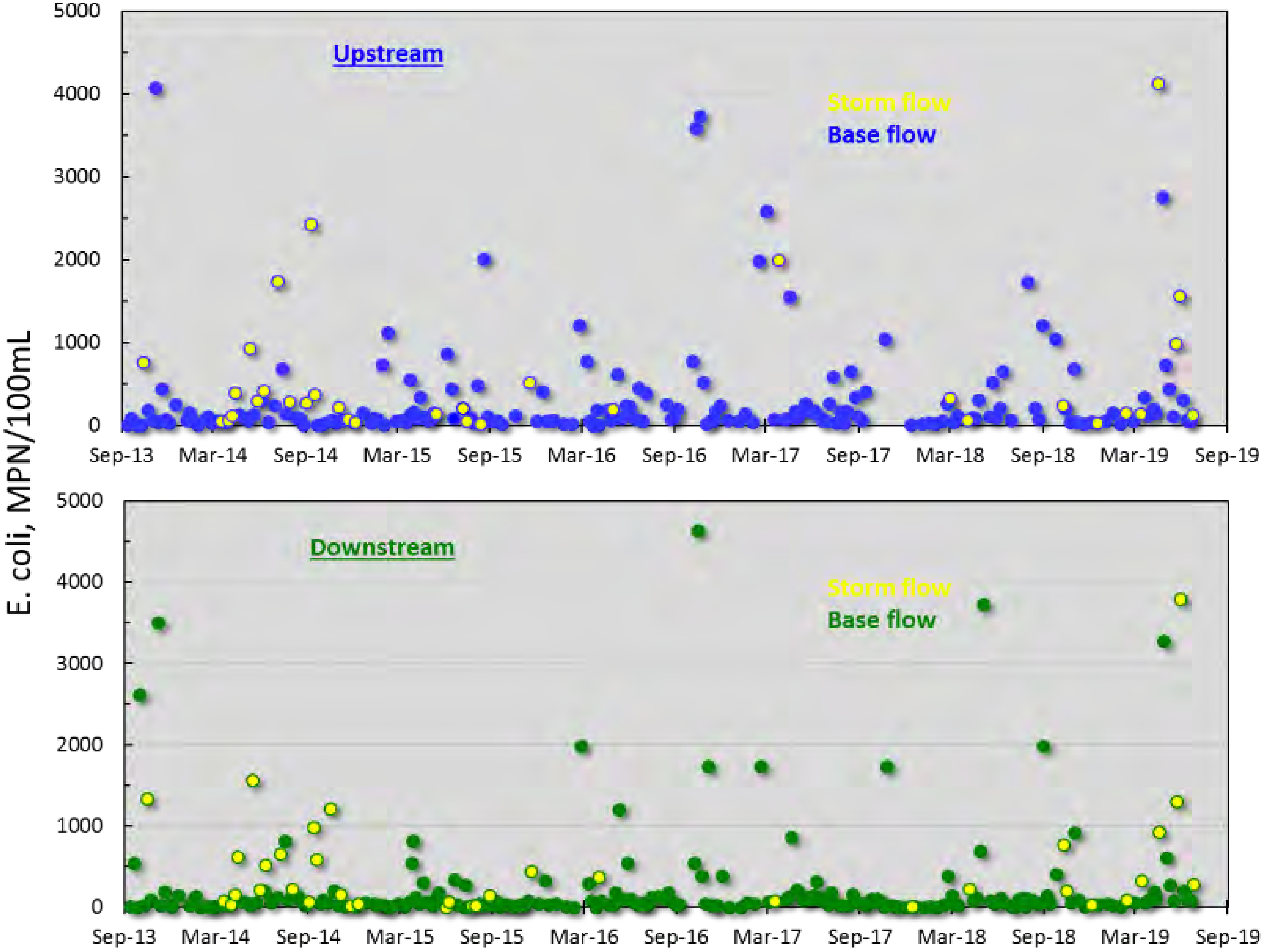


Figure S 5. E. coli numbers at the Big Creek monitoring site up- and downstream of the C&H Farm.

