AECOM

WESTAR DRILLING RIG 1-HOUR NO_2 AND NO_x EMISSIONS AND AMBIENT AIR IMPACTS

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Table of Contents

Page

Table of Contents

Page

Appendices

List of Figures

Page

List of Figures (continued)

List of Tables

EXECUTIVE SUMMARY

A field study was performed to develop a dataset of emission rates from diesel generators at drill rigs and associated ambient air concentrations immediately downwind of the drill rigs. Continuous 1-hour average concentrations of nitrogen dioxide (NO_2) and oxides of nitrogen (NO_x) were measured along with meteorological variables such as wind direction and wind speed. The field work was carried out by AECOM Corporation under contract by the Western States Air Resources (WESTAR) Council.

The monitoring was conducted over a six-week period in October 2014 and November 2014 at two well pads in the Denver – Julesburg Basin, in Weld County, Colorado, approximately 15 miles south of Greeley and approximately six miles east of Platteville. Anadarko Petroleum Corporation provided access to the test sites. Three oil and gas wells were drilled near the center of each pad, with each well taking six to ten days to drill. The same equipment was used at each well pad.

The ambient levels of NO_2 and NO_x were monitored at up to 12 locations upwind, downwind and crosswind to the rig. At the same time, emissions from the five stacks associated with the three diesel generators were measured. The dataset was generated to support future studies of the:

1. Short-term impacts of natural gas drilling on the near-field ambient air quality in the Western United States; and
2. Accuracy of 1-hour average estimates of rig impacts obtained using AERMOD or other atmospheric dispersion models, relative to the measured concentrations.

AERMOD is the U.S. Environmental Protection Agency's (EPA) recommended air dispersion model for regulatory air quality applications. The scope of work included collection of data needed in future studies to adequately evaluate and interpret the results of the NO_2 and NO_x measurements. Meteorological variables were measured because they determine the downwind displacement and dispersion of the stack emissions. The levels of ozone (O_3) in ambient air were measured because ozone reactions convert nitric oxide (NO) to NO_2.

This report describes the technical approach, test site layouts, and operational challenges that were encountered during the field testing. The dataset is included as an appendix to this report, along with supporting documentation such as calibration records, quality assurance documents, plot plans, and field logbook.

1.0 INTRODUCTION

Nitrogen dioxide (NO_2) emissions and oxides of nitrogen (NO_x) emissions from the diesel generators that power a gas well drilling rig were monitored continuously on two well pads in the Denver – Julesburg Basin, near Platteville, Colorado in October 2014 and November 2014. The levels of NO_2 and NO_x were also monitored in the near-field ambient air at up to 12 locations upwind, downwind and crosswind to the rig as the emissions were being measured. Meteorological variables that drive the emissions' downwind displacement and dispersion; and the levels of ozone (O_3) in ambient air, which regulate the conversion of nitric oxide (NO) emissions to NO_2 via the ozone titration pathway, were also monitored.

The emissions, ambient air quality, and meteorological measurements were carried out for 30 days by URS Corporation (URS)[1], under contract by the Western States Air Resources (WESTAR) Council. This report describes the technical approach, test site layouts, and operational challenges that were encountered during the field testing; this report also gives a brief summary of the monitoring results and the data quality.

1.1. Project Objectives

The project objective was to develop a dataset of continuous 1-hour average NO_2 and NO_x emission rates, ambient air concentrations, and meteorological variables to support future studies of: 1) the short-term impacts of natural gas drilling on the near-field ambient air quality in the Western United States and 2) the accuracy of 1-hour average estimates of rig impacts obtained using AERMOD[2] and possibly other air dispersion models, relative to the measured concentrations.

1.2. Acknowledgements

This project was co-sponsored by the United States Bureau of Land Management (BLM) and the American Petroleum Institute (API). WESTAR provided project oversight. WESTAR was advised by a Study Management Team with representation from BLM, API, the United States Environmental Protection Agency (EPA) and the Wyoming Department of Environmental Quality – Air Quality Division (WDEQ-AQD). Anadarko Petroleum Corporation provided access to the test sites, while the drilling company provided logistical support to the URS measurements team.

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[1] AECOM provided air monitoring, modeling, and data analysis support to this project as a URS subcontractor. In October 2014, as this project was being implemented, AECOM completed a financial transaction to acquire URS. The formerly two companies are now integrated as one and go by the name, AECOM.

[2] AERMOD is the United States Environmental Protection Agency (EPA) recommended air dispersion model for regulatory air quality applications (40 CFR § 51).

The following organizations loaned equipment to WESTAR for the project:

- Montana Dept. of Environmental Quality;
- North Dakota Dept. of Health;
- Utah Dept. of Environmental Quality;
- WDEQ AQD;
- API; and
- the BLM-Utah State Office.

2.0 SOURCE DESCRIPTIONS

The field testing took place on two well pads in Weld County, Colorado, approximately 15 miles south of Greeley and approximately 6 miles east of Platteville. Figure 2-1 is a map of an area northeast of Denver, showing the general location of the test sites. Table 2-1 gives the coordinates at the center of each pad. The distance between the centers of the two well pads is less than 0.5 kilometers (km) (Figure 2-2). Figures 2-3 and 2-4 illustrate the surrounding land use and topography, respectively. The landscape is flat, the area is rural, and the land is mostly used for ranching and natural gas development. The elevation at the center of both sites is approximately 5050 feet.

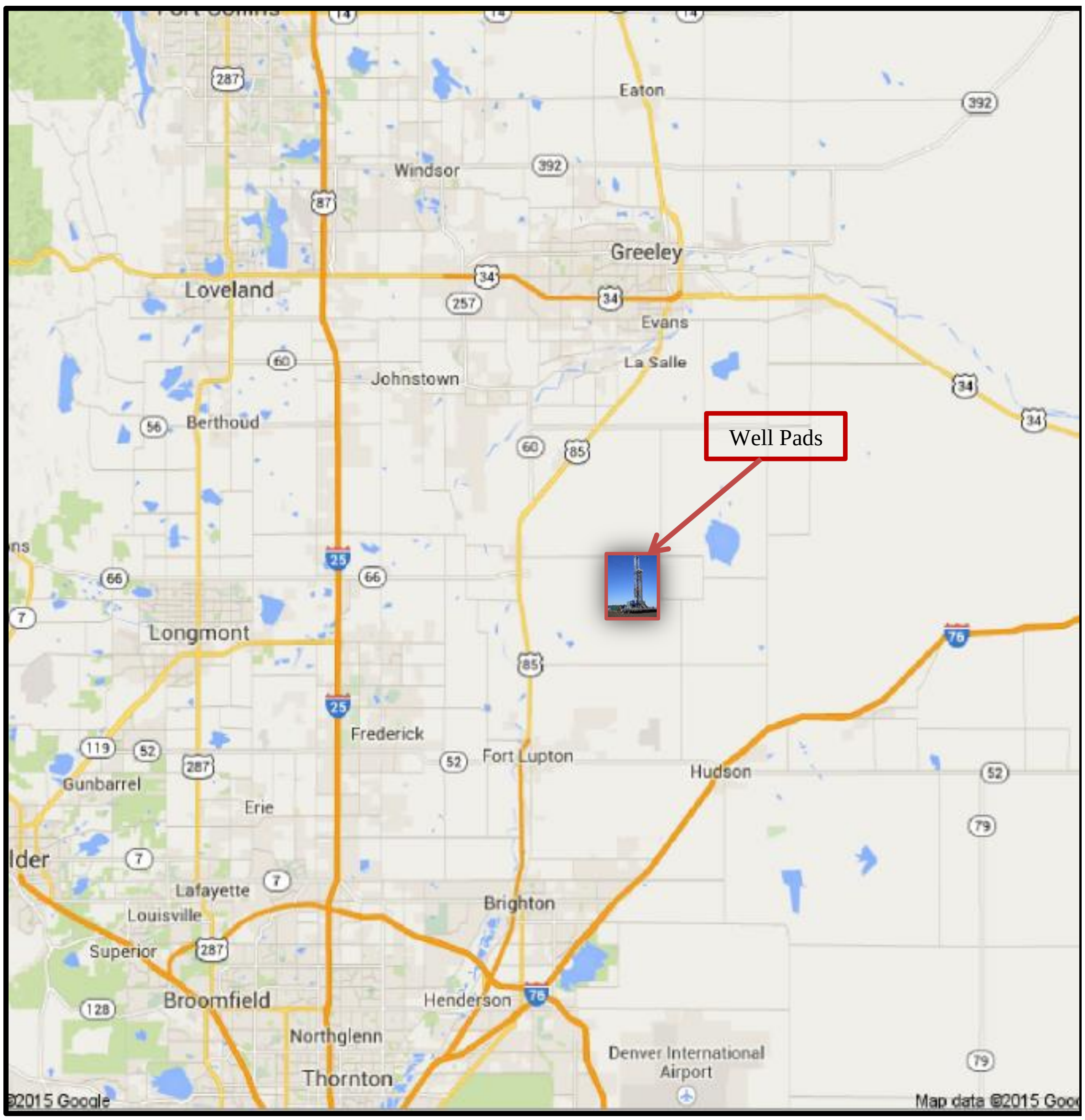

Figure 2-1. Map Showing the General Location of the Two Test Sites

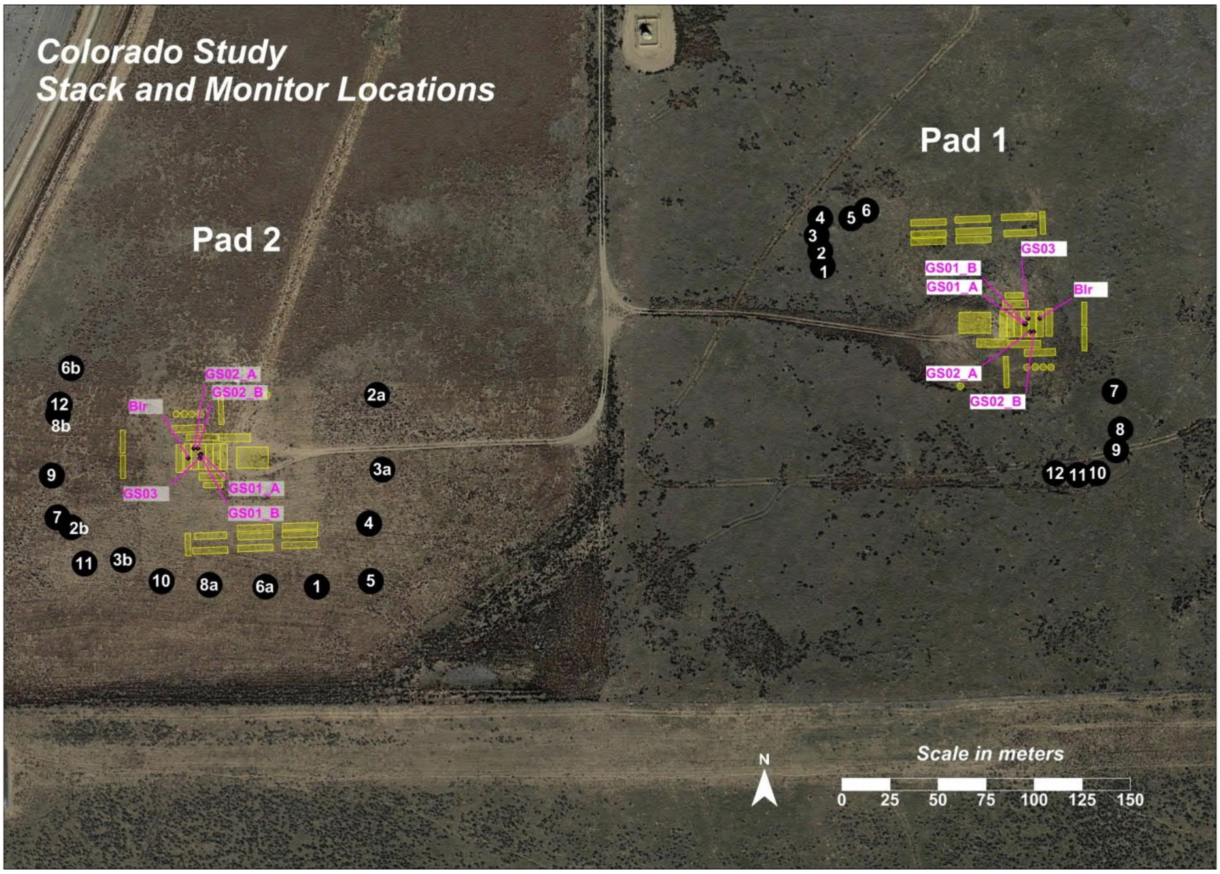

Figure 2-2. Layout of Colorado Study Emission Source and Monitoring Locations at Pads 1 and 2

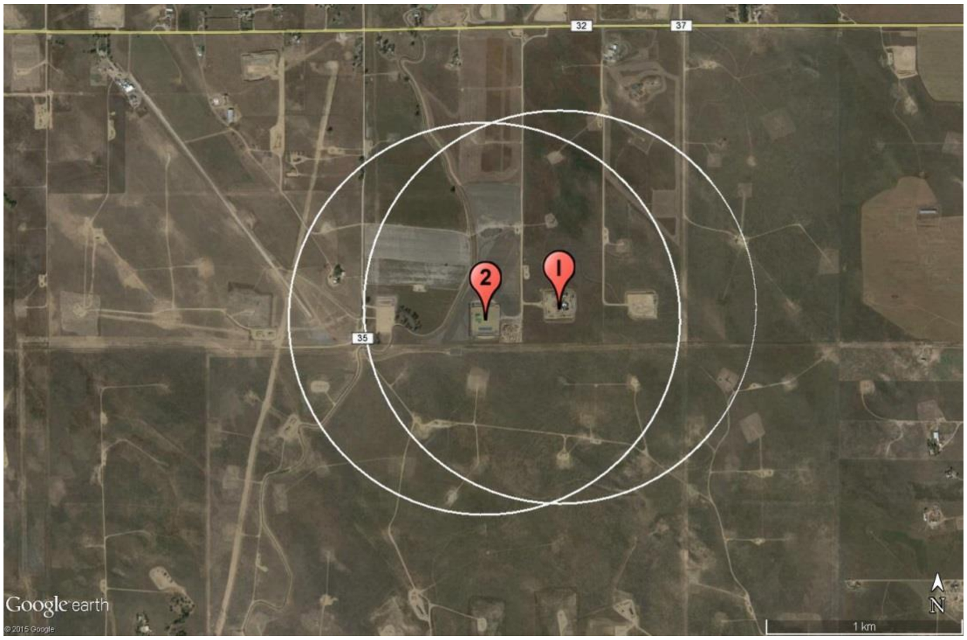

Figure 2-3. Aerial Photograph of the Area Surrounding the Two Test Sites (the radius of each circle is 1 km)

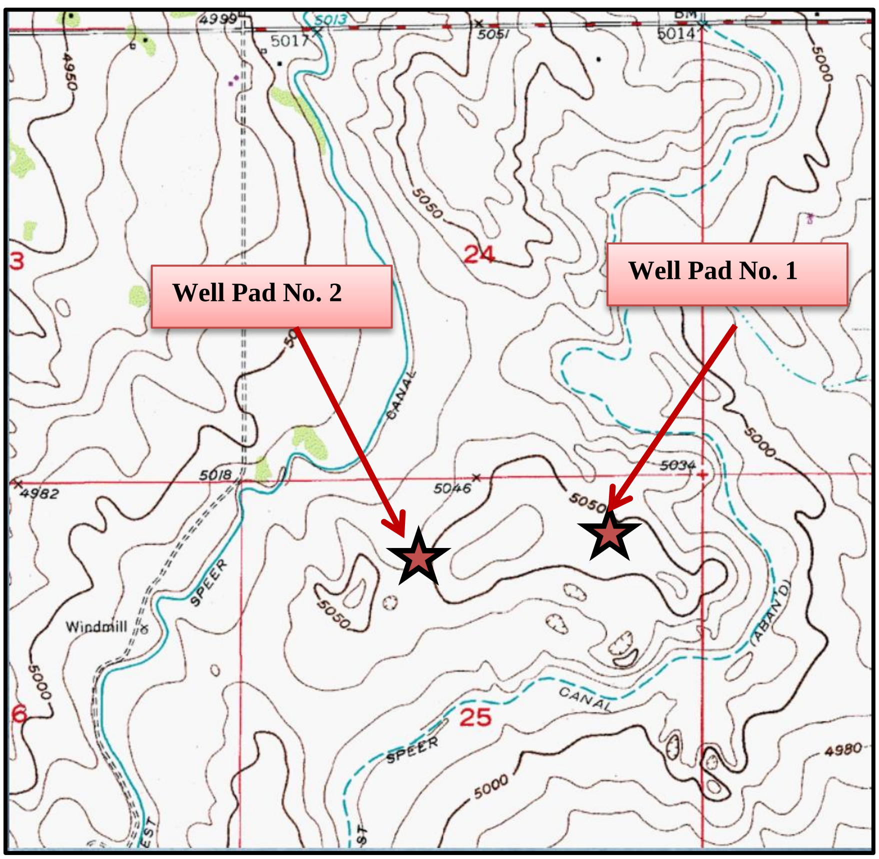

Figure 2-4. Topographic Map Showing the Approximate Locations of the Two Test Sites

The host company selected the first test site based on the following criteria:

- The sites were relatively remote and no drilling was anticipated to take place nearby at any other sites while the measurements were being carried out.
- No sound barriers that would disturb the natural displacement and dispersion of the generator NO_2 and NO_x emissions were anticipated to be erected around the well pads.
- Drilling at the first site was anticipated to begin within two weeks after a signed contract agreement between WESTAR and URS was in place.

The second test site was selected because there were relatively minor logistical challenges, time requirements or costs anticipated to relocate the monitoring equipment the short distance; and the drilling started at the second well pad just a few day after the drilling ended at the first site, which minimized downtime during the transition.

Three wells were drilled near the center of each of the two well pads by a triple drilling rig. The wells were expected to produce about 70% oil and 30% natural gas. The wells were drilled in approximately 6 – 10 days, each. Approximately 1½ days were taken to transition from one well to the next on each pad. Approximately four days were taken, after the third well was drilled at Well Pad No. 1, to rig down, relocate and begin drilling at Well Pad No. 2.

The same drilling rig, auxiliary equipment, and supporting structures were used on both well pads. The layout of the equipment and facilities on both pads was almost identical except that all the manmade structures that were brought onsite to support the drilling were transposed 180 degrees at Well Pad No. 2, relative to Well Pad No. 1. Also, the cuttings pit was oriented 90 degrees counterclockwise at Well Pad No. 2, relative to Well Pad No. 1.

The drilling rig (Figure 2-5) was powered by two Caterpillar 3512B generators with 1,475 horsepower ratings, and one Caterpillar C27 generator. The generators were housed inside two of a set of six 12'-wide trailers that are shown next to the rig mast schematically in Figure 2-5 and in an aerial photograph of Well Pad No. 1 in Figure 2-6. Each of the Caterpillar 3512B generators normally exhaust through two separate 10-inch diameter stacks that extend approximately 12-16 inches above the roof of the generator housing. Temporary stack extensions installed by URS for the stack gas velocity measurements raised the stack heights by 3' and increased the stack diameters to 12".

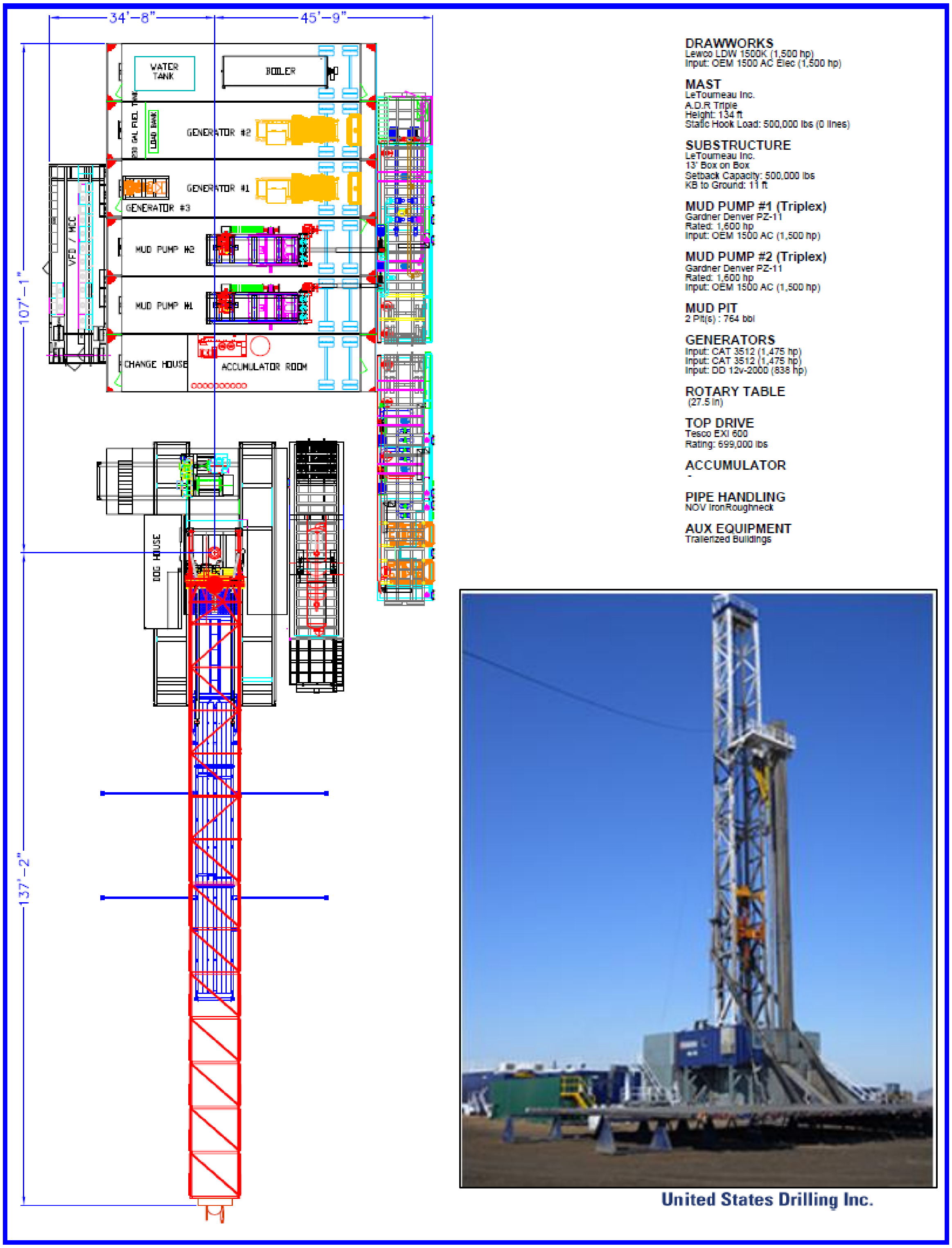

Figure 2-5. Schematic Drawing and Photograph of the Drilling Rig

(http://66.38.151.117/rigfinder/rig_details.jsp?id=70092)

Figure 2-6. Aerial Photograph Looking Down at the Generator Trailers and Other Drill Rig Structures

Other sources of NO_x on the well pad included a boiler, which was used only in very cold weather; 3 – 4 small diesel generators that were used for nightime lighting; a front end loader for transporting cuttings to the cuttings pit; a forklift; a portable flare; and both gasoline and diesel on road vehicles. In addition to these onsite NO_x sources, the ambient air measurements were influenced by offsite sources, including, apparently, emissions from the Denver Metro Area.