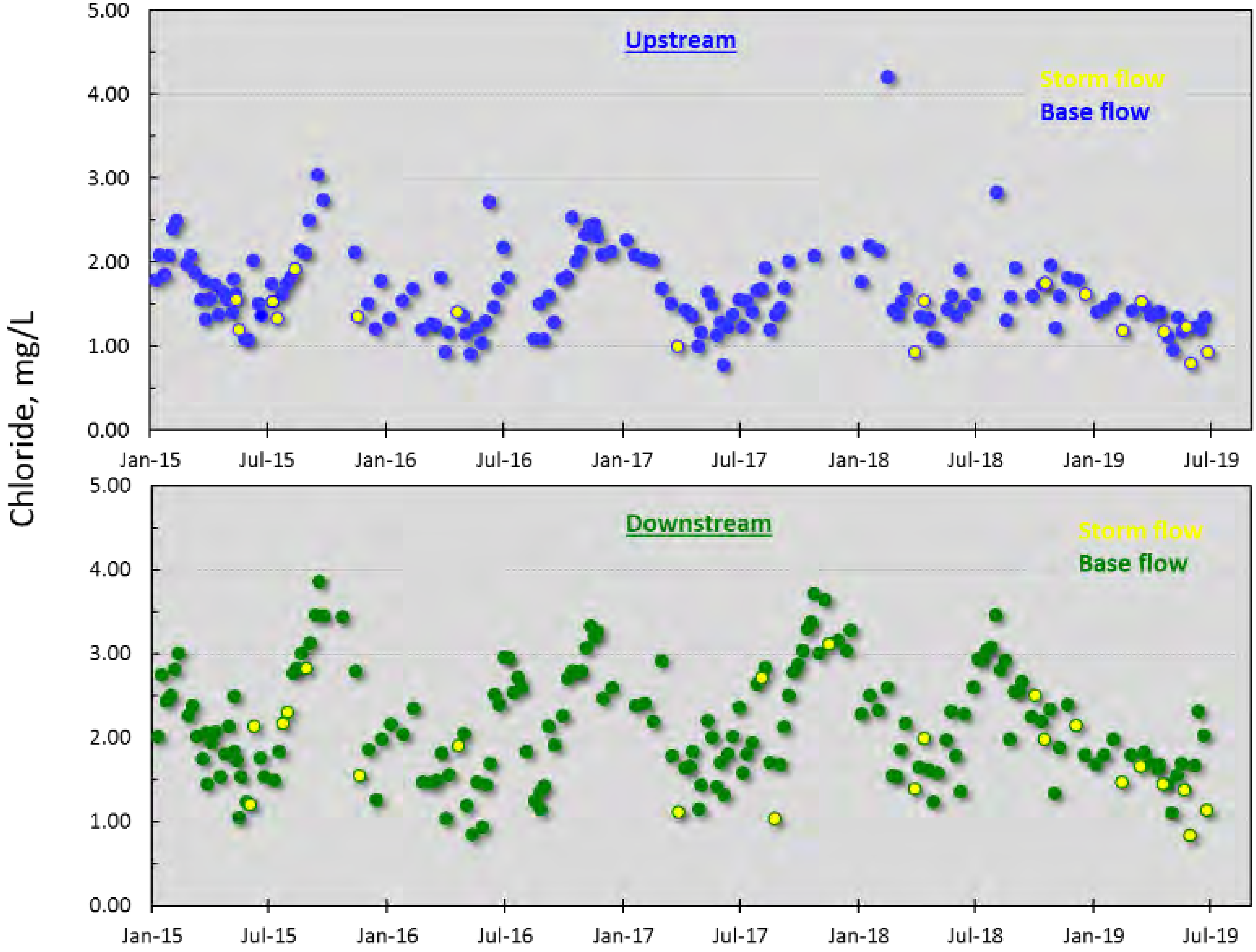


Figure S 6. Chloride concentration at the Big Creek monitoring site up- and downstream of the C&H Farm.

NUTRIENT CONCENTRATIONS IN BIG CREEK CORRELATE TO REGIONAL WATERSHED LAND USE

Contents

Summary

1. Nutrient concentrations in streams draining the Boston and Ozark Mountains region were related to the intensity of watershed land use.
2. Concentrations in Big Creek were similar to other watersheds in the ecoregion with similar land use, suggesting limited impact of the CAFO on Big Creek at the present time. However, this does not preclude future impacts and longer-term monitoring continues.