Tables 2-2 and 2-3 summarize the daily activities of the onsite NO_x sources during the field testing, including the number of hours per day that each generator was operating. Tables 2-2 and 2-3 also give the numbers of hours per day when the boiler, fork lift, front-end loader, and light tower generators were operated. The boiler was not operated on Well Pad No. 1, and was operated on Well Pad No. 2 primarily after November 10, 2014.

Emissions from the light tower generators, fork lifts, and front-end loaders were not measured. Hourly emissions for the light tower generators can be estimated using an appropriate emission factor. Hourly emissions can also be estimated for the fork lifts and front-end loaders with an appropriate emission factor and assumed spatial and temporal allocations of the activity data in Tables 2-2 and 2-3. No estimates were obtained of the emissions or activity of on road mobile sources, including diesel-fueled trucks that entered and exited the well pads each day.

Table 2-2. Well Pad No. 1 Combustion Source Activity Summary [a]

Date	Gen 1 3512B (hours)	Gen 2 3512B (hours)	Gen 3 C27 (hours)	Fork Lift (hours)	Light Generators (hours)	Front-end Loader (hours)
10/9	22	24	2	6	12	3
10/10	15	3	24	3	12	3
10/11 (New Well)	0	12	24	7	12	2
10/12	23	24	24	4	12	5
10/13	24	24	24	4	12	2
10/14	13	20	17	12	12	0
10/15	0	19	24	2	12	2
10/16	12	24	24	4	12	6
10/17	24	0	24	5	12	3
10/18	24	0	24	4	12	2
10/19	24	0	24	6	12	2
10/20	24	0	24	7	12	2
10/21 (New Well)	24	18	18	4	0	3
10/22	24	24	20	8	12	2
10/23	24	24	17	8	12	3
10/24	24	1	18	5	12	3
10/25	24	12	13	7	12	3
10/26	24	24	0	5	12	2
10/27	12	24	12	9	12	3

[a] Morning Reports and Daily Reports provided by John Bunyak, WESTAR.

Table 2-3. Well Pad No. 2 Combustion Source Activity Summary [a]

Date	Gen 1 3512B (hours)	Gen 2 3512B (hours)	Gen 3 C27 (hours)	Boiler (hours)	Fork Lift 938G (hours)	Light Generators (hours)	Front-end Loader (hours)
10/28	24	0	20	0	7	12	3
10/29	13	1	18	0	10	12	5
10/30 (New Well)	0	0	12	0	7	12	1
10/31	22	3	2	0	9	12	5
11/01	24	24	22	0	9	12	7
11/02	24	24	24	0	3	12	2
11/03	24	24	2	5	8	12	2
11/04	24	0	24	24	8	12	3
11/05	24	15	9	5	5	14	4
11/06	24	24	0	0	4	14	3
11/07	1	24	23	6	5	12	2
11/08 (New Well)	0	6	15	6	4	12	3
11/09	23	24	24	0	6	12	10
11/10	24	24	24	8	4	12	9
11/11	24	2	24	19	14	12	5
11/12	19	0	24	24	6	12	3
11/13	3	21	24	24	7	12	3
11/14	21	24	3	24	7	14	2
11/15	13	24	12	24	7	14	4
11/16 (New Well)	1	21.5	23	3.5	7	14	3
11/17	4	4	21	24	14	14	9

[a] Morning Reports and Daily Reports provided by John Bunyak, WESTAR.

3.0 TECHNICAL MONITORING APPROACH

URS was contracted by WESTAR to develop and implement a technical approach for achieving the project objective and the specific monitoring goals given in Section 3.1, below. The scope of work was to provide personnel and equipment to: 1) continuously monitor the NO_2 and NO_x in-stack concentrations and emission rates from three diesel generators; and 2) deploy and operate (a) 12 Federal Reference Method (FRM) or Federal Equivalent Method (FEM) ambient air NO_2/NO_x analyzers, (b) two FRM or FEM O_3 analyzers, (c) two portable meteorological monitoring systems with wind direction and wind speed sensors mounted at 10' above ground, and (d) one instrumented meteorological measurement tower with wind direction and wind speed sensors at 10 meters above ground. URS initially proposed to carry out these measurements using a team of four full-time onsite air quality professionals and technicians; however, budgetary constraints limited the number of full time onsite employees to two.

3.1 Monitoring Goals

The primary monitoring goal was to record as many hours as were reasonably practicable of paired, quality assured emission rate and downwind ambient air concentration measurement data over an approximately 30-day period, where the: 1) emission rates were representative of the NO_2 and NO_x emissions from three diesel generators that power a well drilling rig, and a boiler (when operating); and 2) the ambient air measurements were representative of the concentrations and concentration gradients that define the NO_2 and NO_x plume centerline and width. Other goals were to measure and record (a) continuous hourly averages of the in-stack NO_2 and NO_x concentrations, (b) hourly average concentrations of O_3 in the background air that is mixed with the plume as the emissions are displaced downwind and dispersed, and (c) hourly averages of the meteorological parameters needed to run AERMOD simulations of the generator emissions dispersion.

3.2 Monitoring Methods

URS used standard EPA continuous emissions monitoring (CEM) methods to measure the engine and boiler emission rates. The CEMS were rack-mounted inside a climate controlled 32-feet long trailer that was parked next to the rig. Standard EPA operating procedures and calibration procedures were used to measure and maintain data quality.

Ambient air monitoring for NO_2, NO_x, and O_3 was carried out with FRM and FEM analyzers. The ambient air analyzers were installed in weather-tight transportable enclosures. The instrument enclosures were mounted on wheels to streamline the effort and reduce the time that would be needed to reposition the monitors in case of significant and lasting changes in the weather pattern or as a corrective action to better align the monitors downwind relative to the rig.

Monitors were redeployed only twice after the initial set up. The first redeployment took place during October 30, 2014 – November 2, 2014, when all the air monitoring equipment was transferred from Well Pad No. 1 to Well Pad No. 2. The second redeployment took place on Well Pad No. 2 during November 8, 2014 – November 9, 2014, in anticipation of a significant change in the weather pattern.

3.2.1 Continuous Emissions Monitoring

Before the emissions measurements were started, URS attached a 3-feet length of 12-inch diameter stove pipe to each generator exhaust stack to provide for representative measurements of in-stack gas velocities.

URS also had to modify the exhaust plumbing of the two Caterpillar 3512B generators so that the emissions from five stacks could be monitored using three continuous emissions monitoring systems (CEMS). Since the project schedule did not accommodate a site visit before the testing began, URS mobilized for the field tests equipped with three CEMS, not knowing that the exhausts from each Caterpillar 3512B was split through two parallel catalytic converters upstream of dual exhaust vents. After arriving on site and observing the unanticipated exhaust configuration, URS acquired additional flow controllers and other plumbing materials to balance the flows through the two vents and monitor in-stack NO_2 and NO_x concentrations before the split.

3.2.1.1 NO_X and NO_2 In-Stack Concentrations

The in-stack concentrations of NO_2 and NO_x were monitored continuously using TECO Model 42C chemiluminescence analyzers operated in accordance with EPA Method 7E – *"Determination of nitrogen oxides emissions from stationary sources (instrumental analyzer procedure)"*[3]. Method 7E is designed to provide high-quality data for determining compliance with Federal and State emission standards. The calibration and quality control tests that were performed before, during and after the emission rate testing on each well pad are described below.

Initial Calibration Error Tests

Initial calibration error tests were performed on each analyzer before the emissions testing began on each well pad. The tests were carried out with 990 ppm and 500 ppm nitric oxide (NO) high and mid-level calibration gases, respectively, that were generated by diluting an EPA Protocol NO in N_2 mixture with ultra-high pure (UHP) N_2 using an Environics gas dilution system. The calibration gases were delivered directly to each analyzer at 6 liters per minute (liters/min).

[3] 40 CFR Part 60, Appendix A-4, Method 7E.

The calibration error, E (%) at each certified calibration gas concentration ($Conc_{certified}$), was calculated as:

$$E\ (\%) = \left(\frac{Conc_{measured} - Conc_{certified}}{Conc_{span}}\right) \times 100\%,$$

Where:

$Conc_{measured}$ is the analyzer response (i.e., the measured NO_x concentration), and ($Conc_{span}$) is the certified concentration of the high level (span) calibration gas.

The initial calibration test was passed when the calibration error was within ±2 percent of the calibration span gas (high level) concentration at each calibration point. Corrective actions were taken and the analyzer was recalibrated whenever the calibration error was outside the acceptable range.

NO_2 to NO Conversion Efficiency Tests

The conversion of NO_2 to NO was verified before the emissions testing began on each well pad using the “Bag Procedure” described in Method 7E, Section 16.2.2. The bag procedure monitors the stability over time of the NO_x level inside a Tedlar bag filled approximately 50-50 with a mid-high level NO standard and ambient air. The converter efficiency test is passed when the measured NO_x concentration does not decrease by more than 2% from its peak value over a period of 30 minutes or longer.

System Bias Checks

System bias checks were carried out each day with UHP N_2 and an NO gas standard of approximately 500 ppm. The gases were delivered to each analyzer through the probe using a heated head vacuum pump. The System bias (SB) was calculated as:

$$SB\ (\%) = \left(\frac{Conc_{system} - Conc_{direct}}{Conc_{span}}\right) \times 100\%,$$

Where:

$Conc_{system}$ is the measured concentration of a calibration gas introduced in the system calibration mode; and

$Conc_{direct}$ is the measured concentration when the calibration gas is introduced directly into the analyzer.

The system bias acceptable range at zero ppm and at the gas standard concentration was ±5 percent of the span gas concentration.

3.2.1.2 Stack Temperature

The stack gas temperature was measured using a Type-K thermocouple. Type K thermocouples use chromium-nickel alloys for the positive leg and copper alloys for the negative leg. They are reliable and accurate over a wide temperature range.

3.2.1.3 CO_2 and O_2 In-Stack Concentrations

The oxygen (O_2) and carbon dioxide (CO_2) levels in the engine exhaust were monitored continuously by EPA Method 3A – "*Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources (instrumental analyzer procedure).*" Servomex Servopro 1400 Series multi-gas analyzers were used to monitor the in-stack concentrations of O_2 and CO_2 by paramagnetic detection and infrared absorption, respectively. Daily checks were performed of the analyzer responses to zero and mid-level EPA Protocol gas standards. The O_2 and CO_2 analyzers were recalibrated whenever the output response was outside the acceptable range of ±0.5% of the input concentration.

3.2.1.4 Stack Gas Velocity

Continuous 5-minute and 1-hour block averages of the stack gas volumetric flow rates were measured by EPA Method 2—"*Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)*". This standard method determines the average gas velocity from the pitot tube pressure readings (ΔP); the average stack gas temperature; the stack gas wet molecular weight; and the absolute static pressure. Temperature and pressure were measured using a pressure transducer and a K-type thermocouple. The static gas pressure was measured by rotating the pitot perpendicular to the gas flow and comparing the pressure of one leg of the pitot to the ambient barometric pressure. Stack gas flow rates were calculated by multiplying the average stack gas velocity by the cross-sectional area of the stack.

The average stack gas velocity, V_s, in feet per second (ft/sec) was calculated as:

$$V_s = Kp \times C_p \times \sqrt{\frac{\Delta P_{avg} \times T_s}{P_s \times M_s}}$$

Where:

K_p is the velocity equation constant;

85.49; C_p is the S type Pitot tube coefficient;

ΔP_{avg} is the square of the average of the square roots of the velocity head of stack gas in inches of water (in. H_2O);

T_s is the absolute stack gas temperature in $°R$; P_s is the absolute stack pressure in inches of mercury (in. Hg); and

M_s is the stack gas molecular weight in pounds per pound-mole (lb/lb – mole).

3.2.1.5 Physical Stack Dimensions

Each generator exhaust stack was custom made to have an inside diameters of 12 inches and a length of 3 feet.

3.2.1.6 Calculation of Mass Emission Rate

The stack gas volumetric flow rate, Q_{actual} (ft^3/s) at actual conditions was calculated as:

$$Q_{actual} = V_s \times A$$

Where:

A is the cross-sectional area of the stack in square feet (ft-sq). The stack gas dry volumetric flow rate, Q, was calculated as;

$$Q = 3600 \times (1 - B_{ws}) \times V_s \times A \times \frac{T_{std} \times P_s}{T_s \times P_{std}}$$

Where:

B_{ws} is the average proportion of water vapor, by volume (assumed equal to 2%);
T_{std} is the standard absolute temperature (528°R);
T_s is the average stack gas temperature (°R);
P_s is the absolute stack pressure in Hg; and
P_{std} is the standard absolute pressure, 29.92 in Hg.

Block 1-hour and 5-minute average mass emission rates (ER), in units of pounds per hour (pounds/hour), were calculated for NO_2 and NO_x as:

$$ER_{NO_x} = Conc_{NO_x} \times Q \times MW_{NO_x} \times 28.3 \div (24.0 \times 454)$$

Where:

$Conc_{NO_x}$ is the concentration of NO_x in the stack gas (ppm);
Q is the stack gas flow rate (dscf/hr);
the molecular weight of NO_2 is 46;
28.3 is the conversion factor from ft^3 to liters (l);
24.0 is the number of liters per mole at standard conditions (68); and
454 is the number of grams per pound.

3.2.2 Ambient Air Monitoring

Twelve chemiluminescence NO_2/NO_x analyzers were deployed along the easement that surrounded each of the test sites. The analyzers were housed inside weather-tight air conditioned enclosures for protection against excessive heat and precipitation; however, no protection from excessively cold temperatures was initially provided except for insulation and the heat generated by the analyzer. The temperature inside each shelter was continuously monitored and heaters were installed during the last week of the field testing as the ambient temperatures fell to record lows.

The instrument enclosures were all mounted on wheels to enable towing by a utility cart across the uneven terrain to the designated air monitoring sites. Two of the monitor enclosures were outfitted for wind direction and wind speed measurements at a height of 10’ (approximately 3 m) above ground level (Figure 3-1) and O_3, in addition to NO_2 and NO_x. The ambient air inlets were approximately 2 m above ground.

3.2.2.1 NO_2 and NO_x

The NO_2 and NO_x levels in the near-field ambient air were monitored continuously using ten Thermo Scientific Model 42C and two API Model 200E chemiluminescence FRM analyzers. URS/AECOM provided eight of the Thermo Scientific analyzers. The other NO_2/NO_x analyzers were drawn from a collection of spare and surplus analyzers that were loaned to WESTAR for this project by its members, API, and the BLM Utah State Office. The NO_2/NO_x analyzers were operated with temperature and pressure compensation to correct for any changes to the output signals caused by variations in the instrument internal temperature or the reaction chamber pressure. The continuous data streams were averaged and stored in 5-minute and 1-hour intervals.

Figure 3-1. Air Monitor Enclosure at Site 1 on Well Pad No. 1

The performance of each analyzer, including assessments of baseline drift and calibration drift, was checked every day by comparing the output responses to inputs of zero and approximately 400 ppb NO. Corrective actions were taken whenever the analyzer span response was outside the acceptable range of ±10 percent of the input concentration or the zero response was outside the range of ±5 parts per billion (ppb). An additional calibration check at approximately100 ppb was performed every day at each site on Well Pad No. 2. The 100 ppbv calibration checks were used in the calculation of measurement precision. The calibration system was housed in an enclosure similar to the analyzer shelters and was towed from site to site for the QC checks after a 30-minute warmup (Figure 3-2). Electricity to run the calibrator was accessed at various points along the route.

Figure 3-2. Transportable Ambient Air Quality Analyzer Calibration System

3.2.2.2 Ozone

Two ozone analyzers from the collection that WESTAR borrowed were used to measure the O_3 levels in the background air. An Ecotech UV analyzer was installed at Site 1 and a 2B Tech Model 205 UV analyzer was installed at Site 12. Both types of analyzers have FEM designations.

The Ecotech UV analyzer would not calibrate and it was replaced with another Ecotech UV analyzer, which also would not calibrate. After several attempts to repair the analyzers, URS site personnel had a Thermo 49i analyzer shipped to the site. The Thermo 49i analyzer was installed, calibrated, and online for Well Pad 2 sampling.

The 2B Tech Model 205 UV analyzer did not have the proper signal wires to connect to URS' datalogger. After several attempts by field personnel to connect the analyzer to the datalogger, an adapter was located and shipped to the site. The 2B Tech Model 205 UV analyzer signal adapter was installed, calibrated, and online for Well Pad 2 sampling.

The ongoing performance of the O_3 analyzers was evaluated using daily zero and span checks.

3.2.2.3 Ambient Air Monitor Calibrations

The NO_2/NO_x analyzer calibrations were verified at the start of the field testing on each well pad, approximately 24 hours after they were powered on to allow the converters to warm up and stabilize. The calibration of each analyzer for NO_x detection was verified by comparing the output response to inputs of zero air and NO concentrations of approximately 100 ppb, 200 ppb, and 400 ppb (the NO calibration verification standards were generated by diluting a certified standard containing 51.6 ppm NO with zero air). The calibration was accepted when the analyzer response to every calibration point was within ±10% of the input concentration. The NO to NO_2 converter efficiencies were checked at a single point at the start of the monitoring program by titrating an NO calibration standard with a known concentration of ozone. Calibration and converter efficiency verifications were repeated at the end of the monitoring period, at zero ppb and at three upscale concentrations to demonstrate continued calibration acceptance and verification of converter efficiencies of greater than 95% over the entire calibrating range.

The ozone analyzer calibrations were checked at the beginning and end of the monitoring period on each well pad by comparing the output responses to zero ppb and five upscale ozone concentrations that were generated using an ozone generator and certified transfer standard.

3.2.3. Meteorological Parameter Monitoring

URS installed a 10-meter instrumented telescoping tower to monitor meteorological conditions relevant to modeling the displacement and dispersion of the generator emissions (Figure 3-3). Because of available space on the pad, URS was not permitted to install the tower on the active drilling site. Therefore, the 10-meter tower was set up on well Pad No. 2 when the drilling was taking place on Well Pad No. 1 and was moved to Well Pad No. 1 when the drilling rig moved to Well Pad No. 2.

URS also equipped two of the transportable air monitoring systems with wind speed and wind direction sensors. The wind sensors were mounted at the top of 3-meter masts that were attached to two of the shelters. The instruments that were used for monitoring meteorological parameters are described below.

Figure 3-3. Photograph of the 10-meter Tower

3.2.3.1 Wind Speed, Wind Direction, and Sigma-Theta

Wind speed, wind direction, and sigma-theta were monitored at 10 m above ground using an RM Young Model 81005A Ultrasonic Anemometer mounted at the top of the 10-meter telescoping tower shown in Figure 3-3. The RM Young Model 81000 series anemometers measure three dimensional wind velocity and speed of sound based on the transit time of ultrasonic acoustic signals. The 81000 series instruments are intended for applications that require fast response, high resolution, and three-dimensional wind measurements. The sensor performance characteristics reported in product literature are given below:

RM YOUNG 81000 SERIES ULTRASONIC WIND SPEED	
Range	0 to 40 m/s (0 to 90 mph)
Resolution	0.01 m/s
Threshold	0.01 m/s
Accuracy	±1% rms ±0.05 m/s
	±3% rms (30 to 40 m/s)
RM YOUNG 81000 SERIES ULTRASONIC WIND DIRECTION	
Azimuth Range	0.0 to 359.9 degrees
Elevation Range	±60.0 degrees
Resolution	0.1 degree
Accuracy	±2° (1 to 30 m/s)
	±5° (30 to 40 m/s)

Wind speed, wind direction, and sigma-theta were also monitored at 3 m above ground using Met One Instruments Model 010C three-cup anemometers and Model 020C airfoil vanes. The Met One instruments were installed on masts that were attached to two of the transportable equipment enclosures (as shown in Figure 3-1). The 010C anemometers and 020C vanes are intended for applications that require a fast response and low starting threshold. Both instruments meet EPA and NRC specifications for critical measurement applications. The performance characteristics for the Model 010C wind speed and Model 020C wind direction sensors that are reported in product literature are given below.

MET ONE INSTRUMENTS, INC. MODEL 010C WIND SPEED SENSOR	
Maximum Operating Range	0 – 125 mph (0 – 60 m/s)
Stating Speed	0.5 mph (0.22 m/s)
Calibrated Range	0 – 100 mph (0 – 50 m/s)
Accuracy	±1% or 0.15 mph (0.07 m/s)
Resolution	<0.1 mph or m/s
Temperature Range	-50 C to +65 C (-58 F to +149 F
Distance Constant	Less than 5’ (1.5 m) of flow
MET ONE INSTRUMENTS, INC. MODEL 020C WIND DIRECTION SENSOR	
Azimuth	Electrical 0° - 357°
	Mechanical 0° - 360°
Threshold	0.5 mph (0.22 m/s)
Linearity	±0.5% of full scale
Accuracy	±3°
Resolution	<0.1°
Damping Ratio	Standard 0.6 (magnesium tail)
Delay Distance	Less than 3’ (91 cm)
Temperature Range	-50 C to +65 C (-58 F to +149 F

Vector averaging and calculations of the standard deviations of the vector mean wind directions (i.e., sigma-theta) were carried out according to the guidance provided in the EPA document, “*Meteorological Monitoring Guidance for Regulatory Modeling Applications,”*[4] using the software internal to the Campbell Scientific CR10X data loggers. Sigma-theta was calculated using the Yamartino algorithm, which is described in the EPA guidance document.

3.2.3.2 Air Temperature and Vertical Temperature Gradient

The outside air temperature and vertical temperature gradient (ΔT) were monitored using a matched pair of Met One Instruments Model 062 solid-state, multi-element thermistor devices. The temperature sensors were calibrated by the manufacturer and checked onsite by comparing the temperature output to the readings from an NIST traceable reference standard when submerged in ice water, room temperature, and hot water baths. The sensors were mounted at 10 m and 2 m above ground on the telescoping tower. Continuous airflow over each sensor was maintained using aspirated housings.

4 U.S. Environmental Protection Agency, Office Of Air And Radiation, Office Of Air Quality Planning And Standards Research Triangle Park, NC 27711, February 2000

3.2.3.3 Barometric Pressure

The barometric pressure was measured with a Vaisala CS106 silicon capacitive barometer that is designed for environmental applications.

3.2.3.4 Rainfall

A Met One 360 tipping bucket rain gauge was used to measure rainfall.

3.2.3.5 Relative Humidity

Relative humidity was measured with a Met One 083E capacitance-based sensor. This instrument has a fast linear response to changes in the relative humidity with little hysteresis, according to the manufacturer's product literature. It is designed for meteorological and other applications.

3.2.3.6 Meteorological Monitoring Sensor Calibration

The wind direction sensors were aligned to true north by calculating the magnetic declination based on the longitudinal location of the sensor for the area at the time of measurement. Magnetic north was found using a certified traceable surveyor's transit and true north was then calculated by correcting for the magnetic declination. The wind direction sensors were then adjusted to point directly at true north.

The precipitation gauge was calibrated by slowly introducing 80 mL of water into the rain gauge by use of an acrylic burette. The 80mL of water equates to 0.10 inches of precipitation, which were counted and verified to the precipitation response on the data logger.

3.2.3.7 Data Acquisition

A Campbell CR10X data logger and RF modem was installed in each instrument shelter to record and transmit data in real-time to an onsite central computer where the data streams from all the emissions and ambient air monitoring systems were synchronized, merged, and stored in 5-minute and 1-hour averaging intervals. The monitoring data were backed up several times each day and transmitted to the URS Project Manager in Austin, and other key team members, at the start of the next work day. The URS Project Manager reviewed the monitoring data and then distributed the raw unvalidated 5-minute and 1-hour averaged data with any applicable caveats and other comments to the Study Management Team in the formats that were requested.

4.0 WELL PAD LAYOUTS AND AMBIENT MONITOR LOCATIONS

As previously noted, the same equipment and general set-up was used for both Well Pads. The generator stack coordinates and equipment dimensions are given in Tables 4-1 and 4-2.