List of Figures

List of Tables

Background

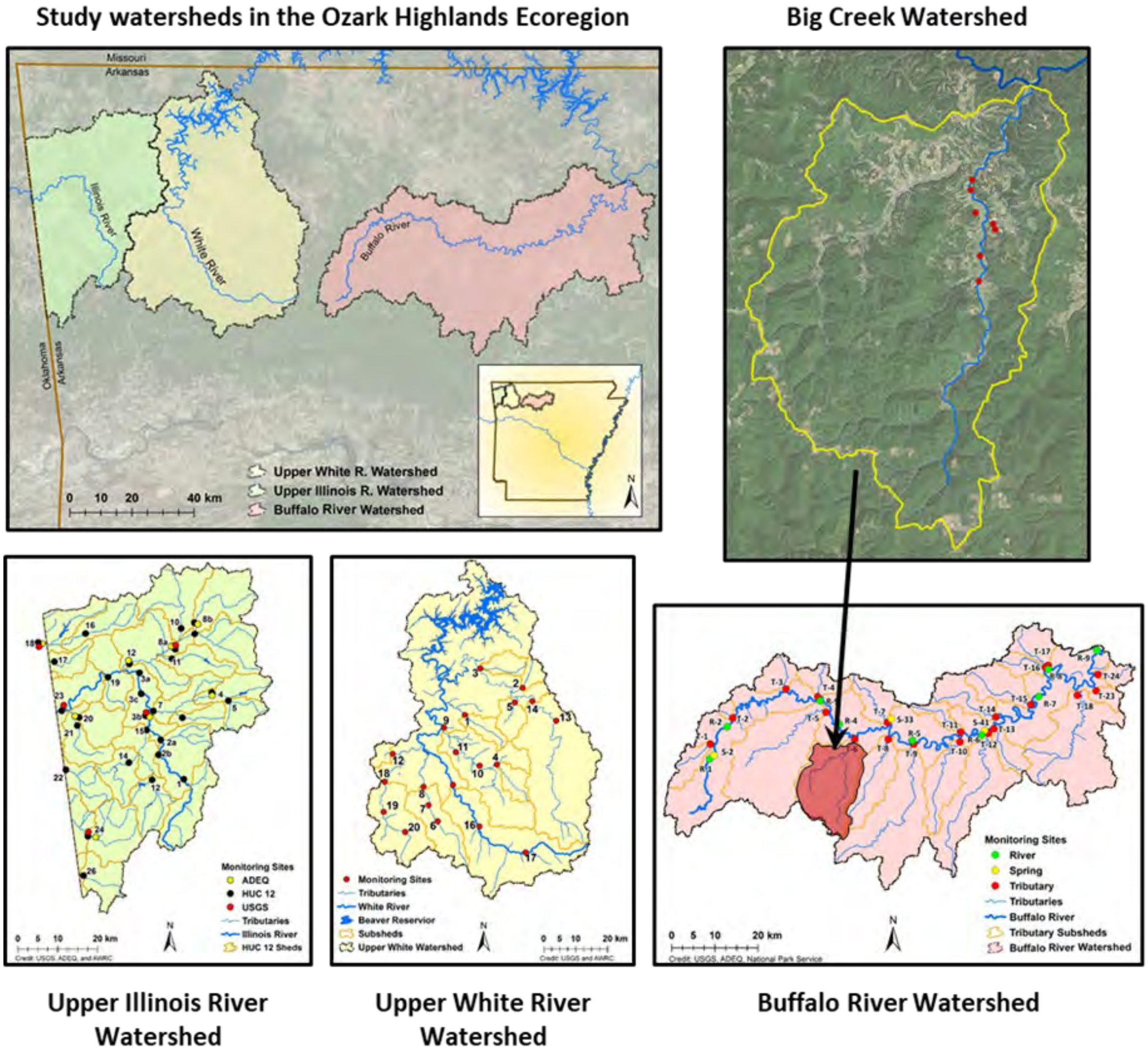
Nutrient impairment of surface waters continues despite widespread conservation efforts to reduce losses from urban, rural, and agricultural land uses (Scavia et al., 2014). Land use within watersheds influences the quality and quantity of water in streams draining the landscape. As land disturbance increases and use intensifies, an increase in stormwater runoff and nutrient inputs that lead to a greater potential for transport to receiving water is generally observed (Dubrovsky et al., 2010; Rebich et al., 2011). This has led to efforts to identify and quantify nutrient sources within watersheds, strategically target, and apportion nutrient loss reduction (Reckhow et al., 2011).

Numerous factors influence the relationship between land use in a given watershed and nutrient transport downstream from that watershed. With an increase in percent of the drainage area in pasture, row crop, and/or urban use, a general trend of increasing nutrient concentrations in storm and base flows will be manifested (Buck et al., 2004; Giovannetti et al., 2013; Haggard et al., 2003; Migliaccio et al., 2007). Thus, nutrient concentrations in streams draining forested lands tend to be less than in watersheds with considerable anthropogenic land use.

Methods

Water samples have been collected over varying periods at the outlet of subwatersheds of the BRW, Upper Illinois River Watershed (UIRW) and Upper White River Watershed (UWRW; Figure 1). Land use and cover (i.e., forest, pasture, and urban) for each subwatershed was obtained from high-resolution (4 m) imagery from U.S. Geological Survey (USGS) National Elevation Dataset (see https://lta.cr.usgs.gov/NED; Gesch et al., 2002), National Land-Cover Dataset (see https://catalog.data.gov/dataset/usgs-national-land-cover-dataset-nlcd-downloadable-data-collection), and National Hydrologic Dataset (see https://nhd.usgs.gov/). In the UWRW, Giovannetti et al. (2013) monitored 20 sites monthly for one year (June 2005 to July 2006), collecting water samples during base-flow conditions. In the UIRW, Haggard et al. (2010) monitored 29 sites monthly during calendar year 2009, also collecting water samples during base-flow conditions.

In the BRW, the National Park Service (NPS) in partnership with the Arkansas Department of Environmental Quality (ADEQ) periodically collected water samples and measured nutrient concentrations at 20 stream sites from 1985 through 2015. Dissolved P, total P, nitrate-N, and total N concentrations were obtained directly from these data. Forest, pasture, and urban land-use areas were determined from 2006 high-resolution (4 m) land use-land cover imagery (Table 1).



Study watersheds in the Ozark Highlands Ecoregion

Big Creek Watershed

Upper Illinois River Watershed

Upper White River Watershed

Buffalo River Watershed

Figure 1. Location of the Big Creek, Buffalo River, Upper Illinois River and Upper White River Watersheds in the Boston Mountains and Ozark Highlands ecoregion. Information from U.S. Geological Survey (USGS), Environmental Systems Research Institute (ESRI), and National Aeronautics and Space Administration (NASA).

Big Creek water samples were analyzed at an Arkansas Department of Environmental Quality certified water quality laboratory within the Arkansas Water Resources Center (http://arkansas-water-center.uark.edu/water-quality-lab.php), according to methods detailed in Table 2.