Table 4-1. Generator Stack Coordinates and Equipment Dimensions

Stack	Height		Well Pad No. 1		Well Pad No. 2	
	Feet/Inches	Meters	UTM E (Zone 13 T)	UTM N (Zone 13 T)	UTM E (Zone 13 T)	UTM N (Zone 13 T)
Generator 1A	18’2	5.54	523600	4450587	523172	4450519
Generator 1B	18’2	5.54	523601	4450587	523171	4450519
Generator 2A	18’2	5.54	523603	4450603	523168	4450522
Generator 2B	18’2	5.54	523605	4450583	523170	4450522
Generator 3	18’2	5.54	523602	4450590	523171	4450517
Boiler Building	13’5”	4.09	523606	4450581	523164	4450513
Structure						
Generator Trailer #1			523599	4450581	523171	4450513
Generator Trailer #2			523602	4450581	523167	4450513
Mud Pump #1			523592	4450581	523177	4450513
Mud Pump #2			523595	4450581	523174	4450513
URS Trailer			523591	4450601	523172	4450504
AC Trailer			523590	4450595	523172	4450508
Drill (Derrick) Structure			523572	4450581	523188	4450504
Light Towers			523501 523501 523620	4450575 4450606 4450570		

Table 4-2. Equipment Dimensions

Item	Length	Width	Height
“Company Man” Trailer	50’	11’	12’
Crew Camp Trailer #1	50’	11’	12’
Crew Camp Trailer #2	50’	11’	12’
Crew Camp Trailer #3	50’	11’	12’
Crew Camp Trailer #4	50’	11’	12’
Crew Camp Trailer #5	50’	11’	12’
“Tool Pusher” Trailer	50’	11’	12’
Mud Tank #1	53’ 6”	12’ 3”	11’ 7”
Mud Tank #2	53’ 6’’	12’	11’ 7”
Generator Trailer #1	43’ 8”	12’	15’ 2”
Generator Trailer #2	43’ 8”	12’	15’ 2”
Boiler	43’ 8”	12’	13’ 3”
Change House	43’ 8”	12’	13’ 3”
AC House	43’ 6”	12’ 6”	15’ 4”
Catwalk	62’ 4”	9’ 10”	6’ 6”
Rig Floor	36’	54’	13’
Rig Mast	10’	10’	134’
Mud Pump #1	43’ 8”	12’	13’ 3”
Mud Pump #2	43’ 8”	12’	13’ 3”
URS Trailer	32’	12’	7’
Draw Works	30’ 6”	14’ 5”	11’5”
DS Sub	60’ 4”	14’	13’ 10”
ODS Sub	60’ 4”	11’ 10”	14’
Crown Sec	73’ 4”	15’ 1”	11’ 11”
A-Leg Sec	75’ 10”	13’ 11”	11’ 11”
20’ Container	21’ 7”	9’ 7”	8’ 6”

4.1 Well Pad No. 1

Figure 4-1 gives an aerial view of the entire Well Pad No. 1 layout, taken on October 6, 2014; a few days after the drilling on Well Pad No. 1 had begun (a plot plan of Well Pad No.1 is located in the appendices). Figure 4-2 gives a magnified view of the structures near the center of the well pad. The drilling rig mast was near the center of the well pad, to the west (left) of six trailers that housed two mud pumps, the three generators, a change house, and a boiler. The six trailers were all 43’8” long by 12’ wide, and varied in height from 13’3’’ to 15’2”. Temporary stack extensions raised the stack height to 18’2”. The distance along the interior perimeter of Well Pad No. 1 was approximately 400’ (approximately 120 m) on each side.

Figure 4-1. Aerial Photograph of the Well Pad No. 1 Layourt Captured on October 6, 2014

Figure 4-2. Same Aerial View as in Figure 4-1 but Magnified for Clearer View of the Rig Structures

4.1.1 Modeled Estimates of Plume Dispersion

Dispersion of the generator emissions was modeled before the start of the field campaign to estimate the distance from the rig to the maximum ground level concentration for a range of anticipated wind speeds. The modeling was used to estimate how far downwind the monitors needed to be placed. The modeling was performed using AERMOD with the actual engine stack parameters and potential downwash structures. The model was run for wind speeds ranging from 1-15 meters/second (m/s) and the two most frequent wind directions indicated from monitoring data collected by the Colorado Department of Public Health and Environment (CDPHE) at the Greeley/Weld County Tower County Ozone Monitoring Site (AQS# 08-123-0009). The Greeley monitoring site is approximately 13 miles north of the well pad. Data accessed in September 2014 from AirNow-Tech at www.airnowtech.org for October 2012 and October 2013 indicated a diurnally varying wind pattern with predominant north to north-northwest winds at night, light and variable winds in the morning, and east to east-southeast winds from approximately 12:00 p.m. to 8:00 p.m.

The modeling was conducted using the actual engine stack parameters with the 3-feet extensions and the measured dimensions of onsite structures that could affect plume downwash. The model was run for wind speeds ranging from 1-15 meters/second (ms^{-1}). The modeled maximum NO_2 concentration was predicted to occur inside the well pad perimeter in each of the hypothetical scenarios except for low wind speeds, when the predicted NO_2 offsite impacts were comparatively low and of no regulatory significance.

4.1.2 Monitor Locations and Constraints

The 12 NO_2/NO_x ambient air analyzers were split into two groups of six on Well Pad No. 1, in anticipation of a repeating diurnally varying wind pattern, which was observed in October 2012 and October 2013 at the Greely/Weld county site.[5] The archived data indicated a high probability of north-northeasterly winds overnight and east-southeasterly winds in the afternoon and early evening (the winds in the morning were typically light and variable). To achieve a relatively high probability of monitor exposure to the generator emissions without having to move monitors, sets of six analyzers, each, were placed near the northwest and southeast corners of the well pad. Table 4-3 gives the UTM and latitude and longitude coordinates of the Well Pad No. 1 ambient air NO_2/NO_x monitoring sites.

Land access for deploying monitors was limited to the approximately 3-4 m wide easement that surrounded the well pad. Based on the preliminary modeling that was conducted, points along the easement were anticipated to be reasonably representative of the distances to the maximum downwind ambient NO_2 concentrations except when the wind speeds were very low and the maximum downwind NO_2 levels were predicted to be low compared with the National Ambient Air Quality Standard. Various obstacles and obstructions along all four sides of the rectangular-shaped easement, however, constrained the crosswind distances over which monitors could be placed and may have reduced the amount of useful data.

At every corner and on all four sides of the rectangular well pad, the precise placement of the monitors was constrained by access restrictions, obstacles in the terrain, or other physical obstructions. The least obstructed segments of the well pad perimeter were: (1) along the western boundary, north of the entrance gate and (2) along the eastern boundary, south of the cuttings pit.

[5] The Colorado Department of Public Health and Environment (CDPHE) Greeley/Weld County Tower Ozone Monitoring Site (AQS# 08-123-0009) is approximately 13 miles north of the test sites. Wind data were accessed from AirNow-Tech at www.airnowtech.org.

Table 4-3. Well Pad No. 1 Ambient NO_2/NO_x Monitoring Site Coordinates and Distances to Generator Stack 1B

Site No.	Latitude	Longitude	UTM E (Zone 13 T)	UTM N (Zone 13 T)	Distance to Generator Stack 1B (m)	Heading (degrees)
1	40.205632	-104.72391	523495	4450617	110	286
2	40.205702	-104.72392	523494	4450625	113	290
3	40.205775	-104.72394	523492	4450633	117	294
4	40.205858	-104.72393	523494	4450642	120	298
5	40.205862	-104.72374	523510	4450642	106	302
6	40.205886	-104.72364	523518	4450646	101	306
7	40.205040	-104.72213	523649	4450532	56	126
8	40.204864	-104.72210	523649	4450532	70	138
9	40.204760	-104.72212	523648	4450521	79	144
10	40.204653	-104.72224	523638	4450509	85	154
11	40.204615	-104.72236	523628	4450508	32	162
12	40.204616	-104.72249	523616	4450509	76	167

Monitors 1 through 4 were deployed along the segment of the well pad's western boundary that extended northward from a point approximately 15 m north of the well pad entrance to the northwest corner (Figure 4-3). The analyzers along this segment were spaced approximately 8 m to 10 m apart and had unobstructed lines of site to the drilling rig (Figure 4-4). Monitor deployment south of Site 1 was avoided due to potential interference from a portable light generator that was situated approximately 10 m away. South of the entrance road was another light generator and the pipe yard.

Monitors 5 and 6 were deployed on the north side of the well pad, squaring off the northwest corner approximately 15 m and 25 m, respectively, to the east of site 4. Further to the east, winds from the interior of the well pad were obstructed by rows of office and crew camp trailers, and uneven terrain (Figure 4-5).

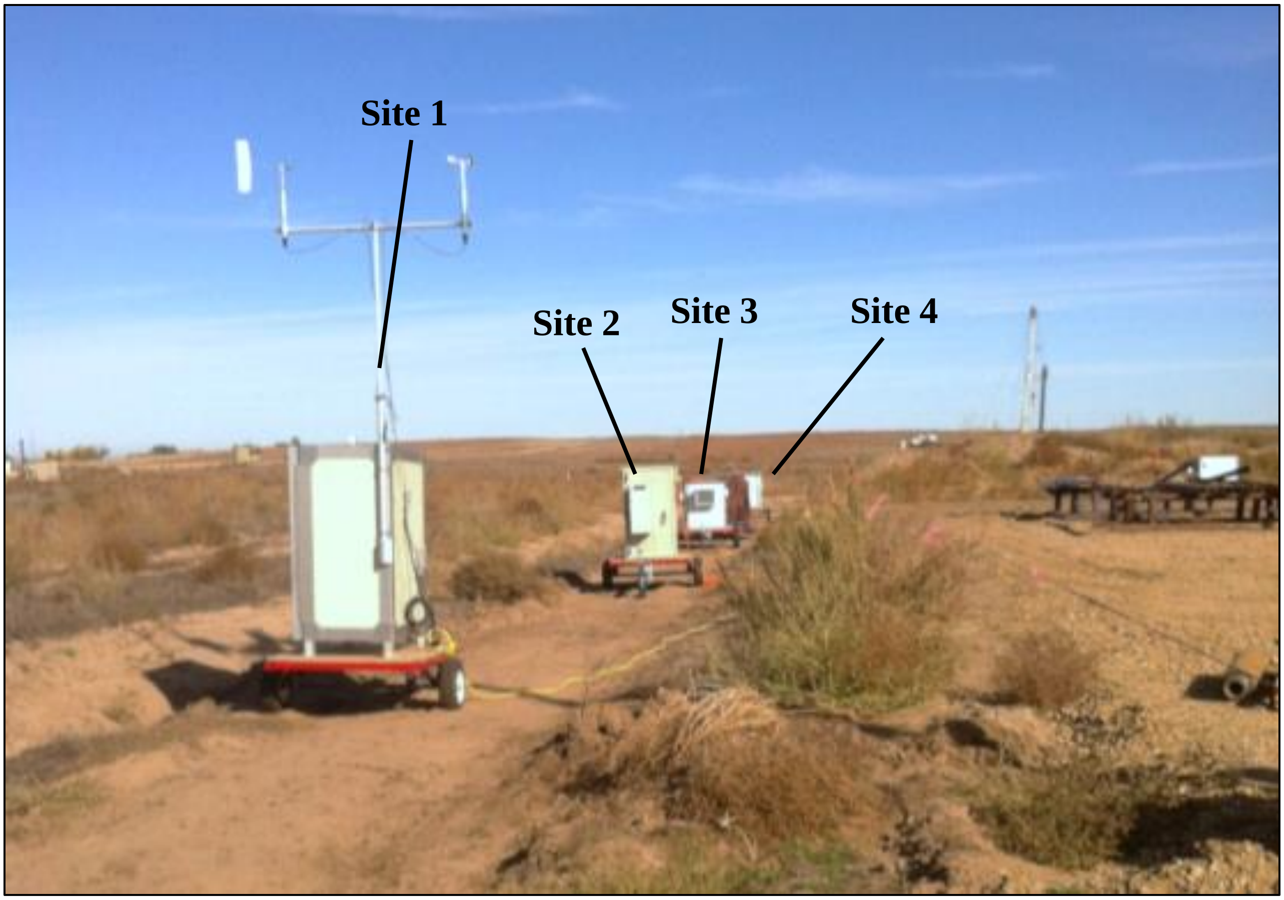

Figure 4-3. Ambient Air Monitoring Sites 1-4 from South to North along the Well Pad West Side

Figure 4-4. Line of Sight from the Northwest Corner to the Drilling Rig

Figure 4-5. View Looking East from the Northwest Corner of the Well Pad

Monitors 7, 8, and 9 were deployed along the segment of the eastern well pad boundary from slightly south of the cuttings pit to southeast corner, where the road begins to curve toward the west. North of Site 7, wind flow and access were obstructed by the cuttings pit. The distances from Site 7 to sites 8 and 9 were approximately 65’ and 105’ respectively.

Monitors 10, 11, and 12 were deployed along a segment of the southern well pad boundary, from east to west. Site 10 was approximately 50’ southwest of Site 9. The distances from Site 10 to sites 11 and 12 were approximately 35’ and 70’, respectively. Wind flow from the interior of the well west of Site 12 was obstructed by the terrain (Figure 4-6).

Figure 4-6. Monitoring Sites 9 through 12 Wrapping Around the Southeast Corner of the Well Pad (West of Site 12, the dune to the right obstructs wind flow to sites along the perimeter easement)

4.2 Well Pad No. 2

The inventory of structures and equipment at Well Pad No. 2 was the same as at Well Pad No.1; however, the layout was transposed (i.e., flipped 180°) from that on Well Pad No. 1. The drill rig was still near the center of the well pad, but the generators, boilers, etc. were west of the rig mast instead of east, the offices and crew camp trailers were at the south end of the pad instead of the north, and so on. The dimensions of the equipment were unchanged.

The layout of the well pad and ambient monitoring equipment is shown in plot plans located in the appendices. The starting ambient air monitoring locations were chosen based on siting restrictions (i.e., cutting area to the north of the pad), and the desire to balance the crosswind resolution and a wide range of wind directions. The starting monitoring locations are shown in Table 4-4 and these are the locations depicted in Figure 4-7. A change in wind direction was forecasted and a consensus decision to adjust the monitoring locations was made on November 7. Monitors #6 and #8 were moved on November 8 and monitors #2 and #3 were moved on November 9, to account for changes in forecasted winds. The overall effect was to move more monitors to the Southwest quadrant of the well pad. The locations after these moves are those depicted in Figure 4-8. The changes in locations are summarized in Table 4-5. The Well Pad and various monitoring locations are shown in the photographs included as Figures 4-9 through 4-11.

Table 4-4. Well Pad No. 2 Ambient NO_2/NO_x Original Monitoring Site Coordinates

Site Number	Analyzer Model	Analyzer Serial No.	Latitude	Longitude
1	TECO 42 C	328102424	N 40° 12.248	W 104° 43.621
2	TECO 42 C	3.232E+13	N 40° 12.302	W 104° 43.599
3	TECO 42 C	431009027	N 40° 12.281	W 104° 43.597
4	TECO 42 C	419106881	N 40° 12.266	W 104° 43.602
5	TECO 42 C	601614921	N 40° 12.250	W 104° 43.601
6	TECO 42 C	602015011	N 40° 12.248	W 104° 43.640
7	TECO 42 C	42C-77980-387	N 40° 12.268	W 104° 43.716
8	TECO 42 C	42C-69756-364	N 40° 12.249	W 104° 43.660
9	TECO 42 C	436610044	N 40° 12.280	W 104° 43.718
10	API 200E	480	N 40° 12.250	W 104° 43.678
11	API 200E	481	N 40° 12.255	W 104° 43.706
12	TECO 42 C	512211360	N 40° 12.300	W 104° 43.715

Table 4-5. Well Pad No. 2 Ambient NO_2/NO_x Final Monitoring Site Coordinates

Site Number	Analyzer Model	Analyzer Serial No.	Latitude	Longitude
1	TECO 42 C	328102424	N 40° 12.248	W 104° 43.621
2	TECO 42 C	3.232E+13	N 40° 12.265	W 104° 43.711
3	TECO 42 C	431009027	N 40° 12.256	W 104° 43.692
4	TECO 42 C	419106881	N 40° 12.266	W 104° 43.602
5	TECO 42 C	601614921	N 40° 12.250	W 104° 43.601
6	TECO 42 C	602015011	N 40° 12.310	W 104° 43.711
7	TECO 42 C	42C-77980-387	N 40° 12.268	W 104° 43.716
8	TECO 42 C	42C-69756-364	N 40° 12.297	W 104° 43.716
9	TECO 42 C	436610044	N 40° 12.280	W 104° 43.718
10	API 200E	480	N 40° 12.250	W 104° 43.678
11	API 200E	481	N 40° 12.255	W 104° 43.706
12	TECO 42 C	512211360	N 40° 12.300	W 104° 43.715

Figure 4-7. Southeast Corner of the 2nd Well Pad

Figure 4-8. South Side of the 2nd Well Pad

Figure 4-9. Trailers No. 1 through No. 6 at the 2nd Well Pad

Figure 4-10. Trailers No. 7 through No. 10 at the 2nd Well Pad

Figure 4-11. Trailer No. 7 at the 2nd Well Pad

5.0 ADDITIONAL SUPPORTING INFORMATION

Information is given in this section that may help in using the dataset or in understanding and interpreting the measurement results. Three topics are presented below: the weather conditions during the field study, quality control checks, and time-series plots.

5.1 Weather Conditions during the Field Study

The ambient temperatures versus time for Well Pad No. 1 are shown in Figure 5-1. The data showed the expected diurnal pattern and the daily high and low temperatures were relatively consistent throughout the test period. Wind directions as a function of time for Well Pad No. 1 are shown in Figure 5-2 and the wind rose for the test period (i.e., October 10 – 26) is shown in Figure 5-3. The predominant winds were from the Southwest (SW) with wind speeds mostly under 11 mph.

The ambient temperatures versus time for Well Pad No. 2 are shown in Figure 5-4. The data showed the expected diurnal pattern till midway through the test period when temperatures dropped well below freezing. Wind directions as a function of time for Well Pad No. 2 are shown in Figure 5-5 and the wind rose for the test period (i.e., November 3 – 16) is shown in Figure 5-6. The predominant winds were from the Southwest (SW) and the Northeast (NE). The highest wind speeds were associated with the NE winds.

5.2 Quality Control Checks

The effect of the cold temperatures encountered during the field program was evaluated. The shelter temperature for some monitors was controlled within recommended specifications, while the shelter temperature was below the recommended range for other monitors. It was found that the shelter temperature did not have an appreciable effect on the measured values. Two data plots are shown to illustrate this finding and these plots are representative of similar data plots generated for other pairs of monitors. In Figure 5-7, the NO_2 data for monitoring locations #1 and #2 are shown to closely track one other even though the temperature at location #1 (green line) showed large diurnal fluctuations whereas the temperature at location #2 (purple line) was much more constant. Figure 5-8 is a scatter plot showing the good agreement of two monitors #4 and #5) even though one was in temperature control and one was out.

Precision and bias were calculated for the monitors at each monitoring location and found to have minimal imprecision and bias. The results are summarized in Table 5-1.

5.3 Time-Series Plots

A plot of NO_2, NO_x and wind direction for each monitoring location at each well pad was generated to provide a quick, visual representation of the dataset. The data plots for Well Pad No. 1 are given in Figures 5-9 through 5-20. The data plots for Well Pad No. 2 are given in Figures 5-21 through 5-32.

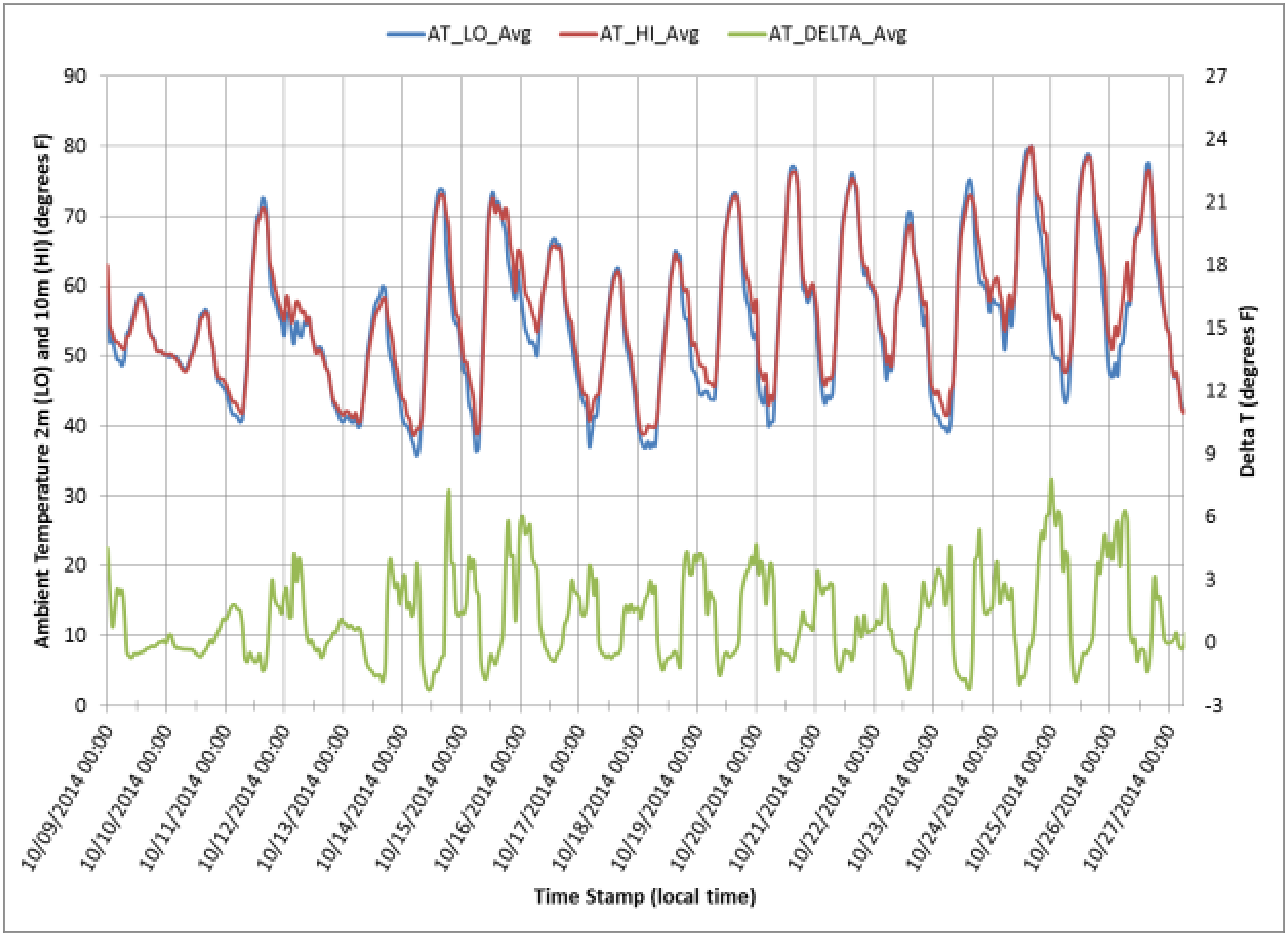

Figure 5-1. Ambient Temperature vs. Time – Well Pad No. 1

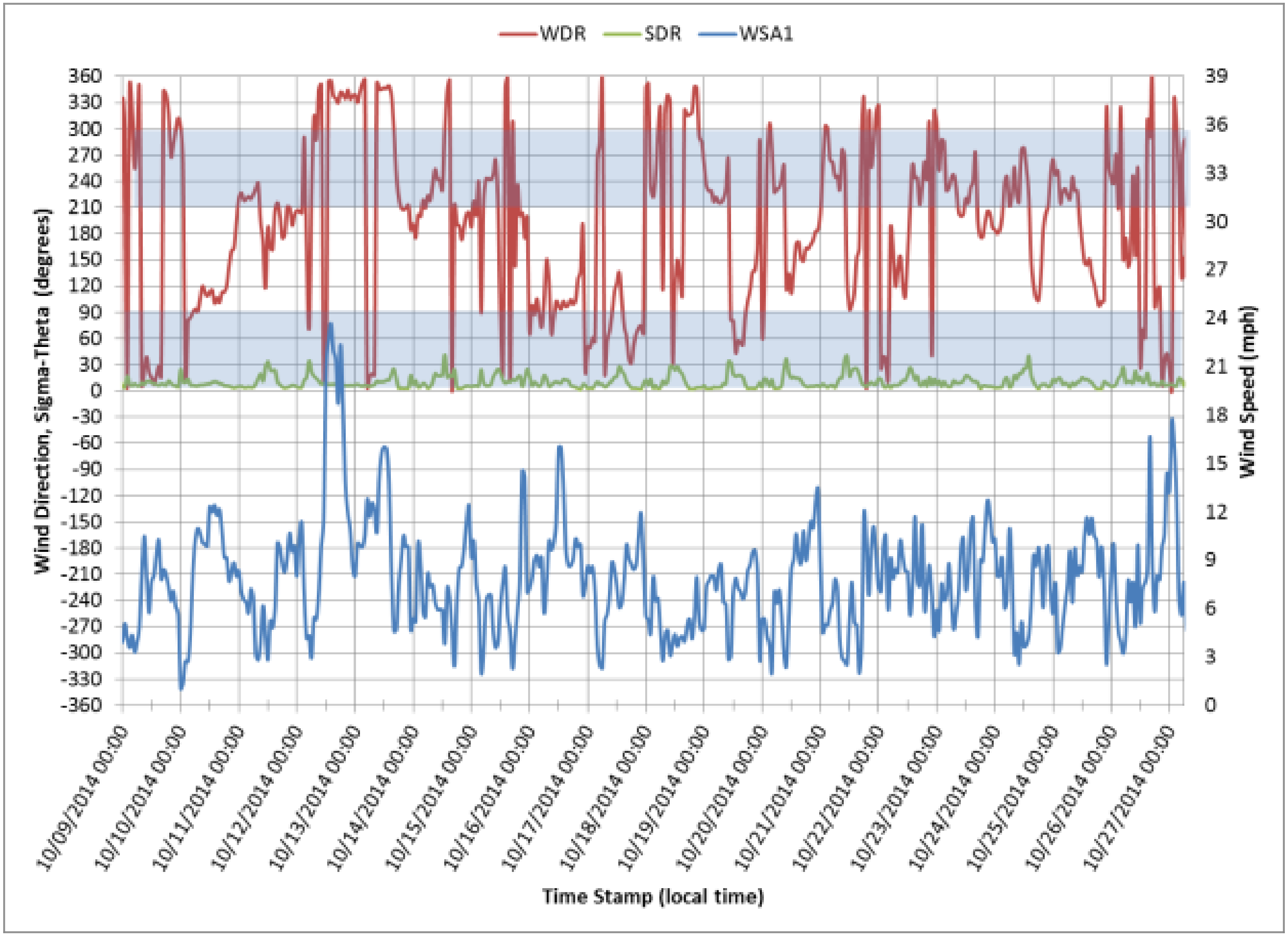

Figure 5-2. Wind Direction vs. Time – Well Pad No. 1

AECOM

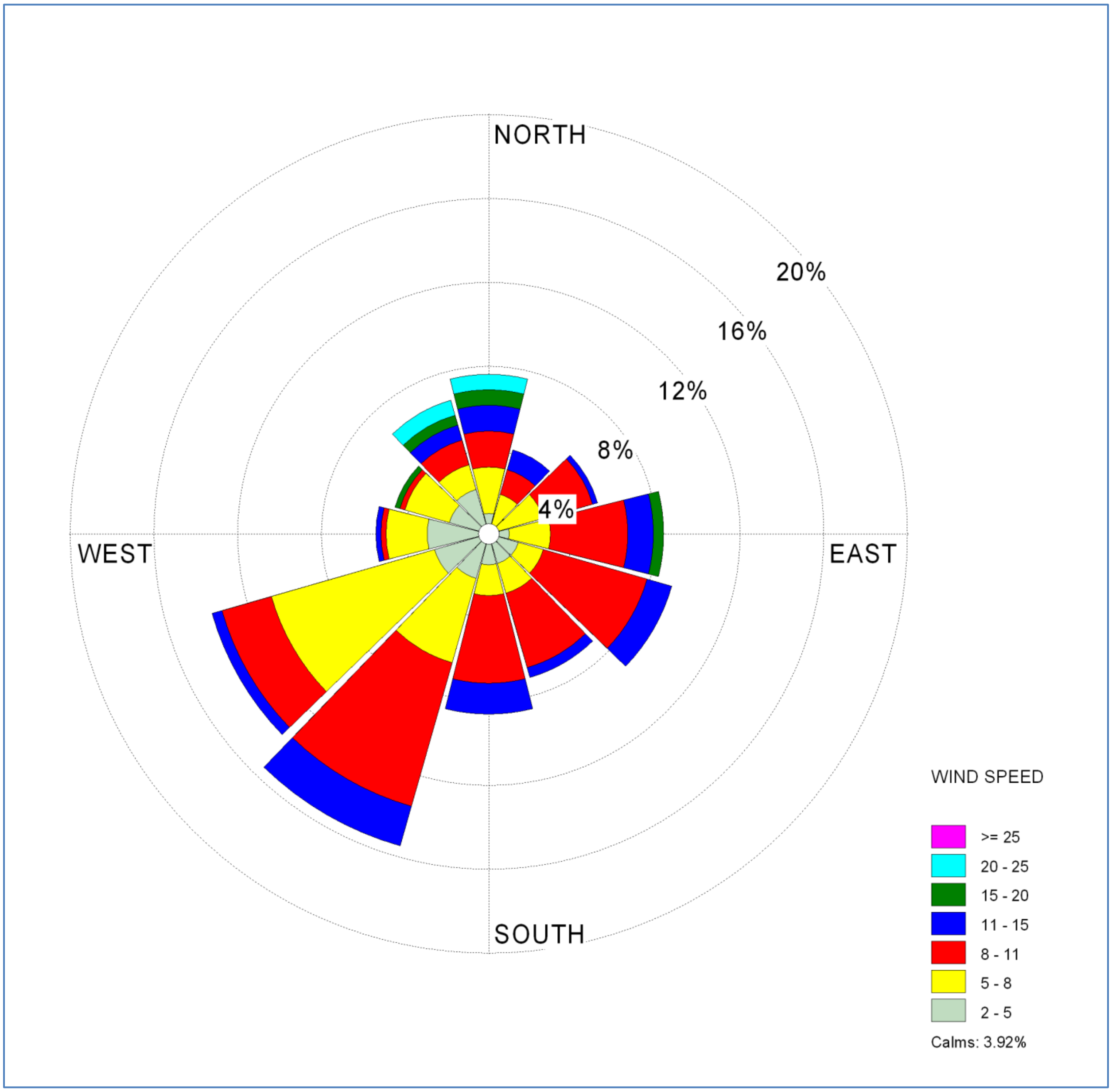

Figure 5-3. Wind Rose (mph) – Well Pad No. 1 (Oct 10 – 26)

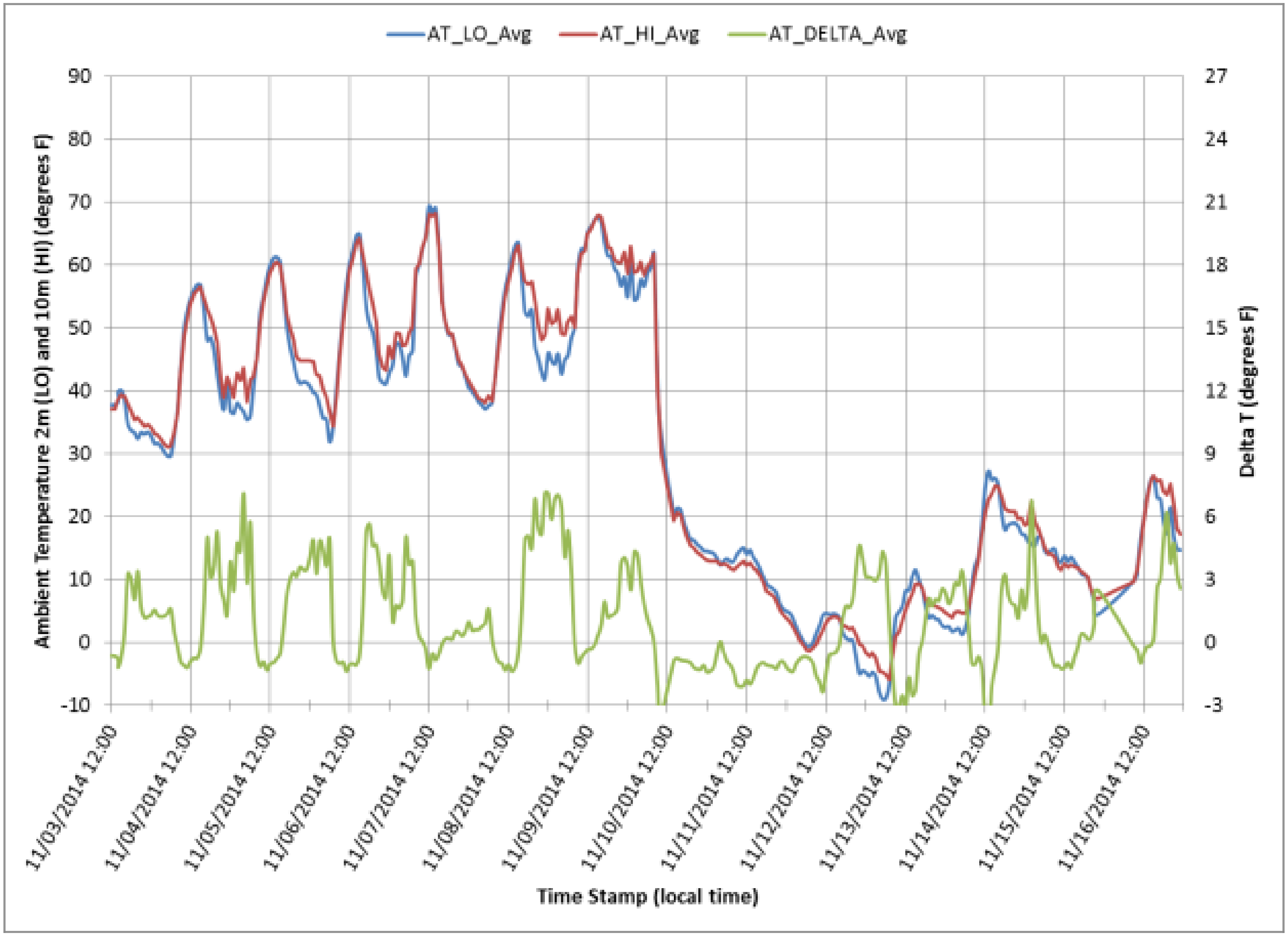

Figure 5-4. Ambient Temperature vs. Time – Well Pad No. 2

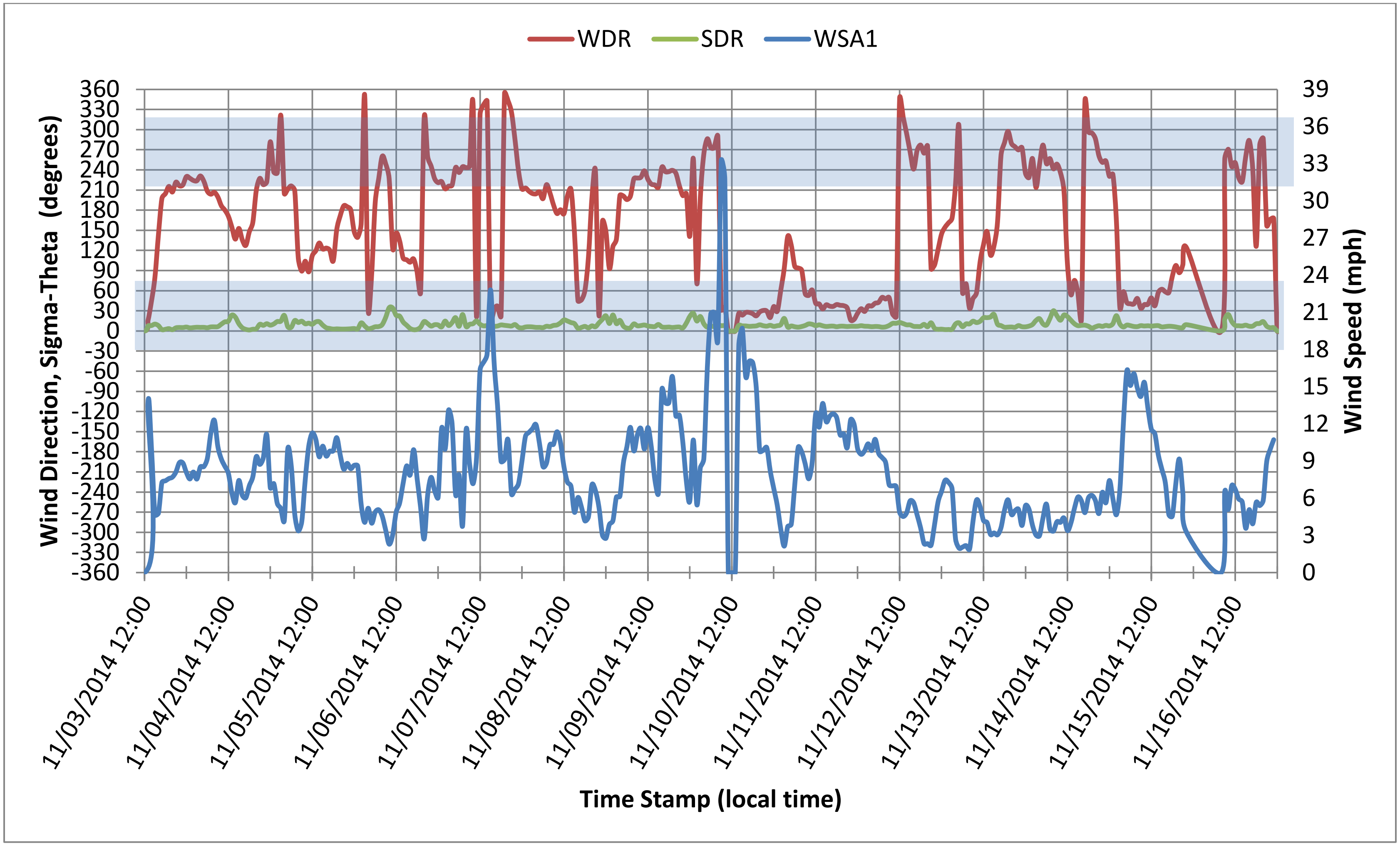

Figure 5-5. Wind Direction vs. Time – Well Pad No. 2

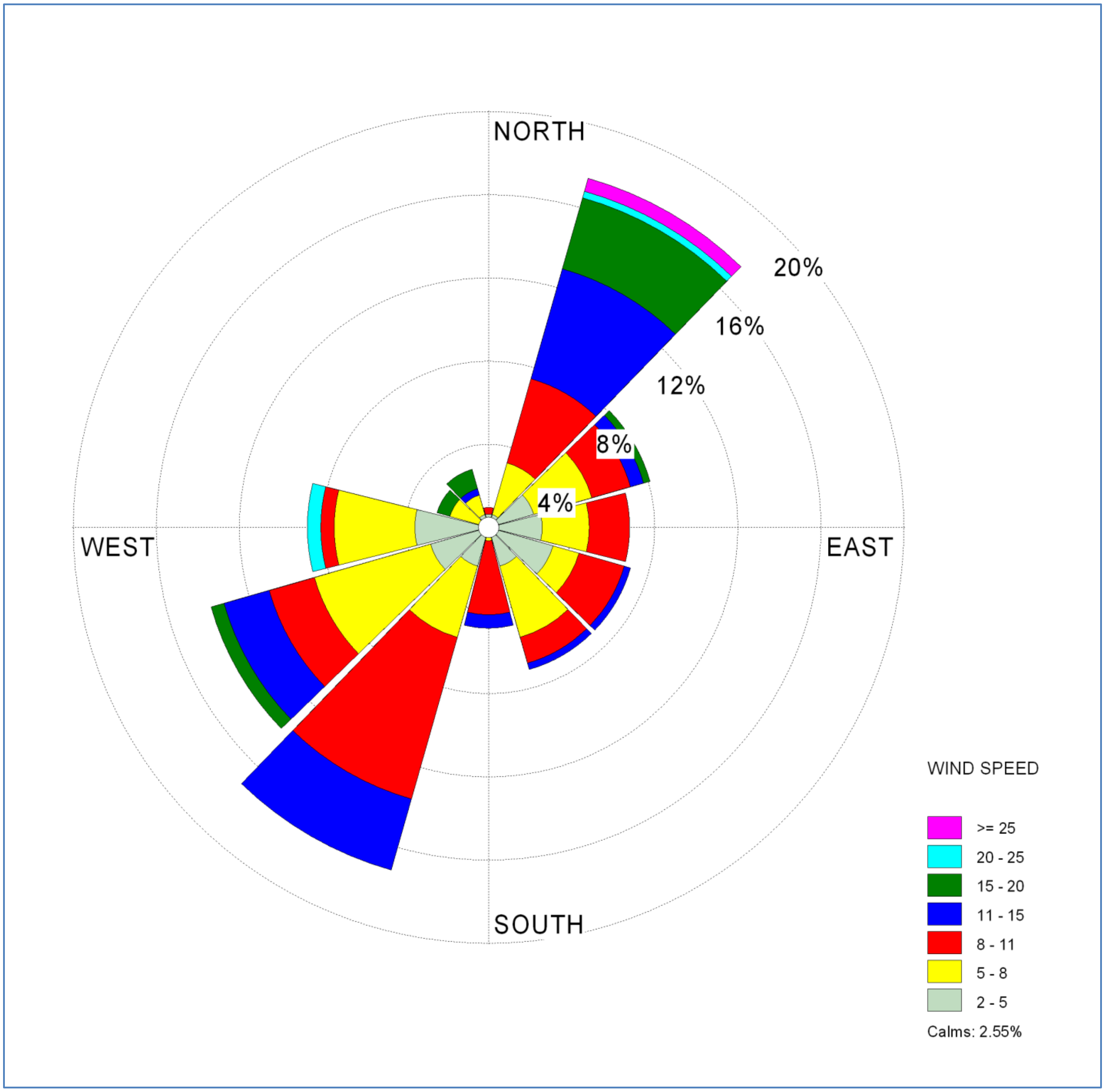

Figure 5-6. Wind Rose (mph) – Well Pad No. 2 (Nov 3 – 16)

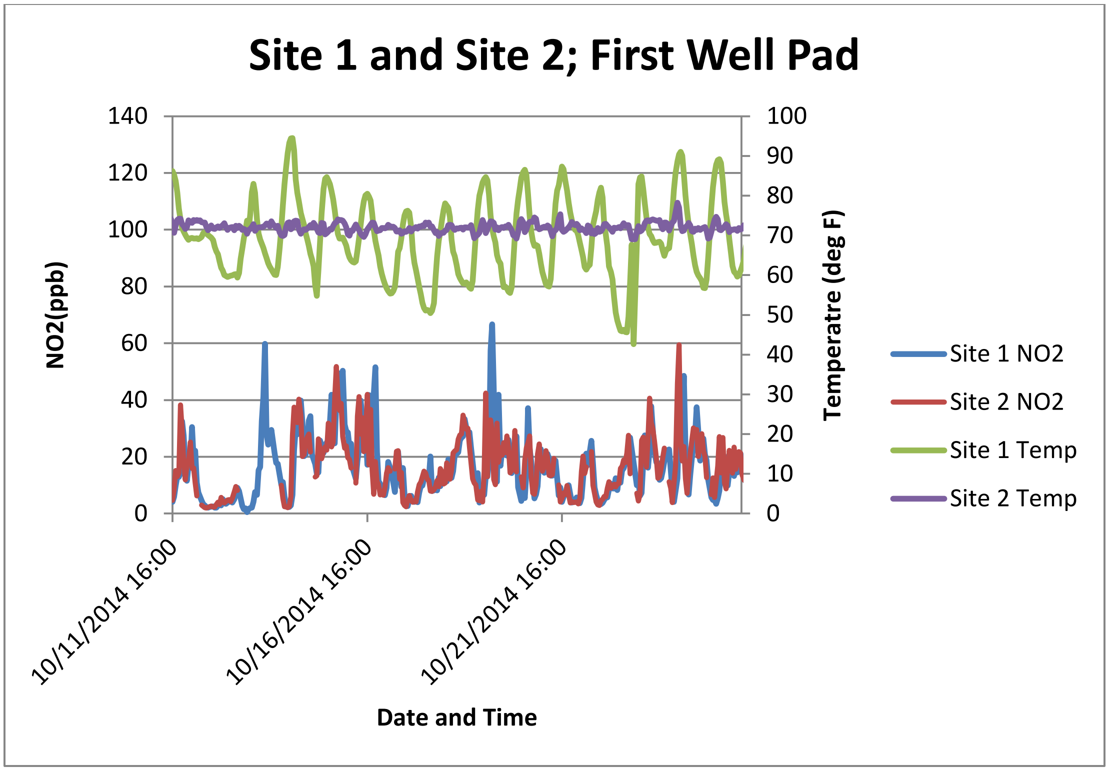

Figure 5-7. NO_2 Data and Shelter Temperatures

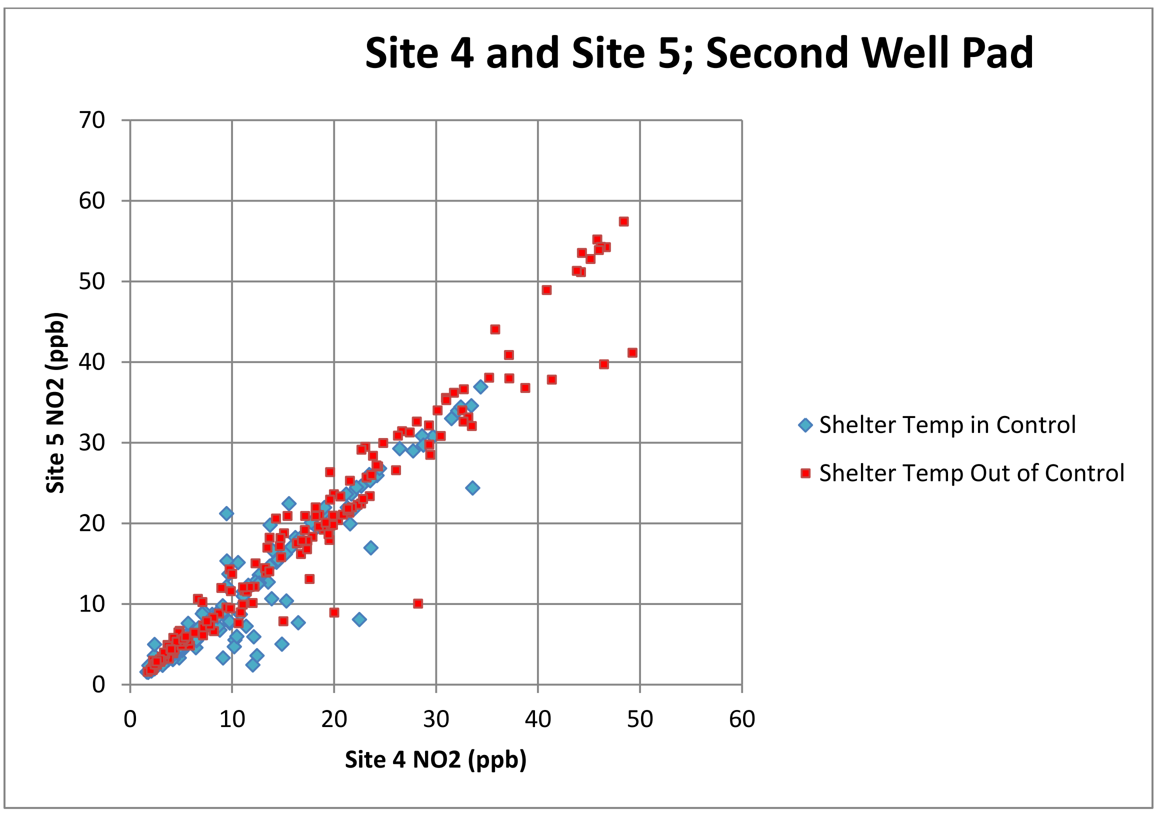

Figure 5-8. Correlation of NO_2 Data

Table 5-1. Precision and Bias Statistics

Site Number	Parameter	Bias (%)	Precision (%)
1	O3 Data	4.16	3.16
	NO Data	4.21	4.51
	NOx Data	4.18	4.73
2	NO Data	4.38	4.44
	NOx Data	3.90	4.26
3	NO Data	4.78	5.82
	NOx Data	4.46	5.36
4	NO Data	3.13	2.73
	NOx Data	3.04	2.84
5	NO Data	3.11	3.51
	NOx Data	4.13	4.35
6	NO Data	2.76	2.02
	NOx Data	2.76	2.02
7	NO Data	2.99	2.72
	NOx Data	2.88	3.13
8	NO Data	4.80	1.94
	NOx Data	4.80	2.16
9	NO Data	4.10	2.18
	NOx Data	4.39	1.73
10	NO Data	4.47	4.45
	NOx Data	5.08	6.57
11	NO Data	4.76	6.06
	NOx Data	4.99	4.45
12	O3 Data	3.11	2.82
	NO Data	1.38	1.71
	NOx Data	1.70	2.21