The geometric mean of nutrient concentrations of base-flow samples collected between September 2013 and April 2017 were determined, to compare with base-flow nutrient concentrations available for BRW, UIRW, and UWRW. Base-flow conditions in Big Creek were classified from hydrograph inspection when flow had not increased or decreased within three days of sample collection. McCarty and Haggard (2016) suggested that stream nutrient concentrations under base flow can be used to identify nonpoint sources and target remedial measures in Boston Mountains and Ozark Highland watersheds.

Table 1. Percent of forest pasture, and urban land use in the Big Creek, Buffalo River, Upper Illinois, and Upper White Watersheds.

Watershed	Forest	Pasture	Urban
	- - - - - - - - - - - - - - - - -	%	- - - - - - - - - - - - - - - - - -
Big Creek †			
Upstream	89.5	8.0	2.6
Downstream	79.5	17.0	3.5
Buffalo River	52 - 99	0 - 25	0 - 1
Upper White River	34 - 90	7 - 55	0 – 44
Upper Illinois River	2 - 70	27 – 69	3 – 61

† Up and downstream of CAFO operation and fields permitted to receive manure.

Table 2. Minimum detection limits for each chemical and biological constituent.

Constituent	Analytical method †	Minimum detection limit ‡	Reporting limit ¶
Dissolved P, mg/L	EPA 365.2	0.002	0.010
Total P, mg/L	APHA 4500-P J	0.012	0.020
Nitrate-N, mg/L	EPA 300.0	0.004	0.050
Total N, mg/L	APHA 4500-P J; EPA 365.2	0.006	0.050

† EPA is Environmental Protection Agency Approved CWA Chemical Test Methods, available at https://www.epa.gov/cwa-methods/approved-cwa-chemical-test-methods#number and APHA is American Public Health Association from the Wadeable Streams Assessment, Water Chemistry Laboratory Manual http://www.epa.gov/owow/monitoring/wsa/WRS_lab_manual.pdf.

‡ The Minimum detection limit of an analyte is the value, which can be measured and reported with 99% confidence that the analyte concentration is greater than zero. Further information is available at http://water.usgs.gov/owq/OFR_99-193/detection.html

¶ The Reporting limit is the least (non-zero) calibrated standard used in analysis, or as defined by method for total suspended solids.

Using all above-listed data sources, the geometric means of nutrient concentrations for streams in the BRW, UIRW, and UWRW were used to develop a relationship with human development within the watershed. Human development is defined as the percent of pasture plus urban land use within the watershed. Exponential relationships with 95% confidence bands around the observations were developed for dissolved P, total P, nitrate-N, and total N concentrations to put nutrient concentration at Big Creek into the context of regional stream nutrients and watershed land use.

Data from Big Creek were paired with discharge available from a gaging station just downstream from the swine CAFO, where the USGS developed the rating curve; discharge information was only available from May 2014 through April 2017. The data were then used in a simple three-step process (White et al., 2004) to look at monotonic changes in the nutrients at Big Creek: (1) log-transform concentration (mg/L) and associated instantaneous discharge (m^3/s); (2) use locally weighted regression (LOESS) to smooth the data with a sampling proportion (n) of 0.5; and (3) plot the residuals from LOESS (i.e., the flow-adjusted concentrations), over time and use linear regression to evaluate monotonic trends.

Putting Stream Nutrient Concentrations into Context at Big Creek

In Big Creek, upstream of the swine CAFO, geometric mean concentrations of base flow for the monitoring period extending from September 13, 2013 to July 11, 2019 (121 samples) for dissolved P, total P, nitrate-N, and total N were 0.008, 0.025, 0.10, and 0.19 mg/L, respectively. Directly downstream of the CAFO, geometric mean concentrations at Big Creek during base flow conditions during the same period (151 samples) were 0.010, 0.024, 0.27, and 0.38, mg/L for dissolved P, total P, nitrate-N, and total N, respectively. Arkansas has narrative criteria for nutrient concentrations in streams (Arkansas Pollution Control and Ecology Commission, 2016), but its proposed assessment methodology has numeric screening concentrations for total N (0.45 - 2.43 mg/L) and total P (0.04 - 0.10 mg/L) in the Boston Mountains and Ozark Highlands. The geometric mean concentrations at Big Creek upstream and downstream from the CAFO were below these values for the Boston Mountains and Ozark Highlands ecoregion.

Nutrient concentrations in Big Creek upstream and downstream from the CAFO are low with respect to nutrient–biological–response thresholds for algae, macroinvertebrates and fish. Evan-White et al. (2014) reviewed the literature, summarizing nutrient–biological–response thresholds across the U.S.:

- *Algal Metric Responses* total N: 0.38–1.79 mg/L total P: 0.011–0.28 mg/L
- *Macroinvertebrate Metric Responses* total N: 0.61–1.92 mg/L P: 0.04–0.15 mg/L
- *Fish Metric Responses* total N: 0.54–1.83 mg/L total P: 0.06–0.14 mg/L

Total N concentrations at Big Creek upstream and downstream of the swine CAFO were well below thresholds that result in some expected biological response, whereas total P concentrations were below thresholds for expected macroinvertebrate and fish response and on the low end of the range for expected algal response. However, these lower total P thresholds (0.006 - 0.026 mg/L; Stevenson et al., 2008) were focused on shifts in diatom species and metrics rather than nuisance algal biomass. A recent study on the Illinois River Watershed showed that stream total P thresholds with *Cladophora* biovolume and nuisance taxa proportion of biovolume were observed between 0.032 and 0.058 mg/L (Joint Study

Committee, 2017). Thus, total P concentrations at Big Creek upstream and downstream of the CAFO were in the range where the natural assemblage of algae is shifting, but these concentrations would likely not be indicative of problematic nuisance algae in this ecoregion.

Geometric mean nutrient concentrations varied upstream and downstream of the swine CAFO at Big Creek, and Kosic et al. (2015) used the publicly available data to allude to the N increase being from human activities on the landscape, e.g., the CAFO. However, the historic land use and how stream nutrient concentrations during base-flow conditions increase with human development within the Boston Mountain and Ozark Highland watersheds need to be considered (e.g., see Giovannetti et al., 2013; Haggard et al., 2003; Migliaccio et al., 2007). In the Big Creek watershed, the percent of land influenced by human activities (i.e., pasture plus urban) doubles from ~10 to ~20% in the drainage area upstream and downstream of the CAFO. Nutrient concentrations in Big Creek upstream and downstream of the CAFO are within the range typical of streams draining similar land uses (Figure 2).

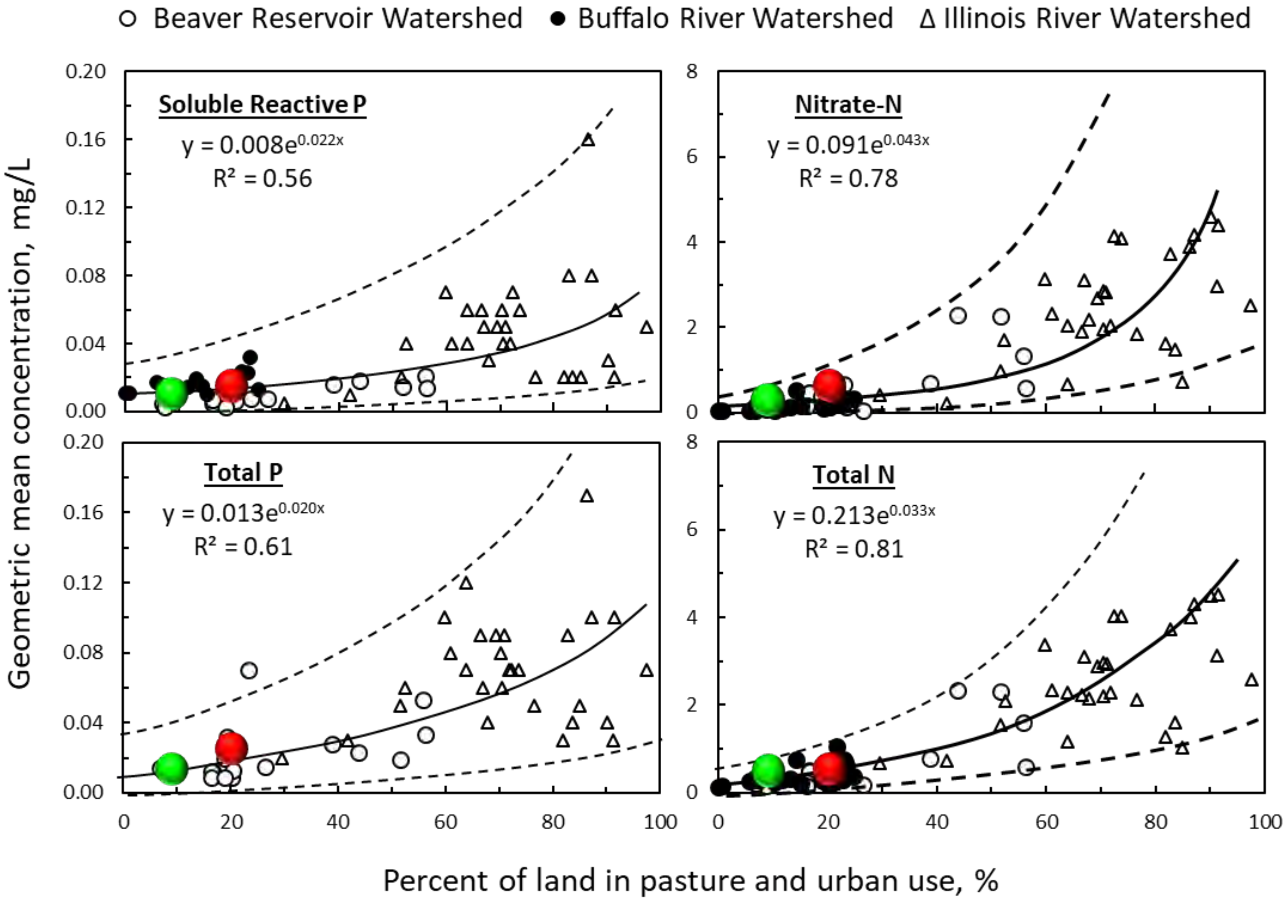


Figure 2. Relationship between land use and the geometric mean N and P concentrations (mg/L) in the Buffalo, Upper Illinois, and Upper White River Watersheds. Dashed lines represent the 95% confidence intervals for the estimated mean (solid line). Green points are geometric mean concentration measured upstream of the CAFO on Big Creek and red points are geometric mean concentration measured downstream of the CAFO on Big Creek.