Notes: Calculations performed using equations given in 40 CFR 58A
All results based on dataset from the 2^{nd} Well Pad

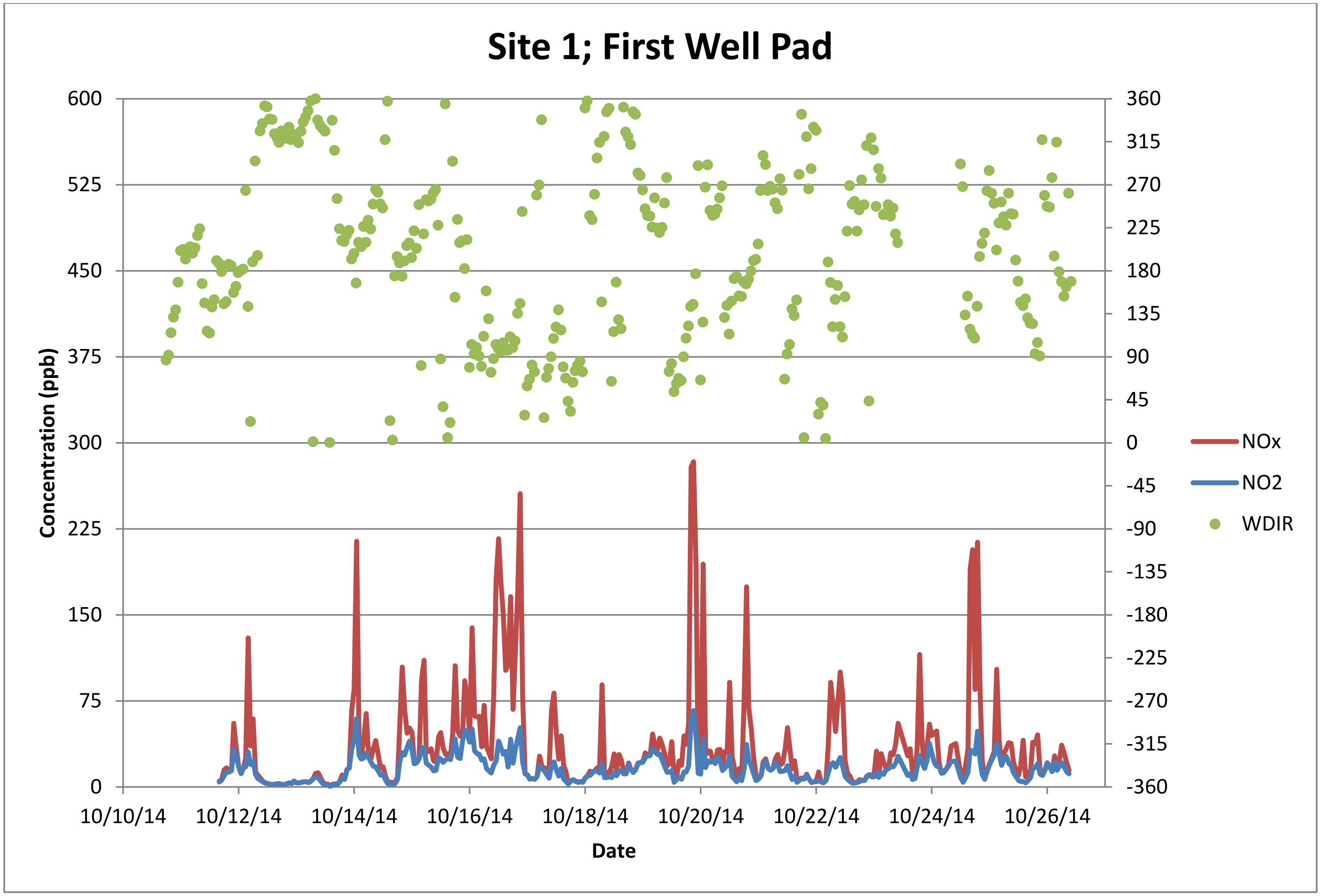

Figure 5-9. Time Series Plot for Well Pad No. 1 – Site #1

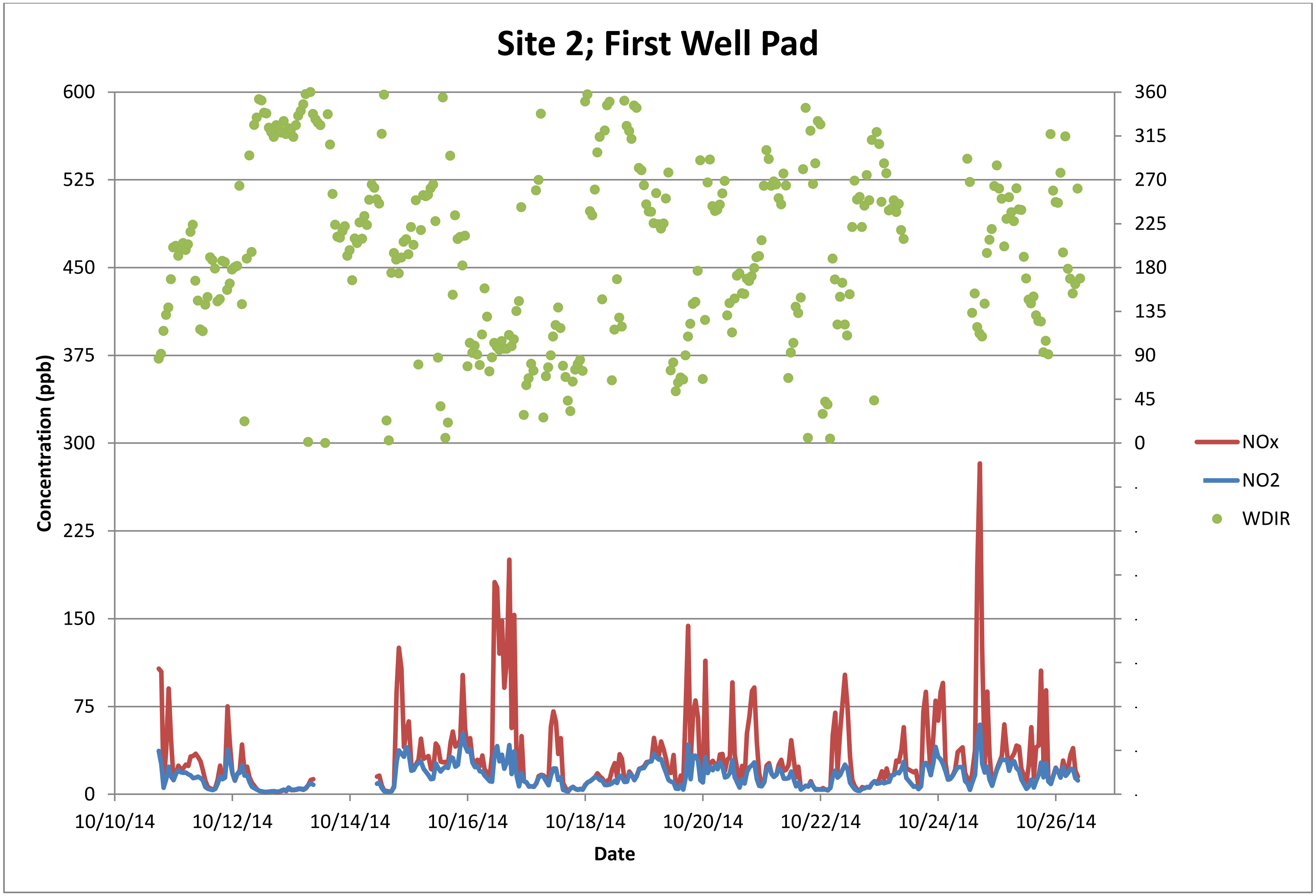

Figure 5-10. Time Series Plot for Well Pad No. 1 – Site #2

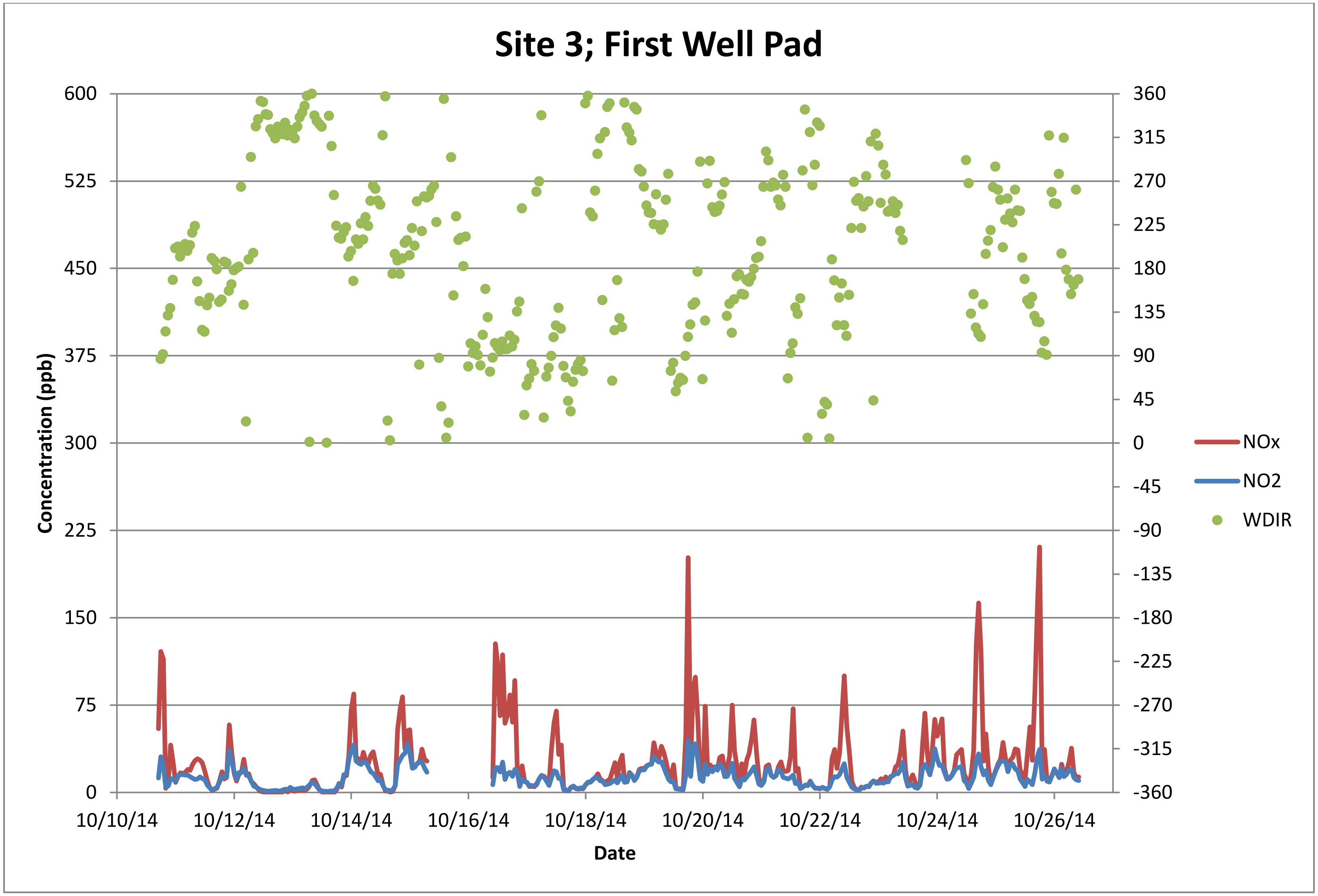

Figure 5-11. Time Series Plot for Well Pad No. 1 – Site #3

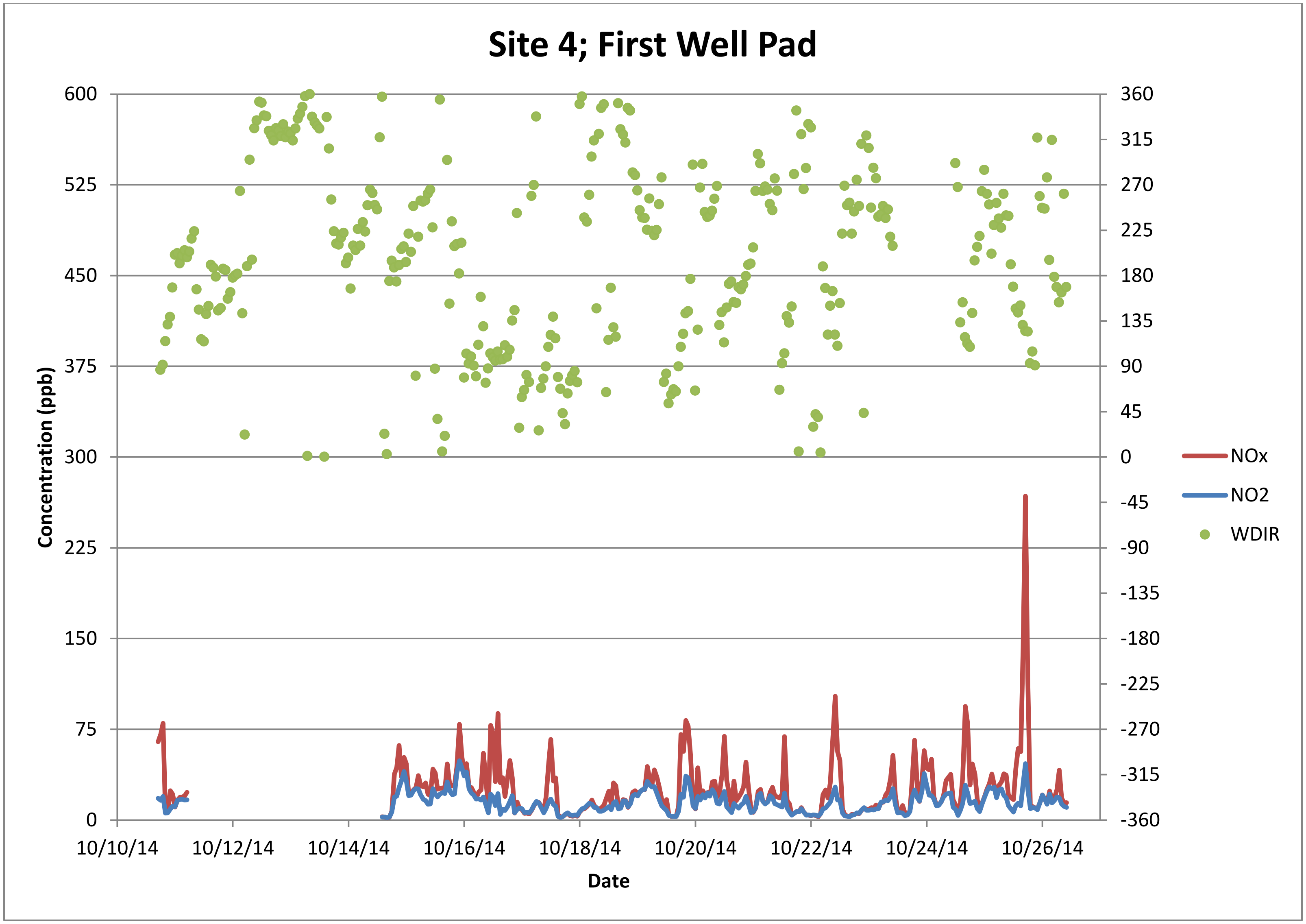

Figure 5-12. Time Series Plot for Well Pad No. 1 – Site #4

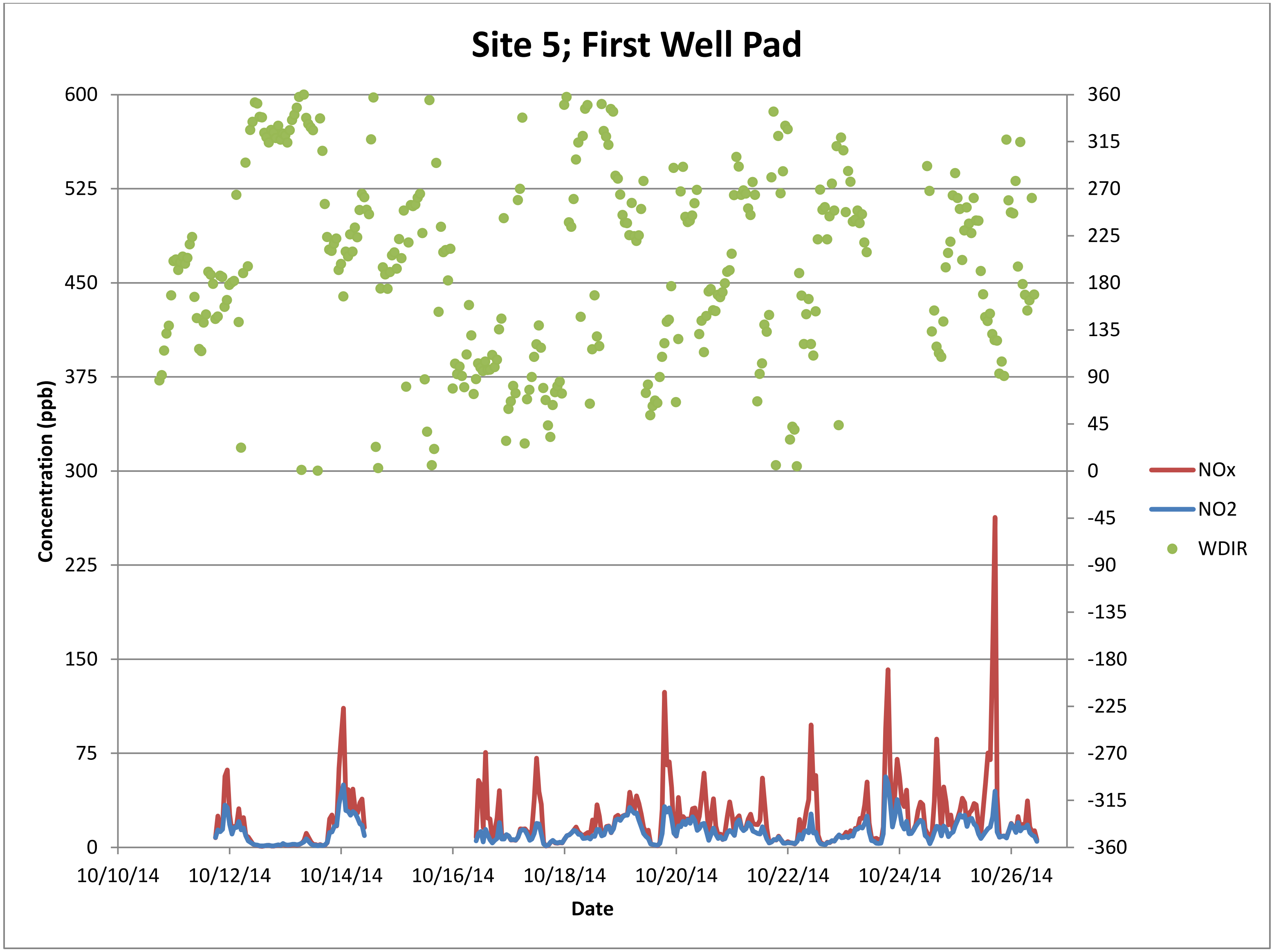

Figure 5-13. Time Series Plot for Well Pad No. 1 – Site #5