At this time, nutrient concentrations in Big Creek upstream and downstream from the swine CAFO are consistent with the range in concentrations for other watersheds with similar pasture and urban land use characteristics (Figure 2), as well as less than most nutrient thresholds for nuisance water-quality conditions (Omernik and Griffith, 2014). However, this does not preclude the possibility that nutrient concentrations at Big Creek may increase over time especially if human development and activity in the drainage areas increase. The most important observation is that nutrient concentrations were low in Big Creek providing the ability to detect changes over time.

First, understanding that long-term (e.g., decadal scale) water–quality data are needed to reliably assess how stream nutrient concentrations have changed in response to watershed management and climate variations is of critical importance (Hirsch et al., 2015). The literature shows that stream nutrient concentrations can change relatively quickly in response to effluent management (e.g., Haggard, 2010; Scott et al., 2011), but seeing a response (i.e., decrease in concentrations) from landscape management can take decades or more (Green at al., 2015; Sharpley et al., 2013). A myriad of factors may influence observed nutrient concentrations in streams, including discharge (Petersen et al., 1998), biological processes and climactic conditions (i.e., drought and floods; Jones and Stanley, 2016), and dominant transport pathways (Sharpley et al., 2013). Thus, we need to use caution when interpreting trends in water quality over databases that only cover a limited timeframe.

Nutrient concentrations at Big Creek upstream and downstream of the swine CAFO, and indeed most tributaries of the Buffalo River, are low relative to other watersheds in this ecoregion (Figure 2). This provides a starting point to build a framework to evaluate changes in nutrient concentrations of streams as a function of land use and management and to establish baseline, in-stream nutrient concentrations and a process by which time and/or land use and management impacts can be determined.

References

Arkansas Pollution Control and Ecology Commission. 2016. Regulation No. 2: Regulations establishing water quality standards for surface waters of the State of Arkansas. Available at: https://www.epa.gov/sites/production/files/2014-12/documents/arwqs.pdf

Buck, O., D.K. Niyogi, and C.R. Townsend. 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. Environ. Poll. 130(2):287-299.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, and M.D. Munn. 2010. The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350. 174 pages. Available at: http://water.usgs.gov/nawqa/nutrients/pubs/circ1350

Evan-White, M.A. B. E. Haggard, and J. T. Scott. 2014. A review of stream nutrient criteria development in the United States. J. Environ. Qual. 42:1002-1014.

Gesch, D., M. Oimoen, S. Greenlee, C. Nelson, M. Steuck, and D. Tyler. 2002. The National Elevation Dataset. J. Am. Soc. Photogram. Remote Sensing 68(1). 9 pages. Available at https://nationalmap.gov/PERS_Jan2002_NED_highlight_article.pdf

Giovannetti, J., L.B. Massey, B.E. Haggard, and R.A. Morgan. 2013. Land use effects on stream nutrients at Beaver Lake Watershed. J. Am. Water Works Assoc. 105:E1–E10. Available at: http://www.awwa.org/publications/journal-awwa/abstract/articleid/34406246.aspx

Green, C.T., B.A. Bekins, S.J. Kalkhoff, R.M. Hirsch, L. Liao, and K.K. Barnes. 2014. Decadal surface water quality trends under variable climate, land use, and hydrogeochemical setting in Iowa, USA. Water Resour. Res. 50(3):2425–2443. Available at: http://onlinelibrary.wiley.com/doi/10.1002/2013WR014829/epdf

Haggard, B.E. 2010. Phosphorus concentrations, loads, and sources within the Illinois River drainage area, northwest Arkansas, 1997–2008. J. Environ. Qual. 39:2113–2120.

Haggard, B.E., P.A. Moore, Jr., I. Chaubey, and E.H. Stanley. 2003. Nitrogen and phosphorus concentrations and export from an Ozark Plateau Catchment in the United States. Biosys. Eng. 86(1):75-85.

Haggard, B.E., A.N. Sharpley, L. Massey, and K. Teague. 2010. Final report to the Illinois River Watershed Partnership: Recommended watershed based strategy for the Upper Illinois River Watershed, Northwest Arkansas, Arkansas. Water Resources Center, University of Arkansas. Technical Publication Number MSC 355. 126 pages. Available at: http://arkansas-water-center.uark.edu/publications/msc/MSC355.pdf

Hirsch, R.M., S.A. Archfield, and L.A. De Cicco. 2015. A bootstrap method for estimating uncertainty of water quality trends. Environ. Model. Software 73:148-166.

Hirsch, R.M., D.L. Moyer, and S.A. Archfield. 2010. Weighted regression on time, discharge, and season (WRTOS), with an application to the Chesapeake Bay River inputs. J. Am. Water Resour. Assoc. 46(5)857-880.

Joint Study Committee. 2017. Final report to Governors from the Joint Study Committee and Scientific Professionals. December 19, 2016. 70 pages. Available at: https://www.ok.gov/conservation/documents/IR%202016.12.19%20Final%20Report.pdf

Jones, J.B., and E.H. Stanley. 2016. Stream ecosystems in a changing environment. Academic Press, Amsterdam, The Netherlands.

Kosic, K., C.L. Bitting, J.V. Brahana, and C.J. Bitting. 2015. Proposals for integrating karst aquifer evaluation methodologies into national environmental legislations: Case study of a concentrated animal feeding operation in Big Creek Basin and Buffalo National River Watershed, Arkansas, USA. Sustain. Water Resour. Manag. 1:363-374.

McCarty, J.A., and B.E. Haggard. 2016. Can we manage nonpoint-source pollution using nutrient concentrations during seasonal baseflow? Agric. Environ. Lett. doi:10.2134/ael2016.03.0015

Migliaccio, K.W., B.E. Haggard, I. Chaubey, and M.D. Matlock. 2007. Linking watershed subbasin characteristics to water quality parameters in War Eagle Creek Watershed. Trans. Am. Soc. Agric. Eng. 50(6):2007-2016.

Omernik, J.M., and G.E. Griffith. 2014. Ecoregions of the conterminous United States: evolution of a hierarchical spatial framework. Environ. Managt. 54(6):1249-1266. Available at http://dx.doi.org/10.1007/s00267-014-0364-1

Peterson, J.C., J.C. Adamski, R.W. Bell, J.V. Davis, S.R. Femmer, D.A. Freiwald, and R.L. Joseph. 1998. Water quality in the Ozark Plateaus, Arkansas, Kansas, Missouri, and Oklahoma, 1992-95. U.S. Geological Survey Circular 1158. Fort Collins, CO. Available at: https://pubs.usgs.gov/circ/circ1158/circ1158.pdf

Rebich, R.A., N.A. Houston, S.V. Mize, D.K. Pearson, P.B. Ging, and C.E. Hornig. 2011. Sources and delivery of nutrients to the northwestern Gulf of Mexico from streams in the south-central United States. J. Am. Water Res. Assoc. 47(5):1062-1086.

Reckhow, K.H., P.E. Norris, R.J. Budell, D.M. Di Toro, J.N. Galloway, H. Greening, A.N. Sharpley, A. Shirmhhammadi, and P.E. Stacey. 2011. Achieving nutrient and sediment reduction goals in the Chesapeake Bay: An evaluation of program strategies and implementation. The National Academies Press, Washington, DC. 258 pages.

Scavia, D., J.D. Allan, K.K. Arend, S. Bartell, D. Beletsky, N.S. Bosch, S.B. Brandt, R.D. Briland, I. Daloglu, J.V. DePinto, D.M. Dolan, M.A. Evans, T.M Farmer, D. Goto, H. Han, T.O. Hoeoek, R. Knight, S.A. Ludsin, D. Mason, A.M. Michalak, R.P. Richards, J.J. Roberts, D.K. Rucinski, E. Rutherford, D.J. Schwab, T.M. Sesterhenn, H. Zhang, and Y. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res. 40:226-246.

Scott, J.T., B.E. Haggard, A.N. Sharpley, and J.J. Romeis. 2011. Change point analysis of phosphorus trends in the Illinois River (Oklahoma) demonstrates the effects of watershed management. J. Environ. Qual. 40:1249-1256.

Sharpley, A.N., H.P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. 2013. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42:1308-1326. Available at: https://www.soils.org/publications/jeq/pdfs/42/5/1308?search-result=1

Stevenson, R.J., Y. Pan, K.M. Manoylov, C.A. Parker, D.P. Larsen, and A.T. Herlihy. 2008. Development of diatom indicators of ecological conditions for streams of the western U.S. J. North Am. Benthol. Soc. 27:1000–1016.

White, K.L., B.E. Haggard, and I. Chaubey. 2004. Water quality at the Buffalo National River, Arkansas, 1991−2001.

CONCLUSIONS

The Memorandum of Understanding with the Arkansas Department of Environmental quality was to:

1. Monitor the fate and transport of nutrients and bacteria from land-applied swine effluent to pastures.
2. Assess the impact of farming operations (effluent holding ponds and land-application of effluent) on the quality of critical water features on and surrounding the farm.
3. Determine the effectiveness and sustainability of alternative manure management techniques, including solid separation, which may enhance transport and export of nutrients out of the watershed.

Based on data collected during the five-year project, the following overall conclusions to these three objectives can be drawn:

Objective 1:

1. Three fields (two receiving slurry and one mineral fertilizer) were sampled biannually (2014, 2016, 2018) on a 0.25-acre grid. Considering only the area of the field receiving slurry (excluding a 50 to 100 foot edge-of-field buffer), surface (0 – 4 inch) soil test P (STP) levels significantly increased from 65 to 115 mg/kg for Field 1 and from 56 to 126 mg/kg for Field 12 between 2014 and 2018. Soil test P averaged across the field receiving mineral fertilizer and prior poultry litter, showed no significant increase between 2014 and 2018 (i.e., 45 and 47 mg/kg in 2014 and 2018).