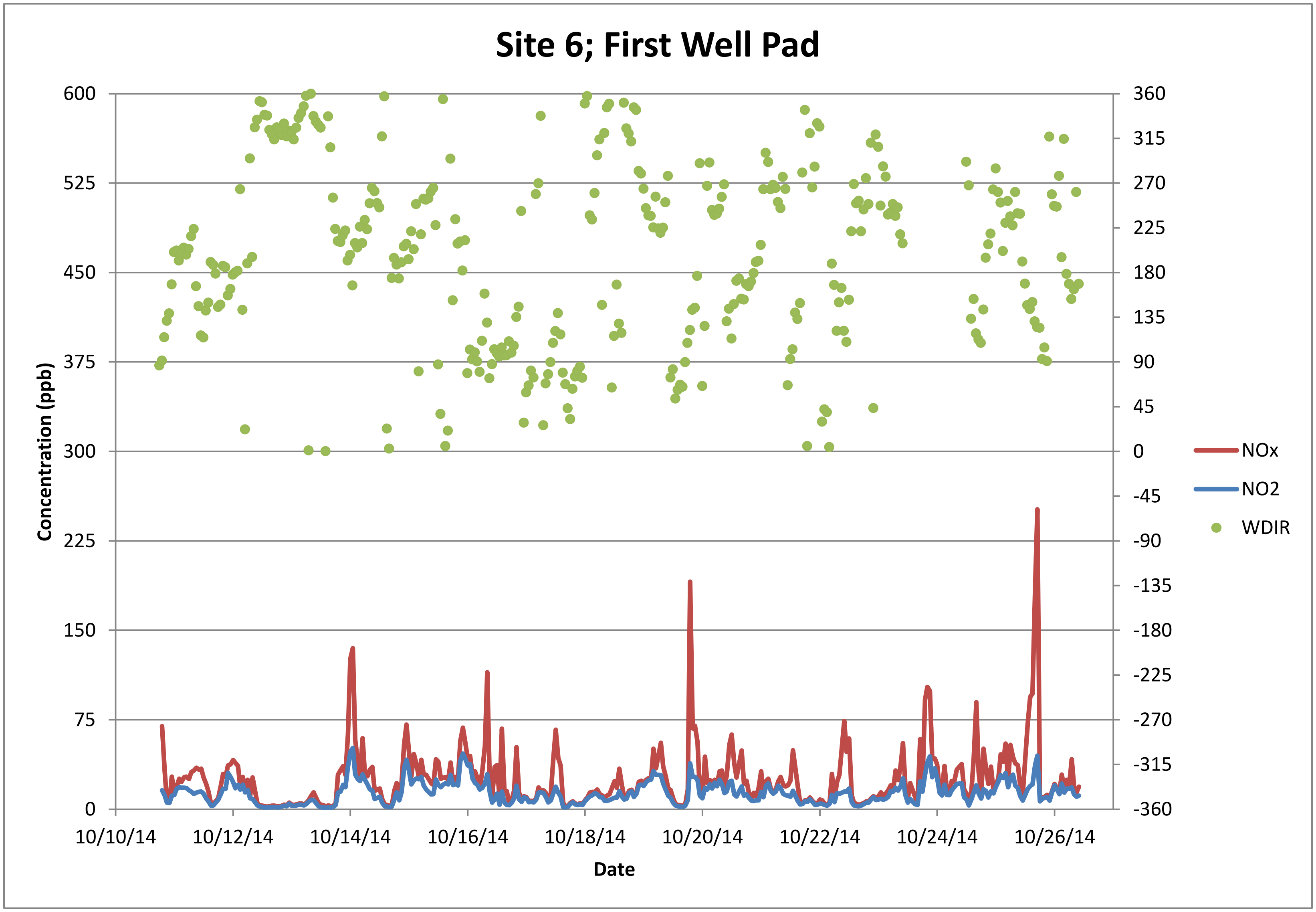

Figure 5-14. Time Series Plot for Well Pad No. 1 – Site #6

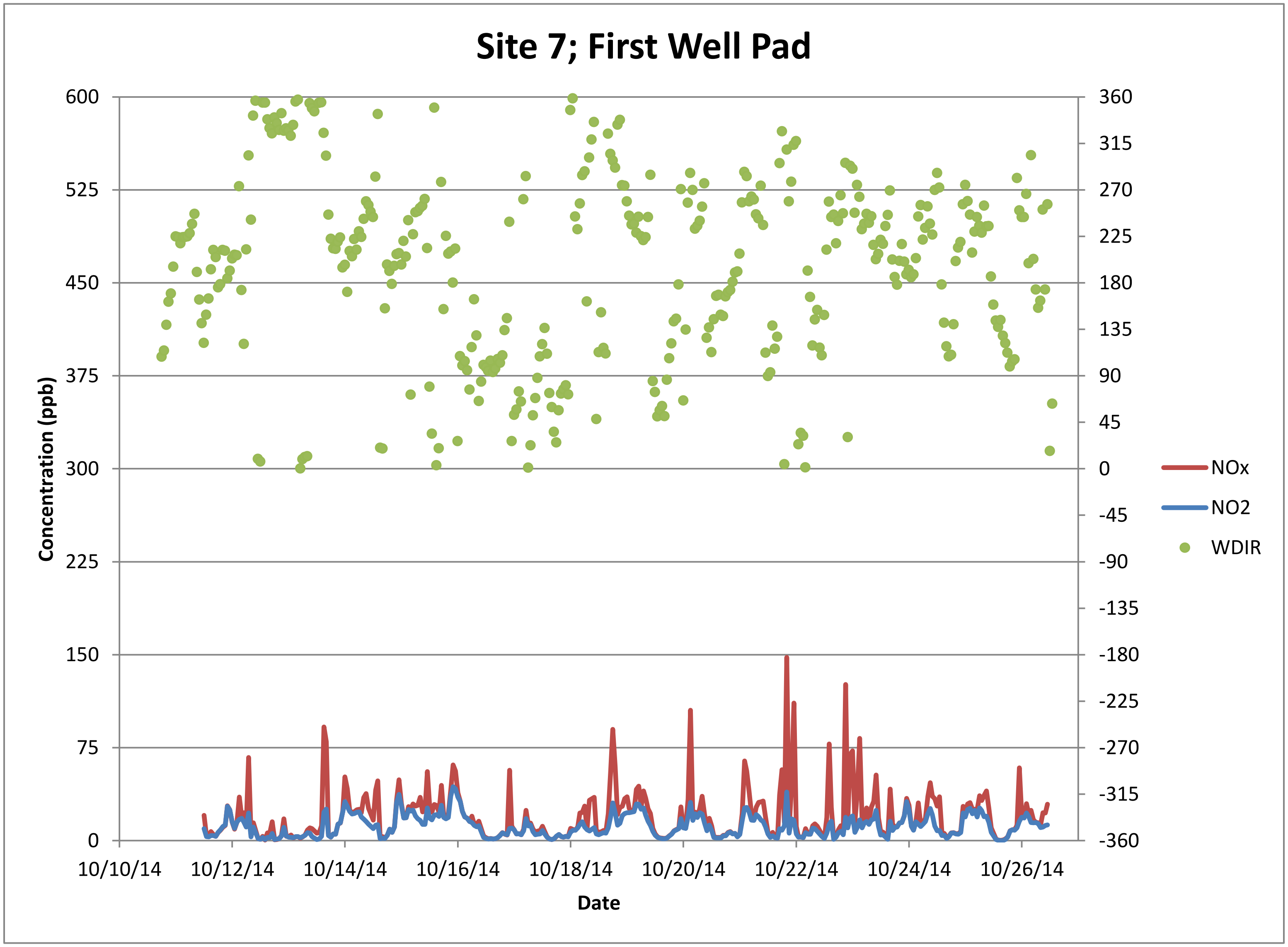

Figure 5-15. Time Series Plot for Well Pad No. 1 – Site #7

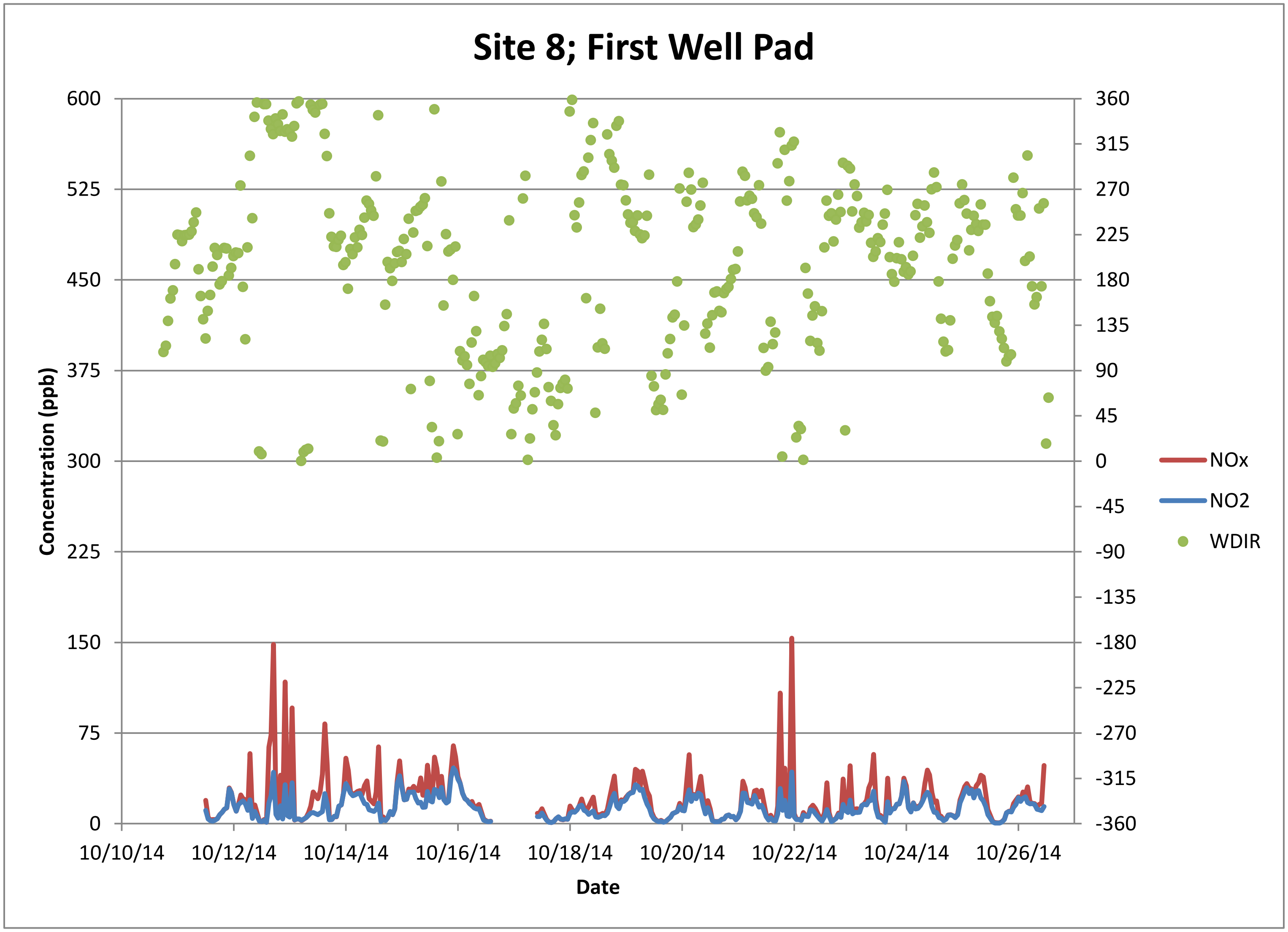

Figure 5-16. Time Series Plot for Well Pad No. 1 – Site #8

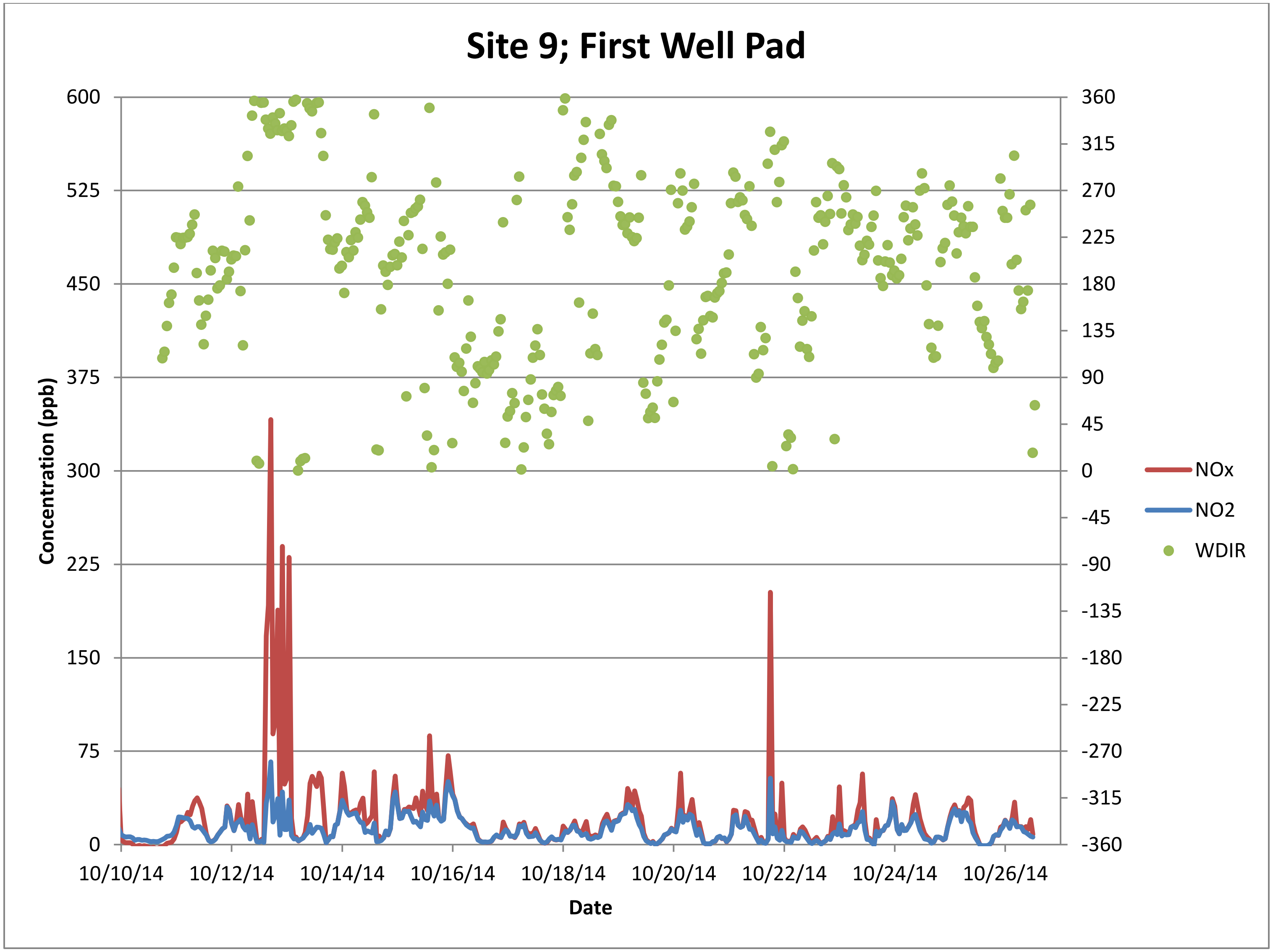

Figure 5-17. Time Series Plot for Well Pad No. 1 – Site #9

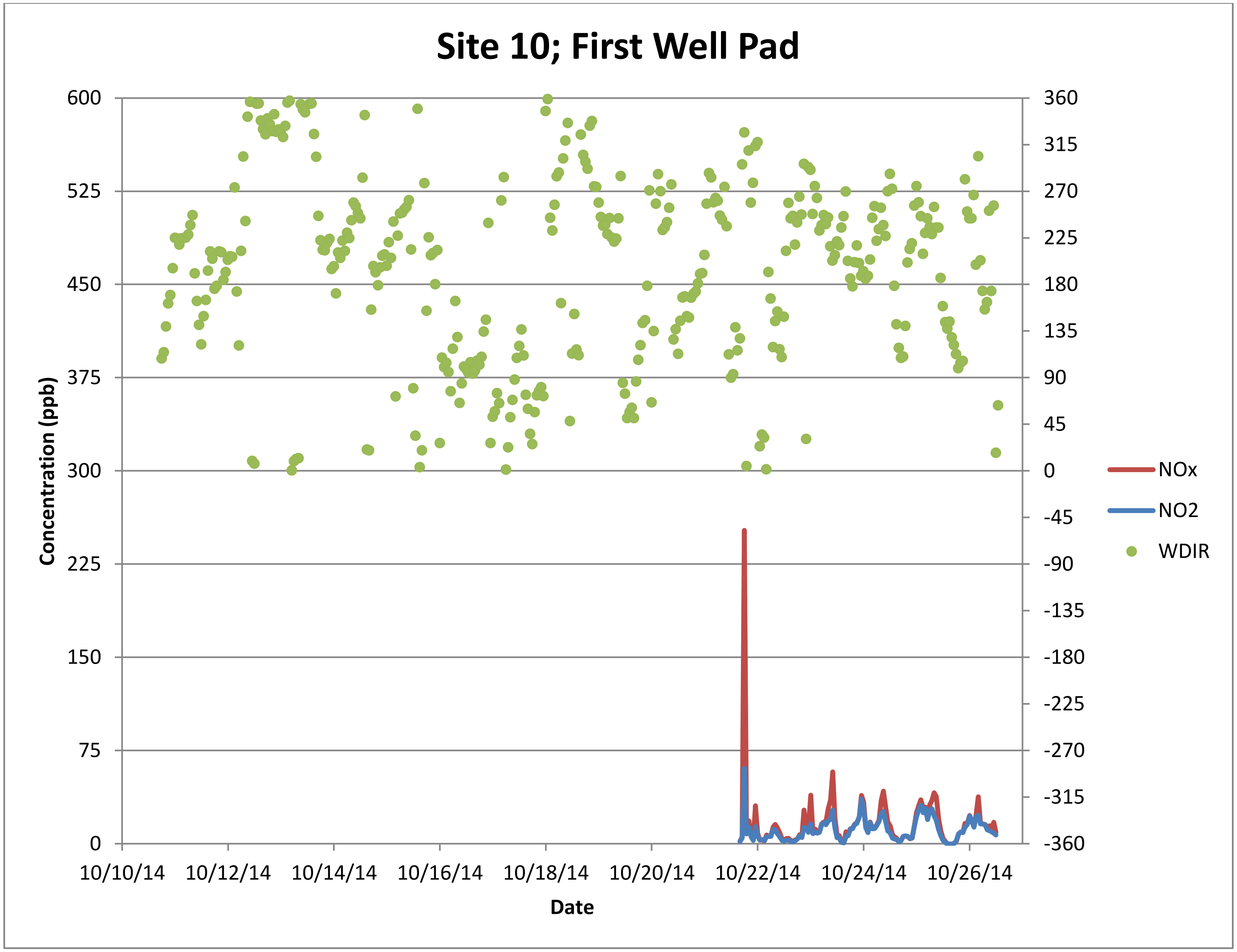

Figure 5-18. Time Series Plot for Well Pad No. 1 – Site #10

AECOM

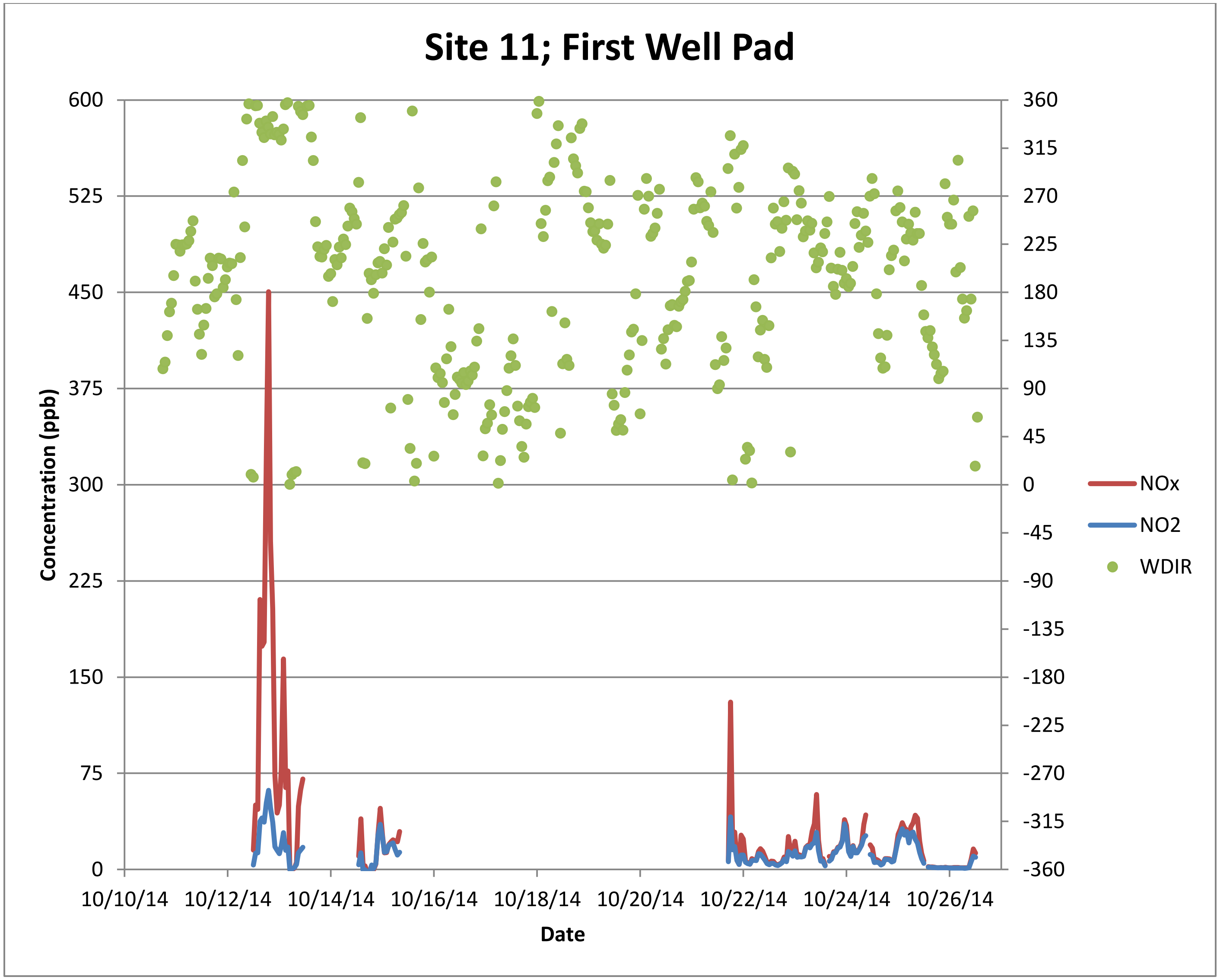

Figure 5-19. Time Series Plot for Well Pad No. 1 – Site #11

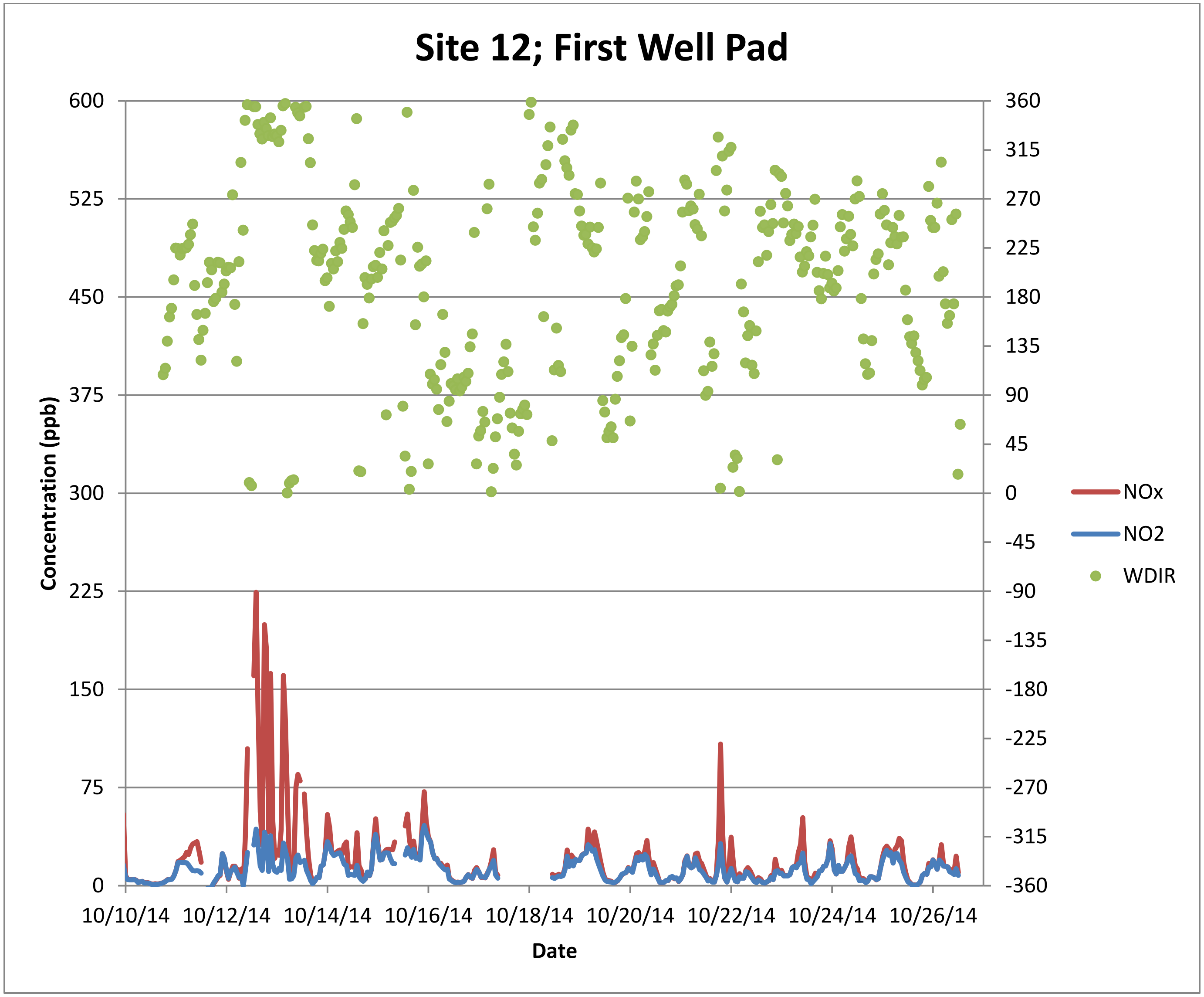