2. Complicating the interpretation of STP increases on the two fields receiving slurry is the fact that the grid-soil sampling identified specific, well-defined areas or hotspots of STP accumulation adjacent to a farm pond, field gate, and shade trees, where physical evidence of cattle grazing and loafing was apparent.

3. It is clear that several interrelated factors, including slurry, fertilizer, and cattle management have influenced the extent and magnitude of STP accumulation. To limit further accumulation in excess of optimum agronomic levels for forage production, future applications of any nutrients (i.e., as mineral fertilizer, swine slurry, or poultry litter) to fields, which received slurry from C&H Farms, should be carefully managed. This can be achieved by application of nitrogen (N) fertilizer or slurry and poultry litter at P-based rates, where P applied is equivalent to expected forage uptake of P.

Objective 2:

1. Flow-adjusted nitrate-N (and thereby total N) concentrations were greater downstream (mean of 0.29 mg/L) than upstream (mean of 0.13 mg/L) of the C&H Farm. Also, mean annual nitrate-N concentrations downstream of the C&H Farm increased slightly over the five-years of monitoring, averaging 0.275, 0.304, 0.274, 0.297, and 0.311 mg/L in 2015, 2016, 2017, 2018, and 2019, respectively (May 1 to April 30; 2014 to 2019). At the upstream site, mean annual nitrate-N averaged 0.112, 0.131, 0.118, 0.124, 0.161 mg/L in 2015, 2016, 2017, 2018, and 2019, respectively,

over the same period. No other consistent or significant trends in other monitored nutrients and E. coli were observed in Big Creek.

2. There was a statistically significant increase in nitrate-N concentrations in the well (265 to 285 feet deep) and ephemeral stream adjacent to the C&H Farm production facility over the five-year monitoring period. Mean annual nitrate-N of well water was 0.474, 0.515, 0.633, 0.657, and 0.799 mg/L for 2014, 2015, 2016, 2017, 2018, and 2019, respectively, for May 1 through April 30 of each year. For the ephemeral stream, mean annual nitrate-N was 0.760, 0.739, 1.034, 1.110, and 1.152 mg/L for 2014, 2015, 2016, 2017, 2018, and 2019, respectively, over the same period.
3. Interceptor trenches below the holding ponds showed no increasing or decreasing trends in nutrient or E. coli. Given trench flow was highly correlated with precipitation, no concomitant increase in chloride or electrical conductivity in well, ephemeral stream, and trench waters, the collected information fails to suggest the holding ponds were the major contributor to observed nitrate-N increases in well and ephemeral stream at this point in time.
4. The overall conclusions of the 2014 dye-tracer studies conducted in the Big Creek Watershed by Drs. Brahana and Kosic, demonstrate the complexity of subsurface flows can be in the karst system of in this area of the Boone formation.
5. Although on-farm nutrient management planning occurs at the field scale, there is a lack of consistent and well-maintained GIS databases of karst features and geologic mapping at this scale. In Arkansas, the AGS topographic-scale geologic mapping (which includes an inventory of karst features), usually maps 1- 3 quads a year. Thus, NMP development and risk assessment would be aided by the availability of consistent karst feature databases and geologic mapping.

Objective 3:

The general findings were:

1. Hydrated lime amendments tended to enhance the manure solids separation effectiveness as related to increasing the % Solids and P concentration of the separated solids. In principle, this would be beneficial for transport of P off the generating farm.
2. Hydrated lime amendments also increased the manure pH enough that N losses via ammonia volatilization seemed to be increased. If the manure were viewed as a desirable N fertilizer, the increased losses would not be desirable. If air quality were, it atmospheric ammonia emissions would not be desirable.
3. Use of granular agricultural grade lime at the rates used, had no consistent effect on the solids separation process.

Despite the potential benefits of lime treatment providing options to manage slurry in compliance with nutrient management planning requirements, all presented economic, logistical, labor, and legal constraints severely limit their viability for adoption.

Overall Conclusions:

Differences in nitrate-N concentrations between down and upstream sites were strongly influenced by stream flow, where the difference (i.e., downstream was greater than upstream) is very large at low flow and small at high flow. This suggests that at low flows, base flow nitrate-N emerges into Big Creek between upstream and downstream sites and that this base flow has a higher nitrate-N concentration than in base flow above the upstream site. However, at high flows it appears that water entering Big Creek from both the subwatershed above the upstream site and the intervening subwatershed between the downstream site, is similar.

Despite higher nitrate-N concentrations at the down than upstream site on Big Creek, the relationship between upstream and downstream concentrations is unchanged over time, suggesting that over the 5 years of monitoring, the input of nitrate-N into Big Creek between up and downstream sites did not change (i.e., no increase or decrease).

Finally, it is concluded that as long as the integrity of the holding ponds is maintained, the main long-term environmental concerns with CAFO operation lies with land use and nutrient management of the fields permitted to receive slurry.