Figure 5-20. Time Series Plot for Well Pad No. 1 – Site #12

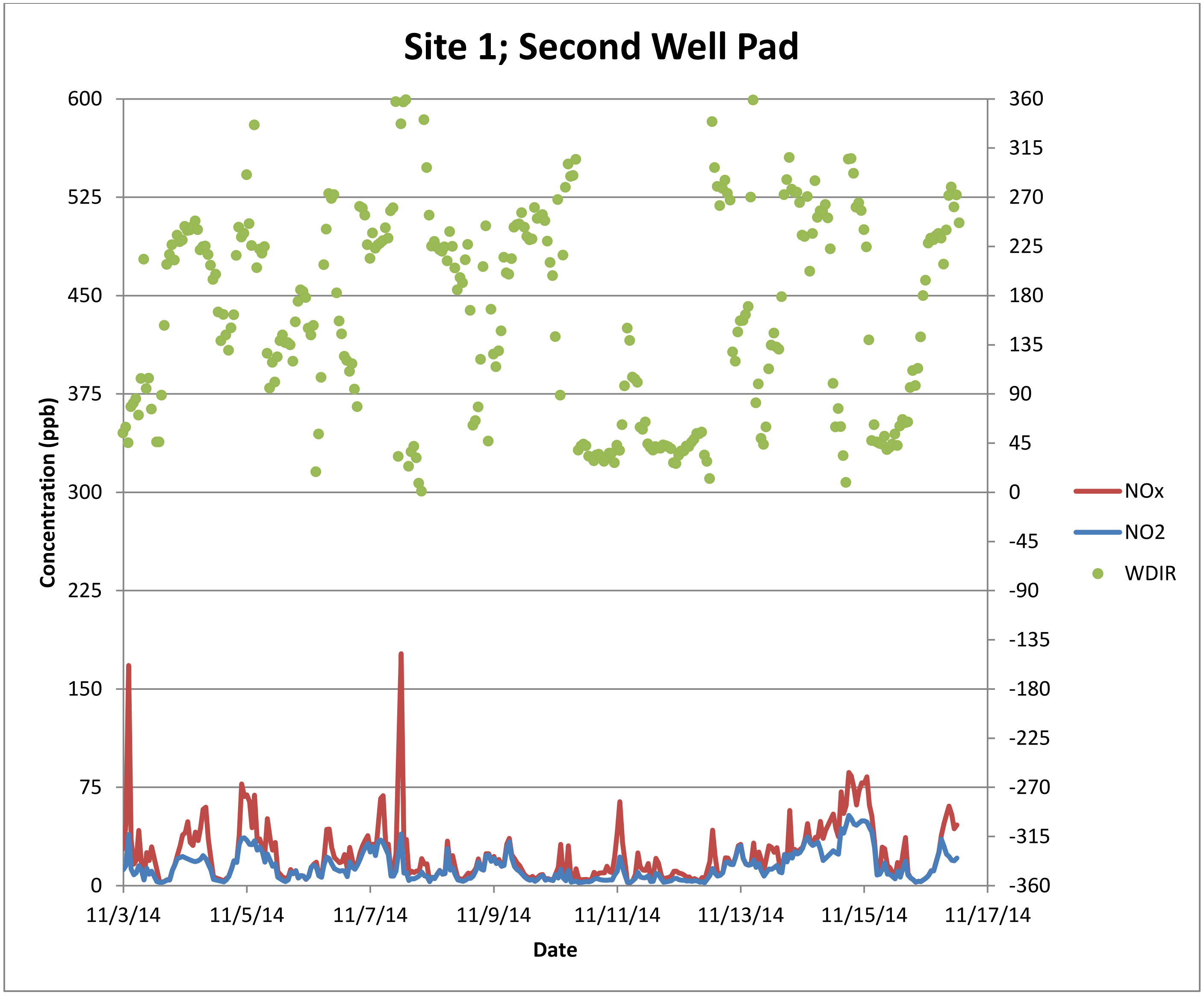

Figure 5-21. Time Series Plot for Well Pad No. 2 – Site #1

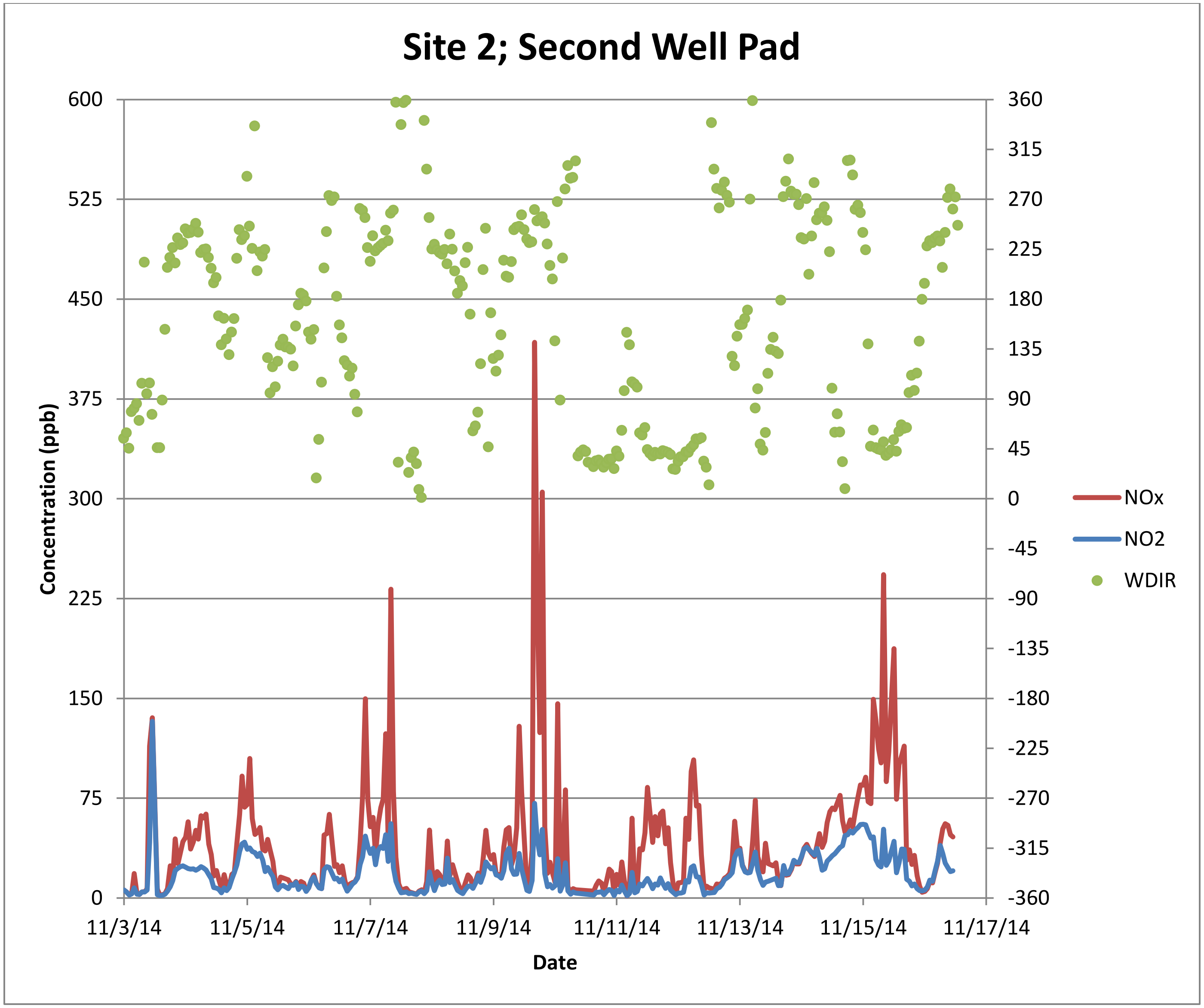

Figure 5-22. Time Series Plot for Well Pad No. 2 – Site #2

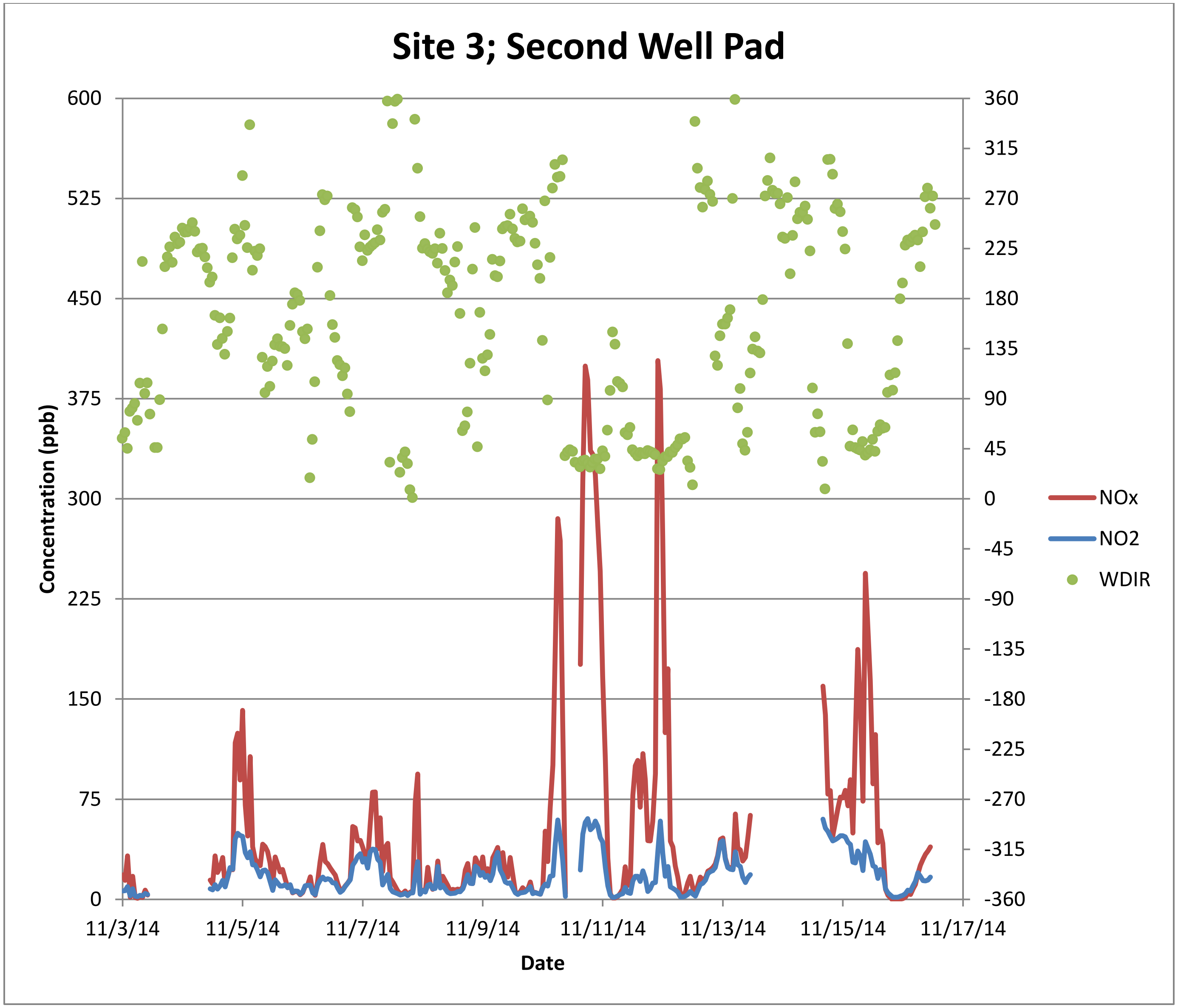

Figure 5-23. Time Series Plot for Well Pad No. 2 – Site #3

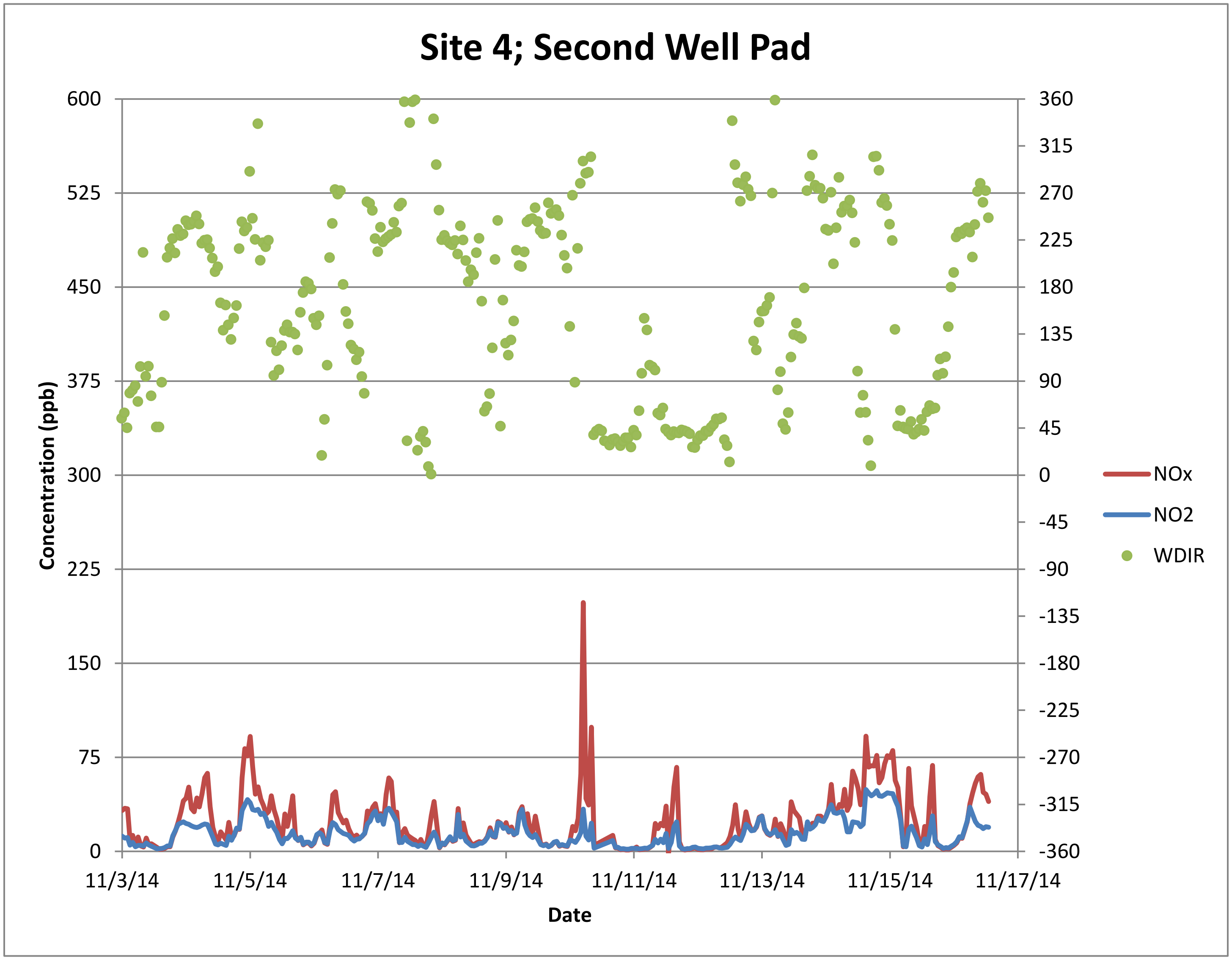

Figure 5-24. Time Series Plot for Well Pad No. 2 – Site #4

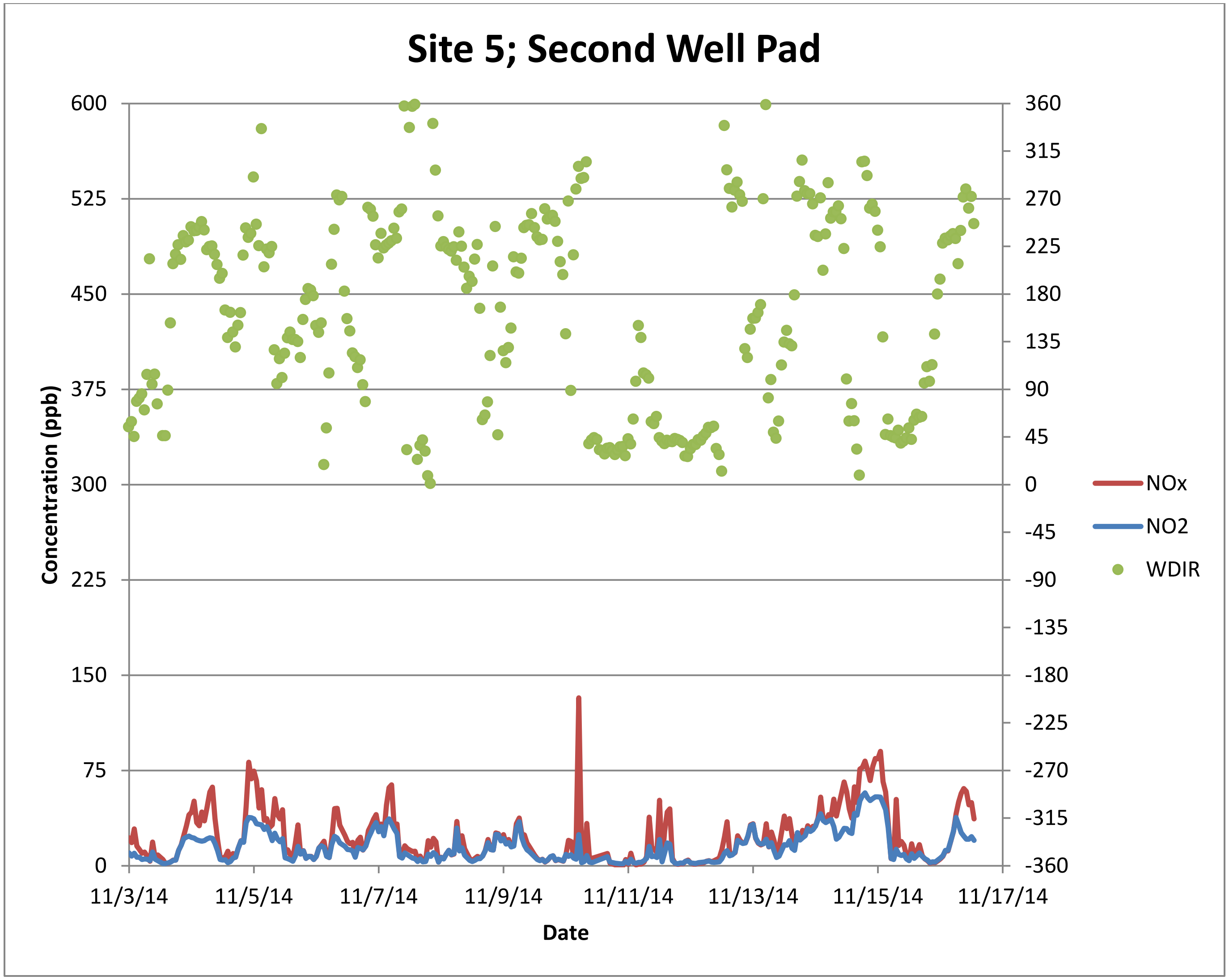

Figure 5-25. Time Series Plot for Well Pad No. 2 – Site #5

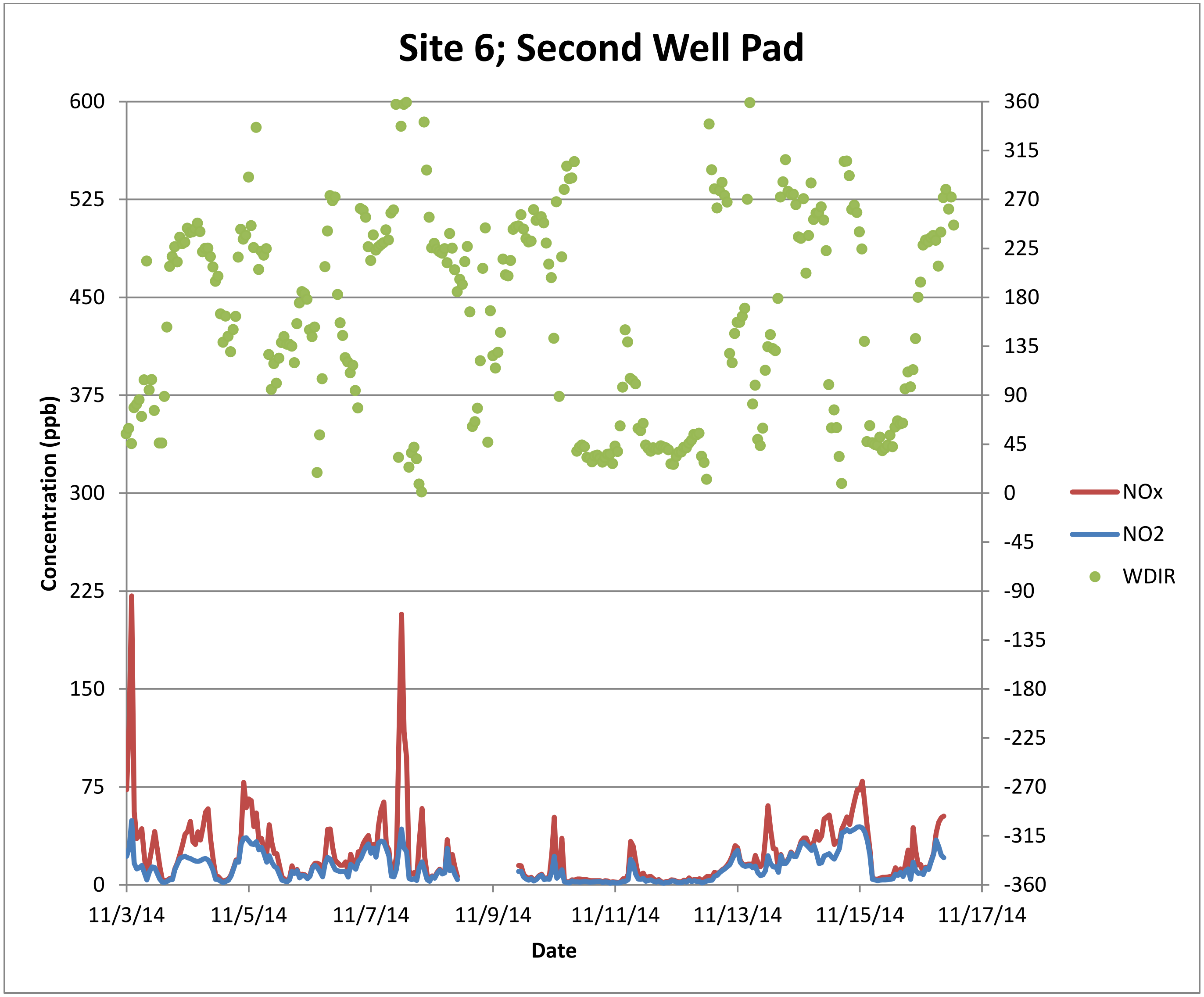

Figure 5-26. Time Series Plot for Well Pad No. 2 – Site #6

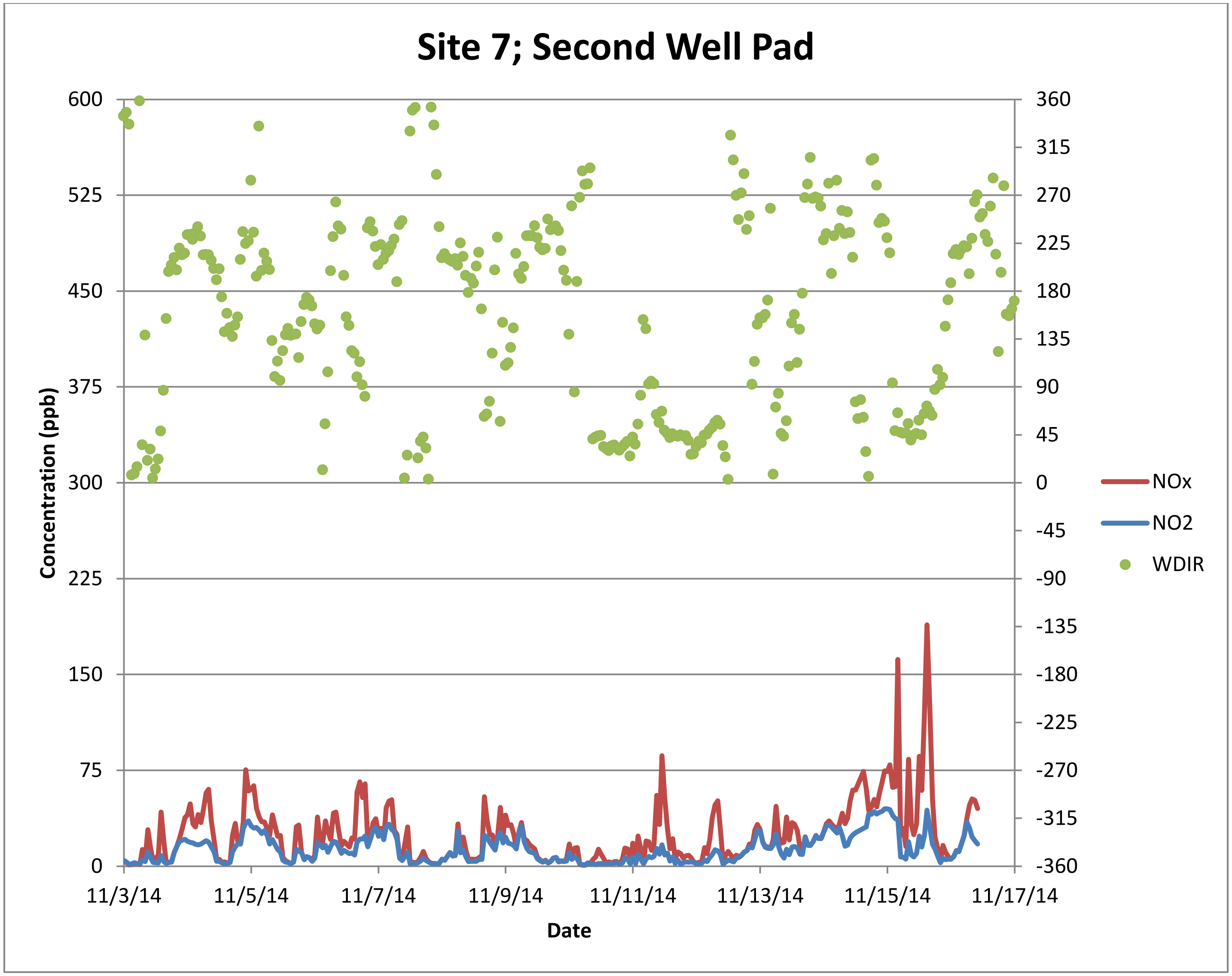

Figure 5-27. Time Series Plot for Well Pad No. 2 – Site #7

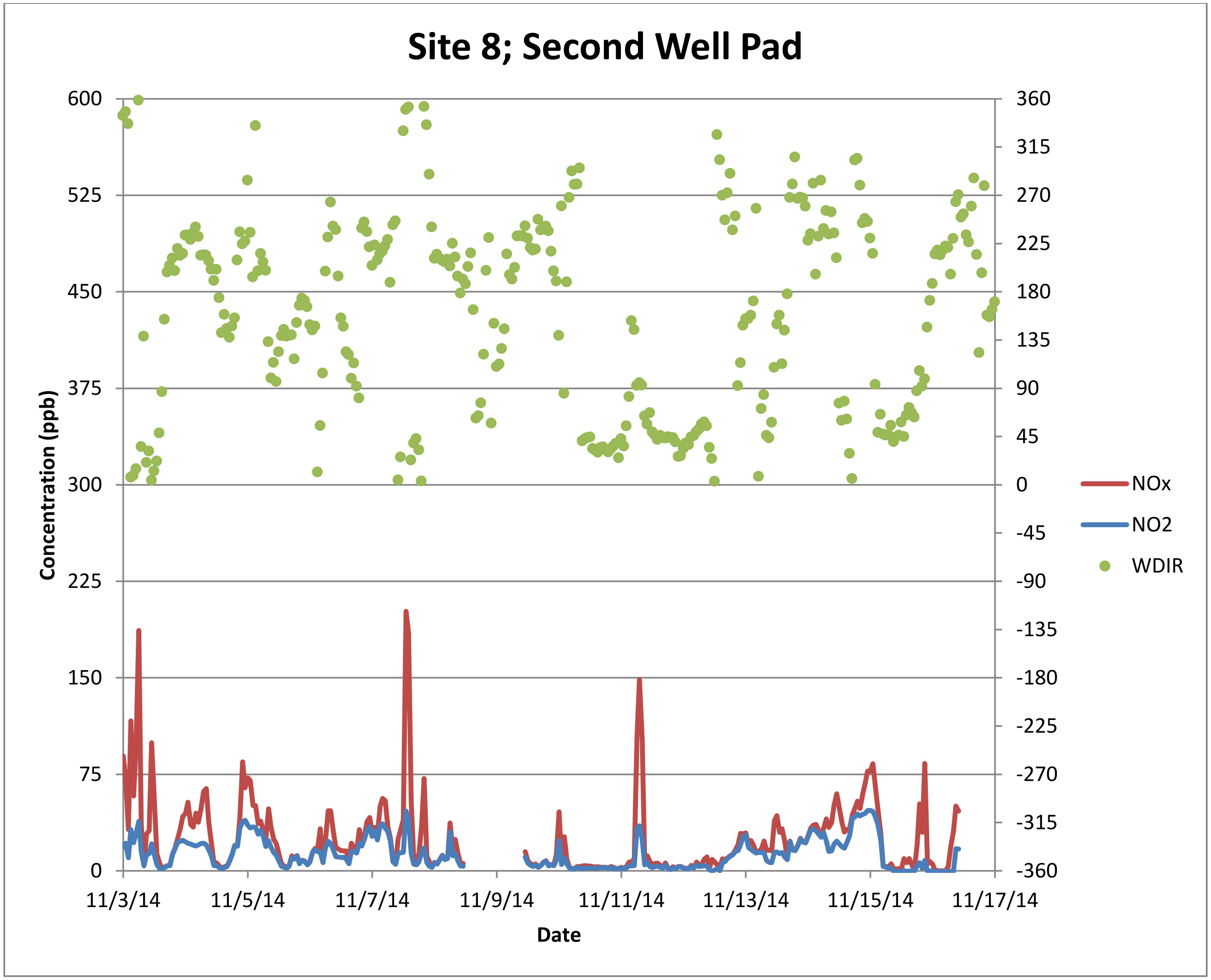

Figure 5-28. Time Series Plot for Well Pad No. 2 – Site #8

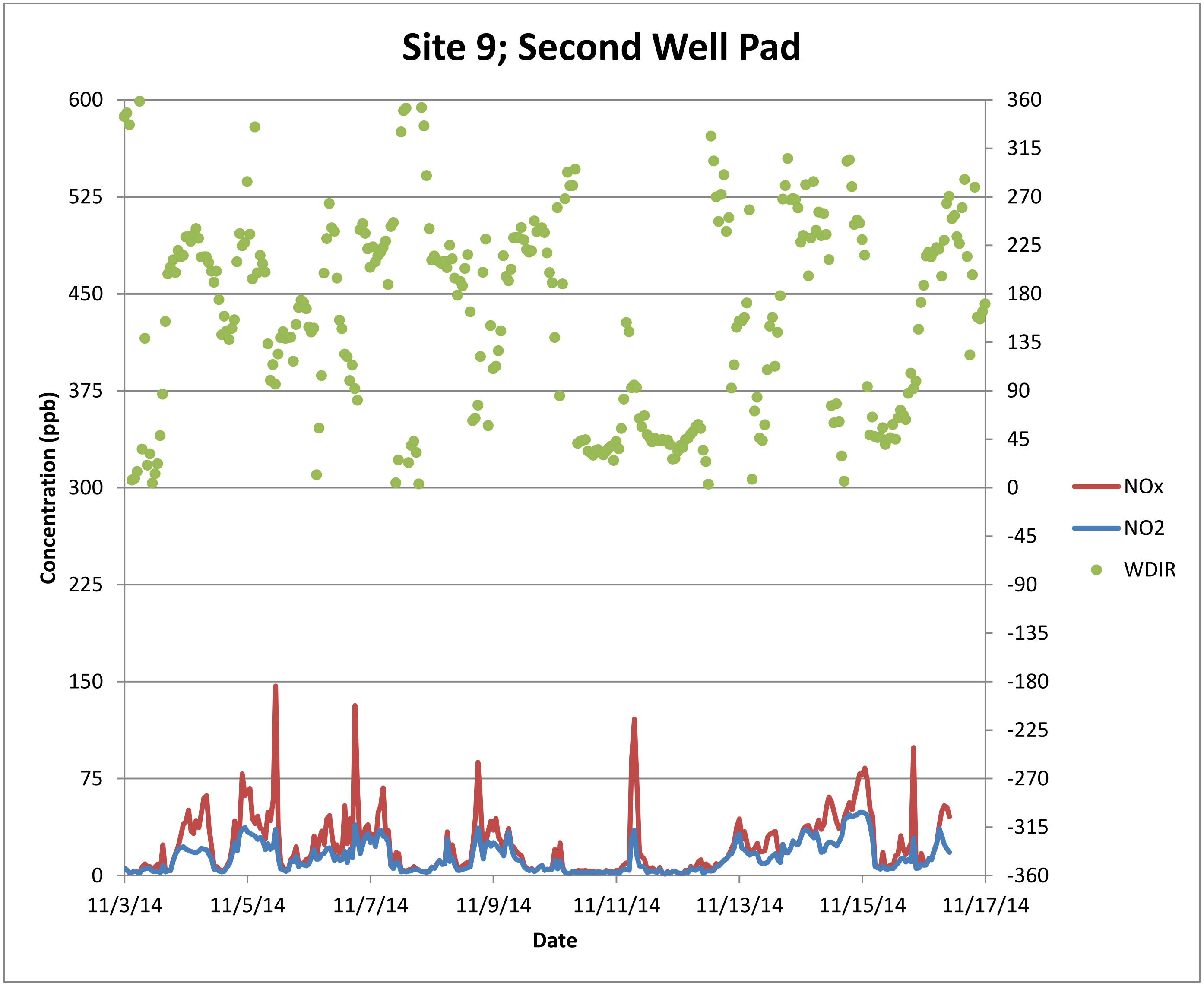

Figure 5-29. Time Series Plot for Well Pad No. 2 – Site #9

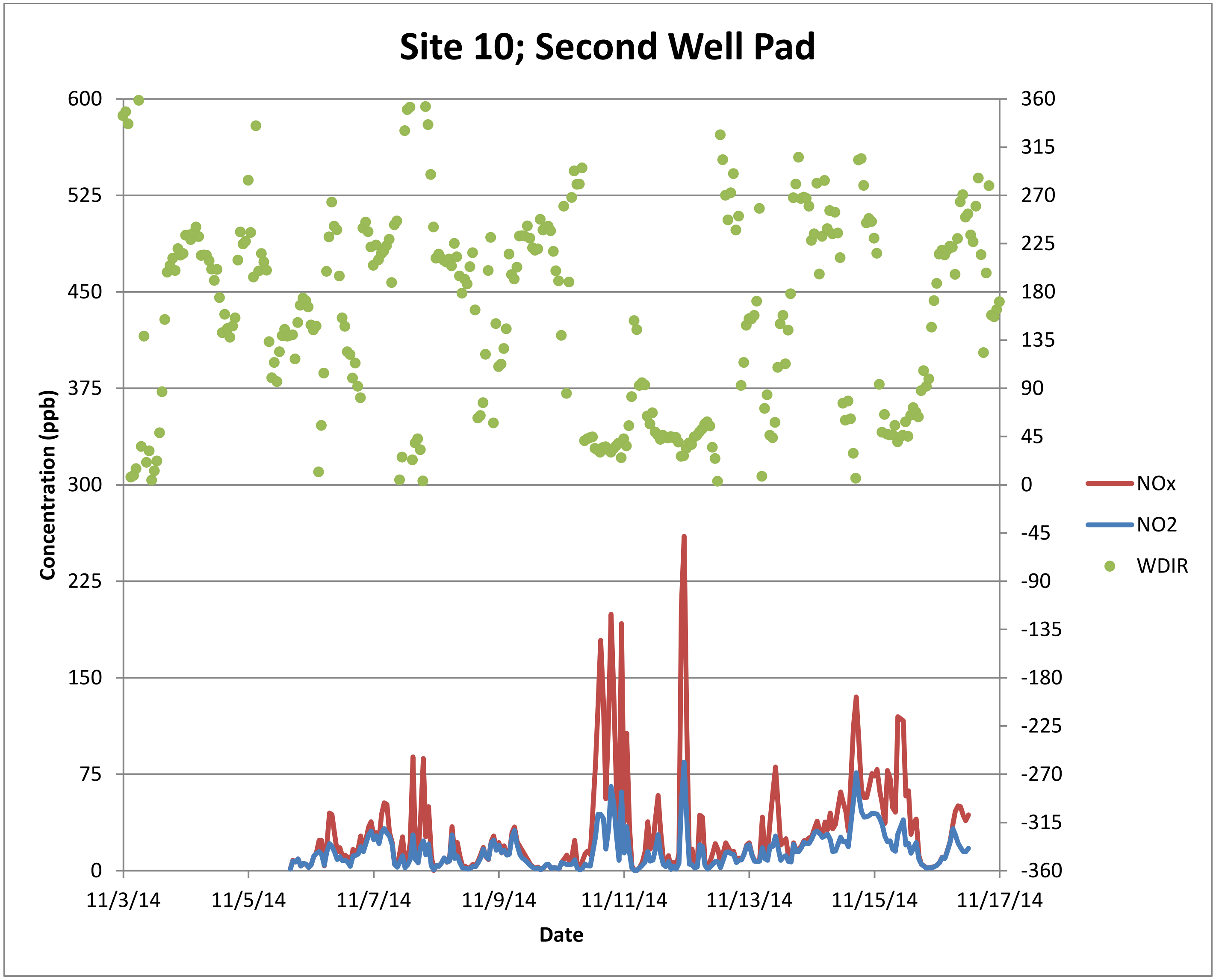

Figure 5-30. Time Series Plot for Well Pad No. 2 – Site #10

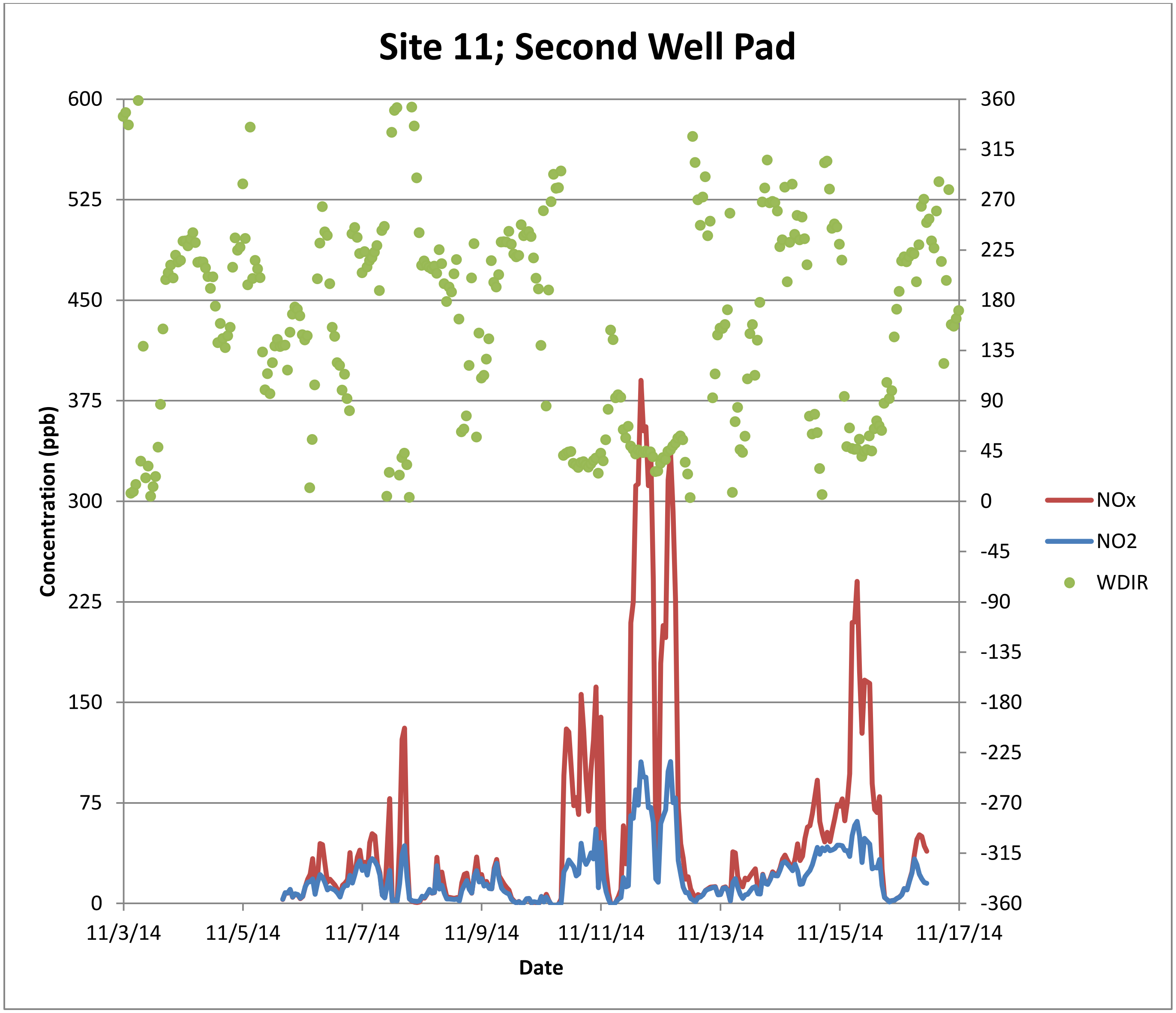

Figure 5-31. Time Series Plot for Well Pad No. 2 – Site #11

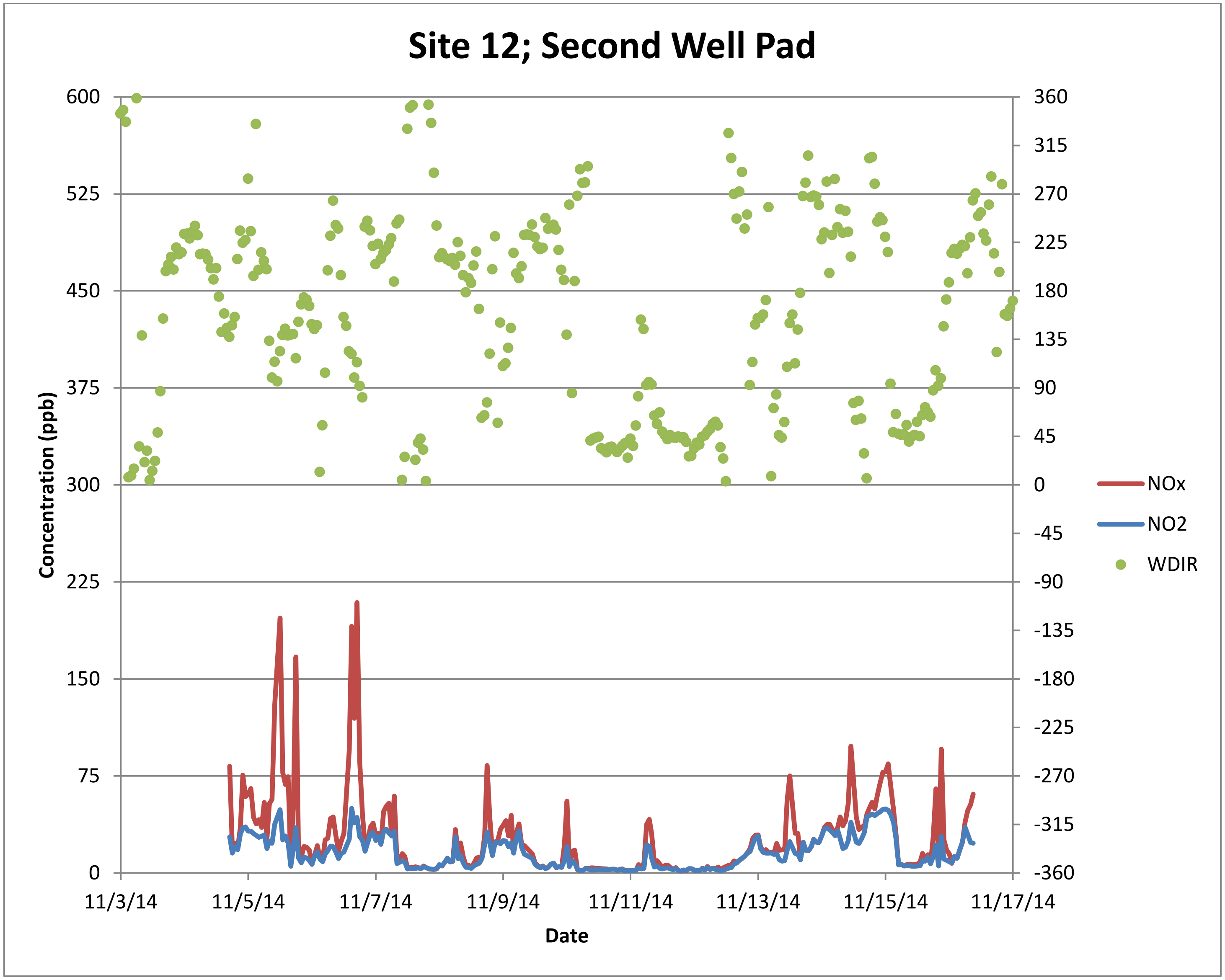

Figure 5-32. Time Series Plot for Well Pad No. 2 – Site #12